Positive Environmental Impacts from Reduced Levels of Energy Transportation – A Hidden Benefit of Self-Sufficiency?

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Executive Summary

The move towards US energy self-sufficiency encompasses the idea of using energy where it is sourced. This echoes the move towards community based energy systems with distributed electricity production and mini-grids and shares common features with the move towards short food supply chains. The geographic concentration of sourcing, production and consumption can have positive environmental impacts, from reduced transport and also from reduced transport infrastructure needs, but these benefits remain 'hidden' in many real-life cases because of inconsistencies in the way we assign value to the environmental externalities associated with transport.

This study looks at specific cases of energy sourcing to identify the incentives and measurement tools used to encourage positive environmental choices[i], with a focus on how transport is incorporated into our environmental evaluation models. The cases analysed here are:

A. A power plant in the region of York in England that replaced local coal with wood pellets shipped from the USA and Canada as fuel for electricity generation;

B. Renewable diesel and biodiesel fuels made from used fats in Asia or Europe and shipped to California as part of the Low Carbon Fuel System program.

These cases were chosen because they both involve the use of sophisticated environmental evaluation models (the BEAC and CA-GREET models) that explicitly take into account the life cycle carbon dioxide emissions related to transport. At first glance they appear counterfactual – we are demonstrating that the environmental impacts of transport matter by looking at two projects that involve high levels of transport but were implemented anyway. This contradiction is explained by data availability - it is the success of these projects that allows us to access published data relative to their analysis: the transport was effectively valued by the models, but offset by other characteristics, or ignored for lack of alternatives, so the choice was made to go ahead despite the transport externalities.

In Case A, the carbon emissions from transport (forest to pellet plant to England to York power plant) vary from 30 to 57 kg $CO2_e$ / mwh for the different sourcing options analysed (all from North America to England), and the energy input to output ratio[ii] varies from 1 to 10 to 1.9 to 10. The carbon emissions of electricity production for the site are less than 200 kg $CO2_e$ / mwh for wood and 854 kg $CO2_e$ / mwh for coal, so the fuel choice impact overwhelms the transport impact[iii], but the case nevertheless illustrates that transport to the site accounts for up to 16% of the total energy use (=1.9 / 11.9) and up to 22% of the final carbon emissions (=57 / 257). For the used fats converted to renewable diesel and biodiesel fuels[iv] and sold in California analysed in case B, the carbon emissions from transport vary from .33 to 2.29 kg $CO2_e$ / gallon and make up 7% to 48% of the total carbon emissions. In both cases the transport emissions vary between scenarios but remain peripheral in the choice of alternatives as the key driver is the production process technology: electricity generation from coal or wood in Case A and variations in the fat rendering or transformation process and the type of energy used to drive this process for biofuel production in case B.

Both of these cases illustrate 'carbon leakage': the supplying country and the international transport space increase their carbon emissions to facilitate reductions in the final-use country. In theory we could reduce worldwide carbon emissions even more by using these low carbon fuels closer to the source (there is coal based electricity production in North America and Asia is a major user of transport fuels, mostly imported fossil fuels), but this doesn't happen because local subsidies in the end-use countries assign a significantly higher value to these fuels than the local markets do. This is an example of the 'wide discrepancies in the implicit price of carbon put on different emissions' through 'local Command and Control' policies discussed by Jean Tirole[v] in his recent paper on Carbon Pricing.

The overall stakes of the potential for environmental benefits from the shorter fuel supply chains that increased national and regional energy self-sufficiency would bring are demonstrated by the importance of long distance transport of oil and coal which make up 15% - 20% of worldwide ocean freight.

Methodology

This paper is a case study based on publically available databases, models and study evaluations, and supplemented by a discussion with Michael Wang at the Argonne National Laboratory. The primary data comes from two publically available Excel models that provide excellent evaluation tools for transportation costs (among other things): the BEAC[vi] model from the UK DECC and the CA-GREET[vii] model used in the California LCFS program and based on the GREET model from Argonne National Laboratory.

The analysis focuses on life cycle (well to wheel) evaluations of greenhouse gas emissions, measured as carbon dioxide equivalent emissions and referred to throughout as 'carbon emissions'. The life cycle evaluation includes multiple stages of transportation required to cover all aspects of the fuel sourcing process from the setup of the extraction site to the delivery to the final user. The detail sections that follow show extracts from the models that show the level of detail included for each stage of the transport process (method, distance, type of fuel).

The units of measure used are:

- Kilograms of equivalent carbon emissions per megawatt hour (kg $CO2_e$ / mwh) for the UK electricity case
- Kilograms of equivalent carbon emissions per gallon of diesel fuels (kg $CO2_e$ / gal) for the LCFS case
- The LCFS coefficients are in grams of equivalent carbon emissions per million joules (g $CO2_e$ / MJ) and this measure is also used to compare the cases
- Kilograms of equivalent carbon emissions per million British thermal units (kg $CO2_e$ / Mbtu) as a comparison between the cases
- Annual carbon emissions are given in million metric tons (Mt $CO2_e$) which are the equivalent of 10^9 kg
- The carbon intensity of individual transport types is given in grams per tonne kilometer transported (g $CO2_e$ / t_ km) in the text and this measure is also used in the BEAC model (actually shown as kg $CO2_e$ / t_km)
- The carbon intensity of transport in the GREET model is not given directly by transport type but rather is calculated in terms of grams per million Btu of fuel transported for each type of fuel based on a series of parameters on transport types used, payload, fuel, and energy intensity for each product transported

This analysis does not assign a monetary value to carbon emissions, but assumes that each tonne of equivalent carbon emitted has the same environmental 'cost' no matter where the emission occurs. We mention in passing some of the related environmental issues (particulate pollution from coal, deforestation from woody biomass usage, indirect land use issues for biofuels and the food versus fuel conflicts) but the term 'positive environmental impacts' in the title refers to the possibility of reduced carbon emissions from fuel transport.

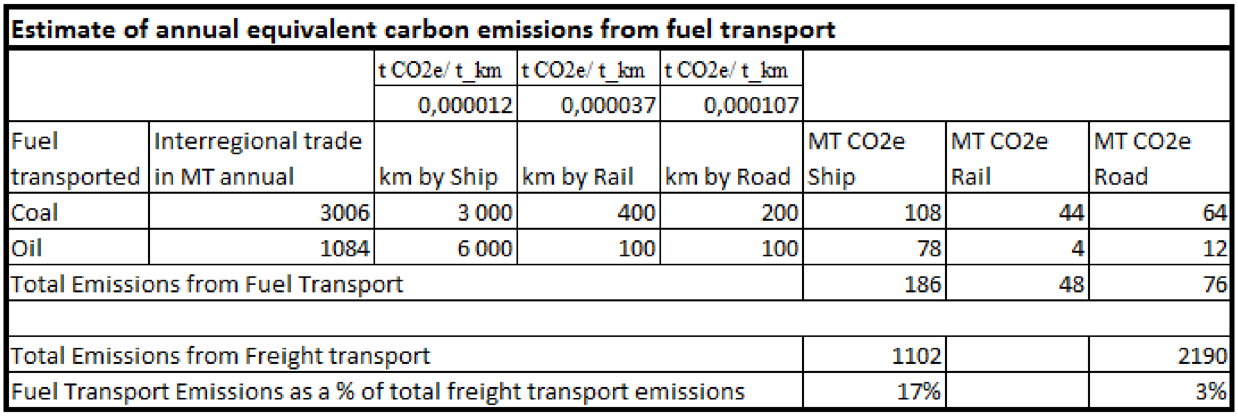
We started this study with a third case involving the environmental impacts of energy transport infrastructure that we tried to analyse using these tools but concluded that other analytical tools are necessary to adequately measure infrastructure impacts. The infrastructure case was removed from this study and we plan a specific study on this issue in 2017.

General Context of Carbon Emissions from Transport

The inspiration for this project came from the observation through multiple consulting studies on the cost of compliance with environmental regulations that transport of fuel to point of use is largely 'free' in terms of its measured environmental cost under current rules (considering only carbon based costs like taxes or emissions trading and excluding pre-existing fossil fuel taxes that are primarily motivated by revenue collection). We set out to determine if this is because fuel transport is truly not significant or just too complex to analyse and cost.

Our first step was to do a literature review. The results were disappointing – despite trying numerous techniques of data search we were unable to find any general studies on the transport of energy, let alone the carbon emissions impact of fuel transport (all the internet search data comes back in reverse form – transport of energy is always transformed into energy for transportation). The next step was to look at data tables – this led to an interesting find in the US EPA data[viii] which isolates 'Pipelines' as a type of transport[ix] and lists the related carbon emissions at 47 Mt $CO2_e$ which is 2.4% of overall US transport $CO2_e$, while the remainder total US transport emissions for freight transport are at 472 Mt $CO2_e$ (24%)[viii]. On a worldwide basis the annual carbon emissions value for road freight, based on oil consumption only, is 2190 Mt $CO2_e$ [viii] which is 13% of total emissions and bunker fuel, which is a good proxy for transport by ocean tanker, contributes 1102 Mt $CO2_e$ [viii] to annual emissions for another 7% of total. Freight is a significant source of carbon emissions and the potential for environmental benefits from shortening supply chains is real.

The next step was to get an estimate of how much of the freight transport is dedicated to transporting fuel. Energy transport is heavily concentrated at the low end of the carbon footprint transport types[x] with heavy use of ships (4 to 19 g CO2/km) for petrol, coal, gas, also rail use (37 g CO2/km) for coal, road transport for most at beginning or end (107 to 303 g CO2/km) and almost no air travel for fuel (733 g CO2/km). We then took an estimate of interregional trade[xi] of coal and oil (both crude and refined) and estimated average trade distances by type[xii] of fuel and transport method. The calculation [xi] shown below remains approximate but enables us to appreciate the potential stakes of reduced long haul energy transport.



Estimate of annual equivalent carbon emissions from fuel transport

		t CO2e/ t_km	t CO2e/ t_km	t CO2e/ t_km			
		0,000012	0,000037	0,000107			
Fuel transported	Interregional trade in MT annual	km by Ship	km by Rail	km by Road	MT CO2e Ship	MT CO2e Rail	MT CO2e Road
Coal	3006	3 000	400	200	108	44	64
Oil	1084	6 000	100	100	78	4	12
Total Emissions from Fuel Transport					186	48	76
Total Emissions from Freight transport					1102		2190
Fuel Transport Emissions as a % of total freight transport emissions					17%		3%

If we extrapolate from this estimate to define a range, it is reasonable to say that long haul or interregional transport of fuel accounts for 15% to 20% of total worldwide ship freight and is therefore a potential lever for environmental improvement. The impact on road and rail however is marginal – while fuel does move by road and rail, most of this transport is local and would exist anyway even with a reduction in long haul transport from increased national and regional self-sufficiency.

Case A – UK York power plant using woody biomass from North America in place of local coal

Project Description

This project was initiated in 2014 as a way to meet the EU requirement for 20% renewable energy by 2020. The UK has a number of coal-fired electricity generation plants. These plants can be converted over to burn wood pellets at reasonable cost. But, although wood is considered 'renewable' it takes time and available forest land to renew it and the UK decided that in-country resources were insufficient to meet electricity generation needs. So a large coal-fired plant near York (Eastern England, coastal site) contracted with suppliers in North America to harvest wood, produce wood pellets and ship them (by road or rail, then by ship) to the power plant.

In addition to the requirement for 20% renewable energy there is also a requirement that the new renewable energy solution can't involve more carbon emissions than the energy source it is replacing, and that these emissions must be calculated on a life cycle basis, including land use and carbon stock criteria. In order to respond to this the UK DECC (Department of Energy and Climate Change) commissioned a study on the wood project which led to the creation of the BEAC model (Biomass Emissions and Counterfactual model). This model is publically available (in the form of an Excel spreadsheet) and provides excellent detail on the transport calculations which were used for this project.

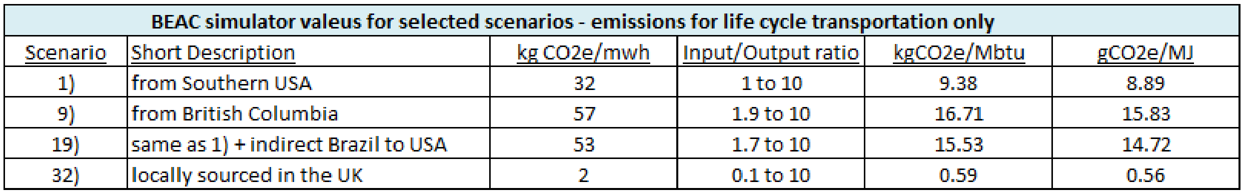
The model identifies transport in 4 'legs' – the first is transport of the raw wood to the pre-treatment facility (the factory that compresses the wood into pellets in most scenarios), and the next three 'legs' involve transport of the pellets to the UK power generation plant with a separate analysis of road, ship and rail transportation.

There are numerous different scenarios simulated within the calculations (many have the same transport characteristics but differ in indirect land use and carbon storage factors). In order to illustrate the benefits of self-sufficiency through reduced transport of energy to point of use, we chose 4 of the 33 scenarios for analysis:

- Scenario 1 – wood pellets from the Southern USA (Louisiana and South Carolina)
- Scenario 9 – wood pellets from British Columbia (special case of wood killed by a beetle so available as waste)
- Scenario 19 – same as Scenario 1 but including the indirect impact that the USA may need to import wood from Brazil to make particleboard because their sawmill waste has been sold to the UK
- Scenario 32 – wood chips from the UK that otherwise would be used for particle board in the UK

Results for Transport

The table below shows the carbon emissions related to the transport of the wood from the forest to the pellet plant to the power plant (expressed as kilograms of equivalent carbon emissions per megawatt hour). It also shows the energy input to output ratio related to the transport needed to arrive at the power plant (based on energy used) and standardized measures of kilograms of equivalent carbon emissions per million British thermal units and grams of equivalent carbon emissions per million joules which enable comparisons between Case A (based on megawatt hours of electricity produced) and Case B (the LCFS coefficients are expressed in equivalent carbon emissions per million joules).

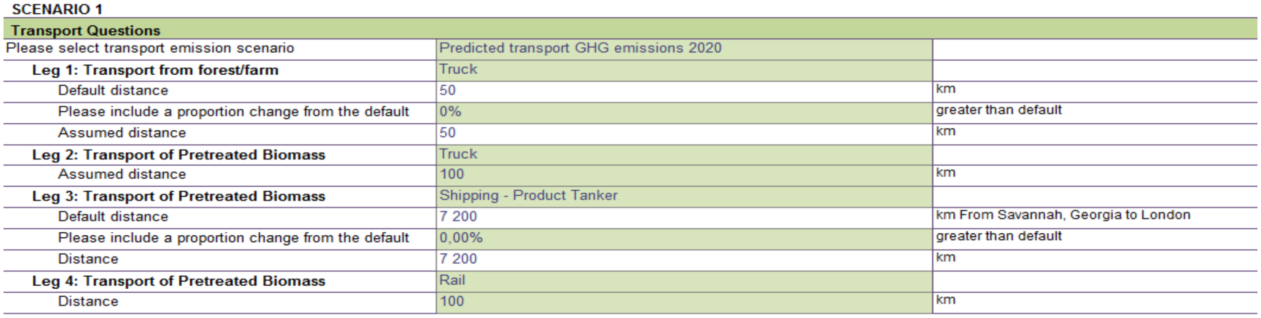


BEAC simulator valeus for selected scenarios - emissions for life cycle transportation only

Scenario	Short Description	kg CO2e/mwh	Input/Output ratio	kgCO2e/Mbtu	gCO2e/MJ
1)	from Southern USA	32	1 to 10	9.38	8.89
9)	from British Columbia	57	1.9 to 10	16.71	15.83
19)	same as 1) + indirect Brazil to USA	53	1.7 to 10	15.53	14.72
32)	locally sourced in the UK	2	0.1 to 10	0.59	0.56

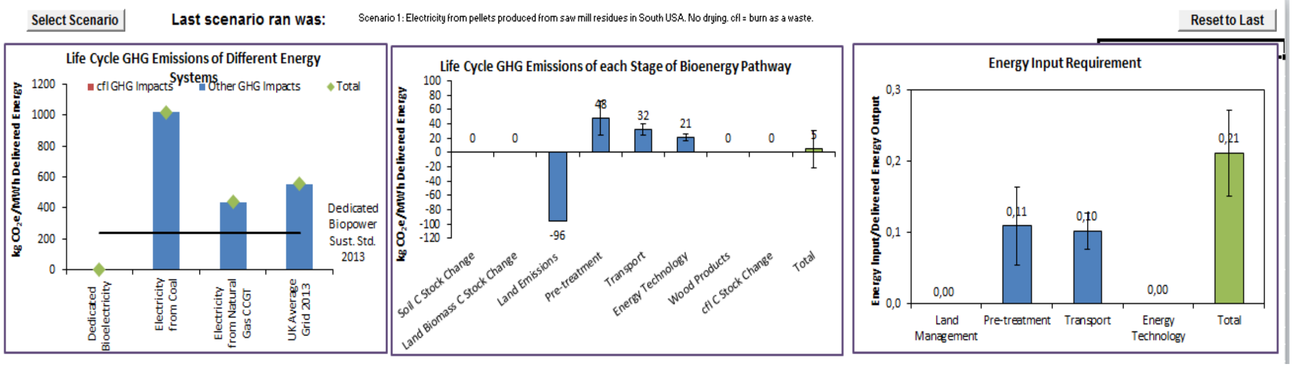
The detail behind the transport options chosen is shown below for each scenario, followed by the results charts:

Scenario 1 – wood pellets from the Southern USA (Louisiana and South Carolina)



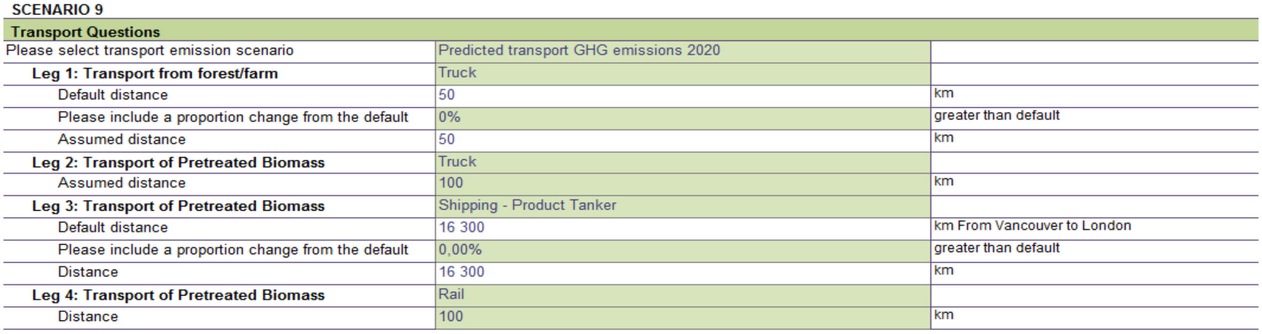
SCENARIO 1

Transport Questions		
Please select transport emission scenario	Predicted transport GHG emissions 2020	
Leg 1: Transport from forest/farm	Truck	
Default distance	50	km
Please include a proportion change from the default	0%	greater than default
Assumed distance	50	km
Leg 2: Transport of Pretreated Biomass	Truck	
Assumed distance	100	km
Leg 3: Transport of Pretreated Biomass	Shipping - Product Tanker	
Default distance	7 200	km From Savannah, Georgia to London
Please include a proportion change from the default	0,00%	greater than default
Distance	7 200	km
Leg 4: Transport of Pretreated Biomass	Rail	
Distance	100	km



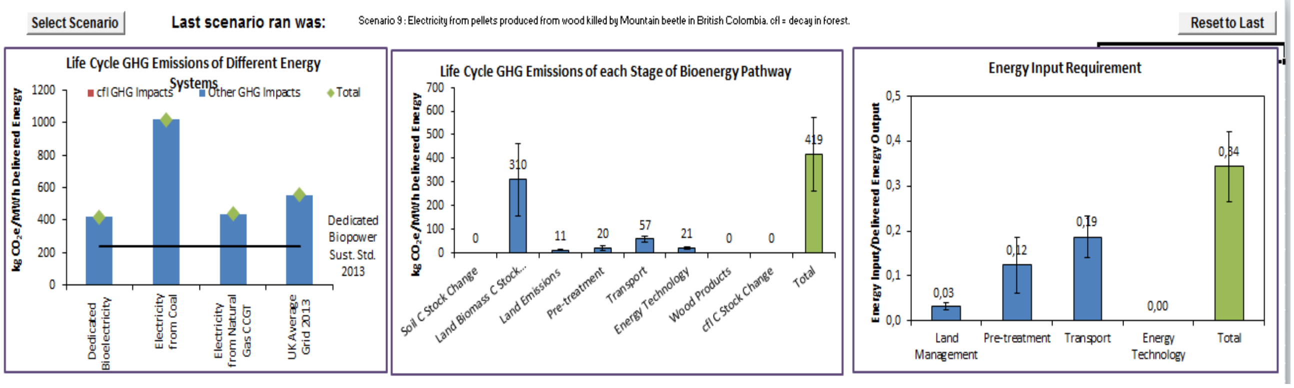
Last scenario ran was: Scenario 1: Electricity from pellets produced from saw mill residues in South USA. No drying. cfl = burn as a waste.

Scenario 9 – wood pellets from British Columbia (special case of wood killed by a beetle so available as waste)



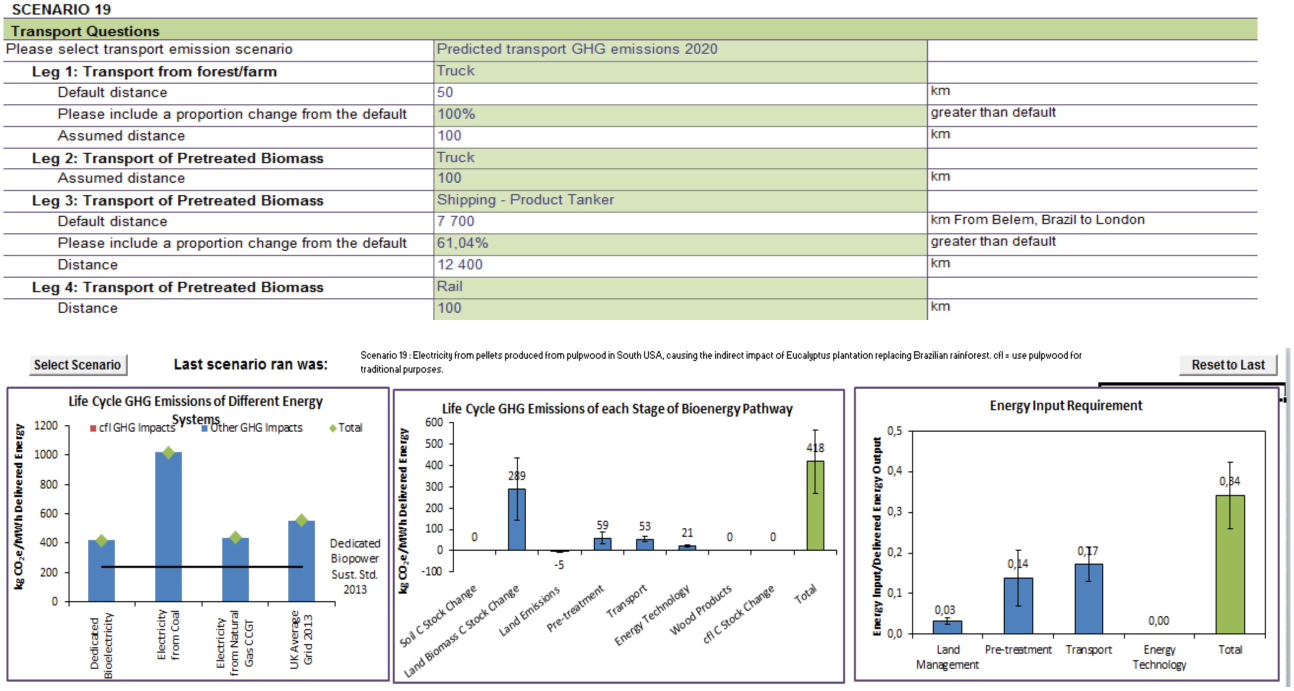
SCENARIO 9

Transport Questions		
Please select transport emission scenario	Predicted transport GHG emissions 2020	
Leg 1: Transport from forest/farm	Truck	
Default distance	50	km
Please include a proportion change from the default	0%	greater than default
Assumed distance	50	km
Leg 2: Transport of Pretreated Biomass	Truck	
Assumed distance	100	km
Leg 3: Transport of Pretreated Biomass	Shipping - Product Tanker	
Default distance	16 300	km From Vancouver to London
Please include a proportion change from the default	0,00%	greater than default
Distance	16 300	km
Leg 4: Transport of Pretreated Biomass	Rail	
Distance	100	km



Last scenario ran was: Scenario 9 : Electricity from pellets produced from wood killed by Mountain beetle in British Colombia. cfl = decay in forest.

Scenario 19 – same as Scenario 1 but including the indirect impact that the USA may need to import wood from Brazil to make particleboard because their sawmill waste has been sold to the UK

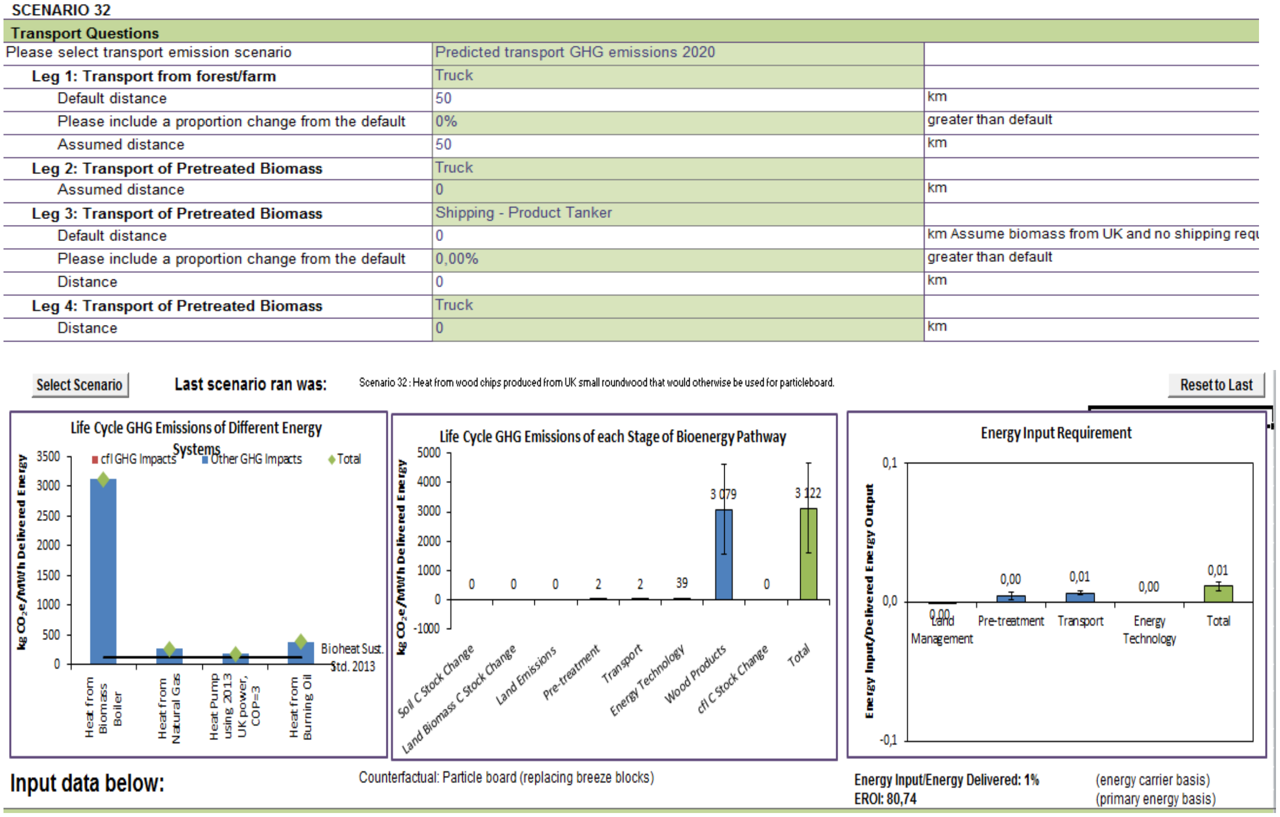


SCENARIO 19

Transport Questions		
Please select transport emission scenario	Predicted transport GHG emissions 2020	
Leg 1: Transport from forest/farm	Truck	
Default distance	50	km
Please include a proportion change from the default	100%	greater than default
Assumed distance	100	km
Leg 2: Transport of Pretreated Biomass	Truck	
Assumed distance	100	km
Leg 3: Transport of Pretreated Biomass	Shipping - Product Tanker	
Default distance	7 700	km From Belem, Brazil to London
Please include a proportion change from the default	61,04%	greater than default
Distance	12 400	km
Leg 4: Transport of Pretreated Biomass	Rail	
Distance	100	km

Last scenario ran was: Scenario 19 : Electricity from pellets produced from pulpwood in South USA, causing the indirect impact of Eucalyptus plantation replacing Brazilian rainforest. cfl = use pulpwood for traditional purposes.

Scenario 32 – wood chips from the UK that otherwise would be used for particle board in the UK



SCENARIO 32

Transport Questions		
Please select transport emission scenario	Predicted transport GHG emissions 2020	
Leg 1: Transport from forest/farm	Truck	
Default distance	50	km
Please include a proportion change from the default	0%	greater than default
Assumed distance	50	km
Leg 2: Transport of Pretreated Biomass	Truck	
Assumed distance	0	km
Leg 3: Transport of Pretreated Biomass	Shipping - Product Tanker	
Default distance	0	km Assume biomass from UK and no shipping requ
Please include a proportion change from the default	0,00%	greater than default
Distance	0	km
Leg 4: Transport of Pretreated Biomass	Truck	
Distance	0	km

Last scenario ran was: Scenario 32 : Heat from wood chips produced from UK small roundwood that would otherwise be used for particleboard.

Input data below:

Counterfactual: Particle board (replacing breeze blocks)

Energy Input/Energy Delivered: 1% (energy carrier basis)
EROI: 80,74 (primary energy basis)

The carbon emissions from transport factors used in the BEAC model involve assumptions on reductions by 2020 and come in at the low-end relative to other sources like DEFRA (discussed in the **General Context of Carbon Emissions from Transport** section above) and the reference values from the European Environmental Agency:

- Transport by truck – BEAC value 98 g CO2e/t_km versus 107 to 303 g CO2e/t_km DEFRA and 115 CO2e/t_km EEA
- Transport by ship – BEAC value 8 g CO2e/t_km versus 4 to 19 g CO2e/t_km DEFRA and 12 g CO2e EEA
- Transport by rail – BEAC value 15 g CO2e/t_km (versus 37 g CO2e/t_km DEFRA and 22 g CO2e EEA)

On a purely transport basis, the results clearly show the benefits of sourcing fuel as close to home as possible. – the local supply in scenario 32 is has transport emissions that are 15 times lower than the next best international case (scenario 1), and the British Columbia case (Scenario 9) which requires 16300 km of ocean transport comes out at the bottom of the transport list.

Implementation Decision

Transport was not the driver for the decision and the UK government chose Scenario 1 – with the risk that downstream impacts on demand in the USA move the process over to Scenario 19 which involves importing wood to the USA to cover the shortage triggered by the quantity of wood sold to the UK.

The key drivers for this decision were:

- The gains in carbon emissions from moving from coal to wood
    - Emissions from electricity production at this site from coal are evaluated at 854 kg/mwh
    - Emissions from using wood to produce electricity at this site are given as "less than 200 kg/mwh', based on a life cycle evaluation, but it is not clear how much of this value covers 'savings from alternative uses of wood'. Other sources list 'dedicated biomass' electricity production at 420 kg/mwh and even as high as 983 [xiii].
    - The authors of the BEAC model do emit a caution in their final report that < *other...scenarios could lead to high GHG intensities (e.g. greater than electricity from coal..) but would be found to have GHG intensities less than 200 kg/mwh (versus 845 for coal) under the Renewable Energy Directive LCA methodology*.> xiv. This implies an acknowledgement of the variations induced by changes in assumptions about alternative uses.
- The EU requirement to meet the 20% renewable energy target.
    - Wood qualifies as 'renewable' even when demand exceeds the local capacity to renew supplies. The UK is particularly sensitive to this issue as they experienced drastic deforestation issues in the 17th century from their dependence on wood as a fuel, that were only resolved by .... the introduction of coal! [xv]

The economic incentives to make the environmentally optimal choices are murky. We are faced with a mix of regulatory constraints, price subsidies, and the absence of a real price on carbon emissions. The power plant contract involves a subsidized price for electricity (£105 per mwh, versus wholesale market prices of £25 - £40 per mwh) and this ripples down through the process to act as a subsidy for wood pellet purchases that leads to an imbalance in the incentives between the UK and the USA. Pellet producers have an incentive to sell to the UK because the price offered makes this business quite profitable – so profitable that Scenario 1 can shift to Scenario 19 and lead to selling sawmill waste to the UK and importing wood from Brazil to make particle board, with no mechanism to cover the environmental impacts in Brazil. A group of US scientists protested to the UK government about the deforestation impacts in the US, but without any economic incentive to counter the UK subsidies change is unlikely.

Were there other alternatives?

There was an analysis done on a CCS (Carbon Capture and Storage) alternative but this project was not chosen. Technical estimates of the potential of combined Coal / CCS and IGCC[xvi] show that this process may reach the 200 kg $CO2_e$ / kwh level once it reaches the commercial phase. This might have provided a locally sourced option in the future, but even if the equivalent level of carbon emissions is reachable, this still wouldn't satisfy the '20% renewable' target. As discussed by David MacKay[xvii] in his book Sustainable Energy without the Hot Air, the geography of the UK does not lend itself to massive use of solar, wind or hydroelectricity as energy sources. The choice of imported wood was clearly rational based on existing incentives and regulations.

Case B – The California Low Carbon Fuel System (LCFS)

Project Description

The California Low Carbon Fuel System was initiated in 2009 and implementation started on January 1, 2011. The program was introduced to stimulate production and usage of low carbon fuels in California. It is administered by the California Air Resources Board, who describe the program as follows[xviii]:

> *The Low Carbon Fuel Standard is designed to encourage the use of cleaner low-carbon fuels in California, encourage the production of those fuels, and therefore, reduce greenhouse gas emissions. The LCFS standards are expressed in terms of the "carbon intensity" (CI) of gasoline and diesel fuel and their respective substitutes. The LCFS is performance-based and fuel-neutral, allowing the market to determine how the carbon intensity of California's transportation fuels will be reduced. This program is based on the principle that each fuel has "lifecycle" greenhouse gas emissions that include* CO_2, N_2O, *and other greenhouse gas contributors. This lifecycle assessment examines the greenhouse gas emissions associated with the production, transportation, and use of a given fuel. The lifecycle assessment includes direct emissions associated with producing, transporting, and using the fuels, as well as significant indirect effects on greenhouse gas emissions, such as changes in land use for some biofuels. Subjecting this lifecycle greenhouse gas rating to a declining standard for the transportation fuel pool in California would result in a decrease in the total lifecycle greenhouse gas emissions from fuels used in California.*

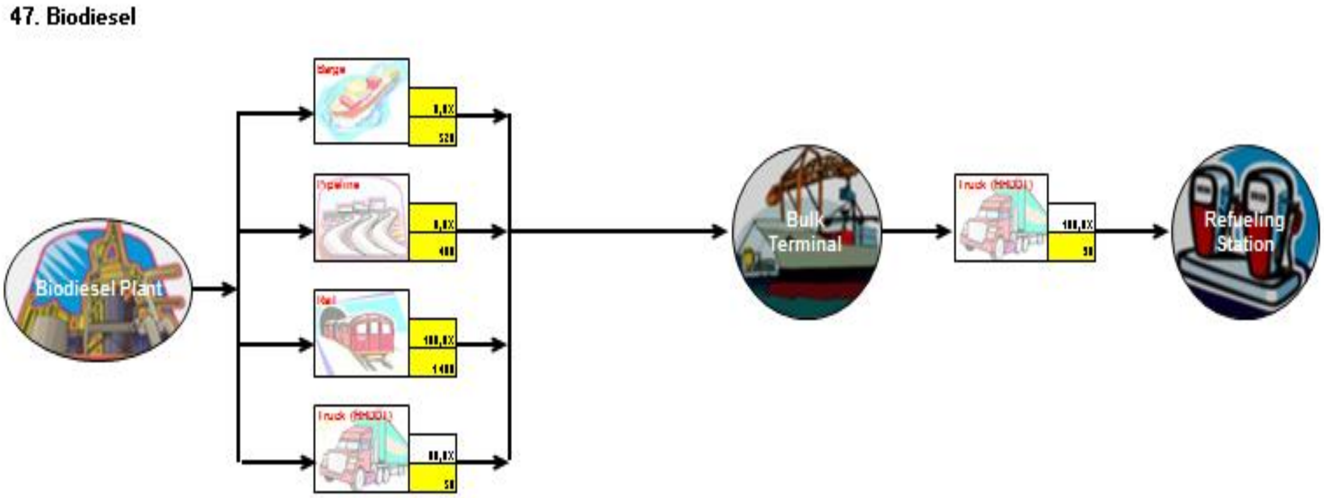
Producers must apply for a CI (Carbon Intensity) Pathway that covers the life cycle carbon emissions of a specific production and distribution process. The CI Pathway value is then used to define the amount of LCFS 'credits' each sale produces, based on the difference between the fossil fuel CI value and the CI Pathway value of the product – for example for Canola Biodiesel the CI default value is 32 and the related fossil diesel value is 98 so there is an LCFS credit of 66 for each gallon sold. The goal of each producer is thus to have the lowest CI Pathway possible. This is where transport comes in – the CI Pathway calculation includes sophisticated logic to take into account the carbon emissions from all the different types of transport included in process, from the sourcing of source feedstocks like corn or canola to the delivery of the fuel to the pump. These calculations are all included in a publically available Excel spreadsheet called the CA GREET model [vii] which is the California version of the GREET model developed by Argonne national laboratory. As in the BEAC model discussed above, the transport is analysed in different steps or 'legs', and analysed in terms of the transport method (road, rail, ship) and the distance travelled. There are also adjustments made depending on the type of fuel used for the transport.

The transport calculation methodologies in the BEAC model and the CA GREET model are similar (see examples below), but there is a critical difference between the two: the LCFS process is not 'just a study' – it is an ongoing and dynamic process that has led to the creation of a 'market' for LCFS credits that is a form of carbon market (it is actually considered to be an offshoot of the California carbon market). At the start of LCFS, the full details of the Excel model calculations to define the CI Pathways were published on their website. But, the producers objected to this public sharing of competitively sensitive data and the option was introduced for a producer to choose to not transmit certain details and to block public access to the Excel files. A summary of key elements is available in the Application files[xix], but most of the Excel files are now blocked. We are working on reproducing the full details of the transport calculations and hope to have this data available for presentation at the Tulsa Conference but we were not able to include input/output ratios here for case B like we did for case A because the requisite data is blocked.

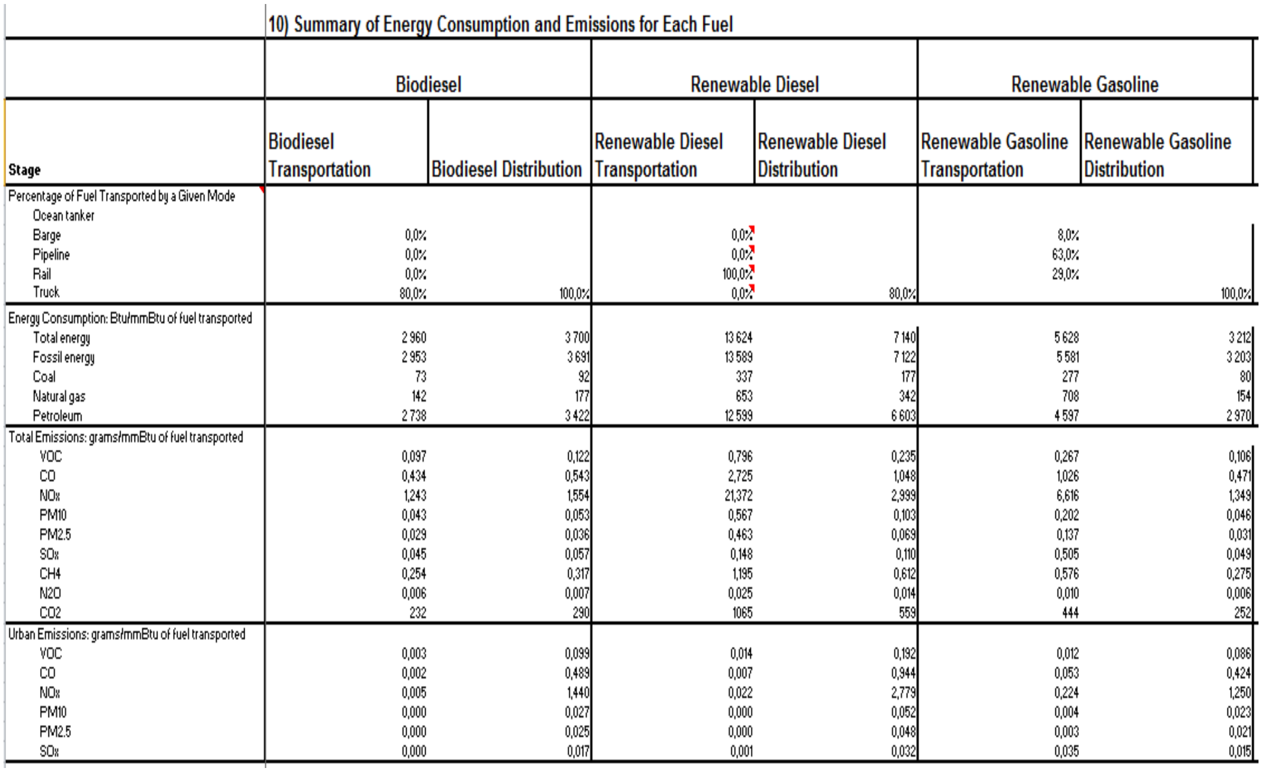
Transport Calculations in CA GREET

The diagrams below show the types of calculations done in CA GREET for a case involving corn oil biodiesel. This case is not analysed in detail but is shown here the Excel file is available and illustrates the way the model functions.

The model breaks the transport down into different steps and analyses each step by transport method. The same process is used to analyse the transport of the feedstock to the biodiesel plant (this step is prior to the diagram below).



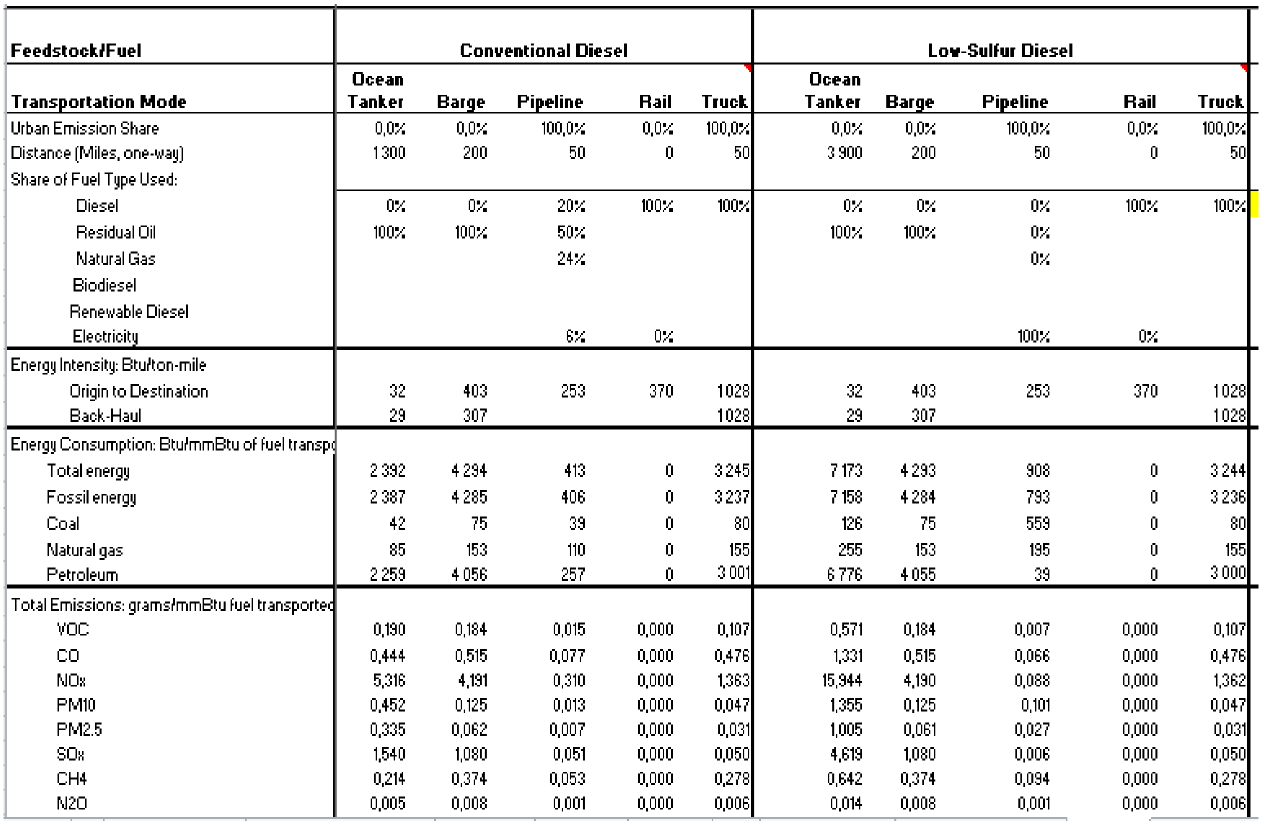
Each fuel is analysed separately, in accordance with its energy density and other specific characteristics.



10) Summary of Energy Consumption and Emissions for Each Fuel

	Biodiesel		Renewable Diesel		Renewable Gasoline	
Stage	Biodiesel Transportation	Biodiesel Distribution	Renewable Diesel Transportation	Renewable Diesel Distribution	Renewable Gasoline Transportation	Renewable Gasoline Distribution
Percentage of Fuel Transported by a Given Mode						
Ocean tanker						
Barge	0,0%		0,0%		8,0%	
Pipeline	0,0%		0,0%		63,0%	
Rail	0,0%		100,0%		29,0%	
Truck	80,0%	100,0%	0,0%	80,0%		100,0%
Energy Consumption: Btu/mmBtu of fuel transported						
Total energy	2 960	3 700	13 624	7 140	5 628	3 212
Fossil energy	2 953	3 691	13 589	7 122	5 581	3 203
Coal	73	92	337	177	277	80
Natural gas	142	177	653	342	708	154
Petroleum	2 738	3 422	12 599	6 603	4 597	2 970
Total Emissions: grams/mmBtu of fuel transported						
VOC	0,097	0,122	0,796	0,235	0,267	0,106
CO	0,434	0,543	2,725	1,048	1,026	0,471
NOx	1,243	1,554	21,372	2,999	6,616	1,349
PM10	0,043	0,053	0,567	0,103	0,202	0,046
PM2.5	0,029	0,036	0,463	0,069	0,137	0,031
SOx	0,045	0,057	0,148	0,110	0,505	0,049
CH4	0,254	0,317	1,195	0,612	0,576	0,275
N2O	0,006	0,007	0,025	0,014	0,010	0,006
CO2	232	290	1065	559	444	252
Urban Emissions: grams/mmBtu of fuel transported						
VOC	0,003	0,099	0,014	0,192	0,012	0,086
CO	0,002	0,489	0,007	0,944	0,053	0,424
NOx	0,005	1,440	0,022	2,779	0,224	1,250
PM10	0,000	0,027	0,000	0,052	0,004	0,023
PM2.5	0,000	0,025	0,000	0,048	0,003	0,021
SOx	0,000	0,017	0,001	0,032	0,035	0,015

The values below show the energy intensity and the equivalent carbon emissions by fuel type. The values for carbon emissions are expressed in terms of grams of equivalent carbon emissions per unit of energy transported for the averaged transport types rather than by distance travelled under each transport type so we were not able to compare the values between the BEAC and CA GREET models.



Feedstock/Fuel	**Conventional Diesel**					**Low-Sulfur Diesel**				
Transportation Mode	**Ocean Tanker**	**Barge**	**Pipeline**	**Rail**	**Truck**	**Ocean Tanker**	**Barge**	**Pipeline**	**Rail**	**Truck**
Urban Emission Share	0,0%	0,0%	100,0%	0,0%	100,0%	0,0%	0,0%	100,0%	0,0%	100,0%
Distance (Miles, one-way)	1 300	200	50	0	50	3 900	200	50	0	50
Share of Fuel Type Used:										
Diesel	0%	0%	20%	100%	100%	0%	0%	0%	100%	100%
Residual Oil	100%	100%	50%			100%	100%	0%		
Natural Gas			24%					0%		
Biodiesel										
Renewable Diesel										
Electricity			6%	0%				100%	0%	
Energy Intensity: Btu/ton-mile										
Origin to Destination	32	403	253	370	1028	32	403	253	370	1028
Back-Haul	29	307			1028	29	307			1028
Energy Consumption: Btu/mmBtu of fuel transp										
Total energy	2 392	4 294	413	0	3 245	7 173	4 293	908	0	3 244
Fossil energy	2 387	4 285	406	0	3 237	7 158	4 284	793	0	3 236
Coal	42	75	39	0	80	126	75	559	0	80
Natural gas	85	153	110	0	155	255	153	195	0	155
Petroleum	2 259	4 056	257	0	3 001	6 776	4 055	39	0	3 000
Total Emissions: grams/mmBtu fuel transporte										
VOC	0,190	0,184	0,015	0,000	0,107	0,571	0,184	0,007	0,000	0,107
CO	0,444	0,515	0,077	0,000	0,476	1,331	0,515	0,066	0,000	0,476
NOx	5,316	4,191	0,310	0,000	1,363	15,944	4,190	0,088	0,000	1,362
PM10	0,452	0,125	0,013	0,000	0,047	1,355	0,125	0,101	0,000	0,047
PM2.5	0,335	0,062	0,007	0,000	0,031	1,005	0,061	0,027	0,000	0,031
SOx	1,540	1,080	0,051	0,000	0,050	4,619	1,080	0,006	0,000	0,050
CH4	0,214	0,374	0,053	0,000	0,278	0,642	0,374	0,094	0,000	0,278
N2O	0,005	0,008	0,001	0,000	0,006	0,014	0,008	0,001	0,000	0,006

Pathway Results for Sample Analysis

In this study we focus only on fuels made from recycled used cooking oil (UCO) and animal fat (Tallow). These cases include both renewable diesel and biodiesel[iv] as these fuels have identical transport characteristics and provide a number of cases involving long transport distances. The cases we used are described below. The numbers shown correspond to the CI Pathway application numbers from the application site[xix].

- Default Dec12 – a Default case for Tallow biodiesel from within California
  The LCFS program manages a number of default cases to assist producer's in understanding the model – applicants use the default case as a starting point and modify parameters to reflect their situation

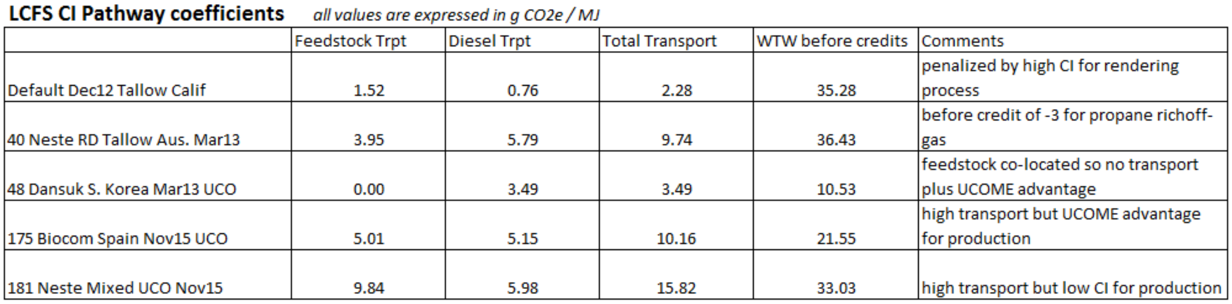
- 40 – Renewable Diesel produced in Singapore from Australian Tallow
  This producer was one of the early participants and has been very successful – they are the primary supplier of Renewable Diesel in California and the only one so far to have a commercial brand (NEXBTL)

- 48 – Biodiesel produced from UCO in South Korea

- 175 – Biodiesel produced from UCO in Spain

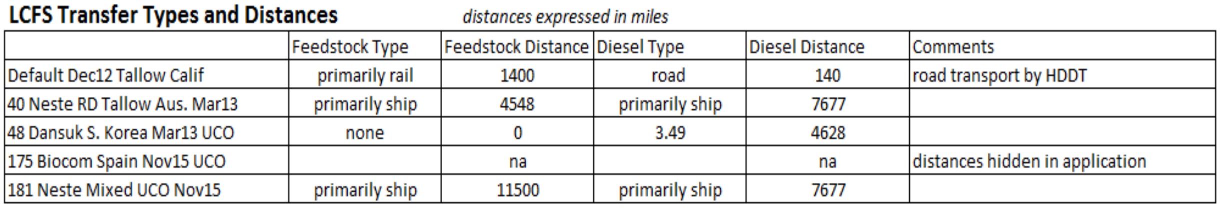
- 181 – Renewable Diesel from UCO that is sourced anywhere in the world
  This is a 'catch-all' case from the producer in 40 above that uses a maximum transport distance

The tables below show the CI (carbon intensity) Pathway coefficient values for these fuels for use in California under the LCFS system. These values are expressed in grams of equivalent carbon emissions per million joules, for suppliers from around the world. The transport coefficients take into account the distance travelled, the type of transport and certain local specificities of each transport type. The table also shows the full 'well to wheel' (WTW) coefficient values, shown prior to the application of specific credits, but including indirect land-use impacts.



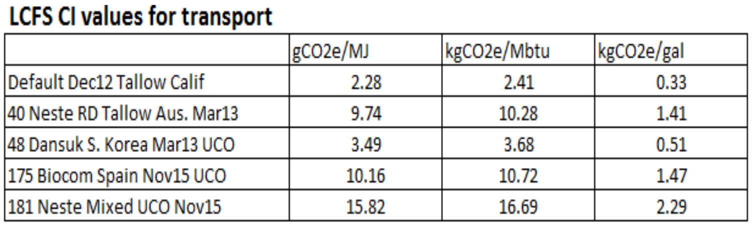
LCFS CI Pathway coefficients *all values are expressed in g CO2e / MJ*

	Feedstock Trpt	Diesel Trpt	Total Transport	WTW before credits	Comments
Default Dec12 Tallow Calif	1.52	0.76	2.28	35.28	penalized by high CI for rendering process
40 Neste RD Tallow Aus. Mar13	3.95	5.79	9.74	36.43	before credit of -3 for propane richoff-gas
48 Dansuk S. Korea Mar13 UCO	0.00	3.49	3.49	10.53	feedstock co-located so no transport plus UCOME advantage
175 Biocom Spain Nov15 UCO	5.01	5.15	10.16	21.55	high transport but UCOME advantage for production
181 Neste Mixed UCO Nov15	9.84	5.98	15.82	33.03	high transport but low CI for production



LCFS Transfer Types and Distances *distances expressed in miles*

	Feedstock Type	Feedstock Distance	Diesel Type	Diesel Distance	Comments
Default Dec12 Tallow Calif	primarily rail	1400	road	140	road transport by HDDT
40 Neste RD Tallow Aus. Mar13	primarily ship	4548	primarily ship	7677	
48 Dansuk S. Korea Mar13 UCO	none	0	3.49	4628	
175 Biocom Spain Nov15 UCO		na		na	distances hidden in application
181 Neste Mixed UCO Nov15	primarily ship	11500	primarily ship	7677	



LCFS CI values for transport

	gCO2e/MJ	kgCO2e/Mbtu	kgCO2e/gal
Default Dec12 Tallow Calif	2.28	2.41	0.33
40 Neste RD Tallow Aus. Mar13	9.74	10.28	1.41
48 Dansuk S. Korea Mar13 UCO	3.49	3.68	0.51
175 Biocom Spain Nov15 UCO	10.16	10.72	1.47
181 Neste Mixed UCO Nov15	15.82	16.69	2.29

The sample results are listed in order by pathway number, which also represents a progression from oldest to more recent.

- The Default case for Tallow in California is unsurprisingly the lowest in terms of transport, but there has been almost no activity under this case as it is based on an inefficient fat rendering process.
- Pathway 48 (Korea) benefits from ship transport in direct line and also from tight logistics management (they source their feedstock from on-site).
- Next in line is pathway 40 involving Australian tallow processed in Singapore – they are higher than Korea in transport and also in full WTW but this has not stopped them from becoming one the major supplier of renewable diesel in California.
- Pathway 175 (Spain) has higher transport but a lower overall WTW as they benefit from the advantages granted to UCOME (used cooking oil treated by methyl esterification).
- Pathway 181 is an intriguing example of the zeal for economies of scale overriding the transport impact – this is a 'catch-all' CI Pathway from the producer already operating at a high level in LCFS through case 40. This new case qualifies the use of used cooking oil sourced from anywhere in the world

Details for Specific Pathways

The information below shows more details of the transport calculations for certain pathways. The information shown is based on what the producer chose to share on internet, so varies between cases, but is included to enhance the visibility of the transport calculations.

The Default case is defined in more detail than the others, but shows high emissions for the rendering process:

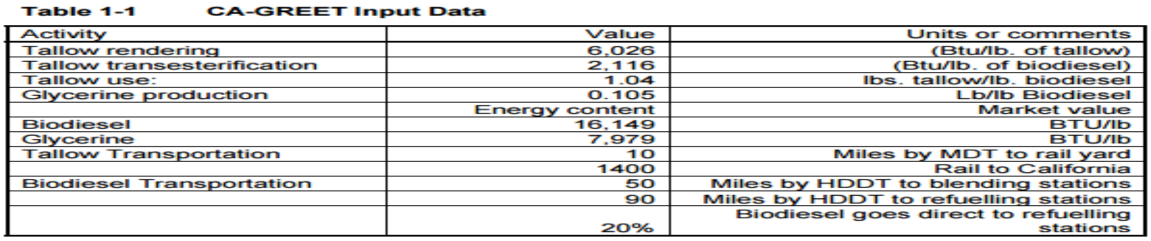


Table 1-1 CA-GREET Input Data

Activity	Value	Units or comments
Tallow rendering	6,026	(Btu/lb. of tallow)
Tallow transesterification	2,116	(Btu/lb. of biodiesel)
Tallow use:	1.04	lbs. tallow/lb. biodiesel
Glycerine production	0.105	Lb/lb Biodiesel
	Energy content	Market value
Biodiesel	16,149	BTU/lb
Glycerine	7,979	BTU/lb
Tallow Transportation	10	Miles by MDT to rail yard
	1400	Rail to California
Biodiesel Transportation	50	Miles by HDDT to blending stations
	90	Miles by HDDT to refuelling stations
	20%	Biodiesel goes direct to refuelling stations

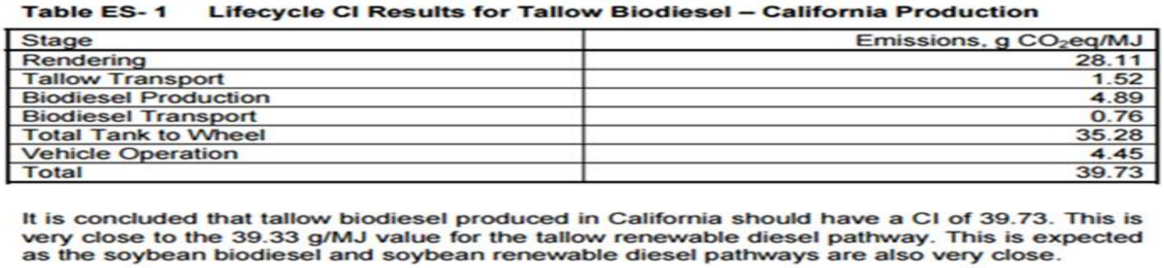


Table ES- 1 Lifecycle CI Results for Tallow Biodiesel – California Production

Stage	Emissions, g CO_2eq/MJ
Rendering	28.11
Tallow Transport	1.52
Biodiesel Production	4.89
Biodiesel Transport	0.76
Total Tank to Wheel	35.28
Vehicle Operation	4.45
Total	39.73

It is concluded that tallow biodiesel produced in California should have a CI of 39.73. This is very close to the 39.33 g/MJ value for the tallow renewable diesel pathway. This is expected as the soybean biodiesel and soybean renewable diesel pathways are also very close.

The South Korea case (48) includes an interesting table comparing the same process done in the Midwest USA and in South Korea[xx]: The striking element here is that there is almost no difference between the two cases – transport by rail from the US Midwest is very close to transport by tanker from Korea to California.

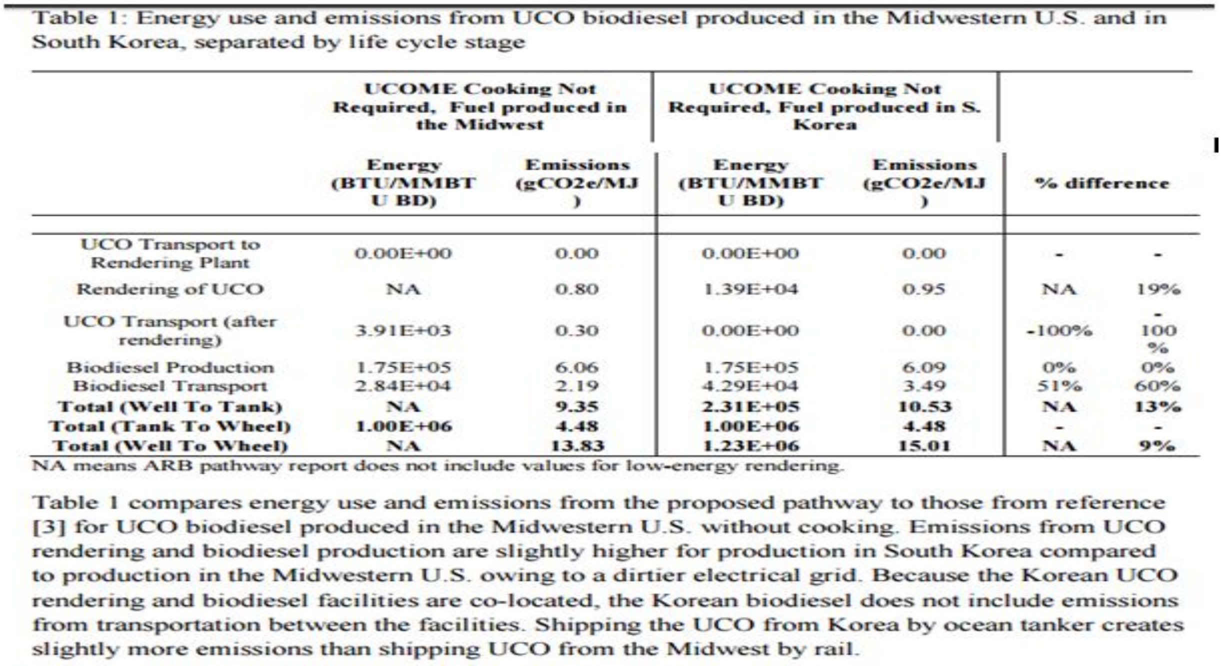


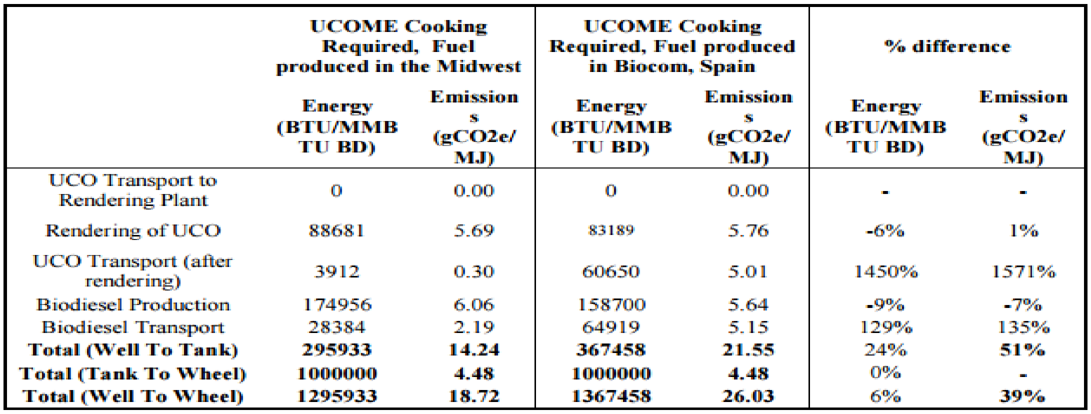
Table 1: Energy use and emissions from UCO biodiesel produced in the Midwestern U.S. and in South Korea, separated by life cycle stage

	UCOME Cooking Not Required, Fuel produced in the Midwest		UCOME Cooking Not Required, Fuel produced in S. Korea			
	Energy (BTU/MMBTU BD)	**Emissions (gCO2e/MJ)**	**Energy (BTU/MMBTU BD)**	**Emissions (gCO2e/MJ)**	**% difference**	
UCO Transport to Rendering Plant	0.00E+00	0.00	0.00E+00	0.00	-	-
Rendering of UCO	NA	0.80	1.39E+04	0.95	NA	19%
UCO Transport (after rendering)	3.91E+03	0.30	0.00E+00	0.00	-100%	-100%
Biodiesel Production	1.75E+05	6.06	1.75E+05	6.09	0%	0%
Biodiesel Transport	2.84E+04	2.19	4.29E+04	3.49	51%	60%
Total (Well To Tank)	**NA**	**9.35**	**2.31E+05**	**10.53**	**NA**	**13%**
Total (Tank To Wheel)	**1.00E+06**	**4.48**	**1.00E+06**	**4.48**	**-**	**-**
Total (Well To Wheel)	**NA**	**13.83**	**1.23E+06**	**15.01**	**NA**	**9%**

NA means ARB pathway report does not include values for low-energy rendering.

Table 1 compares energy use and emissions from the proposed pathway to those from reference [3] for UCO biodiesel produced in the Midwestern U.S. without cooking. Emissions from UCO rendering and biodiesel production are slightly higher for production in South Korea compared to production in the Midwestern U.S. owing to a dirtier electrical grid. Because the Korean UCO rendering and biodiesel facilities are co-located, the Korean biodiesel does not include emissions from transportation between the facilities. Shipping the UCO from Korea by ocean tanker creates slightly more emissions than shipping UCO from the Midwest by rail.

We find the same type of comparative table between the Midwest and Europe for the Spain case (175), but the transport differences comes out more strongly here:



	UCOME Cooking Required, Fuel produced in the Midwest		UCOME Cooking Required, Fuel produced in Biocom, Spain		% difference	
	Energy (BTU/MMBTU BD)	Emissions (gCO2e/MJ)	Energy (BTU/MMBTU BD)	Emissions (gCO2e/MJ)	Energy (BTU/MMBTU BD)	Emissions (gCO2e/MJ)
UCO Transport to Rendering Plant	0	0.00	0	0.00	-	-
Rendering of UCO	88681	5.69	83189	5.76	-6%	1%
UCO Transport (after rendering)	3912	0.30	60650	5.01	1450%	1571%
Biodiesel Production	174956	6.06	158700	5.64	-9%	-7%
Biodiesel Transport	28384	2.19	64919	5.15	129%	135%
Total (Well To Tank)	**295933**	**14.24**	**367458**	**21.55**	24%	**51%**
Total (Tank To Wheel)	**1000000**	**4.48**	**1000000**	**4.48**	0%	-
Total (Well To Wheel)	**1295933**	**18.72**	**1367458**	**26.03**	6%	**39%**

Implementation Decisions

This case is critically different from the UK wood case because in the LCFS program the Pathway values are not used to 'choose' between projects, but rather to assign values for LCFS credits. All of the producers shown above were awarded a CI Pathway and are eligible to sell through the program. The amount of LCFS credits they receive is calculated as the difference between the CI coefficient of 98 for fossil diesel and the pathway value of each project – for example 98 – 21.55 = 76.45 for the Spain 175 case. Once they have a CI Pathway value it is up to each producer to decide how much he sells in California.

LCFS credits are tradable and the California Air Resources Board operates an LCFS market on an 'over-the-counter' basis. The trade price is quoted in US dollars per tonne of avoided carbon emissions and thus is comparable to a 'carbon price'. The value of LCFS credits traded[xxi] is shown below:

- H1 2016 $115
- 2015 $62
- 2014 $31
- 2013 $55

So what does this imply for energy self-sufficiency? As for case A, there is an advantage for reducing transport distances and this advantage is reflected in the carbon emissions coefficients, but the transport impacts are not the primary source of variation. The primary driver that comes through in the overall LCFS program coefficients is the production process used and how the CI coefficients for this process are analysed, in particular with respect to other specific environmental programs, like indirect land use coefficients which are defined explicitly in LCFS but used only indirectly in BEAC. This is evidenced by the high overall CI coefficient of the California Tallow Default case, despite the lower transport differences, which is driven by the coefficient assigned to the production process for tallow rendering. There is a clear advantage for used cooking oil over used animal fat, which is related to the process of rendering. Vegetable oil processed by methyl esterification (UCOME) systematically comes out lower than animal fat. (This appears to echo the 'double counting'[xxii] of environmental credits for UCOME in Europe and the advantage given to UCOME over tallow.) There are also definite advantages under the LCFS program from improving fuel efficiency use within the production process – there are a number of special credits for using different types of secondary fuels like recovered gas and clean electricity some producers are actively exploiting.

There has been discussion of extending the LCFS system to western North America (California, Oregon, Washington and British Columbia). This would create a larger subgroup to emphasize the self-sufficiency impacts. But, this may also just amplify the flows of biofuels made from waste products in Asia and Europe into the USA and Canada.

The LCFS market does provide clear incentives to take actions that reduce carbon emissions. But, because the LCFS credits only have value if 'earned' in California, it creates alot of transport of low carbon fuels from around the world into California because they are 'worth more' in California, when the overall environmental impact would be greater if these low carbon fuels were consumed closer to home. For example, the key renewable diesel producer in Asia ships 75% - 95% of their production (over 200 million gallons in 2013 and still growing) to California while their near neighbours import oil (often from the Middle East). This is in effect a powerful demonstration of the argument that if we really want to do something about carbon emissions we need a price on carbon that applies to everybody on everything – otherwise we get carbon laundering phenomenon from transporting low carbon fuels all over the world to get them to the places where low carbon has a value. (This is the same phenomenon shown in the UK wood pellets case with long transport flows to take advantage of selling low carbon products to those who place a value on low carbon, but in the UK case the impact comes from a subsidy rather than a carbon market.)

Alternative Approaches

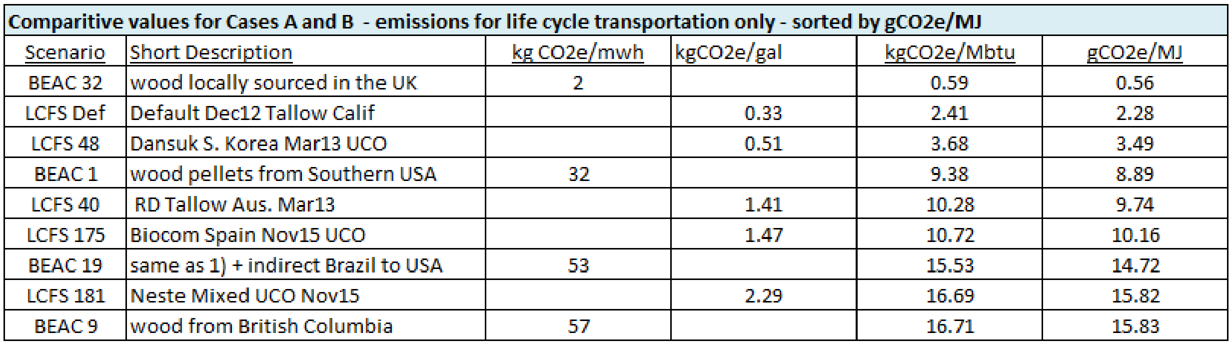
Is reducing fuel transport and moving to shorter supply chains a viable option? The answer is a definite yes in the LCFS case.

Everything that is being done with converting fats to biofuels in Asia and Europe could be done in the USA. It would however require setting up factories to do so which is not a simple task in California where there is a culture of environmental opposition (fat rendering plants are neither attractive nor sweet-smelling). It also would require adapting the production processes to make them environmentally efficient (improving electricity sourcing, using recovered gas), as evidenced by the high production process values shown in the Default Tallow case versus the low production process values in the Singapore Tallow pathway (40). Incidentally, it is interesting to note that there is clear evidence that the LCFS program has stimulated innovation in biofuels – many new processes have been set-up and others have been fine-tuned, and that in the waste re-use processes the innovation is coming from Asian producers.

There are also numerous other options for making biofuels – there have been a number of legal challenges of the LCFS program from Midwest USA producers who contend that their corn, canola or soybeans are getting short shrift in the program, often because of high transport coefficients for transport by rail and indirect land use coefficients that represent high expectations of environmental care in the USA that do not necessarily apply to other jurisdictions (the coefficients are defined centrally but analysed based on data supplied by the applying producer[xxiii]). This debate is ongoing and the proposal to modify the EPA Biodiesel Blenders tax credit to a Biodiesel Producers tax credit is another attempt to push the process towards greater support for production within the country.

Comparative Results of Case A versus case B

These two projects look very different – it is hard to imagine a direct link between shipping wood pellets from the US to the UK to replace coal and shipping low carbon fuel from Asia to California, but if we look at the actual impact of the transport on the carbon intensity of the solutions based on a common measure of energy (grams of equivalent carbon per million joules) the different scenarios sort into well-aligned groups with the locally sourced options at the top of the list, followed by the direct line transport by ship, followed by the more complex cases with multiple legs and the very long haul routes.



Comparitive values for Cases A and B - emissions for life cycle transportation only - sorted by gCO2e/MJ

Scenario	Short Description	kg CO2e/mwh	kgCO2e/gal	kgCO2e/Mbtu	gCO2e/MJ
BEAC 32	wood locally sourced in the UK	2		0.59	0.56
LCFS Def	Default Dec12 Tallow Calif		0.33	2.41	2.28
LCFS 48	Dansuk S. Korea Mar13 UCO		0.51	3.68	3.49
BEAC 1	wood pellets from Southern USA	32		9.38	8.89
LCFS 40	RD Tallow Aus. Mar13		1.41	10.28	9.74
LCFS 175	Biocom Spain Nov15 UCO		1.47	10.72	10.16
BEAC 19	same as 1) + indirect Brazil to USA	53		15.53	14.72
LCFS 181	Neste Mixed UCO Nov15		2.29	16.69	15.82
BEAC 9	wood from British Columbia	57		16.71	15.83

In both of the cases and all scenarios, energy transportation increases the carbon intensity of the solution, but is never the primary driver behind the investment choice (the production process used is always the key determinant). The weight given to the negative impact of transportation varies between the different types of models used in different regulatory environments, but the general tendency is the same: the life cycle models pick up the impacts but don't lead to clear decisions in favor of national self-sufficiency or shorter supply chains because these impacts are always dwarfed by other factors.

- In the UK case, the incentive for the implementation of the project was the need to meet a regulatory % of renewable energy. The BEAC study is in fact fairly negative on the solution chosen, in part due to the transport of wood pellets but also due to the deforestation, but did not lead to a revision of the decision as there was no other viable alternative on the table at the time. The program has led to public opposition in the UK, primarily over the taxpayer burden of the subsidies but also around the deforestation impacts in the USA and Brazil.

- The California LCFS system explicitly creates incentives and valuation tools related to life cycle transport impacts. These impacts are combined with indirect land use aspects and promotion of new types of energy. Conflicts have arisen over the criteria relative to the coefficients assigned to different pathways, in particular relative to the lack of rules to promote a preference for national production (the system is currently drawing in alot of imports, with imports dominant in renewable diesel). In this case there are lots of alternatives, but the mechanisms in place allow everyone to compete in the market on an even footing (albeit with a high administrative burden) and many foreign producers show a keen interest for this market (44 of the 233 CI Pathway applications in LCFS are from outside the US and Canada, with a clear dominance of Asian producers and Brazil and low participation so far from Europe).

Conclusions and Follow-up Projects

There are environmental benefits from reducing energy transport but these benefits are overshadowed by production technology choices. The use of life cycle carbon emissions calculators in project analysis and supplier qualification provides data on these impacts, and decisions made using these tools respond fairly well to standard criteria of economic efficiency. However, the overall economic choice process is distorted by the selective application of subsidies and carbon pricing in certain jurisdictions and leads to significant 'carbon laundering' phenomena and other regional distortions like deforestation. In addition, these environmental programs consume taxpayer money in the initiating countries and regions and generate public demand for tools to actively promote various forms of national preference.

The challenges that led to the creation of the tools analysed here remain in force and we will continue to face difficult choices around coal, wood, and biofuels in North America, Europe and Asia in the coming decade. The tools analysed here enable us to understand the transport impacts of our choices. These tools will continue to assist in future decisions but will not by themselves trigger a change in direction towards the shorter fuel supply chains implied by energy self-sufficiency and the incumbent improvement in input/output ratios. This change can only come from a conscious choice to pursue this objective. These tools will then assist us in measuring our progress.

Follow-up projects include deeper analysis on the input /output ratios for different types of energy and the weight of transporting energy to point of use in the inputs. This will include digging deeper into the LCFS data to get beyond the various 'credits' used to create incentives for specific solutions to find the 'pure' input / output ratio. We are also looking at various input / output ratios specific to gas like the use of LNG to power the ships used to deliver LNG to point of use and the use of gas to run pumps on gas pipelines (according to an EPA study [viii] the carbon emissions from pipeline operation in the US are almost equivalent to the emissions from transport in agriculture). We also plan to dig more deeply into the reasoning behind the assignment of indirect land use coefficients to better understand the discrepancies between the values used in Europe versus North America.

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http://www.developpement-durable.gouv.fr/IMG/pdf/Carbon_pricing_Jean_Tirole_June_10_2016.pdf

Dr Anna L. Stephenson and Professor David J. C. MacKay, "North American Woody Biomass for Electricity Generation in the UK" (2014), published by HMG DECC. Also referred to as the BEAC Report and available online at
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/349024/BEAC_Report_290814.pdf

The 'Bioenergy Emissions and Contrafactual Model' (BEAC) of the UK Department of Energy and Climate Change: https://www.gov.uk/government/uploads/system/uploads/...data/.../beac_2015.xlsm

Professor David J. C. MacKay, 2009, Sustainable Energy without the Hot Air, Cambridge, UIT

The 'LCFS Pathway Certified Carbon Intensities' pages of the California Air Resources Board website: http://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm

To visualize the LCFS CI Pathway application details (summary report, some analysis, occasionally Excel details) http://www.arb.ca.gov/fuels/lcfs/2a2b/2a-2b-apps.htm

Descriptive information on the California LCFS system from the home page of the LCFS program http://www.arb.ca.gov/fuels/lcfs/lcfs.htm

The narrative pages, definitions and data tables available on the sites of the following biodiesel organizations:
http://www.californiabiodieselalliance.org/
http://biodiesel.org/
http://westerncanadabiodiesel.org/biodiesel/

The CA-GREET model version 1.8 and supplemental information from the California Air Resources Board site, http://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm

Special thanks to Michael Wang, manager of the Systems Assessment Group, Energy Systems Division at Argonne National Laboratory for his guidance on the details of the GREET transportation calculations (the Argonne GREET model is the basis for the CA-GREET model used in California).

Footnotes

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[i] In this study, life cycle equivalent carbon emissions (CO2e) are quantified as the primary measure of environmental impacts, while other issues like particulate emissions, deforestation and other environmental impacts are outside the model measures but mentioned in the text for major impacts.

[ii] The input to output ratio measures the ratio of the quantity of energy used to get the fuel to its point of use to the quantity of energy generated from the fuel.

[iii] The use of local wood is not an option due to local land use constraints and other environmental legislation.

[iv] Renewable diesel fuel is diesel fuel made by hydrogenating fatty oils (animal or vegetable), that can be used directly in most vehicles. Biodiesel fuel can also be made from fatty oils (animal or vegetable) but it is made through an esterification processes and must be mixed with fossil diesel at ratios from 5% to 30% to make it compatible with standard vehicles.

[v] http://www.developpement-durable.gouv.fr/IMG/pdf/Carbon_pricing_Jean_Tirole_June_10_2016.pdf

[vi] BEAC stands for the 'Biomass Emissions and Counterfactual model of the DECC (United Kingdom Department of Energy and Climate Change). This model was originally developed in 2011 and updated through 2015.

[vii] CA-GREET is the California version of the GREET model of Argonne National Laboratory. GREET stands for 'Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation'. This model was originally developed in 1996, sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), and is regularly updated and enhanced by the team at Argonne.

[viii] Fast Facts - US transport sector - GHG emissions from the US Environmental Agency website for US data https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100ONBL.pdf while the worldwide data is from World Energy Outlook 2015 (IEA, Paris) page 403.

[ix] Transport or mobility related use of energy covering OPEX (operating expenses) only, primarily gas used for pumps and ventilation.

[x] These values are from the DEFRA (UK Department of Environment, Food, and Rural Affairs) emissions factors found on http://shrinkthatfootprint.com/ . They are reasonably aligned with the EEA (European Environment Agency) values of 115 g CO2e/ t_km for road, 22 g CO2e/ t_km for rail and 12 g CO2e/ t_km for ocean ship from 2009. The values used in the BEAC model are lower, particularly for truck (98 g CO2e/ t_km) as BEAC makes assumptions on improvements in energy efficiency through 2020.

[xi] Coal trade estimate from Table 7.5 of World Energy Outlook 2015 (IEA) and the Oil trade value is from page 18 of the BP Statistical Review of World Energy 2016. The carbon emissions data is from DEFRA (see x). Estimation methodology by author.

[xii] For transport of oil by ship we looked at the distance from Dubai to: Singapore 3971km, Tokyo 7708 and Houston 10942 km and used a lower mid-point value of 6000; for coal transport by ship we used only half that as there are more suppliers within the intercontinental zones). The rail and road distances are much smaller as these methods are typically used only to get to and from the sea for long haul transport.

[xiii] Value for French electricity production published by RTE at http://www.rte-france.com/fr/eco2mix/eco2mix-co2

[xiv] See Conclusions from the BEAC report point 237 (reference available in bibliography)

[xv] See Smil 2016 Power Densities chapter 1, Boston, MIT Press

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[xvi] IGCC stands for Integrated Gasification Combined Cycle – see estimation as a 'Pre-Commercial' technology at https://en.wikipedia.org/wiki/Life-cycle_greenhouse-gas_emissions_of_energy_sources

[xvii] See bibliography for book specifics. David Mackay is both the author of this book and the author (or creator) of the BEAC model (together with Anna Stephenson). The recent news of his premature death fills me with sadness – he contributed greatly to our knowledge of energy options and sustainable development and will be sorely missed.

[xviii] From the ARB website at http://www.arb.ca.gov/fuels/lcfs/lcfs.htm

[xix] See http://www.arb.ca.gov/fuels/lcfs/2a2b/2a-2b-apps.htm

[xx] See detail at http://www.arb.ca.gov/fuels/lcfs/2a2b/apps/dsk-rpt-071513.pdf

[xxi] Market data available at http://www.arb.ca.gov/fuels/lcfs/credit/20160809_julcreditreport.pdf

[xxii] Europe has a 'double counting' program for used cooking oil (UCO) waste that provides twice the standard environmental credit but this doesn't apply to animal fat waste (Tallow), apparently as a result of lobbying by groups opposed to meat consumption.

[xxiii] The fragility of indirect land use coefficients (also known as ILUC values) is illustrated by the quandary of palm oil coefficients. In the LCFS process, palm oil is assigned such a high coefficient that it is essentially banned (because of the deforestation impact in Indonesia). But in the European Union, palm oil has a favorable ILUC value, on the grounds that it generates by- products useful in agriculture and facilitates co-processing.