Electronic Supplementary Material (ESI) for Energy & Environmental Science.

Supplemental Information

Sustainable development of biorefineries: integrated assessment method for co-production pathways

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S.1 Trends in bio-based energy production and prices

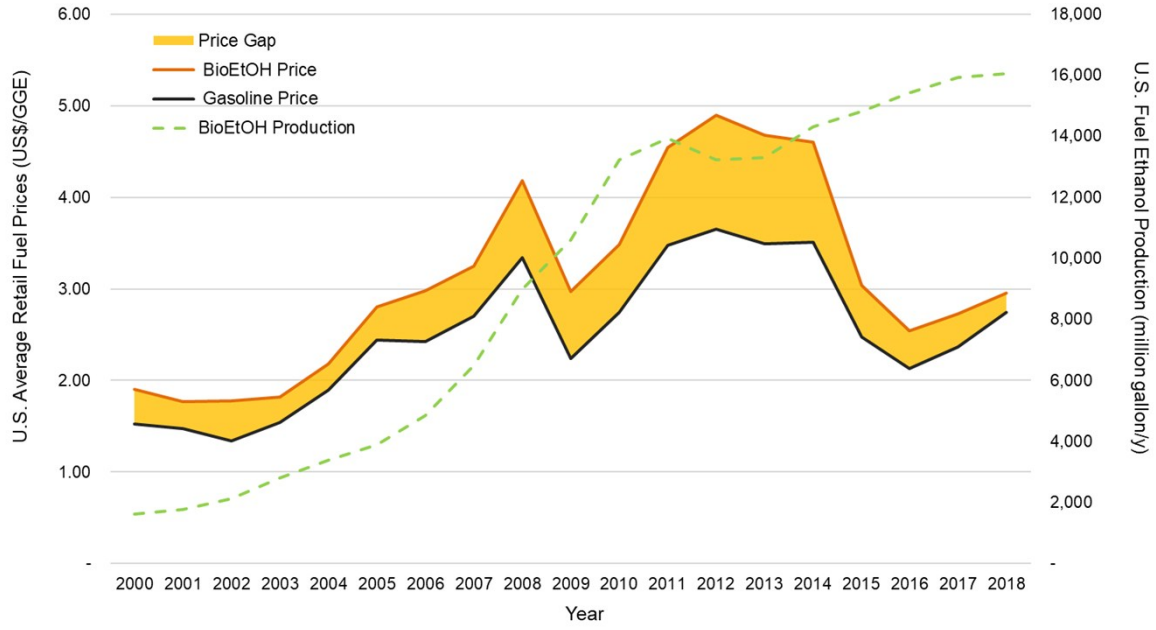


Figure S1 U.S. fuel prices (gasoline and bioethanol [bioEtOH]) and bioEtOH production in the 2000s. The solid lines indicate the average retail fuel prices of gasoline (black) and bioEtOH (orange), while the dotted line indicates fuel ethanol production. The solid fill area indicates the price gap between gasoline and bioEtOH. Average U.S. retail fuel prices per GGE data were taken from clean city alternative fuel price reports from the U.S. Department of Energy.[1] These data included price data for fossil fuels and biofuels from 2000 to 2018.

S.2 Literature reviews of feasibility research on coproduction pathways

This study determined five main categories for the feasibility assessment, as follows: M1 (system boundary), M2 (technological level), M3 (allocation), M4 (environmental aspect), and M5 (uncertainties). Each main category included the following detailed categories: M1—s1 (conversion), s2 (separation), s3 (disposal), and s4 (feedstock); M2—s1 (capital cost growth) and s2 (plant performance reduction); M3—s1 (mass-based allocation), s2 (energy-based allocation), s3 (economic-based allocation), and s4 (credit-based allocation); M4—s1 (global warming potential) and s2 (fossil depletion); M5—s1 (uncertainty in feedstock price), s2 (uncertainty in utility price), and s3 (uncertainty in product yield).

Table S1 Literature review of LCA studies on the coproduction pathways.

			M1				M2		M3				M4		M5				
No.	**Authors**	**Year**	**s1**	**s2**	**s3**	**s4**	**s1**	**s2**	**s1**	**s2**	**s3**	**s4**	**s1**	**s2**	**s1**	**s2**	**s3**	**Bioenergy**	**Bioproduct**
1	Soh, L. et al. [2]	2014	O	O		O							O					Biofuel	Glycerol
2	Tao, L. et al. [3]	2014	O	O						O			O					Butanol, ethanol	
3	Aitken, D. et al. [4]	2014	O	O		O							O					Ethanol, electricity	
4	Fortier, M. et al. [5]	2014	O										O				O	Biofuel, bio-oil	
5	Orfield, N. et al. [6]	2014	O										O					Bio-oil	
6	Fiorentino, G. et al. [7]	2014	O	O	O	O					O		O		O		O	Electricity, diesel	
7	Karlsson, H. et al. [8]	2014	O	O		O				O			O					Ethanol, heat	
8	Schmer, M. et al. [9]	2014	O	O						O			O					Ethanol, biofuel	
9	Pieragostini, C. et al. [10]	2014	O	O		O			O		O		O	O	O			Ethanol, heat	
10	Kajaste, R. et al. [11]	2014	O	O	O	O				O	O		O	O			O	Ethanol	Arabinoxylan
11	Gabrielle, B. et al. [12]	2014	O	O	O	O					O		O	O				Ethanol, heat	
12	Guo, M. et al. [13]	2014	O	O	O	O				O			O	O				Electricity, Ethanol	
13	Schmer, M. et al. [14]	2014	O	O			O						O					Biofuel, electricity	
14	Falano, T. et al. [15]	2014	O		O	O					O		O	O				Ethanol	Lactic acid
15	Scown, C. D. et al. [16]	2014	O	O					O	O			O					Ethanol, electricity	
16	Yao, Y. et al. [17]	2014	O	O				O					O					Electricity, bio-oil	

Table S1 Literature review of LCA studies on the coproduction pathways (continued).

			M1				M2		M3				M4		M5				
No.	**Authors**	**Year**	**s1**	**s2**	**s3**	**s4**	**s1**	**s2**	**s1**	**s2**	**s3**	**s4**	**s1**	**s2**	**s1**	**s2**	**s3**	**Bioenergy**	**Bioproduct**
17	Wu, M. M.et al.[18]	2014	O		O								O					Biofuel	
18	Sanchez, A. et al.[19]	2014	O	O									O					Biofuel, Ethanol	
19	Wang, L. et al.[20]	2014	O	O	O								O					Ethanol	Sugar
20	McKechnie, J et al. [21]	2015	O	O		O			O				O					Electricity, ethanol	
21	Morales. M et al. [22]	2015	O	O	O	O			O	O	O		O	O			O	Ethanol	lignin
22	Bennion, E. et al. [23]	2015	O			O		O					O					Biofuel	Ammonium phosphate
23	Schmidt, T. et al. [24]	2015	O	O	O	O							O					Biofuel, ethanol	
24	Parajuli, R. et al. [25]	2015	O		O	O			O	O	O		O	O				Electricity, ethanol	
25	Goglio, P. et al. [26]	2015	O	O	O				O				O					Biofuel, biochar	
26	Pereira, L. et al. [27]	2015	O			O				O	O		O	O				Ethanol, buthanol	
27	Maranduba, H. et al. [28]	2015	O	O	O	O			O	O			O	O				Biochar	Pyrolysis gas
28	Valle, C. et al. [29]	2015	O	O		O	O			O			O					Electricity, ethanol	
29	Nanda, S. et al. [30]	2015	O		O	O			O	O	O		O					Electricity, ethanol	Arabinoxylan
30	Morales. M et al. [31]	2015	O	O	O	O							O					Glycerol	Lactic acid
31	Daystar, J. et al. [32]	2015	O	O	O	O			O	O	O		O					Ethanol, methanol	
32	Haro, P. et al. [33]	2015	O			O				O			O	O				Ethanol	Methyl acetate
33	Barlow Jay et al. [34]	2016	O	O	O	O		O		O	O		O					Biodiesel, heat, electricity	
34	Gnansounou et al. [35]	2016	O	O		O			O		O		O					Biodiesel, heat, electricity	Succinic acid
35	Gerbrandt et al. [36]	2016	O			O					O							Ethanol, heat, electricity	
36	Watanabe et al. [37]	2016	O	O		O				O	O		O					Ethanol, heat, electricity	
37	Suganya et al.[38]	2016	O	O		O					O							Biodiesel, ethanol, heat, electricity	
38	Pourhashem et al. [39]	2016		O		O					O							Biodiesel, ethanol, heat, electricity	
39	Manganaro et al. [40]	2016	O	O		O					O		O					Biodiesel, heat, electricity	Animal feed
40	Pan et al. [41]	2016	O	O		O			O		O		O					Ethanol, heat, electricity	
41	Yahm et al.[42]	2016	O	O		O				O	O							Ethanol, bio-gas	
42	Patel, Bhavish et al. [43]	2016	O	O		O	O				O		O	O				Biodiesel, heat, electricity	

Table S1 Literature review of LCA studies on the coproduction pathways (continued).

			M1				M2		M3				M4		M5				
No.	**Authors**	**Year**	**s1**	**s2**	**s3**	**s4**	**s1**	**s2**	**s1**	**s2**	**s3**	**s4**	**s1**	**s2**	**s1**	**s2**	**s3**	**Bioenergy**	**Bioproduct**
43	Crawford et al. [44]	2016	O	O	O	O	O	O			O							Biofuel, heat, electricity	
44	Zhao, Lili et al. [45]	2016	O	O		O			O		O		O					Ethanol, biofuel	
45	Wang et al. [46]	2016	O	O		O					O							Biofuel	
46	Nanda et al. [47]	2016	O	O		O			O		O		O					Heat, electricity	Bio-char
47	Chew et al. [48]	2017	O			O			O				O					Biofuel	
48	Mandegari et al. [49]	2017	O			O	O		O	O			O					Ethanol, electricity	
49	Parajuli et al. [50]	2017	O			O			O	O			O		O	O		Ethanol, electricity	Lactic acid
50	Carneiro et al. [51]	2017	O			O			O	O			O					Biofuel, biodiesel	
51	Jez, Sabina et al. [52]	2017	O			O			O	O			O	O	O	O		Biofuel, biodiesel	
52	Farzad, Somayeh et al[53]	2017	O	O	O	O	O		O	O			O	O				Heat, electricity, ethanol	Lactic acid, ethanol
53	Seghetta, Michele et al. [54]	2017	O	O		O							O					Heat, electricity	Protein
54	Quiroz-Arita, Carlos [55]	2017	O	O		O					O		O					biofuel, biodiesel	
55	Tu, Qingshi [56]	2017	O		O	O			O	O			O		O	O	O	Biofuel, biodiesel	
56	Shurtz, Benjamin K. et al. [57]	2017	O			O		O	O									Biofuel, biodiesel	
57	Cavalett, Otávio, et al. [58]	2017	O			O			O				O					Electricity, ethanol	
58	Bello, Muhammadu et al. [59]	2017	O			O				O			O			O	O	biofuel, biodiesel	
59	Fozer, Daniel, et al. [60]	2017	O			O												biofuel, biodiesel, biogas	
60	Cronin, Keith R., et al. [61]	2017	O			O			O				O					Electricity, biofuel, ethanol	
61	Mandegari et al. [62]	2016	O	O		O	O	O			O		O					Electricity, heat	Sugar
62	Olofsson et al. [63]	2016	O	O		O	O			O			O					Ethanol, steam, electricity	
63	Hernandez, E. M. et al. [64]	2018	O				O			O			O					Butanol, ethanol	acetone
64	Mandegari, M et al. [65]	2018	O						O				O					Ethanol	Methanol, Lactic acid
65	Liard, G. et al. [66]	2018				O						O	O					Ethanol	Polylactic acid
66	Liu, H. et al. [67]	2018				O				O			O					Ethanol, biodiesel	
67	Guerrero, A. B. et al. [68]	2018		O	O					O			O	O				Ethanol	Lignin, methane
68	Jin, Q. et al. [69]	2018			O	O				O			O	O				Ethanol, biogas	Lactic acid

Table S1 Literature review of LCA studies on the coproduction pathways (continued).

			M1				M2		M3				M4		M5				
No.	**Authors**	**Year**	**s1**	**s2**	**s3**	**s4**	**s1**	**s2**	**s1**	**s2**	**s3**	**s4**	**s1**	**s2**	**s1**	**s2**	**s3**	**Bioenergy**	**Bioproduct**
69	González-García, S. et al. [70]	2018	O	O		O					O		O		O			Ethanol	xyloligosaccharides
70	Yang, M. et al. [71]	2018				O					O		O					Ethanol	ethylene
71	Tu, Q. et al. [72]	2018		O		O						O	O					Biodiesel, heat, electricity	
72	Braz, D. S et al. [73]	2018	O	O	O	O			O	O	O		O					Biofuel, electricity	
73	Spekreijse, J et al. [74]	2019			O	O				O								oil, heat, electricity	
74	DeRose, K. [75]	2019	O			O					O	O	O						Struvite, fusel alcohol
75	Somers, M. D. [76]	2019	O								O	O	O					Biodiesel	Naphtha
76	Dunn, J. B. et al. [77]	2019	O		O	O				O			O					Ethanol	2,3-butanediol
77	Zhang, Y. et al .[78]	2019	O		O	O					O	O	O		O	O		Biodiesel	
78	Nieder-Heitmann, M. et al. [79]	2019	O		O	O		O	O				O						Polyhydroxy butyrate, succinic acid
79	Dasan, Y. K. et al. [80]	2019	O		O	O					O	O	O					Ethanol, biodiesel	
80	Khoo, C. G. et al. [81]	2019				O				O			O					Biodiesel	Lactic acid, isopropanol,
81	Meng, F. et al. [82]	2019	O	O		O					O	O	O					Ethanol, electricity	acetone, hydrogen,
82	DeRose, K. et al. [83]	2019	O	O		O				O			O						Fusel alcohols, enriched protein
83	Carvalho, F. S. [84]	2019		O		O				O			O					Biodiesel	
84	Navarro-Pineda, F. S. [85]	2019			O	O	O						O					Biodiesel, electricity	Biochar
85	Jonker, J. G. [86]	2019	O	O		O	O	O			O	O	O					Ethanol	Ethylene, 1,3-PDO, succinic acid

Table S2 Literature review of TEA studies on the coproduction pathways.

			M1				M2		M3				M4		M5				
No.	**Authors**	**Year**	**s1**	**s2**	**s3**	**s4**	**s1**	**s2**	**s1**	**s2**	**s3**	**s4**	**s1**	**s2**	**s1**	**s2**	**s3**	**Bioenergy**	**Bioproduct**
1	Tao, L. et al. [3]	2014		O		O	O					O						Ethanol, butanol	
2	Brown, T. et al. [87]	2014		O	O	O	O	O				O	O	O		O	O	Ethanol	H_2
3	Brown, T. et al. [88]	2014		O		O	O					O	O	O			O	LPG, electricity	
4	Sanchez, A. et al. [19]	2014		O		O	O					O	O					Biofuel, electricity	
5	Davis, R. E. et al. [89]	2014		O		O						O	O					Biodiesel, biofuel	Hydrocarbon
6	Xiang, Z. et al. [90]	2014		O	O	O	O	O				O						Heat	Furfural
7	Lanzaafame, P. et al. [91]	2014		O		O						O	O					Ethanol, methane	
8	Wang, L. et al. [20]	2014		O		O	O	O				O						Electricity, ethanol	
9	Xiang, Z. et al. [92]	2014		O		O						O							DG-gum, Animal Feed
10	Jones, S. B. et al. [93]	2014		O	O	O	O	O				O	O					Electricity	naphtha
11	Zhu, L. et al. [94]	2015		O		O						O						Biodiesel, Ethanol	
12	Brown, T. R. et al. [95]	2015		O		O	O					O	O					Bio-oil, electricity	
13	Li, B. et al. [96]	2015		O		O	O					O					O	Biofuel, biodiesel, electricity	
14	Morales. M et al. [31]	2015	O	O	O	O							O						Lactic acid, glycerol
15	Zhao, X. et al. [97]	2015		O		O	O					O	O					Biofuel	
16	Suhag, M. et al. [98]	2015		O		O	O					O						Biogas, ethanol	
17	Yuan, Z. et al. [99]	2015		O		O	O					O						Biofuel, electricity	
18	Fasahati, P. et al. [100]	2015		O		O	O	O				O						Electricity	Alcohols
19	Laurens, L. et al. [101]	2015		O		O		O				O						Biofuel, ethanol	
20	Valle, C. R. et al. [29]	2015		O		O	O					O	O					Electricity	Alcohol
21	Romero-García, J. M., et al. [102]	2016	O	O		O	O					O						Ethanol, heat, electricity	
22	Barlow Ja, et al. [34]	2016	O	O	O	O		O		O		O	O					Biodiesel, heat, electricity	
23	Gnansounou, et al. [35]	2016	O	O								O	O	O				Biodiesel, heat, electricity	Succinic acid
24	Dong, Tao, et al. [103]	2016	O	O		O						O						Bio-oil, ethanol	
25	Suganya, T., et al. [38]	2016	O	O	O	O						O						Bio-oil, bio-gas, ethanol	
26	Unrean, et al. [104]	2016	O	O	O	O	O	O				O						Ethanol, heat, electricity	

Table S2 Literature review of TEA studies on the coproduction pathways (continued).

			M1				M2		M3				M4		M5				
No.	**Authors**	**Year**	**s1**	**s2**	**s3**	**s4**	**s1**	**s2**	**s1**	**s2**	**s3**	**s4**	**s1**	**s2**	**s1**	**s2**	**s3**	**Bioenergy**	**Bioproduct**
27	Moncada, Jonathan, et al. [105]	2016		O		O		O				O						Ethanol, heat, electricity	
28	Sanchez, A., et al. [106]	2017	O	O		O		O				O						Butanol, heat	Acetone
29	Snehesh, et al. [107]	2017	O	O			O					O						Heat, electricity	
30	Mandegari, et al. [62]	2017	O	O		O	O	O				O	O					Electricity, heat	Sugar
31	Olofsson, et al. [63]	2017	O	O		O	O					O	O					Ethanol, heat, electricity	
32	Tao, et al. [108]	2017	O	O		O	O	O				O			O	O	O	Ethanol, biodiesel	
33	Shurtz, et al. [57]	2017	O	O		O						O						Ethanol, biodiesel	
34	Hoffman, et al. [109]	2017	O	O		O						O						Biodiesel, electricity, heat	
35	Hernandez, E. M. et al. [64]	2018	O				O					O						Butanol, ethanol	Acetone
36	Jin, Q. et al. [69]	2018			O	O						O						Biogas, ethanol,	Lactic acidc
37	Mandegari, M et al. [65]	2018	O									O						Ethanol	Methanol, lactic acid
38	Solarte-Toro, J. C. [110]	2018	O	O		O	O					O						Ethanol	Lignin
39	Nieder-Heitmann, M. et al. [111]	2018	O	O		O	O					O						Electricity	Itaconic acid
40	Pérez-López, P. et al. [112]	2018	O	O		O	O					O			O	O		Biodiesel, electricity	
41	Li, X. et al. [113]	2018	O	O	O	O	O	O				O						Biofuel, biodiesel	
42	Gunukula, S. et al. [114]	2018	O	O	O	O	O					O						Biofuel	Furfural, levulinic acid
43	Jang, M. O. et al. [115]	2018	O	O		O						O						Butanol, ethanol	Acetone
44	Braz, D. S et al. [73]	2018	O	O	O	O						O						Biofuel, electricity	
45	Thaore, V. et al. [116]	2018	O	O	O	O						O							Caprolactone
46	Mupondwa, E. et al. [117]	2018	O	O		O						O						Ethanol, steam	
47	Huang, K. et al. [118]	2018	O	O		O	O					O						Ethanol	Pentanediol
48	Parsons, S. [119]	2019	O	O		O	O	O				O	O	O	O			Phenylethanol	Cell oils
49	Lopes, T. F. [120]	2019	O	O		O						O	O					Ethanol	Zeaxanthin, phycocyanin
50	Somers, M. D. [76]	2019	O									O						Biodiesel	Naphtha
51	Dasan, Y. K. et al. [80]	2019	O		O	O						O						Biodiesel, ethanol	
52	DeRose, K. et al. [83]	2019	O	O		O						O						Biofuel	Alcohols, Enriched protein

Table S2 Literature review of TEA studies on the coproduction pathways (continued).

			M1				M2		M3				M4		M5				
No.	**Authors**	**Year**	**s1**	**s2**	**s3**	**s4**	**s1**	**s2**	**s1**	**s2**	**s3**	**s4**	**s1**	**s2**	**s1**	**s2**	**s3**	**Bioenergy**	**Bioproduct**
53	Larnaudie, V. [121]	2019	O	O	O	O	O					O						Ethanol, electricity	Furfural, acetic acid formic acid
54	Ghayur, A. [122]	2019	O	O	O	O						O	O		O				Acetic acid, dimethyl ether
55	Navarro-Pineda, F. S. [85]	2019			O	O	O					O						Biodiesel, electricity	Bio-char
56	Nieder-Heitmann, M. et al. [79]	2019	O	O		O	O	O				O	O	O	O				Polyhydroxybutyrate, succinic acid
57	Nieder-Heitmann, M. et al [123]	2019	O	O		O						O	O						succinic acid polyhydroxybutyrate
58	Jonker, J. G. et al. [86]	2019	O									O						Ethanol	Ethylene, pentanediol, succinic acid
59	Mesfun, S. et al. [124]	2019	O		O	O						O						Ethanol, heat, electricity	
60	Wang, W. C. et al. [125]	2019	O	O		O						O						Biofuel	Naphtha

S.3 A coincident feasibility assessment compensating for limitations and combining methodologies

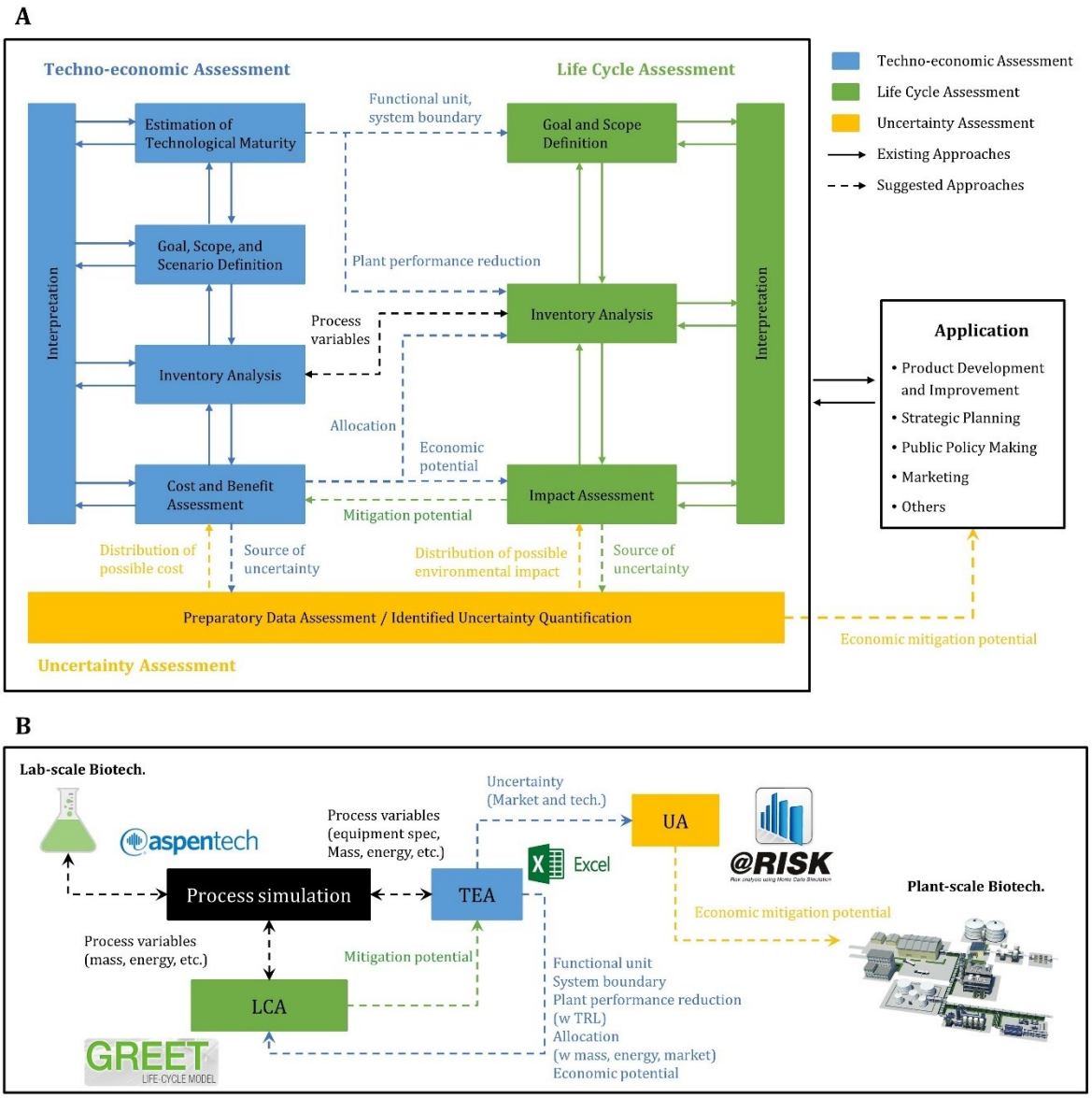


Figure S2 Methodological framework for feasibility assessments (TEA, LCA, and UA). The solid boxes represent the phases in each feasibility assessment (blue box [TEA], green box [LCA], and yellow box [UA]] and the application of the feasibility assessment. The solid arrows indicate the transfer of information or results within each assessment, while the dotted arrows indicate the transfer of information or results between different types of assessments [blue arrow [TEA to others], green arrow [LCA to others], yellow arrow [UA to others], and black arrow [TEA and LCA exchange]).

S.4 Process description

This study compared 10 coproduction pathways processing 2,000 tonnes per day (t/d) of corn stover. The process data for each strategy were obtained from previous system-level studies[126, 127] that developed simulation models based on experimental data. Et1, producing sugar by enzymatic hydrolysis, is composed of six main steps (pretreatment, enzymatic hydrolysis, fermentation, ethanol recovery, heat/power generation, and wastewater treatment [WWT]),[126] and Et2, producing sugar by catalytic hydrolysis, is composed of six main steps (catalytic hydrolysis, sugar and γ-valerolactone (GVL) recovery, ethanol recovery, heat/power generation, and WWT)[127] A block flow diagram for each strategy is show in Supplementary Figure 3.

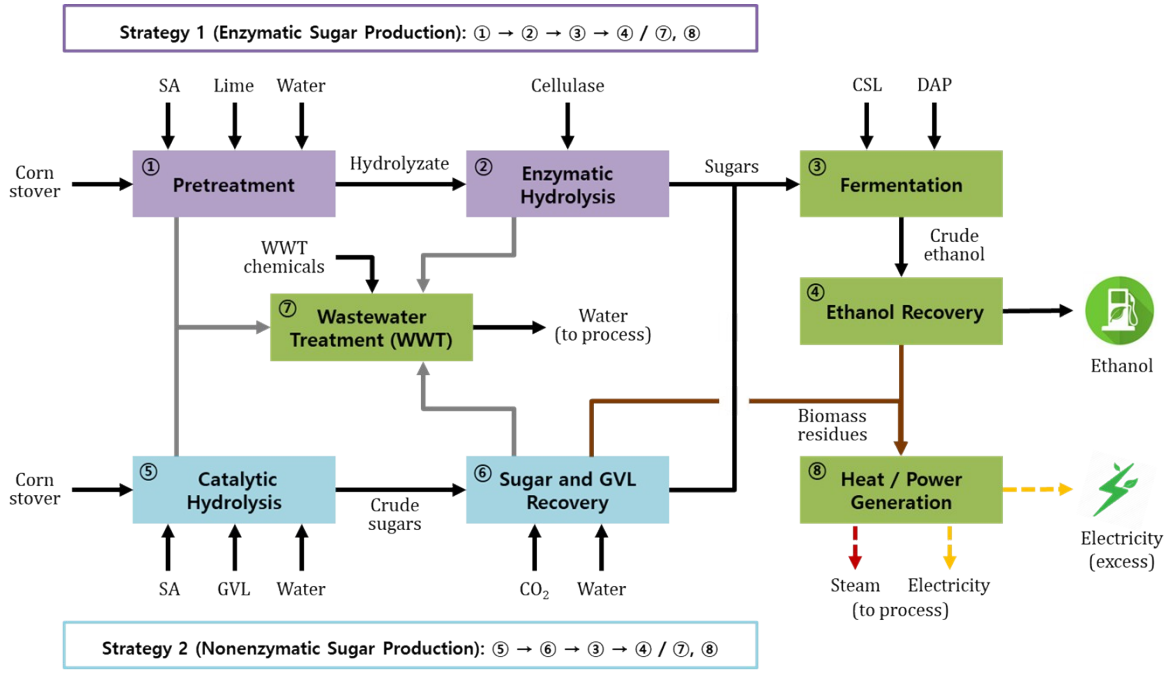


Figure S3 Block flow diagram of enzymatic hydrolysis based bioEtOH production (Et1) and catalytic hydrolysis based bioEtOH production (Et2).

S.4.1 Enzymatic hydrolysis based bioEtOH production (Et1)

Corn stover is processed in enzymatic sugar production, which involves pretreatment, enzymatic hydrolysis, fermentation, EtOH recovery, heat/power generation, and WWT. In the Et1, 153,000 gallons of EtOH (102,000 GGE) are daily produced from 2000 tons/day (t/d) of corn stover. Firstly, washed and shredded corn stover (19.606 kg/GGE_{EtOH}) is sent to the pretreatment step with steam (11.813 kg/GGE_{EtOH}) and sulfuric acid (1.951 kg/GGE_{EtOH}). After the hydrolysis of the corn stover, $Ca(OH)_2$ (1.441 kg/GGE_{EtOH}) is added to reduce toxicity by neutralizing the sulfuric acid in the

hydrolysate. The hydrolysate (97.904 kg/GGE_{EtOH}) with gypsum (3.255 kg/GGE_{EtOH}) is subsequently removed by pressure filtration and sent to the enzymatic hydrolysis step, where glucose is produced from cellulose by using cellulase (2.049 kg/GGE_{EtOH}). After enzymatic hydrolysis, 10% of the sugar liquor (9.999 kg/GGE_{EtOH}) is sent to seed fermenter, while 90% of the sugar liquor (89.954 kg/GGE_{EtOH}) is sent to the EtOH fermenter. In the seed fermenter, inoculum (9.597 kg/GGE_{EtOH}) is produced from sugar liquor (9.999 kg/GGE_{EtOH}), corn steep liquor (CSL; 0.049 kg/GGE_{EtOH}), and diammonium phosphate (DAP; 0.007 kg/GGE_{EtOH}). Then, fermented beer (96.708 kg/GGE_{EtOH}) is produced from sugar liquor (89.954 kg/GGE_{EtOH}), inoculum (9.597 kg/GGE_{EtOH}), and CSL (1.010 kg/GGE_{EtOH}) in the EtOH fermenter. Through the EtOH recovery step, high purity EtOH (99.5 wt%) is obtained by distillation and molecular sieve adsorption, and the biomass residues (29.694 kg/GGE_{EtOH}) are sent to the heat/power generation step. The heating and electricity requirements for the Et1 are satisfied by the combustion of the biomass residues, and the excess electricity (4.411 kWh/GGE_{EtOH}) is sold to the grid. The wastewater (20.136 kg/GGE_{EtOH}) discharged in the Et1 is treated in anaerobic and aerobic digesters in the WWT step using nutrients and chemicals, and treated water (19.969 kg/GGE_{EtOH}) is recycled as process water.

S.4.2 Catalytic hydrolysis based bioEtOH production (Et2)

Corn stover is processed in nonenzymatic sugar production, which involves sugar production, sugar and GVL recovery, fermentation, EtOH recovery, heat/power generation, and WWT. In the Et2, 144,000 gallons of EtOH (96 thousand GGE) are produced daily from 2000 t/d of corn stover. Firstly, washed and shredded corn stover (20.768 kg/GGE_{EtOH}) is sent to sugar production step using a GVL-water solvent (4:1 mass ratio; 276.131 kg/GGE_{EtOH}) and sulfuric acid catalyst (1.321 kg/GGE_{EtOH}). In the sugar production step, which consists of a two-stage hydrolysis step, the cellulose fraction is converted to C_6 sugar, levulinic acid, and 5-hydroxymethylfurfural, while the hemicellulose fraction is converted to C_5 sugar and furfural. The resulting mixture contains certain materials that can inhibit the fermentation of C_6 and C_5 sugars, such as solvent (GVL), catalyst (sulfuric acid [SA]), and byproducts (levulinic acid, formic acid, furfural, biomass residues [lignin and humins]). The resulting mixture (316.454 kg/GGE_{EtOH}) is sent to the sugar and GVL recovery step using CO_2 extraction and evaporation. Through the CO_2 extraction, most of the byproducts (29.482 kg/GGE_{EtOH}) and 99% of GVL solvent (221.278 kg/GGE_{EtOH}) are extracted from the resulting mixture using CO_2 (144.096 kg/GGE_{EtOH}), and the sugars (10.068 kg/GGE_{EtOH}) and SA (1.321 kg/GGE_{EtOH}) are sent to the fermentation step. After the extraction, the CO_2 and GVL are separated for reuse in the extraction and hydrolysis reactions, respectively. The CO_2 (144.096 kg/GGE_{EtOH}) is separated from the byproducts and solvent stream using a series of vapor-liquid separators and is recycled to the extraction process after compression. The byproducts and GVL stream extracted by CO_2 (251.309 kg/GGE_{EtOH}) are split

into three streams that are sent to the gas-solid separator for separating GVL from biomass residues, to the reactor for producing GVL to make up the loss of GVL, and to the two-stage hydrolysis step. Prior to fermentation, SA in the sugar stream is neutralized using $Ca(OH)_2$ (1.000 kg/GGE_{EtOH}), and the precipitate (2.323 kg/GGE_{EtOH}) is removed by pressure filtration. Similar to the Et1, sugar streams diluted with a water to mass ratio of 0.2 are converted to 5 wt% EtOH over engineered yeast (0.088 kg/GGE_{EtOH}) in fermentation, and high purity EtOH (99.5 wt%) is obtained from EtOH recovery. Combustion energy of biomass residues (11.140 kg/GGE_{EtOH}) satisfy the heating and electricity requirements, and the excess electricity (1.029 kWh/GGE_{EtOH}) is sold to the grid. The wastewater (32.169 kg/GGE_{EtOH}) discharged in the Et2 is treated in anaerobic and aerobic digesters in the WWT step using nutrients and chemicals, and the treated water (19.969 kg/GGE_{EtOH}) is recycled as process water.

S.4.3 Selection of coproduction pathway

In this study, five bio-based coproducts (adipic acid [AdA], caprolactam [CaL], pentanediol [Diol], phthalic anhydride [PAN], furan dicarboxylic acid [FDCA]) are selected for coproduction strategies by considering the following criteria: (1) a current or future market size of at least 100 kilotonnes per year, (2) a significant substitution potential of bio-based products to replace their petrochemical reference products with a well-known GHG emission intensity, (3) availability of sufficient data derived from the conceptual design developed in the literature. The market size of each coproduct is shown in Supplementary Table 3.

Table S3 Market size of coproducts

	Market size (million t per year)*	Year basis
Adipic acid (AdA)[128]	2.02	2016
Caprolactam (CaL)[129]	4.21	2014
Pentanediol (Diol)[118]	2.33	2016
Phthalic anhydride (PAN)[130]	4.04	2013
Furan dicarboxylic acid (FDCA)[131]	50.0#	2013

* Market size is estimated based on the market forecast data and market price of each product.
# Potential market size (building block of polyester)

S.5 Techno-economic assessment

The goal of TEA is to quantify the economic feasibility of the coproduction pathways using corn stover. The economic potential (EP) of the coproduction pathways in each scenario is estimated by TEA. The total cost, which consists of capital and operating costs and revenues of the strategies, is calculated based on the process data and economic parameters.[126]

For each pathway, the total cost is calculated. Firstly, equipment costs are assumed using the ASPEN Process Economic Analyzer or exponential scaling expressions based on equipment size and material data. Following this, the total capital investment is determined by considering the direct and indirect overhead cost factors, such as the installation costs and project contingencies. In addition, the TCI is converted to an annualized capital cost by considering the project year and depreciation. Operating costs include variable operating costs (e.g., materials, utilities) and fixed operating costs (e.g., labor, maintenance, insurance) related to the capital cost, and the sales revenue of excess electricity from the strategies is counted as revenue.

Understanding the current technology level and depth of knowledge is important in TEA because these factors are used as basic data in assessing the applicability of a proposed technology in real-plant conditions and assuming cost growth with unexpected problems, such as inflation, unanticipated regulatory changes, and force majeure events like difficulties in process operations arising from technical and mechanical limitations.[132]

Pioneer plant analysis is another method that enables estimations of cost growth at low TRL technologies using two regression equations (cost misestimation and plant performance reduction) that are derived from data from 44 commercial plants.[132] This method can be applied to various refinery processes, and has been used in some feasibility studies on biorefineries to consider the effect of technological immaturity on process economics. Supplementary Tables 4 and 5 show the plant performance reduction and capital cost growth variables for Et1 and Et2.

Finally, the EP of bioEtOH is determined and is expressed in terms of GGE to facilitate a comparison of the results with commercial transportation fuels.

Table S4 Plant performance reduction and capital cost growth variables for Et1.

Plant Performance Reduction (Equation 1)		Capital Cost Growth (Equation 2)	
Variables	Values	Variables	Values
New steps [a]	3	PCTNEW	51.3
BALEQS	50	IMPURITIES	0
WASTE	1	COMPLEXITY [a]	3
SOLIDS	1	INCLUSIVE-NESS	33
		C1	0.06361
		PROJECT DEFINITION	6
Plant performance (%)	51.17	**Cost growth**	0.59

[a] Pretreatment, Saccharification, BioEtOH recovery

Table S5 Plant performance reduction and capital cost growth variables for Et2.

Plant Performance Reduction (Equation 1)		Capital Cost Growth (Equation 2)	
Variables	Values	Variables	Values
New steps [a]	3	PCTNEW	58.91
BALEQS	50	IMPURITIES	0
WASTE	1	COMPLEXITY [a]	3
SOLIDS	1	INCLUSIVE-NESS	33
		C1	0.06361
		PROJECT DEFINITION	6
Plant performance (%)	51.17	**Cost growth**	0.57

[a] Two-stage catalytic hydrolysis, Sugar and GVL recovery, BioEtOH recovery

The four scenarios for TEA are as follows (Figure 3 in the manuscript): base case—EP of bioEtOH excluding the separation process**,** M1—EP of bioEtOH including the separation process, M2—EP of bioEtOH considering TRLs, and M4—EMP of bioEtOH considering carbon credit.

Figure 3 shows the EP of bioEtOH, revenue from electricity, and carbon credit. Thus, this section focuses on presenting changes in capital and operating costs. The base case only considers conversion processes, which assumes that bioEtOH and coproducts obtained after the conversion process can be sold without separation. Following this, a further factor is considered as the scenario changes. In M1, the system boundary is expanded by considering the separation process. Compared to the base scenario, M1 includes equipment and heating requirements for recovering bioEtOH. This leads to an increase in capital costs (11% [Et1f] and 35% [Et2f]) and a decrease in electricity revenue (50% [Et1f] and 88% [Et2f]) due to the use of byproducts to meet heating requirements. The M2 shows the effect of low TRLs on the EP of bioEtOH. Pioneer plant analysis is applied to Et1f and Et2f, based on the immature technology. A significant increase in capital costs (69–76%) and decrease in the amount of bioEtOH and coproducts produced over the lifetime of the plant (2%) for Et1f and Et2f lead to a decline in profitability and an increase in the EP of bioEtOH for each pathway. The large capital cost of Et2f for additional separation processes is the main reason for the inversion of EP of two pathways. The M4 shows the effect of carbon credits. Based on the carbon price (US$60/t CO_2e)[133] and mitigation potential (11.5 kg CO_2 [Et1f] and 12.6 kg CO_2 [Et2f]), which is obtained from LCA, the carbon credits of each strategy are calculated. The M5 presents the effect of price fluctuations on the EMP of bioEtOH. Historical information (average, minimum, and maximum) about the two variables (corn stover price and carbon price) is transferred from the TEA to the UA, and statistical information for the EMP (possible range, mean, and range at each confidence level) is obtained.

Table S6 Discounted cash flow sheet for Et1f (base case).

Year	-2	-1	0	1	2	3	4	5	6	7	8
Capital Investment	23,606,112	177,045,840	94,424,448								
Working Capital			44,261,460								
Fuel Sales				15,167,317	20,223,090	20,223,090	20,223,090	20,223,090	20,223,090	20,223,090	20,223,090
Chemical Sales				107,397,921	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228
Electricity Sales				17,591,197	23,454,930	23,454,930	23,454,930	23,454,930	23,454,930	23,454,930	23,454,930
Carbon Credit				0	0	0	0	0	0	0	0
Total Annual Sales				140,156,436	186,875,248	186,875,248	186,875,248	186,875,248	186,875,248	186,875,248	186,875,248
Feedstock Cost				50,713,475	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials				48,228,258	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010
Other Variable Costs				5,950,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000
Fixed Operating Costs				8,986,500	8,986,500	8,986,500	8,986,500	8,986,500	8,986,500	8,986,500	8,986,500
Total Product Cost				113,878,233	128,862,767	128,862,767	128,862,767	128,862,767	128,862,767	128,862,767	128,862,767
Annual Depreciation											
General Plant											
DDB				50,034,694	35,739,067	25,527,905	18,234,218	13,024,441	9,303,172	6,645,123	
SL				25,017,347	20,847,789	17,869,534	15,954,941	15,195,182	15,195,182	15,195,182	
Actual				50,034,694	35,739,067	25,527,905	18,234,218	15,195,182	15,195,182	15,195,182	
Remaining Value				125,086,735	89,347,668	63,819,763	45,585,545	30,390,363	15,195,182	-	
Power and Steam Plant											
DDB				8,996,623	8,321,876	7,697,735	7,120,405	6,586,375	6,092,397	5,635,467	5,212,807
SL				5,997,749	5,839,913	5,702,026	5,584,632	5,488,646	5,415,464	5,367,111	5,346,469
Actual				8,996,623	8,321,876	7,697,735	7,120,405	6,586,375	6,092,397	5,635,467	5,346,469
Remaining Value				110,958,348	102,636,472	94,938,737	87,818,332	81,231,957	75,139,560	69,504,093	64,157,624
Net Revenue				-32,753,114	13,951,538	24,786,840	32,657,858	36,230,924	36,724,903	37,181,832	52,666,012
Losses Forward					-32,753,114	-18,801,577	0	0	0	0	0
Taxable Income				-32,753,114	-18,801,577	5,985,264	32,657,858	36,230,924	36,724,903	37,181,832	52,666,012
Income Tax				0	0	2,334,253	12,736,565	14,130,061	14,322,712	14,500,915	20,539,745
Annual Cash Flow				26,278,202	58,012,481	55,678,228	45,275,916	43,882,420	43,689,769	43,511,566	37,472,736
Discount Factor	1.21	1.10	1.00	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47
Annual Present Value				23,889,275	47,944,199	41,831,877	30,924,060	27,247,531	24,661,736	22,328,313	17,481,308
TPI + Interest	28,563,396	194,750,424	138,685,908								
NPV			0								

Table S6 Discounted cash flow sheet for Et1f (base case) (continued).

Year	9	10	11	12	13	14	15	16	17	18	19	20
Capital Investment												
Working Capital												-44,261,460
Fuel Sales	20,223,090	20,223,090	20,223,090	20,223,090	20,223,090	20,223,090	20,223,090	20,223,090	20,223,090	20,223,090	20,223,090	20,223,090
Chemical Sales	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228
Electricity Sales	23,454,930	23,454,930	23,454,930	23,454,930	23,454,930	23,454,930	23,454,930	23,454,930	23,454,930	23,454,930	23,454,930	23,454,930
Carbon Credit	0	0	0	0	0	0	0	0	0	0	0	0
Total Annual Sales	186,875,248	186,875,248	186,875,248	186,875,248	186,875,248	186,875,248	186,875,248	186,875,248	186,875,248	186,875,248	186,875,248	186,875,248
Feedstock Cost	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010
Other Variable Costs	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000
Fixed Operating Costs	8,986,500	8,986,500	8,986,500	8,986,500	8,986,500	8,986,500	8,986,500	8,986,500	8,986,500	8,986,500	8,986,500	8,986,500
Total Product Cost	128,862,767	128,862,767	128,862,767	128,862,767	128,862,767	128,862,767	128,862,767	128,862,767	128,862,767	128,862,767	128,862,767	128,862,767
Annual Depreciation												
General Plant												
DDB												
SL												
Actual												
Remaining Value												
Power and Steam Plant												
DDB	4,821,846	4,460,208	4,125,692	3,816,265	3,530,046	3,265,292	3,020,395	2,793,866	2,584,326	2,390,501	2,211,214	2,045,373
SL	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469
Actual	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469	5,346,469
Remaining Value	58,811,156	53,464,687	48,118,218	42,771,750	37,425,281	32,078,812	26,732,343	21,385,875	16,039,406	10,692,937	5,346,469	0
Net Revenue	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012
Losses Forward	0	0	0	0	0	0	0	0	0	0	0	0
Taxable Income	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012	52,666,012
Income Tax	20,539,745	20,539,745	20,539,745	20,539,745	20,539,745	20,539,745	20,539,745	20,539,745	20,539,745	20,539,745	20,539,745	20,539,745
Annual Cash Flow	37,472,736	37,472,736	37,472,736	37,472,736	37,472,736	37,472,736	37,472,736	37,472,736	37,472,736	37,472,736	37,472,736	37,472,736
Discount Factor	0.42	0.39	0.35	0.32	0.29	0.26	0.24	0.22	0.20	0.18	0.16	0.15
Annual Present Value	15,892,098	14,447,362	13,133,965	11,939,969	10,854,517	9,867,743	8,970,675	8,155,159	7,413,781	6,739,801	6,127,092	5,570,083
TPI + Interest												-6,579,184
NPV												

Table S7 Discounted cash flow sheet for Et1f (M1).

Year	-2	-1	0	1	2	3	4	5	6	7	8
Capital Investment	26,149,296	196,119,720	104,597,184								
Working Capital			49,029,930								
Fuel Sales				28,918,105	38,557,474	38,557,474	38,557,474	38,557,474	38,557,474	38,557,474	38,557,474
Chemical Sales				107,397,921	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228
Electricity Sales				8,775,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000
Carbon Credit				0	0	0	0	0	0	0	0
Total Annual Sales				145,091,027	193,454,702	193,454,702	193,454,702	193,454,702	193,454,702	193,454,702	193,454,702
Feedstock Cost				50,713,475	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials				48,228,258	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010
Other Variable Costs				5,950,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000
Fixed Operating Costs				9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000
Total Product Cost				114,791,733	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267
Annual Depreciation											
General Plant											
DDB				61,463,480	43,902,486	31,358,918	22,399,227	15,999,448	11,428,177	8,162,984	
SL				30,731,740	25,609,783	21,951,243	19,599,324	18,666,023	18,666,023	18,666,023	
Actual				61,463,480	43,902,486	31,358,918	22,399,227	18,666,023	18,666,023	18,666,023	
Remaining Value				153,658,699	109,756,214	78,397,296	55,998,068	37,332,046	18,666,023	0	
Power and Steam Plant											
DDB				8,380,802	7,752,241	7,170,823	6,633,012	6,135,536	5,675,371	5,249,718	4,855,989
SL				5,587,201	5,440,169	5,311,721	5,202,362	5,112,946	5,044,774	4,999,731	4,980,501
Actual				8,380,802	7,752,241	7,170,823	6,633,012	6,135,536	5,675,371	5,249,718	4,980,501
Remaining Value				103,363,219	95,610,978	88,440,154	81,807,143	75,671,607	69,996,237	64,746,519	59,766,017
Net Revenue				-39,544,988	12,023,708	25,148,694	34,646,196	38,876,877	39,337,042	39,762,695	58,697,934
Losses Forward					-39,544,988	-27,521,280	-2,372,586	0	0	0	0
Taxable Income				-39,544,988	-27,521,280	-2,372,586	32,273,610	38,876,877	39,337,042	39,762,695	58,697,934
Income Tax				0	0	0	12,586,708	15,161,982	15,341,446	15,507,451	22,892,194
Annual Cash Flow				30,299,293	63,678,435	63,678,435	51,091,727	48,516,453	48,336,989	48,170,984	40,786,241
Discount Factor	1.21	1.10	1.00	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47
Annual Present Value				27,544,812	52,626,806	47,842,551	34,896,337	30,124,900	27,284,970	24,719,332	19,027,083
TPI + Interest	31,640,648	215,731,692	153,627,114								
NPV			0								

Table S7 Discounted cash flow sheet for Et1f (M1) (continued).

Year	9	10	11	12	13	14	15	16	17	18	19	20
Capital Investment												
Working Capital												-49,029,930
Fuel Sales	38,557,474	38,557,474	38,557,474	38,557,474	38,557,474	38,557,474	38,557,474	38,557,474	38,557,474	38,557,474	38,557,474	38,557,474
Chemical Sales	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228
Electricity Sales	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000
Carbon Credit	0	0	0	0	0	0	0	0	0	0	0	0
Total Annual Sales	193,454,702	193,454,702	193,454,702	193,454,702	193,454,702	193,454,702	193,454,702	193,454,702	193,454,702	193,454,702	193,454,702	193,454,702
Feedstock Cost	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010
Other Variable Costs	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000
Fixed Operating Costs	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000
Total Product Cost	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267
Annual Depreciation												
General Plant												
DDB												
SL												
Actual												
Remaining Value												
Power and Steam Plant												
DDB	4,491,790	4,154,906	3,843,288	3,555,041	3,288,413	3,041,782	2,813,648	2,602,625	2,407,428	2,226,871	2,059,855	1,905,366
SL	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501
Actual	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501	4,980,501
Remaining Value	54,785,516	49,805,015	44,824,513	39,844,012	34,863,510	29,883,009	24,902,507	19,922,006	14,941,504	9,961,003	4,980,501	0
Net Revenue	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934
Losses Forward	0	0	0	0	0	0	0	0	0	0	0	0
Taxable Income	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934	58,697,934
Income Tax	22,892,194	22,892,194	22,892,194	22,892,194	22,892,194	22,892,194	22,892,194	22,892,194	22,892,194	22,892,194	22,892,194	22,892,194
Annual Cash Flow	40,786,241	40,786,241	40,786,241	40,786,241	40,786,241	40,786,241	40,786,241	40,786,241	40,786,241	40,786,241	40,786,241	40,786,241
Discount Factor	0.42	0.39	0.35	0.32	0.29	0.26	0.24	0.22	0.20	0.18	0.16	0.15
Annual Present Value	17,297,348	15,724,862	14,295,329	12,995,753	11,814,321	10,740,292	9,763,902	8,876,274	8,069,340	7,335,764	6,668,876	6,062,615
TPI + Interest												-7,287,987
NPV												

Table S8 Discounted cash flow sheet for Et1f (M2).

Year	-2	-1	0	1	2	3	4	5	6	7	8
Capital Investment	37,240,173	279,301,300	148,960,693								
Working Capital			69,825,325								
Fuel Sales				42,494,075	59,103,055	75,712,035	83,044,900	83,044,900	83,044,900	83,044,900	83,044,900
Chemical Sales				73,274,022	101,913,467	130,552,913	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228
Electricity Sales				5,986,890	8,326,890	10,666,890	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000
Carbon Credit				0	0	0	0	0	0	0	0
Total Annual Sales				121,754,987	169,343,413	216,931,839	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129
Feedstock Cost				57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials				55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010
Other Variable Costs				6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000
Fixed Operating Costs				9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000
Total Product Cost				129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267
Annual Depreciation											
General Plant											
DDB				87,532,400	62,523,143	44,659,388	31,899,563	22,785,402	16,275,287	11,625,205	
SL				43,766,200	36,471,833	31,261,571	27,912,117	26,582,969	26,582,969	26,582,969	
Actual				87,532,400	62,523,143	44,659,388	31,899,563	26,582,969	26,582,969	26,582,969	
Remaining Value				218,831,000	156,307,857	111,648,469	79,748,907	53,165,938	26,582,969	0	
Power and Steam Plant											
DDB				11,935,407	11,040,252	10,212,233	9,446,316	8,737,842	8,082,504	7,476,316	6,915,592
SL				7,956,938	7,747,545	7,564,617	7,408,875	7,281,535	7,184,448	7,120,301	7,092,915
Actual				11,935,407	11,040,252	10,212,233	9,446,316	8,737,842	8,082,504	7,476,316	7,092,915
Remaining Value				147,203,359	136,163,107	125,950,874	116,504,558	107,766,716	99,684,213	92,207,897	85,114,982
Net Revenue				-107,489,087	-33,996,249	32,283,951	66,819,984	72,845,051	73,500,389	74,106,577	101,072,947
Losses Forward					-107,489,087	-141,485,336	-109,201,385	-42,381,401	0	0	0
Taxable Income				-107,489,087	-141,485,336	-109,201,385	-42,381,401	30,463,650	73,500,389	74,106,577	101,072,947
Income Tax				0	0	0	0	11,880,823	28,665,152	28,901,565	39,418,449
Annual Cash Flow				-8,021,280	39,567,146	87,155,572	108,165,862	96,285,038	79,500,710	79,264,297	68,747,413
Discount Factor	1.21	1.10	1.00	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47
Annual Present Value				-7,292,072	32,700,121	65,481,271	73,878,739	59,785,433	44,876,078	40,675,117	32,071,175
TPI + Interest	45,060,610	307,231,430	218,786,018								
NPV			0								

Table S8 Discounted cash flow sheet for Et1f (M2) (continued).

Year	9	10	11	12	13	14	15	16	17	18	19	20
Capital Investment												
Working Capital												-69,825,325
Fuel Sales	83,044,900	83,044,900	83,044,900	83,044,900	83,044,900	83,044,900	83,044,900	83,044,900	83,044,900	83,044,900	83,044,900	83,044,900
Chemical Sales	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228
Electricity Sales	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000
Carbon Credit	0	0	0	0	0	0	0	0	0	0	0	0
Total Annual Sales	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129
Feedstock Cost	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010
Other Variable Costs	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000
Fixed Operating Costs	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000
Total Product Cost	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267
Annual Depreciation												
General Plant												
DDB												
SL												
Actual												
Remaining Value												
Power and Steam Plant												
DDB	6,396,923	5,917,154	5,473,367	5,062,865	4,683,150	4,331,913	4,007,020	3,706,493	3,428,506	3,171,368	2,933,516	2,713,502
SL	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915
Actual	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915
Remaining Value	78,022,066	70,929,151	63,836,236	56,743,321	49,650,406	42,557,491	35,464,576	28,371,661	21,278,745	14,185,830	7,092,915	0
Net Revenue	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947
Losses Forward	0	0	0	0	0	0	0	0	0	0	0	0
Taxable Income	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947
Income Tax	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449
Annual Cash Flow	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413
Discount Factor	0.42	0.39	0.35	0.32	0.29	0.26	0.24	0.22	0.20	0.18	0.16	0.15
Annual Present Value	29,155,614	26,505,104	24,095,549	21,905,044	19,913,677	18,103,342	16,457,584	14,961,440	13,601,309	12,364,826	11,240,751	10,218,865
TPI + Interest												-10,379,090
NPV												

Table S9 Discounted cash flow sheet for Et1f (M4).

Year	-2	-1	0	1	2	3	4	5	6	7	8
Capital Investment	37,240,173	279,301,300	148,960,693								
Working Capital			69,825,325								
Fuel Sales				33,860,584	47,095,129	60,329,674	66,172,725	66,172,725	66,172,725	66,172,725	66,172,725
Chemical Sales				73,274,022	101,913,467	130,552,913	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228
Electricity Sales				5,986,890	8,326,890	10,666,890	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000
Carbon Credit				8,633,492	12,007,927	15,382,362	16,872,175	16,872,175	16,872,175	16,872,175	16,872,175
Total Annual Sales				121,754,987	169,343,413	216,931,839	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129
Feedstock Cost				57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials				55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010
Other Variable Costs				6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000
Fixed Operating Costs				9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000
Total Product Cost				129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267
Annual Depreciation											
General Plant											
DDB				87,532,400	62,523,143	44,659,388	31,899,563	22,785,402	16,275,287	11,625,205	
SL				43,766,200	36,471,833	31,261,571	27,912,117	26,582,969	26,582,969	26,582,969	
Actual				87,532,400	62,523,143	44,659,388	31,899,563	26,582,969	26,582,969	26,582,969	
Remaining Value				218,831,000	156,307,857	111,648,469	79,748,907	53,165,938	26,582,969	0	
Power and Steam Plant											
DDB				11,935,407	11,040,252	10,212,233	9,446,316	8,737,842	8,082,504	7,476,316	6,915,592
SL				7,956,938	7,747,545	7,564,617	7,408,875	7,281,535	7,184,448	7,120,301	7,092,915
Actual				11,935,407	11,040,252	10,212,233	9,446,316	8,737,842	8,082,504	7,476,316	7,092,915
Remaining Value				147,203,359	136,163,107	125,950,874	116,504,558	107,766,716	99,684,213	92,207,897	85,114,982
Net Revenue				-107,489,087	-33,996,249	32,283,951	66,819,984	72,845,051	73,500,389	74,106,577	101,072,947
Losses Forward					-107,489,087	-141,485,336	-109,201,385	-42,381,401	0	0	0
Taxable Income				-107,489,087	-141,485,336	-109,201,385	-42,381,401	30,463,650	73,500,389	74,106,577	101,072,947
Income Tax				0	0	0	0	11,880,823	28,665,152	28,901,565	39,418,449
Annual Cash Flow				-8,021,280	39,567,146	87,155,572	108,165,862	96,285,038	79,500,710	79,264,297	68,747,413
Discount Factor	1.21	1.10	1.00	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47
Annual Present Value				-7,292,072	32,700,121	65,481,271	73,878,739	59,785,433	44,876,078	40,675,117	32,071,175
TPI + Interest	45,060,610	307,231,430	218,786,018								
NPV			0								

Table S9 Discounted cash flow sheet for Et1f (M4) (continued).

Year	9	10	11	12	13	14	15	16	17	18	19	20
Capital Investment												
Working Capital												-69,825,325
Fuel Sales	66,172,725	66,172,725	66,172,725	66,172,725	66,172,725	66,172,725	66,172,725	66,172,725	66,172,725	66,172,725	66,172,725	66,172,725
Chemical Sales	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228	143,197,228
Electricity Sales	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000	11,700,000
Carbon Credit	16,872,175	16,872,175	16,872,175	16,872,175	16,872,175	16,872,175	16,872,175	16,872,175	16,872,175	16,872,175	16,872,175	16,872,175
Total Annual Sales	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129	237,942,129
Feedstock Cost	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010	55,118,010
Other Variable Costs	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000	6,800,000
Fixed Operating Costs	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000	9,900,000
Total Product Cost	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267	129,776,267
Annual Depreciation												
General Plant												
DDB												
SL												
Actual												
Remaining Value												
Power and Steam Plant												
DDB	6,396,923	5,917,154	5,473,367	5,062,865	4,683,150	4,331,913	4,007,020	3,706,493	3,428,506	3,171,368	2,933,516	2,713,502
SL	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915
Actual	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915	7,092,915
Remaining Value	78,022,066	70,929,151	63,836,236	56,743,321	49,650,406	42,557,491	35,464,576	28,371,661	21,278,745	14,185,830	7,092,915	0
Net Revenue	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947
Losses Forward	0	0	0	0	0	0	0	0	0	0	0	0
Taxable Income	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947	101,072,947
Income Tax	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449	39,418,449
Annual Cash Flow	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413	68,747,413
Discount Factor	0.42	0.39	0.35	0.32	0.29	0.26	0.24	0.22	0.20	0.18	0.16	0.15
Annual Present Value	29,155,614	26,505,104	24,095,549	21,905,044	19,913,677	18,103,342	16,457,584	14,961,440	13,601,309	12,364,826	11,240,751	10,218,865
TPI + Interest												-10,379,090
NPV												

Table S10 Discounted cash flow sheet for Et2f (base case).

Year	-2	-1	0	1	2	3	4	5	6	7	8
Capital Investment	23,139,319	173,544,891	92,557,275								
Working Capital			43,386,223								
Fuel Sales				-20,071,783	-26,762,377	-26,762,377	-26,762,377	-26,762,377	-26,762,377	-26,762,377	-26,762,377
Chemical Sales				111,035,567	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423
Electricity Sales				12,171,763	16,229,018	16,229,018	16,229,018	16,229,018	16,229,018	16,229,018	16,229,018
Carbon Credit				0	0	0	0	0	0	0	0
Total Annual Sales				103,135,548	137,514,063	137,514,063	137,514,063	137,514,063	137,514,063	137,514,063	137,514,063
Feedstock Cost				50,713,475	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials				7,403,776	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458
Other Variable Costs				4,792,743	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420
Fixed Operating Costs				10,004,519	10,004,519	10,004,519	10,004,519	10,004,519	10,004,519	10,004,519	10,004,519
Total Product Cost				72,914,512	81,901,653	81,901,653	81,901,653	81,901,653	81,901,653	81,901,653	81,901,653
Annual Depreciation											
General Plant											
DDB				58,660,106	41,900,076	29,928,626	21,377,590	15,269,707	10,906,934	7,790,667	
SL				29,330,053	24,441,711	20,950,038	18,705,391	17,814,658	17,814,658	17,814,658	
Actual				58,660,106	41,900,076	29,928,626	21,377,590	17,814,658	17,814,658	17,814,658	
Remaining Value				146,650,265	104,750,189	74,821,564	53,443,974	35,629,316	17,814,658	0	
Power and Steam Plant											
DDB				6,294,834	5,822,721	5,386,017	4,982,066	4,608,411	4,262,780	3,943,071	3,647,341
SL				4,196,556	4,086,120	3,989,642	3,907,503	3,840,342	3,789,138	3,755,306	3,740,863
Actual				6,294,834	5,822,721	5,386,017	4,982,066	4,608,411	4,262,780	3,943,071	3,740,863
Remaining Value				77,636,281	71,813,560	66,427,543	61,445,477	56,837,066	52,574,286	48,631,215	44,890,352
Net Revenue				-34,733,904	7,889,613	20,297,767	29,252,755	33,189,341	33,534,972	33,854,680	51,871,547
Losses Forward					-34,733,904	-26,844,290	-6,546,523	0	0	0	0
Taxable Income				-34,733,904	-26,844,290	-6,546,523	22,706,232	33,189,341	33,534,972	33,854,680	51,871,547
Income Tax				0	0	0	8,855,430	12,943,843	13,078,639	13,203,325	20,229,903
Annual Cash Flow				30,221,036	55,612,410	55,612,410	46,756,980	42,668,567	42,533,771	42,409,085	35,382,507
Discount Factor	1.21	1.10	1.00	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47
Annual Present Value				27,473,669	45,960,669	41,782,427	31,935,646	26,493,823	24,009,205	21,762,566	16,506,200
TPI + Interest	27,998,576	190,899,380	135,943,498								
NPV			0								

Table S10 Discounted cash flow sheet for Et2f (base case) (continued).

Year	9	10	11	12	13	14	15	16	17	18	19	20
Capital Investment												
Working Capital												-43,386,223
Fuel Sales	-26,762,377	-26,762,377	-26,762,377	-26,762,377	-26,762,377	-26,762,377	-26,762,377	-26,762,377	-26,762,377	-26,762,377	-26,762,377	-26,762,377
Chemical Sales	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423
Electricity Sales	16,229,018	16,229,018	16,229,018	16,229,018	16,229,018	16,229,018	16,229,018	16,229,018	16,229,018	16,229,018	16,229,018	16,229,018
Carbon Credit	0	0	0	0	0	0	0	0	0	0	0	0
Total Annual Sales	137,514,063	137,514,063	137,514,063	137,514,063	137,514,063	137,514,063	137,514,063	137,514,063	137,514,063	137,514,063	137,514,063	137,514,063
Feedstock Cost	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458
Other Variable Costs	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420
Fixed Operating Costs	10,004,519	10,004,519	10,004,519	10,004,519	10,004,519	10,004,519	10,004,519	10,004,519	10,004,519	10,004,519	10,004,519	10,004,519
Total Product Cost	81,901,653	81,901,653	81,901,653	81,901,653	81,901,653	81,901,653	81,901,653	81,901,653	81,901,653	81,901,653	81,901,653	81,901,653
Annual Depreciation												
General Plant												
DDB												
SL												
Actual												
Remaining Value												
Power and Steam Plant												
DDB	3,373,791	3,120,756	2,886,700	2,670,197	2,469,932	2,284,687	2,113,336	1,954,836	1,808,223	1,672,606	1,547,161	1,431,124
SL	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863
Actual	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863	3,740,863
Remaining Value	41,149,489	37,408,627	33,667,764	29,926,901	26,186,039	22,445,176	18,704,313	14,963,451	11,222,588	7,481,725	3,740,863	0
Net Revenue	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547
Losses Forward	0	0	0	0	0	0	0	0	0	0	0	0
Taxable Income	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547	51,871,547
Income Tax	20,229,903	20,229,903	20,229,903	20,229,903	20,229,903	20,229,903	20,229,903	20,229,903	20,229,903	20,229,903	20,229,903	20,229,903
Annual Cash Flow	35,382,507	35,382,507	35,382,507	35,382,507	35,382,507	35,382,507	35,382,507	35,382,507	35,382,507	35,382,507	35,382,507	35,382,507
Discount Factor	0.42	0.39	0.35	0.32	0.29	0.26	0.24	0.22	0.20	0.18	0.16	0.15
Annual Present Value	15,005,637	13,641,488	12,401,353	11,273,957	10,249,052	9,317,320	8,470,291	7,700,264	7,000,240	6,363,855	5,785,323	5,259,384
TPI + Interest												-6,449,086
NPV												

Table S11 Discounted cash flow sheet for Et2f (M1).

Year	-2	-1	0	1	2	3	4	5	6	7	8
Capital Investment	31,019,172	232,643,788	124,076,687								
Working Capital			58,160,947								
Fuel Sales				5,763,045	7,684,060	7,684,060	7,684,060	7,684,060	7,684,060	7,684,060	7,684,060
Chemical Sales				111,035,567	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423
Electricity Sales				1,404,654	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872
Carbon Credit				0	0	0	0	0	0	0	0
Total Annual Sales				118,203,266	157,604,355	157,604,355	157,604,355	157,604,355	157,604,355	157,604,355	157,604,355
Feedstock Cost				50,713,475	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials				7,403,776	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458
Other Variable Costs				4,792,743	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420
Fixed Operating Costs				12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383
Total Product Cost				74,969,376	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518
Annual Depreciation											
General Plant											
DDB				86,994,766	62,139,118	44,385,084	31,703,632	22,645,451	16,175,322	11,553,802	
SL				43,497,383	36,247,819	31,069,559	27,740,678	26,419,693	26,419,693	26,419,693	
Actual				86,994,766	62,139,118	44,385,084	31,703,632	26,419,693	26,419,693	26,419,693	
Remaining Value				217,486,914	155,347,796	110,962,711	79,259,079	52,839,386	26,419,693	0	
Power and Steam Plant											
DDB				6,244,348	5,776,022	5,342,820	4,942,108	4,571,450	4,228,592	3,911,447	3,618,089
SL				4,162,898	4,053,348	3,957,644	3,876,163	3,809,542	3,758,748	3,725,188	3,710,860
Actual				6,244,348	5,776,022	5,342,820	4,942,108	4,571,450	4,228,592	3,911,447	3,710,860
Remaining Value				77,013,620	71,237,599	65,894,779	60,952,670	56,381,220	52,152,629	48,241,181	44,530,321
Net Revenue				-50,005,223	5,732,697	23,919,933	37,002,097	42,656,694	42,999,552	43,316,697	69,936,977
Losses Forward					-50,005,223	-44,272,526	-20,352,593	0	0	0	0
Taxable Income				-50,005,223	-44,272,526	-20,352,593	16,649,503	42,656,694	42,999,552	43,316,697	69,936,977
Income Tax				0	0	0	6,493,306	16,636,110	16,769,825	16,893,512	27,275,421
Annual Cash Flow				43,233,890	73,647,837	73,647,837	67,154,531	57,011,726	56,878,012	56,754,325	46,372,416
Discount Factor	1.21	1.10	1.00	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47
Annual Present Value				39,303,536	60,865,981	55,332,710	45,867,448	35,399,797	32,106,155	29,123,943	21,633,074
TPI + Interest	37,533,198	255,908,167	182,237,634								
NPV			0								

Table S11 Discounted cash flow sheet for Et2f (M1) (continued).

Year	9	10	11	12	13	14	15	16	17	18	19	20
Capital Investment												
Working Capital												-58,160,947
Fuel Sales	7,684,060	7,684,060	7,684,060	7,684,060	7,684,060	7,684,060	7,684,060	7,684,060	7,684,060	7,684,060	7,684,060	7,684,060
Chemical Sales	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423
Electricity Sales	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872
Carbon Credit	0	0	0	0	0	0	0	0	0	0	0	0
Total Annual Sales	157,604,355	157,604,355	157,604,355	157,604,355	157,604,355	157,604,355	157,604,355	157,604,355	157,604,355	157,604,355	157,604,355	157,604,355
Feedstock Cost	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458
Other Variable Costs	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420
Fixed Operating Costs	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383
Total Product Cost	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518
Annual Depreciation												
General Plant												
DDB												
SL												
Actual												
Remaining Value												
Power and Steam Plant												
DDB	3,346,732	3,095,727	2,863,548	2,648,781	2,450,123	2,266,364	2,096,386	1,939,157	1,793,721	1,659,192	1,534,752	1,419,646
SL	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860
Actual	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860	3,710,860
Remaining Value	40,819,461	37,108,601	33,397,741	29,686,881	25,976,021	22,265,161	18,554,301	14,843,440	11,132,580	7,421,720	3,710,860	0
Net Revenue	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977
Losses Forward	0	0	0	0	0	0	0	0	0	0	0	0
Taxable Income	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977	69,936,977
Income Tax	27,275,421	27,275,421	27,275,421	27,275,421	27,275,421	27,275,421	27,275,421	27,275,421	27,275,421	27,275,421	27,275,421	27,275,421
Annual Cash Flow	46,372,416	46,372,416	46,372,416	46,372,416	46,372,416	46,372,416	46,372,416	46,372,416	46,372,416	46,372,416	46,372,416	46,372,416
Discount Factor	0.42	0.39	0.35	0.32	0.29	0.26	0.24	0.22	0.20	0.18	0.16	0.15
Annual Present Value	19,666,431	17,878,574	16,253,249	14,775,681	13,432,437	12,211,306	11,101,188	10,091,989	9,174,535	8,340,487	7,582,261	6,892,964
TPI + Interest												-8,645,254
NPV												

Table S12 Discounted cash flow sheet for Et2f (M2).

Year	-2	-1	0	1	2	3	4	5	6	7	8
Capital Investment	54,623,730	409,677,974	218,494,920								
Working Capital			102,419,494								
Fuel Sales				40,795,884	56,741,119	72,686,354	79,726,175	79,726,175	79,726,175	79,726,175	79,726,175
Chemical Sales				75,755,866	105,365,351	134,974,836	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423
Electricity Sales				958,349	1,332,923	1,707,497	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872
Carbon Credit				0	0	0	0	0	0	0	0
Total Annual Sales				117,510,099	163,439,393	209,368,687	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470
Feedstock Cost				57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials				8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458
Other Variable Costs				5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420
Fixed Operating Costs				12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383
Total Product Cost				83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518
Annual Depreciation											
General Plant											
DDB				153,194,889	109,424,921	78,160,658	55,829,041	39,877,887	28,484,205	20,345,860	
SL				76,597,445	63,831,204	54,712,460	48,850,411	46,524,201	46,524,201	46,524,201	
Actual				153,194,889	109,424,921	78,160,658	55,829,041	46,524,201	46,524,201	46,524,201	
Remaining Value				382,987,223	273,562,302	195,401,644	139,572,603	93,048,402	46,524,201	-	
Power and Steam Plant											
DDB				10,996,088	10,171,382	9,408,528	8,702,889	8,050,172	7,446,409	6,887,928	6,371,334
SL				7,330,726	7,137,812	6,969,280	6,825,795	6,708,477	6,619,030	6,559,932	6,534,701
Actual				10,996,088	10,171,382	9,408,528	8,702,889	8,050,172	7,446,409	6,887,928	6,534,701
Remaining Value				135,618,424	125,447,042	116,038,514	107,335,625	99,285,454	91,839,044	84,951,116	78,416,415
Net Revenue				-130,637,397	-40,113,428	37,842,983	81,158,022	91,115,579	91,719,342	92,277,823	139,155,251
Losses Forward					-130,637,397	-170,750,824	-132,907,841	-51,749,819	-	-	-
Taxable Income				-130,637,397	-170,750,824	-132,907,841	-51,749,819	39,365,760	91,719,342	92,277,823	139,155,251
Income Tax				-	-	-	-	15,352,646	35,770,543	35,988,351	54,270,548
Annual Cash Flow				33,553,581	79,482,875	125,412,169	145,689,952	130,337,306	109,919,409	109,701,601	91,419,404
Discount Factor	1.210	1.100	1.000	0.909	0.826	0.751	0.683	0.621	0.564	0.513	0.467
Annual Present Value				30,503,255	65,688,326	94,224,019	99,508,198	80,929,212	62,046,641	56,294,267	42,647,827
TPI + Interest	66,094,713	450,645,772	320,914,413								
NPV			0								

Table S12 Discounted cash flow sheet for Et2f (M2) (continued).

Year	9	10	11	12	13	14	15	16	17	18	19	20
Capital Investment												
Working Capital												-102,419,494
Fuel Sales	79,726,175	79,726,175	79,726,175	79,726,175	79,726,175	79,726,175	79,726,175	79,726,175	79,726,175	79,726,175	79,726,175	79,726,175
Chemical Sales	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423
Electricity Sales	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872
Carbon Credit	0	0	0	0	0	0	0	0	0	0	0	0
Total Annual Sales	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470
Feedstock Cost	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458
Other Variable Costs	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420
Fixed Operating Costs	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383
Total Product Cost	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518
Annual Depreciation												
General Plant												
DDB												
SL												
Actual												
Remaining Value												
Power and Steam Plant												
DDB	5,893,484	5,451,472	5,042,612	4,664,416	4,314,585	3,990,991	3,691,667	3,414,792	3,158,682	2,921,781	2,702,648	2,499,949
SL	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701
Actual	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701
Remaining Value	71,881,714	65,347,012	58,812,311	52,277,610	45,742,909	39,208,207	32,673,506	26,138,805	19,604,104	13,069,402	6,534,701	0
Net Revenue	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251
Losses Forward	-	-	-	-	-	-	-	-	-	-	-	0
Taxable Income	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251
Income Tax	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548
Annual Cash Flow	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404
Discount Factor	0.424	0.386	0.350	0.319	0.290	0.263	0.239	0.218	0.198	0.180	0.164	0.149
Annual Present Value	38,770,752	35,246,138	32,041,943	29,129,040	26,480,945	24,073,586	21,885,079	19,895,526	18,086,842	16,442,583	14,947,803	13,588,912
TPI + Interest												-15,224,005
NPV												

Table S13 Discounted cash flow sheet for Et1f (M4).

Year	-2	-1	0	1	2	3	4	5	6	7	8
Capital Investment	54,623,730	409,677,974	218,494,920								
Working Capital			102,419,494								
Fuel Sales				31,047,730	43,182,860	55,317,990	60,675,649	60,675,649	60,675,649	60,675,649	60,675,649
Chemical Sales				75,755,866	105,365,351	134,974,836	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423
Electricity Sales				958,349	1,332,923	1,707,497	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872
Carbon Credit				9,748,154	13,558,259	17,368,364	19,050,526	19,050,526	19,050,526	19,050,526	19,050,526
Total Annual Sales				117,510,099	163,439,393	209,368,687	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470
Feedstock Cost				57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials				8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458
Other Variable Costs				5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420
Fixed Operating Costs				12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383
Total Product Cost				83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518
Annual Depreciation											
General Plant											
DDB				153,194,889	109,424,921	78,160,658	55,829,041	39,877,887	28,484,205	20,345,860	
SL				76,597,445	63,831,204	54,712,460	48,850,411	46,524,201	46,524,201	46,524,201	
Actual				153,194,889	109,424,921	78,160,658	55,829,041	46,524,201	46,524,201	46,524,201	
Remaining Value				382,987,223	273,562,302	195,401,644	139,572,603	93,048,402	46,524,201	-	
Power and Steam Plant											
DDB				10,996,088	10,171,382	9,408,528	8,702,889	8,050,172	7,446,409	6,887,928	6,371,334
SL				7,330,726	7,137,812	6,969,280	6,825,795	6,708,477	6,619,030	6,559,932	6,534,701
Actual				10,996,088	10,171,382	9,408,528	8,702,889	8,050,172	7,446,409	6,887,928	6,534,701
Remaining Value				135,618,424	125,447,042	116,038,514	107,335,625	99,285,454	91,839,044	84,951,116	78,416,415
Net Revenue				-130,637,397	-40,113,428	37,842,983	81,158,022	91,115,579	91,719,342	92,277,823	139,155,251
Losses Forward					-130,637,397	-170,750,824	-132,907,841	-51,749,819	-	-	-
Taxable Income				-130,637,397	-170,750,824	-132,907,841	-51,749,819	39,365,760	91,719,342	92,277,823	139,155,251
Income Tax				-	-	-	-	15,352,646	35,770,543	35,988,351	54,270,548
Annual Cash Flow				33,553,581	79,482,875	125,412,169	145,689,952	130,337,306	109,919,409	109,701,601	91,419,404
Discount Factor	1.210	1.100	1.000	0.909	0.826	0.751	0.683	0.621	0.564	0.513	0.467
Annual Present Value				30,503,255	65,688,326	94,224,019	99,508,198	80,929,212	62,046,641	56,294,267	42,647,827
TPI + Interest	66,094,713	450,645,772	320,914,413								
NPV			0								

Table S13 Discounted cash flow sheet for Et1f (M4) (continued).

Year	9	10	11	12	13	14	15	16	17	18	19	20
Capital Investment												
Working Capital												-102,419,494
Fuel Sales	60,675,649	60,675,649	60,675,649	60,675,649	60,675,649	60,675,649	60,675,649	60,675,649	60,675,649	60,675,649	60,675,649	60,675,649
Chemical Sales	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423	148,047,423
Electricity Sales	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872	1,872,872
Carbon Credit	19,050,526	19,050,526	19,050,526	19,050,526	19,050,526	19,050,526	19,050,526	19,050,526	19,050,526	19,050,526	19,050,526	19,050,526
Total Annual Sales	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470	229,646,470
Feedstock Cost	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257	57,958,257
Other Raw Materials	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458	8,461,458
Other Variable Costs	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420	5,477,420
Fixed Operating Costs	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383	12,059,383
Total Product Cost	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518	83,956,518
Annual Depreciation												
General Plant												
DDB												
SL												
Actual												
Remaining Value												
Power and Steam Plant												
DDB	5,893,484	5,451,472	5,042,612	4,664,416	4,314,585	3,990,991	3,691,667	3,414,792	3,158,682	2,921,781	2,702,648	2,499,949
SL	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701
Actual	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701	6,534,701
Remaining Value	71,881,714	65,347,012	58,812,311	52,277,610	45,742,909	39,208,207	32,673,506	26,138,805	19,604,104	13,069,402	6,534,701	0
Net Revenue	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251
Losses Forward	-	-	-	-	-	-	-	-	-	-	-	0
Taxable Income	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251	139,155,251
Income Tax	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548	54,270,548
Annual Cash Flow	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404	91,419,404
Discount Factor	0.424	0.386	0.350	0.319	0.290	0.263	0.239	0.218	0.198	0.180	0.164	0.149
Annual Present Value	38,770,752	35,246,138	32,041,943	29,129,040	26,480,945	24,073,586	21,885,079	19,895,526	18,086,842	16,442,583	14,947,803	13,588,912
TPI + Interest												-15,224,005
NPV												

S.6 Life cycle assessment

The goal of this study is to quantify life cycle emissions and energy use in the coproduction pathways using corn stover. In coproduction pathways, sugar production technology for the enzymatic hydrolysis of polymeric compounds, such as cellulose and hemicellulose, could have a major effect on the overall environmental impact. This study analyzed the effects of different sugar production techniques and coproducts on the environment impact based on large-scale process modeling data. We conducted well-to-pump (WTP) analyses of two cellulosic EtOH production strategies with the GREET model.[134, 135] Among the various environmental impacts, this study focused on the global warming potential (GWP). The functional unit was 1 GGE, which facilitated a comparison of the results of this study with other environmental assessment results for transportation fuels. One GGE of EtOH is equivalent to 5.68 L (1.5 gallon) or 4.48 kg of EtOH. Prior to the impact assessment, we collected the material and energy input-output data for the target process. The data for the processes of Et1 (enzymatic hydrolysis based bioEtOH production) and Et2 (catalytic hydrolysis based bioEtOH production) were obtained from previous studies,[126, 127] and details of process are shown in Supplementary Section 4.

Similar to the TEA, the base case and M1 only considered the conversion process or an extended process including the separation process, respectively. However, a key difference was that LCA only considered the operating aspects, such as the input and output of materials and energy. In the M3, information regarding the decrease in the amount of bioEtOH produced over the lifetime of the plant (2%) in Et1f and Et2f was obtained from the TEA, and this was applied in the LCA. The M3 presents the effect of the allocation method. The method changes from energy-based allocation to credit-based allocation, assuming that coproducts from biorefineries replace fossil fuel-based products. The coproducts are credited with reducing the GWP in the pathway.

Table S14 Life cycle inventory.

	Et1	Et2
Corn stover (kg/GGE_{EtOH})	17.79	20.77
Sulfuric Acid (g/GGE_{EtOH})	596.71	1,323.61
Lime ($Ca(OH)_2$) (g/GGE_{EtOH})[#]	434.65	999.91
Corn Steep Liquor (g/GGE_{EtOH})	237.01	150.69
Purchased Cellulase (g/GGE_{EtOH})	1,238.42	-
Diammonium Phosphate (g/GGE_{EtOH})	29.58	-
Make-up Water (gallon/GGE_{EtOH})	8.95	2.75
WWT Chemicals (g/GGE_{EtOH})	10.51	3.68
Ash Disposal (g/GGE_{EtOH})[#]	815.21	900.17
Gypsum Disposal (g/GGE_{EtOH})[#]	1,309.75	2323.50
Electricity Credit (Btu/GGE_{EtOH})	11,608.85	3513.40

[#] GREET model database does not contain information about lime and disposals. Thus, lime and disposals are not considered in this LCA.

Table S15 GWP of bioEtOH for the Et1f and Et2f. (Unit: kg CO_2e/GGE_{EtOH})

Strategies	**Et1f**				**Et2f**			
Scenarios	**Base case**	**M1**	**M2**	**M3**	**Base case**	**M1**	**M2**	**M3**
GWP	3.12	3.38	3.45	0.89	1.17	1.40	1.43	-0.69

S.7 Uncertainty assessment

There are three main sources of uncertainty: data uncertainty, modeling uncertainty, and completeness uncertainty.[136] Data uncertainties are associated with the quality or appropriateness of data used as inputs to an assessment model, and modeling uncertainties result from an incomplete understanding of modeled phenomena or numerical approximation. Omissions caused by a lack of knowledge lead to completeness uncertainties, which, in contrast to other major uncertainties, are unquantifiable and irreducible.[136] Identified uncertainty quantification involves estimating individual uncertainties identified in the previous step based on the large sample dataset. Important statistical information, including the mean, standard deviation, confidence interval, and probability distribution, is obtained in this step using mathematical techniques, such as first-order error propagation (Gaussian method) or a Monte Carlo simulation. Compared to the first approach, which is applicable to limited data that meet certain assumptions, such as having a normal distribution, no biases, and limited individual uncertainties, the second approach based on a Monte Carlo simulation allows uncertainties of any probability range, distribution, and correlation structure to be estimated.

Based on the results of the deterministic assessments, we conducted UA using @Risk software, which is an Excel spreadsheet add-in from Palisades Corporation.[137] A stochastic analysis was performed to estimate the distribution of the EMP of bioEtOH, considering uncertainty in two parameters (corn stover price[97] and carbon price[133]). A Monte Carlo simulation with 10,000 iterations was performed to show the probability distribution of the EMP of bioEtOH. In each iteration, uncertain input variables were sampled from distributions of economic parameters that were assumed based on historical data obtained from TEA and LCA. The details of the UA are presented in Supplementary Figures 4–31.

Figure S4 Accumulated probability of EMP for Et1f (2,000 t per day)

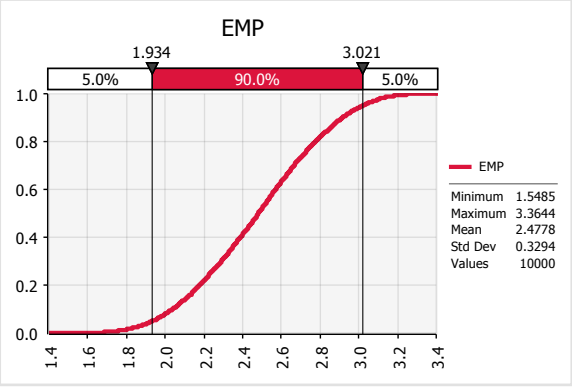


Figure S5 Input ranked by effect on output mean for Et1f (2,000 t per day)

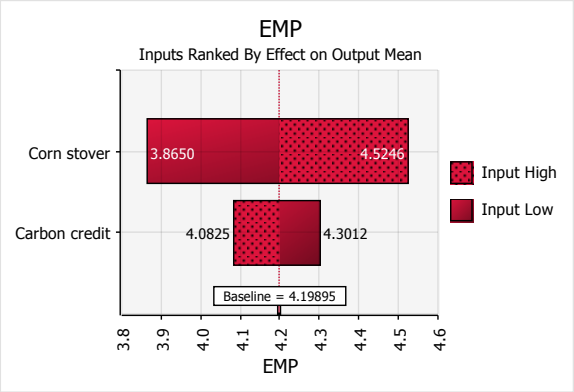


Figure S6 Probability of EMP for Et1a (2,000 t per day)

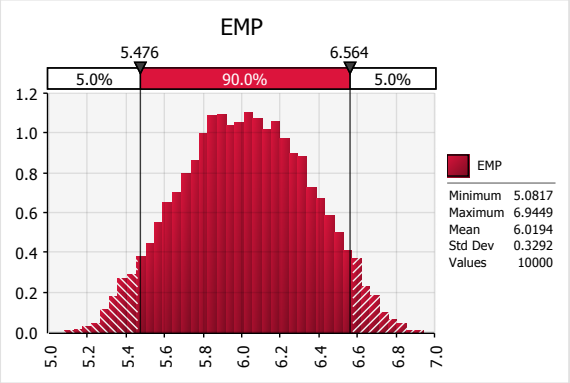


Figure S7 Accumulated probability of EMP for Et1a (2,000 t per day)

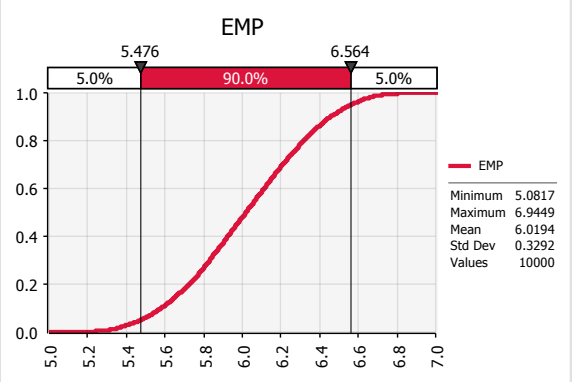


Figure S8 Input ranked by effect on output mean for Et1a (2,000 t per day)

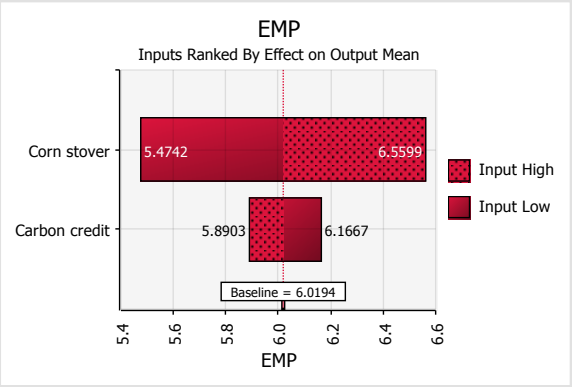


Figure S9 Probability of EMP for Et1c (2,000 t per day)

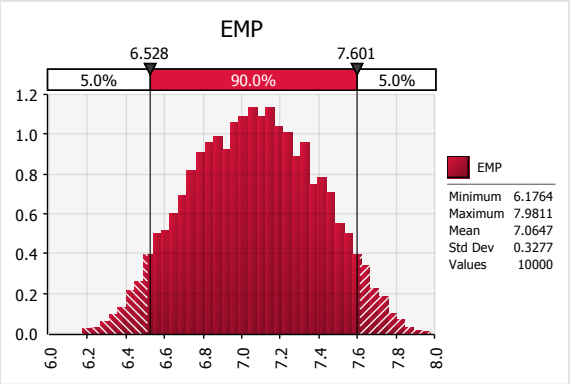


Figure S10 Accumulated probability of EMP for Et1c (2,000 t per day)

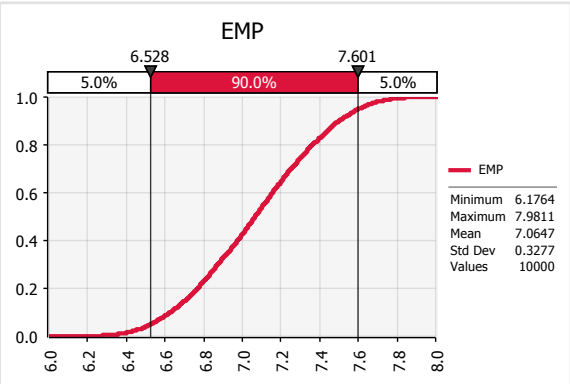


Figure S11 Input ranked by effect on output mean for Et1c (2,000 t per day)

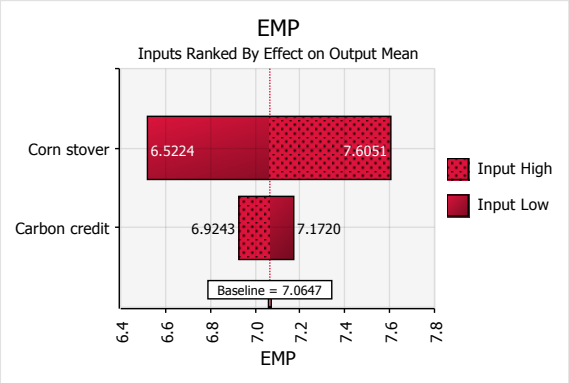


Figure S12 Probability of EMP for Et1d (2,000 t per day)

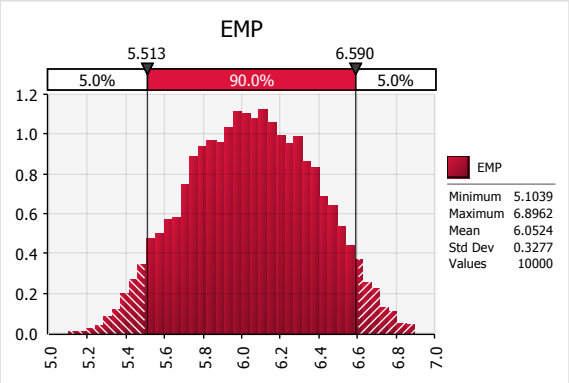


Figure S13 Accumulated probability of EMP for Et1d (2,000 t per day)

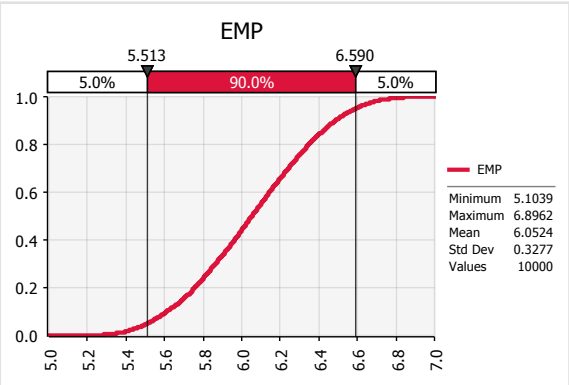


Figure S14 Input ranked by effect on output mean for Et1d (2,000 t per day)

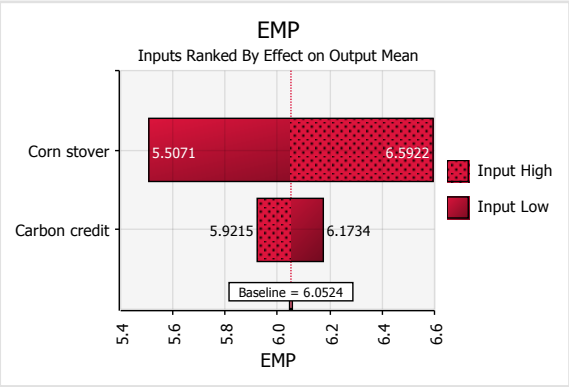


Figure S15 Probability of EMP for Et1p (2,000 t per day)

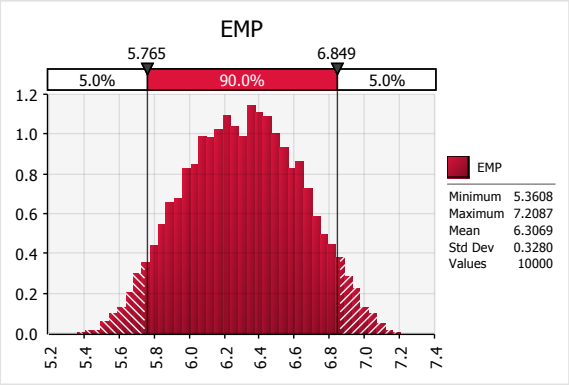


Figure S16 Accumulated probability of EMP for Et1p (2,000 t per day)

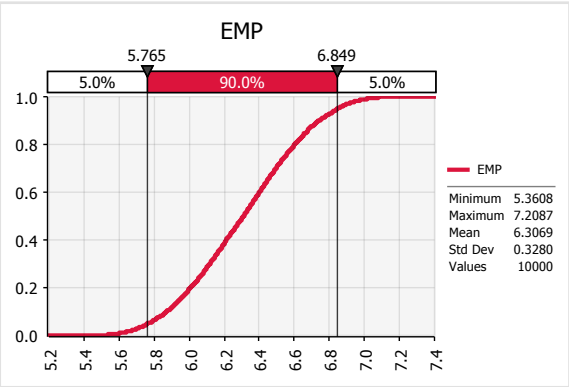


Figure S17 Input ranked by effect on output mean for Et1p (2,000 t per day)

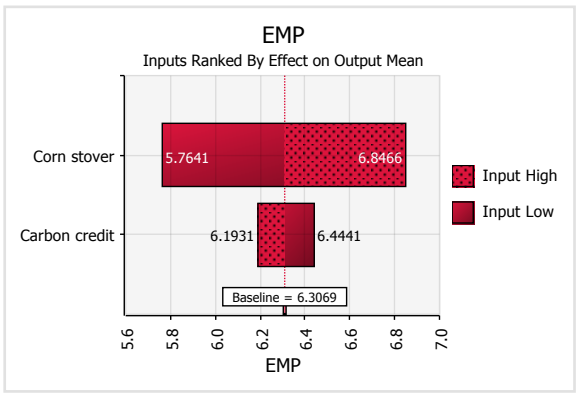


Figure S18 Accumulated probability of EMP for Et2f (2,000 t per day)

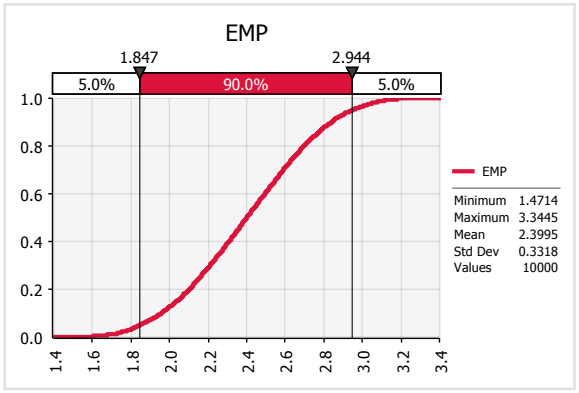


Figure S19 Input ranked by effect on output mean for Et2f (2,000 t per day)

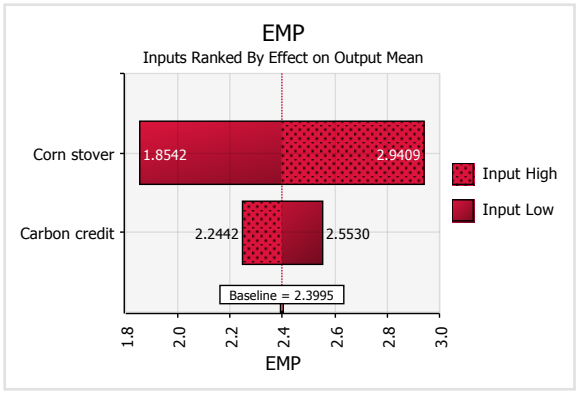


Figure S20 Probability of EMP for Et2a (2,000 t per day)

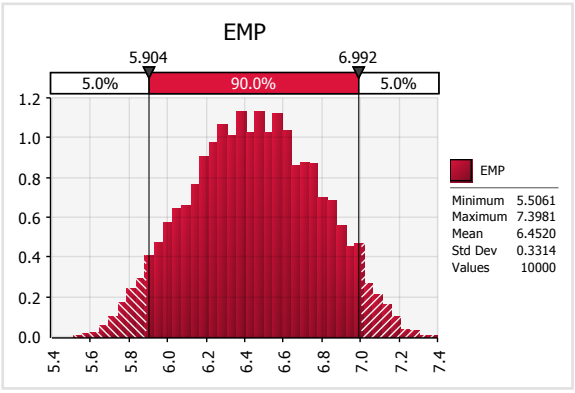


Figure S21 Accumulated probability of EMP for Et2a (2,000 t per day)

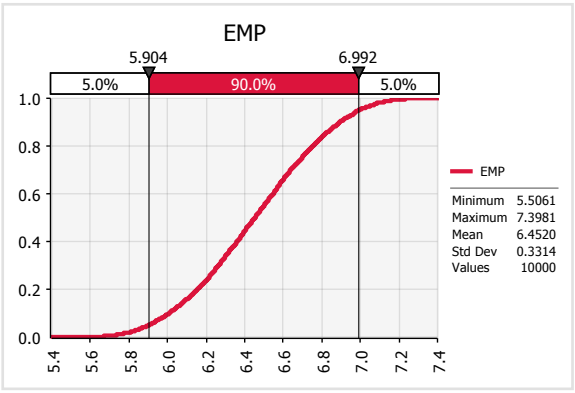


Figure S22 Input ranked by effect on output mean for Et2a (2,000 t per day)

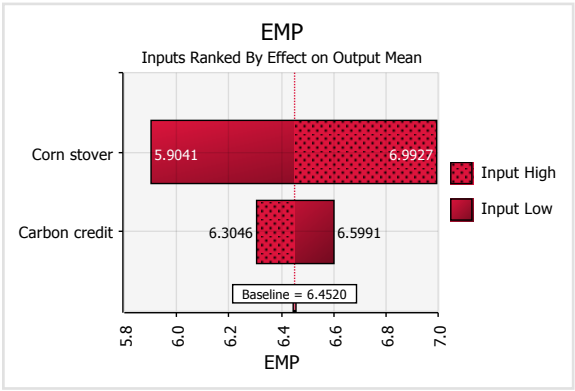


Figure S23 Probability of EMP for Et2c (2,000 t per day)

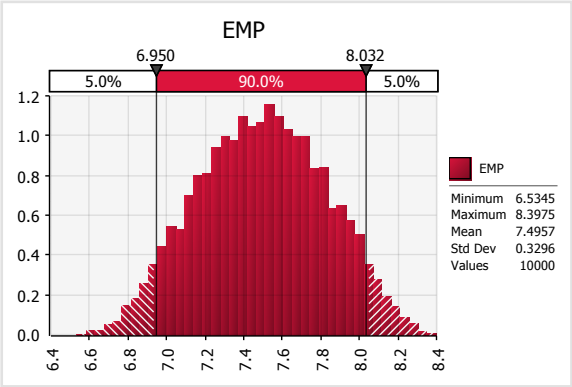


Figure S24 Accumulated probability of EMP for Et2c (2,000 t per day)

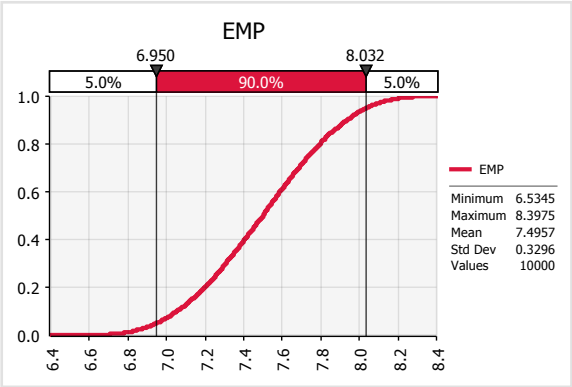


Figure S25 Input ranked by effect on output mean for Et2c (2,000 t per day)

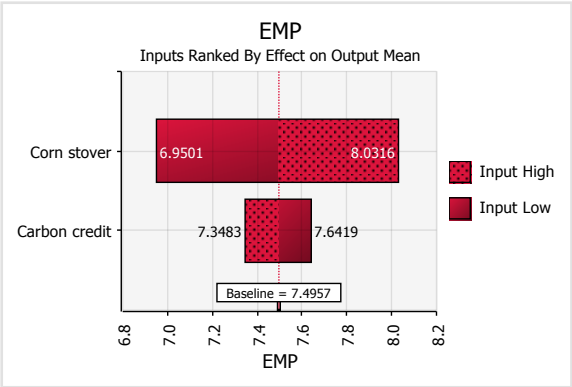


Figure S26 Probability of EMP for Et2d (2,000 t per day)

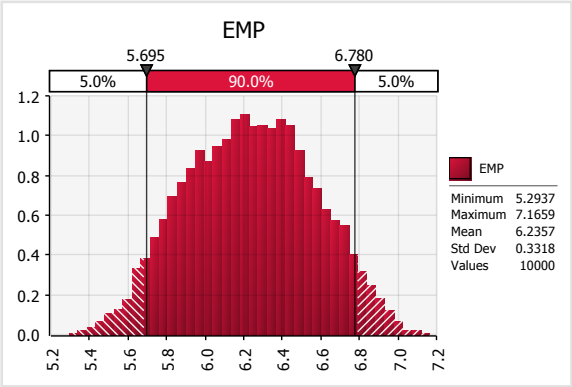


Figure S27 Accumulated probability of EMP for Et2d (2,000 t per day)

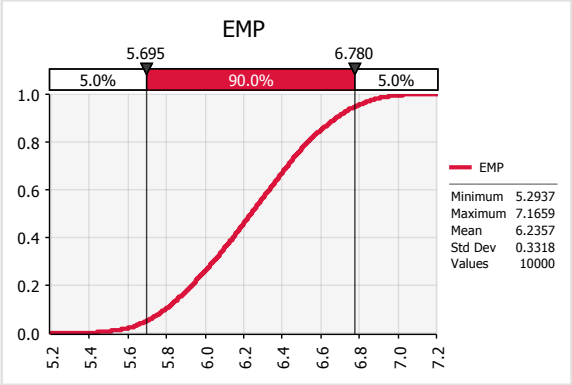


Figure S28 Input ranked by effect on output mean for Et2d (2,000 t per day)

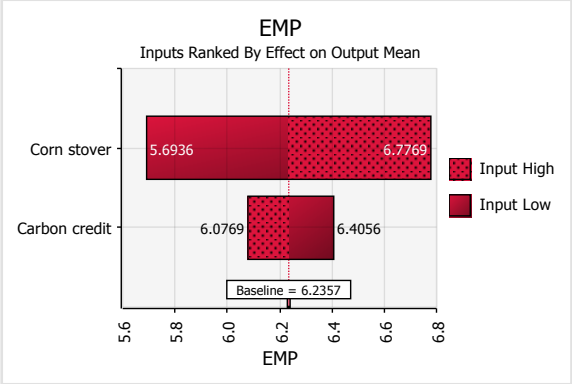


Figure S29 Probability of EMP for Et2p (2,000 t per day)

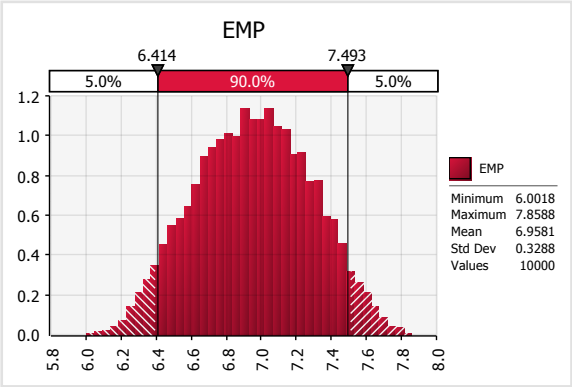


Figure S30 Accumulated probability of EMP for Et2p (2,000 t per day)

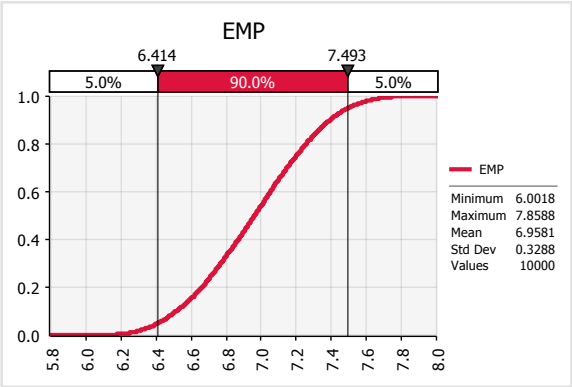


Figure S31 Input ranked by effect on output mean for Et2p (2,000 t per day)

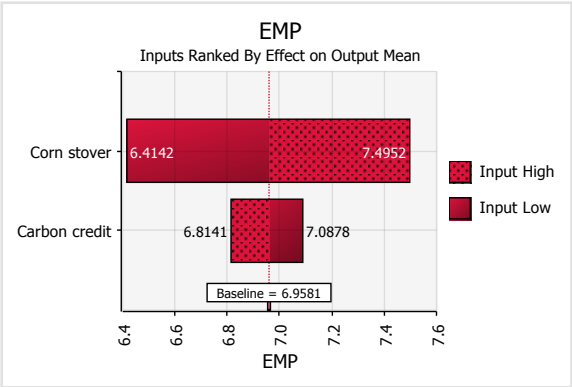


Figure S32 Probability of EMP for Et1a (30,000 t per day)

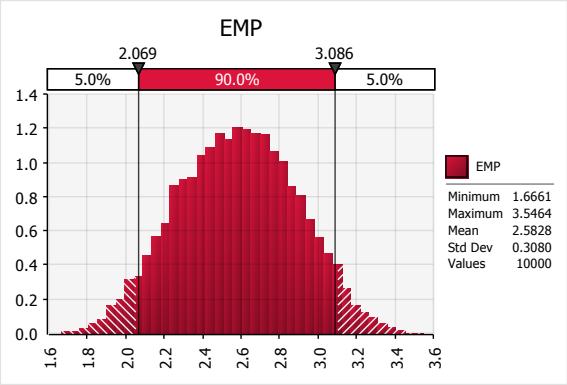


Figure S33 Accumulated probability of EMP for Et1a (30,000 t per day)

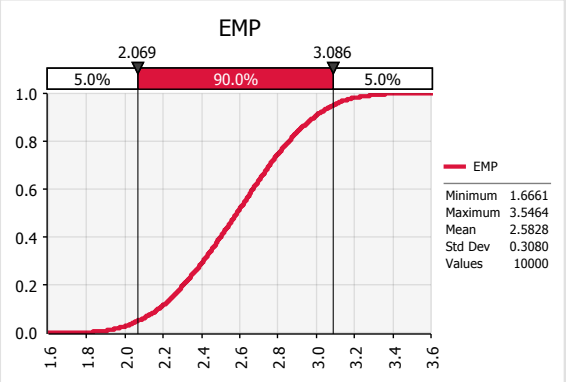


Figure S34 Input ranked by effect on output mean for Et1a (30,000 t per day)

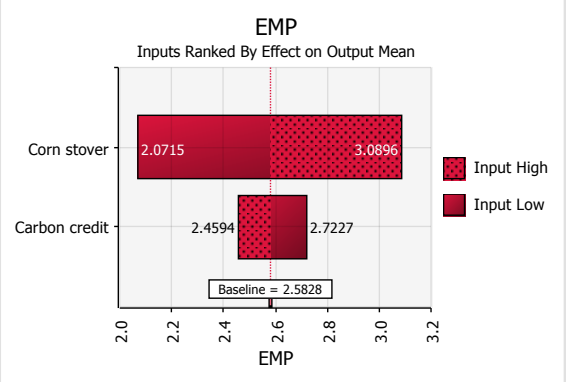


Figure S35 Probability of EMP for Et1c (30,000 t per day)

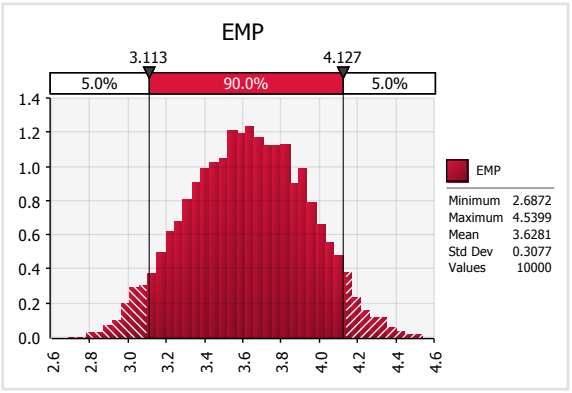


Figure S36 Accumulated probability of EMP for Et1c (30,000 t per day)

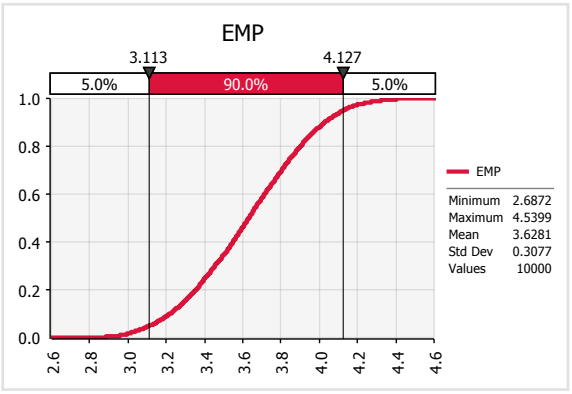


Figure S37 Input ranked by effect on output mean for Et1c (30,000 t per day)

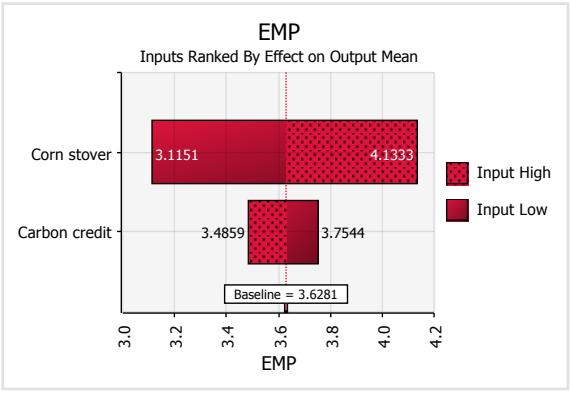


Figure S38 Probability of EMP for Et1d (30,000 t per day)

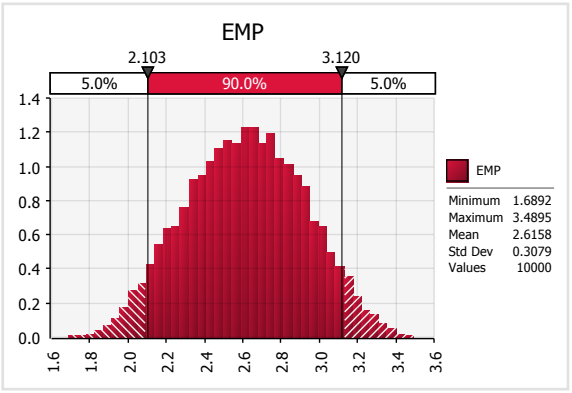


Figure S39 Accumulated probability of EMP for Et1d (30,000 t per day)

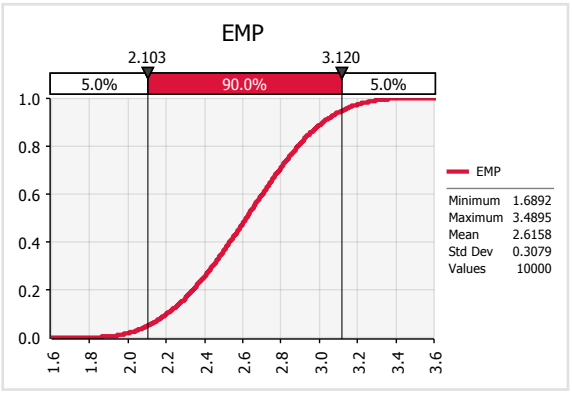


Figure S40 Input ranked by effect on output mean for Et1d (30,000 t per day)

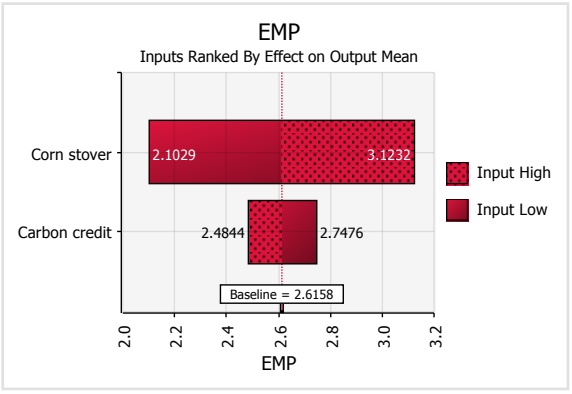


Figure S41 Probability of EMP for Et1p (30,000 t per day)

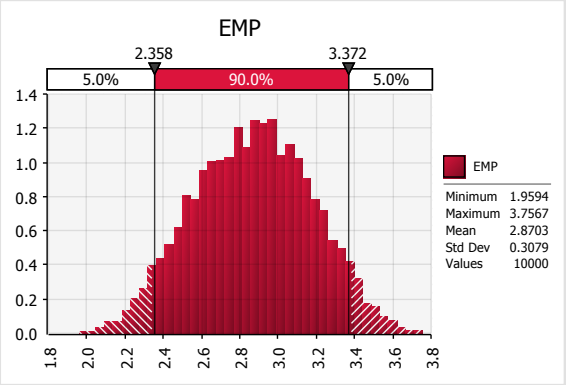


Figure S42 Accumulated probability of EMP for Et1p (30,000 t per day)

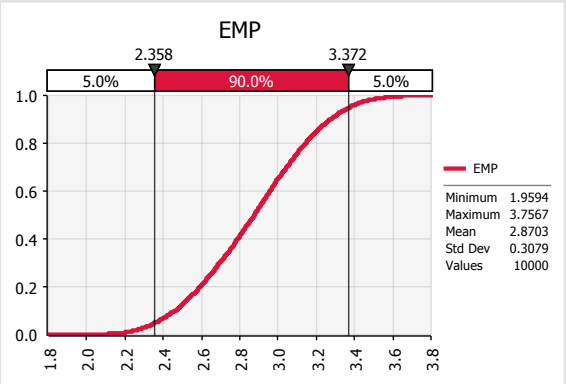


Figure S43 Input ranked by effect on output mean for Et1p (30,000 t per day)

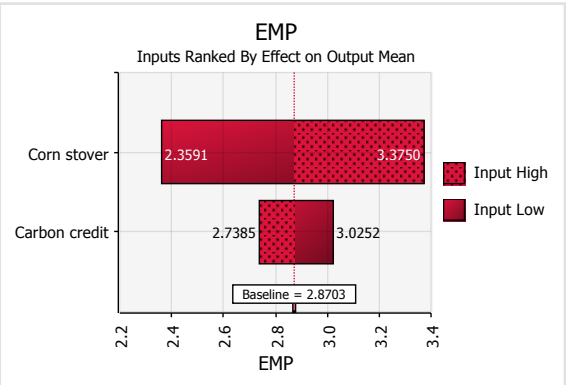


Figure S44 Probability of EMP for Et2a (30,000 t per day)

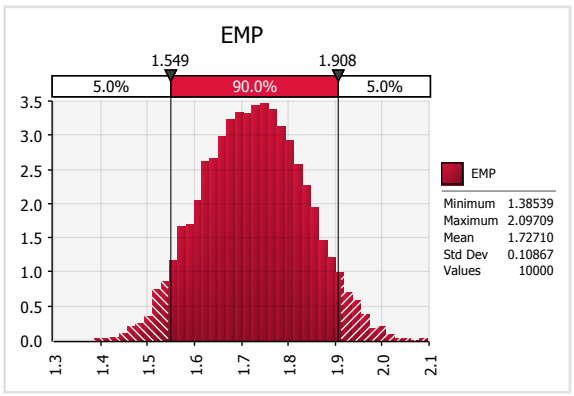


Figure S45 Accumulated probability of EMP for Et2a (30,000 t per day)

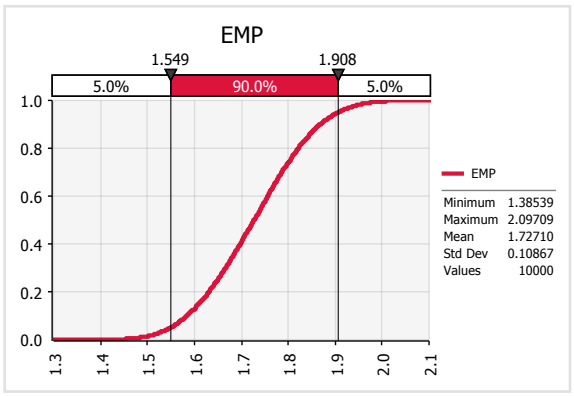


Figure S46 Input ranked by effect on output mean for Et2a (30,000 t per day)

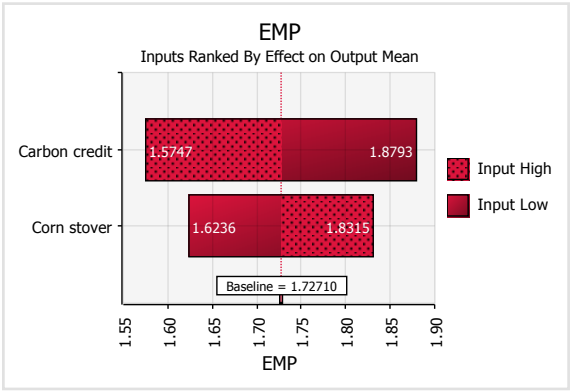


Figure S47 Probability of EMP for Et2c (30,000 t per day)

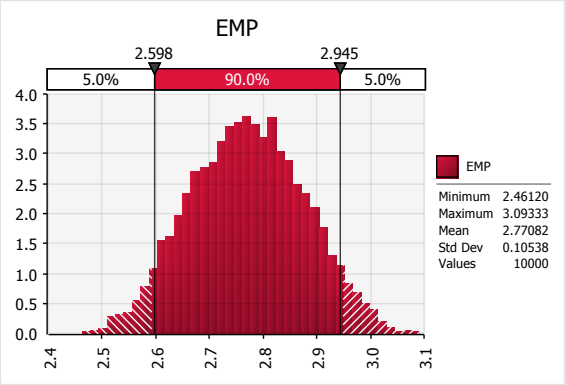


Figure S48 Accumulated probability of EMP for Et2c (30,000 t per day)

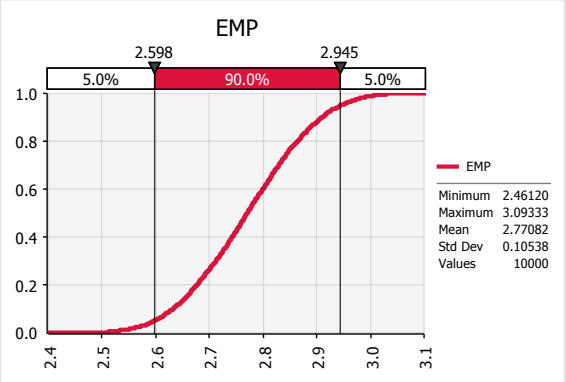


Figure S49 Input ranked by effect on output mean for Et2c (30,000 t per day)

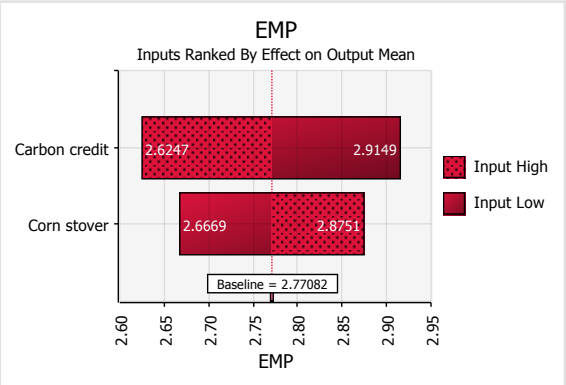


Figure S50 Probability of EMP for Et2d (30,000 t per day)

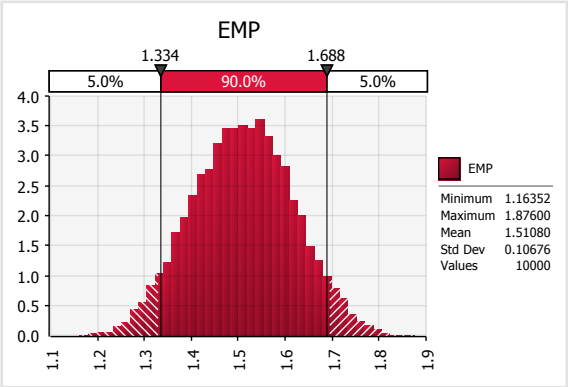


Figure S51 Accumulated probability of EMP for Et2d (30,000 t per day)

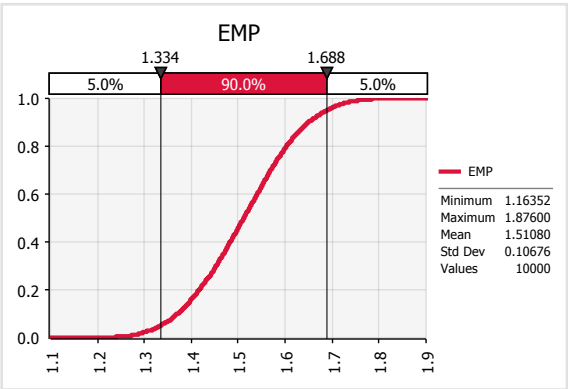


Figure S52 Input ranked by effect on output mean for Et2d (30,000 t per day)

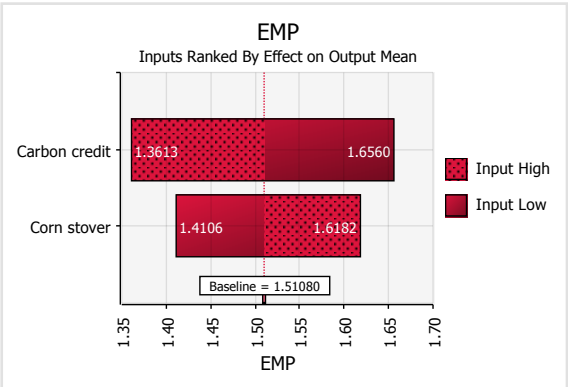


Figure S53 Probability of EMP for Et2p (30,000 t per day)

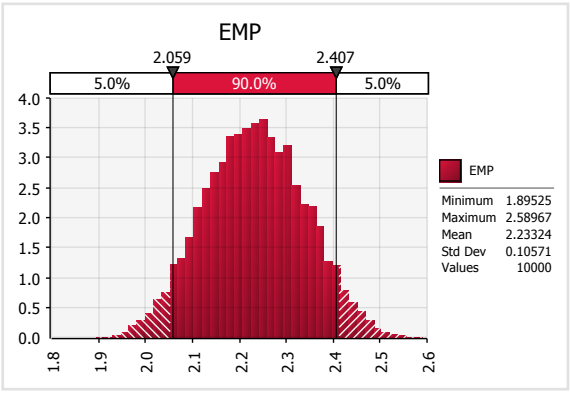


Figure S54 Accumulated probability of EMP for Et2p (30,000 t per day)

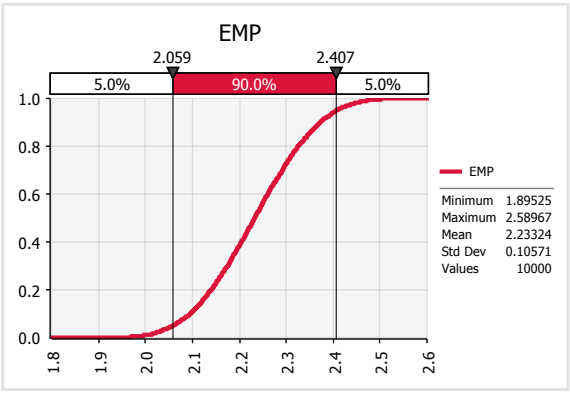
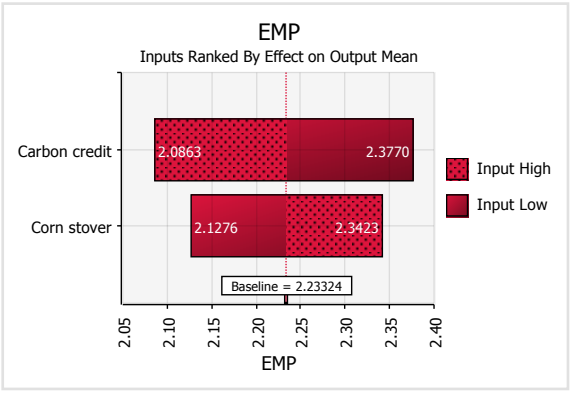


Figure S55 Input ranked by effect on output mean for Et2p (30,000 t per day)



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