DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Well-to-Wheels Energy and Greenhouse Gas Emission Analysis of Bio-Blended High-Octane Fuels for High-Efficiency Engines

Appendix 3 – WTP Analysis of Finished Gasolines

by
Pingping Sun, Amgad Elgowainy, and Michael Wang
Systems Assessment Group, Energy Systems Division, Argonne National Laboratory

February 2019

Appendix 3 – WTP Analysis of Finished Gasolines

Contents

Figures

Figures (Cont.)

Tables

Tables (Cont.)

The WTP analyses of E set and BR set finished gasolines are calculated by combining the WTP energy uses and GHG emissions of gasoline BOBs with that of ethanol/bioreformate, based on energy basis. The energy content shares are the measured values from the lab produced fuels (which were used for engine tests in ORNL), which was reported in the report by S. Sluder and D. Smith 2018.

Table A3-1. The Energy Shares of Gasoline BOB and Bio-component in Each E Set or BR Set HOF Gasolines

Fuel	EtOH	Bioreformate	BOB
Baseline gasoline (E10)	6.9%		93.1%
F1 HOF	7.1%		92.9%
F7 HOF	7.1%		92.9%
F10 HOF	6.7%		93.3%
F14 HOF	7.0%		93.0%
F15 HOF	22.4%		77.6%
F16 HOF	6.9%		93.1%
F18 HOF	14.1%		85.9%
F19 HOF	22.6%		77.4%
F20 HOF	14.1%		85.9%
BR1 HOF		9.9%	90.1%
BR2 HOF		29.7%	70.3%
BR4 HOF		29.3%	70.7%

In 2022, the domestic gasoline has 50 vol% of BAU gasoline and 50 vol% HOF gasoline. The energy shares of gasoline BOB and ethanol in the baseline gasoline (93.1% and 6.9%) is adopted for each BAU gasoline in all the E set and BR set fuels.

A3.1 WTP Analysis of E Set Domestic Fuels

The WTP energy uses and GHG emissions of E set domestic gasolines produced in aggregate refineries and configuration refineries are studied.

A3.1.1 WTP Analysis of Aggregate Refineries Base Case Gasolines

The WTP energy uses of base case E10 domestic gasolines are calculated. The calculation for PADD 2 baseline in 2015 is shown below as an example.

In 2015, the WTP total energy use for gasoline BOB production in PADD 2 is 0.35 MJ/MJ (see main report Figure 7-2) and the WTP total energy use for corn starch ethanol is 0.61 MJ/MJ (see main report Table 7-2). Thus, by using the energy shares in Table A3-1, the total energy of E10 gasoline in PADD 2 in 2015 = 0.35 × 93.1% + 0.61 × 6.7% = 0.367 MJ/MJ.

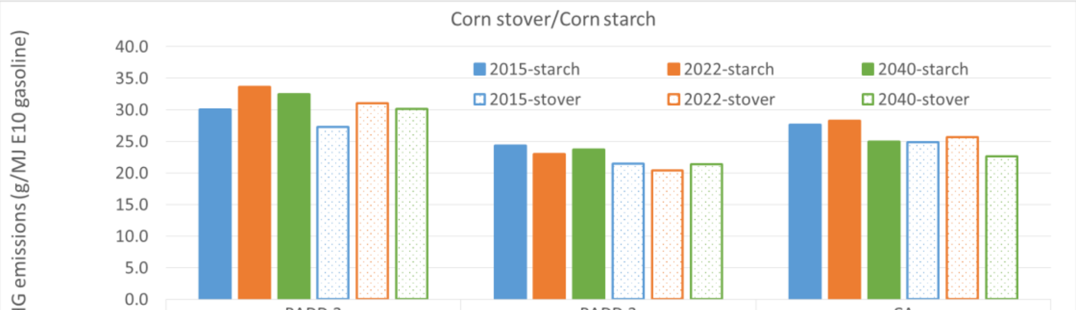
Similarly, the WTP energy uses for all baseline E10 gasolines are calculated and shown in Table A3-2.

Table A3-2. WTP Total Energy, Fossil Energy and Petroleum Energy Uses for the Production of E10 Gasolines from PADD Refinery Base Cases (MJ/MJ of fuel.)

Base Cases	EtOH Source	E10 with Corn Starch Ethanol			E10 with Corn Stover Ethanol		
Year	PADD	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
2015	PADD 2	0.367	0.356	0.080	0.458	0.329	0.084
	PADD 3	0.291	0.283	0.069	0.382	0.255	0.073
	CA	0.334	0.325	0.092	0.425	0.297	0.095
2022	PADD 2	0.435	0.425	0.089	0.520	0.400	0.092
	PADD 3	0.276	0.270	0.069	0.362	0.245	0.072
	CA	0.335	0.327	0.075	0.421	0.302	0.079
2040	PADD 2	0.437	0.426	0.082	0.524	0.402	0.086
	PADD 3	0.315	0.307	0.067	0.401	0.284	0.071
	CA	0.309	0.300	0.068	0.396	0.277	0.072

In the WTP stage, the difference between fossil energy and petroleum energy is mostly attributable to natural gas use. It is because both direct and indirect coal use (for electricity generation) is very small compared to natural gas use, in all the major processes of the WTP stage (crude recovery, refining process, corn farming, and ethanol production/transportation), as shown in the GREET 2016 model.

Combining the WTP GHG emissions from E set gasoline BOB production and those from ethanol production gives the WTP GHG emissions for E10 finished gasoline fuel, in each studied year, shown in the figure below.



	PADD 2	PADD 3	CA
2015-starch	30.1	24.3	27.7
2022-starch	33.6	23.0	28.2
2040-starch	32.5	23.7	25.0
2015-stover	27.2	21.5	24.9
2022-stover	31.1	20.4	25.7
2040-stover	30.1	21.4	22.6

Figure A3-1. WTP GHG Emissions for Domestic Finished Gasoline of PADD and CA Base Cases in Various Years.

As expected, the base cases in PADD 2 have higher GHG emissions than that in other regions along the WTP pathways; due to the more use of energy intensive and GHG emission intensive oil sands. The baseline E10 fuels with corn starch ethanol have higher GHG emissions than that with corn stover ethanol. However, the difference is about 2 g/MJ E10 gasoline (6-10% to WTP gasoline GHG emissions), due to the low blending level of 10 vol% ethanol in the E10 gasoline pool.

A3.1.2 WTP Analysis of Aggregate Refineries E Set Gasolines

In 2022, the WTP energy uses of E set BAU gasolines and HOF gasolines produced in PADD 3 refinery and in CA refinery in year 2022 and 2040 are calculated, and shown in the Tables A3-3 through A3-6.

Table A3-3. WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of E Set Gasolines (BAU and HOF) in PADD 3 Refinery in 2022

EtOH Source	E Set BAU and HOF Gasoline with EtOH from Corn Starch					
Gasoline Pool	BAU			HOF		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F1	0.287	0.281	0.053	0.253	0.246	0.066
F7	0.294	0.288	0.055	0.258	0.251	0.083
F10	0.272	0.266	0.049	0.267	0.260	0.071
F14	0.283	0.278	0.047	0.257	0.251	0.074
F15	0.292	0.286	0.051	0.265	0.259	0.046
F16	0.278	0.272	0.066	0.256	0.249	0.085
F18	0.274	0.268	0.046	0.296	0.289	0.078
F19	0.290	0.284	0.050	0.296	0.289	0.067
F20	0.279	0.273	0.048	0.284	0.277	0.070

EtOH Source	E Set BAU and HOF Gasoline with EtOH from Corn Stover					
Gasoline Pool	BAU			HOF		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F1	0.373	0.256	0.057	0.341	0.221	0.070
F7	0.380	0.263	0.059	0.346	0.226	0.086
F10	0.357	0.241	0.053	0.350	0.236	0.075
F14	0.369	0.253	0.051	0.344	0.226	0.078
F15	0.377	0.261	0.054	0.544	0.178	0.059
F16	0.364	0.247	0.070	0.341	0.224	0.089
F18	0.360	0.243	0.050	0.472	0.238	0.086
F19	0.375	0.259	0.054	0.577	0.207	0.080
F20	0.365	0.248	0.052	0.459	0.226	0.078

Table A3-4. WTP Total Energy, Fossil Energy, and Petroleum Energy Use for the Production of E Set Gasolines (BAU and HOF) in CA Refinery in 2022

EtOH Source	Corn Starch					
Gasoline Pool	BAU			HOF		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F1	0.350	0.342	0.082	0.315	0.307	0.074
F7	0.346	0.339	0.079	0.324	0.316	0.084
F10	0.341	0.333	0.069	0.332	0.324	0.079
F14	0.344	0.336	0.074	0.334	0.326	0.083
F15	0.350	0.342	0.077	0.345	0.337	0.057
F18	0.335	0.327	0.064	0.364	0.355	0.083
F19	0.347	0.338	0.072	0.370	0.361	0.061
F20	0.340	0.332	0.070	0.364	0.356	0.076
EtOH Source	Corn Stover					
Gasoline Pool	BAU			HOF		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F1	0.435	0.317	0.086	0.403	0.281	0.078
F7	0.432	0.314	0.083	0.412	0.290	0.088
F10	0.427	0.309	0.073	0.415	0.300	0.083
F14	0.430	0.311	0.078	0.421	0.300	0.087
F15	0.436	0.317	0.081	0.623	0.256	0.069
F18	0.421	0.302	0.067	0.539	0.304	0.091
F19	0.433	0.313	0.076	0.651	0.280	0.073
F20	0.426	0.307	0.073	0.540	0.305	0.084

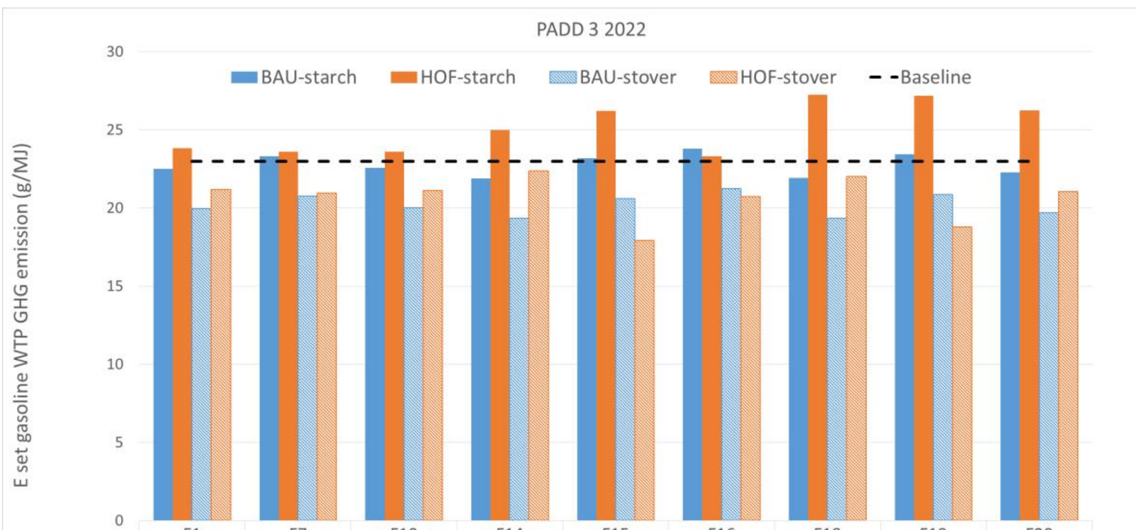
Table A3-5. WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of E Set Gasolines (all HOF) in PADD 3 Refinery in 2040

EtOH Source	Corn Starch			Corn Stover		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F1	0.304	0.296	0.054	0.393	0.272	0.058
F10	0.301	0.294	0.054	0.386	0.271	0.058
F14	0.279	0.271	0.071	0.367	0.247	0.075
F15	0.327	0.319	0.039	0.609	0.243	0.052
F18	0.302	0.294	0.072	0.479	0.246	0.080
F19	0.355	0.347	0.056	0.640	0.270	0.068
F20	0.326	0.319	0.059	0.504	0.271	0.067

Table A3-6. WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of E Set Gasolines (All HOF) in CA Refinery in 2040

EtOH Source	Corn Starch			Corn Stover		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F1	0.316	0.307	0.073	0.405	0.283	0.077
F10	0.317	0.308	0.069	0.401	0.285	0.073
F14	0.326	0.318	0.077	0.415	0.294	0.081
F15	0.339	0.330	0.059	0.621	0.254	0.072
F18	0.338	0.329	0.071	0.516	0.281	0.078
F19	0.355	0.346	0.066	0.640	0.269	0.078
F20	0.331	0.322	0.065	0.509	0.274	0.073

In 2022, the WTP GHG emissions for the production of BAU gasoline and HOF gasoline in PADD 3 and in CA are calculated, and compared with that of baseline which uses corn starch ethanol.



	F1	F7	F10	F14	F15	F16	F18	F19	F20
BAU-starch	22.5	23.3	22.6	21.9	23.2	23.8	21.9	23.4	22.3
HOF-starch	23.8	23.6	23.6	25.0	26.2	23.3	27.2	27.2	26.2
BAU-stover	19.9	20.7	20.0	19.3	20.6	21.2	19.3	20.9	19.7
HOF-stover	21.2	21.0	21.1	22.4	17.9	20.7	22.0	18.8	21.0
Baseline	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0

Figure A3-2. WTP GHG Emissions of E set BAU and HOF Gasolines Production in PADD 3 Refinery in 2022 (Baseline Gasoline Ethanol from Corn Starch).

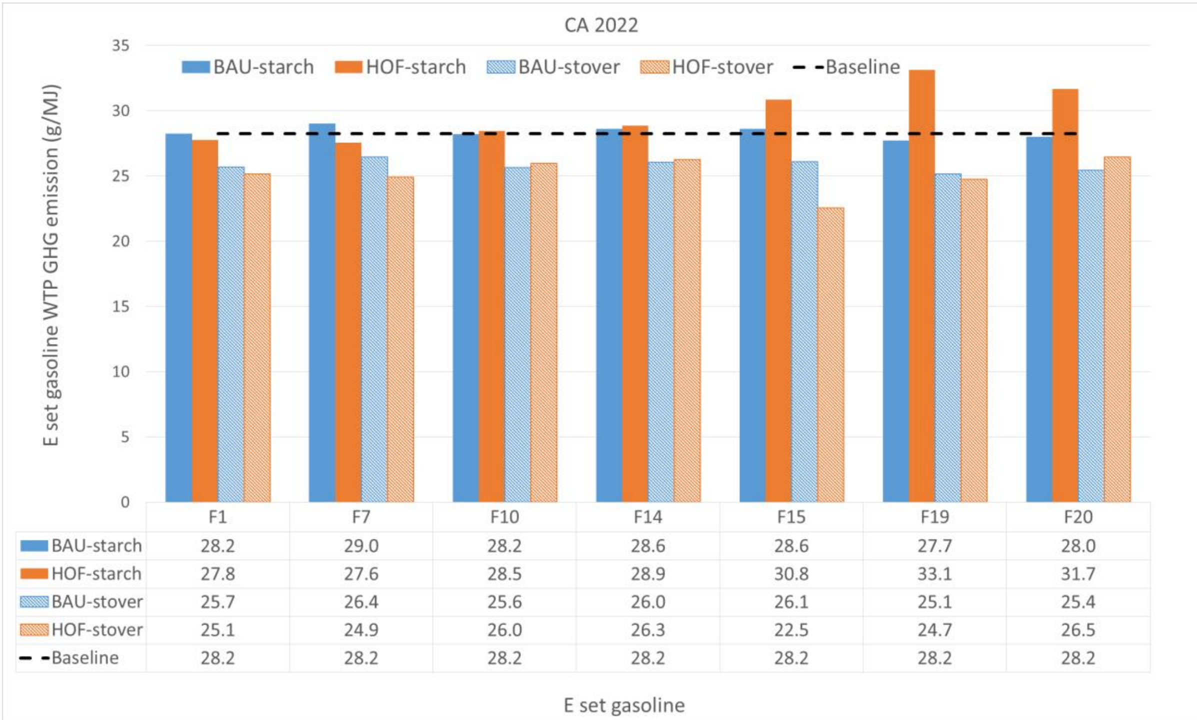


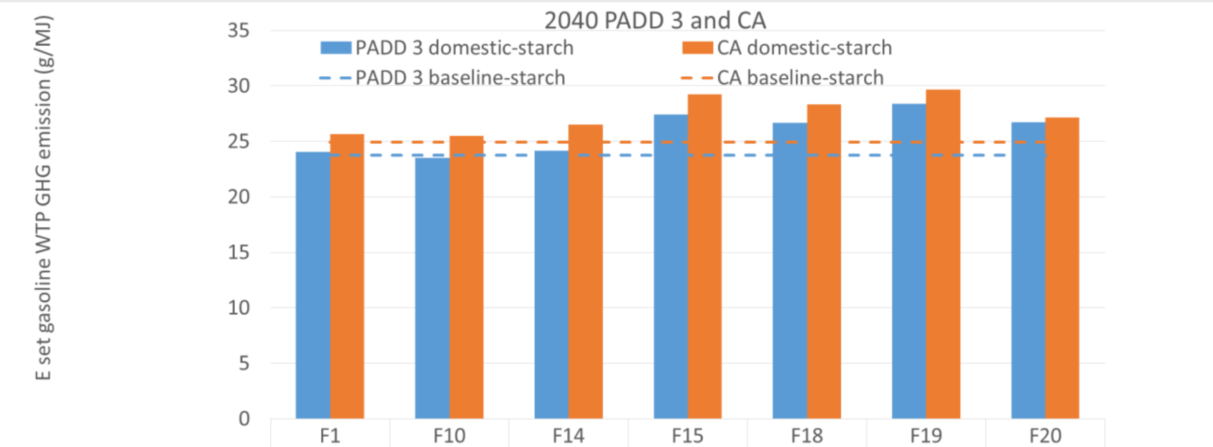
Figure A3-3. WTP GHG Emissions of E set BAU and HOF Gasolines Production in CA Refinery in 2022 (Baseline Gasoline Ethanol from Corn Starch).

Combining the GHG emissions of the BAU pool and the HOF pool (in 2022) yields the domestic gasoline GHG emissions shown in Figure A3-4. Note that for year 2022, the LP modeling of Fuel 16 in CA did not yield feasible solutions. It is also worth noting that in 2022, the baseline is projected to use corn starch ethanol only.

	F1	F7	F10	F14	F15	F16	F18	F19	F20
PD3-starch	23.2	23.4	23.1	23.4	24.6	23.5	24.5	25.2	24.2
PD3-stover	20.6	20.8	20.6	20.9	19.3	21.0	20.7	19.9	20.4
CA-starch	28.0	28.3	28.3	28.7	29.7		29.7	30.3	29.8
CA-stover	25.4	25.7	25.8	26.2	24.4		25.9	25.0	25.9
PD3 baseline	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
CA baseline	28.2	28.2	28.2	28.2	28.2	28.2	28.2	28.2	28.2

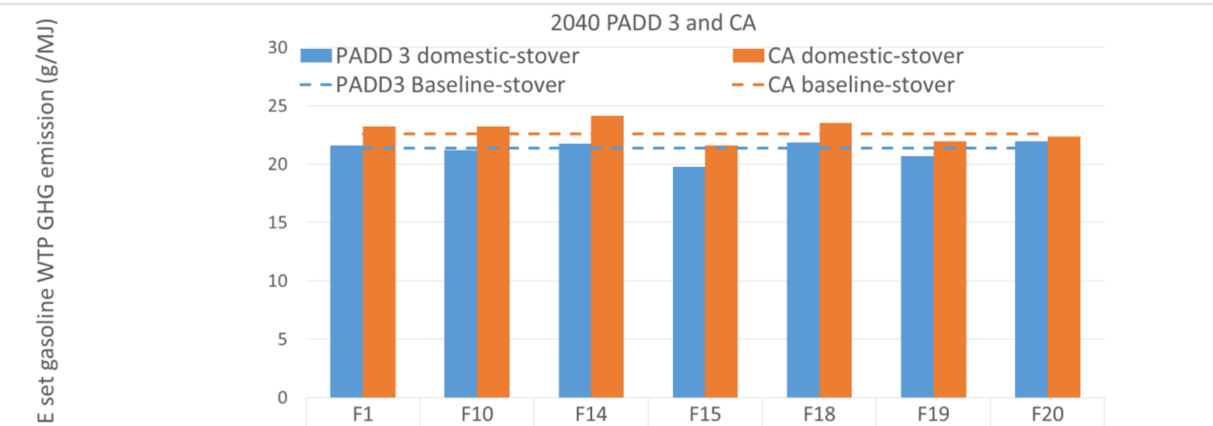
Figure A3-4. WTP GHG Emissions of E Set Domestic Gasolines Production in PADD 3 and in CA in 2022 (Baseline Gasoline Ethanol from Corn Starch).

For the 2040, all gasolines are HOF gasolines with high octane requirements. The LP modeling results show that only seven out of nine cases can be solved. The LP modeling of Fuel 7 and Fuel 16 cannot yield feasible solutions to meet targeted high octanes, stringent specifications, and targeted production volume. The WTP GHG emissions for E set fuels in PADD 3 and CA in 2040 are shown in Figure A3-5, and are compared with that of baselines. In 2040, duel baselines are used with ethanol from corn starch and corn stover, respectively. The E set fuels are compared with the baselines containing the same ethanol source.



	F1	F10	F14	F15	F18	F19	F20
PADD 3 domestic-starch	24.0	23.5	24.1	27.4	26.7	28.4	26.7
CA domestic-starch	25.6	25.5	26.5	29.2	28.3	29.7	27.2
PADD 3 baseline-starch	23.7	23.7	23.7	23.7	23.7	23.7	23.7
CA baseline-starch	25.0	25.0	25.0	25.0	25.0	25.0	25.0

E set gasoline



	F1	F10	F14	F15	F18	F19	F20
PADD 3 domestic-stover	21.6	21.2	21.8	19.8	21.9	20.7	21.9
CA domestic-stover	23.2	23.2	24.1	21.6	23.5	22.0	22.4
PADD3 Baseline-stover	21.4	21.4	21.4	21.4	21.4	21.4	21.4
CA baseline-stover	22.6	22.6	22.6	22.6	22.6	22.6	22.6

E set gasoline

Figure A3-5. WTP GHG Emissions of E Set Fuels Production in PADD 3 and in CA in 2040 (Dual Baselines Used with Corn Starch Ethanol and Corn Stover, Respectively).

In 2040, most E set domestic gasolines with corn starch ethanol show higher GHG emissions than baselines, especially for fuels with higher ethanol blending levels. This is because ethanol produced from corn starch is energy intensive, relying mostly on fossil energy.

In contrast, the E set domestic gasolines with corn stover ethanol in PADD 3 and CA have different GHG emission responses to higher octane requirements, compared with their individual regional baselines. In PADD 3, four out of seven fuels have minor GHG increases relative to baseline GHG emission, while for CA, six out of seven fuels show higher GHG emissions relative to the baseline GHG emission. This is not surprising, given that CA has more stringent gasoline specifications while using heavier crude slates (which are generally more challenging and more energy intensive to process, e.g. requiring more hydrogen), posing more challenges in refining operations.

The relative changes of E set gasoline WTP GHG emissions to baselines are shown in the figures below.

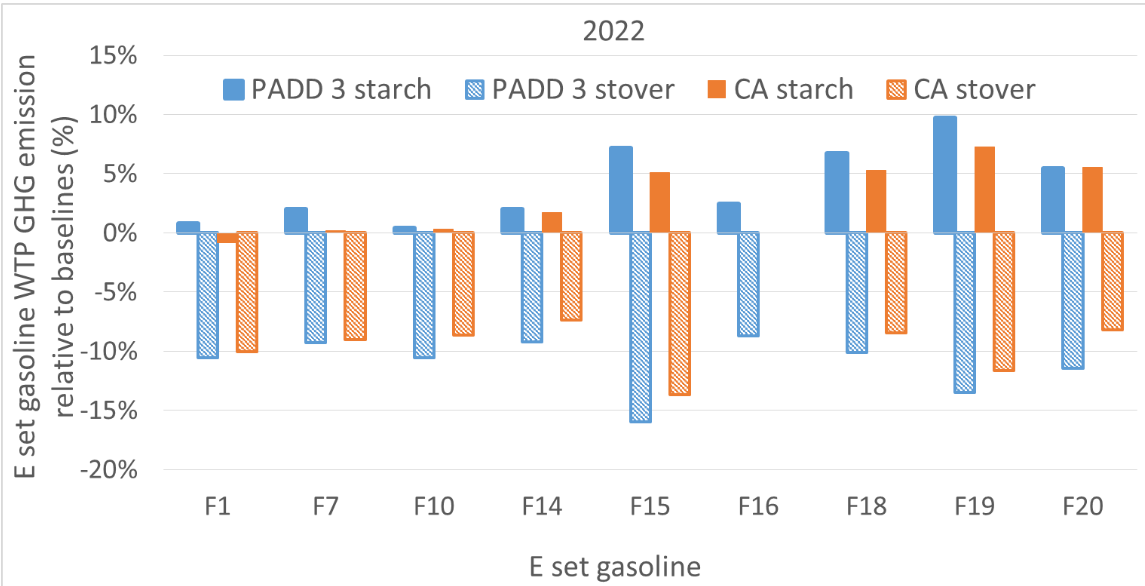


Figure A3-6. The Comparison of E Set Domestic Gasolines WTP GHG Emissions with Baselines in PADD 3 and CA in 2022. A Single Baseline with Corn Starch Ethanol Used for Each Region.

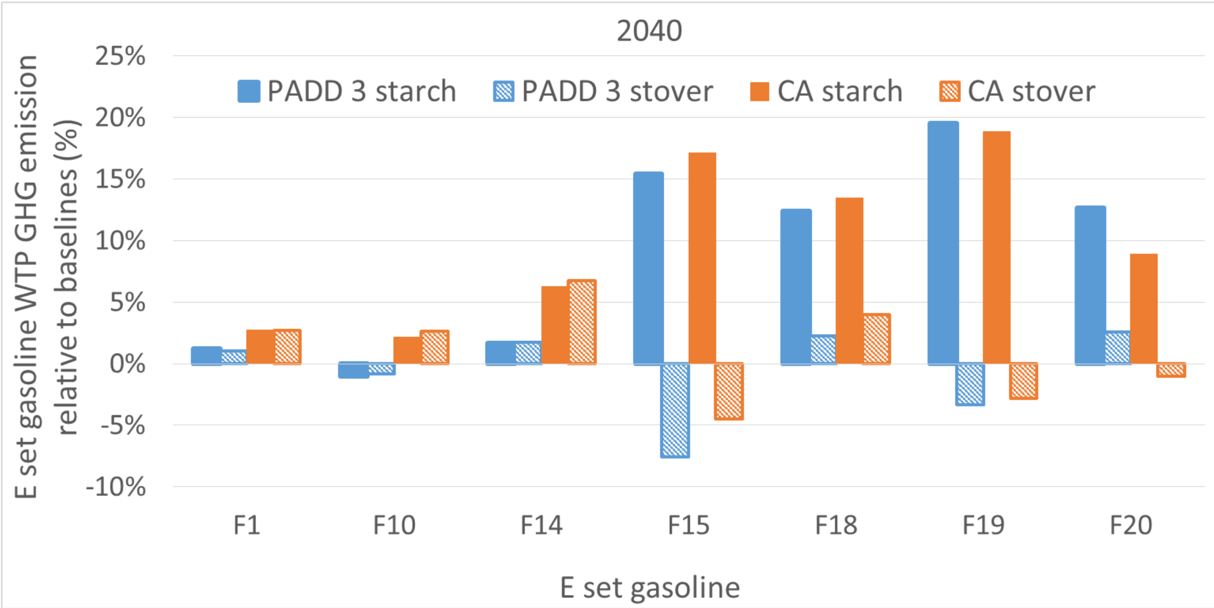


Figure A3-7. The Comparison of E Set Domestic Gasolines WTP GHG Emissions with Baselines in PADD 3 and CA in 2040. Dual Baselines Used with Corn Starch Ethanol and Corn Stover Ethanol.

A3.1.3 WTP Analysis of Configuration Refineries Base Cases

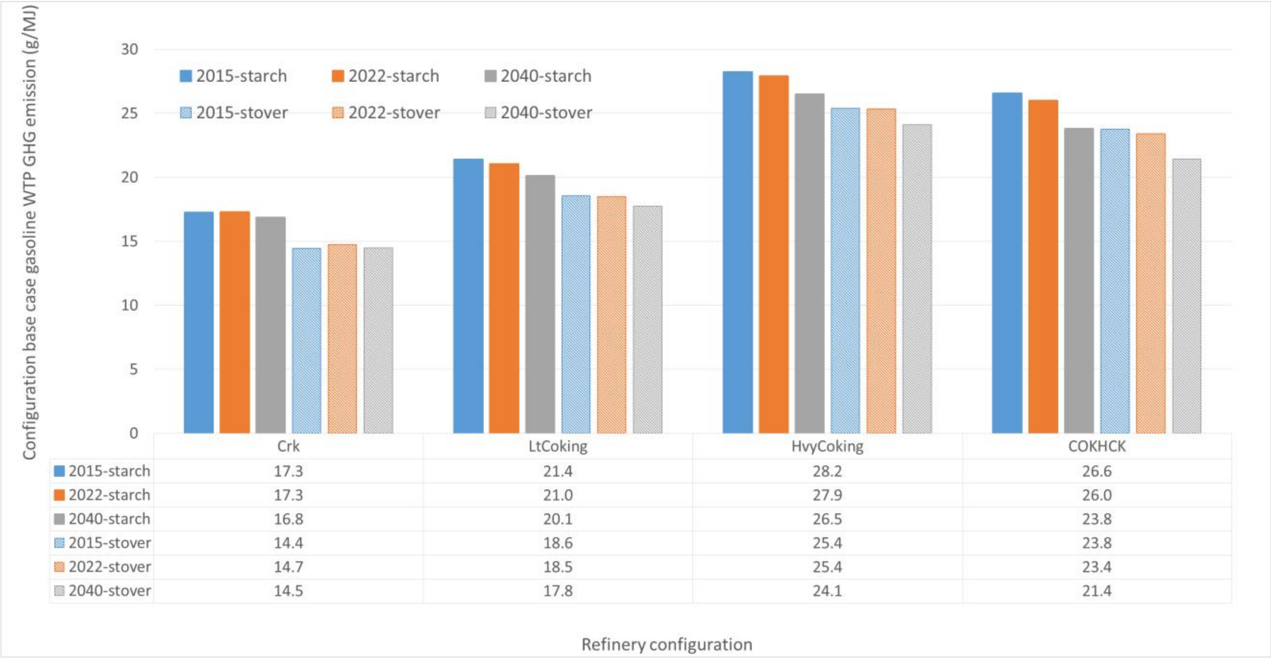
The WTP energy use and GHG emissions of E set fuels produced in configuration refineries are summarized below.

For the configuration refinery base cases, combining the energy uses and GHG emissions for the WTP gasoline BOB production and that for ethanol production yields the WTP energy uses and GHG emission of the baseline E10 gasolines. The results are shown in Table A3-7 and Figure A3-8.

Table A3-7. The WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of E10 Gasolines of Configuration Refinery Base Cases.

Base Cases	EtOH Source	E10 from Corn Starch			E10 from Corn Stover		
Year	PADD	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
2015	CRK	0.178	0.172	0.071	0.269	0.144	0.074
	LtCOK	0.235	0.228	0.082	0.326	0.200	0.086
	HvyCOK	0.345	0.336	0.085	0.436	0.308	0.089
	COKHCK	0.301	0.292	0.068	0.391	0.264	0.072
2022	CRK	0.176	0.172	0.069	0.262	0.147	0.073
	LtCOK	0.228	0.223	0.082	0.314	0.198	0.085
	HvyCOK	0.340	0.332	0.085	0.426	0.307	0.088
	COKHCK	0.290	0.283	0.070	0.376	0.258	0.074
2040	CRK	0.171	0.166	0.065	0.258	0.143	0.069
	LtCOK	0.221	0.215	0.075	0.308	0.191	0.079
	HvyCOK	0.325	0.317	0.079	0.412	0.293	0.083
	COKHCK	0.265	0.257	0.063	0.352	0.234	0.067

For the WTP production of E10 fuels in the base cases, petroleum energy constitutes a small share of fossil energy use, and the results are similar for corn stover ethanol production and corn starch ethanol production.



	Crk	LtCoking	HvyCoking	COKHCK
2015-starch	17.3	21.4	28.2	26.6
2022-starch	17.3	21.0	27.9	26.0
2040-starch	16.8	20.1	26.5	23.8
2015-stover	14.4	18.6	25.4	23.8
2022-stover	14.7	18.5	25.4	23.4
2040-stover	14.5	17.8	24.1	21.4

Figure A3-8. Configuration Base Cases WTP GHG Emissions for E10 Gasoline Production.

The GHG emissions associated with E10 gasoline production vary greatly among different configurations, with the lowest emissions for simple cracking configurations and the highest emissions for more sophisticated heavy coking and coking hydrocracking configurations. The latter can be 50%-80% higher than the former. As expected, the base case E10 fuels with ethanol from corn starch have higher GHG emissions than those with ethanol from corn stover.

A3.1.4 WTP Analysis of E Set Fuels in Configuration Refineries

The WTP energy uses of E set fuels produced in configuration refineries are listed in the Tables A3-8 through A3-11 for four configuration refineries for year 2022 and in Table A3-12 for year 2040.

Table A3-8. WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of E Set Gasolines (BAU and HOF) in CRK Configuration Refinery in 2022

EtOH Source	2022 CRK-Corn Starch					
Gasoline Pool	BAU			HOF		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F10	0.174	0.170	0.068	0.175	0.170	0.070
F14	0.159	0.155	0.058	0.188	0.183	0.082
F18	0.155	0.150	0.053	0.218	0.213	0.080
F19	0.165	0.160	0.056	0.240	0.234	0.068
F20	0.166	0.162	0.057	0.209	0.204	0.070
EtOH Source	**2022 CRK-Corn Stover**					
Gasoline Pool	BAU			HOF		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F10	0.260	0.145	0.072	0.258	0.146	0.073
F14	0.245	0.130	0.062	0.275	0.158	0.086
F18	0.241	0.126	0.057	0.394	0.162	0.087
F19	0.251	0.135	0.059	0.521	0.153	0.081
F20	0.252	0.137	0.061	0.384	0.153	0.077

Table A3-9. WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of E Set Gasolines (BAU and HOF) in LtCOK Configuration Refinery in 2022

EtOH Source	2022 LtCOK-Corn Starch					
Gasoline Pool	BAU			HOF		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F10	0.320	0.203	0.089	0.305	0.192	0.082
F14	0.296	0.180	0.075	0.330	0.212	0.099
F18	0.290	0.174	0.069	0.450	0.217	0.102
F19	0.305	0.189	0.076	0.563	0.194	0.091
F20	0.300	0.184	0.073	0.438	0.205	0.094

EtOH Source	2022 LtCOK-Corn Stover					
Gasoline Pool	BAU			HOF		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F10	0.260	0.145	0.072	0.258	0.146	0.073
F14	0.245	0.130	0.062	0.275	0.158	0.086
F18	0.241	0.126	0.057	0.394	0.162	0.087
F19	0.251	0.135	0.059	0.521	0.153	0.081
F20	0.252	0.137	0.061	0.384	0.153	0.077

Table A3-10. WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of E Set Gasolines (BAU and HOF) in HvyCOK Configuration Refinery in 2022

EtOH Source	2022 HvyCOK-Corn Starch					
Gasoline Pool	BAU			HOF		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F10	0.336	0.328	0.084	0.340	0.333	0.084
F14	0.322	0.314	0.071	0.358	0.350	0.101
F18	0.318	0.310	0.072	0.380	0.372	0.095
F19	0.317	0.309	0.073	0.378	0.370	0.085
F20	0.309	0.301	0.072	0.376	0.368	0.098
EtOH Source	**2022 HvyCOK-Corn Stover**					
Gasoline Pool	BAU			HOF		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F10	0.421	0.303	0.088	0.424	0.308	0.088
F14	0.407	0.289	0.075	0.445	0.325	0.105
F18	0.404	0.285	0.076	0.555	0.321	0.103
F19	0.403	0.284	0.077	0.659	0.288	0.098
F20	0.395	0.276	0.076	0.552	0.317	0.106

Table A3-11. WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of E Set Gasolines (BAU and HOF) in COKHCK Configuration Refinery in 2022

EtOH Source	2022 COKHCK-Corn Starch					
Gasoline Pool	BAU			HOF		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F10	0.291	0.284	0.072	0.289	0.281	0.075
F18	0.277	0.270	0.063	0.305	0.297	0.079
F19	0.286	0.278	0.070	0.313	0.305	0.060
F20	0.273	0.266	0.074	0.290	0.283	0.064

EtOH Source	2022 COKHCK-Corn Stover					
Gasoline Pool	BAU			HOF		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F10	0.377	0.259	0.076	0.372	0.257	0.079
F18	0.363	0.245	0.067	0.480	0.246	0.086
F19	0.372	0.253	0.074	0.593	0.223	0.072
F20	0.359	0.241	0.078	0.466	0.232	0.072

Table A3-12. WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of E Set Gasolines in CRK, LTCOK, HVYCOK and COKHCK Configuration Refineries in 2040

CRK

EtOH Source	Corn Starch			Corn Stover		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F10	0.170	0.165	0.064	0.254	0.142	0.068
F14	0.170	0.165	0.073	0.259	0.141	0.077
F18	0.199	0.194	0.071	0.377	0.146	0.079
F19	0.234	0.227	0.060	0.518	0.150	0.073
F20	0.201	0.195	0.063	0.379	0.147	0.071

LtCOK

EtOH Source	Corn Starch			Corn Stover		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F10	0.220	0.213	0.075	0.304	0.191	0.078
F14	0.222	0.215	0.084	0.310	0.191	0.088
F18	0.248	0.241	0.081	0.426	0.193	0.089
F19	0.273	0.266	0.070	0.558	0.189	0.083
F10	0.248	0.241	0.073	0.426	0.193	0.081

HvyCOK

EtOH Source	Corn Starch			Corn Stover		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F10	0.325	0.317	0.079	0.410	0.294	0.082
F14	0.332	0.323	0.088	0.420	0.299	0.092
F18	0.343	0.334	0.084	0.520	0.286	0.092
F19	0.355	0.345	0.073	0.639	0.269	0.086
F10	0.339	0.330	0.077	0.517	0.283	0.085

COKHCK

EtOH Source	Corn Starch			Corn Stover		
E Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
F10	0.270	0.262	0.063	0.354	0.239	0.067
F18	0.297	0.288	0.066	0.475	0.240	0.074
F19	0.307	0.298	0.055	0.592	0.221	0.068
F10	0.297	0.288	0.061	0.474	0.240	0.069

Combining the WTP GHG emissions of ethanol production and the GHG emissions of gasoline BOBs produced in configuration refineries (both BAU and HOF for year 2022 cases) yields the GHG emissions for these E set fuels, shown in Figure A3-9 (for ethanol from corn starch) and Figure A3-10 (for ethanol from corn stover). In both figures, the baseline uses corn starch ethanol.

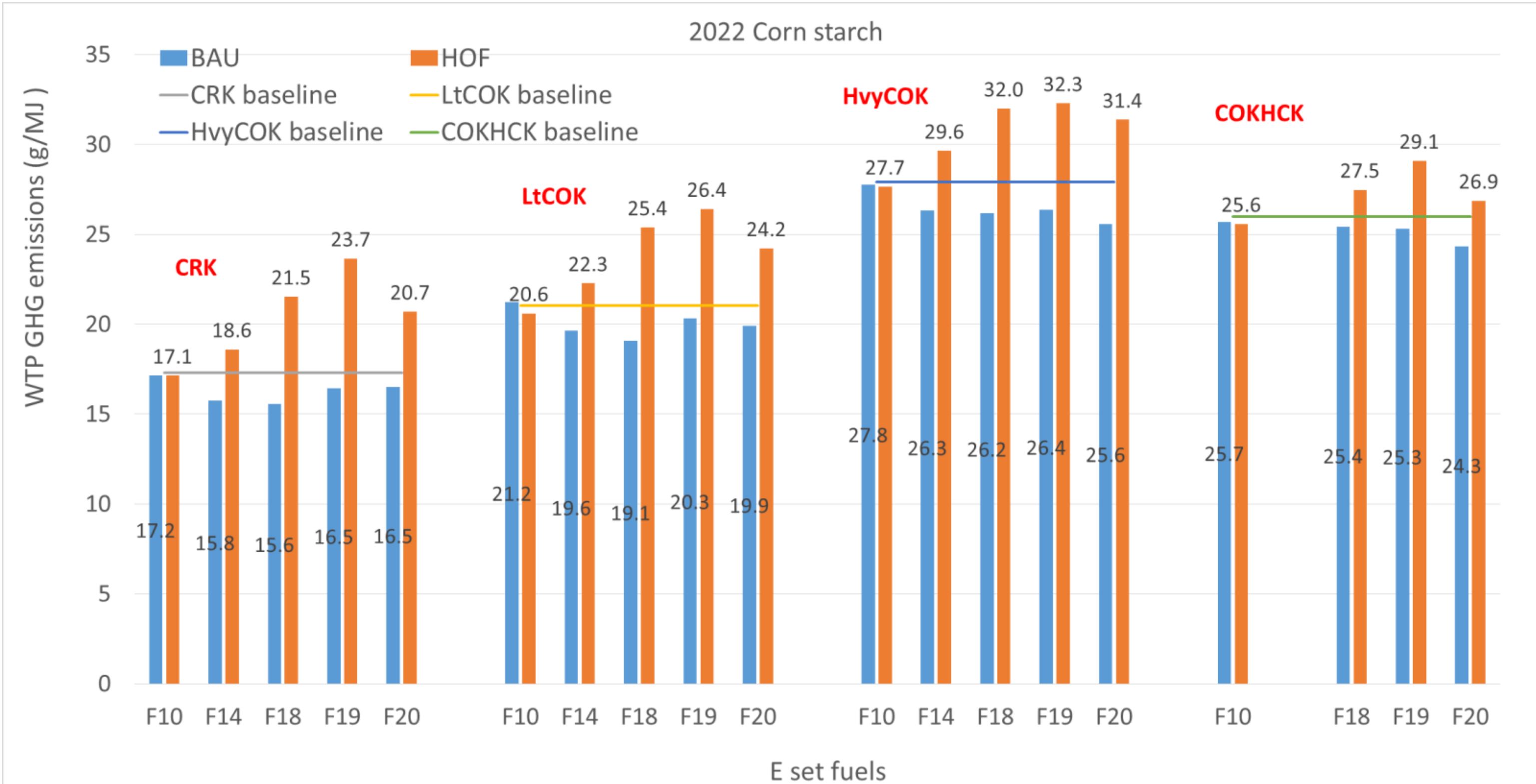


Figure A3-9. The WTP GHG Emissions of E set BAU and HOF Gasolines with Corn Starch Ethanol Produced at Four Configuration Refineries in Year 2022 (Baseline Ethanol from Corn Starch).

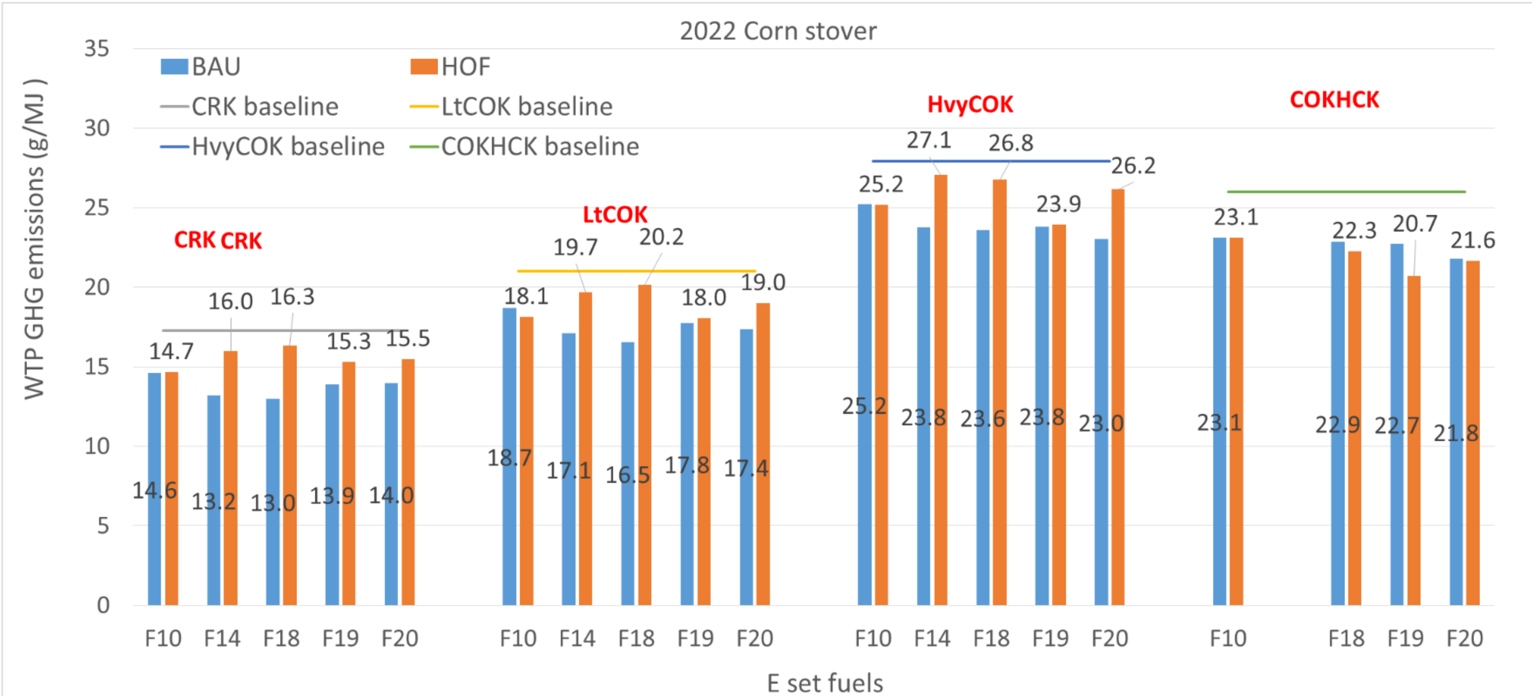
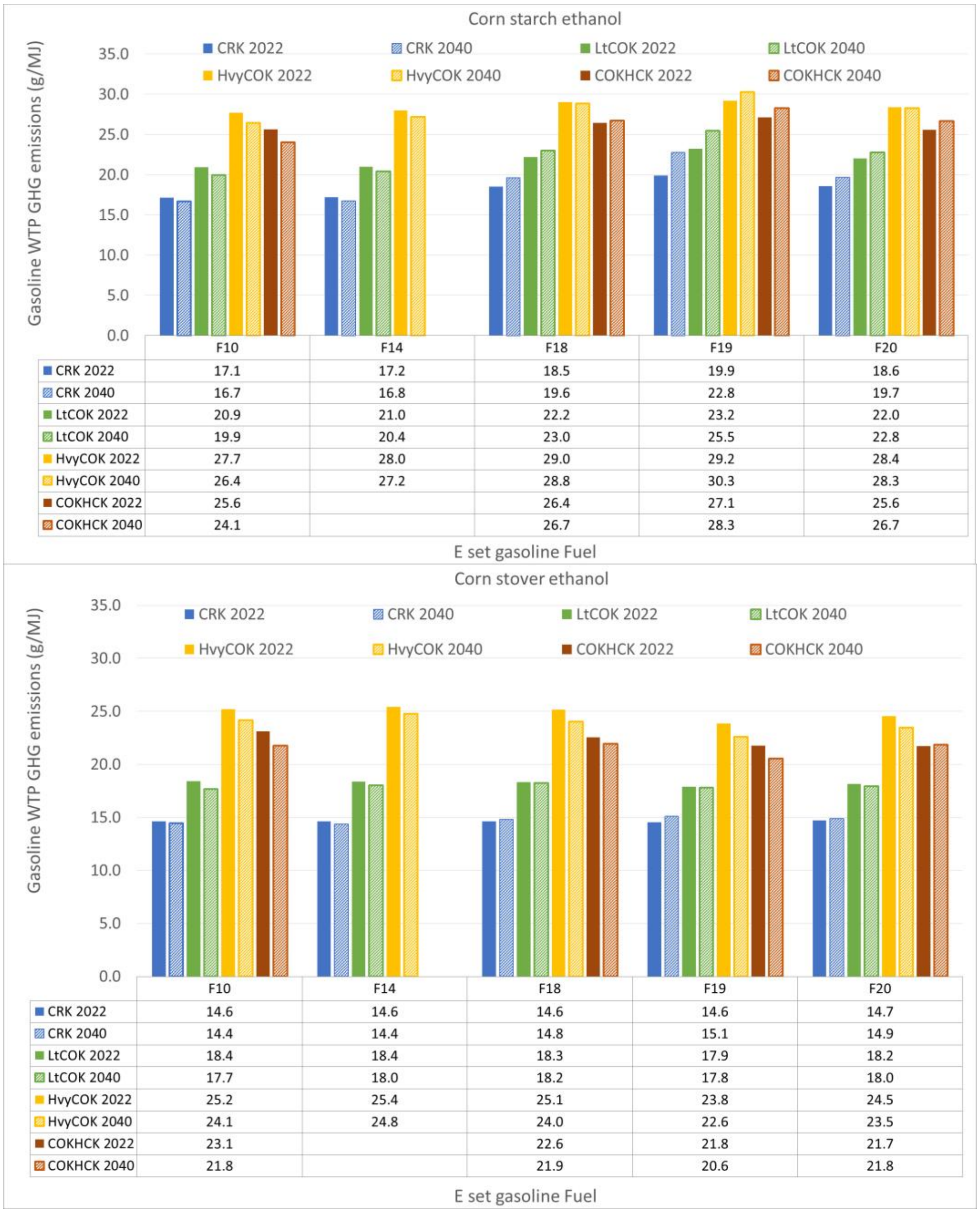


Figure A3-10. The WTP GHG Emissions of E set BAU and HOF Gasolines with Corn Stover Ethanol Produced at Four Configuration Refineries in Year 2022 (Baseline Ethanol from Corn Starch).

Similar with the base cases, the more complex configuration refineries have much higher WTP GHG emissions for (finished) gasoline production than the simpler configuration. In 2022, each configuration refinery base case uses corn starch ethanol. For each configuration refinery, with corn starch ethanol blended in E set fuels, BAU gasolines show similar or lower GHG emissions than baselines, while the HOF gasoline have similar or higher GHG emissions than baselines. Whether the BAU or HOF gasoline of the E set fuels have higher GHG emissions relative to the baselines are highly dependent on the ethanol blending levels and gasoline BOB components. Each gasoline BOB component is from various conversion or separation units in refineries with various energy intensities. Meanwhile, with corn stover ethanol blended in E set fuels, both BAU and HOF gasolines have lower GHG emissions than baselines that use corn starch ethanol.

The WTP GHG emissions for the total domestic (finished) gasoline (combining BAU and HOF gasolines) production in various configuration refineries in year 2022 and year 2040 are displayed in the Figure A3-11 below.



Corn starch ethanol

	F10	F14	F18	F19	F20
CRK 2022	17.1	17.2	18.5	19.9	18.6
CRK 2040	16.7	16.8	19.6	22.8	19.7
LtCOK 2022	20.9	21.0	22.2	23.2	22.0
LtCOK 2040	19.9	20.4	23.0	25.5	22.8
HvyCOK 2022	27.7	28.0	29.0	29.2	28.4
HvyCOK 2040	26.4	27.2	28.8	30.3	28.3
COKHCK 2022	25.6		26.4	27.1	25.6
COKHCK 2040	24.1		26.7	28.3	26.7

Corn stover ethanol

	F10	F14	F18	F19	F20
CRK 2022	14.6	14.6	14.6	14.6	14.7
CRK 2040	14.4	14.4	14.8	15.1	14.9
LtCOK 2022	18.4	18.4	18.3	17.9	18.2
LtCOK 2040	17.7	18.0	18.2	17.8	18.0
HvyCOK 2022	25.2	25.4	25.1	23.8	24.5
HvyCOK 2040	24.1	24.8	24.0	22.6	23.5
COKHCK 2022	23.1		22.6	21.8	21.7
COKHCK 2040	21.8		21.9	20.6	21.8

Figure A3-11. The WTP GHG Emissions of E set Domestic Gasolines Produced in Four Configuration Refineries in Year 2022 and 2040, with Corn Starch Ethanol (Top Plot) and Corn Stover Ethanol (Bottom Plot).

From year 2022 to year 2040, the GHG emissions for these E set fuels production have minor changes of 1-2 g/MJ for all four configuration refineries. The comparison of these E set fuels WTP GHG emissions with base case gasoline GHG emissions for year 2022 and year 2040, are shown in Figure A3-12 and Figure A3-13, respectively.

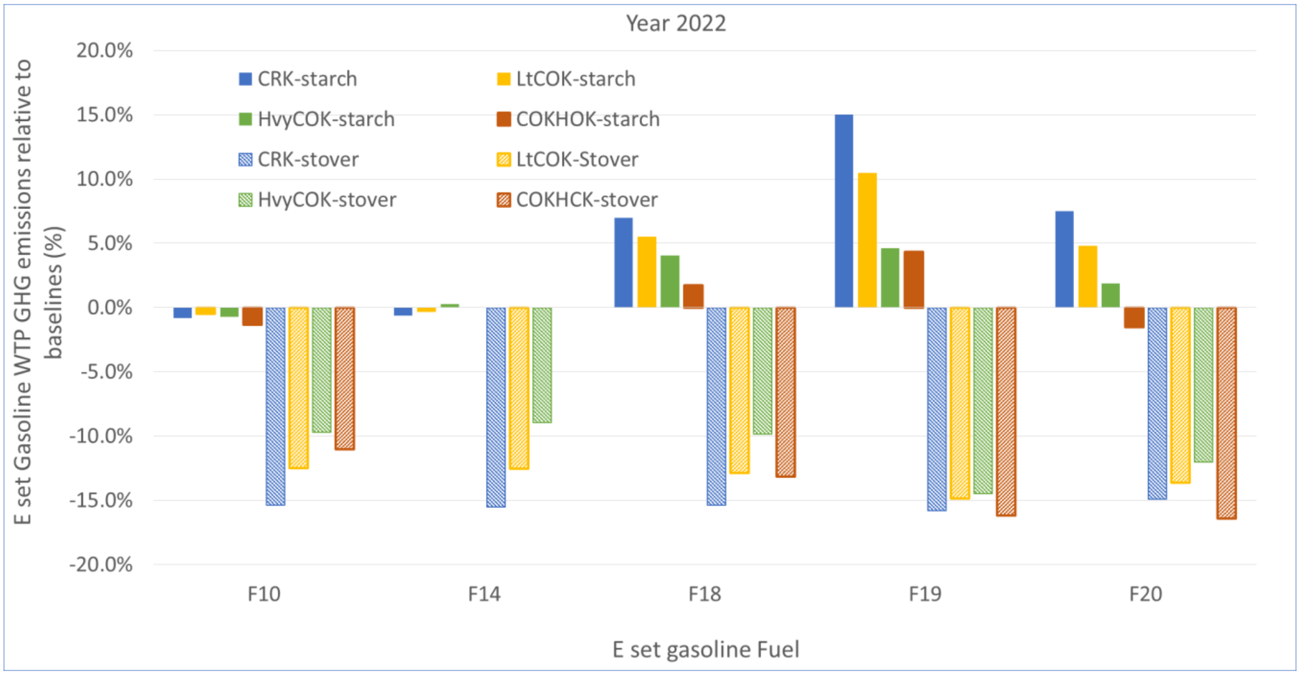


Figure A3-12. The Comparison of E set Fuels WTP GHG Emissions with Baselines in Four Configuration Refineries in 2022 (Baselines Use Corn Starch Ethanol).

In 2022, for the E set gasoline cases with ethanol from corn starch, many cases show higher WTP GHG emissions than baselines that contains corn starch ethanol. For the E set fuels with corn starch ethanol, high ethanol blending level leads to higher GHG emissions relative to baselines. It is because corn starch ethanol emits more GHG than gasoline BOB production per MJ basis (53–57 g/MJ corn starch ethanol vs. 20-30 g/MJ gasoline BOB). In contrast, for the E set fuels with corn stover ethanol, most cases show GHG emissions reductions than baselines. It is because corn stover production mostly uses renewable energy, thus produces biogenic CO_2, not fossil CO_2. As a result, corn stover production emits less GHG than all gasoline BOB production per MJ basis (14–17 g/MJ corn stover ethanol vs. 20–30 g/MJ gasoline BOB). For the ethanol blended finished gasoline fuels, higher corn stover ethanol blending will dilute the fossil energy presence per energy basis, resulting in greater GHG reduction benefit.

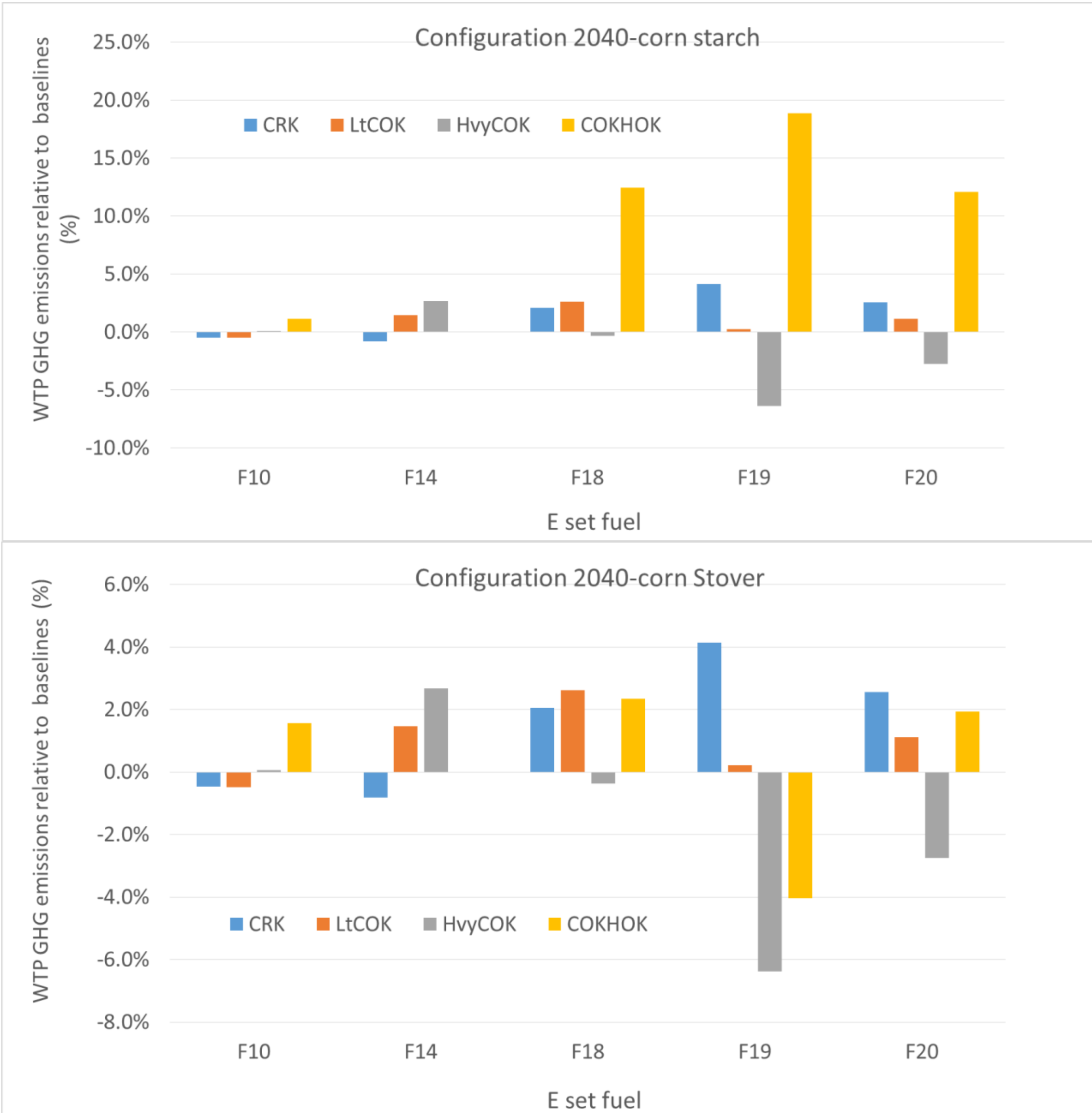


Figure A3-13. The Comparison of E Set Fuels WTP GHG Emissions with Baselines in Four Configuration Refineries in 2040. Dual Baselines Used with Corn Starch Ethanol and Corn Stover Ethanol, Respectively.

In year 2040, two sets of baselines are used, with ethanol from corn starch and corn stover, respectively. Relative to the baselines with the same ethanol source, many E set gasolines show higher WTP GHG emissions than baselines. The change of E set gasoline production GHG emissions relative to baselines varies from one case to another, really depending on how an individual configuration refinery adjusts operations to meet the high octane demand while maximizing profits, and also depending on how the energy use intensity of ethanol production process are compared with that of gasoline BOB production.

A3.2 WTP Analysis of BR Set Fuels

The energy uses and GHG emissions of BR domestic gasolines produced in aggregate refineries and in configuration refineries are analyzed for year 2022 and 2040. In 2022, half of the domestic gasoline pools (by volume) are BAU E10 gasoline, with ethanol produced from two sources, corn starch and corn stover. The other half of domestic gasoline is HOF gasoline with BR stream blend, which could be produced in various ways differentiated by hydrogen source: purchased hydrogen, in-situ hydrogen and gasification hydrogen (see main report). In 2040, the domestic gasoline only consists of HOF gasoline, thus the WTP GHG varies only with different hydrogen sources.

A3.2.1 WTP Analysis of BR Set Fuels in Aggregate Refineries

Combining the WTP energy uses of BAU gasoline BOB with the energy uses of ethanol (from corn starch or stover) yields the WTP GHG emission of BAU (finished) gasoline. Similarly, the energy uses of WTP HOF (finished) gasoline is calculated by combining the energy uses of HOF BOB gasoline with that of the BR blendstock. Both are also shown in the tables below.

Table A3-13. The WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of BR Set BAU Gasolines in PADD 2 and PADD 3 Refinery in 2022

		BR BAU Gasoline					
EtOH Source		Corn Starch			Corn Stover		
PADD	BR Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
PADD 2	BR1-T	0.465	0.454	0.100	0.550	0.429	0.104
	BR2	0.420	0.410	0.073	0.506	0.385	0.077
	BR4-T	0.450	0.440	0.097	0.536	0.415	0.101
PADD 3	BR1	0.310	0.304	0.066	0.396	0.279	0.070
	BR2	0.281	0.275	0.046	0.367	0.250	0.049
	BR4-T	0.287	0.281	0.053	0.373	0.256	0.057

Table A3-14. The WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of BR Set HOF Gasolines in PADD 2 and PADD 3 Refinery in 2022

	BR HOF Gasoline								
H2	Purch H2			In situ H2			Gasification H2		
BR Set	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
				PADD 2					
BR1-T	0.567	0.425	0.074	0.686	0.370	0.079	0.617	0.359	0.077
BR2	0.986	0.576	0.095	1.341	0.413	0.111	1.135	0.378	0.105
BR4-T	0.944	0.540	0.075	1.295	0.379	0.091	1.091	0.345	0.085
				PADD 3					
BR1	0.413	0.273	0.065	0.531	0.219	0.070	0.463	0.207	0.068
BR2	0.861	0.454	0.085	1.217	0.290	0.101	1.010	0.256	0.095
BR4-T	0.811	0.410	0.059	1.162	0.249	0.075	0.958	0.215	0.069

Combining the energy uses of BAU gasoline and HOF gasoline based on their energy shares results in the WTP energy uses of BR domestic (finished) gasolines, shown in the table below.

Table A3-15. The WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of BR Domestic Gasolines (Combining BAU and HOF gasolines) in PADD 2 Refinery and PADD 3 Refinery in 2022

2022 BR Domestic Gasoline-Corn Starch									
H2	Purch H2			In situ H2			Gasification H2		
BR set	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
PADD 2									
BR1-T	0.517	0.439	0.087	0.577	0.411	0.089	0.542	0.406	0.088
BR2	0.709	0.495	0.084	0.890	0.411	0.093	0.785	0.394	0.090
BR4-T	0.704	0.491	0.086	0.884	0.408	0.094	0.779	0.391	0.091
PADD 3									
BR1	0.363	0.288	0.066	0.423	0.261	0.068	0.388	0.255	0.067
BR2	0.577	0.366	0.066	0.758	0.283	0.074	0.653	0.265	0.071
BR4-T	0.556	0.347	0.056	0.736	0.264	0.065	0.632	0.247	0.062

2022 BR Domestic Gasoline-Corn Stover									
H2	Purch H2			In situ H2			Gasification H2		
BR set	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
PADD 2									
BR1-T	0.559	0.427	0.088	0.620	0.399	0.091	0.584	0.393	0.090
BR2	0.751	0.483	0.086	0.932	0.399	0.095	0.827	0.382	0.091
BR4-T	0.745	0.479	0.088	0.925	0.396	0.096	0.821	0.379	0.093
PADD 3									
BR1	0.405	0.276	0.067	0.465	0.248	0.070	0.430	0.243	0.069
BR2	0.619	0.354	0.068	0.800	0.271	0.076	0.695	0.253	0.073
BR4-T	0.598	0.335	0.058	0.778	0.252	0.067	0.673	0.235	0.063

Table A3-16. The WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of BR Set Domestic Gasolines (all HOF) in PADD 2 and PADD 3 Refinery in 2040

	BR HOF Gasoline								
H_2 Source	Purch H_2			In situ H_2			Gasification H_2		
BR set	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
				PADD 2					
BR2	0.973	0.563	0.077	1.326	0.396	0.093	1.121	0.363	0.087
BR4-T	0.960	0.555	0.083	1.308	0.391	0.099	1.106	0.358	0.093
				PADD 3					
BR2	0.867	0.459	0.080	1.220	0.293	0.096	1.015	0.260	0.090
BR4-T	0.834	0.432	0.066	1.182	0.268	0.082	0.980	0.235	0.076

Consistent with the trends of the WTP energy uses of BR BOB gasolines, for a given BR (finished) gasoline, the WTP energy use in PADD 2 is higher than that in PADD 3, mostly attributing to the oil sand usage in PADD 2, because the oil sand recovery consumes more energy (than conventional crudes recovery). The hydrogen source has a large impact on BR gasoline WTP energy uses. For the total energy and petroleum energy, the BR domestic gasoline WTP energy use increase in the order purchased hydrogen < gasification hydrogen < in-situ hydrogen. For the fossil energy, the BR domestic gasoline WTP energy use increases in the order gasification hydrogen< in-situ hydrogen < purchased hydrogen.

The energy uses in 2022 and 2040 are also displayed in the figures below for comparison.

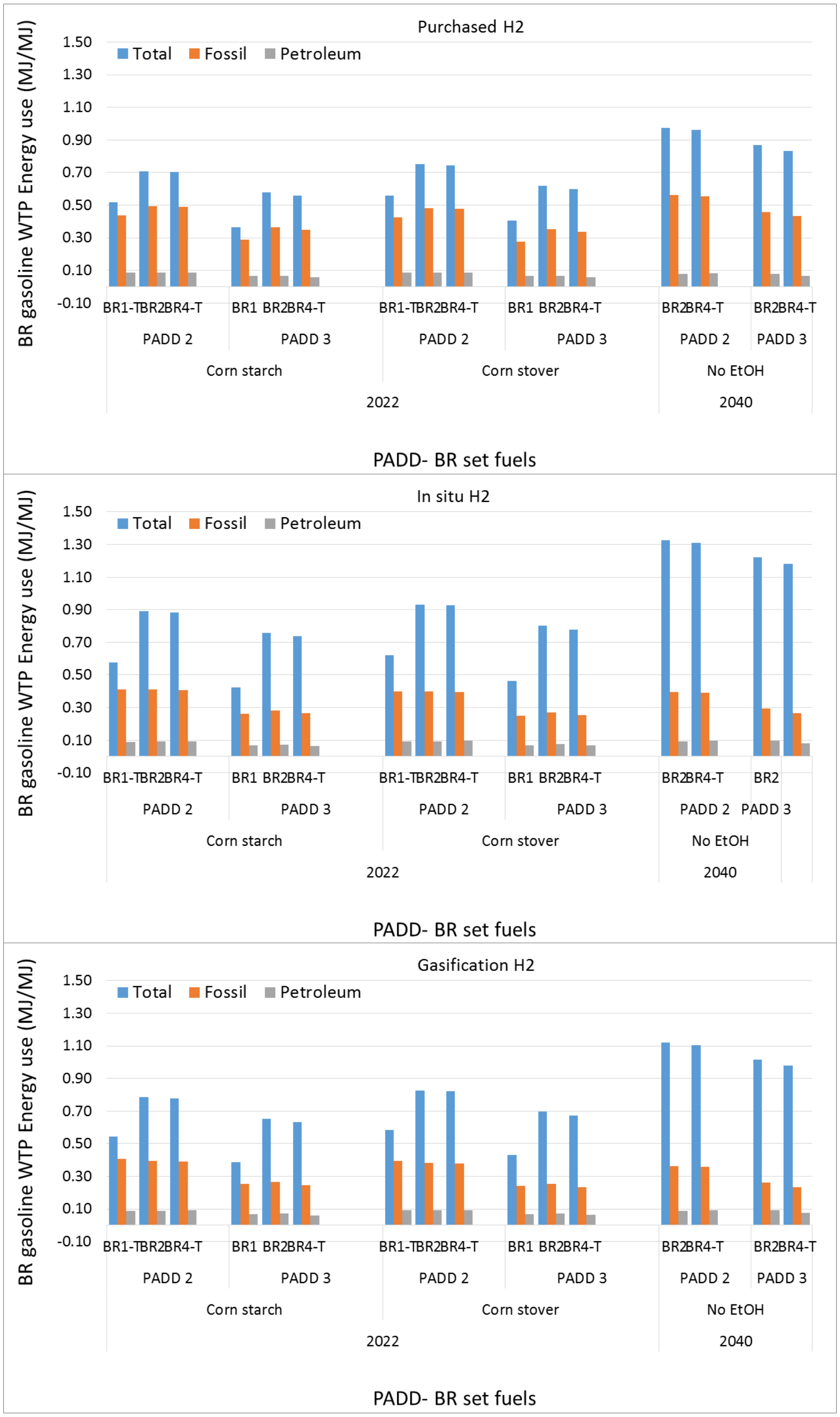
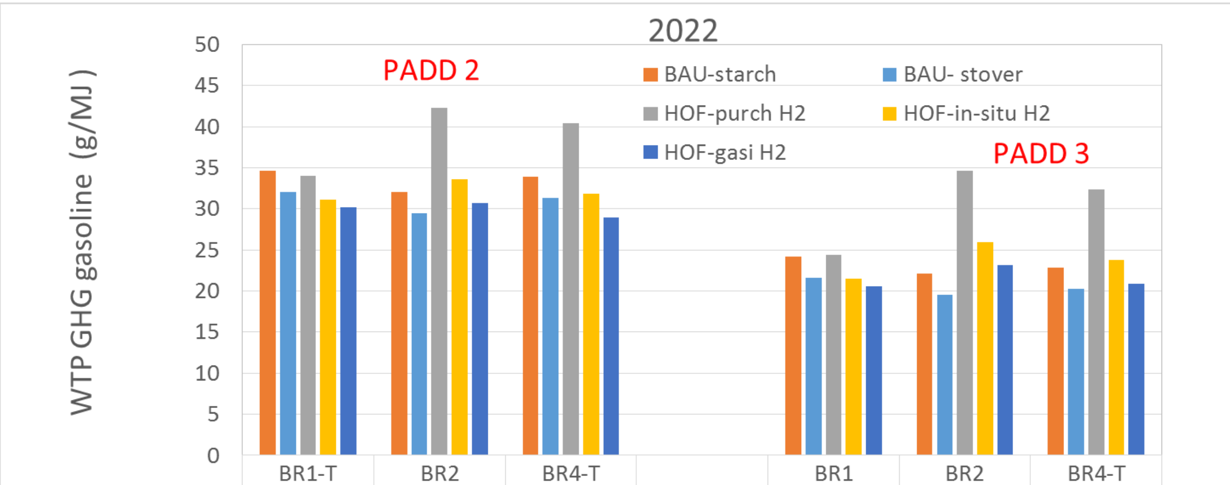


Figure A3-14. The WTP Energy Uses of BR Domestic Gasolines Produced in PADD 2 and PADD 3 with various ethanol sources and Various Hydrogen Sources for Bioreformate Production in 2022 and 2040.

From 2022 to 2040, with purchased hydrogen source, for a given BR domestic gasoline, both total energy use and fossil energy use increase. For in-situ hydrogen source and gasification hydrogen source, from 2022 to 2040, the total energy use increases and the fossil energy use decreases. For all three hydrogen source cases, the changes of petroleum energy use from 2022 to 2040 varies for each case.

Combining the WTP GHG emissions of BAU gasoline BOB with GHG emissions of ethanol (from corn starch or stover) yields the WTP GHG emission of BAU (finished) gasoline. Similarly, combining the GHG emissions of WTP HOF gasoline BOB with the GHG emissions of bioreformate yields the WTP GHG emission of HOF (finished) gasoline. Both are shown in Figure A3-15 for year 2022.



	BR1-T	BR2	BR4-T		BR1	BR2	BR4-T
BAU-starch	34.6	32.0	33.9		24.2	22.1	22.9
BAU- stover	32.1	29.5	31.4		21.6	19.5	20.3
HOF-purch H2	34.0	42.3	40.4		24.4	34.7	32.3
HOF-in-situ H2	31.1	33.6	31.8		21.5	26.0	23.7
HOF-gasi H2	30.2	30.7	29.0		20.6	23.1	20.9

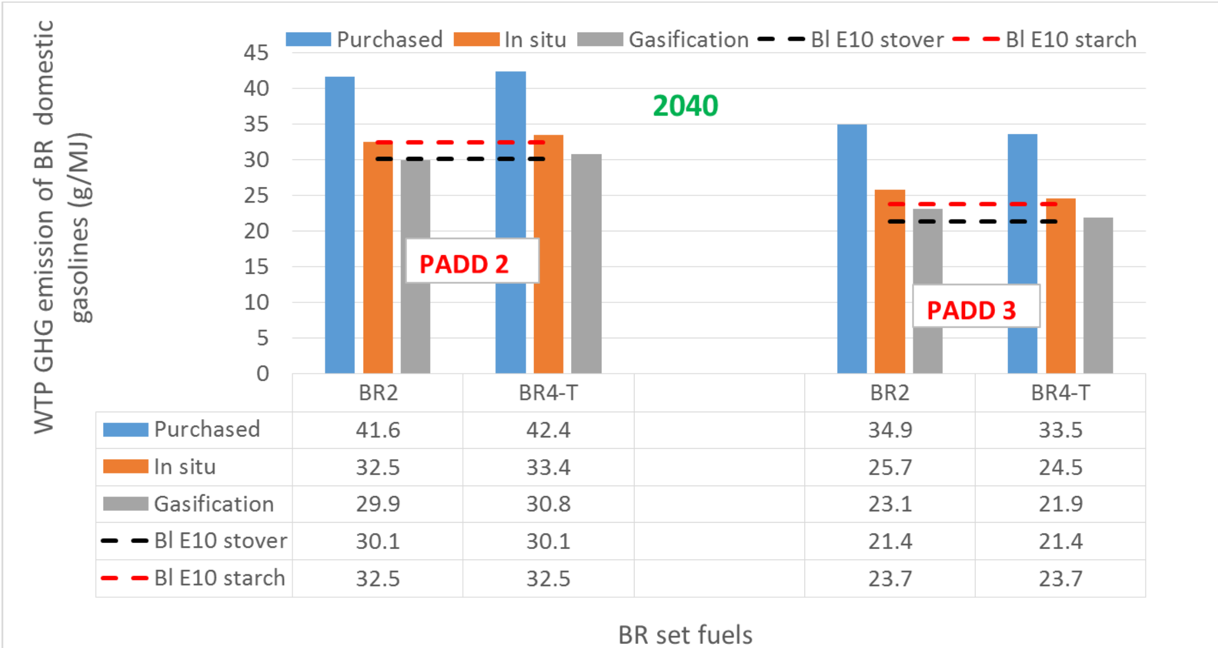
Figure A3-15. The 2022 WTP GHG Emissions of BR BAU and HOF Gasolines Produced in PADD 2 and PADD 3 Refinery with Various Ethanol Sources and Various Hydrogen Sources for Bioreformate Production.

As expected, the WTP GHG emissions of BAU and HOF gasolines produced in PADD 2 are higher than those in PADD 3. In each PADD, the comparison between BAU and HOF gasolines are specific for each set of fuel, depending on the BOB components, refinery operation, and BR bioreformate hydrogen source. However, for all the BR/BR-T fuels, one notable feature is that the HOF gasoline with the purchased H_2 shows much higher GHG emissions than the other gasolines with different bio-blendstock production sources/technologies, suggesting the large role SMR plays in GHG emissions for the production of BR set fuels.

Similarly, in 2040, the WTP GHG emissions of HOF gasolines (no BAU gasoline in 2040) with bioreformate using purchased hydrogen (via SMR) are much higher than that with in-situ hydrogen or with gasification hydrogen.

The WTP GHG emissions of BR domestic gasoline in PADD 2 and in PADD 3 are shown in the figures below.

Figure A3-16. WTP GHG Emissions of BR Set Domestic Gasolines Produced in PADD 2 and PADD 3 refinery in 2022 (g/MJ Domestic Gasoline). Baselines Use Corn Starch Ethanol.



	BR2	BR4-T		BR2	BR4-T
Purchased	41.6	42.4		34.9	33.5
In situ	32.5	33.4		25.7	24.5
Gasification	29.9	30.8		23.1	21.9
Bl E10 stover	30.1	30.1		21.4	21.4
Bl E10 starch	32.5	32.5		23.7	23.7

Figure A3-17. The WTP GHG Emissions of BR Set Domestic Gasolines Produced in PADD 2 and PADD 3 Refinery in 2040 (g/MJ Domestic Gasoline). Dual Baselines Used with Corn Starch Ethanol and Corn Stover Ethanol.

The WTP GHG emissions of the BR/BR-T set fuels are highly dependent on refinery type, refinery operation, gasoline BOB components, bioreformate production technology/hydrogen source, and bioreformate blending level. As expected, the WTP GHG emissions of the BR/BR-T set fuels produced in PADD 2 are much higher than those produced in PADD 3, in the range of 9-10 g/MJ fuel. For each fuel, WTP GHG emissions of the BR domestic gasolines decreases, in the order purchased H_2> in-situ H_2 > gasification H_2. In 2022, for each configuration, with a given ethanol blending share and BR blending share with certain hydrogen supplies, the WTP GHG emissions of BR 2 domestic gasoline are similar to those of BR4-T domestic gasoline. The difference between BR2 and BR4-T widens slightly in 2040.

Over all, from 2022 to 2040, most cases show somewhat GHG emissions increases, about 0-7 g/MJ fuel, in response to increasing HOF share from 50 vol% to 100 vol%. A detailed comparison of the BR set fuels WTP GHG emissions with baselines are shown in the figures below.

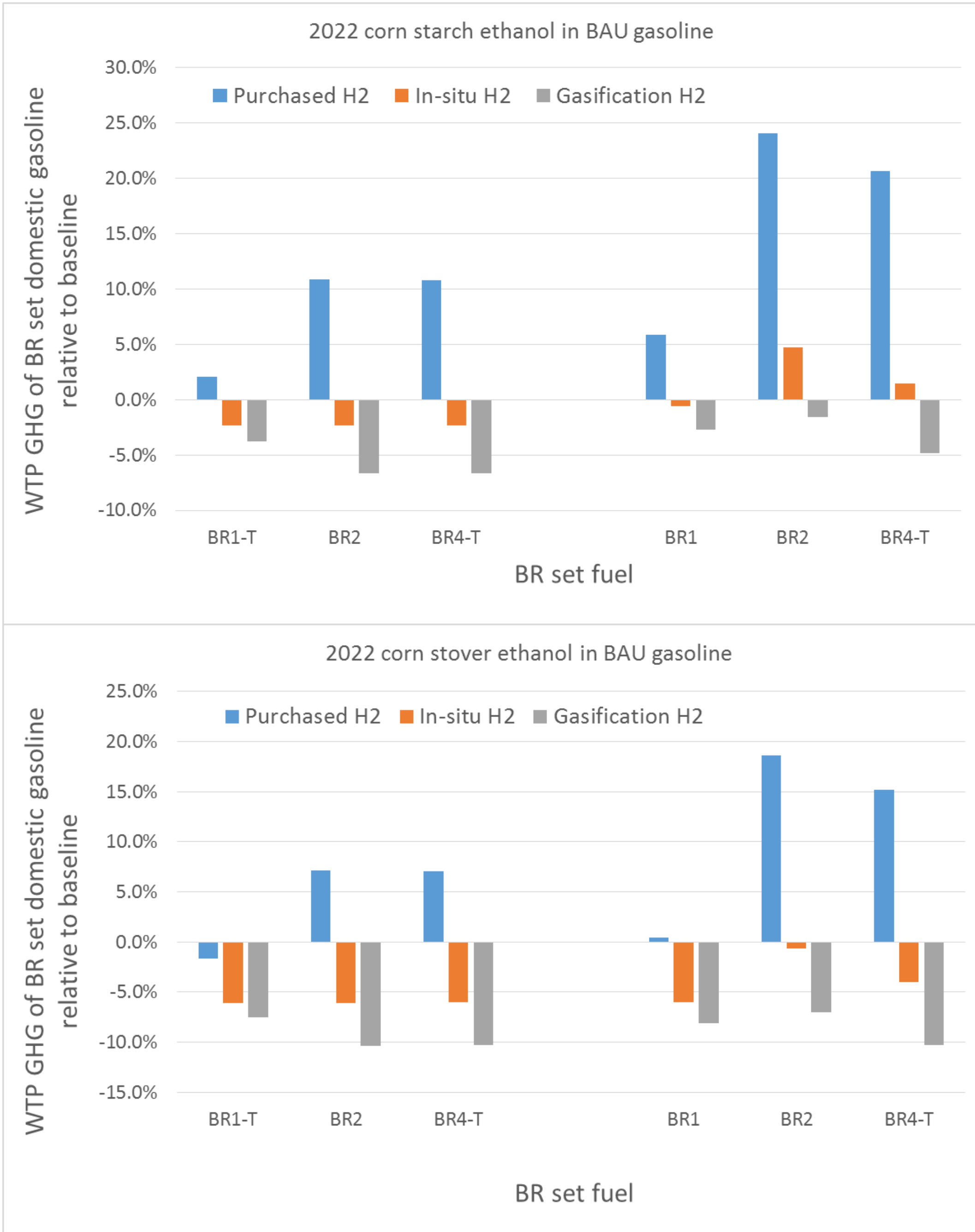


Figure A3-18. Comparison of BR Set Fuels WTP GHG Emissions to Baselines in 2022. Baselines Use Corn Starch Ethanol

In 2022, the baselines of PADD 2 refinery and PADD 3 refinery include corn starch ethanol. Compared with the baselines, the BR domestic gasolines show noticeable higher GHG emissions (2-24%) when BAU gasolines have corn starch ethanol and HOF gasolines use purchased H_2 for bioreformate production. The BR domestic gasolines with in-situ H_2 and gasification H_2 for bioreformate production in HOF gasoline show minor to moderate increase or decrease (-7±5%) in GHG emissions relative to baselines, and the differnces vary with fuel, PADD and hydrogen source. With corn stover ethanol in

BAU gasoline pool, the BR domestic gasoline with purchased H_2 still show noticeable higher GHG emissions for BR2 and BR4-T (7-18%), but the BR domestic gasoline with in-situ H_2 and gasification H_2 show GHG emissions decrease for all cases (-10%– -1%).

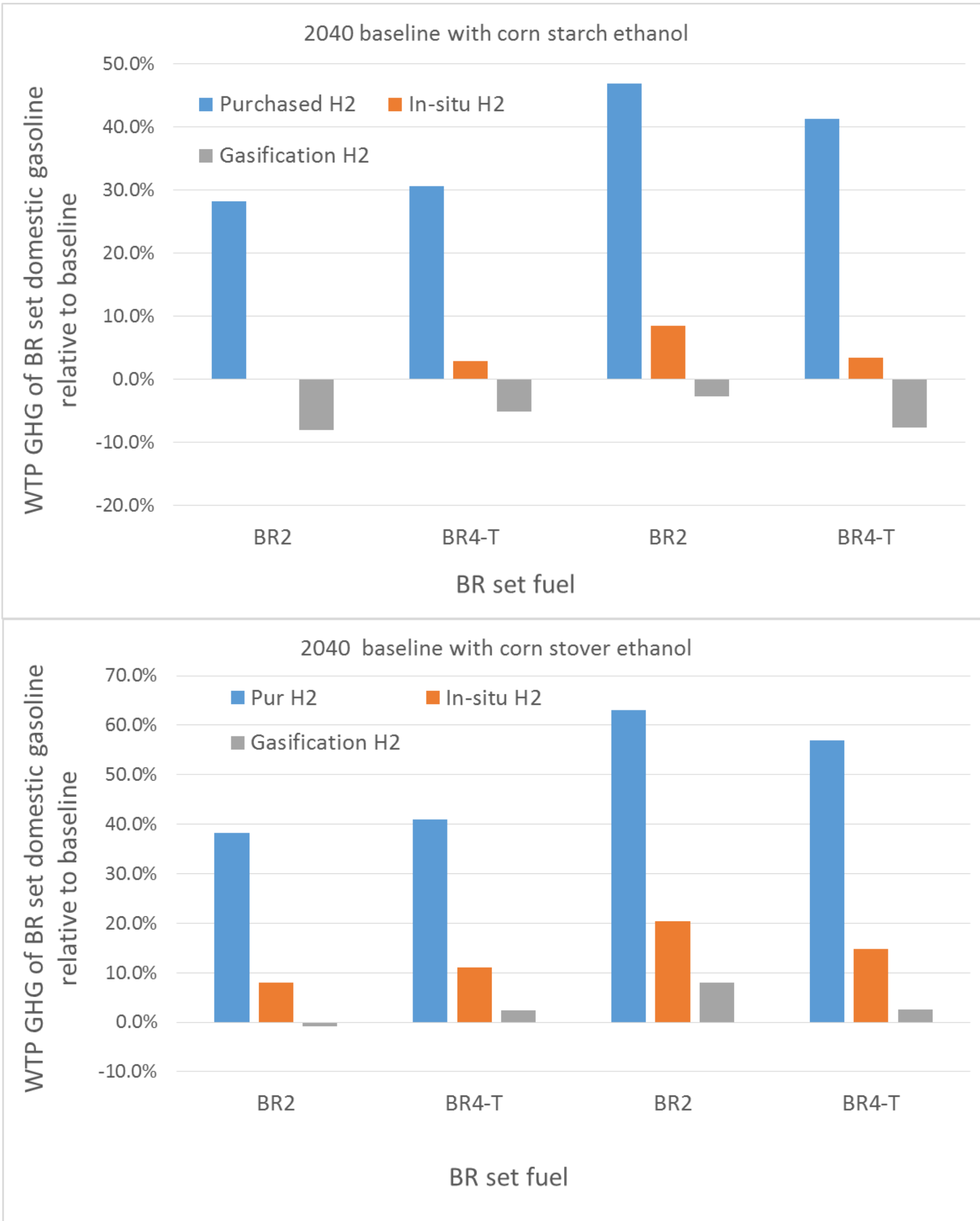


Figure A3-19. Comparison of BR Set Fuels WTP GHG Emissions to Baselines in 2040 (Dual Baselines Used with Corn Starch Ethanol and Corn Stover Ethanol, Respectively)

In 2040, the BR domestic gasolines do not have ethanol, but the baselines still contains ethanol. Relative to baselines with corn starch ethanol, BR domestic gasolines in PADD 2 and PADD 3 show higher GHG emissions with purchased H_2 (for bioreformate production), but show GHG emission reductions with in-situ H_2 and gasification H_2 (for bioreformate production). In contrast, relative to baselines with corn stover ethanol, BR domestic gasolines in PADD 2 and PADD 3 show higher GHG emissions with all H_2 sources.

For both year 2022 and year 2040, compared to the cases in PADD 2, the BR domestic gasolines produced in PADD 3 have greater extent of GHG increase or less extent of GHG reduction relative to the baselines. It is because the WTP GHG emissions of gasoline BOB produced in PADD 3 are about 33% lower than that in PADD 2 (about 20 g/MJ vs 30 g/MJ), thus shows higher percentage responses when blended with ethanol and bioreformate that are produced with various souces/technologies.

<u>A3.2.2 WTP Analysis of BR Set Fuels in Configuration Refineries</u>

The WTP energy uses of BR gasolines produced in configuration refineries are shown in Table A3-17 throught Table A3-20. All the LP modelings of BR cases in COKHCK refinery were not feasible and the modeling of BR1/BR1-T and BR3/BR3-T were not feasible.

Table A3-17. The WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of BR Set BAU Gasolines in CRK, LtCOK and HvyCOK Refinery in 2022

2022 BR BAU Gasoline							
EtOH Source		Corn Starch			Corn Stover		
PADD	BR Set Fuels	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
BR-2	CRK	0.146	0.142	0.054	0.232	0.117	0.058
	LtCOK	0.200	0.194	0.071	0.286	0.169	0.075
	HvyCOK	0.323	0.315	0.082	0.409	0.290	0.086
BR4-T	CRK	0.163	0.159	0.068	0.249	0.134	0.072
	LtCOK	0.219	0.213	0.083	0.305	0.188	0.087
	HvyCOK	0.343	0.335	0.092	0.429	0.310	0.096

Table A3-18. The WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of BR Set HOF Gasolines in CRK, LtCOK and HvyCOK Refinery in 2022

2022 BR HOF Gasoline									
H2	Purch H2			In situ H2			Gasification H2		
BR set	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
BR-2									
CRK	0.810	0.404	0.094	1.165	0.240	0.110	0.959	0.206	0.104
LtCOK	0.846	0.439	0.098	1.202	0.276	0.114	0.995	0.241	0.108
HvyCOK	0.931	0.523	0.098	1.287	0.360	0.114	1.080	0.325	0.108
BR4-T									
CRK	0.788	0.388	0.081	1.139	0.227	0.097	0.936	0.193	0.091
LtCOK	0.825	0.423	0.088	1.175	0.262	0.104	0.972	0.228	0.098
HvyCOK	0.909	0.506	0.093	1.260	0.345	0.109	1.056	0.311	0.103

Table A3-19. The WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of BR Set Domestic Gasolines in CRK, LtCOK and HvyCOK Refinery in 2022

2022 BR Domestic Gasoline-Corn Starch									
H2	Purch H2			In situ H2			Gasification H2		
BR set	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
BR-2									
CRK	0.485	0.275	0.074	0.666	0.192	0.083	0.561	0.174	0.080
LtCOK	0.530	0.319	0.085	0.711	0.236	0.093	0.606	0.218	0.090
HvyCOK	0.633	0.421	0.090	0.815	0.338	0.099	0.709	0.320	0.096
BR4-T									
CRK	0.484	0.277	0.075	0.665	0.194	0.083	0.560	0.176	0.080
LtCOK	0.530	0.321	0.086	0.710	0.238	0.094	0.606	0.221	0.091
HvyCOK	0.634	0.423	0.093	0.814	0.340	0.101	0.709	0.323	0.098

2022 BR Domestic Gasoline-Corn Stover									
H2	Purch H2			In situ H2			Gasification H2		
BR set	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
BR-2									
CRK	0.527	0.263	0.076	0.708	0.180	0.084	0.603	0.162	0.081
LtCOK	0.572	0.307	0.087	0.753	0.224	0.095	0.648	0.206	0.092
HvyCOK	0.675	0.409	0.092	0.857	0.326	0.101	0.751	0.308	0.097
BR4-T									
CRK	0.526	0.264	0.077	0.706	0.182	0.085	0.602	0.164	0.082
LtCOK	0.572	0.309	0.087	0.752	0.226	0.096	0.647	0.209	0.093
HvyCOK	0.675	0.411	0.095	0.855	0.328	0.103	0.751	0.310	0.100

Table A3-20. The WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of BR Set Domestic Gasolines (all HOF) in CRK, LtCOK and HvyCOK Refinery in 2040

2040 BR Domestic (all HOF) Gasoline									
H2	Purch H2			In situ H2			Gasification H2		
BR set	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
				BR2-T					
CRK	0.790	0.384	0.072	1.143	0.218	0.088	0.938	0.185	0.082
LtCOK	0.820	0.413	0.073	1.173	0.247	0.089	0.968	0.214	0.083
HvyCOK	0.894	0.486	0.077	1.248	0.320	0.093	1.042	0.287	0.087
				BR4-T					
CRK	0.776	0.376	0.076	1.125	0.211	0.092	0.922	0.179	0.086
LtCOK	0.816	0.414	0.084	1.164	0.250	0.100	0.962	0.217	0.094
HvyCOK	0.895	0.492	0.088	1.243	0.328	0.104	1.041	0.295	0.098

The WTP energy uses of BR domestic gasolines with different ethanol sources and hydrogen sources are also shown in the figures below for comparison.

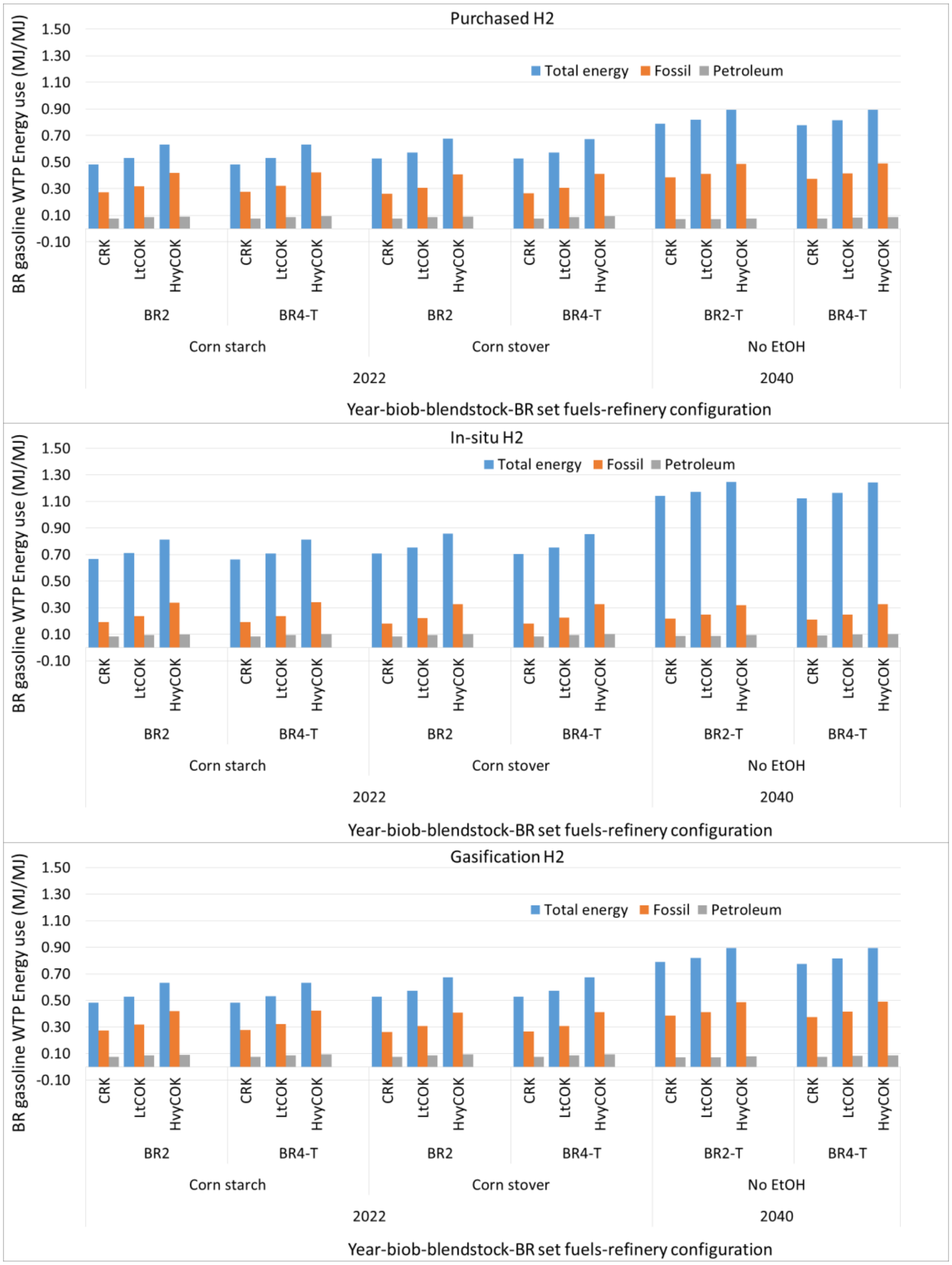
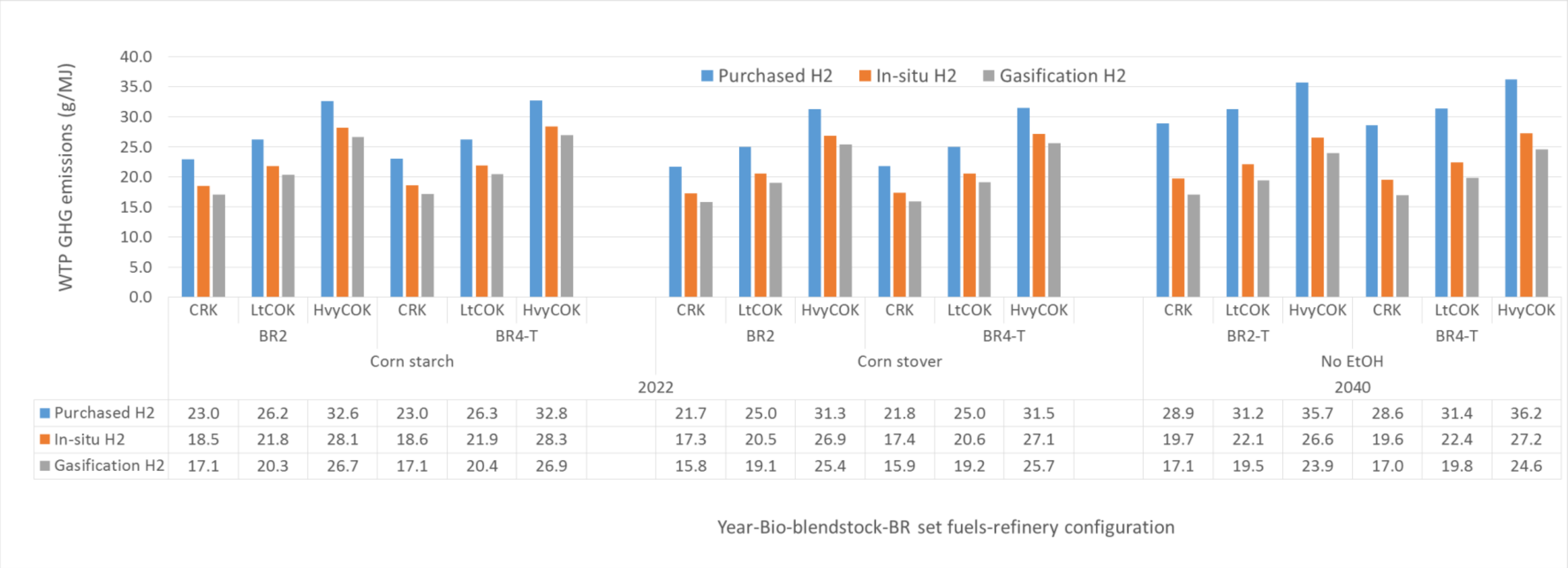


Figure A3-20. The WTP Energy Uses of BR Domestic Gasolines Produced in Configuration Refineries with Various Ethanol Sources and Hydrogen sources for Bioreformate Production in 2022 and 2040.

As expected, for a given BR domestic (finished) gasoline, the energy uses increase with increasing refinery complexity, in the order CRK< LtCOK< HvyCOK. From 2022 to 2040 with the share of HOF gasoline increasing from 50% to 100%, with purchased hydrogen, there is a sizeable increase in total energy use and fossil energy use (with either corn starch ethanol or corn stover ethanol used in 2022). In contrast, with in-situ hydrogen and gasification hydrogen, from 2022 to 2040, the BR domestic gasoline WTP total energy uses increase, however, the change of fossil energy use and petroleum energy use varies with fuels and refinery configurations.

The WTP GHG emissions of BR domestic gasolines are calculated by combining the WTP GHG emissions of gasoline BOB, WTP GHG emissions of ethanol and that of bioreformate.



	2022												2040					
	Corn starch						Corn stover						No EtOH					
	BR2			BR4-T			BR2			BR4-T			BR2-T			BR4-T		
	CRK	LtCOK	HvyCOK	CRK	LtCOK	HvyCOK	CRK	LtCOK	HvyCOK	CRK	LtCOK	HvyCOK	CRK	LtCOK	HvyCOK	CRK	LtCOK	HvyCOK
Purchased H2	23.0	26.2	32.6	23.0	26.3	32.8	21.7	25.0	31.3	21.8	25.0	31.5	28.9	31.2	35.7	28.6	31.4	36.2
In-situ H2	18.5	21.8	28.1	18.6	21.9	28.3	17.3	20.5	26.9	17.4	20.6	27.1	19.7	22.1	26.6	19.6	22.4	27.2
Gasification H2	17.1	20.3	26.7	17.1	20.4	26.9	15.8	19.1	25.4	15.9	19.2	25.7	17.1	19.5	23.9	17.0	19.8	24.6

Figure A3-21. The WTP GHG Emissions of BR Domestic Gasoline with Ethanol from Corn Starch and Corn Stover, and Bioreformate Using Various Hydrogen Sources.

For each fuel, as expected, the BR2 and BR4-T domestic gasolines WTP GHG emissions decrease, in the order purchased H_2 >in-situ H_2 > gasification H_2. In 2022, for each configuration, with same ethanol and BR blending levels and production source/technology, the WTP GHG emissions of BR 2 domestic gasoline are similar to those of BR4-T domestic gasoline. The difference between BR2 and BR4-T widens slightly in 2040.

From 2022 to 2040, with purchased hydrogen, the WTP GHG emissions of domestic gasoline increases greatly regardless of the BR fuel, refinery configuration and ethanol type. This trend does not hold for hydrogen from in-situ production or gasification. With various technology options and scenarios for providing the ethanol and BR blendstock, it is important to compare the resulting GHG emissions with the baseline GHGs. The 2022 results are shown in Figure A3-22.

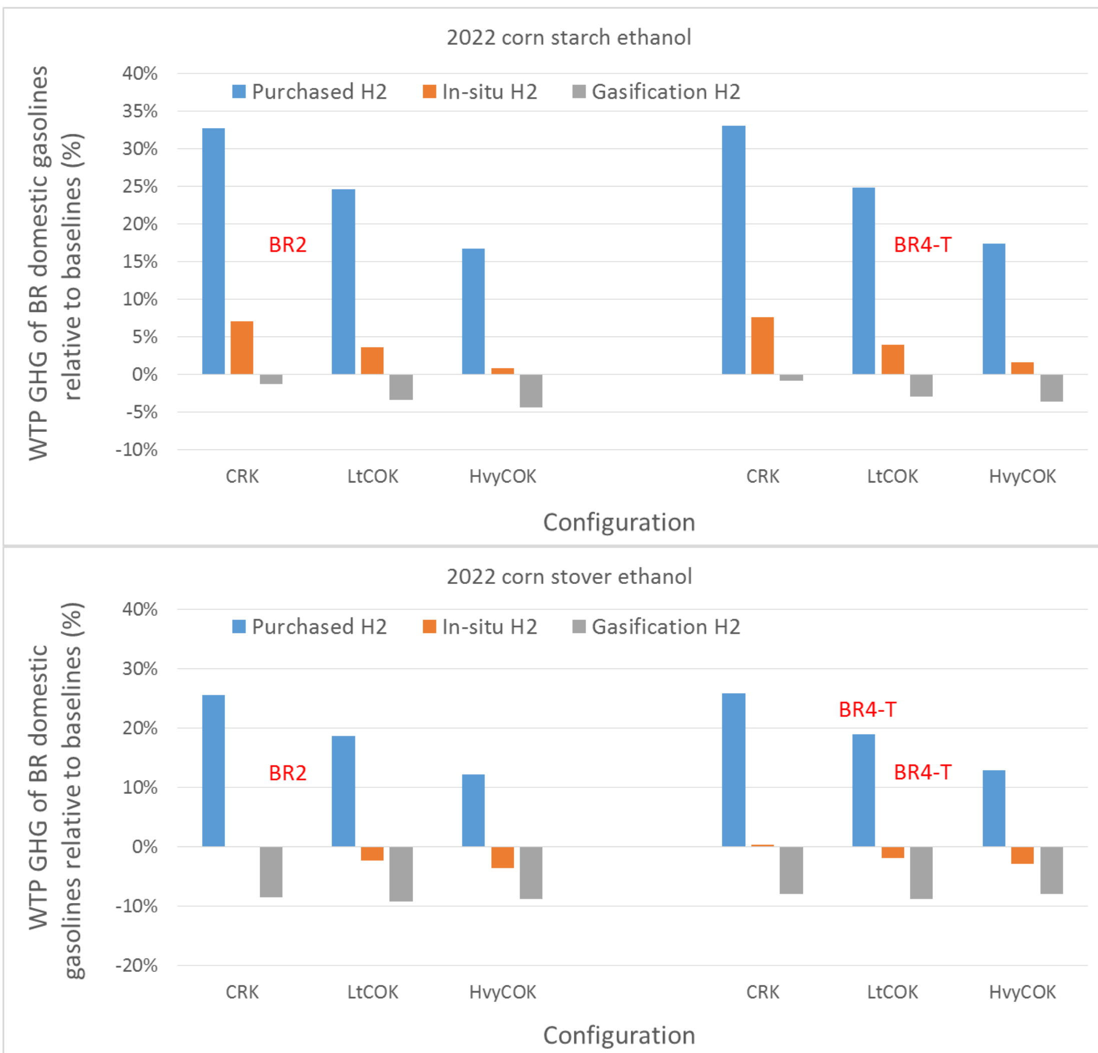


Figure A3-22. Comparison of the WTP GHG emissions of BR domestic gasolines with baselines in various configuration refineries, in 2022 (Baselines Use Corn Starch Ethanol).

The upper figure shows the comparison results of 2022 BR domestic gasolines with corn starch ethanol (in BAU gasoline) and the bottom figure shows that with corn stover ethanol (in BAU gasoline). For both set of comparisons, the baselines are the same—E10 fuels with ethanol from corn starch. The comparison shows that for the WTP stage, with corn starch ethanol, BR domestic gasolines with purchased hydrogen and in-situ hydrogen have higher GHG emissions than baselines. With ethanol from corn stover, the GHG emissions of BR domestic gasoline with purchased hydrogen are still higher than baseline, but with in-situ and gasification hydrogen, BR domestic gasolines have lower WTP GHG emissions than baselines.

In 2040, the domestic gasolines are 100% HOF, thus do not include any ethanol content. However, two sets of E10 baselines are used for comparison with ethanol from corn starch and corn stover, respectively, in Figure A3-23.

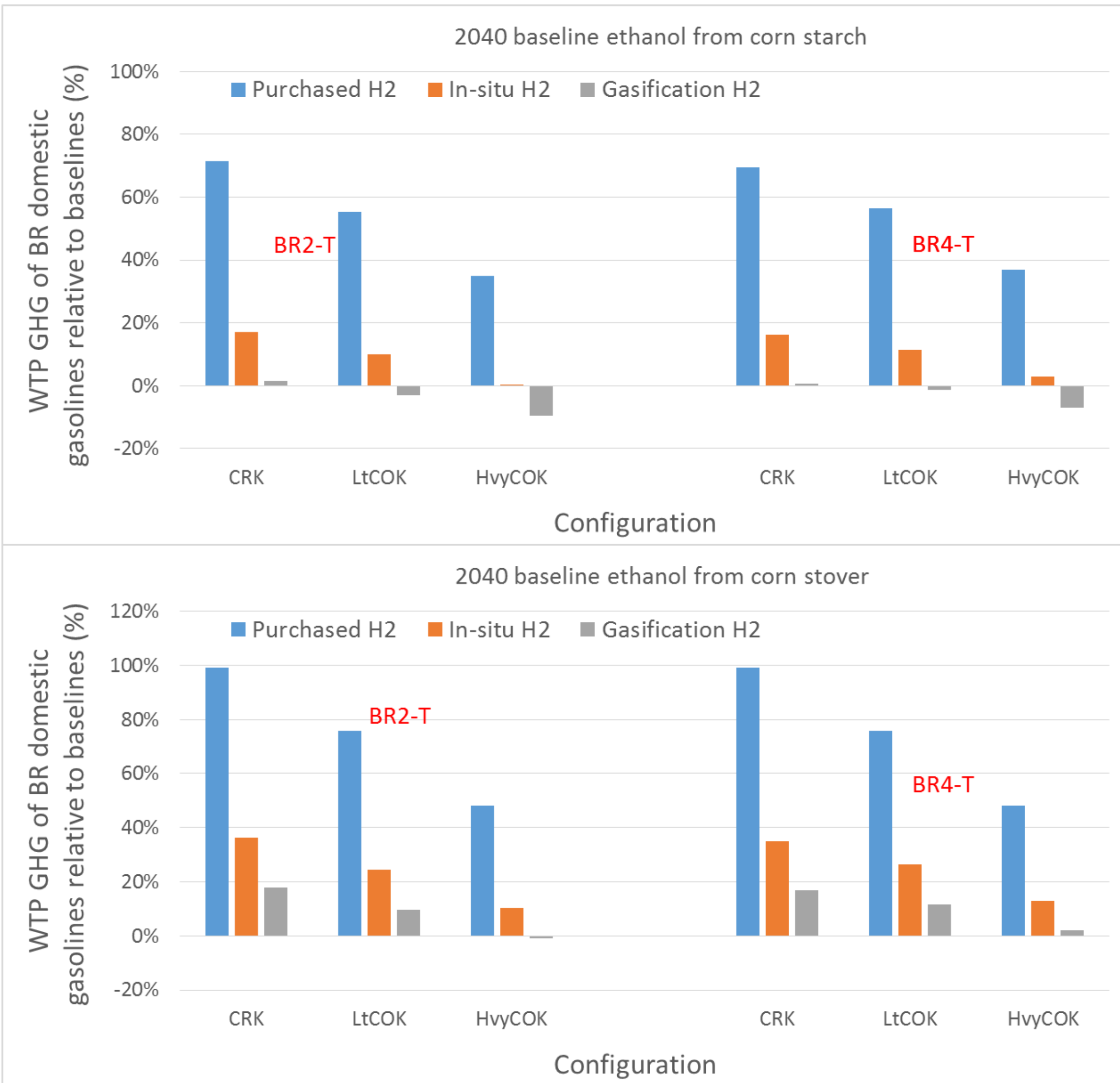


Figure A3-23. The comparison of the BR set domestic gasolines WTP GHG emissions with baselines in three configuration refineries in 2040. Dual Sets of Baselines Used with Corn Starch Ethanol and Corn Stover Ethanol.

With purchased hydrogen, all BR domestic gasolines have significantly higher WTP GHG emissions than both baselines, by 35-99%. With in-situ hydrogen, all BR domestic gasolines have moderate higher WTP GHG relative to both baselines, by 0.4% to 36%. The WTP GHG emissions of BR domestic gasolines with hydrogen provided via gasification have the lowest GHG emissions, leading to similar or lower GHG emissions relative to baselines with corn starch ethanol, but still have higher GHG emissions than baselines with corn stover ethanol, by 0-18%.

It is worth emphasizing that the comparisons here are for WTP stage, not the full life cycle of WTW stage. Only the full WTW analysis results will provide an overall life cycle evaluation on the impact of using the bio-blended high octane gasolines on environment.