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# Evaluating opportunities to improve material and energy impacts in commodity supply chains

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**Abstract** When evaluated at the scale of individual processes, next-generation technologies may be more energy and emissions intensive than current technology. However, many advanced technologies have the potential to reduce material and energy consumption in upstream or downstream processing stages. In order to fully understand the benefits and consequences of technology deployment, next-generation technologies should be evaluated in context, as part of a supply chain. This work presents the Materials Flow through Industry (MFI) supply chain modeling tool. The MFI tool is a cradle-to-gate linear network model of the US industrial sector that can model a wide range of manufacturing scenarios, including changes in production technology and increases in industrial energy efficiency. The MFI tool was developed to perform supply chain scale analyses in order to quantify the impacts and benefits of next-generation technologies and materials at that scale. For the analysis presented in this paper, the MFI tool is utilized to explore a case study comparing three lightweight vehicle supply chains to the supply chain of a conventional, standard weight vehicle. Several of the lightweight vehicle supply chains are evaluated under manufacturing scenarios that include next-generation production technologies and next-generation materials. Results indicate that producing lightweight vehicles is more energy and emission intensive than producing the non-lightweight vehicle, but the fuel saved during vehicle use offsets this increase. In this case study, greater reductions in supply chain energy and emissions were achieved through the application of the next-generation technologies than from application of energy efficiency increases.

**Keywords** Supply chain modeling · Manufacturing · Energy efficiency · Materials

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## 1 Introduction

Decisions on next-generation technology development and deployment can be informed from a supply chain or larger-scale analysis of the technology's impacts, in addition to process scale analysis of the technology itself (Miller and Keoleian 2015). While next-generation technologies may be more intensive at the process scale, the shifts in material and energy flows resulting from technology deployment can create positive impacts elsewhere in the economy. Supply chain and other large-scale analyses are thus essential when evaluating next-generation technologies in order to fully understand the benefits and consequences of such technologies and to prioritize efforts toward commercialization and deployment (Wender et al. 2014).

The Materials Flow through Industry (MFI)[1] supply chain modeling tool was developed with the goal of performing supply chain analyses within the US industrial and manufacturing sectors. A database of products and recipes forms the basis of the MFI tool. Products are industrial commodities and materials such as primary metals, bulk

[1] Information on accessing the MFI tool is given in Supplementary Information.

chemicals, and fossil fuels. Recipes are physical unit input–output models of production technologies and consist of quantities of material and energy inputs required to produce a unit of product. The recipes in the database are linked to form a linear network model that captures fuel, electricity, water, and material flows within the US industrial sector. Models of different manufacturing scenarios are derived from the baseline model, which represents current US industrial practice, by varying parameters that control the technology mixes used to produce commodities and increase industrial energy efficiency. These parameters are discussed further in the next section. The MFI tool can represent a baseline scenario which reflects current industrial practice or alternative scenarios that incorporate new technologies, new materials, or other advances.

While MFI is similar to both process-based life cycle assessment (LCA) and environmentally extended input–output (EEIO) analysis, there are key differences among the three models. All three models are used for large-scale analyses of production systems. Both process-based LCA and MFI are bottom-up physical unit models (Guinée et al. 1993); EEIO relies on a top-down economic model extended with physical data (Leontief 1970; Green Design Institute 2008). The MFI tool primarily quantifies energy consumption, greenhouse gas (GHG) emissions, and material inventories (commodities used in the production of other commodities). LCA and EEIO generally focus on environmental impacts and natural resource consumption, although the focus varies from study to study. Table 1 summarizes the similarities and differences between MFI, LCA, and EEIO.

Two advantages that MFI has over both LCA and EEIO are an increased level of detail in the production technology models that make up the model and greater flexibility in modeling production systems. MFI contains data for individual production technologies that can be used as is or can be aggregated to form national average models as discussed in the next section. In contrast, LCA tends to include primarily industry averaged and/or aggregated data, and EEIO relies on economic sector data at even higher levels of aggregation. The MFI tool also incorporates parameters that allow users to model and analyze custom manufacturing scenarios. LCA models can vary in scope and the product being analyzed, but the life cycle inventories used in LCA tend to be fixed and cannot easily be altered by users. EEIO models are even more static, relying on economic data compiled on an annual basis.

In summary, of the three models, MFI has the benefit of being more flexible and has access to more detailed background data. While MFI has a smaller system boundary than either LCA or EEIO models, its boundary can be expanded with user-added data.

The primary objectives of this work are to establish the modeling capabilities of the MFI tool and to demonstrate the results that MFI provides with a case study analyzing the supply chains of three lightweight vehicles and a standard weight vehicle. Section 2 presents further details on the MFI tool's capabilities and inner workings. Section 3 discusses the scenarios analyzed in the case study and provides further context for the analysis. Sections 4 and 5 contain, respectively, the case study results and discussion.

## 2 Model description

Recipes in the MFI database are obtained from sources including the IHS Process Economics Program Yearbook (IHS Chemical 2014), the U.S. Life Cycle Inventory (NREL 2016), the ecoinvent v2.2 life cycle inventory database (Frischknecht et al. 2005), and scientific literature; sources for all recipes are cited in the database. Currently, the MFI database contains 1413 recipes for 671 products as well as 604 products without recipes. Products without recipes include by-products such as coal slag and low-purity chemicals; for other products, recipe data have not yet been found. The database contains recipes in 81 unique industrial sectors according to the North American Industry Classification System (NAICS). However, complete coverage of the US industrial sector using bottom-up data is difficult, and gaps still exist in the MFI database, particularly in the agricultural sector. Additional recipes

**Table 1** MFI compared to typical process-based LCA and EEIO models

| | MFI | Process-based LCA | EEIO |
|---|---|---|---|
| Model type | Bottom up | Bottom up | Top down |
| Level of detail | Individual production technologies | Average production technologies | Economic sectors |
| Units | Physical | Physical | Monetary and physical |
| User options | Variety of scenario parameters | Product demand, analysis scope | Product demand |
| Summary | Very flexible | Slightly flexible | Inflexible |
| | Very detailed | Moderately detailed | Least detailed |
| | Moderate, expandable boundary | Large, expandable boundary | Largest, fixed boundary |

are added to MFI as gaps in the database coverage are identified and as recipe data are found. MFI users have the option of adding custom recipes to the database to represent commodity use, alternate production technologies, or new production technologies for commodities not already in the database.

### 2.1 Results and outputs

The raw output generated by the MFI tool is an inventory of all materials, fuels, and other inputs used in the supply chain. This inventory is organized both by the process consuming the individual inputs and by the supply chain step in which the inputs were consumed. From this inventory, the primary MFI results of total energy consumption and GHG emissions are obtained by summing up all fuel and renewable electricity inputs to the supply chain. The total energy consumption is similar to embodied energy, the energy consumed to produce a commodity from raw materials, (Gutowski et al. 2013) but is here referred to as supply chain energy to distinguish the different method of calculation. Supply chain energy results are disaggregated by fuel type and by how the fuel was used: for instance, as process fuel or for electricity generation. GHG emissions are calculated from these fuel consumption totals using emissions factors and 100-year global warming potential factors obtained from the Intergovernmental Panel on Climate Change (IPCC) (Eggleston et al. 2006). Some additional emission factors were sourced from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) fuel cycle model developed by Argonne National Laboratory (ANL 2015). Emissions from process fuel and from electricity generation are calculated using the same factors, as sufficient recipe-level data do not exist to allow for the use of equipment-specific emission factors. Emissions from biomass are calculated as part of the results but are presented separately from the total emissions.

### 2.2 Scenario parameters

Recipe weights are a set of parameters in MFI that control the mix of technologies used to produce commodities. Changing technology mixes allows for either comparing supply chains for a particular product or evaluating the broader effects of technology shifts by analyzing supply chains that use the new technology mix in an upstream processing stage. For instance, after defining a new technology mix to produce benzene, the current and new benzene supply chains can be compared, and the impact on supply chains of other chemicals that use benzene as a feedstock can also be evaluated.

Where multiple recipes exist for a product, a weighted average recipe for the product is calculated and used in the MFI model in place of the individual technology recipes. Baseline weighted average recipes are derived from information on the current market share of each production technology (ICF 2012), and custom weights may be specified by the user to model-specific technology mixes. For an arbitrary commodity with $K$ recipes, the weighted average recipe is derived as follows. Each recipe $\boldsymbol{r}_k$ for the commodity is expressed as a vector of $J$ recipe inputs $r_{kj}$,

$$\boldsymbol{r}_k = \begin{bmatrix} r_{k1} \\ r_{k2} \\ \vdots \\ r_{kJ} \end{bmatrix} \tag{1}$$

and is assigned a recipe weight $w_k$, $k = 1, \ldots, K$. The set of recipe weights for a commodity must satisfy Eq. 2:

$$\begin{cases} 0 \le w_k \le 1 \\ \sum_k w_k = 1 \end{cases} \tag{2}$$

Input amounts in the weighted average recipe $\bar{\boldsymbol{r}}$ are calculated by taking the weighted average amount of each recipe input $j$ across all recipes $\boldsymbol{r}_k$:

$$\bar{\boldsymbol{r}} = \frac{1}{K} \begin{bmatrix} \sum_{k=1}^{K} w_k r_{k1} \\ \sum_{k=1}^{K} w_k r_{k2} \\ \vdots \\ \sum_{k=1}^{K} w_k r_{kJ} \end{bmatrix} \tag{3}$$

Equation 3 is used to calculate the weighted average recipes from either baseline recipe weights or custom, user-defined weights. In either situation, Eq. 2 must hold for the average recipe to be valid.

Sector efficiency potentials (SEPs), which affect industrial energy efficiency, are another set of scenario parameters. SEPs quantify the maximum possible energy savings achievable when process equipment in use is upgraded to the most efficient equipment available, as a percentage of the current energy use (Masanet et al. 2009a, b). A SEP of 0.1 implies that the current energy use in a sector can be reduced by 10% if all available equipment upgrades are implemented. SEPs can be applied to individual recipes, to all recipes in a particular NAICS sector, or to every recipe in a supply chain. SEPs are implemented by percentage; for instance, a 0% implementation represents baseline energy efficiency, with no increase, and a 50% implementation means that half of the maximum possible energy savings is achieved. Implementing 50% of a SEP of 0.1 reduces the process energy use by 5%. Figure 1 demonstrates the

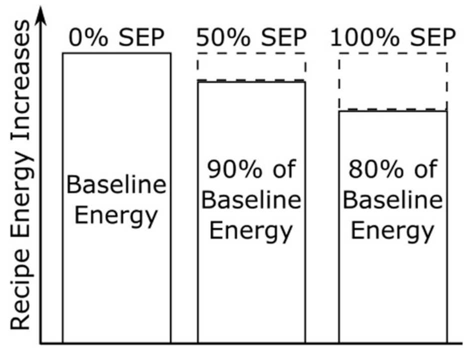


**Fig. 1** SEP implementation. This figure illustrates the effect of implementing a SEP of 0.2: a higher percentage implemented means greater energy savings

effects on recipe energy consumption of implementing different percentages of a SEP of 0.2.

### 2.3 System boundary and limitations

The default scope of the MFI database is cradle-to-gate; it contains recipes related to US-manufactured industrial commodities from natural resource extraction through to commodity production. While the MFI database currently does not include the use and end-of-life phases for commodities not consumed in a supply chain, the database can be extended with recipes representing these phases for cradle-to-grave analyses.

Uncertainty in recipe data is not currently included in the MFI database, nor is uncertainty in baseline recipe weights. For many MFI recipes, uncertainty was not provided with the source data. It is possible to perform sensitivity analyses within the MFI tool by manually varying recipe data and by varying the recipe weights; however, performing general sensitivity analyses is not currently part of the basic MFI capabilities. Work is ongoing to locate useful sources of recipe uncertainty data and on implementing the sensitivity analysis capability.

MFI is a linear model in physical units and as such cannot capture complexities such as the economic impacts of commodity price changes or fluctuations in commodity demand. Spatial and temporal information is also not currently included in the MFI database. GHG emissions from fossil-fuel combustion are calculated as part of the model, but there is no information as to where and when the resulting environmental impacts are likely to occur.

## 3 Case study

In this case study, four vehicle supply chains are analyzed to determine how much energy is consumed and GHG emissions produced to manufacture each vehicle. All four vehicles are assumed to be gasoline-powered passenger vehicles: three of the vehicles are lightweight, and the fourth is a standard non-lightweight vehicle. The lightweight vehicles consume significantly less energy in the use phase, but require more energy to manufacture using current production technologies (Das et al. 2016; Modaresi et al. 2014; Park et al. 2012). This case study is part of an ongoing analysis on energy use in lightweight vehicle manufacturing (Hanes et al. 2016).

Each of the lightweight vehicles uses a different lightweighting material in place of steel: aluminum, carbon fiber-reinforced plastic (CFRP), or glass fiber-reinforced plastic (GFRP). The MFI tool is applied to evaluate the vehicle supply chains under fifteen manufacturing scenarios (Table 2) that incorporate either standard or next-generation production technologies and apply different increases in industrial energy efficiency. Each vehicle is also analyzed under a baseline manufacturing scenario that reflects current industrial practice. In the MFI tool, the recipe weight parameters are used to implement the next-generation production technologies, and SEPs are used to implement the increases in energy efficiency. Although, as discussed in the previous section, the MFI database does not include recipes for use phase, for this case study the MFI results were combined with use phase data on energy consumption and emissions obtained from Das et al. (2016) and GREET (ANL 2015). Vehicle material inventories are given in Table S1 in Supplementary Information. Materials that are used in the same amounts in all four vehicles are excluded from the analysis.

The aluminum technology options are for alumina smelting, which is a highly energy-intensive process of extracting aluminum from alumina ore. The baseline technology is the modern Hall–Heroult process, which is the only smelting technology currently in operation at a commercial scale in the USA (Das 2012). The two next-generation smelting technologies considered are clay carbochlorination and the carbothermic electric furnace process; both of these technologies offer process scale reductions in energy consumption over the Hall–Heroult process, but neither has been yet developed past the pilot plant scale (Das 2012). Implementing either of the next-generation smelting technologies at a commercial scale would require additional research and technology development.

Production technology options are also explored for carbon fiber. Carbon fiber manufactured in the USA is currently produced primarily from polyacrylonitrile (DOE 2016), but one next-generation production option is to produce carbon fiber from lignin, a renewable material sourced from biomass (Das 2013). This technology substitution does not reduce the direct process energy

**Table 2** Scenarios analyzed for the case study. An X indicates a scenario that combines the vehicle type and production technology options to the left with the efficiency increase option at the top right of the table

| Vehicle type | Production technology | Efficiency increase | | |
|---|---|---|---|---|
| | | No increase | Process | Supply chain |
| Non-lightweight | Basic oxygen process[a] | X | X | X |
| Aluminum lightweight | Hall–Heroult smelting[a] | X | X | X |
| | Clay carbochlorination smelting | X | NA | NA |
| | Carbothermic electric furnace smelting | X | NA | NA |
| CFRP lightweight | Carbon fiber from polyacrylonitrile[a] | X | X | X |
| | Carbon fiber from lignin | X | NA | NA |
| GFRP lightweight | E-glass production[a] | X | X | X |

*NA* not analyzed

[a] Baseline production technology

required to produce carbon fiber, but reduces upstream energy consumption by replacing polyacrylonitrile, a fossil-based material, with lignin, a biomass-based material.

The sector efficiency potential options considered in the case study are: (1) no efficiency increase (baseline energy efficiency) and full (100%) efficiency potential implementation for, (2) a process scale increase in efficiency that affects individual production technologies, and (3) a supply chain scale efficiency increase that affects all processes in a supply chain. The two next-generation alumina smelting processes and the carbon fiber from lignin process are not evaluated under the process efficiency increase, because it is assumed that the baseline recipe data for these next-generation technologies already reflect the use of the most efficient process equipment available. Process efficiency increases in the remaining scenarios were applied to production of the vehicle's primary material: steel in the non-lightweight vehicle, aluminum in the aluminum vehicle, carbon fiber in the CFRP vehicle, and glass fiber in the GFRP vehicle. The supply chain scale efficiency increase is a less realistic scenario than the others, as increasing energy efficiency in every process in a supply chain would be significantly more costly and time-consuming compared to implementing a single new technology or increasing the efficiency of one process. These efficiency scenarios serve as a "best-case" scenario against which the other scenarios can be compared.

## 4 Results and discussion

Figure 2 shows the supply chain energy consumption and GHG emissions for all scenarios, calculated with the MFI tool. Point color indicates the manufacturing scenario (either the technology option or the efficiency option), and the point shape indicates the vehicle type.

The supply chain analysis shows that the three lightweight vehicles have higher supply chain energy consumption and GHG emissions relative to the non-lightweight vehicle. The exception is the GFRP lightweight vehicle under a supply chain scale efficiency increase, which has higher energy and lower emissions than the non-lightweight vehicle. This is due to the differing mix of process fuels used in the two supply chains: the steel intensive non-lightweight vehicle supply chain relies heavily on coal, coke and blast furnace gas, while the GFRP vehicle supply chain uses more natural gas. The CFRP lightweight vehicle in particular has both higher supply chain energy and GHG emissions than the other vehicles under current technology, next-generation technology and the process scale efficiency increase. The aluminum lightweight vehicle has lower energy consumption and emissions, and the GFRP lightweight vehicle is best overall out of the three lightweight vehicles.

Further details of the results in Fig. 2 are given in Supplementary Information. In Figures S1–S4, the supply chain energy consumption of each scenario is broken down by fuel use type: nonrenewable fuel for electricity generation, renewable electricity, process fuel, fuel used as chemical feedstock and fuel used for transportation. Figures S5–S8 similarly break down supply chain emissions for each scenario by source: electricity generation, process fuel or transportation.

Figure 2 is informative but, because the results are based only on the vehicles' supply chains, it does not capture the whole picture. Figure 3 shows energy and emissions results for a more complete analysis covering both the vehicles' supply chains and the energy consumption and GHG emissions associated with the use of each vehicle. To create Fig. 3, the results from the MFI tool were combined with external data on the expected vehicle lifetime mileage and the type of fuel used (Das et al. 2016). Emissions factors and 100-year global warming potentials were used to calculate GHG emissions associated with vehicle use, (ANL 2015; Eggleston et al. 2006), and the resulting data are given in Table S2 in Supplementary Information.

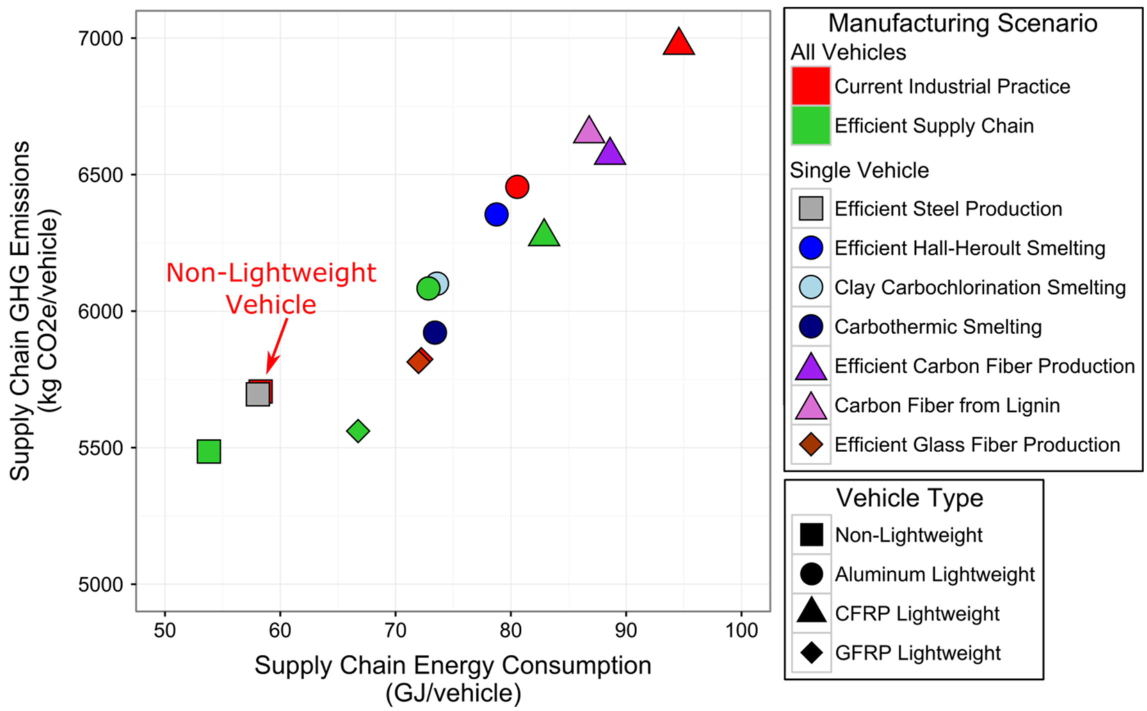


**Fig. 2** Supply chain energy consumption and GHG emissions of all scenarios. This figure does not include energy and emissions from the vehicle use phase, and materials used in the same amount in all vehicles are excluded from the analysis. Note that some points in the figure overlap

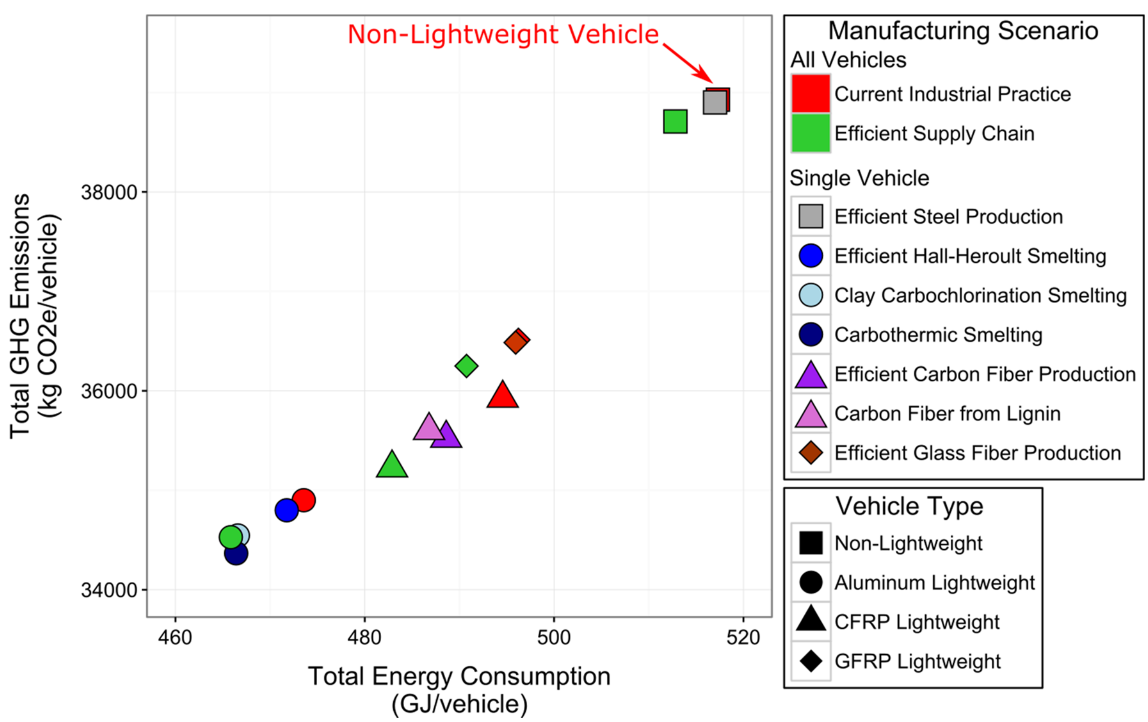


**Fig. 3** Life cycle (supply chain plus use phase) energy consumption and GHG emissions of all scenarios. Vehicle lightweighting tends to increase the energy and emissions from vehicle manufacturing, but this is offset by energy savings in the vehicle use phase. Note that some points in the figure overlap

All three lightweight vehicles had significantly lower life cycle energy consumption and emissions compared to the non-lightweight vehicle, under all technology and efficiency options analyzed. In the supply chain only analysis, the GFRP lightweight vehicle performed best, followed by the aluminum and CFRP vehicles; in the life cycle analysis, the aluminum vehicle performed best, followed by the CFRP and GFRP vehicles. This is due to the effects of vehicle weight: the aluminum lightweight vehicle had the lowest mass of the three lightweight vehicles, meaning it also had the lowest use phase energy consumption and emissions.

The aluminum and CFRP lightweight vehicles were analyzed under both next-generation technology options and efficiency increase options. For these two vehicles, the next-generation technologies offered greater energy and emissions reductions than the process scale efficiency increase. Although this result is likely not generalizable to other supply chains, it indicates that for lightweight vehicle production, implementing next-generation production technologies can provide greater energy and emissions reductions than improvements to existing production technologies. This information, in conjunction with additional data such as the time and investment required for technology implementation, could be used to make decisions about improvements in lightweight vehicle supply chains and to prioritize research and development efforts toward specific next-generation technologies.

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## References

Argonne National Laboratory (2015) The Greenhouse gases, regulated emissions, and energy use in transportation fuel-cycle model. https://greet.es.anl.gov/

Das S (2012) Achieving carbon neutrality in the global aluminum industry. JOM 64(2):285–290

Das S (2013) Life cycle assessment of carbon fiber-reinforced polymer composites. Int J Life Cycle Assess 16(3):268–282

Das S, Graziano D, Upadhyayula VKK, Masanet E, Riddle M, Cresko J (2016) Vehicle lightweighting energy use impacts in U.S. light-duty vehicle fleet. J Sustain Mater 8:5–13

Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (2006) Guidelines for national greenhouse gas inventories. IPCC National Greenhouse Gas Inventories Programme, Hayama

Frischknecht R, Jungbluth N, Althaus H-J, Doka G, Dones R, Heck T, Hellweg S, Hischier R, Nemecek T, Rebitzer G, Spielmann M (2005) The ecoinvent database: overview and methodological framework. Int J Life Cycle Assess 10:3–9

Green Design Institute (2008) Economic input–output life cycle assessment (EIO-LCA), US 2002 Industry Benchmark model. Carnegie Mellon University. www.eiolca.net

Guinée JB, De Haes HAU, Huppes G (1993) Quantitative life cycle assessment of products 1: goal definition and inventory. J Clean Prod 1(1):3–13

Gutowski TG, Sahni S, Allwood JM, Ashby MF, Worrell E (2013) The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand. Philos Trans R Soc A 371(1986):20120003

Hanes RJ, Das S, Carpenter A (2016) Reducing supply chain energy use in next-generation vehicle lightweighting. Presented at *LCA XVI*, Charleston, SC, September 2016. http://www.nrel.gov/docs/fy16osti/67172.pdf

ICF International (2012) Internal report. Note: Reference available from authors on request

IHS Chemicals (2014) Process Economics Program Yearbook

Leontief W (1970) Environmental repercussions and the economic structure: an input-output approach. Rev Econ Stat 52(3):262–271

Masanet E, Kramer KJ, Homan G, Brown R, Worrell E (2009a) Assessment of supply chain energy efficiency potentials: A US case study. In: IEEE international symposium on sustainable systems and technology, vol 2009, pp 1–6

Masanet E, Kramer KJ, Homan G, Brown R, Worrell E (2009b) Assessment of household carbon footprint reduction potentials. Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US). No. LBNL-2291E

Miller S, Keoleian G (2015) Framework for analyzing transformative technologies in life cycle assessment. Environ Sci Technol 49(5):3067–3075

Modaresi R, Pauliuk S, Løvik AN, Müller DB (2014) Global carbon benefits of material substitution in passenger cars until 2050 and the impact on the steel and aluminum industries. Environ Sci Technol 48(18):10776–10784

National Renewable Energy Laboratory (2016) U.S. Life Cycle Inventory Database. https://uslci.lcacommons.gov/uslci/search

Park C-K, Kan C-D, Hollowell W, Hill SI (2012) Investigation of opportunities for lightweight vehicles using advanced plastics and composites (Report No. DOT HS 811 692). National Highway Traffic Safety Administration, Washington

U.S. Department of Energy (2016) Carbon fiber reinforced polymer bandwidth study (DRAFT). http://energy.gov/eere/amo/energy-analysis-sector#5

Wender BA, Foley RW, Hottle TA, Sadowski J, Prado-Lopez V, Eisenberg DA, Laurin L, Seager TP (2014) Anticipatory life-cycle assessment for responsible research and innovation. J. Responsible Innov 1(2):200–207