

Life Cycle Energy and Greenhouse Gas (GHG) Assessments
of Automotive Material Substitution

User Guide for Version 5
of the
UCSB Automotive Energy and GHG Model

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Frequent Acronyms

BOM	Bill of Materials
GHG	Greenhouse gas
AHSS	Advanced high strength steel
ICEV-G	Gasoline-based pure internal combustion engine vehicle
ICEV-D	Diesel-based pure internal combustion engine vehicle
HEV	Gasoline-based hybrid electric vehicle
FCV	Fuel cell vehicle
BEV	Pure battery electric vehicle
PHEV20	Plug-in hybrid electric vehicle with a 20 mile range
PHEV40	Plug-in hybrid electric vehicle with a 40 mile range
WLTP	Worldwide harmonized Light vehicles Test Procedure
kWh (MWh)	Kilo Watt hour (Mega Watt hour)
MJ	Mega Joule
CO ₂ eq	Carbon dioxide equivalent

Important Variables

VM	Vehicle mass in kg
ED	Energy demand of the vehicle in MJ fuel energy and electricity / 100km driven
ES	Energy savings per mass savings in MJ fuel energy and electricity/ 100 km driven and 100 kg mass saved
TM	Total distance driven over the life of the vehicle (in km)
$m_i^{shipped}$	Amount of shipped material i required to manufacture the specified vehicle
$I_{ij}^p (I_{ij}^s)$	Environmental impact j from primary (secondary) production of 1kg of material i
I_{ij}^f	Environmental impact j from finishing of 1kg of material i
$I_j^{fp} (I_j^{fc})$	Environmental impact j from production (combustion) of 1MJ of fuel
I_j^{elp}	Environmental impact j from production of 1MJ of electricity
r_i^{cont}	Fraction of unfinished material i coming from secondary production
$(\alpha_i - 1)$	Reduction of external scrap collection due to scrap flows to and from the vehicle life cycle (in kg reduced collection / kg net scrap flow)
δ_i	Displaced external primary material production due to scrap flows to and from the vehicle life cycle (in kg displaced production / kg unfinished material)

1 Introduction

The main goal of the UCSB Automotive Energy and Greenhouse Gas (GHG) Model is to quantify the energy and GHG impacts of automotive material substitution under a broad range of conditions and in a completely transparent fashion. The functional unit *FU* of all studied product systems is defined as transportation services of passenger vehicles of equivalent size, utility, equipment, and power train configuration over their total vehicle life. The model uses attributional life cycle assessment (ALCA) methodology, even though consequential system expansion is used to account for the GHG and energy implications of scrap inputs to and outputs from the vehicle life cycle.

Version 4 of the model expanded the system boundaries of Version 3 in order to include most of the significant GHG-emitting processes in a vehicle life cycle. It is estimated that Version 4 captures 98-99% of the life cycle impacts of the studied vehicle life cycles. More importantly, it is estimated that Version 4 captures a least 99% of the energy and GHG impacts of the studied automotive material substitutions, i.e. the difference in impact between the alternative vehicles of equivalent size, utility, equipment, and power train configuration.

The new Version 5 of the model has the same goal and scope as Version 4. The fundamental calculations, i.e. the conversion of input data into GHG and energy results are identical between the two versions. However, the way the computations are implemented on the spreadsheets of Version 5 is very different from Version 4. This happened for the following reasons:

1. Version 5 can now be used in conjunction with the autoLCA model, which, in turn, enables the user to obtain results for a wide range of impact indicators. Version 5 has a feature that allows the user to transfer the selected input data to autoLCA.
2. Strictly separating the calculation of the activity levels for each unit process from their multiplication with the unit process inventories (and implicitly, the global warming potentials of the GHG emissions) dramatically simplifies the computational structure of the spreadsheet model.
3. The new, simplified computational structure of Version 5 simplifies maintenance and further development of the spreadsheet model.

4. Using the spreadsheet model to populate the autoLCA model radically simplifies the computational structure of autoLCA.
5. The new computational structure facilitates detailed contribution analysis

There are some important changes between Versions 4 and 5, which are listed here:

1. Data input has been separated into two parts, data input required by all model users (*Data Input* spreadsheet), and data input that should only be changed from the default setting by expert users (*Expert Data Input* spreadsheet). This makes the Version 5 more user-friendly and avoids that non-expert users inadvertently change default expert input data.
2. To the extent possible, Version 5 uses process inventory data from autoLCA, i.e. the GaBi life cycle inventory database from thinkstep. The sources of all inventory data are listed in column R of the *LCA Calculations* spreadsheet.
3. To the extent possible, Version 5 uses driving energy demand, *ED*, and energy savings, *ES*, data generated with the Malen & Geyer Power Train Model. The only power train types currently not supported by the Malen & Geyer Power Train Model are HEV and FCV. For those two, the original Version 4 data from fka is used.
4. The use of the Malen & Geyer Power Train Model made it possible to add *ED* and *ES* data for the WLTP 3b driving cycle for ICEV-G, ICEV-D, PHEV20, PHEV40, and BEV.
5. Scrap inputs to and outputs from the vehicle life cycle are accounted for through consequential system expansion only, i.e. multistep recycling (MSR) methodology has been removed. It recently emerged that MSR methods are based on a flawed assumption and should thus be avoided.
6. The scrap market response parameter was changed from α to $(\alpha - 1)$, in order to improve intuition and align it with the way it is used in more recent models and publications.

2 Description of the Calculations in Model Version 5

Version 5 of the UCSB Automotive Energy and GHG Model calculates environmental impacts from vehicle life cycles in three distinct life cycle stages, which are

1. Production of the vehicle
2. Use of the vehicle
3. Recycling of vehicle

Figure 1 shows a high-level process flow diagram of the model.

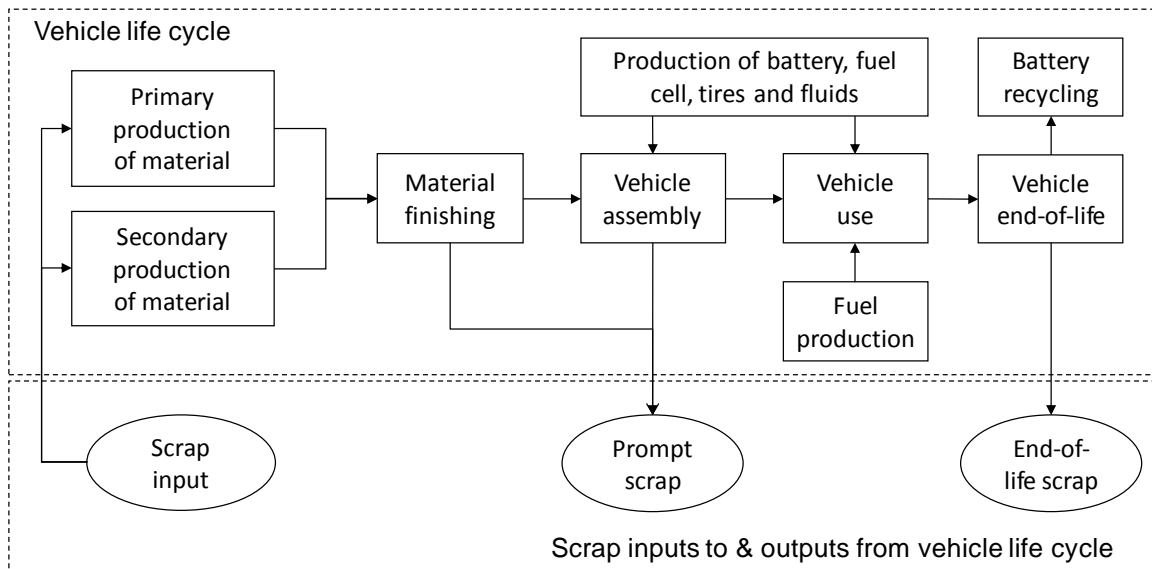


Figure 1: System boundaries of Version 5 of the UCSB Automotive Energy and GHG Model

The vehicle production stage distinguishes between 20 different material classes and also accounts for the production of drive battery, fuel cell, fluids, and tires. Replacements of drive battery, fluids, and tires are modelled in accordance with their chosen lifetimes. Scrap inputs to and outputs from production are modelled through consequential system expansion. The vehicle use phase consists of production and combustion/use of the selected fuel mix. End-of-life vehicle recycling models drive battery and automotive material recycling. Consequential system expansion is applied to battery and material recycling. For each material i a parameter α_i is defined which determines the resulting recycling methodology. Available recycling methodologies include recycled content, avoided burden, 50/50, and any other split of recycling benefit, i.e. $(1 - \alpha)/\alpha$. The environmental impact indicators are GHG emissions, total and fossil energy consumption. The following three sections summarize the calculations of each of the three life cycle stages.

2.1 Impacts from Vehicle Production

Vehicle production comprises the GHG and energy impacts from

- production and finishing of the 19 main types of automotive materials,
- production of drive battery, fuel cell, fluids, and tires (as applicable),
- vehicle assembly, and
- prompt scrap recycling (modeled through consequential system expansion).

The impacts from producing and finishing the materials are calculated according to the following equation:

$$I_{ij}^{mat} = m_i^{shipped} [(1 - r_i^{cont}) I_{ij}^p + r_i^{cont} I_{ij}^s + I_{ij}^f]$$

For material type i , $m_i^{shipped}$ is the amount of shipped material, r_i^{cont} is the fraction of shipped material from secondary production, I_{ij}^p is the environmental impact j from primary production of 1kg of material i , I_{ij}^s is the environmental impact j from secondary production of 1kg of material i , and I_{ij}^f is the environmental impact j from finishing 1kg of material i . The calculations therefore account for the difference in environmental impacts from primary and secondary material production according to the secondary material contents I_{ij}^f of the vehicles.

The tires are modelled as a mix of long steel and rubber and are calculated in the same way as the 19 materials. Impacts from drive battery, fuel cell, and fluids production are simply calculated as impacts per kg of component times the mass of the component. For the mass-reduced contender vehicles, the battery mass is reduced so as to yield the same pure electric driving range as the baseline vehicle. Replacements of drive battery, tires, and fluids are derived from the ratio between vehicle and component lifetimes, both given in km.

Vehicle assembly accounts for paint production, painting, HVAC and lighting, material handling, welding, and compressed air. The impacts are the same for every vehicle, i.e. it does currently not distinguish between vehicle type, class, or material composition.

Scrap inputs to automotive material production and prompt scrap generation during vehicle manufacturing is modeled through consequential system expansion and part of the production phase. The environmental impact of scrap inputs and outputs during production are calculated as follows:

$$I_{ij}^{scrap} = m_i^{shipped} \delta_i^{prod} (I_{ij}^s - I_{ij}^p)$$

The calculation of δ_i^{prod} is explained and detailed in Section 3.6 of this user guide.

2.2 Impacts from Vehicle Use

Here, the environmental impacts from using the vehicle are calculated. This is done according to the following equation:

$$I_j^{use} = I_j^{elp} \frac{ED_{el}}{CE} TM_{el} + (I_j^{fp} + I_j^{fc}) ED_f TM_f$$

I_j^{elp} , I_j^{fp} , and I_j^{fc} are the environmental impacts j of electricity production, fuel production, and fuel combustion (in impact/MJ), ED_{el} and ED_f are the average electricity and fuel energy demands of the vehicle (in MJ/100km), CE is the charging efficiency of the battery. TM_{el} and TM_f are the total distances driven over the life of the vehicle powered by electricity and by fuel (in km). The energy demand of the two contender vehicles, ED^c , is calculated from the energy demand of the baseline vehicle, ED^b :

$$ED^c = ED^b - \Delta ED = ED^b - ES(VM^b - VM^c)$$

ES denotes the energy savings per mass savings, while VM^b and VM^c are the baseline and contender vehicle masses. The model has many different fuel types and mixes and therefore denotes vehicle energy demand ED in MJ fuel energy per 100 km instead of more conventional volumetric terms (e.g. liters/100km), which only work for liquid fuels.

2.3 Impacts from Vehicle Recycling

The impacts of end-of-life scrap recycling are modeled through consequential system expansion and calculated according to the following equation:

$$I_{ij}^{eol} = m_i^{shipped} \delta_i^{eol} (I_{ij}^s - I_{ij}^p)$$

$m_i^{shipped}$, I_{ij}^p , and I_{ij}^s have been defined in Section 2.1, while the end-of-life displacement parameter δ_i^{prod} is explained and detailed in Section 3.6.

The impacts from the actual processes of end-of-life vehicle recycling are not within the scope of the model as they constitute a very small fraction of the total life cycle impacts of vehicles. GREET2_2012, e.g., estimates the GHGs of end-of-life vehicle recycling to be 278 kg CO₂eq per vehicle (ANL 2012).

3 Description of the Spreadsheets in Model Version 5

To facilitate the use, analysis, and modification of this spreadsheet model, all used spreadsheet cells are color-coded. The color-coding of the spreadsheet cells follows this scheme:

	Blue: User inputs (used within the same and/or in other spreadsheets)
	Light Blue: Model input data that should only be changed by expert users
	Green: Intermediate results used within the spreadsheet
	Orange: Model outputs that are used in another spreadsheet
	Pink: Data inputs that come from another spreadsheet
	White: Data that is displayed for information only, and not used to calculate results

Every colored cell in the spreadsheet model is either an independent parameter or a dependent variable. Model parameters can be either dependent or independent. **The blue and light blue cells are independent model parameters.** They are defined directly by the value that has been entered into the cell. **All other colored cells are dependent model variables.** They are defined by model equations that become visible when the cell is highlighted. In principle, these equations can be overwritten by entering parameter values directly into the cell, i.e. by treating them like independent parameters. Generally, this should be avoided, since it is likely to lead to errors in the model calculations. Also, if equations are overwritten, and the spreadsheet file is saved subsequently, the equation will have been deleted permanently.

However, there are a few **useful instances of overwriting equations:** There are a few cells on the input spreadsheet that are independent model parameters, i.e. user input, even though they have default values defined through model equations. They are baseline vehicle mass in cell B22, total mass of material removed from the baseline vehicle in cell B28, and composition of removed material in cells B35-37. For example, the default value for total removed material is the mass of the body structure of the specified vehicle, but the user may want to explore other scenarios. In this case the user should simply enter the desired value into cell B28 (which will overwrite the equation). No part of the spreadsheet model is write-protected, so, in principle, every equation can be modified. The user is encouraged to customize every part of the spreadsheet model, while keeping at least one copy of the original model.

3.1 Results Spreadsheet

The *Results* spreadsheet displays the life cycle GHG emissions and total and fossil energy requirements for the specified baseline and the two associated contender vehicles. The three environmental indicators are displayed separately, but with identical layout.

Results for each indicator are visualized in two figures. One shows the cumulative environmental impact as a function of driven distance. For each vehicle, the cumulative impact starts at kilometer zero with the vehicle production impacts and increases with the use phase impacts per kilometer driven until the lifetime driving distance has been reached. Eol recycling benefits are subtracted at the end of the vehicle life. The second figure is a traditional column chart with the life cycle stages as columns plus one column for the total life cycle impact. The eol recycling benefits show up as negative numbers.

The twelve numbers shown in the column charts are also displayed in the top left section of the table below, e.g. cell array B25 to E27 for GHG emissions. In the two columns to the right, life cycle contributions are aggregated in alternative ways, and in the three rows below, the results are displayed as differences between two scenario vehicles. All these values are derived from the main twelve numbers in the top left table section.

3.2 Data Input Spreadsheet

The Energy and GHG model is highly parameterized and therefore requires significant amounts of data input from the user. The *Data Input* spreadsheet is the main data input interface for the model user. All blue cells on this spreadsheet are data input fields that require the attention of the user. Rather than being empty, all blue data input cells on the *Data Input* spreadsheet are already filled with default data. This exemplifies as well as simplifies the use of the model. The objective of the model is to assess the life cycle GHG and energy impacts of two mass-reduced vehicles relative to a baseline vehicle under a wide range of conditions. To do this, the user needs to review all blue data entry cells and enter the desired input parameters. In order to structure the data input process, the *Data Input* spreadsheet is split into five separate areas:

The **top left data entry box** specifies type and class, as well as driving and fuel characteristics of all three vehicles. In cells H4 and H6, power train and class of the three vehicles are selected from drop-down menus. The vehicle classes for BEV and PHEV are different than those for ICEV, HEV and FCV. It is important to make sure that vehicle class and power train match, since this is not

done automatically. In cell H8, the driving cycle is selected from a drop-down menu, which contains the options NEDC, Hyzem, FTP/HWFET according to SAE J1711, and WLTP 3b. Together with vehicle class and power train, the driving cycle determines ED, the driving energy demand of the baseline vehicle (in MJ fuel energy per 100km). Cell H9 determines whether the engine size of the mass-reduced vehicles is the same as that of the benchmark vehicle, or whether it is reduced to match the acceleration of the baseline vehicle. Together with vehicle class, power train, and driving cycle, this choice determines ES, the relationship between vehicle mass reduction and driving energy savings (in MJ fuel energy per 100km and 100kg mass reduction). The values for ED and ES are based on the Malen & Geyer power train model where available and model simulations by FKA from 2010 and 2011 where not. Cell H11 contains the lifetime vehicle mileage in kilometres (km).

The last step in the top left part of the *Data Input* spreadsheet is to further specify the fuel and/or electricity used by the chosen power train. The following parameters need to be specified: Volumetric ethanol content, which can be anywhere between 0% and 100%, and ethanol source are selected in cells P6 and P7. Volumetric biodiesel content, which can be anywhere between 0% and 100%, and biodiesel source are selected in cells P9 and P10. The electricity source is selected in cell P12. Obviously, not all of these fuel/electricity specifications are relevant for all power trains. The model simply ignores all irrelevant driving energy parameters.

The **bottom left data entry box** specifies the material compositions of the three vehicles. In cell F17 the user determines whether material compositions are entered directly as three separate bills of materials (BOMs) or with material replacement coefficients. If BOM-based data entry is selected, the user can ignore the rest of the bottom left data entry box and go to the *BOM Entry* spreadsheet instead. If not, material compositions are completely specified within the box.

The default mass of the baseline vehicle with the selected power train and class is shown in cells B24 (in kg) and B25 (in lbs). The baseline vehicle mass used in the model is contained in cell B22, which is pre-set to the default mass, but can be overwritten. Cell B28 contains the mass of mild steel removed from the baseline vehicle. This cell is also pre-set with a default value, which can be overwritten. The breakdown of the removed mild steel into flat, long, and cast is entered in cells B35 to B37. The alternative lightweight materials covered by the model are AHSS, aluminium, fibre reinforced composites, and magnesium. The replacement coefficients of these materials relative to conventional steel denote the amount of material required to replace the removed steel (in

kg lightweight material per kg mild steel) and are entered in rows 18 to 21 of columns J and M. The materials replacing the removed mild steel are specified as percentages of removed material in rows 26 to 36 of columns J and M and automatically translated into absolute masses in columns K and N. The available materials are rolled, long, and cast AHSS, rolled, extruded, and cast aluminium, sheet molding composite (SMC), glass fiber reinforced polymer (GFRP), carbon fiber reinforced polymer (CFRP), cast magnesium, and rolled magnesium. The data input for the material compositions of the vehicles is completed by specifying the secondary mass savings in terms of their size and their material composition. The size of secondary mass savings is entered in cell B41 (in % of primary mass savings).

The **top right box** explains the color coding of the spreadsheet model, which is designed to help use the model and follow its computational structure.

The **bottom right box** shows the material compositions that result when material replacement is modelled via material replacement coefficients, i.e. using the **bottom left data entry box**. If BOM-based data entry is selected the bottom right box does not contain any data.

The **bottom left box** of the *Data Input* spreadsheet contains buttons that let the user record up to three model scenarios. Main input data and model results of each recorded scenario is saved on the *Saved Scenarios* spreadsheet.

3.3 BOM Entry Spreadsheet

The *BOM Entry* spreadsheet allows the model user to enter the material compositions of baseline and contender vehicles directly, without having to use the material removal and replacement approach used on the *Data Input* spreadsheet. The user has to enter the masses of all twenty material classes and the four components, drive battery, fuel cell, fluids, and tires, for baseline and contender vehicles. The **top left data entry box** specifying type and class, as well as driving and fuel characteristics of all three vehicles still has to be filled out in the *Data Input* spreadsheet. To avoid unrealistic parameter combinations, it is important that the power train and vehicle class selections on the *Data Input* Spreadsheet match the vehicle BOM entered on the *BOM Entry* spreadsheet.

3.4 Expert Data Input Spreadsheet

The *Expert Data Input* spreadsheet contains default input data that should only be changed by expert users. One set of expert default input data is the material composition of the baseline vehicle, entered in cells B5-23. Another is the material composition of the secondary mass savings, entered in cells D6-11. Secondary mass savings are either in steel or aluminium. This is not a significant limitation of the model since steel and aluminum span a wide range of greenhouse gas and energy intensities and could thus be used to simulate many other materials. Cells D14-17 contain a few details about material production and forming: Fraction of magnesium produced by the Pidgeon process rather than electrolysis, source of primary aluminum (including or excluding China), fraction of steel that is hot rolled coiled rather than hot dip galvanized, and fraction of rubber that is compression rather than injection molded.

Other expert default input data are drive battery specifications (B28-32), tire specifications (B20-23), liquid fuel densities (B39-42), and the fraction of driving energy coming from plug electricity (B35, for PHEVs only).

Cells C48-63 contain the polymer composition of the non-reinforced plastic used in the vehicles. The model accounts for 16 types of polymers. It also contains 9 types of plastic forming together with their yields (E45-M45). Array E48-M63 matches polymer type to forming processes. The results are kg of shipped polymer per kg of non-reinforced plastic contained in the vehicle (B48-63) and forming activity per kg of non-reinforced plastic contained in the vehicle (L65-73). These results are passed on to the *LCA Calculations* spreadsheet.

The last expert default input data on this spreadsheet are the amounts of fluids in the vehicle as a function of power train type and vehicle class. The model accounts for engine oil, brake fluid, transmission fluid, powertrain coolant, and windshield fluid. The fluid amounts and the total number of replacements over the life of the vehicle are reported to the *LCA Calculations* spreadsheet.

3.5 Saved Scenarios Spreadsheet

A scenario is a set of model inputs and results for a specified baseline and two associated mass-reduced contenders. If a *Record Scenario* button is pressed on either the *Data Input* or the *BOM Entry* spreadsheet, greenhouse gas results and a number of important input parameters are saved to the *Saved Scenarios* spreadsheet. The saved input parameters are material replacement coeffi-

cients, secondary mass savings, lifetime driving distance, alpha values α_i , and the material composition of the three vehicles. To facilitate scenario and sensitivity analysis three different scenarios can be saved to the spreadsheet at the same time. The *Record Scenario 1* button saves the current scenario to the Scenario 1 part of the spreadsheet, and so on. Pushing a record button overwrites the existing entries with the current scenario.

3.6 Material Flows Spreadsheet

The *Material Flows* spreadsheet calculates and balances the intermediate material flows of the three vehicle life cycles and has two main functions:

1. For each material class, the spreadsheet calculates the amounts of shipped primary and secondary material used in vehicle production.
2. For each material class, the spreadsheet calculates and balances the scrap flows into and out of the vehicle life cycles.

Both calculation processes start with the material compositions of the three vehicles, which are imported from the *Data Input* or the *BOM Entry* spreadsheet and displayed in rows 5 to 28 of columns F, J, and N. Next, the amounts of shipped material required for vehicle manufacturing, $m_i^{shipped}$, are calculated by dividing the material composition data by the forming yields of each material and forming type. The forming yields γ_i are displayed in array E38 to G61. For a given material type, different forming yields can be defined for each of the three vehicles. This enables the user to compare vehicle design concepts that use the same material type but different forming technologies. An example would be two AHSS front end structures, one of which is stamped from a laser-welded blank with a yield of 55%, while the other is hydroformed with a yield of 86%. The resulting total amounts of shipped material, $m_i^{shipped}$, are shown in rows 5 to 28 of columns E, I, and M. The amounts of shipped material from primary and secondary production are shown in rows 5 to 28 of columns C, D, G, H, K, and L, and calculated using the secondary material content rates (r_i^{cont} in Figures 5 and 6) given in rows 38 to 61 of column C. This concludes task 1 from above. The required amounts of shipped material are passed on to the *LCA Calculations* spreadsheet (columns F, G, and H) and the *Recycling* spreadsheet (rows 6 to 29 of columns C, F, and I).

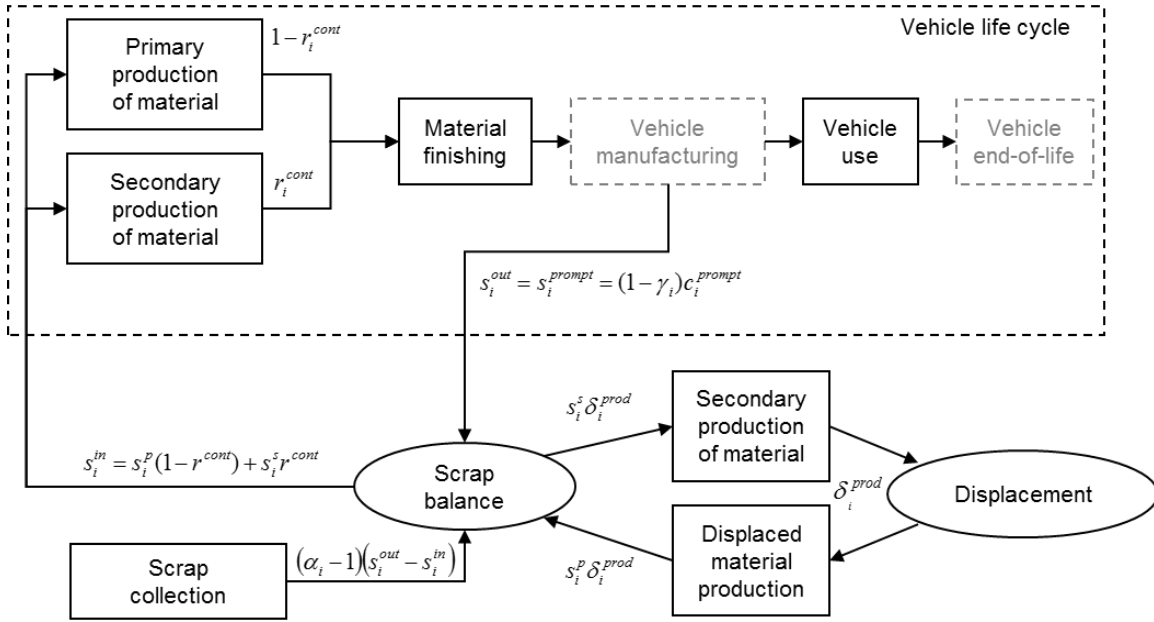


Figure 2: Calculation and balancing of the scrap flows during vehicle production (δ_i^{prod})

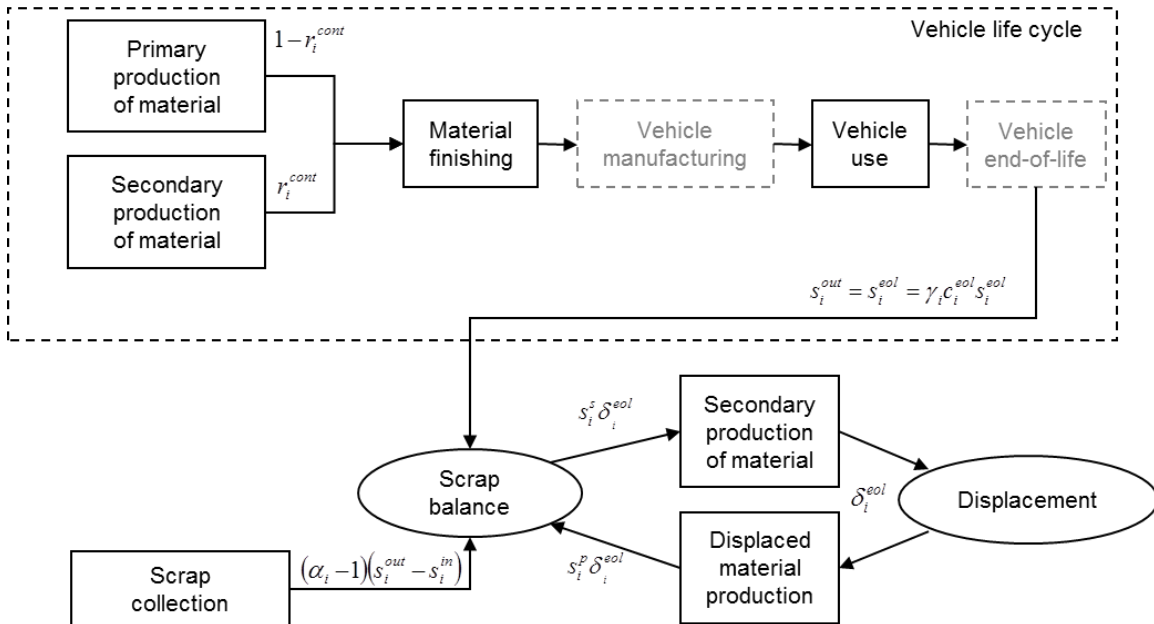


Figure 3: Calculation and balancing of the scrap flows during vehicle recycling (δ_i^{eol})

The GHG and energy implications of automotive material recycling are calculated in the *Recycling* spreadsheet using consequential system expansion. This method requires the calculation of displacement rates, called δ_i , which quantify the change in the primary production of material i outside of the vehicle life cycles due to the scrap flows in and out of the vehicle life cycles, s_i^{in} and

s_i^{out} (in kg scrap per kg shipped material). The calculation of the displacement rates δ_i accounts for the scrap inputs to secondary and primary production, s_i^s and s_i^p (in kg scrap input per kg material output), as well as the impact of s_i^{in} and s_i^{out} on scrap collection outside of the vehicle life cycles (quantified as parameters α_i). As shown in Figures 5 and 6, δ_i is calculated by balancing all external scrap flows:

$$s_i^{out} - s_i^{in} + (\alpha_i - 1)(s_i^{out} - s_i^{in}) - s_i^s \delta_i + s_i^p \delta_i = 0 \Rightarrow \delta_i = \alpha_i \frac{s_i^{out} - s_i^{in}}{s_i^s - s_i^p}$$

Scrap flows during vehicle production are balanced separately from scrap flows during vehicle recycling. Scrap generated during production is called new or prompt scrap (see Figure 5). Scrap generated during vehicle recycling is called old or end-of-life scrap (see Figure 6). The amount of scrap generated at end of life is identical with the material contained in the vehicle. The amount of scrap generated during production is the difference between shipped material and material contained in the vehicle. The total amount of collected and separated scrap output during vehicle production is $s_i^{out} = s_i^{prompt} = (1 - \gamma_i)c_i^{prompt}$, with c_i^{prompt} being the prompt scrap collection rate. The total amount of collected and separated scrap output during vehicle recycling is $s_i^{out} = s_i^{eol} = \gamma_i s_i^{eol} c_i^{eol}$, with c_i^{eol} and s_i^{eol} being the end-of-life scrap collection rates and separation yields. The calculated values for s_i^{prompt} and s_i^{eol} are displayed in arrays C69-E92 and F69-H92. The scrap input to secondary production per kg of secondary output is calculated as $s_i^s = (s_i^{prompt} + s_i^{eol})/r_i^{car}$, with $r_i^{car} = (1 - \gamma_i)r_i^{prompt} c_i^{prompt} + \gamma_i r_i^{eol} s_i^{eol} c_i^{eol}$ being the overall recycling rate of the shipped automotive material. r_i^{prompt} and r_i^{eol} are the reprocessing yields of prompt and eol scrap, e.g. the scrap to ingot yields of electric arc furnaces in the case of steel. The secondary material input rates, r_i^{cont} , and the scrap inputs to primary production per kg of primary output, s_i^p , are given in rows 38 to 61 of columns C and D. Only primary production of steel has significant scrap inputs. The calculation results for the displacement rates δ_i^{prompt} and δ_i^{eol} are shown in arrays O69-Q92 and R69-T92. If $\delta_i > 0$ primary production outside of the vehicle life cycle decreases due to the net scrap generation of the vehicle life cycle; if $\delta_i < 0$, external primary production increases due to the net scrap input to the vehicle life cycle. The values for δ_i^{prompt} and δ_i^{eol} are passed on to the *Recycling* spreadsheet.

3.7 Use Spreadsheet

On the *Use* spreadsheet, the total fuel consumption (in MJ) of the three vehicles is calculated as the product of energy demand ED (in MJ/100km) and lifetime vehicle mileage TM (in km). In the case of electricity, the electricity demand of the powertrain is divided by the charging efficiency CE of the vehicle to account for charging losses. The model contains seven different types of liquid fuel, plus hydrogen and electricity. Selected fuel type depends on the chosen power train and the user choices regarding biofuel content. The resulting fuel mix is displayed in cells J18-22.

Each combination of power train, vehicle class, and driving cycle is characterized by a driving energy demand ED (in MJ/100km) and by driving energy savings due to mass savings ES (in MJ/100km100kg), sometimes called fuel reduction value. The $ED - ES$ spreadsheet supplies the electricity and fuel energy demands ED_{el}^d and ED_f^d of the default vehicle and the values for the energy savings per mass savings ES_{el} and ES_f , which serve to calculate the energy demands ED_{el}^k and ED_f^k for baseline and contender vehicles via the following equation:

$$ED^k = ED^d - \Delta ED = ED^d - ES \cdot (VM^d - VM^k)$$

The masses of all three vehicles VM^k come from the *Material Flows* spreadsheet and are displayed in row 3. The values for ES , $\Delta ED = ES \cdot (VM^b - VM^c)$, and ED of each vehicle are displayed in rows 6-11. The total electricity and fuel energy demands of each vehicle during its life (in MJ), $ED_{el} \cdot TM / CE$ and $ED_f \cdot TM$, are shown right below in rows 13-21.

One note on biofuel content: On the *Data Input* spreadsheet the fuel blends are specified through their volumetric biofuel content, which can be anywhere between 0% and 100%. The calorific biofuel content is calculated according to the equation

$$c_b = \frac{v_b \cdot E_b}{v_b \cdot E_b + (1 - v_b) \cdot E_f},$$

where c_b is the calorific biofuel content, v_b is the volumetric biofuel content, while E_b and E_f are the volumetric energy densities of the biofuel and the fossil fuel, respectively. E85, for example is a gasoline/ethanol fuel blend that contains 85% ethanol by volume and therefore has a volumetric energy density of 22.72 MJ net calorific value (NCV) per litre, given that gasoline and ethanol have net calorific values of $E_f = 31.88$ MJ per litre and $E_b = 21.10$ MJ per litre. 79% of the energy contained in a unit of E85 comes from ethanol, since

$$0.79 = \frac{0.85 \cdot 21.10}{0.85 \cdot 21.10 + 0.15 \cdot 31.88}$$

The volumetric energy densities of the fuels are given in cells J4-7. If the specified fuel is a blend, its calorific composition is displayed in cells J18-21. If the specified fuel is pure gasoline, pure diesel, or hydrogen, the calculations explained above are unnecessary.

3.8 Recycling Spreadsheet

On the *Recycling* spreadsheet, consequential system expansion (CSE) is used to calculate the environmental implications of the scrap flows into and out of the vehicle life cycles during vehicle production and vehicle recycling. It is assumed that these scrap flows impact, to a lesser or larger extent, scrap collection and secondary material production outside of the vehicle life cycle (see Figure 5 and 6). It is also assumed that the sum over all scrap flows is zero, i.e. the stock of scrap remains constant. The values for parameters α_i , which are entered by the user on the *Data Input* spreadsheet, determine to what extent the scrap flows impact external scrap collection or external secondary production. For example, $\alpha_i = 0$ means that the scrap flows from and to the vehicle life cycle lead to equal but opposite changes in external scrap collection and have thus no impact on external secondary production. Setting $\alpha_i = 1$, on the other hand, means that the scrap flows from and to the vehicle life cycle lead to equal changes in external secondary production and have no impact on external scrap collection. Any value between zero and one means that the impact of the scrap flows from and to the vehicle life cycle is split accordingly between external scrap collection and external secondary production. For example, $\alpha_i = 0.9$, which is the default value for all materials, means that each kg of scrap from the vehicle life cycle reduces scrap collection by 0.1 kg, while the remaining 0.9 kg of scrap increase external secondary material production. A change in external secondary material production is assumed to lead to an equal but opposite change in external primary production of the same material type, i.e. an increase in secondary production leads to an equal decrease in primary production and vice versa. The size of the change in external secondary and primary material production is quantified by the displacement rates δ_i^{prompt} and δ_i^{eol} , which are calculated on the *Material Flows* spreadsheet (see Section 3.6). The values are passed on to the *Recycling* spreadsheet, where they are displayed in rows 6 to 29 of columns D, E, G, H,

J, and K. The activity levels of recycling and displaced primary production are calculated by multiplying displacement rates with the amounts of shipped material:

$$m_i^{shipped} \delta_i^{prompt} = m_i^{shipped} \alpha_i \left(\frac{s_i^{prompt} - s_i^{in}}{s_i^s - s_i^p} \right)$$

$$m_i^{shipped} \delta_i^{eol} = m_i^{shipped} \alpha_i \left(\frac{s_i^{eol}}{s_i^s - s_i^p} \right)$$

The required amounts of shipped material, $m_i^{unfinished}$, are also imported from the *Material Flows* spreadsheet and displayed in rows 6 to 29 of columns C, F, and I. The resulting activity levels for prompt scrap recycling are displayed in array L6-N29, the ones for eol scrap recycling in array O6-Q29.

3.9 ED – ES Spreadsheet

The main task of the *ED - ES* spreadsheet is to convert the user inputs from the *Data Input* spreadsheet, which are power train type, vehicle class, power train adjustment, driving cycle, and the fraction of driving energy being grid electricity, into the energy demand (in MJ/100km) of the baseline vehicle and the energy savings (in MJ/100km100kg) due to vehicle mass reduction. Additional tasks are to a) calculate baseline battery mass and battery mass reduction factor, and report both to the *Data Input* spreadsheet and b) pick the default masses of the baseline vehicle and its body structure from lookup tables and report them to the *Data Input* spreadsheet.

The four user inputs are listed in row 3, while column B reports the eight corresponding output values. The output values are default energy demands ED_f^d and ED_{el}^d (in MJ/100km) in cells B7 (for fuel) & B8 (for grid electricity), energy savings per mass savings ES_f and ES_{el} (in MJ/100km100kg) in cells B22 (for fuel) & B23 (for grid electricity), default vehicle mass VM^d (in kg) in cell B52, default baseline body structure mass (in kg) in cell B56, baseline battery size BS^b (in kWh) in cell B59, and the battery mass reduction factor $BMRF$ in cell B72. ED_f^d , ED_{el}^d , ES_f , ES_{el} , VM^d , and default baseline body structure mass are selected from lookup tables in columns D to M. Baseline battery size BS^b is calculated as a function of the vehicle mass chosen on the *Data Input* spreadsheet. The function has been interpolated from the values in the lookup table I55 to K56 and therefore yields slightly different values.

Default energy demands ED_f^d and ED_{el}^d and energy savings per mass savings ES_f and ES_{el} for power trains ICEV-G, ICEV-D, BEV, and PHEV are obtained from the Malen & Geyer power train model. For power trains HEV and FCV they come from power train simulations conducted by FKA, which is the reason why values for the WLTP 3b driving cycle are currently unavailable for HEV and FCV power trains. PHEV is the only power train that has values for both fuel and electricity. All others have one or the other. The relationship between mass savings and energy savings, everything else being equal, is assumed to be linear. In other words, for each set of vehicle and driving characteristics ES is a constant, i.e. independent of the amount of vehicle mass reduction.

A unique characteristic of BEVs and PHEVs is their all-electric driving range. The mass-reduced contender vehicles achieve the all-electric driving range of the baseline vehicle with smaller batteries. This down-sizing of the battery is done automatically based on the following assumptions and calculations: The baseline battery mass (in kg) is calculated as $BM^b = BS^b / BED$, where BS^b is the baseline battery size (in kWh) and BED is the energy density of the battery technology (155Wh/kg assumed for Li-ion technology). The value for BED is imported from the *Materials* spreadsheet. The vehicle mass VM is the sum of the battery mass BM and the rest of the vehicle, i.e. $VM = BM + Rest$. The main assumption is that the required battery size is a linear function of all-electric range BR , vehicle mass VM , and the frontal area of the vehicle FA , i.e. $BS = const \cdot FA \cdot VM \cdot BR$ or $BS = BC \cdot VM \cdot BR$ with $BC := const \cdot FA$ being the frontal-area-adjusted battery constant. The battery constant $const$ has been derived from the FKA simulation data

as $const = 0.0623 \frac{Wh}{m^2 \cdot kg \cdot km}$. It now follows that

$$\begin{aligned} VM = BM + Rest &= \frac{BS}{BED} + Rest = \frac{BC \cdot VM \cdot BR}{BED} + Rest \\ \Rightarrow VM - \frac{BC \cdot VM \cdot BR}{BED} &= Rest \Rightarrow VM = \frac{BED \cdot Rest}{BED - BC \cdot BR} \\ \Rightarrow BM = VM - Rest &= \frac{BED \cdot Rest}{BED - BC \cdot BR} - Rest = Rest \frac{BC \cdot BR}{BED - BC \cdot BR} \end{aligned}$$

This means that the required mass of the battery can be calculated once the battery range BR , the frontal-area-adjusted battery constant BC , the battery energy density BED , and the mass of the vehicle without the battery, $Rest$, are known. In cell B72 all battery-related data are consolidated

into the battery mass reduction factor $BMRF := \frac{BC \cdot BR}{BED - BC \cdot BR}$, which is passed on to the *Data Input* spreadsheet. There the contender battery masses are calculated according to the equation derived above, i.e. $BM^c = Rest^c \cdot BMRF$.

3.10 LCA Calculations Spreadsheet

The *LCA Calculations* spreadsheet is where the activity levels of all 105 unit processes are converted into greenhouse gas and energy results (in kg CO₂eq and MJ). The structure of this spreadsheet is simple. Column A contains the name of each unit process. Column B contains the unit of its intermediate output. Columns C, D, and E contain the environmental impacts per unit output. Columns F, G, and H contain the activity levels of each unit process for baseline, contender 1, and contender 2 vehicle. Total environmental impacts of each unit process are calculated by multiplying unit impacts with the activity level of the process. The results are contained in Columns I-Q. The source of the unit impact data is shown in column R. GaBi data are used where possible. This simple computational structure makes the model very transparent, very easy to maintain or extend, and makes it very easy to conduct contribution analysis.

In arrays I120-K122, I125-K127, and I130-K132, the individual impacts are aggregated into the three life cycle stages, production, use, and end of life. These are the values that are reported to the *Results* spreadsheet.

3.11 autoLCA Results Spreadsheet

This spreadsheet contains pre-formatted tables and charts to display the results when the autoLCA model is used. The results must be imported manually. The top of the spreadsheet briefly explains how this is done.

3.12 GaBi Envision Parameters Spreadsheet

This spreadsheet contains all the parameter values and the activity levels (scaling factors) of all GaBi unit processes necessary to run autoLCA based on the data input specified in the spreadsheet model. The spreadsheet is formatted so that all parameter values can be readily copied into the Envision autoLCA model.