Life Cycle Associates

Stefan Unnasch
1. 650.461.9048 direct
1.484.313.9504 facsímile
unnasch@LifeCycleAssociates.com
884 Portola Road, Suite A11
Portola Valley, CA 94028 USA

Sept. 15, 2014

California Air Resources Board
Katrina Sideco
(916) 323-1082
ksideco@arb.ca.gov

Reference: **Comments on Petroleum Refining Emissions**

Dear Ms. Sideco,

We are pleased to provide comments on ARB's presentations and regarding the LCFS. The comments herein address the question of emissions from oil refineries. Refinery emissions contribute to the CARBOB and ULSD fuel pathways. Also, diesel and residual oil are inputs for the production, transport, and distribution of other fuels.

Refinery Emission Calculations

The GREET model estimates emissions from oil refining and assigns the emissions to gasoline blendstock, diesel, LPG, and residual oil. The key input is the refinery efficiency, which translates into energy used per mmBtu of product fuel. Table 1 summarizes the refinery efficiency assumptions used in CA_GREET1.8b, GREET1_2103, recommended inputs, and literature references.

The inputs for petroleum refining have evolved over the years with differ considerably values for both baseline gasoline and diesel. The CA_GREET inputs were adapted from the GREET 1.8b model with adjustments for CA RFG production. These values were derived from the original 2004 paper from Argonne National Laboratory that attempts to assign a refining intensity to each petroleum product (Wang, 2004).

Most recently, Argonne National Laboratory published two papers that examined crude oil refinery emissions in GREET. One paper discusses the linear programming approach to determining refinery emissions (Elgowainy, 2014). A second paper examines variability in refinery efficiency based on regional refinery configuration (Forman, 2014) The Forman paper shows the latest refinery data by PADD, (Forman, 2014). These studies provide a more solid basis for the determination of GREET inputs. A series of reports by Jacobs Consultancy also examined how refinery emissions varied with different crude oil types (Keesom, 2012, 2009). The study found that refinery emissions assigned to gasoline and diesel were higher for heavier crude oils and for more complex refineries. Distinct differences in GHG emissions for gasoline, diesel, and residual oil were determined by following product flows though refinery unit operations. The method of tracking energy flows showed that the yield from crude oil to gasoline was not a 1:1 ratio. The crude to gasoline yields are not explicitly reported but can be deduced by inspecting Tables 5-4, 8-8, and 8-9 in Keesom, 2009. Refining crude oil to gasoline requires about 1.01 to 1.04 Btu of crude oil per Btu of gasoline, depending upon refinery configuration and crude oil type.

Implications for GREET

The recent studies have provided improved data on the effect of crude oil type, API gravity, and refinery configuration for fuel-specific refinery emissions. These studies are an improvement over the prior GREET inputs because they provide a more sound basis for determining refinery emissions. However, issues with the material balance around the refinery and crude oil to product yields remain unaddressed in GREET1_2013. Also, the fuel shares for each product represent an oversimplified scaling of the base gasoline results.

Stefan Unnasch
1. 650.461.9048 direct
1.484.313.9504 facsímile
unnasch@LifeCycleAssociates.com
884 Portola Road, Suite A11
Portola Valley, CA 94028 USA

Table 1. Key Inputs for Crude Oil Refining

	CA_ GREET 1.8b	GREET1 _2013[a]	Recommended Input	Wang 2004	Forman 2014
Crude Oil Resource	**All**	**U.S. Average**	**For CA**	**U.S. Average**	**PADD V**
API Gravity	N/A	30.4	30		--
Refining Efficiency					
CARBOB/Gasoline	84.50%	89.3%	89%	86.4%	89%
Conv. Diesel	90.30%	89.3%	88%	91%	88%
Low-Sulfur Diesel	86.70%	89.3%	88% + H_2	--	88%
LPG	94.30%	89.3%	--	92.7%	--
Kerosene	--	89.8%	--	92.1%	95%
Naphtha	94.30%	95.7%	--	93.1%	--
Residual Oil	94.30%	95.7%	95.7%	94.2%	--
Waxes	--	--	--	80.8%	--
Lube Oil	--	--	--	80.7%	--
Coke	--	85%	--	86.9%	--
Non Combustion Emissions (g/mmBtu)[b]					
CO_2	1,267	1,172	1,172		--

[a] GREET refinery efficiency has been updated periodically, supported by brief reports from ANL.
[b] Result shown for low S diesel. Non combustion CO_2 is an input for gasoline and scales with refinery efficiency in GREET

Fuel Shares for Each Refined Product

GREET1 calculates the fired fuels through the fuel shares assumptions in Table 2. Several issues are apparent with the data in the model.

The fuel shares are constant for all refined products. This approach is not reasonable because the flow of products through refinery units lends itself to modeling and tracking by refined product (Keesom 2012, 2009). For example, fluid catalytic crackers represent a larger share of gasoline production. Coke for export is produced in cokers. Hydrocrackers are a source of diesel and lubricants and secondary feeds. Kerosene is largely a straight run distillation product. These well-known refinery configuration yields should be reflected in the fuel shares.

For example the share of fuel gas (still gas) is based on 41.6% fuel shares for conventional gasoline scaled to the refinery energy use for each fuel option.

Energy Still gas = 41.6% x $(1/\eta_k-1)/(1/\eta_G-1)$ x 1,000,000

where the efficiency η for fuel k represents any fuel modeled in GREET and G represents the baseline gasoline.

Recommendation: Adjust fuel shares inputs to reflect refinery units used to produce each refined product.

Stefan Unnasch
1. 650.461.9048 direct
1.484.313.9504 facsímile
unnasch@LifeCycleAssociates.com
884 Portola Road, Suite A11
Portola Valley, CA 94028 USA

Table 2. Efficiency inputs and fuel shares for select refined products.

	Gasoline			CA Gasl	Liquefied Petroleum Gas		Residual Oil			
	Gasoline Blendstock Refining: Process Fuel Inputs	Gasoline Blendstock Refininig: Intermediate Product Combustion	Gasoline Blendstock Transportation and Distribution	CA Gasoline Blendstock Refining: Process Fuel Inputs	LPG Refining	LPG Refining: Non-Combustion Emissions	Residual Oil Refining	Resi. Oil Refining: Non-Combustion Emissions	Resi. Oil Transportation and Distribution	Resi. Oil Storage
Energy efficiency	89.2%			89.0%	89.2%		95.7%			
Urban emission share	76.4%		67.0%	100.0%	76.4%		76.4%		59.0%	70.0%
Loss factor	1.000		1.001	1.000	1.000		1.000		1.000	1.000
Shares of process fuels										
Crude oil	0.0%			0.0%	0.0%		0.0%			
Residual oil	39.8%			39.8%	39.8%		39.8%			
Diesel fuel	0.0%			0.0%	0.0%		0.0%			
Gasoline	0.0%			0.0%	0.0%		0.0%			
Natural gas	26.8%			26.8%	26.8%		26.8%			
Coal	0.0%			0.0%	0.0%		0.0%			
Liquefied petroleum gas	8.1%			8.1%	8.1%		8.1%			
Electricity	4.3%			4.3%	4.3%		4.3%			
Hydrogen	20.9%			20.9%	20.9%		20.9%			
Pet coke	0.0%			0.0%	0.0%		0.0%			
Produced gas										
Refinery still gas	0.0%			0.0%	0.0%		0.0%			
Feed loss	0.0%			0.0%	0.0%		0.0%			
Energy use: Btu/mmBtu of fuel throughput										
Crude oil / SCO	0			0	0		0			
Residual oil	48,020			49,200	48,020		17,817			
Diesel fuel	0			0	0		0			
Gasoline	0			0	0		0			
Natural gas	32,348			33,142	32,348		12,002			
Coal	34			35	34		13			
Liquefied petroleum gas	9,829			10,071	9,829		3,647			
Electricity	5,137			5,263	5,137		1,906			
Hydrogen	25,264			25,885	25,264		9,374			
Petcoke	0	17,384		0	0	17,384	0	6,450		
Feed loss	0		813	0	0		0		0	0
Produced gas										
Refinery still gas	0	50,195		0	0	50,195	0	18,624		
Diluent flared										
Natural gas flared										

Crude Oil to Product Yield

GREET treats the upstream fuel cycle emissions from crude oil as a 1:1 conversion yield. The upstream fuel cycle results for crude oil represent the feedstock phase. GREET could simply be modified to reflect the crude oil to gasoline and diesel yield by multiplying the upstream results by a yield factor (1.01 to 1.04). However, the model embeds some upstream results in the refining phase. For example the upstream fuel cycle emissions for natural gas and hydrogen are included in the refinery phase. Thus, the crude oil to product yield can also be handled in the oil refinery portion of GREET.

California Crude Oil Production

The OPGEE inputs are not explicitly modeled in CA GREET. Therefore, the upstream fuel cycle emissions from California crude oil production are not represented in GREET unless the primary crude oil production inputs are changed for the entire model, which was the approach used with the Regional Look Up table in CA_GREET1.8b. Adding a column for California crude oil provides a more elegant solution to addressing these emissions. Table 3 shows the default GREET inputs for crude oil production and a column that reflects California production. These inputs provide the OPGEE result of 12 g CO_2e/MJ; however, the values are imputed to arrive at a

Stefan Unnasch
1. 650.461.9048 direct
1.484.313.9504 facsímile
unnasch@LifeCycleAssociates.com
884 Portola Road, Suite A11
Portola Valley, CA 94028 USA

CI of 12 g/MJ rather than converted from OPGEE Btu/day to GREET Btu/mmBtu and fuel shares inputs.

Recommendation: Convert OPGEE intermediate fuel use and fugitive emissions in Btu/day and kg per day to GREET compatible units and calculate the weighted average for all crude types. Then add a column in CA GREET for California Crude Oil Production, which flows to CA CARBOB and ULSD production.

Table 3. Example of CA Crude Oil Inputs that Result in the Same CI as OPGEE Predictions.

	U.S. Recovery	California Recovery
Energy efficiency	93.0%	96.8%
Urban emission share	0.0%	0.0%
Loss factor		
Shares of process fuels		
Crude oil	0.2%	2.0%
Residual oil	0.2%	0.2%
Diesel fuel	2.5%	18.0%
Gasoline	0.3%	0.3%
Natural gas	94.3%	2.0%
Coal	2.4%	2.4%
Liquefied petroleum gas		
Electricity	0.0%	75.0%
Hydrogen	0.0%	0.0%
Pet coke		
Produced gas		
Refinery still gas	0.0%	0.0%
Feed loss	0.1%	0.1%

Upstream Emissions in Refining

With California crude oil refining explicitly modeled in GREET, a simple modification allows for the correct calculation of upstream fuel cycle emissions from crude oil production. The following equation reflects the CO_2 emissions from California CARBOB refining. Cell B232 refers to U.S. Average crude oil production. Modifying these cells for the new column recommended previously for California Crude oil would address the upstream emissions from crude oil (AA80) and residual oil (AA81) fired in oil refineries. Of course, similar modifications should be implemented for the entire array of pollutants for CARBOB and California low sulfur diesel.

Stefan Unnasch
1. 650.461.9048 direct
1.484.313.9504 facsímile
unnasch@LifeCycleAssociates.com
884 Portola Road, Suite A11
Portola Valley, CA 94028 USA

Recommendation: Modify CA GREET to include upstream fuel cycle (Crude oil phase) for California CARBOB and ULSD refining for all pollutants.

Exhibit 1. Calculation of fired emissions from CARBOB refining.

```
Petroleum!AA109=(AA$80*(EF!$W14+$B232)+AA$81*($F$42*EF!$L14+$B232*$J$218+$J232)
+AA$82*($F$44*EF!$Q14+$F$45*EF!$R14+$F$46*EF!$S14+$B232*$K$218+$K232)
+AA$83*(EF!$U14+$B232*$E$218+$E232)
+AA$84*($F$49*EF!$G14+$F$50*EF!$D14+$F$51*EF!$B14+$F$52*EF!$C14+NG!$B94)
+AA$85*($F$54*EF!$AC14+Coal!$B76)
+AA$86*($F$55*EF!$Y14+$B232*$I$218+$I232)
+AA$87*(Electric!$B184+Electric!$C184)
+AA$92*($F$49*EF!$G14+$F$50*EF!$D14+$F$51*EF!$B14+$F$52*EF!$C14)
+AA$89*($F$57*EF!$BH14+$B232*$N$218+$N232))/1000000
+AA$88/1000000*SUM(Hydrogen!$BB161:$BC161)
```

Crude Oil Yields

GREET is not configured with an explicit yield for crude oil to refined products but instead shows the internally fired fuel gas (AB92) and petroleum coke (AB89) that are burned in the refinery. The model multiplies the fuel gas and petroleum coke by their respective emission factors. These terms do not include the upstream fuel cycle emission for the crude oil. Thus the upstream emissions for 1 mmBtu of crude oil contribute only to the crude oil feed phase.

However, the GREET model does not take into account the crude oil to make this fuel gas and petroleum coke. One approach would be to add the upstream fuel cycle emissions for California crude oil to the terms for fuel gas and petroleum coke. These terms, configured in Cell D232, are shown in Exhibit 2.

Exhibit 2. CO2 emissions from internally produced fuels in oil refineries.

```
Petroleum!AB109=[zero](AB$80*EF!$W14+AB$81*$F$42*EF!$L14
+AB$82*($F$44*EF!$Q14+$F$45*EF!$R14+$F$46*EF!$S14)
+AB$83*EF!$U14+AB$84*($F$49*EF!$G14+$F$50*EF!$D14 +$F$51*EF!$B14
+$F$52*EF!$C14) +AB$85*$F$54*EF!$AC14+AB$86*$F$55*EF!$Y14
+AB$92*($F$49*EF!$G14+$F$50*EF!$D14+$F$51*EF!$B14+$F$52*EF!$C14
+D232) +AB$89*($F$57*EF!$BH14+D232))/1000000
```

Recommendation: Modify CA_GREET to include the upstream fuel cycle emissions for U.S. average crude oil for conventional gasoline, diesel, LPG, and residual oil for the energy inputs for refinery still gas and petroleum coke. Similarly, modify CARBOB and California ULSD for to reflect the upstream fuel cycle emission for crude oil production.

Stefan Unnasch
1. 650.461.9048 direct
1.484.313.9504 facsímile
unnasch@LifeCycleAssociates.com
884 Portola Road, Suite A11
Portola Valley, CA 94028 USA

Thank you for taking into account these comments. I look forward to discussing these comments with you in more detail.

Best Regards,

Stefan Unnasch
Managing Director
Life Cycle Associates, LLC

References

Abella, J.P., Bergerson, J.A., 2012. Jessica P. Abella. and Joule A. Bergerson., Model to investigate energy and greenhouse gas implications of refining petroleum: impacts of crude quality and refinery configuration 1–69.

Elgowainy, A., Han, J., Cai, H., Wang, M., Forman, G.S., Divita, V.B., 2014. U.S. Re fi nery E ffi ciency: Impacts Analysis and Implications for Fuel Carbon Policy Implementation.

Forman, G.S., Divita, V.B., Han, J., Cai, H., Wang, M., 2014. U . S . Refinery Efficiency : Impacts Analysis and Implications for Policy Implementation 1–17.

Keesom, Blieszner, J., Unnasch, S., 2012. EU Pathway Study: Life Cycle Assessment of Crude Oils in a European Context.

Keesom, W., Unnasch, S., Moretta, J., 2009. Life Cycle Assessment Comparison of North American and Imported Crudes. Jacobs, AERI.

Wang Lee, H., & Molburg, J., M., 2004. Allocation of energy use in petroleum refineries to petroleum products. Int. J. LCA 9, 34–44.

Wang, M., Lee, H., Molburg, J., 2004. LCA Case Studies Allocation of Energy Use in Petroleum Refineries to Petroleum Products Implications for Life-Cycle Energy Use and Emission Inventory of Petroleum Transportation Fuels 9, 34–44.