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

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Abstract. When evaluated at the process level, 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 Material Flows through Industry (MFI) scenario modeling tool. The MFI tool is a cradle-to-gate linear network model of the U.S. industrial sector that can model a wide range of manufacturing scenarios, including changes in production technology, increases in industrial energy efficiency, and substitution between functionally equivalent materials. 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 a steel supply chain to the supply chains of several functionally equivalent materials. Several of the alternatives to the baseline steel supply chain include next-generation production technologies and materials. Results of the case study show that aluminum production scenarios can out-perform the steel supply chain by using either an advanced smelting technology or an increased aluminum recycling rate. The next-generation material supply chains do not perform as well as either aluminum or steel, but may offer additional use phase reductions in energy and emissions that are outside the scope of the MFI tool. Future work will combine results from the MFI tool with a use phase analysis.

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Introduction. Decisions on next-generation technology development and deployment benefit from analysis of the impacts the technology has at a supply chain or larger scale, in addition to process level analysis of the technology itself. While next-generation technologies may not be less intensive at the process level, the shifts in material and energy flows resulting from technology deployment can create positive impacts elsewhere in the economy. Supply chain and sectoral-level analyses are thus critical when evaluating next-generation technologies in order to fully understand the benefits and consequences of such technologies, and to prioritize efforts towards commercialization and deployment.

The current work is in support of the U.S. Department of Energy's Advanced Manufacturing Office's objective of identifying and analyzing opportunities to reduce the energy and carbon intensities of the U.S. industrial sector. In this work we focus on two such opportunities: next-generation materials and production technologies that offer reductions in life cycle energy use and emissions, and improvements in the energy efficiency of existing industrial processes.

Model description. The Material Flows through Industry (MFI) scenario modeling tool was developed with the goal of performing supply chain analyses within the U.S. industrial and manufacturing sectors. The basis of the MFI tool is a database of products and recipes. Each recipe, essentially an input-output model in physical units of a specific production technology, consists of quantities of material and energy inputs required to produce a unit of product. Products are industrial commodities and materials such as primary metals, bulk chemicals and fossil fuels. Sources for recipe data include the IHS Process Economics Program Yearbook (IHS Chemical, 2014), the ecoinvent life cycle inventory database (Frischknecht et al., 2005) the U.S. Life Cycle Inventory (NREL, 2016), and various additional literature sources. Currently, the MFI database contains 1,365 recipes for 639 products as well as 670 products without recipes.

Where multiple recipes exist for a product, a baseline weighted average recipe is derived from information on the current market share of each production technology. (ICF, 2012) The averaged recipes are linked to form a linear network model of the U.S. industrial sector. Flows in the model consist of fuels, electricity, water and materials. Greenhouse gas emissions are calculated from fuel consumption using 100-year global warming potential factors from the Intergovernmental Panel on Climate Change. (IPCC, 2006)

Scenario parameters. Models of different manufacturing scenarios are derived from the baseline model, which represents current U.S. industrial practice, by varying parameters that control technology mixes, material substitutions, and energy efficiency. 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 old 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.

Material substitutions are another set of model parameters, and are implemented by substituting existing products with next-generation alternatives according to mass- or usage-based substitution factors. Two examples of material substitutions are replacing steel with aluminum and replacing a fossil fuel-derived chemical feedstock with a biomass-derived equivalent. Material substitutions can be implemented either in a single recipe, throughout a particular manufacturing sector, or throughout the entire model.

Sector efficiency potentials (SEPs), which affect energy efficiency, are the third set of model

parameters. SEPs quantify the reduction in process level electricity and fuel consumption achievable when process equipment in use is upgraded to the most efficient equipment available. (Masanet et al, 2009) SEPs, like material substitutions, can be applied to individual recipes, to all recipes in a sector, or to every recipe in the model. SEPs can also be implemented only for certain types of fuel or equipment, for instance to model an increase in natural gas efficiency of water heaters.

System boundary and limitations. The scope of MFI is cradle-to-gate; it captures the supply chain of industrial commodities manufactured in the U.S. MFI does not include the use phase for commodities not consumed in a supply chain, although additional recipes representing these steps can be added to the existing model framework. While the MFI database covers a broad swathe of the U.S. industrial sector, there are known data gaps in the plastics, paper products and agricultural sectors; MFI thus has limited capability to model supply chains that are heavily dependent on products from these sectors. Additional recipes are added to MFI as gaps in the database coverage are identified and as recipe data is found.

MFI is a linear model in physical units. Economic complexities such as economies of scale and the effects of changes in commodity supply and demand are not captured. MFI is thus an attributional rather than a consequential tool. Spatial and temporal information is also not currently included in the MFI database. Supply chain emissions 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.

Research Objectives. The primary objective of this work is to demonstrate the modeling capabilities, applications and results of the MFI tool. This is accomplished with a case study analyzing the supply chains of steel and three functionally equivalent materials: aluminum, carbon fiber reinforced plastic (CFRP) and glass fiber reinforced plastic (GFRP). The supply chains are evaluated under several manufacturing scenarios that incorporate either baseline or advanced alumina smelting technologies, and apply several different assumptions about increases in energy efficiency. Results of this case study could be used to identify opportunities to reduce energy and emissions associated with steel production and could inform prioritization of research and development efforts towards advanced technologies and materials that offer the greatest benefits.

Investigative Method. Nineteen scenarios shown in Table 1 are included in the case study. The baseline scenario has steel as the end product and no efficiency increase; all other scenarios are based on a combination of end product and efficiency option. The aluminum supply chains also have further options relating to the smelting technology and the level of aluminum recycling.

The efficiency options considered in the case study are: 1) no efficiency increase (baseline energy efficiency), 2) a process-level increase in efficiency that affects only the end product's production technology, and 3) an economy-wide efficiency increase that affects the entire model. Two of the alumina smelting technologies, clay carbochlorination and the carbothermic electric furnace process, are not evaluated under the process-level efficiency increase. Because these smelting technologies are next-generation, the baseline data already reflects the use of the most efficient process equipment available. (Das, 2012)

For the results to be comparable across end products, they must represent production of equivalent material amounts. Aluminum and fiber-reinforced plastics are lighter than steel; thus 1 kg of steel is equivalent to less than 1 kg of the lighter materials. The material amounts used

in this case study are 1 kg steel, 0.5 kg aluminum, 0.55 kg CFRP, and 0.7 kg GFRP. (Park et al., 2012)

Table 1. Scenarios analyzed for the case study. An X indicates a scenario that combines the end product and technology options to the left with the efficiency increase option at the top of the table.

End Product	Technology Option	Efficiency Increase		
		None	Process Level	Entire Economy
Steel	--	X	X	X
Aluminum	Hall-Heroult Smelting	X	X	X
	Clay Carbochlorination Smelting	X		X
	Carbothermic Electric Furnace Smelting	X		X
	Incremental Increased Recycling (45% primary, 55% secondary)	X		
	Moderate Increased Recycling (35% primary, 65% secondary)	X		
	Significant Increased Recycling (25% primary, 75% secondary)	X		
Carbon Fiber Reinforced Plastic	--	X	X	X
Glass Fiber Reinforced Plastic	--	X	X	X

The aluminum production technology options are for alumina smelting, which is a highly energy-intensive process of extracting aluminum from alumina ore. Three alumina smelting technologies are considered as part of the aluminum supply chain evaluation. The baseline technology is the modern Hall-Heroult process, which is the only smelting technology currently in operation at a commercial scale in the U.S. (Das, 2012) The two alternative smelting technologies considered are clay carbochlorination and the carbothermic electric furnace process. Both of these technologies offer process-level reductions in energy consumption over the Hall-Heroult process, but neither has been developed past the pilot plant scale. (Das, 2012) Implementing either of the alternative technologies at a commercial scale would require additional research and technology development.

Another aspect of the aluminum supply chain evaluated in this case study is the ratio of primary aluminum from smelters to secondary aluminum from recycled streams. Using a greater proportion of secondary aluminum in the mix decreases the amount of primary aluminum that must be produced, which in turn decreases supply chain energy and emissions. Three scenarios that change the proportions of primary and secondary aluminum are evaluated. At baseline levels, aluminum consists of 48% primary and 52% secondary. (DOE EERE, 2004) The incremental increased recycling scenario changes this mix to 45% primary aluminum and 55% secondary. The moderate increased recycling scenario has 35% primary and 65% secondary, and the significant increased recycling scenario has 25% primary and 75% secondary. The primary/secondary ratios are also shown in Table 1 next to the relevant technology option. All three increased recycling scenarios use the baseline Hall-Heroult

smelting technology and the baseline energy efficiency to avoid confounding the impacts of increased recycling with the impacts of other supply chain options. The implications of ramping up the industrial recovery and recycling systems are outside the scope of this analysis.

The other end product options are CFRP and GFRP, advanced materials that can substitute for steel or aluminum in automotive, aerospace and other structural applications. (Das, 2013) CFRP and GFRP are both more energy intensive than aluminum at the process level; this analysis will show if they are more intensive at the supply chain level.

Results. Figure 1 shows the supply chain energy consumption and greenhouse gas emissions for all scenarios. Point color indicates the end product and technology, the color of the border around each point indicates the aluminum recycling options, and the point shape indicates the efficiency option. Both emissions and energy values are normalized to 1 kg of steel equivalent, which as stated above is 0.5 kg aluminum, 0.55 kg CFRP and 0.7 kg GFRP.

Figure 1: Supply chain energy and emissions of all scenarios. Improvement over the steel baseline supply chain is possible, but not all options reduce supply chain energy and emissions.

Further details of the results in Figure 1 are given in the Supplementary Information. In Figures S1 – S4, the total energy consumption of each scenario is broken down by fuel use type: nonrenewable fuel for electricity generation, renewable electricity, process fuel and fuel used as chemical feedstock. Figures S5 – S8 similarly break down emissions for each scenario by source: electricity generation or process fuel.

Discussion and Conclusions. Several scenarios offer reductions in supply chain energy and emissions over the steel baseline, but neither of the advanced material supply chains perform well compared to the other options. Among the aluminum production scenarios, both of the advanced smelting technologies offer reductions in supply chain energy and emissions over

baseline aluminum production. The carbothermic electric furnace technology was the best overall. This trend remained the same under all efficiency options.

Scenarios with increased aluminum recycling also performed well, with both the moderate and the significant increased recycling scenarios having lower supply chain energy and emissions compared to the steel baseline. The significant increased recycling scenario also performed best overall, out of all scenarios evaluated. While increasing recycling may seem simple compared to other supply chain options, it is complex from a policy, implementation and technology development point of view. The intricacies and complications of implementing such a change, which may include improvements to recycling infrastructure, government policies encouraging or incentivizing increased recycling, and more advanced technologies for separating and processing recycled waste streams, are outside the scope of the MFI tool. Further analyses in areas outside the current MFI system boundary are necessary to determine that increased recycling is truly a beneficial supply chain option. It is possible that one of the other scenarios may be more feasible and cost effective in the long term even if the reductions in supply chain energy and emissions are not as significant.

Both CFRP and GFRP had higher supply chain energy consumption and higher supply chain combustion emissions than the baseline steel scenario under all efficiency options, including the economy-wide increase in efficiency. Additional effort towards technology development is needed before either of these advanced material supply chains becomes competitive. (U.S. DOE, 2015) However, the advanced materials as well as aluminum have use phase benefits not captured by MFI. Replacing steel with a lighter material can reduce fuel consumption in vehicles through vehicle lightweighting. Over the lifetime of a vehicle, the use phase savings in fuel and emissions can outweigh the increase in supply chain energy and emissions, meaning the fiber reinforced plastic may become competitive with aluminum. Future work in this area will combine a vehicle lightweighting analysis with supply chain results from MFI to gain more complete information.

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Supplementary Information

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Figures S1 – S4 give the total energy consumption for 1 kg steel equivalent under all scenarios analyzed, broken down by fuel use and type: renewable and non-renewable fuel for electricity generation, process fuel, and fuels used as chemical feedstock. The nineteen scenarios are separated into steel production (Figure S1), aluminum production (Figure S2), increased aluminum recycling (Figure S3) and fiber reinforced plastic production (Figure S4). All four figures have the same y-axis scale for easier comparison.

Figure S1: Energy consumption by fuel use and type for steel production scenarios.

Figure S2: Energy consumption by fuel use and type for aluminum production scenarios.

Figure S3: Energy consumption by fuel use and type for increased aluminum recycling scenarios.

Figure S4: Energy consumption by fuel use and type for reinforced plastic scenarios.

Figures S5 – S8 show the supply chain emissions for all scenarios analyzed, again separated into steel production (Figure S5), aluminum production (Figure S6), increased aluminum recycling (Figure S7) and fiber reinforced plastic production (Figure S8). Figures S5 – S8 have the same y-axis scale. Supply chain emissions are separated by source, either electricity generation or process fuel. Fugitive emissions are not currently contained in the MFI database and are not included in the total.

Figure S5: Emissions by source for steel production scenarios.

Figure S6: Emissions by source for aluminum production scenarios.

Figure S7: Emissions by source for increased aluminum recycling scenarios.

Figure S8: Emissions by source for fiber reinforced plastic production scenarios.