ADDITION OF MATERIALS DATA TO THE DANISH TRANSPORTATION LCA MODEL

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EXECUTIVE SUMMARY

The Danish Energy Agency is developing an LCA model for transportation fuels. This model includes all modes of transportation, cars, trucks, buses, trains, planes, and ships. It also includes a significant number of conventional and alternative fuels pathways. The model does not currently include the energy use and the emissions associated with the manufacture of the vehicles and vessels. It is the goal of this work to expand the model to include these emissions.

The emissions associated with the materials in vehicles and the assembly of the vehicles have been successfully added to the Danish LCA model. The new page in the model (Materials) is the last page in the Excel Workbook. It is linked to the other sheets in the model where it draws some of the required data for the calculations but the results from this sheet have not be linked to the results on other sheets although that could be done.

The report and the additions to the model have been undertaken in English. The work that has been done for this project is briefly described below.

1. Developed a bill of materials for each of the modes of transport. Information on cars, trucks, buses, trains, ships, and planes has been obtained. To the degree possible European data for the bill of materials has been used. There can also be some variation with the five broad categories that we are looking at.

   The model provides some flexibility in these bills of materials. There are primarily 12 bills of materials, cars, hybrid cars, electric vehicles, fuel cell vehicles, trucks, buses, hybrid buses, airplane, fast ferry, 9000 TEU marine vessels, IC Train, and local trains. However, there are a total of 25 vehicle/fuel combinations currently in the model but the difference between some of them is just the fuel system and the materials difference is quite small. We have made minor modifications to the 12 primary bills of material for the other 13 pathways.

2. Added all of the required materials that have been identified in the bill of materials (approximately 30 materials). The total energy and the breakdown of the types of energy are required for each material. GREET and GHGenius basically have 4 energy types, power, coal, petroleum, and natural gas. This model has 12 energy types and has the capacity to add eight more. We have ensured that the materials page can potentially use all 20 types of energy that could be included in the model. We have added some flexibility to the model so that additional materials can be added in the future without making significant structural changes to the model.

3. Estimated and included information on the lifetime energy consumption of the transport mode so that the emissions can be reported on a GJ of fuel or per kilometre basis for comparison to the other stages of the lifecycle. This is currently in the model for some vehicles but not for all of the 25 vehicle/fuel combinations.

4. We have used the same sumproduct approach that is used in the rest of the model to calculate the emissions. The results presented in such a way that they can be easily transferred to other sheets in you model.

The results are presented on a per vehicle, per GJ, and a per kilometre basis as shown in the following examples where the emissions for the materials in the vehicles are shown.

Table ES- 1 Results for ICE Vehicles - Materials

	Std gasoline motor	Std diesel motor	Diesel motor DME	Natural Gas Motor
	g/Vehicle			
Energy (MJ)	56,193	58,010	60,414	61,253
CO_2	4,365,310	4,545,314	4,727,341	4,726,348
CH_4	586	591	621	631
N_2O	29	30	32	31
SOx	5,132	5,192	5,306	5,295
NOx	4,756	4,836	5,017	5,091
Particulate	73	76	80	79
Total GHG	4,388,593	4,569,079	4,752,274	4,751,414

Table ES- 2 Results for ICE Vehicles per Kilometre - Materials

	Std gasoline motor	Std diesel motor	Diesel motor DME	Natural Gas Motor
	g/km travelled			
CO_2	14.9	15.5	16.1	16.1
CH_4	0.0	0.0	0.0	0.0
N_2O	0.0	0.0	0.0	0.0
SOx	0.0	0.0	0.0	0.0
NOx	0.0	0.0	0.0	0.0
Particulate	0.0	0.0	0.0	0.0
Total GHG	15.0	15.6	16.2	16.2

Table ES- 3 Results for ICE Vehicles per GJ - Materials

	Std gasoline motor	Std diesel motor	Diesel motor DME	Natural Gas Motor
	g/GJ fuel consumed			
CO_2	7,041	9,932	9,773	6,935
CH_4	0.9	1.3	1.3	0.9
N_2O	0.0	0.1	0.1	0.0
SOx	8.3	11.3	11.0	7.8
NOx	7.7	10.6	10.4	7.5
Particulate	0.1	0.2	0.2	0.1
Total GHG	7,079	9,984	9,825	6,971

The new sheet does have some flexibility. Spaces for four additional materials have been added. All that is required is the data on the materials to be added and the bills of materials to be changed. No equations need to be changed. Similarly if new process fuels are added then the equations will handle the new information and all that will be required is to change the types of energy used in the manufacture of the materials or in the assembly process.

Hybrid and Electric Vehicles

The bill of materials for the vehicles with lithium ion batteries has been done differently than the rest of the pathways. In the other pathways the fraction of each material is fixed and changing the weight of the vehicle will change the total energy use and emissions linearly to the change in weight. The vehicle weight is extracted from the vehicle sheet for that particular vehicle and fuel.

For the vehicles with the lithium ion battery, the vehicle weight and the proportion of each material changes with tree user inputs. The user can select the size of the battery (in kWh), the energy density of the battery (kg/kWh), and the number of battery changes required over the vehicle lifetime. These inputs will select the battery weight, which is added to the rest of the vehicle weights to get the bill of materials. The fraction of each material is then calculated in the model.

This approach gives a first order approximation. In actual practice the battery weight also has an impact on all other vehicle components. More batteries require stronger support structures, bigger brakes, etc.

Process Fuel Emissions

The upstream emissions for the various process fuels have been taken from a number of different places in the model and in some cases the data is incomplete, for example there are not separate details on methane and nitrous oxide emissions for natural gas production. Ideally the emissions for all of the process fuels could be located in a single place in the model and be a complete accounting of the emissions. This will become more important if more process fuels are added.

The base load electricity information has been assumed to the electricity used for materials production and vehicle assembly. Consideration could be given to using a generic EU power production number for this power. It could be added to one of the spaces for the spare process fuels and then have the electricity consumption in the model transferred to that source of power.

Vehicle Data

The information on the light duty vehicles in terms of weight, fuel economy, etc. appears to be taken from the JEC report version 4, whereas a version 4a has been released with slightly different data in some cases. The cells on the Materials sheet have a light green background and have comments in them where some of the differences were found.

There were a few cases (ferries and airplanes) where data was missing from the detail sheets for the vehicles. The required information was added to the materials sheet; however this added data doesn't change with time. This information should be added to the appropriate sheets with the information for all four time periods. These cells also have a light green background in the Materials sheet.

There were other places where the data was on the detail sheet but as a note and not in the main data location. These cells are also shaded and commented.

Transparency

The model uses the Offset and Indirect functions in Excel throughout the model. While this allows the model to function perfectly well it doesn't allow for full transparency as the Formula Audit function doesn't function with the Offset and Indirect functions. There are alternative ways of accomplishing the same function without using Offset and Indirect. If the model is released for use by a broader public consideration should be given to maximizing the transparency of the model.

The MMULT function has been used on the Materials sheet. This is similar to the Sumproduct function except that it allows one series to be vertical and the other to be horizontal. However there can't be any blank cells in the two ranges as there can be with the Sumproduct function. Zeros must be entered in the MMULT function where blank cells are acceptable in the Sumproduct function.

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1. INTRODUCTION

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4. We have used the same sumproduct approach that is used in the rest of the model to calculate the emissions. The results presented in such a way that they can be easily transferred to other sheets in you model. The results are presented on a per vehicle, per GJ, and a per kilometre basis.

2. TYPES OF PROCESS ENERGY

The existing model includes twelve types of process energy. For each type of energy the emissions from the use of the energy are provided. These are shown in the following table. The model also has spaces for an additional eight types of process energy.

Table 2-1 Emissions from Energy Use

	CO_2	CH_4	N_2O	SO_2	NOx	Particulate matter
	g/GJ					
Electricity – peakload	72,282	37.87	1.25	62	116	4.00
Electricity – baseload	72,282	37.87	1.25	62	116	4.00
Heat	12,457	9.38	0.43	21	26	2.00
Steam	12,457	9.38	0.43	21	26	2.00
Oil	78,900	0.90	0.30	344	142	0.00
Coal	93,600	0.90	0.80	10	30	2.10
Natural gas	56,740	0.10	0.10	0	42	0.10
Slurry	-66,200	0.00	0.00	0	0	0.00
Waste	37,000	0.34	1.20	8	102	0.29
Hydrogen	0	0.00	0.00	0	0	0.00
Biomass	0	0.00	0.00	0	0	0.00
Methanol	107,700	0.00	0.00	0	0	0.00

The model can be run using either the average of the marginal source of power. We have used the average electric power emissions for the materials production. Vehicles are all being manufactured today with the existing power production and so it would not be appropriate to use the future marginal emissions for these activities.

The emissions associated with producing the fuels are also required for the lifecycle emissions of the materials production. These have been extracted from various places in the model and are summarized in the following table.

Table 2-2 Upstream Emissions for Fuel Production

	CO_2	CH_4	N_2O	SO_2	NOx	Particulate matter
	g/GJ					
Electricity – peakload	8,869			0.06	84.08	
Electricity – baseload	8,710	4.56	0.15	7.49	13.94	0.48
Heat						
Steam						
Oil	13,442	0.00	0.00	0.00	0.05	0.00
Coal	15,320	0.00	0.00	0.00	0.06	0.00
Natural gas	6,127	0.00	0.00	0.02	3.10	0.00

The upstream and fuel conversion emissions are combined to produce the lifecycle emissions as shown in the following table.

Table 2-3 Lifecycle Emissions for Fuels

	CO_2	CH_4	N_2O	SO_2	NOx	Particulate matter
	g/GJ					
Electricity – peakload	81,151	37.87	1.25	62.22	200	4.00
Electricity – baseload	80,992	42.43	1.40	69.65	130	4.48
Heat	12,457	9.38	0.43	21.42	26	2.00
Steam	12,457	9.38	0.43	21.42	26	2.00
Oil	92,342	0.90	0.30	344.00	142	0.00
Coal	108,920	0.90	0.80	10.00	30	2.10
Natural gas	62,867	0.10	0.10	0.32	45	0.10

The lifecycle emissions from the use of coal, oil, natural gas, and electricity will be used to calculate the emissions associated with the materials production and vehicle manufacture.

Electricity emissions are highly variable depending on how they are produced. Ecometrica (2011) reported on the grid power intensity for most countries in the world. A few countries of interest are shown in the following table.

Table 2-4 Power Production Carbon Intensity

Country/Region	Carbon Intensity, kg/GJ
Denmark	104
Germany	187
OECD Europe	125
United Kingdom	141
United States	152
Canada	50

The carbon intensity of power production in the model is a forecast for 2015, which may explain the difference between the model and the Ecometrica value. However, when the emission intensity of the materials in the model is compared to the published data from German auto manufacturers or from the values in GREET, the model values should be lower due to the lower carbon intensity of the power in the model.

3. MATERIALS

A number of materials that are found in transportation vehicles have been added to the model. For each of the materials the energy required to produce a kilogram of the material by the type of energy has been added to the model. The emissions for the material will be the sumproduct of the energy used and the lifecycle emissions for each type of energy.

The data considered for the energy used for each type of material has been sourced from GREET2_2014, GHGenius 4.03s, or from EcoInvent 3. A comparison of the data from the three sources is made and a rational for the final choice for the model is provided.

3.1 GHGENIUS

The GHGenius model has been developed for Natural Resources Canada over the past fourteen years. GHGenius is capable of analyzing the energy balance and emissions of many contaminants associated with the production and use of traditional and alternative transportation fuels.

GHGenius is capable of estimating life cycle emissions of the primary greenhouse gases and the criteria pollutants from combustion sources. The specific gases that are included in the model include:

- Carbon dioxide (CO_2),
- Methane (CH_4),
- Nitrous oxide (N_2O),
- Chlorofluorocarbons (CFC-12),
- Hydro fluorocarbons (HFC-134a),
- The CO_2-equivalent of all of the contaminants above.
- Carbon monoxide (CO),
- Nitrogen oxides (NOx),
- Non-methane organic compounds (NMOCs), weighted by their ozone forming potential,
- Sulphur dioxide (SO_2),
- Total particulate matter.

The model is capable of analyzing the emissions from conventional and alternative fuelled internal combustion engines or fuel cells for light duty vehicles, for class 3-7 medium-duty trucks, for class 8 heavy-duty trucks, for urban buses and for a combination of buses and trucks, and for light duty battery powered electric vehicles. There are over 200 vehicle and fuel combinations possible with the model. The model is also capable of analyzing the emissions from electricity production from a wide variety of fuel and processes.

It has the energy requirements and calculated emissions for the materials that are normally found in vehicles. It also includes estimates of the energy use and emissions associated with vehicle assembly and manufacturing.

The description of the data reviewed for the materials section in GHGenius was last updated in 2006 ((S&T)^2, 2006). The report identifies and compares a number of sources of data for materials that are used in transportation vehicles.

3.2 GREET2

The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model was developed by Argonne National Laboratory under the sponsorship of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. GREET allows researchers and analysts to evaluate various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis.

The first version of GREET was released in 1996. Since then, Argonne has continued to update and expand the model. The most recent GREET versions are:

- GREET 1 2014 for fuel-cycle analysis; and
- GREET 2 2014 for vehicle-cycle analysis.

Both versions of the model are available free over the Internet as spreadsheet models in Microsoft Excel.[1] A new self-contained platform for GREET was released in Beta version in December 2012. This new platform will eventually replace the Excel version. At this time both versions are being maintained and both versions use the same input data and produce the same results.

The model covers all stages of the fuel life cycle, from well-to-pump and pump-to-wheels, including:

- feedstock production, transportation, and storage;
- fuel production, transportation, distribution, and storage,
- vehicle operation, refuelling, fuel combustion/conversion, fuel evaporation, and tire/break wear.

In addition, GREET simulates vehicle-cycle energy use and emissions from material recovery to vehicle disposal (raw material recovery, material processing and fabrication, vehicle component production, vehicle assembly, and vehicle disposal and recycling).

There are a number of reports that describe the data that is in the GREET2 model. The first report was prepared in 2006 (Argonne National Laboratory, 2006).

3.3 ECOINVENT

EcoInvent - an association founded by ETHZ, EPFL, PSI, Empa and Agroscope - is a leading supplier of consistent and transparent life cycle inventory (LCI) data. It is widely used throughout the world and has a significant amount of European data in it.

Dr. Ir. Joost G. Vogtländer is part time Associate Professor at the Delft University of Technology, Design for Sustainability in the Netherlands. He has published data on the ecocosts of materials and products based on a number of different lifecycle inventories, including EcoInvent 3.0 (Ecocosts 2012). This information is compared to the data in GHGenius and GREET.

The data on energy use for the materials is the lifecycle energy use, whereas GREET and GHGenius have data on the secondary energy use, so the ecocost data should always be higher. All three models produce information on the lifecycle GHG emissions for the materials so these can be directly compared.

[1] http://greet.es.anl.gov/

3.4 RECYCLING

A provision in the model is made for changing the fraction of some of the materials produced from virgin sources versus from recycled sources. This choice is provided for six metals, steel, aluminum (cast and wrought), lead, nickel, and magnesium. The choice is made in rows 30 to 35 and in column C, the fraction from virgin materials. The fraction from recycled materials is calculated automatically. The default values are taking from GREET2, but they can be adjusted by the users. The default values are shown in the following table.

Table 3-1 Virgin vs. Recycled Materials

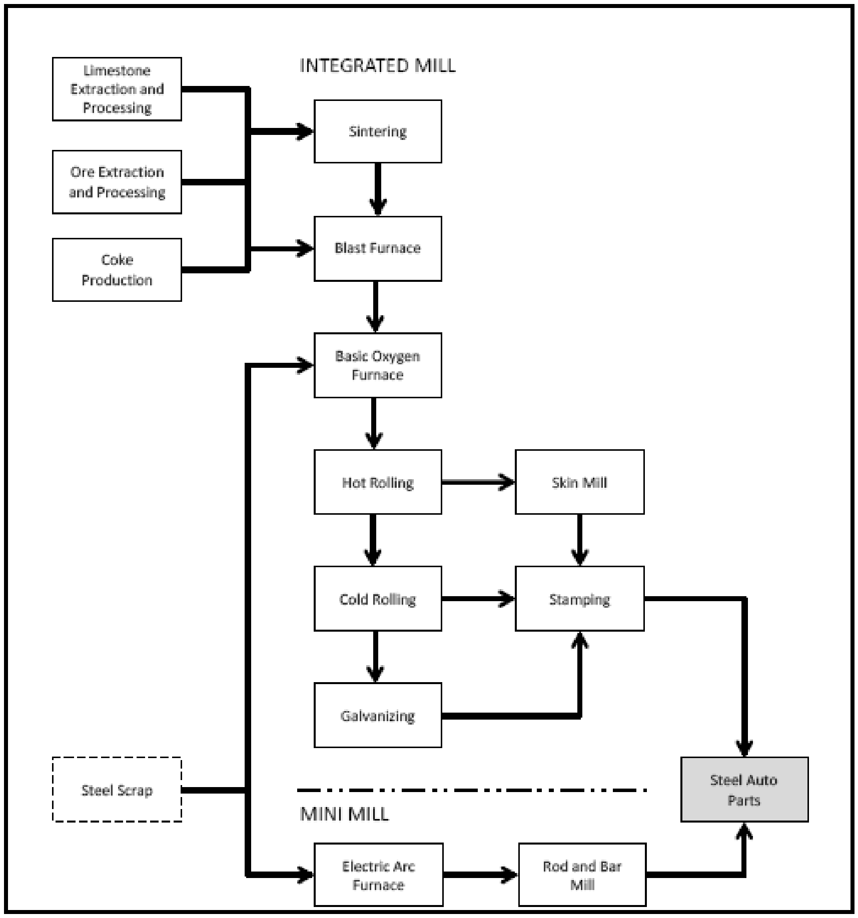
	Virgin Material Product	Recycled Material Product
Steel	0.74	0.26
Wrought Aluminum	0.89	0.11
Cast Aluminum	0.15	0.85
Lead	0.27	0.73
Nickel	0.56	0.44
Magnesium	0.67	0.33

GREET2 provides a reference for the value for steel (Keoleian et al. 2012) and aluminum (Roy F. Weston, 1998) but not for the other three metals. The magnesium is assumed to be 2/3 virgin materials.

3.5 STEEL

There can be a wide variety of types of steels used in the manufacture of vehicles. We have provided an average value for regular strength steel which can be either from virgin materials or from recycle materials and a high strength steel. The steel production process is shown in the following figure.

Figure 3-1 Steel Production Process



3.5.1 Virgin Steel

For virgin steel the energy use from the three models is shown in the following table. The GHGenius values and the values used in the model are secondary energy and the GREET and EcoInvent values are primary energy (includes the energy required to produce the energy). Primary values should be about 10% higher for fossil fuels and up to three times higher for electricity. GREET provides the secondary energy requirements for individual stages for materials production but when the stages are rolled together to provide the lifecycle energy use and emissions, only the primary energy use is reported. Thus the fraction of energy supplied by electricity is not available. The GREET information is thus not sufficient for use in this model and the fraction of energy supplied by electricity, coal, oil and natural gas must be estimated. The energy values used in the model are partly driven by the energy use data from the different sources and from GHG emission results of the different sources.

Table 3-2 Steel Energy Requirements

Energy	GREET2	GHGenius	EcoInvent	Used in Model
	Hot Rolled	Virgin plain carbon	Unalloyed steel	
	MJ/kg			
Electricity	0.0	6.7		6.7
Oil	-0.2	2.5		2.5
Coal	22.1	3.6		3.6
Natural gas	4.4	13.8		13.8
Total	27.9	26.6	21.4	26.6

3.5.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source. They will therefore differ from one region to another as the carbon intensity of the power changes and to a lesser extent the other energy sources. The GHGenius values are from the model set to Canada and they include some end of life credits. The chosen data for energy use is higher than the EcoInvent energy used but the GHG emissions are lower.

Table 3-3 Steel Emissions

	GREET2	GHGenius	EcoInvent	Model Results
	Hot Rolled	Virgin plain carbon	Unalloyed steel	
	g/kg			
CO_2	2,500			2,033
CH_4	4			0.3
N_2O	0			0.0
SO_2	11			1.4
NOx	3			2.0
Particulate	2			0.0
Total GHG	2,675	1,620	2,300	2,045

Norgate (2006) reported GHG emissions for steel of 2.3 kg CO_2eq/kg and a gross energy requirement of 23 MJ/kg, providing some confirmation of the values used here.

3.5.2 Recycled Steel

For recycled steel the energy use from the three models is shown in the following table. The GHGenius values and the values used in the model are secondary energy and the GREET values are primary energy (includes the energy required to produce the energy). Primary values should be about 10% higher for fossil fuels and three times higher for electricity. There was no recycled steel in the EcoInvent data based used.

Table 3-4 Recycled Steel Energy Requirements

Energy	GREET2	GHGenius	Used in Model
	Arc Furnace plus Rod and Bar Mill	Recycled plain carbon	
	MJ/kg		
Electricity	-	1.6	1.5
Oil	0.3	2.6	2.5
Coal	9.6	2.8	3.0
Natural gas	9.3	4.2	5.0
Total	21.8	11.2	12.0

3.5.2.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-5 Recycled Steel Emissions

	GREET2	GHGenius	Model Results
	Arc Furnace plus Rod and Bar Mill	Recycled plain carbon	
	g/kg		
CO_2	1,469		993
CH_4	3		0.1
N_2O	0		0.0
SO_2	4		1.0
NOx	2		0.9
Particulate	1		0.0
Total GHG	1,567	911	997

3.5.3 Average Steel

The average steel energy use and emissions are calculated from the user set fraction from virgin materials and the energy and emissions for virgin steel and for recycled steel.

3.5.4 High Strength Steel

As vehicle manufactures strive to improve fuel efficiency they are using more high strength steels in the vehicle. This allows the weight of some parts to be reduced while maintaining the required strength of the parts. There is no high strength steel in GREET2.

Table 3-6 High Strength Steel Energy Requirements

Energy	GHGenius	EcoInvent	Used in Model
	Virgin plain carbon	Low alloy hot rolled	
	MJ/kg		
Electricity	8.8		9.0
Oil	2.7		2.5
Coal	3.6		3.6
Natural gas	16.0		16.0
Total	31.1	25.6	31.1

3.5.4.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source. The energy inputs are again set higher than EcoInvent to get similar GHG emissions.

Table 3-7 High Strength Steel Emissions

	GHGenius	EcoInvent	Model Results
	Virgin plain carbon	Low alloy hot rolled	
	g/kg		
CO_2			2,358
CH_4			0.4
N_2O			0.0
SO_2			1.5
NOx			2.4
Particulate			0.0
Total GHG	1,937	2,300	2,373

3.6 STAINLESS STEEL

Stainless steel use has also been slowly increasing in vehicles, its corrosion properties allow less material to be used while maintaining component life. The energy requirements from the different sources are shown in the following table.

Table 3-8 Stainless Steel Energy Requirements

Energy	GREET2	GHGenius	EcoInvent	Used in Model
	Ex Machining	Stainless Steel	Chromium Steel 18/8	
	MJ/kg			
Electricity	-	19.8		20.0
Oil	0.4	4.9		5.0
Coal	14.0	3.6		4.0
Natural gas	12.3	30.2		30.0
Total	30.5	58.5	56.6	59.0

3.6.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-9 Stainless Steel Emissions

	GREET2	GHGenius	EcoInvent	Model Results
	Ex Machining	Stainless Steel	Chromium Steel 18/8	
	g/kg			
CO_2	2,071			4,403
CH_4	4			0.9
N_2O	0			0.0
SO_2	5			3.2
NOx	3			4.8
Particulate	2			0.1
Total GHG	2,208	3,423	4,700	4,435

Norgate (2006) reported GHG emissions for stainless steel of 6.8 kg CO_2eq/kg and a gross energy requirement of 75 MJ/kg, these are both higher than are found in the other sources.

3.7 CAST IRON

Cast iron is widely used in engine blocks, exhaust manifolds and some suspension pieces. It is also found in some of the other vehicles in the model such as the rail cars. The GREET numbers are a combination of cast and forged iron. The energy use and emissions are much higher for the forged iron.

Table 3-10 Cast Iron Energy Requirements

Energy	GREET2	GHGenius	EcoInvent	Used in Model
	85% Cast Iron, 15% Forged Iron	Cast Iron	Cast Iron	
	MJ/kg			
Electricity	-	1.3		1.3
Oil	1.9	2.9		2.0
Coal	25.4	24.6		22.0
Natural gas	7.3	5.1		5.0
Total	35.1	33.9	23.1	30.3

3.7.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source. The GREET emissions are for 100% recycled cast iron with 85% cast and 15% forged. The forging emissions are much higher than the cast emissions.

Table 3-11 Cast Iron Emissions

	GREET2	GHGenius	EcoInvent	Model Results
	85% Cast Iron, 15% Forged Iron	Cast Iron	Cast Iron	
	g/kg			
CO_2	825			3,001
CH_4	5			0.1
N_2O	0			0.0
SO_2	4			1.0
NOx	2			1.3
Particulate	1			0.1
Total GHG	977	3,063	2,100	3,009

3.8 ALUMINUM

There are four aluminum data sets in the model. There are cast and wrought aluminums and for each option there are virgin and recycled options. The average values used in the model are calculated from the user set ratio of virgin to recycled metals as described earlier.

Wrought alloys, which are initially cast as ingots or billets and subsequently hot and/or cold worked mechanically into the desired form i.e.

- rolling to produce sheet, foil or plate
- extrusion to produce profiles, tubes or rods
- forming to produce more complex shapes from rolled or extruded stock
- forging to produce complex shapes with superior mechanical properties

Cast alloys are directly cast into their final form by one of various methods such as sand-casting, die or pressure die casting. Casting is used for complex product shapes. These alloys contain high levels of silicon to improve their castability.

3.8.1 Virgin Wrought Aluminum

The energy used information from the three data sources is shown in the following table. GHGenius does not separate wrought and cast aluminum, just virgin and recycled.

Table 3-12 Virgin Wrought Aluminum Energy Requirements

Energy	GREET2	GHGenius	EcoInvent	Used in Model
	87% extruded, 13% cold rolled	Virgin aluminum	Wrought alloy	
	MJ/kg			
Electricity	-	155.2		100.0
Oil	10.9	16.2		8.5
Coal	78.2	4.6		2.4
Natural gas	22.0	55.6		29.2
Total	156.4	231.7	152	140.1

3.8.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-13 Virgin Wrought Aluminum Emissions

	GREET2	GHGenius	EcoInvent	Model Results
	87% extruded, 13% cold rolled	Virgin aluminum	Wrought alloy	
	g/kg			
CO_2	10,110			10,981
CH_4	15.6			4.3
N_2O	0.1			0.1
SO_2	35.2			9.9
NOx	11.6			15.6
Particulate	21.4			0.5
Total GHG	11,210	11,500	14,400	11,131

3.8.2 Recycled Wrought Aluminum

There is recycling information in GREET and GHGenius but not in EcoInvent.

Table 3-14 Recycled Wrought Aluminum Energy Requirements

Energy	GREET2	GHGenius	Used in Model
	87% extruded, 13% cold rolled	Recycled	
	MJ/kg		
Electricity	-	7.6	1.0
Oil	1.4	3.8	2.0
Coal	2.1	0.0	2.0
Natural gas	7.5	36.0	5.0
Total	11.6	47.4	10.0

3.8.2.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-15 Recycled Wrought Aluminum Emissions

	GREET2	GHGenius	Model Results
	87% extruded, 13% cold rolled	Recycled	
	g/kg		
CO_2	700		798
CH_4	1.7		0.0
N_2O	0.0		0.0
SO_2	1.3		0.8
NOx	0.9		0.7
Particulate	0.1		0.0
Total GHG	756	2,276	800

3.8.3 Average Wrought Aluminum

The average emissions for wrought aluminum are calculated based on the fraction of virgin aluminum set by the user. The default value is 0.89 virgin material.

3.8.4 Virgin Cast Aluminum

The information on aluminum castings is shown in the following table. GHGenius does not differentiate between wrought and vast aluminum. The GREET energy use and emissions are only slightly higher than the values for wrought aluminum. The same values are used in the model for cast and wrought aluminum.

Table 3-16 Virgin Cast Aluminum Energy Requirements

Energy	GREET2	GHGenius	EcoInvent	Used in Model
	Cast Aluminum	Virgin aluminum	Cast alloy	
	MJ/kg			
Electricity	-	155.2		100.0
Oil	11.4	16.2		8.5
Coal	81.5	4.6		2.4
Natural gas	27.5	55.6		29.2
Total	167.8	231.7	35.0	140.1

3.8.4.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-17 Virgin Cast Aluminum Emissions

	GREET2	GHGenius	EcoInvent	Model Results
	Cast Aluminum	Virgin aluminum		
	g/kg			
CO_2	10,805			10,981
CH_4	17.0			4.3
N_2O	0.2			0.1
SO_2	11.4			9.9
NOx	12.3			15.6
Particulate	22.5			0.5
Total GHG	11,977	11,500	3,200	11,131

3.8.5 Recycled Cast Aluminum

The GREET information on recycled cast aluminum is shown below. The GHGenius information is the same as for wrought and there is no EcoInvent data.

Table 3-18 Recycled Cast Aluminum Energy Requirements

Energy	GREET2	GHGenius	Used in Model
	Recycled Cast Aluminum	Recycled	
	MJ/kg		
Electricity	-	7.6	1.0
Oil	2.8	3.8	3.0
Coal	2.2	0.0	3.0
Natural gas	13.5	36.0	10.0
Total	19.1	47.4	17.0

3.8.5.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-19 Recycled Cast Aluminum Emissions

	GREET2	GHGenius	Model Results
	87% extruded, 13% cold rolled	Recycled	
	g/kg		
CO_2	1,057		1,313
CH_4	2.9		0.0
N_2O	0.0		0.0
SO_2	1.4		1.1
NOx	1.4		1.1
Particulate	0.2		0.0
Total GHG	1,154	2,276	1,316

3.8.6 Average Cast Aluminum

The average emissions for wrought aluminum are calculated based on the fraction of virgin aluminum set by the user. The default value is 0.15 virgin materials, very different than the value for wrought aluminum.

3.9 COPPER

Copper is used in wiring systems and it is a component of most of the electrical components found in vehicles. Copper can also be alloyed with other metals to produce bronze and brass parts. GHGenius also has a recycled copper with about one third less energy and emissions. The GHGenius value is between the GREET and EcoInvent values, it is used in the model.

Table 3-20 Copper Energy Requirements

Energy	GREET2	GHGenius	EcoInvent	Used in Model
	Copper	Virgin copper	Copper for market	
	MJ/kg			
Electricity	-	11.5		11.5
Oil	3.0	19.7		19.7
Coal	13.8	4.0		4.0
Natural gas	15.5	19.7		19.7
Total	35.2	54.9	75.0	54.9

3.9.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source. The model produces emissions for copper between the GHGenius and EcoInvent values.

Table 3-21 Copper Emissions

	GREET2	GHGenius	EcoInvent	Model Results
	Copper	Virgin copper	Copper for market	
	g/kg			
CO_2	2603			4,425
CH_4	5.3			0.5
N_2O	0.0			0.0
SO_2	144.8			7.6
NOx	6.7			5.3
Particulate	0.8			0.1
Total GHG	2,780	3,590	5,100	4,446

3.10 ZINC

Zinc is used for galvanizing steel plate and for some castings. The total use in automobiles is less than 1%. The data from the three primary sources is shown in the following table. The

GHGenius values are used in the model as they are close to the EcoInvent values after allowing for the difference between primary and secondary energy.

Table 3-22 Zinc Energy Requirements

Energy	GREET2	GHGenius	EcoInvent	Used in Model
	Zinc	Zinc	Zinc for market	
	MJ/kg			
Electricity	-	5.6		5.6
Oil	48.2	0.1		0.1
Coal	5.0	19.6		19.6
Natural gas	55.6	30.2		30.2
Total	110.1	56.0	61.1	55.5

3.10.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source. The high GREET emissions are a function of the higher energy use in GREET.

Table 3-23 Zinc Emissions

	GREET2	GHGenius	EcoInvent	Model Results
	Zinc	Zinc		
	g/kg			
CO_2	8,275			4,496
CH_4	17.3			0.3
N_2O	0.2			0.0
SO_2	35.9			0.6
NOx	12.9			2.7
Particulate	4.0			0.1
Total GHG	8,860	4,100	5,500	4,511

Norgate (2006) reported GHG emissions for zinc produced from the electrolytic process of 4.6 kg CO_2eq/kg and a gross energy requirement of 48 MJ/kg, providing some confirmation of the values used here.

3.11 MAGNESIUM

There is a virgin and a recycled magnesium in the model. Magnesium is used in some castings, but like zinc, these contribute less than 1% to the light duty passenger vehicle.

3.11.1 Virgin Magnesium

The results for the energy use for virgin magnesium from two of the data sources are shown in the following table. Magnesium is not included in GHGenius. The GREET and EcoInvent values are quite close. The process uses about 35% of the secondary energy as electricity and that has been used to estimate the secondary energy requirements for the model.

Table 3-24 Virgin Magnesium Energy Requirements

Energy	GREET2	EcoInvent	Used in Model
	Virgin magnesium	magnesium	
	MJ/kg		
Electricity	-		60.0
Oil	3.5		-
Coal	73.2		-
Natural gas	150.9		110.0
Total	247.7	263.1	170.0

3.11.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source. Surprisingly, the calculated emissions are significantly lower than the two sources considering the energy consumption.

Table 3-25 Virgin Magnesium Emissions

	GREET2	EcoInvent	Model Results
	Virgin magnesium		
	g/kg		
CO_2	17,568		11,775
CH_4	39.86		2.6
N_2O	0.4		0.1
SO_2	28.0		4.2
NOx	22.9		12.7
Particulate	3.6		0.3
Total GHG	57,674	84,200	11,867

3.11.2 Recycled Magnesium

GREET2 included some recycled magnesium so that has been included in the model.

Table 3-26 Recycled Magnesium Energy Requirements

Energy	GREET2	Used in Model
	Recycled magnesium	
	MJ/kg	
Electricity	-	0
Oil	0.4	0
Coal	6.8	0
Natural gas	54.7	50.0
Total	63.7	50.0

3.11.2.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-27 Recycled Magnesium Emissions

	GREET2	Model Results
	Recycled magnesium	
	g/kg	
CO_2	4,198	3,143
CH_4	11.7	0.0
N_2O	0.1	0.0
SO_2	3.0	0.0
NOx	5.0	2.3
Particulate	0.5	0.0
Total GHG	43,369	3,145

3.11.3 Average Magnesium

The average emissions for magnesium are calculated based on the fraction of virgin magnesium set by the user. The default value is 0.67 virgin materials.

3.12 POWDER METALS

The powder metallurgy process generally consists of four basic steps: powder manufacture, powder blending, compacting, and sintering. Compacting is generally performed at room temperature, and the elevated-temperature process of sintering is usually conducted at atmospheric pressure. The applications are frequently found in the drive train and transmission. One other major application is connecting rods. Data on these parts is only found in GHGenius.

Table 3-28 Powder Metal Energy Requirements

Energy	GHGenius	Used in Model
	MJ/kg	
Electricity	13.0	13.0
Oil	17.2	17.2
Coal	1.8	1.8
Natural gas	13.0	13.0
Total	45	45.0

3.12.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-29 Powder Metal Emissions

	GHGenius	Model Results
	g/kg	
CO_2		3,655
CH_4		0.6
N_2O		0.0
SO_2		6.8
NOx		4.8
Particulate		0.1
Total GHG	3,340	3,677

3.13 Glass

Glass is found in almost all vehicles and it can contribute 2-3% to the total vehicle weight. The energy data from the three primary sources is found in the following table. EcoInvent also has data on tempering glass which adds 2.5 MJ/kg to the energy use and 0.2 kg CO_2eq/kg to the GHG emissions. It is tempered glass which is used for comparison here.

Table 3-30 Glass Energy Requirements

Energy	GREET2	GHGenius	EcoInvent	Used in Model
	Glass	Glass	Tempered Flat Glass uncoated	
	MJ/kg			
Electricity	-	1.0		1.0
Oil	0.6	0.0		0.0
Coal	1.4	0.0		0.0
Natural gas	18.0	17.8		17.0
Total	20.5	18.8	16.7	18.0

3.13.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source. The reported GHG emissions are all fairly close to each other.

Table 3-31 Glass Emissions

	GREET2	GHGenius	EcoInvent	Model Results
	Glass	Glass		
	g/kg			
CO_2	1,353			1,150
CH_4	7.4			0.0
N_2O	0.0			0.0
SO_2	1.9			0.1
NOx	1.4			0.9
Particulate	0.4			0.0
Total GHG	1,587	1,390	1,300	1,152

3.14 RUBBER

Rubber is used for gaskets and tires in vehicle applications. Tires do not last for the lifetime of the vehicle and must be replaced on a regular basis. In GREET, the user specifies how many times the tires are replaced. This functionality has not been built into the Danish model.

Table 3-32 Rubber Energy Requirements

Energy	GREET2	GHGenius	EcoInvent	Used in Model
	Rubber Products	Rubber		
	MJ/kg			
Electricity		0.7		0.7
Oil	20.7	76.0		76.0
Coal	4.3	0.0		0.0
Natural gas	30.0	23.3		23.3
Total	56.2	110.0	91.2	100.0

3.14.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-33 Rubber Emissions

	GREET2	GHGenius	EcoInvent	Model Results
	Rubber Products	Rubber	Synthetic rubber	
	g/kg			
CO_2	3,760			8,540
CH_4	8.0			0.1
N_2O	0.1			0.0
SO_2	14.7			26.2
NOx	5.7			11.9
Particulate	1.0			0.0
Total GHG	4,047	10,430	3,100	8,550

3.15 FLUIDS

The fluids used in the vehicles will include brake fluid, anti-freeze, power steering fluid and the initial oil fill. The energy requirements are shown in the following table. In GREET the fluids are dominated by the engine oil, since it is replaced much more frequently that the other fluids.

Table 3-34 Fluids Energy Requirements

Energy	GREET2	Used in Model
	Fluids	
	MJ/kg	
Electricity	-	2.0
Oil	47.1	43.0
Coal	0.9	0.0
Natural gas	6.3	5.0
Total	54.6	50.0

3.15.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source. They include the disposal stage.

Table 3-35 Fluids Emissions

	GREET2	Model Results
	Fluids	
	g/kg	
CO_2	4,333	4,447
CH_4	6.1	0.1
N_2O	0.1	0.0
SO_2	30.0	14.9
NOx	9.6	6.6
Particulate	1.7	0.0
Total GHG	4,545	4,455

3.16 FIBER GLASS

Fibre glass is used in many vehicles, particularly the lower volume heavy duty sector and in trains. This material is neither in GHGenius nor in EcoInvent. The GREET value is just for the glass component and not for the composite material. The plastic resin would have a lower carbon intensity than the glass.

Table 3-36 Fiber Glass Energy Requirements

Energy	GREET2	Ide-Mat	Used in Model
	Fiber Glass		
	MJ/kg		
Electricity	-		1.0
Oil	0.6		0.0
Coal	1.4		0.0
Natural gas	18.0		8.0
Total	20.5	8.6	9.0

3.16.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-37 Fiber Glass Emissions

	GREET2	Ide-Mat	Model Results
	Fiber Glass		
	g/kg		
CO_2	1,353		584
CH_4	7.4		0.0
N_2O	0.0		0.0
SO_2	1.9		0.1
NOx	1.4		0.5
Particulate	0.4		0.0
Total GHG	1,587	600	586

3.17 PLASTICS

There are a large number of plastics that are used in vehicles, three different types of plastic have been added to the model, and an average plastic is also included when the specific type of plastic is unknown.

3.17.1 High-Density Polyethylene

High-Density Polyethylene is particularly useful where moisture resistance and low cost are required. It can be used to make tanks (including fuel tanks), wire insulation, and other applications. Plastics Europe (2008) reports an energy use of 76.8 MJ/kg (including the feedstock energy) and 1.96 kg CO_2e/kg for the GHG emissions (this would exclude the end of life emissions).

Table 3-38 High-Density Polyethylene Energy Requirements

Energy	GREET2	EcoInvent	Used in Model
	HDPE	HDPE granules	
	MJ/kg		
Electricity			5.0
Oil	9.4		0.0
Coal	9.1		0.0
Natural gas	62.3		65.0
Total	83.3	78.0	70.0

3.17.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-39 High-Density Polyethylene Emissions

	GREET2	EcoInvent	Model Results
	HDPE	HDPE granules	
	g/kg		
CO_2	2,318		4,491
CH_4	27.1		0.2
N_2O	0.1		0.0
SO_2	27.2		0.4
NOx	4.4		3.6
Particulate	0.6		0.0
Total GHG	3,169	2,000	4,501

3.17.2 Polypropylene

Polypropylene can be found in battery cases and a number of injection molded plastic parts. The energy use data is summarized in the following table. The energy use includes the feedstock energy. Plastics Europe (2014) reports energy use of 77.8 MJ/kg and a GWP of 1.63 CO_2e/kg (excluding end of life).

Table 3-40 Polypropylene Energy Requirements

Energy	GREET2	EcoInvent	Used in Model
	Polypropylene		
	MJ/kg		
Electricity	-		5.0
Oil	19.1		0.0
Coal	6.4		0.0
Natural gas	53.1		65.0
Total	80.3	76.3	70.0

3.17.2.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source. The model results include the final end of life oxidation emissions, which the other two sources do not include.

Table 3-41 Polypropylene Emissions

	GREET2	EcoInvent	Model Results
	Polypropylene		
	g/kg		
CO_2	1,888		4,491
CH_4	25.6		0.2
N_2O	0.1		0.0
SO_2	24.6		0.4
NOx	3.9		3.6
Particulate	0.5		0.0
Total GHG	2,696	2,100	4,501

3.17.3 Polyethylene Terephthalate

Polyethylene Terephthalate is used in the lithium ion batteries packs. It is the same material used to make plastic soft drink and water bottles. Plastic Europe (2010) reports energy use of 78 MJ/kg and GHG emissions of 2.15 kg CO_2e/kg.

Table 3-42 Polyethylene Terephthalate Energy Requirements

Energy	GREET2	EcoInvent	Used in Model
	Polyethylene Terephthalate		
	MJ/kg		
Electricity	-		5.0
Oil	31.3		0.0
Coal	9.1		0.0
Natural gas	36.4		65.0
Total	79.1	77.6	70.0

3.17.3.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-43 Polyethylene Terephthalate Emissions

	GREET2	EcoInvent	Model Results
	Polyethylene Terephthalate		
	g/kg		
CO_2	3,007		4,491
CH_4	17.6		0.2
N_2O	0.1		0.0
SO_2	13.6		0.4
NOx	5.7		3.6
Particulate	0.6		0.0
Total GHG	3,582	3,100	4,501

3.17.4 Average Plastic

In many cases the exact type of plastic is not known. GREET2 has an average plastic so this has been added to the model. This is compared to the GHGenius values. GHGenius excludes the feedstock energy but it does include the end of life emissions. The values used in the model are higher than those of the other plastics because GREET has higher energy for the other plastics.

Table 3-44 Average Plastic Energy Requirements

Energy	GREET2	GHGenius	Used in Model
	Average Plastic		
	MJ/kg		
Electricity	-	0.03	7.0
Oil	20.9	15	0.0
Coal	8.7	-	0.0
Natural gas	58.1	15	70.0
Total	90.0	30	77.0

3.17.4.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-45 Average Plastic Emissions

	GREET2	GHGenius	Model Results
	Average Plastic		
	g/kg		
CO_2	3,317		4,968
CH_4	21.8		0.3
N_2O	0.3		0.0
SO_2	19.0		0.5
NOx	6.1		4.1
Particulate	1.4		0.0
Total GHG	4,054	6,162	4,980

3.18 COMPOSITES

Three composites are added to the model, a glass fibre and two carbon fibre products for use in low and high pressure applications.

3.18.1 Glass Fiber Composite Plastic

GREET has values for glass fibre composites (GF composites) which are distinct from fibre glass. This will probably cause some confusion since fibre glass is often used to describe GF composites. Both can be used in vehicle applications. The energy data is shown below.

Table 3-46 GF Composite Energy Requirements

Energy	GREET2	EcoInvent	Used in Model
	GF Composites	Glass fibre reinforced plastic	
	MJ/kg		
Electricity	-		5.0
Oil	19.8		0.0
Coal	9.7		0.0
Natural gas	65.5		60.0
Total	97.6	68.6	65.0

3.18.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source. The model emissions will include the end of life emissions.

Table 3-47 GF Composite Emissions

	GREET2	EcoInvent	Model Results
	GF Composites		
	g/kg		
CO_2	5,010		4,177
CH_4	15.7		0.2
N_2O	0.1		0.0
SO_2	15.7		0.4
NOx	14.0		3.4
Particulate	4.8		0.0
Total GHG	5,529	4,400	4,186

3.18.2 Carbon Fiber Composite Plastic for General Use

Carbon Fibre (CF) use is growing in vehicles. Two different properties are included in the one, one for low pressure applications and one for high pressure applications. The energy use is shown below. Carbon fibre production is very energy intensive.

Table 3-48 CF Low Pressure Energy Requirements

Energy	GREET2	Ide-Mat	Used in Model
	CF Composites LP		
	MJ/kg		
Electricity	-		57.0
Oil	43.9		30.0
Coal	56.1		13.0
Natural gas	214.3		200.0
Total	327.8	339	300.0

3.18.2.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-49 CF Low Pressure Emissions

	GREET2	Ide-Mat	Model Results
	CF Composites LP		
	g/kg		
CO_2	19,151		21,376
CH_4	50.5		2.5
N_2O	0.5		0.1
SO_2	41.2		14.5
NOx	26.7		21.1
Particulate	9.2		0.3
Total GHG	20,827	12,500	21,474

3.18.3 Carbon Fiber Composite Plastic for High Pressure Vessels

CF is also used in high pressure vessels like storage tanks for hydrogen or natural gas. The GREET model has this product and it uses much more energy than the low pressure product. The product is 70% CF and 30% resin, the opposite ratio of the low pressure product.

Table 3-50 CF High Pressure Energy Requirements

Energy	GREET2	Used in Model
	CF Composites HP	
	MJ/kg	
Electricity	-	100.0
Oil	56.0	50.0
Coal	112.1	20.0
Natural gas	358.1	330.0
Total	552.7	500.0

3.18.3.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-51 CF High Pressure Emissions

	GREET2	Model Results
	CF Composites HP	
	g/kg	
CO_2	34,566	35,641
CH_4	83.2	4.3
N_2O	0.8	0.2
SO_2	72.9	24.5
NOx	46.6	35.5
Particulate	9.3	0.5
Total GHG	37,340	35,810

3.19 LEAD

Lead is used in batteries, solder, and in some alloys. Lead is included as both a virgin material and as a recycled material in the model.

3.19.1 Virgin Lead

The energy consumed in lead production is shown in the following table.

Table 3-52 Lead Energy Requirements

Energy	GREET2	GHGenius	EcoInvent	Used in Model
	Virgin Lead	Virgin Lead		
	MJ/kg			
Electricity		10.2		3.0
Oil	1.0	3.4		1.0
Coal	23.8	6.8		2.0
Natural gas	1.9	13.6		4.0
Total	27.6	34.0	8.7	10.0

3.19.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-53 Lead Emissions

	GREET2	GHGenius	EcoInvent	Model Results
	Virgin Lead	Virgin Lead		
	g/kg			
CO_2	656			804
CH_4	7.4			0.1
N_2O	0.0			0.0
SO_2	31.1			0.6
NOx	1.3			0.8
Particulate	5.2			0.0
Total GHG	887	2,025	600	810

3.19.2 Recycled Lead

Lead from batteries is often recycled. The energy requirements for recycled lead are shown below.

Table 3-54 Recycled Lead Energy Requirements

Energy	GREET2	GHGenius	Used in Model
	Recycled Lead	Recycled Lead	
	MJ/kg		
Electricity		2.0	1.5
Oil	0.1	0.7	0.2
Coal	0.0	1.4	1.0
Natural gas	4.8	2.7	2.7
Total	4.9	6.8	5.4

3.19.2.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-55 Recycled Lead Emissions

	GREET2	GHGenius	Model Results
	Recycled Lead	Recycled Lead	
	g/kg		
CO_2	463		419
CH_4	0.7		0.1
N_2O	0.0		0.0
SO_2	6.5		0.2
NOx	1.1		0.4
Particulate	0.2		0.0
Total GHG	489	104	421

3.19.3 Average Lead

The average emissions for lead are calculated based on the fraction of virgin lead set by the user. The default value is 0.27 virgin materials.

3.20 NICKEL

Nickel is used in some steel alloys and was identified as part of the bill of materials in airplanes.

3.20.1 Virgin Nickel

The energy consumed in nickel production is shown in the following table. Norgate (2007) identified the gross energy requirement as 114 to 194 MJ/kg and the GHG emissions of 11.4 kg to 16.1 CO_2eq/kg nickel, depending on the process used. The low energy process is the most common. The values used in the model have been influenced by this.

Table 3-56 Virgin Nickel Energy Requirements

Energy	GREET2	GHGenius	EcoInvent	Used in Model
	Virgin Nickel	Nickel	Nickel	
	MJ/kg			
Electricity	-	-		20.0
Oil	77.2	239		10.0
Coal	27.4	-		50.0
Natural gas	90.2	-		50.0
Total	202.4	239	151.2	130.0

3.20.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-57 Virgin Nickel Emissions

	GREET2	GHGenius	EcoInvent	Model Results
	Virgin Nickel	Nickel		
	g/kg			
CO_2	13,871			11,133
CH_4	27.3			0.9
N_2O	0.3			0.1
SO_2	732.5			5.3
NOx	21.1			7.8
Particulate	5.7			0.2
Total GHG	14,792	19,900	12,800	11,178

3.20.2 Recycled Nickel

The energy consumed in nickel production is shown in the following table.

Table 3-58 Recycled Nickel Energy Requirements

Energy	GREET2	Used in Model
	Recycled Nickel	
	MJ/kg	
Electricity	-	4.0
Oil	1.6	1.0
Coal	4.7	0.0
Natural gas	17.5	15.0
Total	25.1	20.0

3.20.2.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-59 Recycled Nickel Emissions

	GREET2	Model Results
	Recycled Nickel	
	g/kg	
CO_2	1,560	1,359
CH_4	3.8	0.2
N_2O	0.0	0.0
SO_2	2.6	0.6
NOx	2.0	1.3
Particulate	0.3	0.0
Total GHG	1,687	1,366

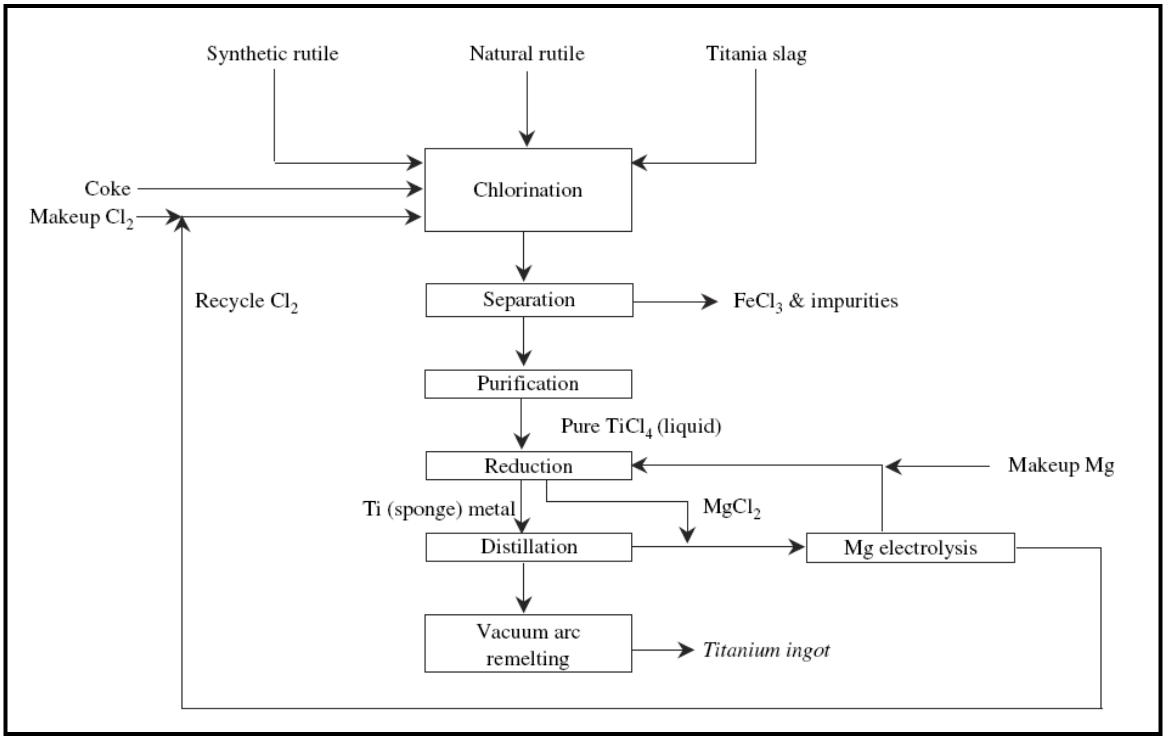
3.20.3 Average Nickel

The average emissions for nickel are calculated based on the fraction of virgin nickel set by the user. The default value is 0.56 virgin materials.

3.21 TITANIUM

Titanium is used in airplanes and in some high performance vehicles. It has high strength and light weight. The metal is in GREET2, but all of the data there is blank. The information in GHGenius and in EcoInvent is shown in the following table. The Ide-Mat database has the energy requirements for titanium at 1,509 MJ/kg, which is an order of magnitude higher than the other estimates. Other sources of information have been identified and are included in the following table. The model is set up to use similar data to that developed by Norgate as that seems to include the most detail on the process steps for producing metals from the titanium ores. Their process is shown in the following figure.

Figure 3-2 Kroll Process for Titanium Metal Production



The collected data on titanium production is summarized in the following table.

Table 3-60 Titanium Energy Requirements

Energy	GHGenius	EcoInvent	Ide-Mat	Norgate	Nuss	Used for Model
MJ/kg	Titanium	Titanium Dioxide	Titanium	Titanium metal		
Electricity	97					200.0
Oil	25					50.0
Coal	4					10.0
Natural gas	14					60.0
Total	140	83.5	1,509	361	703	320.0

3.21.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source. They will therefore differ from one region to another as the carbon intensity of the power changes and to a lesser extent the other energy sources. The GHGenius values are from the model set to Canada and they include some end of life credits.

Table 3-61 Titanium Emissions

	GHGenius	EcoInvent	Ide-Mat	Norgate	Nuss	Model Results
		Titanium Dioxide				g/kg
CO_2						25,677
CH_4						8.5
N_2O						0.3
SO_2						31.2
NOx						36.0
Particulate						0.9
Total GHG	9,820	7,300	73,500	35,700	45,100	25,982

3.22 LITHIUM

Lithium is becoming a more important component as Li ion battery use becomes more widespread. The energy consumed in lithium production is shown in the following table. There is a wide range in the values but some of the difference is caused by the different compositions. GREET has done a lot of work detailing the system so those values are used as guidance.

Table 3-62 Lithium Energy Requirements

Energy	GREET2	GHGenius	EcoInvent	Used in Model
	$LiMn_2O_4$	Lithium	$LiMn_2O_4$	
	MJ/kg			
Electricity	-			4.0
Oil	6.6			5.0
Coal	8.5			7.0
Natural gas	24.5			20.0
Total	41.6	770	112.1	36.0

3.22.1.1 GHG Emissions

The GHG emissions are compared in the following table. The emissions are calculated from the energy and the emissions associated with each emission source.

Table 3-63 Lithium Emissions

	GREET2	GHGenius	EcoInvent	Model Results
	$LiMn_2O_4$	Lithium	$LiMn_2O_4$	
	g/kg			
CO_2	3,380			2,805
CH_4	6.1			0.2
N_2O	0.0			0.0
SO_2	4.1			2.1
NOx	8.5			2.3
Particulate	4.3			0.0
Total GHG	3,589	55,390	9,700	2,814

3.23 Lithium Battery Pack

A slightly different approach has been taken for the lithium batteries in electric vehicles. It has been assumed that the composition of the battery pack is 30% lithium metals, 20% Copper, 20% Aluminum, 5% fiber glass, 10% carbon fiber, 4% steel, 2% fluids, 4% across 2 types of plastic, 2% rubber, 1% glass, 2% other. The composite energy requirements for this system were identified through the GREET2 model and then this information has been used. The energy requirements are shown below.

Table 3-64 Lithium Battery Pack Energy Use

	MJ/kg Battery Pack
Electricity	20.5
Oil	12.8
Coal	5.1
Natural gas	40.6
Total	79.0

The emissions resulting from this energy use are shown in the following table.

Table 3-65 Lithium Battery Pack Emissions

	g/kg
CO_2	5,949
CH_4	0.9
N_2O	0.0
SO_2	5.9
NOx	6.5
Particulate	0.1
Total GHG	5,983

Lithium ion batteries have a current energy density of about 0.1 kWh/kg (US DOE). Using the energy capacity of the vehicle batteries and this factor the weight of the battery pack can be calculated. Then using the energy and emissions data in the model, the contribution of the battery pack to the total vehicle materials can be simply calculated. This approach has the advantage of being simple and the impact of the desired range on the vehicle materials energy use and range can be determined.

3.24 OTHER MATERIALS

The various bills of material are often not complete and have a category for "other materials". For the model the "other materials" are calculated based on the median value for all of the rest of the materials in the model.

Table 3-66 Other Materials Emissions

	g/kg
CO_2	2,723
CH_4	0.3
N_2O	0.0
SO_2	1.4
NOx	2.5
Particulate	0.0
Total GHG	2,735

Spaces for four additional materials have been provided for in the model. Currently two of these have zero energy and two have the highest energy in the model. This has been done so that they don't impact the median values. The lithium battery pack is also excluded from the median so as to not create a circular reference. If other materials are added then care should be taken so as to not significantly influence the other materials values.

4. VEHICLE BILLS OF MATERIALS

The bill of materials for each of the vehicles in the model has been prepared from various data sources. The bill of material information includes the vehicle weight and the fraction of each type of material found in the vehicles. Additional information on the vehicle lifetime energy use has also been drawn from the model or added to the model where it wasn't available. This additional information allows the emissions for vehicle materials and assembly to be reported on a per kilometre or per GJ of energy consumed basis so that it can be compared to the operating emissions.

4.1 PASSENGER CARS

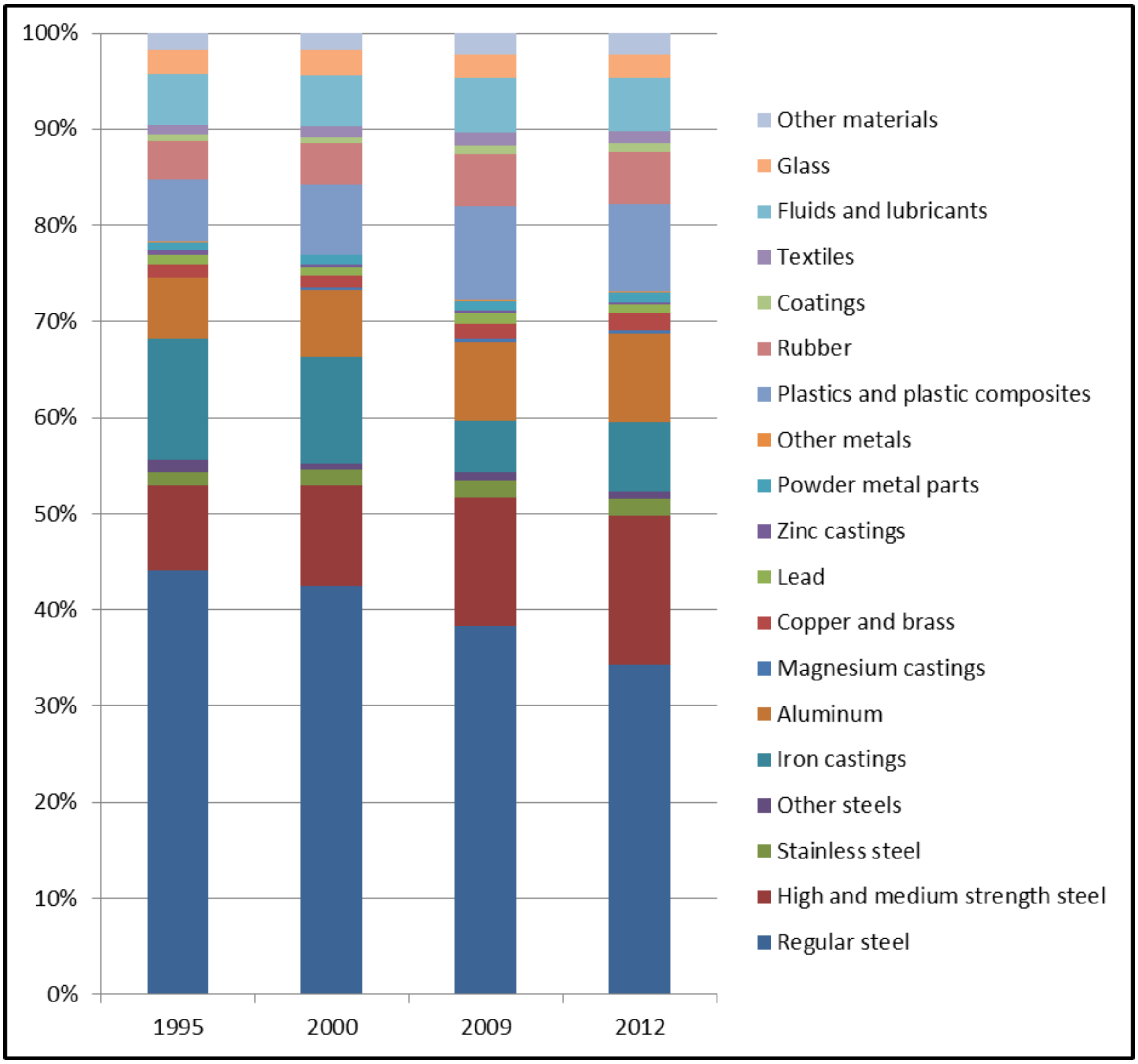
Oak Ridge National Laboratory publishes the Transportation Energy Data Book that has a large collection of data drawn mostly from public data sources. Edition 33 was published in July 2014. It generally contains data up to 2012 or 2013. It contains data on the materials composition of light duty vehicles (Table 4-15). This edition contained data from 2012 as well as earlier years. The data is shown in the following table. For the model, textiles, coatings and other materials have been combined into an other materials category.

Table 4-1 LDV Material Composition

Material	Weight	Percentage
	kilograms	
Regular steel	610	34.3%
High and medium strength steel	275	15.5%
Stainless steel	31	1.7%
Other steels	14	0.8%
Iron castings	127	7.1%
Aluminum	165	9.3%
Magnesium castings	5	0.3%
Copper and brass	33	1.8%
Lead	17	0.9%
Zinc castings	4	0.2%
Powder metal parts	20	1.1%
Other metals	2	0.1%
Plastics and plastic composites	161	9.1%
Rubber	95	5.4%
Coatings	15	0.8%
Textiles	22	1.3%
Fluids and lubricants	98	5.5%
Glass	43	2.4%
Other materials	41	2.3%
Total	1,778	100.0%

There have been some changes over time to the composition as shown in the following figure. All of the data is from various editions of the handbook. The total weight of steel is declining and within the steel category, high strength steel is replacing regular steel.

Figure 4-1 Change in Material Composition



4.1.1 Internal Combustion

There are five types of engines used in the light duty vehicles in the model. The changes made to the base bill of materials are described for each of the vehicle variations.

4.1.1.1 Gasoline

The gasoline vehicle has a weight of 1,310 kg in the model. The vehicle travels 18,000 km per year and consumes 38.0 GJ of fuel in the year 2015. The vehicle has a lifetime of 16 years. The bill of materials is shown in the following table. These are the values used in the model.

Table 4-2 Gasoline LDV Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	459	35.09%
	High Strength	203	15.52%
	Stainless	22	1.68%
Iron	Cast	93	7.11%
Aluminum	Average Wrought	61	4.66%
	Average Cast	61	4.66%
Copper		24	1.83%
Zinc		3	0.23%
Magnesium	Average	4	0.31%
Powder Metals		14	1.07%
Glass		31	2.37%
Rubber		71	5.43%
Fluids & Lubricants		72	5.50%
Fiber Glass		0	0.00%
Plastics	High Density Polyethylene	0	0.00%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	0	0.00%
	Average	119	9.10%
Composites	Glass Fiber Composite Plastic	0	0.00%
	CF Composite for General Use	0	0.00%
	CF Composite for High Pressure	0	0.00%
Lead	Average	12	0.92%
Nickel	Average	0	0.00%
Titanium		0	0.00%
Lithium		0	0.00%
Other		59	4.51%
Total		1,308	100.00%

4.1.1.2 E-85

The E-85 vehicles do not have their own tab in the model. They are assumed to have the same weight and materials distribution as the gasoline vehicle. The fuel efficiency, kilometres travelled, and the vehicle life are the same as gasoline.

4.1.1.3 Natural Gas

The natural gas vehicle has the same distance travelled and lifetime as the gasoline vehicle. The energy use slightly higher at 41.8 GJ/year. The vehicle weight is 1,440 kg.

Natural gas must be stored in high pressure cylinders so the fuel tanks can add extra weight to the vehicle. The extra weight of 130 kg suggests that this could be a wrapped steel tank rather than a carbon fibre tank. It is assumed that 100kg of the extra weight is high strength steel and 30 kg is glass fibre composite. The bill of materials is shown in the following table.

Table 4-3 Natural Gas LDV Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	459	31.92%
	High Strength	303	21.07%
	Stainless	22	1.53%
Iron	Cast	93	6.47%
Aluminum	Average Wrought	61	4.24%
	Average Cast	61	4.24%
Copper		24	1.67%
Zinc		3	0.21%
Magnesium	Average	4	0.28%
Powder Metals		14	0.97%
Glass		31	2.16%
Rubber		71	4.94%
Fluids & Lubricants		72	5.01%
Fiber Glass		0	0.00%
Plastics	High Density Polyethylene	0	0.00%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	0	0.00%
	Average	119	8.28%
Composites	Glass Fiber Composite Plastic	30	2.09%
	CF Composite for General Use	0	0.00%
	CF Composite for High Pressure	0	0.00%
Lead	Average	12	0.83%
Nickel	Average	0	0.00%
Titanium		0	0.00%
Lithium battery		0	0.00%
Other		59	4.10%
Total		1438	100.01%

4.1.1.4 Diesel

The diesel vehicle has a weight of 1,370 kg in the model. The vehicle travels 18,000 km per year and consumes 27.5 GJ of fuel in the year 2015. The vehicle has a lifetime of 16 years. The extra weight of 60 kg will be assumed to be cast iron in the engine. The bill of material is shown in the following table.

Table 4-4 Diesel LDV Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	459	33.55%
	High Strength	203	14.84%
	Stainless	22	1.61%
Iron	Cast	153	11.18%
Aluminum	Average Wrought	61	4.46%
	Average Cast	61	4.46%
Copper		24	1.75%
Zinc		3	0.22%
Magnesium	Average	4	0.29%
Powder Metals		14	1.02%
Glass		31	2.27%
Rubber		71	5.19%
Fluids & Lubricants		72	5.26%
Fiber Glass		0	0.00%
Plastics	High Density Polyethylene	0	0.00%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	0	0.00%
	Average	119	8.70%
Composites	Glass Fiber Composite Plastic	0	0.00%
	CF Composite for General Use	0	0.00%
	CF Composite for High Pressure	0	0.00%
Lead	Average	12	0.88%
Nickel	Average	0	0.00%
Titanium		0	0.00%
Lithium battery		0	0.00%
Other		59	4.31%
Total		1,368	99.99%

4.1.1.5 Diesel RME

The diesel vehicle using RME as the fuel has the same characteristics as the standard diesel vehicle.

4.1.1.6 DME

The diesel vehicle using DME as the fuel has a weight of 1,448 kg. DME is stored in a pressurized tank, but at much lower pressure than a natural gas vehicle. The weight is an increase of 80 kg over the standard diesel engine. It is assumed that the extra weight is high strength steel. The bill of material is shown in the following table.

Table 4-5 Diesel DME LDV Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	459	31.70%
	High Strength	283	19.54%
	Stainless	22	1.52%
Iron	Cast	153	10.57%
Aluminum	Average Wrought	61	4.21%
	Average Cast	61	4.21%
Copper		24	1.66%
Zinc		3	0.21%
Magnesium	Average	4	0.28%
Powder Metals		14	0.97%
Glass		31	2.14%
Rubber		71	4.90%
Fluids & Lubricants		72	4.97%
Fiber Glass		0	0.00%
Plastics	High Density Polyethylene	0	0.00%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	0	0.00%
	Average	119	8.22%
Composites	Glass Fiber Composite Plastic	0	0.00%
	CF Composite for General Use	0	0.00%
	CF Composite for High Pressure	0	0.00%
Lead	Average	12	0.83%
Nickel	Average	0	0.00%
Titanium		0	0.00%
Lithium battery		0	0.00%
Other		59	4.07%
Total		1,448	100.00%

4.1.2 Hybrid Vehicles

The bill of materials of the plug in hybrid vehicle is based on the gasoline vehicle. It has an additional 238 kg of weight. This incremental weight has been reduced in the latest version of the JRC report (2013) to 169 kg. The extra weight in the JEC report is shown in the following table.

Table 4-6 Extra Weight Distribution of PHEV

Component	Weight, kg
Transmission	30
E-machine	44
Battery	80
Wiring Harness	15
Total	169

The bill of materials is based on this extra 169 kg of weight, this should be checked in the model on the PHEV sheet. The weight of this vehicle should be 1,479 kg.

Table 4-7 Hybrid LDV Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	459	31.03%
	High Strength	240	16.23%
	Stainless	22	1.49%
Iron	Cast	103	6.96%
Aluminum	Average Wrought	61	4.12%
	Average Cast	61	4.12%
Copper		58	3.92%
Zinc		3	0.20%
Magnesium	Average	4	0.27%
Powder Metals		14	0.95%
Glass		31	2.10%
Rubber		71	4.80%
Fluids & Lubricants		72	4.87%
Fiber Glass		0	0.00%
Plastics	High Density Polyethylene	0	0.00%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	0	0.00%
	Average	129	8.72%
Composites	Glass Fiber Composite Plastic	0	0.00%
	CF Composite for General Use	0	0.00%
	CF Composite for High Pressure	0	0.00%
Lead	Average	12	0.81%
Nickel	Average	0	0.00%
Titanium		0	0.00%
Lithium battery		80	5.41%
Other		59	3.99%
Total		1,479	99.99%

4.1.3 Electric Vehicles

The electric vehicle specifications are also different in the 2013 JRC report. The difference between the gasoline and the electric vehicle is summarized in the following table.

Table 4-8 Extra Weight Distribution of BEV

Component	Weight, kg
Engine	-145
Transmission	-40
E Machine	76
Battery	200
Wiring harness	20
Fuel tank and fuel	-56
Total	55

The projected bill of materials based on the gasoline vehicle and the changes in weight from the JRC report is shown in the following table.

Table 4-9 Electric Vehicle Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	310	22.71%
	High Strength	240	17.58%
	Stainless	22	1.61%
Iron	Cast	50	3.66%
Aluminum	Average Wrought	61	4.47%
	Average Cast	61	4.47%
Copper		76	5.57%
Zinc		3	0.22%
Magnesium	Average	4	0.29%
Powder Metals		14	1.03%
Glass		31	2.27%
Rubber		71	5.20%
Fluids & Lubricants		22	1.61%
Fiber Glass		0	0.00%
Plastics	High Density Polyethylene	0	0.00%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	0	0.00%
	Average	129	9.45%
Composites	Glass Fiber Composite Plastic	0	0.00%
	CF Composite for General Use	0	0.00%
	CF Composite for High Pressure	0	0.00%
Lead	Average	12	0.88%
Nickel	Average	0	0.00%
Titanium		0	0.00%
Lithium battery		200	14.65%
Other		59	4.32%
Total		1365	99.99%

4.1.4 Fuel Cell Vehicles

The JRC mass impacts compared to a gasoline vehicle for a hydrogen fuel cell vehicle are shown in the following table. This vehicle has a battery so it is more of a hybrid fuel cell vehicle and a pure FCV.

Table 4-10 FCV Mass Impacts

Component	Weight, kg
Engine	-145
Transmission	-40
E Machine	72
Fuel Cell module	167
Battery	34
Wiring harness	20
Fuel tank and fuel	40
Total	148

4.1.4.1 Hydrogen Fuel Cell Vehicle

There is no good detail on the composition of the fuel cell module and there is not a separate accounting for the fuel cell module in GREET2. It is possible to see the percentage point changes in some of the materials between an ICE and FCV in GREET. This is summarized in the following table. In GREET the FCV weighs 277 kg more than the ICE vehicle so working in percent changes is more appropriate than the absolute weight.

Table 4-11 Changes in Materials for FCV

Materials	Change in Percent
Steel	-3.3
Cast Iron	-9.3
Wrought Aluminum	2.8
Cast Aluminum	-1.4
Copper	2.6
Average Plastic	-0.4
Rubber	-0.7
CF general	4.1
CF high pressure	4.1
Nickel	0.4
Others	1.1

The estimated bill of materials for a FCV is shown in the following table. This is built from the gasoline vehicle and the changes identified in the previous table.

Table 4-12 Fuel Cell LDV Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	452	31.05%
	High Strength	220	15.08%
	Stainless	24	1.65%
Iron	Cast	0	0.00%
Aluminum	Average Wrought	90	6.17%
	Average Cast	60	4.11%
Copper		65	4.46%
Zinc		3	0.21%
Magnesium	Average	4	0.27%
Powder Metals		14	0.96%
Glass		31	2.12%
Rubber		68	4.66%
Fluids & Lubricants		65	4.46%
Fiber Glass		0	0.00%
Plastics	High Density Polyethylene	0	0.00%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	0	0.00%
	Average	120	8.23%
Composites	Glass Fiber Composite Plastic	0	0.00%
	CF Composite for General Use	62	4.25%
	CF Composite for High Pressure	62	4.25%
Lead	Average	12	0.82%
Nickel	Average	6	0.40%
Titanium		0	0.00%
Lithium battery		0	0.00%
Other		100	6.85%
Total		1,458	100.00%

4.1.4.2 Hydrogen Hybrid Fuel Cell Vehicle

The hydrogen hybrid fuel cell has a lithium ion battery and presumably a smaller fuel cell. Thirty kg of battery has been added to vehicle and this mass has been removed

Table 4-13 Hybrid Fuel Cell LDV Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	440	30.16%
	High Strength	209	14.39%
	Stainless	24	1.64%
Iron	Cast	0	0.00%
Aluminum	Average Wrought	90	6.17%
	Average Cast	60	4.11%
Copper		60	4.11%
Zinc		3	0.21%
Magnesium	Average	4	0.27%
Powder Metals		14	0.96%
Glass		31	2.12%
Rubber		68	4.66%
Fluids & Lubricants		65	4.46%
Fiber Glass		0	0.00%
Plastics	High Density Polyethylene	0	0.00%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	0	0.00%
	Average	120	8.22%
Composites	Glass Fiber Composite Plastic	0	0.00%
	CF Composite for General Use	62	4.25%
	CF Composite for High Pressure	62	4.25%
Lead	Average	12	0.82%
Nickel	Average	4	0.27%
Titanium		0	0.00%
Lithium battery		30	2.06%
Other		100	6.85%
Total		1458	99.98%

4.1.4.3 Methanol Fuel Cell Vehicle

The methanol fuel cell vehicle will produce the hydrogen on board by reforming methanol. The high pressure carbon fibre tanks will not be required. There is no information on these vehicles available. We have moved the carbon fibre material to stainless steel and kept everything else the same as the hydrogen hybrid FCV.

Table 4-14 Methanol Fuel Cell LDV Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	440	30.18%
	High Strength	209	14.33%
	Stainless	86	5.90%
Iron	Cast	0	0.00%
Aluminum	Average Wrought	90	6.17%
	Average Cast	60	4.12%
Copper		60	4.12%
Zinc		3	0.21%
Magnesium	Average	4	0.27%
Powder Metals		14	0.96%
Glass		31	2.13%
Rubber		68	4.66%
Fluids & Lubricants		65	4.46%
Fiber Glass		0	0.00%
Plastics	High Density Polyethylene	0	0.00%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	0	0.00%
	Average	120	8.23%
Composites	Glass Fiber Composite Plastic	0	0.00%
	CF Composite for General Use	62	4.25%
	CF Composite for High Pressure	0	0.00%
Lead	Average	12	0.82%
Nickel	Average	4	0.27%
Titanium		0	0.00%
Lithium battery		30	2.06%
Other		100	6.86%
Total		1458	100.00%

4.2 Heavy Duty Vehicles

The model contains trucks, buses, and hybrid buses. In addition there can be different fuels used in the same vehicle which has an impact on the vehicle weight and the types of materials that are used. The vehicles are discussed below.

4.2.1 Trucks

The basic truck in the model is identified as a Scania P280 distribution truck. These trucks can come in different axle configurations. The three axle truck is shown in the following figure. A two axle version is also available.

Figure 4-2 Scania P280 Distribution Truck

The vehicle weight specifications are shown in the following table (Scania Australia, 2014). These weights include a full fuel tank but they do not include the van box. Van boxes can be manufactured from aluminum or from FRP. Aluminum is approximately 8-10 percent lighter than FRP.

Table 4-15 Truck Weights

	Two Axle	Three Axle
Front Axle, kg	4,620	5,010
Rear Axles, kg	1,815	3,250
Fuel Tank Capacity, litres	400	450
Full Tank Weight, kg	340	380
Total Weight, ex fuel, kg	6,095	7,880

We will add 1,200 kg for the two axle truck and 1,800 kg for the three axle truck for the weight of the box.

The full distribution of the materials in the Scania trucks does not appear to be available but Scania do state that 72% of the vehicle weight is composed of steel and iron (Scania, 2014).

Volvo produce an Environmental Production Declaration (EPD) for all of their trucks but the detail in the online versions does not provide a full breakdown of the materials used. An older EPD for the Volvo FH trucks (Volvo, 2003) did provide a very detailed breakdown of the materials and that is shown in the following table. 75% of the material is iron and steel, very similar to the Scania average.

Table 4-16 Volvo Truck Materials

Material	Kg	From recycled material	Weight Distribution
Wrought Iron	1,196	50%	17.09%
Cast Iron	1,478	97%	21.11%
Steel Rod	198		2.83%
Hot-rolled	1,645		23.50%
Cold-rolled	925		13.21%
Aluminium	201	90%	2.87%
Lead (battery)	95	50%	1.36%
Copper	14	40%	0.20%
Brass, bronze	9	86%	0.13%
Stainless steel	15	80%	0.21%
Thermoplastics	339		4.84%
Reinforced thermoplastics	74		1.06%
Thermosetting plastics	6		0.09%
Rubber	459		6.56%
Glass	60		0.86%
Textile, other fibres	57		0.81%
Paint	13		0.19%
Brake pads	22		0.31%
Oil, grease	62		0.89%
Electronics	56		0.80%
Sulphuric acid (battery)	36		0.51%
Bitumen	6		0.09%
Wood	11		0.16%
Cooling agent (R134a)	1		0.01%
Glycol	17		0.24%
Ethanol	4		0.06%
Total	7,000	33%	99.99%

Taking this bill of material and adding the 1,200 kg of aluminum for the box and converting it to the materials that are in the model produces the following table for the model.

Table 4-17 Truck Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	2,768	33.76%
	High Strength	0	0.00%
	Stainless	15	0.18%
Iron	Cast	2,674	32.61%
Aluminum	Average Wrought	1,401	17.09%
	Average Cast	0	0.00%
Copper		23	0.28%
Zinc		0	0.00%
Magnesium	Average	0	0.00%
Powder Metals		0	0.00%
Glass		60	0.73%
Rubber		459	5.60%
Fluids & Lubricants		126	1.54%
Fiber Glass		74	0.90%
Plastics	High Density Polyethylene	0	0.00%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	0	0.00%
	Average	345	4.21%
Composites	Glass Fiber Composite Plastic	0	0.00%
	CF Composite for General Use	0	0.00%
	CF Composite for High Pressure	0	0.00%
Lead	Average	95	1.16%
Nickel	Average	0	0.00%
Titanium		0	0.00%
Lithium battery		0	0.00%
Other		159	1.94%
Total		8,199	100.00%

4.2.1.1 RME Truck

There is an RME truck in the model. It is assumed to have identical characteristics to the diesel truck.

4.2.1.2 DME Truck

There is a DME truck in the model. Following the same approach as the DME LDV, the only change is that the fuel tank is heavier and made from high strength steel. We have assumed that 600 litres of fuel are required. The weight of the fuel tanks is approximately 0.3 kg/litre. The extra weight is therefore 180 kg of high strength steel. The following table shows the materials for this vehicle.

Table 4-18 DME Truck Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	2,768	33.03%
	High Strength	180	2.15%
	Stainless	15	0.18%
Iron	Cast	2,674	31.91%
Aluminum	Average Wrought	1,401	16.72%
	Average Cast	0	0.00%
Copper		23	0.27%
Zinc		0	0.00%
Magnesium	Average	0	0.00%
Powder Metals		0	0.00%
Glass		60	0.72%
Rubber		459	5.48%
Fluids & Lubricants		126	1.50%
Fiber Glass		74	0.88%
Plastics	High Density Polyethylene	0	0.00%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	0	0.00%
	Average	345	4.12%
Composites	Glass Fiber Composite Plastic	0	0.00%
	CF Composite for General Use	0	0.00%
	CF Composite for High Pressure	0	0.00%
Lead	Average	95	1.13%
Nickel	Average	0	0.00%
Titanium		0	0.00%
Lithium battery		0	0.00%
Other		159	1.90%
Total		8,379	100.00%

4.2.1.3 Natural Gas Truck

The gas truck is the same as the diesel truck except that 300 kg of carbon fibre for high pressure applications has been added to the vehicle. Other types of tanks could be considered but weight is important for commercial trucks where the payload must be reduced if the truck weight increases. The following table shows the materials for this vehicle.

Table 4-19 Gas Truck Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	2,768	32.57%
	High Strength	0	0.00%
	Stainless	15	0.18%
Iron	Cast	2,674	31.46%
Aluminum	Average Wrought	1,401	16.48%
	Average Cast	0	0.00%
Copper		23	0.27%
Zinc		0	0.00%
Magnesium	Average	0	0.00%
Powder Metals		0	0.00%
Glass		60	0.71%
Rubber		459	5.40%
Fluids & Lubricants		126	1.48%
Fiber Glass		74	0.87%
Plastics	High Density Polyethylene	0	0.00%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	0	0.00%
	Average	345	4.06%
Composites	Glass Fiber Composite Plastic	0	0.00%
	CF Composite for General Use	0	0.00%
	CF Composite for High Pressure	300	3.53%
Lead	Average	95	1.12%
Nickel	Average	0	0.00%
Titanium		0	0.00%
Lithium battery		0	0.00%
Other		159	1.87%
Total		8,499	100.00%

4.2.2 Buses

The bus in the model is based on a Mercedes 12 M city bus as shown in the following figure. This vehicle has a gross vehicle weight of 19,000 kg. It has a curb weight of 10,700 kg (Mercedes-Benz).

Figure 4-3 Mercedes- Benz City Bus

A study compared the lifecycle emissions of diesel, natural gas, and fuel cell busses and that included the vehicle manufacturing stage (Fischer et al, 2005). The study was based on the Citaro bus. The data from that study did not include all of the materials in the model but an estimation of the materials in the bus developed from the data is shown in the following table.

Table 4-20 Diesel Bus Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	5,366	50.0%
	High Strength	0	0.0%
	Stainless	429	4.0%
Iron	Cast	966	9.0%
Aluminum	Average Wrought	966	9.0%
	Average Cast	0	0.0%
Copper		80	0.8%
Zinc		80	0.8%
Magnesium	Average	80	0.8%
Powder Metals		80	0.8%
Glass		537	5.0%
Rubber		644	6.0%
Fluids & Lubricants		429	4.0%
Fiber Glass		0	0.0%
Plastics	High Density Polyethylene	0	0.0%
	Polyethylene Terephthalate	0	0.0%
	Polypropylene	0	0.0%
	Average	644	6.0%
Composites	Glass Fiber Composite Plastic	0	0.0%
	CF Composite for General Use	0	0.0%
	CF Composite for High Pressure	0	0.0%
Lead	Average	0	0.0%
Nickel	Average	0	0.0%
Titanium		0	0.0%
Lithium battery		0	0.0%
Other		429	4.0%
Total		10,732	100.0%

4.2.2.1 Natural Gas Bus

The natural gas bus is similar to the diesel bus except that the weight increases by 1,049 kg. The variation is related to the fuel storage which leads to an increased steel share and to a share of carbon fibre of 4 %, the rest of the materials are scaled down accordingly.

Table 4-21 Gas Bus Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	5,947	50.5%
	High Strength	0	0.0%
	Stainless	429	3.6%
Iron	Cast	966	8.2%
Aluminum	Average Wrought	966	8.2%
	Average Cast	0	0.0%
Copper		80	0.7%
Zinc		80	0.7%
Magnesium	Average	80	0.7%
Powder Metals		80	0.7%
Glass		537	4.6%
Rubber		644	5.5%
Fluids & Lubricants		429	3.6%
Fiber Glass		0	0.0%
Plastics	High Density Polyethylene	0	0.0%
	Polyethylene Terephthalate	0	0.0%
	Polypropylene	0	0.0%
	Average	644	5.5%
Composites	Glass Fiber Composite Plastic	0	0.0%
	CF Composite for General Use	0	0.0%
	CF Composite for High Pressure	468	4.0%
Lead	Average	0	0.0%
Nickel	Average	0	0.0%
Titanium		0	0.0%
Lithium battery		0	0.0%
Other		429	3.6%
Total		11,781	100.0%

4.2.2.2 Electric Bus

The electric bus in the model is based on a 12 m bus manufactured by Ebusco in the Netherlands. According the manufacturer the curb weight of the bus is 11,800 kg. The bus has an all aluminum body. The maximum total weight is 18,000 kg. The capacity of the lithium ion battery pack is 311 kWh. The charging time for a full battery is 1.6 hours. The distance the bus can travel is 300 km. The bus is shown in the following figure.

Figure 4-4 Electric Bus

Lithium ion batteries have a current energy density of about 0.1 kWh/kg (US DOE). This would suggest that the battery pack has a weight of 3,000 kg. There will be less steel and cast iron employed as the weight of the bus is only 100 kg more than the standard bus. The default bill of material for the electric bus used in the model is shown below.

Table 4-22 Electric Bus Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	3,766	31.9%
	High Strength	0	0.0%
	Stainless	429	3.6%
Iron	Cast	100	0.8%
Aluminum	Average Wrought	1,500	12.7%
	Average Cast	0	0.0%
Copper		80	0.7%
Zinc		80	0.7%
Magnesium	Average	80	0.7%
Powder Metals		80	0.7%
Glass		537	4.5%
Rubber		644	5.5%
Fluids & Lubricants		429	3.6%
Fiber Glass		0	0.0%
Plastics	High Density Polyethylene	0	0.0%
	Polyethylene Terephthalate	0	0.0%
	Polypropylene	0	0.0%
	Average	644	5.5%
Composites	Glass Fiber Composite Plastic	0	0.0%
	CF Composite for General Use	0	0.0%
	CF Composite for High Pressure	0	0.0%
Lead	Average	0	0.0%
Nickel	Average	0	0.0%
Titanium		0	0.0%
Lithium battery		3,000	25.4%
Other		429	3.6%
Total		11,800	99.90%

4.2.2.3 Hybrid Buses

The hybrid bus in the model is similar to the Volvo hybrid bus. It has an 86 kW diesel engine and a 5 kWh lithium ion battery pack. The estimated bill of material is shown in the following table.

Table 4-23 Hybrid Bus Bill of Materials

Material		Weight, kg	Percent of Total weight
Steel	Average	5,450	46.2%
	High Strength	0	0.0%
	Stainless	429	3.6%
Iron	Cast	900	7.6%
Aluminum	Average Wrought	1,500	12.7%
	Average Cast	0	0.0%
Copper		80	0.7%
Zinc		80	0.7%
Magnesium	Average	80	0.7%
Powder Metals		80	0.7%
Glass		537	4.5%
Rubber		644	5.5%
Fluids & Lubricants		429	3.6%
Fiber Glass		0	0.0%
Plastics	High Density Polyethylene	0	0.0%
	Polyethylene Terephthalate	0	0.0%
	Polypropylene	0	0.0%
	Average	644	5.5%
Composites	Glass Fiber Composite Plastic	0	0.0%
	CF Composite for General Use	0	0.0%
	CF Composite for High Pressure	468	4.0%
Lead	Average	0	0.0%
Nickel	Average	0	0.0%
Titanium		0	0.0%
Lithium battery		50	0.4%
Other		429	3.6%
Total		11,800	100.00%

4.3 TRAINS

The model contains both local and intercity trains. In both cases there are diesel versions and an electric version for the intercity train and a natural gas version for the commuter train.

4.3.1 Local Trains

The model contains both diesel and natural gas commuter trains. The trains are Alstom designs from the 2006-2007 period (Lint 41). The specifications in the model are summarized below.

Table 4-24 Commuter Train Specifications

	Diesel	Gas
Speed, km/hour	180	180
Weight, tonnes	63	63
Wagon material	Steel	Steel
Energy consumption	0.502 MJ/t-km	0.502 MJ/t-km

No Environmental Product Declaration (EPD) for these trains could be found but one for another Alston (2006) diesel powered model was found. The estimated bill of material is shown in the following table.

Table 4-25 Local Train Bill of Material

Material		Weight, kg	Percent of Total weight
Steel	Average	12,607	20.01%
	High Strength	12,607	20.01%
	Stainless	12,941	20.54%
Iron	Cast	7,235	11.48%
Aluminum	Average Wrought	5,501	8.73%
	Average Cast	0	0
Copper		3,196	5.07%
Zinc		0	0
Magnesium	Average	0	0
Powder Metals		0	0
Glass		1,150	1.83%
Rubber		784	1.24%
Fluids & Lubricants		686	1.09%
Fiber Glass		668	1.06%
Plastics	High Density Polyethylene	229	0.36%
	Polyethylene Terephthalate	0	0
	Polypropylene	41	0.07%
	Average	2,359	3.75%
Composites	Glass Fiber Composite Plastic	0	0
	CF Composite for General Use	0	0
	CF Composite for High Pressure	0	0
Lead	Average	0	0
Nickel	Average	76	0.12%
Titanium		0	0
Lithium battery		0	0
Other		2,920	4.64%
Total		63,000	100.00%

For the natural gas train we have added 2,000 kg of carbon fiber tanks for the fuel storage. The bill of material is shown in the following table.

Table 4-26 Local NG Train Bill of Material

Material		Weight, kg	Percent of Total weight
Steel	Average	12,607	19.40%
	High Strength	12,607	19.40%
	Stainless	12,941	19.91%
Iron	Cast	7,235	11.13%
Aluminum	Average Wrought	5,501	8.46%
	Average Cast	0	0.00%
Copper		3,196	4.92%
Zinc		0	0.00%
Magnesium	Average	0	0.00%
Powder Metals		0	0.00%
Glass		1,150	1.77%
Rubber		784	1.21%
Fluids & Lubricants		686	1.05%
Fiber Glass		668	1.03%
Plastics	High Density Polyethylene	229	0.35%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	41	0.06%
	Average	2,359	3.63%
Composites	Glass Fiber Composite Plastic	0	0.00%
	CF Composite for General Use	0	0.00%
	CF Composite for High Pressure	2,000	3.08%
Lead	Average	0	0.00%
Nickel	Average	76	0.12%
Titanium		0	0.00%
Lithium battery		0	0.00%
Other		2,920	4.49%
Total		65,000	100.01%

4.3.2 IC Trains

The model contains both diesel and electric intercity trains. The trains are based on ABB Scania designs from the 1990’s as shown in the following figure.

Figure 4-5 IC Trains

The train specifications in the model are summarized below.

Table 4-27 IC Trains Specifications

	Diesel	Electric
Speed, km/hour	180	180
Weight, tonnes	97	133
Wagon material	Aluminum	Aluminum
Energy consumption	0.394 MJ/t-km	0.191 MJ/t-km

ABB Scania is now part of Bombardier. Bombardier has published Environmental Product Declarations for several of their trains. Two different intercity trains are compared in the following table. Both are electric designs.

Table 4-28 Bombardier EPD's

Material	REGINA Intercity X55	OMNEO
Metals	79.3%	83.8%
Polymers	4.0%	3.6%
Elastomers	3.3%	2.4%
Glass	3.1%	2.2%
Fluids	0.8%	1.4%
Modified organic natural materials	2.7%	0.3%
Others	6.7%	6.3%
Total	100.0%	100.0%

Since the Alstom material breakdown is more detailed than the Bombardier data we have used that for the diesel intercity train. For the electric IC train we have replaced some of the cast iron with copper and the weight is higher in the model. The Bill of Material for the electric IC train is shown in the following table.

Table 4-29 Electric IC Train Bill of Material

Material		Weight, kg	Percent of Total weight
Steel	Average	26,614	20.01%
	High Strength	26,614	20.01%
	Stainless	27,318	20.54%
Iron	Cast	12,273	9.23%
Aluminum	Average Wrought	14,614	10.99%
	Average Cast	0	0.00%
Copper		6,748	5.07%
Zinc		0	0.00%
Magnesium	Average	0	0.00%
Powder Metals		0	0.00%
Glass		2,428	1.83%
Rubber		1,655	1.24%
Fluids & Lubricants		1,448	1.09%
Fiber Glass		1,411	1.06%
Plastics	High Density Polyethylene	484	0.36%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	87	0.07%
	Average	4,981	3.75%
Composites	Glass Fiber Composite Plastic	0	0.00%
	CF Composite for General Use	0	0.00%
	CF Composite for High Pressure	0	0.00%
Lead	Average	0	0.00%
Nickel	Average	160	0.12%
Titanium		0	0.00%
Lithium battery		0	0.00%
Other		6,165	4.64%
Total		133,000	100.01%

4.4 Marine Vessels

Two maritime vessels are included in the model, a large 9000 TEU container ship and a fast ferry. The specifications of both are described below.

4.4.1 9000 TEU Vessels

A typical 9000 TEU container vessel is shown in the following figure.

Figure 4-6 9000 TEU Container Vessel

With financial support from the Danish Maritime Fund, the Technological University of Denmark (DTU) and the University of Southern Denmark have developed a tool which can calculate ships' fuel gas emissions and energy efficiency. One of the tools is for container ships (Danish Shipholders Association). The data in the tool is based on a regression analysis of the IHS Fairplay data for container ships.

The light ship weight is the actual weight of a vessel when complete and ready for service but empty. The lightship weight for a 9000 TEU ship is 35,000 tonnes. The lightship weight (WL) is composed of:

steel weight + outfit weight + machinery weight + margin

The steel weight of the vessel in the tool is 30,000 tonnes (85.7% of the total weight). The remainder of the weight is divided between cast iron, copper, and other materials. The bill of materials is shown in the following table. The breakdown of the remainder of the vessels has been guided by the final report on the LCA Ship project (Mariterm).

Table 4-30 9000 TEU Vessel Bill of Materials

Material	Weight, tonnes	Percentage
Steel	30,000	85.71%
Cast Iron	2,500	7.14%
Copper	500	1.43%
Other Materials	2,000	5.71%
Total	35,000	99.99%

While the model has two fuels for the container vessel, a diesel and a dual fuel propulsion system, the same bill of materials is used for both as there is insufficient information available to differentiate between the two.

4.4.2 Fast Ferries

Denmark has fast ferry service to Norway with the Color Line Superspeed 1 and 2 Ro-pax ferries. These ferries operate between Kristiansand, Norway and Hirtshals, Denmark. No detailed information was found for these vessels. Ro Pax vessels can have a wide range of sizes. General guidance on the bill of material was derived from the Fusion Technology Ferry Design Report (University of Strathclyde). These vessels have a higher percentage of outfit weight than the container vessels. The estimate weights are shown below.

Table 4-31 Fast Ferries Bill of Materials

Material	Weight, tonnes	Percentage
Steel	5,500	53.14%
Cast Iron	800	7.73%
Copper	50	0.48%
Other Materials	4,000	38.65%
Total	10,350	100.00%

4.5 AIRPLANES

Johanning (2013) identified two papers that considered the lifecycle assessment of airplanes. The first was a Doctoral Thesis by Chester (2008). Chester used the Environmental Input-Output approach to estimating the emissions associated with airplane manufacture. This approach estimates emissions based on the cost of the product and the national Input-Output accounts. The second is the most comprehensive assessment of the materials in airplanes which was developed by Lopez (2010) for the Airbus 330-200 airplane. The Lopez results are shown in the following table.

Table 4-32 Airbus A330 Bill of Materials

Material	Weight, kg	Percentage
Aluminum	61,903	58.28%
Steel	20,388	19.19%
Titanium	8,161	7.68%
Nickel	2,948	2.78%
Carbon Fibre	9,743	9.17%
Glass fibre	1,059	1.00%
Miscellaneous	2,015	1.90%
Total	106,218	100.00%

This manufacturer's empty weight does not include the following operator items.

- Unusable fuel,
- Oil for engines, IDG and APU,
- Water for galleys and lavatories,
- Chemical fluids for waste tanks,
- Aircraft documents and tool kits,
- Passenger seats and life vests,
- Galley structures and fixed equipment,
- Catering,
- Flight and cabin crew and their baggage,

- Emergency equipment.

The operational empty weight for this plane is 109,000 to 124,500 kg.

The model is built around an average SAS flight. The average passenger load is only 65 people. A more appropriate aircraft would be the 107 passenger A318 plane as shown below.

Figure 4-7 Airbus 318

The operating empty weight of this plane is 39,500 kg (Airbus, 2009). This has been scaled to 33,776 kg for the manufacturers' empty weight and the 5,724 kg for operating items has been split to 2,862 kg for fluids and the remainder for other materials. The bill of materials for the model is shown in the following table. The steel will be assumed to be 50% high strength steel and 50% stainless steel.

Table 4-33 Airplane Bill of Materials for Model

Material		Weight, kg	Percent of Total weight
Steel	Average	0	0.00%
	High Strength	3,241	8.21%
	Stainless	3,242	8.21%
Iron	Cast	0	0.00%
Aluminum	Average Wrought	16,685	42.24%
	Average Cast	3,000	7.59%
Copper		1,000	2.53%
Zinc		0	0.00%
Magnesium	Average	0	0.00%
Powder Metals		0	0.00%
Glass		0	0.00%
Rubber		1,000	2.53%
Fluids & Lubricants		1,862	4.71%
Fiber Glass		0	0.00%
Plastics	High Density Polyethylene	0	0.00%
	Polyethylene Terephthalate	0	0.00%
	Polypropylene	0	0.00%
	Average	1,343	3.40%
Composites	Glass Fiber Composite Plastic	337	0.85%
	CF Composite for General Use	3,098	7.84%
	CF Composite for High Pressure	0	0.00%
Lead	Average	0	0.00%
Nickel	Average	160	0.41%
Titanium		937	2.37%
Lithium battery		2,595	6.57%
Other		1,000	2.53%
Total		39,500	99.99%

The airplane bill of material is very different than the land and sea vessels. These materials are dominated by aluminum and other high strength to weight materials.

5. VEHICLE ASSEMBLY

Another important part of the energy use and emissions associated with the manufacture of the vehicles is related to the assembly. Information on this subject is presented below.

5.1 PASSENGER CARS

GREET 2 includes the energy use and combustion emissions associated with vehicle assembly. This includes paint production, painting, heat and light for the plant, welding, and compressed air. The information is presented on a per vehicle basis but the ICE vehicle in the model has a weight of 1,292 kg. The energy is two thirds natural gas and one third electricity.

Table 5-1 GREET Assembly Emissions

	Value
Natural gas, MJ/kg	4.3
Electricity, MJ/kg	2.1
Total Energy	6.4
$CO_{2,}$ g/kg	203
CH_4 g/kg	0.5
N_2O g/kg	0.0
SO_2 g/kg	0.2
NOx g/kg	0.2
Particulate g/kg	0.03
Total GHG g CO_2e/kg	219

GHGenius uses a value for energy for assembly of 5.5 MJ/kg and a similar split with one third electricity and the rest thermal with almost all of that natural gas. Data from Statistics Canada and Natural Resources Canada showed an energy use in the motor vehicle manufacturing sector in 2010 equal to 6.6 GJ/vehicle (this includes cars and trucks).

Boyd (2010) reported electric power use of 2.3 GJ/vehicle and heat use of 4.9 GJ/vehicle. This also equates to 5.5 MJ/kg of vehicle. This value is used in the model for all light duty vehicles. The distribution of energy use is 27% electricity, 7% oil, 5% coal, and 61% natural gas.

5.2 HEAVY DUTY VEHICLES

The available information on the energy use and emissions from heavy duty vehicle manufacture is presented below.

5.2.1 Trucks

The assembly of heavy duty vehicles could be different from the more mass produced passenger vehicles. Li (2009) reports the total emissions per vehicle for Volvo as shown in the following table.

Table 5-2 Volvo Energy and Emissions

Stage	Kg CO_2e/Vehicle
Material production	8,710
Suppliers production	1,810
Transport to Volvo	879
Volvo Manufacturing	945
Transport within Volvo	895
Total	13,239

The assembly emissions total 1,840 kg CO_2e/vehicle or 0.22 kg/kg of vehicle if our 8,200 kg vehicle is an average vehicle. This is quite a bit lower the value that would be calculated from the light duty factor.

Scania (2014) report on the energy use and emissions from all of their factories. Between 2009 and 2013 the energy use per vehicle varied from 27.7 to 50.4 GJ per vehicle. They reported plant related CO_2eq emissions ranged from 0.94 to 1.73 tonnes per vehicle. The average carbon intensity is only 34 g/MJ, indicating a high proportion of renewable energy in the mix. Using the 8,200 kg vehicle weight, the energy use per kg would range from 3.3 to 6.1 MJ/kg (average 4.7 MJ/kg).

Daimler (2014) report GHG emissions of 2.44 tonnes per truck produced in 2013.

We have set the assembly energy for trucks to 4.5 MJ/kg and kept the same distribution of energy sources as used for the light duty vehicles. This produces GHG emissions related to vehicle assembly of 2.7 tonnes/truck.

5.2.2 Buses

Daimler report GHG emissions of 2.39 tonnes per bus in 2013. This is similar to the per truck emissions but our buses are heavier than the trucks. The energy use is set to 3.5 MJ/kg for the buses.

5.3 TRAINS

Several of the EPD's that have been found for trains contain information on the emissions associated with the materials in trains and the emissions associated with the assembly of the trains. The information is not always presented in the same manner but the results are consistent. The data is summarized in the following table.

Table 5-3 Emissions from Train Assembly

Source	Materials	Assembly	Ratio Assembly to Materials
EPD Regina ICE	0.75 kg CO_2/pass-km	0.79 CO_2/pass-km	1.05
EPD Talent 2	0.99 kg CO_2/pass-km	0.67 kg CO_2/pass-km	0.68
	0.00122 MJ/pass-km	0.00051 MJ/pass-km	0.42
Alstom Lirex	750 t CO_2	880 t CO_2	1.17
	13,900 GJ	15,300 GJ	1.10

The Alstom data is for a six car train with a weight of 206 tonnes. The emissions are 3.6 t CO_2/t of train. The trains in the model are 63 to 133 tonnes and have emissions of 3.7 to 4.7 t CO_2/t train, which is reasonably close.

For the assembly energy we have assumed that an equal quantity of energy is consumed in the assembly as in the materials. This requires an energy intensity of 50 MJ/kg of train, an order of magnitude **higher than** LDV, buses and trucks.

5.4 MARINE VESSELS

Kameyama reported that 90% of the GHG emissions for shipbuilding were related to the materials. Of the remainder 5% was related to the electricity use for welding, 1% for the fuel consumed during sea trials, 2% for materials processing and 2% for shipping materials and parts.

Hill et al (2011) assumed that the GHG emissions associated with shipbuilding were 10% of the emissions from the materials although in their study they noted that real data on these emissions were a data gap in their study.

The US Census reported the following data for the US shipbuilding sector in 2004.

Table 5-4 US Shipbuilding

	Value
Value of shipments	$23.7 Billion
Electricity consumed	2,587,715 MWh
Electricity purchased	$129.7 Million
Fuels purchased	$46.1 Million

The cost of electricity was $0.05/kWh or $12/GJ. Natural gas in 2004 was about $6/GJ. This data would support the assumption that electricity comprised about 50 to 60% of the energy consumption of shipbuilding. The cost of electricity is 5.4% of the value of the ship.

The 9000 TEU ship has a cost of 450 million DKK in the model or $75 million USD. Applying the electricity factor from the above table would suggest that the power consumption is 8,200 MWH of power was used in the construction of the ship. This is 29,500,000 MJ for the 35,000,000 kg ship or 850 kJ/kg. At 50% of the energy, there would also be 850 kJ/kg for other fuels which we assume are diesel fuel. This results in GHG emissions for assembly of about 7.5% of the emissions for the materials.

The emissions and energy use for ships are the same order of magnitude **as the** values for LDVs, trucks and buses.

5.5 AIRPLANES

Boeing and Airbus both published environmental performance reports that provide some information on the manufacturing and assembly emissions. In both cases some estimates must be made to estimate the energy and emissions from the manufacturing facilities.

5.5.1 Boeing

The Boeing 2013 Environmental Report (2013) has more data in it than the 2014 report. The data from the 2013 report (on 2012 performance) is shown in the following table. Boeing (2013b) also report the number and type of commercial aircraft delivered in 2012. The estimated average weight of the 601 commercial aircraft was 68,000 kg and it has been assumed that the average weight of the 144 military aircraft delivered was the same, as no information on these is available. This weight is used to estimate the energy use and emissions on a per kilogram basis. The energy is 45% natural gas and 55% electricity.

Table 5-5 Boeing Environmental Data 2012

Parameter	Value
Deliveries, plane	745
Deliveries, commercial planes	601
CO_2 emissions, million tonnes	1.17
CO_2 emissions/plane, tonnes/plane	1,570
CO_2 emissions kg/kg materials	23
Energy, million GJ	13.33
Energy/plane, GJ/plane	17,900
Energy, MJ/kg	263

5.5.2 Airbus

The Airbus Environmental Report (2014) has more detail in some respects than the Boeing report, but less detail in other respects. The energy consumption data is shown in the following table.

Table 5-6 Airbus Energy and Emission Data

Energy	MWh	GJ	%
Natural gas	1,491,201	5,368,324	37.1%
Diesel	38,674	139,226	1.0%
LNG	764	2,750	0.0%
LPG	14,157	50,965	0.4%
Biomass	19,298	69,473	0.5%
Gasoline	6,712	24,163	0.2%
Jet Fuel	989,142	3,560,911	24.6%
Electricity	1,463,417	5,268,301	36.4%
Total	4,023,365	14,484,114	

Airbus (2014b) delivered 626 commercial airplanes in 2013. The estimated average empty weight of the planes was 65,000 kg. The number of military planes delivered was 31 and including those does not significantly change the average weight. The average energy use per plane was 21,400 GJ/plane and the average on a per kilogram basis was 333 MJ/kg.

For the model we have used 300,000 kJ/kg as the average energy consumption and the Airbus split between fuels.

6. ENERGY AND EMISSIONS

The model results for the energy use and emissions associated with the materials and assembly of the vehicles are presented in this section of the report. The model produces results per vehicle, per kilometre travelled and per GJ of energy consumed by the vehicle. The lifecycle emissions of CO_2, CH_4, N_2O, SOx, NOx, particulate matter, and the CO_2eq are provided. The GWPs specified on the Supplementary sheet are used for the CO_2eq calculation, making it consistent with the rest of the model.

6.1 PASSENGER CARS

There are three categories of passenger cars in the model, vehicles powered by an internal combustion engines, fuel cell vehicles, and hybrid electric or pure electric vehicles. The results from each class are presented below.

6.1.1 Internal Combustion

There have been four internal combustion vehicles added to the model and two of the vehicles can use alternative fuels (E-85 or RME) without any significant changes to the vehicles. The results for the four modelled vehicles are shown in the following table.

Table 6-1 Results for ICE Vehicles - Materials

	Std gasoline motor	Std diesel motor	Diesel motor DME	Natural Gas Motor
	g/Vehicle			
Energy (MJ)	56,193	58,010	60,414	61,253
CO_2	4,365,310	4,545,314	4,727,341	4,726,348
CH_4	586	591	621	631
N_2O	29	30	32	31
SOx	5,132	5,192	5,306	5,295
NOx	4,756	4,836	5,017	5,091
Particulate	73	76	80	79
Total GHG	4,388,593	4,569,079	4,752,274	4,751,414

The emissions from the vehicles are quite similar; the requirement for high pressure storage tanks for the DME and natural gas vehicles does increase the GHG emissions by about 8%.

The energy use and emissions associated with the assembly of the vehicles are shown in the following table.

Table 6-2 Results for ICE Vehicles - Assembly

	Std gasoline motor	Std diesel motor	Diesel motor DME	Natural Gas Motor
	g/Vehicle			
Energy (MJ)	7,205	7,535	7,964	7,920
CO_2	519,675	543,477	574,420	571,246
CH_4	84	88	93	92
N_2O	4	4	4	4
SOx	314	328	347	345
NOx	533	557	589	586
Particulate	10	10	11	11
Total GHG	522,842	546,789	577,920	574,727

The emissions associated with the assembly of the vehicles are an order of magnitude lower than those associated with the materials in the vehicles.

Mercedes-Benz (2014b) publishes an environmental certificate for the A class vehicle. The vehicle has a weight of 1,295 kg for the gasoline engine and 1,320 for the diesel engine version. Both are slightly less than the values in the model, 1,310 kg and 1,370 kg for the gasoline and diesel vehicles. They report GHG emissions of 5.8 tonnes for the vehicle production compared to the 4.9 to 5.1 tonnes per vehicle calculated here. Their material breakdown shows more aluminum and plastics used, both of which would lead to higher GHG emissions. The vehicles are also produced in Germany where the electric power has a higher emission intensity. Changing the electric power carbon intensity to that of Germany provides essentially the same emissions as Mercedes reports.

6.1.2 Hybrid and Electric Vehicles

The model includes a plugin hybrid and a battery electric vehicle. There is some flexibility in the model for the user to specify the battery size and the number of battery changes required over the lifetime of the vehicle. These results assume that the battery lasts for the lifetime of the vehicle and have battery sizes that are typical of the literature. The results are compared to the standard gasoline and diesel vehicles.

Table 6-3 Results for Hybrid and Electric Vehicles - Materials

	Std gasoline motor	Std diesel motor	Plugin Hybrid	Electric Vehicle
	g/Vehicle			
Energy (MJ)	56,193	58,010	66,518	69,490
CO_2	4,365,310	4,545,314	5,151,905	5,301,944
CH_4	586	591	692	763
N_2O	29	30	34	36
SOx	5,132	5,192	5,925	5,779
NOx	4,756	4,836	5,586	5,807
Particulate	73	76	87	92
Total GHG	4,388,593	4,569,079	5,179,375	5,331,688

The emissions for the hybrid and electric vehicles are up to 20% higher than those for the gasoline vehicle. The battery plays the major role in the higher emissions. Larger batteries or a requirement to change the batteries during the lifetime of the vehicle would increase the difference further would further.

The assembly emissions are shown in the following table. The differences here are not as large and are driven only by the difference in weight since there is no data available that would support a different energy use for the assembly of these vehicles compared to standard ICE vehicles.

Table 6-4 Results for Hybrid and Electric Vehicles - Assembly

	Std gasoline motor	Std diesel motor	Plugin Hybrid	Electric Vehicle
	g/Vehicle			
Energy (MJ)	7,205	7,535	8,135	7,508
CO_2	519,675	543,477	586,717	541,494
CH_4	84	88	95	87
N_2O	4	4	4	4
SOx	314	328	354	327
NOx	533	557	602	555
Particulate	10	10	11	10
Total GHG	522,842	546,789	590,292	544,793

6.1.3 Fuel Cell Vehicles

The results for the fuel cell vehicles are compared to the standard gasoline engine. The hydrogen fuel cell vehicles must store the fuel at very high pressures and a lightweight carbon fibre wrapped tank has been assumed for the storage tank. The energy and emissions associated with the carbon fibre are very high in the model. The emissions associated with the materials in the vehicles are almost double those of the gasoline vehicle as a result of this. The methanol vehicle can use an atmospheric pressure tank and the emissions associated with this vehicle are about 50% higher than the gasoline vehicle.

Table 6-5 Results for Fuel Cell Vehicles - Materials

	Std gasoline motor	Hydrogen Fuel Cell	Hybrid Hydrogen FCV	Methanol Hybrid FCV
	g/Vehicle			
Energy (MJ)	56,193	110,677	112,048	84,706
CO_2	4,365,310	8,212,647	8,312,344	6,375,604
CH_4	586	1,152	1,169	953
N_2O	29	53	54	43
SOx	5,132	7,928	8,031	6,710
NOx	4,756	8,841	8,956	7,048
Particulate	73	137	139	112
Total GHG	4,388,593	8,257,222	8,357,532	6,412,289

The assembly emissions are shown in the following table. Again, these are just a function of the weight of the vehicle and assume no difference between the standard gasoline vehicle and the fuel cell vehicles other than due to any weight differences.

Table 6-6 Results for Fuel Cell Vehicles - Assembly

	Std gasoline motor	Hydrogen Fuel Cell	Hybrid Hydrogen FCV	Methanol Hybrid FCV
	g/Vehicle			
Energy (MJ)	7,205	8,019	8,019	8,019
CO_2	519,675	578,387	578,387	578,387
CH_4	84	93	93	93
N_2O	4	4	4	4
SOx	314	349	349	349
NOx	533	593	593	593
Particulate	10	11	11	11
Total GHG	522,842	581,911	581,911	581,911

6.2 HEAVY DUTY VEHICLES

There are heavy duty trucks and buses in the model. The emissions associated with the manufacture of these vehicles is discussed below.

6.2.1 Trucks

There are four trucks in the model, a diesel powered truck, and identical truck fuelled by RME, a DME fuelled truck, and a natural gas fuelled truck. The emissions associated with the materials in the vehicles are shown in the following table. The trucks are almost six times heavier than the light duty vehicles to the emissions associated with the materials of the trucks are correspondingly larger.

Table 6-7 Results for Trucks - Materials

	Diesel Truck	DME Truck	RME Truck	Natural Gas Truck
	g/Vehicle			
Energy (MJ)	409,607	415,256	409,307	559,673
CO_2	33,663,365	34,091,924	33,636,683	44,360,884
CH_4	6,418	6,488	6,417	7,720
N_2O	296	300	296	358
SOx	33,242	33,521	33,152	40,587
NOx	36,147	36,575	36,108	46,817
Particulate	828	837	828	985
Total GHG	33,912,146	34,343,440	33,885,416	44,660,477

The higher emissions for the natural gas truck result from the high pressure fuel tanks. Carbon fibre tanks were assumed to be used.

The assembly emissions are shown in the following table. Again, these are just a function of the weight of the vehicle but the available data suggests that about 20% less energy is required to assemble these vehicles per kg of vehicle weight than the light duty vehicles.

Table 6-8 Results for Trucks - Assembly

	Diesel Truck	DME Truck	RME Truck	Natural Gas Truck
	g/Vehicle			
Energy (MJ)	36,900	37,710	36,900	38,250
CO_2	2,661,487	2,719,910	2,661,487	2,758,859
CH_4	429	438	429	445
N_2O	18	19	18	19
SOx	1,608	1,643	1,608	1,667
NOx	2,729	2,789	2,729	2,829
Particulate	51	52	51	53
Total GHG	2,677,705	2,736,484	2,677,705	2,775,670

6.2.2 Buses

There are four buses in the model, a diesel powered bus, a natural gas powered bus, a diesel hybrid bus, and a natural gas bus. The three alternative buses are also about 10% heavier than the diesel bus and they make more extensive use of aluminum, which also leads to higher emissions. The natural gas bus has carbon fibre tanks and the electric buses have their battery packs both of which lead to higher emissions.

Table 6-9 Results for Buses - Materials

	Diesel Bus	Natural Gas Bus	Electric Bus	Hybrid Bus
	g/Vehicle			
Energy (MJ)	481,255	722,999	787,688	787,680
CO_2	37,758,031	55,476,700	60,061,154	60,060,491
CH_4	6,050	10,309	10,183	10,183
N_2O	280	435	449	449
SOx	43,300	62,830	59,975	59,974
NOx	42,083	65,078	66,654	66,653
Particulate	741	1,182	1,211	1,211
Total GHG	37,992,857	55,864,182	60,449,397	60,448,728

The assembly emissions are shown in the following table. The available evidence suggests that buses use even less energy than trucks in the assembly process this may be due to the higher weight of the vehicles.

Table 6-10 Results for Buses - Assembly

	Diesel Bus	Natural Gas Bus	Electric Bus	Hybrid Bus
	g/Vehicle			
Energy (MJ)	37,450	41,230	41,300	41,300
CO_2	2,701,157	2,973,797	2,978,836	2,978,836
CH_4	435	479	480	480
N_2O	19	21	21	21
SOx	1,632	1,797	1,800	1,800
NOx	2,770	3,049	3,054	3,054
Particulate	52	57	57	57
Total GHG	2,717,617	2,991,918	2,996,988	2,996,988

6.3 TRAINS

There are four trains in the model. Two local trains powered by diesel or natural gas, and two intercity trains powered by diesel or electricity. The trains are the heaviest of the land based vehicles in the model and have the highest material emissions as a result.

Table 6-11 Results for Trains - Materials

	Diesel Intercity train	Diesel Local Train	Natural Gas Local Train	Electric Intercity Train
	g/Vehicle			
Energy (MJ)	4,599,649	2,987,401	3,987,401	6,593,240
CO_2	356,964,219	231,842,740	303,124,739	510,030,354
CH_4	67,705	43,973	52,652	103,981
N_2O	2,962	1,923	2,331	4,393
SOx	297,679	193,338	242,277	431,910
NOx	383,768	249,251	320,348	563,958
Particulate	8,313	5,399	6,446	12,462
Total GHG	359,539,375	233,515,264	305,135,779	513,938,986

The assembly emissions are shown in the following table. The available evidence suggests that trains have very high assembly emissions, about equal to the emissions associated with the materials, whereas the other land based vehicles have assembly emissions an order of magnitude lower. It is not clear what might be driving this difference.

Table 6-12 Results for Trains - Assembly

	Diesel Intercity train	Diesel Local Train	Natural Gas Local Train	Electric Intercity Train
	g/Vehicle			
Energy (MJ)	4,850,000	3,150,000	3,250,000	6,650,000
CO_2	349,816,057	227,200,119	234,412,821	479,644,696
CH_4	56,388	36,623	37,786	77,315
N_2O	2,423	1,573	1,623	3,322
SOx	211,356	137,273	141,630	289,798
NOx	358,685	232,960	240,356	491,805
Particulate	6,677	4,337	4,474	9,155
Total GHG	351,947,694	228,584,585	235,841,238	482,567,457

6.4 MARINE VESSELS

There are two marine vessels in the model; a ferry and a container ship. The container ship is the heaviest system in the model and there are three fuels but the three are all treated the same in the model. The bill of materials for the marine vessels is the least well developed of all of vehicles in the model due to a lack of data.

Table 6-13 Results for Marine Vessels - Materials

	Container Ship	Ferry
	g/Vehicle	
Energy (MJ)	862,261,441	305,656,229
CO_2	67,912,644,396	23,185,148,885
CH_4	8,032,914	2,582,646
N_2O	457,970	144,661
SOx	47,142,908	13,677,345
NOx	61,053,194	20,622,684
Particulate	1,208,073	378,573
Total GHG	68,249,942,330	23,292,824,061

The assembly emissions are shown in the following table. Very little information is available on the emissions associated with the assembly of ships. The available information suggests that the energy required per unit of weight is the lowest of all of the pathways in the model.

Table 6-14 Results for Marine Vessels – Assembly

	Container Ship	Ferry
	g/Vehicle	
Energy (MJ)	59,500,000	17,595,000
CO_2	5,156,709,416	1,524,912,641
CH_4	1,289,136	381,216
N_2O	50,454	14,920
SOx	12,306,071	3,639,081
NOx	8,082,592	2,390,138
Particulate	133,341	39,431
Total GHG	5,203,973,231	1,538,889,227

6.5 AIRPLANES

The model has been built around a small passenger jet as the existing data in the model was for an average SAS flight. The materials bill is based on the one bill of materials that is in the public domain and has been scaled to the appropriate size. The results are shown below.

Table 6-15 Results for Airplanes - Materials

	Airplane
	g/Vehicle
Energy (MJ)	4,356,281
CO_2	333,601,135
CH_4	89,089
N_2O	3,341
SOx	325,085
NOx	420,427
Particulate	9,800
Total GHG	336,823,972

The assembly emissions are shown in the following table. The energy use for airplane manufacture is the highest per unit of weight of all of the pathways in the model. It is one order of magnitude higher than train and two orders of magnitude higher than the rest of the vehicles. The information from Boeing and from Airbus was very similar.

Table 6-16 Results for Airplanes – Assembly

	Airplane
	g/Vehicle
Energy (MJ)	11,850,000
CO_2	916,605,076
CH_4	184,338
N_2O	7,358
SOx	1,399,142
NOx	1,205,229
Particulate	19,563
Total GHG	923,406,155

6.6 ALTERNATIVE FUNCTIONAL UNITS

All of the materials and assembly emissions for all of the pathways are also reported on a g/GJ and g/km basis. Both alternative presentations rely on the lifetime of the vehicle, the annual kilometres travelled, and the fuel efficiency; all of these parameters are user inputs in the model. The alternative presentation for the light duty internal combustion vehicles are shown in the following tables. For these vehicles the emissions for making the vehicles are 10 to 15% of the tailpipe emissions.

Table 6-17 Results for ICE Vehicles per Kilometre - Materials

	Std gasoline motor	Std diesel motor	Diesel motor DME	Natural Gas Motor
	g/km			
CO_2	14.9	15.5	16.1	16.1
CH_4	0.0	0.0	0.0	0.0
N_2O	0.0	0.0	0.0	0.0
SOx	0.0	0.0	0.0	0.0
NOx	0.0	0.0	0.0	0.0
Particulate	0.0	0.0	0.0	0.0
Total GHG	15.0	15.6	16.2	16.2

The emissions associated with the assembly of the vehicles are shown in the following table.

Table 6-18 Results for ICE Vehicles per Kilometre - Assembly

	Std gasoline motor	Std diesel motor	Diesel motor DME	Natural Gas Motor
	g/km			
CO_2	1.8	1.9	2.0	1.9
CH_4	0.000	0.000	0.000	0.000
N_2O	0.000	0.000	0.000	0.000
SOx	0.001	0.001	0.001	0.001
NOx	0.002	0.002	0.002	0.002
Particulate	0.000	0.000	0.000	0.000
Total GHG	1.8	1.9	2.0	2.0

The results on a per GJ of energy consumed basis are shown in the following tables.

Table 6-19 Results for ICE Vehicles per GJ - Materials

	Std gasoline motor	Std diesel motor	Diesel motor DME	Natural Gas Motor
	g/GJ			
CO_2	7,041	9,932	9,773	6,935
CH_4	0.9	1.3	1.3	0.9
N_2O	0.0	0.1	0.1	0.0
SOx	8.3	11.3	11.0	7.8
NOx	7.7	10.6	10.4	7.5
Particulate	0.1	0.2	0.2	0.1
Total GHG	7,079	9,984	9,825	6,971

Table 6-20 Results for ICE Vehicles per GJ – Assembly

	Std gasoline motor	Std diesel motor	Diesel motor DME	Natural Gas Motor
	g/GJ			
CO_2	838	1,188	1,188	838
CH_4	0.1	0.2	0.2	0.1
N_2O	0.0	0.0	0.0	0.0
SOx	0.5	0.7	0.7	0.5
NOx	0.9	1.2	1.2	0.9
Particulate	0.0	0.0	0.0	0.0
Total GHG	843	1,195	1,195	843

7. SUMMARY AND DISCUSSION

The emissions associated with the materials in vehicles and the assembly of the vehicles have been successfully added to the Danish LCA model. The new page in the model (Materials) is the last page in the Excel Workbook. It is linked to the other sheets in the model where it draws some of the required data for the calculations but the results from this sheet have not be linked to the results on other sheets although that could be done.

Some of the data on the Materials sheet will change when the year of the model is changed as this changes the data that is drawn from the existing sheets. The emissions associated with the process fuels will change and the vehicle characteristics will change.

The new sheet does have some flexibility. Spaces for four additional materials have been added. All that is required is the data on the materials to be added and the bills of materials to be changed. No equations need to be changed. Similarly if new process fuels are added then the equations will handle the new information and all that will be required is to change the types of energy used in the manufacture of the materials or in the assembly process.

7.1 HYBRID AND ELECTRIC VEHICLES

The bill of materials for the vehicles with lithium ion batteries has been done differently than the rest of the pathways. In the other pathways the fraction of each material is fixed and changing the weight of the vehicle will change the total energy use and emissions linearly to the change in weight. The vehicle weight is extracted from the vehicle sheet for that particular vehicle and fuel.

For the vehicles with the lithium ion battery, the vehicle weight and the proportion of each material changes with tree user inputs. The user can select the size of the battery (in kWh), the energy density of the battery (kg/kWh), and the number of battery changes required over the vehicle lifetime. These inputs will select the battery weight, which is added to the rest of the vehicle weights to get the bill of materials. The fraction of each material is then calculated in the model.

This approach gives a first order approximation. In actual practice the battery weight also has an impact on all other vehicle components. More batteries require stronger support structures, bigger brakes, etc.

7.2 PROCESS FUEL EMISSIONS

The upstream emissions for the various process fuels have been taken from a number of different places in the model and in some cases the data is incomplete, for example there are not separate details on methane and nitrous oxide emissions for natural gas production. Ideally the emissions for all of the process fuels could be located in a single place in the model and be a complete accounting of the emissions. This will become more important if more process fuels are added.

The base load electricity information has been assumed to the electricity used for materials production and vehicle assembly. Consideration could be given to using a generic EU power production number for this power. It could be added to one of the spaces for the spare process fuels and then have the electricity consumption in the model transferred to that source of power.

7.3 VEHICLE DATA

The information on the light duty vehicles in terms of weight, fuel economy, etc. appears to be taken from the JEC report version 4, whereas a version 4a has been released with slightly different data in some cases. The cells on the Materials sheet have a light green background and have comments in them where some of the differences were found.

There were a few cases (ferries and airplanes) where data was missing from the detail sheets for the vehicles. The required information was added to the materials sheet; however this added data doesn’t change with time. This information should be added to the appropriate sheets with the information for all four time periods. These cells also have a light green background in the Materials sheet.

There were other places where the data was on the detail sheet but as a note and not in the main data location. These cells are also shaded and commented.

7.4 TRANSPARENCY

The model uses the Offset and Indirect functions in Excel throughout the model. While this allows the model to function perfectly well it doesn’t allow for full transparency as the Formula Audit function doesn’t function with the Offset and Indirect functions. There are alternative ways of accomplishing the same function without using Offset and Indirect. If the model is released for use by a broader public consideration should be given to maximizing the transparency of the model.

The MMULT function has been used on the Materials sheet. This is similar to the Sumproduct function except that it allows one series to be vertical and the other to be horizontal. However there can’t be any blank cells in the two ranges as there can be with the Sumproduct function. Zeros must be entered in the MMULT function where blank cells are acceptable in the Sumproduct function.

7.5 FULL INTEGRATION

The results on the Materials sheet have not been linked to the results sheets for the rest of the model. This something that should be done.

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