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California Air Resources Board
Anil Prabhu
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Reference: **Co-processing GHG Calculations**

Dear Anil,

The following comments address the calculations and methods for co-processing in petroleum refineries[1] including the treatment of LPG and other co-products in the GREET model.

ARB has analyzed several methods for determining GHG emissions and yields. The follow comments provide recommendations to the calculations for co-products.

- The stoichiometry of hydroprocessing allows for estimates of liquid fuel yield, hydrogen consumption, and LPG production.
- LPG vehicles currently consume several million gallons per year of LPG in California, which are an option for inclusion in the LCFS.
- Biofuel producers currently produce renewable-LPG and the determination of the CI is comparable to that of renewable diesel and renewable jet.
- ARB should develop a temporary fuel pathway code for vegetable oil or other renewable feedstock based LPG.

Hydroprocessing Yields

The hydroprocessing of oils and fats reacts hydrogen with triglycerides to produce liquid fuels and propane. About 5% of the feedstock mass consists of the three carbon "knuckle" which corresponds to a theoretical propane yield[2]. Thus facilities that process renewable feedstocks could produce about 5% more product as renewable propane.

Role of LPG

Several fuel producers currently co-produce LPG with bio-feedstocks or are planning on starting facilities. The following technology options are among the many that co-produce bio LPG.

- Hydroprocessing tallow and other fats to renewable diesel
- Hydroprocessing tallow and other fats with petroleum feed to renewable diesel
- Fluid catalytic cracking of pyrolysis oils to refinery feed

Since bio LPG is produced from various fuel production processes, fuel producers should be able to generated LCFS credits from this fuel. The treatment of renewable LPG should be comparable to that of other fuels including diesel and jet fuel.

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[1] ARB Discussion Paper. Co-processing of Low Carbon Feedstocks in Petroleum Refineries. May 30, 2017, Staff Presentations June 2, 2017.
[2] Unnasch, S. and L. Goyal (2017). Theoretical Yield of Renewable Diesel from Camelina. Lfie Cycle Associates memo LCA.3003.170.2017.

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Treatment of Co-products

The GREET model and several fuel pathways approved by the ARB support the use of energy allocation for processes that produce when multiple fuels. Several key principles surround these co-produced pathways.

1. Energy allocation is applied to fuel and energy products.
    a. ARB RD pathways allocate energy to propane
    b. GREET jet pathway allocates energy to diesel and propane
2. The net effect is that the GREET inputs after allocation are the same in g/lb of product. For example consider the hydrogen use per lb of RD. GREET used the upstream emissions of hydrogen E_H x Btu H_2/lb RD x Allocation Factor where the Allocation factor X

X = (RD/(RD + Jet + Naphtha + LPG)

Similarly if LPG is the primary product, GREET would treat the hydrogen emissions as
E_H x Btu H2/lb LPG x (LPG/(RD + Jet + Naphtha + LPG)

In both cases the upstream emissions associated with hydrogen reduce to the total hydrogen input divided by the sum of RD, Jet, Naphtha, and LPG)

The prior fuel pathways approved by ARB affirm these principles. Therefore, we recommend that LPG, jet fuel and naphtha follow the GREET approach. The method in GREET allocates upstream and direct emissions for the well to tank phase of renewable diesel and FCC based petroleum products is based on energy allocation. The formula results in exactly

Process Inputs and Yields

For the renewable diesel pathways, energy use inputs are combined with feedstock to fuel yields and allocation factors to determine the WTT emissions. Note that the CI for each fuel is the same with energy allocation.

Energy inputs for a fuel production facility provide the basis for the calculation of GREET inputs. The refinery energy inputs are allocated to products by energy content. The basis for the calculation and source of inputs is described for each key input below.

As the facility co-produces four different products namely renewable LPG, renewable diesel (RD), renewable jet fuel (RJ), and renewable naphtha (RN) from the same feed blend, only a part of the energy and material consumption should be allocated to RN to calculate its carbon intensity justifiably. This allocation is done using the respective energy content proportion of the four co-products processed at the facility which is the default GREET method.

In the calculation of the carbon intensity of RD pathway, GREET model assumes the production of fluid products with only one co-product, LPG, which generates credits. The allocation of credits to the RD is based on energy. The GREET model assumes the fuel to be composed 100% of RD. However, in practice, the hydrotreating process used to produce RD also produces other co-products, for example renewable naphtha (RN) and renewable jet fuel (RJ).

Note that the aviation WTT sheet in GREET deals with three fuel products, jet, naphtha and naphtha. Jet fuel is treated as the primary product and naphtha and LPG are co-products. The following examples are based on tallow to renewable fuel pathways.

The fuel yield value, the input in GREET, is calculated as the inverse of feedstock use rate in pounds per pound of fuel produced. With the additional inputs of the co-product yield (lb/lb RD), GREET allocates a percent of system energy inputs to the RD using a calculated allocation

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factor. The allocation factor is the proportion of the energy content of the fuel produced with the total products produced, which is the sum of fuel and co-products produced. The formulas for fuel yield and allocation factor are as follows:

$$GREET\ Input = Fuel\ Yield\ (lb\ fuel\ /\ lb\ rendered\ fat) = \frac{1}{\frac{Feedstock\ used\ (lb)}{Fuel\ produced\ (lb)}}$$

$$\text{Allocation factor} = \chi = \frac{Fuel\ produced\ (Btu)}{Fuel\ produced\ (Btu) + \sum\ coproduct\ produced\ (Btu)}$$

$$Where, \qquad coproduct\ (Btu) = production\ (lb)\ \times\ energy\ density\ (Btu/lb)$$

Given multiple co-products, the first step is to determine the primary product as determined by the pathway. Primary product is the product for which the CI is being calculated. For now, let's assume RD to be our primary product as per renewable diesel pathway. The key effect of this is on the lower heating value to be used. Given the same inputs, a fuel with higher energy density has a lower carbon intensity as the CI is expressed in g CO_2e/MJ.

Secondly, depending on the treatment of co-products (LPG, RN, and RJ) as transportation fuel or co-product, there are two methods of accounting of credits. First method (method A) assumes only RD to be a fuel product while the other method (method B) assumes all of RD, LPG, RJ, and RN to be transportation fuel. Using the method A, the feedstock use rate calculation uses the energy content of RD as the total fuel energy produced. The same applies logic to the allocation factor where the numerator is equal to the energy content of RD.

The method B considers the all four of RD, LPG, RJ and RN as fuel and thus the energy content of all four is added to the "fuel produced" in both, feedstock use rate and allocation factor calculation. Numerically, compared to the method A, method B decreases the value of the feedstock use rate. However, the value of the allocation factor is increased in the method B. This increment in the value of the allocation factor almost exactly compensates the decreased feedstock use rate.

Consequently, both methods result in almost identical value of the fuel yield after incorporating the allocation factor, which, in turn, is the input used in the GREET model. The inputs into the GREET are the values before any allocation is done as GREET model applies the allocation factor to the inputs including the yield and energy inputs.

Our analysis follows the method A, i.e. considering only RD as fuel and LPG, RJ, and RN as co-products. Consequently, the allocation factor calculation is as follows:

$$\chi_A = \frac{RD\ (MMBtu)}{RD\ (MMBtu)\ +\ LPG\ (MMBtu)\ +\ RJ\ (MMBtu)\ +\ Naphtha\ (MMBtu)}$$
$$= \frac{1{,}000{,}000}{1{,}000{,}000\ +\ 100{,}000\ +\ 80{,}000\ +\ 35{,}000} = \mathbf{83.65}\%$$

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For illustration, the allocation factor calculation will be as follows using the method B:

$$\chi_B = \frac{RD\ (MMBtu) + LPG\ (MMBtu) + RJ\ (MMBtu) + RN\ (MMBtu)}{RD\ (MMBtu) + LPG\ (MMBtu) + RJ\ (MMBtu) + RN\ (MMBtu)}$$

$$= \frac{1{,}000{,}000 + 100{,}000 + 35{,}000 + 80{,}000}{1{,}000{,}000 + 100{,}000 + 35{,}000 + 80{,}000} = \mathbf{100\%}$$

The following Table 1 shows the comparison between the post-allocation inputs as calculated by using Method A and Method B. The CI value for RD resulting from method A and B are virtually identical. The table also shows method 1 calculations for the renewable LPG pathway (LPG as primary product) following the same hypothetical production data. As it can be seen, there is only a minor difference in the LPG CI from the RD CI. This is purely the result of a different heating value of the primary product as described previously.

Table 1. System inputs from Method A, Method A1 and Method B based on energy allocation

GREET Input (pre-allocation)	Unit	Method A	Method B	Method A
Primary product		Ren. Diesel	Ren. Diesel	Ren. LPG
Allocation formula		RD/ (RD+RJ+RN +LPG)	(RD+RJ+RN+LPG)/ (RD+RJ+RN+LPG)	(LPG)/ (RD+RJ+RN +LPG)
Feedstock to fuel use rate	lb feed/ lb fuel	1.289	1.078	13.926
Fuel yield, lb fuel/lb rendered fat	lb fuel/ lb feed	0.776	0.927	0.072
Allocation factor value	%	83.65%	100%	7.60%
System inputs (post allocation)				
Fuel yield, lb fuel/lb rendered fat	lb fuel/lb feed	0.927	0.927	0.944
Total Energy	Btu/lb fuel	2,755	2,755	2,706
Thermal Energy	Btu/lb fuel	2,461	2,461	2,417
Natural gas	Btu/lb	719	719	706
Electricity	kWh/lb	0.09	0.09	0.08
Hydrogen	Btu/lb	1,742	1,742	1,711
Carbon Intensity	**g CO_2e/MJ**	**32.18**	**32.18**	**32.57**

Effectively, the CI contribution from a particular input is calculated as shown below:

$$GREET\ Emission = \frac{Fuel\ (Btu)}{Fuel\ + Coproducts\ (Btu)} \times \frac{Energy\ used}{Fuel\ (lb)} \times E_F\ /\ \text{Fuel LHV}$$

$$where\ E_F = GREET\ Emission\ Factor$$

The first part of the equation represents the allocation factor, second represents the GREET input (pre-allocation values, as opposed to system inputs) and third the emission factor built into

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GREET model. The allocation factor is based on energy while the GREET input is based on the proportion of resource used to mass of the fuel product. Because of this combination of both mass and energy proportions, the post allocation GREET inputs and subsequently the GREET emissions result in nominal variation when comparing the above described methods.

This analysis results in the same emission intensity per lb of product for diesel, jet, naphtha, and LPG co-products. The following equations define the WTT emissions for vegetable oils and fats to renewable diesel (RD) which can be extended to all fuel products discussed in this analysis.

$$E_{WTT} = E_{Feed} + E_{Fuel} + iLUC$$

$$= \left\{\frac{\mathrm{E}_{SB} \times \mathrm{X}_{\mathrm{SB}} \times \mathrm{X}_{\mathrm{RD}}}{\rho_{\mathrm{SB}} \times OYF \times \psi_{\mathrm{RD}}}\right\} + \left\{\left(\frac{E_{SO,Extract} \times OYF + E_{SO,T\&D}}{\psi_{RD}} + E_{RD}\right) \times \frac{X_{RD} \times LF_{RD}}{LHV_{RD}} + E_{T\&D}\right\}$$
$$+ iLUC$$

Where,

E_{Feed}	= farming energy, chemical inputs, primary transportation and co-product credits
E_{SB}	= GREET upstream fuel cycle for soybean (= E_{Farm} + $E_{Fert/Chem}$ + $E_{T\&D}$)
ρ_{SB}	= Density of soybean on dry basis (lb soybean/bu soybean)
OYF	= Oil yield factor (lb soy oil / lb soybean)
X_{SO}	= Allocation factor for soybean to soyoil, = OYF for mass allocation
ψ_{RD}	= Yield renewable diesel (lb biofuel/lb soyoil)
X_{RD}	= Energy based allocation of renewable diesel to other co-products (default 94.5%)
ρ_{RD}	= Density for renewable diesel (g/gal)
LHV_{RD}	= Lower heating value for renewable diesel (Btu/gal)
E_{fuel}	= Soyoil extraction and transportation plus RD plant emissions
$E_{SO, Extract}$	= Soy oil extraction energy and emissions
$E_{SO,T\&D}$	= Soy oil transportation and distribution energy and emissions
E_{RD}	= Renewable diesel plant emissions, including natural gas combustion, electric power, hydrogen production, and fugitive emissions from the plant
LF_{RD}	= Loss factor for renewable diesel production
$E_{T\&D}$	= Transportation and distribution

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Therefore, developing CA_GREET pathways for all fuel products is a relatively straightforward effort. The energy inputs and emissions for feedstocks and fuel production are distributed among all of the fuel products with the CI differing due to the varying energy density values for each fuel. The framework is laid out under the renewable jet pathways in GREET and should be applied to renewable diesel, jet, LPG, and naphtha pathways.

Best Regards,

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