Environmental Impacts
From
Carpet Discards Management Methods:
Preliminary Results
(Corrected)

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1. Introduction and Summary

This report compares preliminary estimates for the climate change impacts of four methods currently used to manage carpet discards generated by households and construction and demolition (C&D) activities:

1) Recycle via mechanical and/or chemical methods, with or without the use of heat, into constituents which can be used for manufacturing new carpet components or other products such as automobile body parts.
2) Recover energy via combustion in an industrial boiler as a substitute for coal.
3) Recover energy via combustion in a waste-to-energy (WTE) incineration facility.
4) Landfill.

This report also discusses very preliminary results for six other categories of environmental impacts for scrap carpet recycling:

- Acidification
- Eutrophication
- Human Health – Particulates
- Human Health – Toxicity
- Human Health - Carcinogenicity
- Ecosystems Toxicity

Figure 1, Greenhouse Gas Increase/(Decrease) for Scrap Carpet Management Options [Pounds CO2 Equivalents per Ton Carpet], indicates that the recycling management option has the most beneficial impact on climate change. Recycling one ton of used carpet into new carpet or other products such as automobile body parts reduces greenhouse gas (GHG) emissions between 4,900 and 5,200 pounds of carbon dioxide equivalents (eCO2).

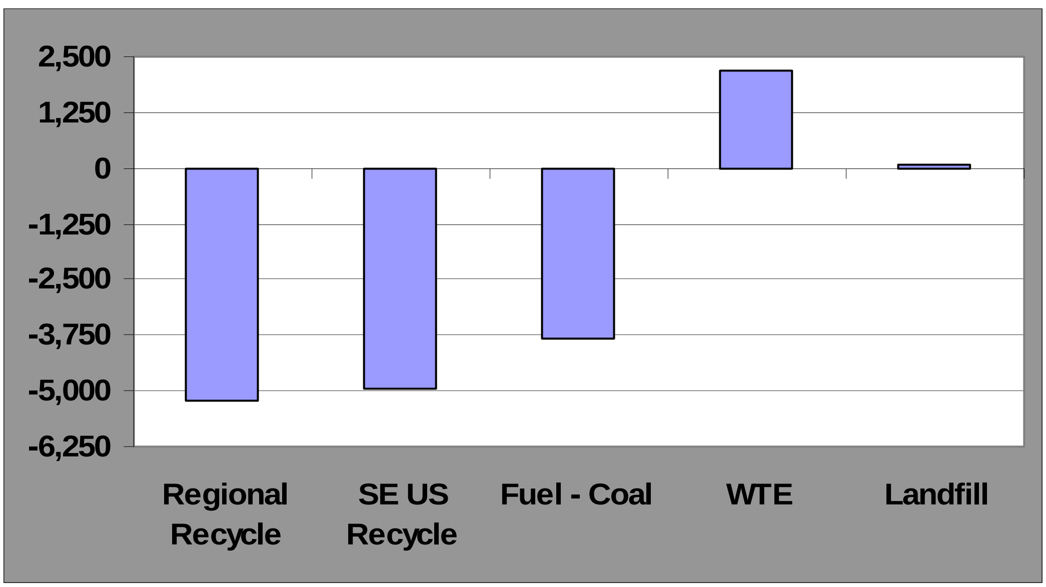
The range relates to the distance which used carpet needs to be hauled to the facilities where it is processed and manufactured into new products. Currently the southeastern US is the region of the country where most carpet recycling facilities are located. Shipping to the southeastern US increases the truck hauling distance by an estimated 2,500 miles compared with shipping to markets in the Northwest region, thereby increasing GHG emissions by nearly 300 pounds eCO2 per ton of carpet shipped across the county.

The release of less than 300 pounds eCO2 per ton of carpet shipped 2,500 miles indicates the relative unimportance of transportation distances in the total climate change impact of carpet recycling. To make the point in another way, each ton of used carpet recovered for recycling could be shipped more than 12,000 miles by truck before recycling would lose its position as the best management option for used carpet.

Using chopped carpet as a fuel substitute for coal in industrial boilers also decreases GHG emissions due to the higher energy content of carpet compared to coal. Used carpet has an estimated heating value of 13,900 Btus per pound, 30% more than coal's heating value of 10,340 Btus per pound. This heating value plus the fact that 53% of the carbon in carpet is non-biogenic (i.e., fossil) according to EPA (2003) means that combustion of one ton of carpet scraps in an industrial boiler releases 3,900 pounds eCO2 while offsetting 7,800 pounds of eCO2 from coal combustion. Thus, combusting scrap carpet in place of coal in industrial boilers reduces GHG emissions by 3,800 pounds eCO2 after accounting for GHG emissions from hauling and processing.

Landfilling comes in third in climate change impacts, increasing GHG emissions by less than 100 pounds eCO2. Hauling and landfill operations cause these small releases of GHGs when used carpet is landfilled.

Figure 1
Greenhouse Gas Increase/ (Decrease) for Scrap Carpet Management Options
[Pounds CO2 Equivalents per Ton Carpet]



It is worth mentioning here that because carpet does not biodegrade in a landfill, the GHG releases associated with landfilling used carpet are the same irrespective of whether the landfill has a landfill gas (LFG) collection system in place or simply vents LFGs to the atmosphere. Used carpet produces no LFGs and so the methane releases from a landfill are not affected by the amount of used carpet buried in a landfill. Thus the climate change impact from landfilling carpet is the same for a landfill with no LFG collection system, a landfill that collects LFGs and flares them, and a landfill that collects LFGs and uses the collected LFG to generate electricity.

Last place in the ranking of used carpet management methods goes to waste-to-energy (WTE) incineration. The amount of CO_2 released as a result of the fossil fuel content of scrap carpet is substantially greater than the avoided emissions from an equivalent amount of electricity produced by a combined cycle natural gas powered turbine. The latter is the marginal source of electrical power in the Northwest. Thus, used carpet disposal in a WTE incinerator increases climate changing emissions by 2,200 pounds eCO_2.

2. Methodology & Data for Estimating Scrap Carpet Climate Impacts

The choice among management methods for scrap carpet has environmental impacts much beyond the boundaries of the processing or disposal facilities where used carpets are sent. To fully account for these impacts one needs to examine the entire life cycle of carpets from petroleum and natural gas extraction and processing into various polymers through to the point at which carpets become discards generated by households or by C&D activities.

Table 1, Scrap Carpet Management Emissions and Emission Offsets, shows the stages in the carpet's life cycle where emissions occur as a result of each current management method for used carpet. The table also shows the offsets, or emissions decreases, which occur as a result of each management method.

For example, recycling used carpets entails emissions from processing the carpet into its constituent components and using those component materials to manufacture new products. Recycling also creates emissions from hauling the component materials to manufacturing end users. The gain from recycling is that the amount of GHG emissions avoided by not using virgin raw materials to manufacture new products is more than two and a half times as great as the emissions from the used carpet processing, shipping, and recycled-content product manufacturing activities needed to recycle used carpet discards. For wool or cotton face fiber carpets, recycling or landfilling likely maintains storage of a portion of the biogenic carbon in these carpets.

Combusting or landfilling used carpets may involve shorter hauling distances than the recycling option. However these options don't avoid the manufacture of new carpet or other products from virgin materials. The two combustion options do avoid fossil fuel usage -- to replace natural gas used for electricity generation in the case of WTE incineration and to replace coal in the case of combustion in industrial boilers. Because carpet does not biodegrade in the landfill, there is no energy offset from methane generation in the case of that disposal option.

Table 1
Scrap Carpet Management Emissions and Emission Offsets

	Recycle	Fuel Replace Coal	WTE Incineration	Landfill
Emissions				
Processing & Use in Manufacturing Recycled-Content Products	X			
Hauling – Regional Market	X	X	X	X
Hauling – Southeast Market	X			
Combustion (incl. Facility Operations)		X	X	
Landfill Operations				X
Offsets				
New Virgin-Content Product Manufacturing	X			
Coal Production & Combustion in Industrial Boilers		X		
Natural Gas Production & Combustion for Electricity			X	
Biogenic Carbon Storage	X			X

The reason the combustion options don't reduce GHG emissions as much as recycling does is that modern carpets are manufactured from mostly synthetic materials that are themselves composed of fossil fuel-based resources such as petroleum and natural gas. EPA (2003) estimates that 53% of the carbon contained in a typical carpet is fossil carbon. Thus, when carpets are burned they release substantial GHGs in the form of fossil CO2.

Substituting carpet chips for coal in industrial boilers results in reduced GHG emissions, due to the fossil CO2 intensive emissions from coal per unit of energy provided from coal combustion. On the other hand, the amount of electricity generated in a modern WTE incineration facility offsets less than half the GHG emissions from carpet combustion. This is because natural gas fired power stations produce much more electrical energy per pound of eCO2 emissions than do WTE facilities burning used carpet.

2.a. Data Sources for Estimation of Emissions and Offsets

A variety of sources provided the data and methods for estimating GHG and other emissions from used carpet discards management, the potential environmental impacts caused by those emissions, and the economic costs for the environmental impacts. These sources include:

- US EPA's WARM model and supporting documentation (available on the internet at http://www.epa.gov/climatechange/wycd/waste/calculators/Warm_home.html).
- US EPA's MSW Decision Support Tool (DST) (available through Research Triangle Institute[1]).

[1] See Research Triangle Institute (1999a and 1999b)

- Carnegie Mellon University Green Design Institute's Economic Input-Output Life Cycle Assessment model (available on the internet at www.eiolca.net).
- US NIST BEES model (available on the internet at http://www.bfrl.nist.gov/oae/software/bees/model.html).
- US EPA's TRACI model (information about TRACI is available on the internet at http://www.epa.gov/nrmrl/std/sab/traci/).
- US EPA's AP-42 emissions data (available on the internet at http://www.epa.gov/ttn/chief/ap42/).
- Peer-reviewed journal articles including Morris (2005) and Morris and Bagby (2008).
- A comprehensive waste management system environmental costs and benefits valuation model (available through Sound Resource Management[2]).
- In-depth interviews and data exchanges with representatives of major carpet manufacturers, as well as researchers at Georgia Tech.

The following section details how we used these data and methods to estimate the climate change impacts of used carpet management methods. Section 4 details our estimates for the six other types of environmental benefits from carpet recycling in addition to its GHG reduction benefits.

3. GHG Releases & Offsets from Carpet Discards Management

Table 2, Estimated GHG Increase/(Decrease) for Carpet Discards Management Methods, shows the estimated greenhouse gas (GHG) releases or reductions for each management method currently used to handle used carpet discards. This section lays out the methodology and emissions estimate for each individual activity and offset listed in Table 1 of the previous section. The emissions from these activities minus the offsets add up to the GHG totals listed in Table 2 for the used carpet management options. Table 3 shows the GHG release or offset estimate for each of the line items and management methods laid out in Table 1.

Table 2
Estimated GHG Increase/(Decrease) for Carpet Discards Management Methods
(pounds CO2 equivalents per ton carpet)

Management Method	*Pounds eCO2/ton*
Recycle	(5,223) to (4,932)
Fuel Sub for Coal	(3,808)
Landfill	78
WTE Incineration	2,205

[2] The model is reviewed in Morawski (2008).

Table 3
Scrap Carpet Management Emissions and Emission Offsets
(pounds eCO2/ton scrap carpet)

	Recycle	Fuel Replace Coal	WTE Incineration	Landfill
<u>Emissions</u>				
Processing & Use in Manufacturing Recycled-Content Products	2,932			
Hauling – Regional Market	58	58	12	12
Hauling – Southeast Market	349			
Combustion (incl. Facility Operations)		3,940	3,866	
Landfill Operations				66
<u>Offsets</u>				
New Virgin-Content Product Manufacturing	-8,213			
Coal Production & Combustion in Industrial Boilers		-7,806		
Natural Gas Production & Combustion for Electricity			-1,673	
Biogenic Carbon Storage	0*			0*
Net Emissions	-4,932 to -5,223	-3,808	2,205	78

*Assumes face fiber is synthetic; for wool or cotton face fiber there would be a non-zero offset.

3.a. GHG Offsets for Avoided Production of Virgin-Content Carpet

Our estimate for GHG emissions from manufacturing virgin carpet is 8,213 pounds of carbon dioxide equivalents (eCO2) per ton of new carpet. At a carpet weight of four pounds per square yard, this amounts to over 16 pounds eCO2 per square yard of new broadloom carpet or carpet tile. We calculated this estimate, as well as the estimates for emissions from virgin carpet production causing the other six environmental impacts discussed in Section 4, using Carnegie Mellon University Green Design Institute's Economic Input-Output Life Cycle Assessment (EIOLCA) model.[3]

According to the EIOLCA model one million dollars (1997 $) of purchases from the carpet and rug mills industry (EIOLCA sector 314110) results in 1,155,000 metric tons eCO2 emissions. These emissions occur due to carpet manufacturing processes, as well as synthetic polymers production, manufacturing of other inputs in the supply chain for carpet making, and energy and material resource extraction and refining required for use across the entire carpet and rug mills supply chain. Based on recent and historical wholesale prices and producer price indices for carpets and rugs, the producer price for a square yard of carpet in 1997 was $6.45. Given an assumed carpet weight averaging 4 pounds per square yard, this yields the estimate of 8,213 pounds eCO2 life cycle emissions to manufacture one ton of carpet from virgin raw materials.

[3] Hendrickson *et al* (2006) provides an overview of the use of input-output analysis for calculating life cycle emissions. Cicas et al (2006) explains the 1997 benchmark version of the Green Design Institute's EIO-LCA model.

3.b. GHG Offsets for Avoided Production & Combustion of Coal

We also used the EIO-LCA model to estimate GHG releases from production and distribution of coal. Emissions caused by purchases from the coal mining industry (EIOLCA sector 212100) amount to 161 pounds eCO2 per ton of coal, based on an estimated 1997 wholesale price for coal of $18.14 per short ton.

Carpets have an average heating value of 13,400 Btus per pound, or 26.8 million Btus per ton. Coal's heating value on average is 20.68 million Btus per ton. Thus, one ton of carpet has the same heating value as 1.30 tons of coal.

EPA's AP-42 reports CO2 emissions per ton of coal at 5,850 pounds. Total GHG emissions from coal combustion amount to 5,863 pounds eCO2 per ton, including emissions of other GHGs such as methane, chloroform and nitrous oxide that are released when coal is burned. Combining production and combustion emissions, substituting one ton of carpet for 1.3 tons of coal saves 7,806 pounds of eCO2 releases caused by coal combustion.

3.c. GHG Offsets for Avoided Production & Combustion of Natural Gas for Electricity Generation

We used the EIO-LCA model to estimate GHG releases from production and distribution of natural gas. Emissions from purchases of natural gas from the natural gas distribution industry (EIOLCA sector 221200) amount to 22 pounds eCO2 per 1000 cubic feet of gas, based on an estimated 1997 wholesale price of $4.52 for 1000 cubic feet.

Carpets have an average heating value of 13,400 Btus per pound, or 26.8 million Btus per ton. According to R W Beck (2007), one ton of carpet combusted in a modern waste-to-energy incineration facility offsets 1,414 pounds eCO2 emitted when natural gas is used to generate electricity in a combined cycle turbine.

EPA's AP-42 reports CO2 emissions per 1000 cubic feet of natural gas combustion at 121.3 pounds. An offset of 1,414 pounds eCO2 thus means that combusting one ton of used carpet in a modern WTE facility offsets 11,660 cubic feet of natural gas. Combining production and combustion emissions for natural gas, one ton of carpet incinerated in a WTE facility offsets 1,673 pounds of eCO2 emissions from natural gas used to generate electricity.

3.d. Biogenic Carbon in Carpets

According to EPA (2003) 53% of carpet is composed of non-biogenic (i.e., fossil) carbon, most of which is released when carpet is combusted.[4] Most if not all of the remaining constituents of synthetic face fiber carpet are not carbonaceous. However, wool or cotton face fiber carpet contains a substantial amount of biogenic carbon. Landfilling or recycling used carpet maintains storage of some of this biogenic carbon by continuing to prevent its

[4] See Exhibit 16 in EPA (2003).

release to the atmosphere; whereas combustion releases it. In comparing recycling, landfilling, and combustion alternatives for managing used carpet, one would need to count the storage of biogenic carbon as an offset for recycling and landfilling. However, In Table 3 we show no offsets for storage of biogenic carbon in discarded carpet because synthetic carpet is the focus of most current used carpet recycling efforts.

3.e. GHG Emissions from Processing and Manufacturing Recycled-Content Products from Used Carpet

We estimated GHG emissions from recycling used carpet into new products in three different ways. The first estimate comes from EPA (2003). This study reported results of a life cycle inventory for GHG releases for manufacturing 100% virgin carpet and the releases from recycling used virgin carpet into three recycled-content products – carpet pad, carpet backing, and molded products for automobiles. The molded automotive products ranged from air intake assemblies to headrests.

The EPA study's estimate of GHG releases from manufacturing one ton of 100% virgin-content carpet is 8,730 pounds eCO2. This is 6.3% higher than our estimate of 8,213 pounds eCO2 developed using the EIO-LCA model. The two estimates are remarkably close considering that our estimate is based on an EIO life cycle inventory (LCI), whereas the EPA estimate was developed using a process LCI methodology.[5]

EPA's estimate of GHG reductions from carpet recycling is 15,924 pounds eCO2 per ton of carpet constituents recycled into three recycled-content products – 65% of the used carpet to carpet pad/cushion, 25% to molded products for motor vehicles, and 8% to backing for carpet tiles. The separate GHG reductions for pad, molded products and tile backing amount to 17,500, 15,580, and 3,030 pounds eCO2, respectively, assuming one ton of used carpet contained only those carpet constituents required for recycling into each of these products. In other words, the used carpet constituents recycled into carpet pads and molded automotive vehicle parts are more than five times as effective at reducing GHG emissions as the used carpet constituents recycled into carpet tile backing. Because the EPA study assumed only 8% of scrap carpet goes to tile backing, carpet recycling saves more than twice as much GHG emissions as manufacturing virgin-content carpet produces in the first place. This seems to be an anomalous result because it suggests that one could produce new products at a lower environmental impact by manufacturing virgin-content carpet and immediately recycling the brand new carpet into carpet pad and molded plastic products, rather than making those products from virgin resources.

The second method we used to estimate GHG savings from used carpet recycling is based on the EIOLCA model and our estimate of what input materials for virgin carpet manufacture would not be needed if one were manufacturing 100% recycled-content carpet. According to

[5] See any standard reference text on life cycle analysis for a discussion of these two basic LCI methods.

the EIOLCA model $1 million of carpet production requires $171,000 in purchases from the noncellulosic organic fiber manufacturing industry, $170,000 from fiber, yarn and thread mills, $54,000 in purchases from broadwoven fiber mills, and $53,000 from textile and fabric finishing mills. Assuming that 100% recycled-content carpet could be manufactured without any purchases from these four industries reduces GHG emissions for carpet manufacturing to 2,932 pounds eCO2 per ton of carpet. This is a reduction of 5,281 pounds eCO2 for closed loop carpet recycling, one-third the reduction estimated by EPA for open loop carpet recycling.

The third method for estimating GHG reductions due to recycling used carpets is based on interviews and confidential data from three major carpet manufacturers, confidential data from Dr. Matthew Realff at Georgia Tech, and the online carbon savings calculator for Invista's Antron carpet fiber (http://antron.net/content/toolbox/ant05_05.shtml). The Antron calculator estimates that emission of 9.4 pounds eCO2 is averted for every square yard of used carpet recycled. At an average weight per square yard of four pounds, that amounts to 4,700 pounds eCO2 per ton of used carpet.

Estimates of GHG savings from carpet recycling based on confidential data from carpet manufacturers and researchers at Georgia Tech are much closer to our estimate of 5,281 pounds eCO2 based on the EIOLCA model than to the EPA's estimate of 15,924 pounds eCO2 per ton of used carpet recycled. In fact, without revealing any particular company's confidential data regarding the very different recycling processes used by the three companies, we can say that carpet manufacturer' estimates of GHG reductions from recycling one ton of used carpet fall in a range between 11% below and 14% above our estimate 5,281 pounds eCO2.

Given the close agreement between industry estimates and the EIOLCA estimate, the 5,281 pounds of eCO2 emissions reductions from carpet recycling appears to be the best estimate to use at this point in our research. This implies that processing and recycling one ton of used carpet into new carpet causes the emissions of 2,932 pounds of eCO2, the difference between the 8,213 pounds eCO2 emitted when virgin carpet is produced and the 5,281 pounds eCO2 that is avoided by recycling used carpet into new recycled-content carpet. This 2,932 pounds eCO2 is the estimate shown in Table 3 for emissions from processing and use of used carpet in manufacturing recycled-content products.

3.f. GHG Emissions from Hauling

The MSW DST database EPA/NCSU/RTI (2003) estimates that GHG emissions for long distance truck hauling amount to under 0.12 pounds eCO2 per ton mile. Trip mileage for the four used carpet management methods discussed in this report are assumed to total 500 miles for regional recycling or industrial fuel markets, 3000 miles for recycling at southeastern US markets, and 100 miles for WTE incineration or landfill. These distances yield eCO2 emissions per ton of used carpet of 58, 349 and 12 pounds, respectively.

3.g. GHG Emissions from Combustion & Combustion Facility Operations

According to EPA (2003) 3,799 pounds eCO2 are released when one ton of used carpet is incinerated. In the case of combustion in industrial boilers we include an additional 141 pounds eCO2 per ton of carpet for processing and chipping to a size suitable for combustion. For WTE incineration we include an additional 67 pounds eCO2 per ton of carpet for WTE facility handling and processing of the used carpet. These estimates are based on EPA (2006) and EPA/NCSU/RTI (2003).

3.h. GHG Emissions from Landfill Operations

EPA's WARM model, EPA(2006), includes 88 pounds eCO2 for curbside collection of a ton of garbage, hauling the garbage to the landfill, and managing the garbage once it is at the landfill site. Because there is no curbside collection involved with used carpet generated at C&D activity sites, and because hauling emissions are accounted for separately in our calculations, we reduced the 88 pounds to 66 to cover just the landfill operations for used carpet.

4. Additional Upstream Environmental Benefits from Used Carpet Recycling

Table 4, Environmental Impact Reductions (%) for Recycled- vs. Virgin-Content Product Manufacturing of Carpet, PET Pellets & HDPE Pellets, shows the estimated percentage reduction in seven environmental impacts from manufacturing with recycled material inputs in place of virgin raw materials. The percentage reduction estimates for carpet are based on the EIOLCA model as detailed for the climate change impact in Section 3. The reductions for PET (polyethylene terephthalate) and HDPE (high density polyethylene) are based on emissions data catalogued in the MSW DST database EPA/NCSU/RTI (2003).

Table 4 compares the reductions in each type of environmental impact attained by employing used carpet, used PET food and beverage bottles, and used HDPE food and beverage containers to manufacture new carpet, new PET plastic pellets, and new HDPE plastic pellets, respectively. These environmental pollution reductions are achieved by avoiding the use of virgin raw materials to manufacture carpet and molded plastics, PET pellets, and HDPE pellets, respectively.

Table 4
Environmental Impact Reductions (%) for Recycled- vs. Virgin-Content Manufacturing of Carpet, PET Pellets & HDPE Pellets

Environmental Impact	Carpet	PET	HDPE
Climate Change	64.3%	87.6%	84.8%
Acidification	59.8	91.5	75.0
Eutrophication	57.7	89.7	77.2
Human Health – Particulates	67.7	87.4	76.6
Human Health – Toxics	83.1	87.3	81.3
Human Health – Carcinogens	76.1	89.5	88.2
Ecosystems Toxicity	69.1	58.4	28.5

PET and HDPE containers are composed of various synthetic plastic polymers. Carpet is composed of a high percentage of synthetic polymers of various types as well. For that reason the data in Table 4 for PET and HDPE provide indirect corroboration for our estimates of environmental impact reductions from carpet recycling, because the percentage reductions for carpet recycling are similar to the percentage reductions for PET and HDPE recycling. That is, the large percentage reductions from recycling PET and HDPE plastics back into PET and HDPE pellets show that recycling these synthetic polymer plastics is especially effective at avoiding the environmental impacts from extracting and refining petroleum and natural gas to make the virgin synthetic polymers used in producing PET and HDPE containers. Thus, one might expect to attain similar environmental benefits from carpet recycling.

The environmental benefits from manufacturing products out of recycled materials are often termed the “upstream” benefits of recycling. In section 3 we also calculated the climate change impacts from hauling used carpet under the four used carpet management options, as well as the climate change impacts from combusting or landfilling used carpet. These impacts are often termed the “downstream” impacts of methods for managing discards.

We do not have data on emissions from combustion of used carpet in industrial boilers or WTE facilities, other than the greenhouse gas emissions data we discussed in Section 3. Thus, we could not fully analyze the downstream impacts of used carpet management options for the other six environmental impacts listed in Table 4. However, we were able to estimate the upstream benefits for these six environmental impact categories. Before reviewing those estimates, however, it may be useful to briefly discuss the methodologies and issues involved in calculating these estimates.

Life cycle analysis and environmental risk assessment provide the methodologies for connecting emissions of hundreds of pollutant to the seven categories of environmental impact listed in Table 4. For example, releases of carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), chlorofluorocarbons (CFCs) and other pollutants cause global warming which leads to climate change. The United Nations Intergovernmental Panel on Climate Change (IPCC) has conducted studies and reviewed scientific data to determine the strength of each pollutant relative to carbon dioxide in causing global warming. Based on these IPCC studies, over a hundred year time frame methane is 23 times and nitrous oxide 296 times more harmful than CO2. Given these global warming potential factors (sometimes called global warming characterization factors) we can aggregate the emissions of all greenhouse gas pollutants into a single indicator quantity for global warming potential. This quantity is CO2 equivalents (herein denoted eCO2).

Similar scientific efforts enable us to express the hundreds of pollutant releases codified in the EIOLCA model in terms of a single indicator quantity for each of the other six categories of environmental damage listed in Table 4. This greatly simplifies reporting and analysis of different levels of pollution. By categorizing pollution impacts into a handful of categories, we are able to reduce the complexity of following trends for hundreds of pollutants. This simplifies life for policy makers.

The trade-off is that we have to sort through complex pollutant aggregation and weighting methodologies. As described in SRMG's report on our development of a Consumer Environmental Index (CEI) for the Washington State Department of Ecology, a "best-of" methodology is in development by the United Nations Environment Program and the Society of Environmental Toxicologists and Chemists.[6] Until that study is released, our environmental impact aggregation and weighting relies on the methodologies used in US EPA's TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) model and the Lawrence Berkeley National Laboratory's CalTOX model.[7, 8]

These tools provided aggregation factors for about half of the 535 substances tracked by TRI and included in the EIOLCA model. Aggregation factors for the other half of the TRI releases were not available at the time of this study. In addition, estimated impact reductions for human toxics and carcinogens and for ecosystem toxics do not include impact reductions for metals. This is due to an ongoing debate about the environmental impacts of metal emissions and the inability of the scientific community to as yet reach consensus on the environmental impacts of metals relative to each other and to other toxics and carcinogens.

[6] See Morris *et al* (2007).
[7] Bare (2002) and Bare *et al* (2003).
[8] See a description of the CalTOX model, references, and downloadable manual and software at http://eetd.lbl.gov/IED/ERA/caltox/index.html .

Nevertheless, the TRACI and CalTOX models enabled us to aggregate pollution reductions for over 250 pollutants into total reductions for the indicator pollutant for each impact category. These indicator pollutants are:

- Climate change – carbon dioxide equivalents (eCO2),
- Human health-particulates – particulate matter less than 2.5 microns equivalents (ePM2.5),
- Human health-toxics – toluene equivalents (eToluene),
- Human health-carcinogens – benzene equivalents (eBenzene),
- Eutrophication – nitrogen equivalents (eN),
- Acidification – sulfur dioxide equivalents (eSO2), and
- Ecosystems toxicity – herbicide 2,4-D equivalents (e2,4-D).

Sections 3.a and 3.e described our estimates of GHG emissions from manufacturing carpet out of virgin raw materials and out of recycled materials, respectively. These estimates are based on the EIOLCA methodology outlined in those two sections. The estimates indicate that upstream GHG reductions from manufacturing products using recycled carpet as a feedstock rather than virgin raw materials amount to 5,281 pounds eCO2 per ton of used carpet.

Based on that same EIOLCA methodology, our estimates of other upstream environmental benefits as a result of manufacturing new carpet from one ton of recycled carpet rather than virgin raw materials include reductions of:

- 4.9 pounds ePM2.5 (particulate matter less than 2.5 microns equivalents) for potential human health impacts from atmospheric particulates caused by the release of criteria air pollutants such as sulfur oxides, nitrogen oxides and particulates themselves,
- 1,795 pounds of eToluene (toluene equivalents) for potential human health impacts caused by releases to the atmosphere, waterways, or ground of pollutants that are toxic to humans,
- 0.1 pounds of eBenzene (benzene equivalents) for potential human health impacts caused by releases to the atmosphere, waterways, or ground of pollutants that are carcinogenic to humans,
- 16.2 pounds eSO2 (sulfur dioxide equivalents) for acidification,
- 0.4 pounds eN (nitrogen equivalents) for eutrophication, and
- 1.0 pounds of e2,4-D (2,4-D equivalents) for potential ecosystem impacts caused by releases to the atmosphere, waterways, or ground of pollutants that are toxic to ecosystems.

Given the estimated pollutant reductions for each category of environmental impact, we still have the issue of figuring out how to compare the reductions in the various categories with each other. Monetization provides a method for evaluating trade-offs between the seven types of environmental impacts, and is a standard approach within the field of environmental economics. The difficulty, as discussed in Morris *et al* (2007), is that monetization is controversial, especially regarding the issue of placing a dollar value on human and non-human lives. The benefit of monetization is that it allows us to compare the value of the seven environmental impacts with each other. It also allows us to compare overall environmental benefits to the financial costs and benefits for recycling.

The final step in estimating an environmental value for used carpet recycling is, then, to determine a dollar value for the damage to public health and/or ecosystems caused by each of the indicator pollutants. The following list shows these estimated damage valuations and the source for each damage cost estimate[9]:

- eCO2 -- $36 per ton of carbon dioxide based on greenhouse gas offset valuation used by Seattle City Light.
- ePM2.5 -- $10,000 per ton of particulates no larger than 2.5 microns based on Eastern Research Group (2006).
- eToluene -- $118 per ton of toluene based on Morris and Bagby (2008).
- eBenzene -- $3,030 per ton of benzene based on Eastern Research Group (2006).
- eN -- $4 per ton of nitrogen based on Morris and Bagby (2008).
- eSO2 -- $661 per ton of sulfur dioxide based on average of 2005 ($690), 2006 ($860) and 2007 ($433) spot prices in EPA's annual acid rain allowance auction.
- e2,4-D -- $3,280 per ton of 2,4-D based on Morris and Bagby (2008).

Based on these valuations for our seven categories of environmental impacts, each ton of used carpet recycled into manufacturing new products provides an upstream environmental benefit amounting to $232, as detailed in Table 5. Even without taking into account the reductions in releases of environmental damaging metals such as cadmium, copper, lead, mercury, and zinc, this estimated economic value for the upstream environmental benefits of pollution reductions due to carpet recycling is quite substantial. Climate change benefits from recycling used carpet account for 41%, or $95, of the $232 value; while reductions in emissions of chemicals toxic to humans account for another 45%, or $106. Reductions in human respiratory pollutant emissions account for 11%, or $24. Reductions in acidifying compounds account for 2%, or $5, of environmental value per ton of used carpet recycling. The remaining three impact reductions account for the last 1%, or $2, in environmental value.[10]

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[9] The reader interested in the analytical basis for these valuations is invited to consult the reference for each impact valuation estimate.

[10] It is important to note that excluding metal emissions from our calculations reduces the estimated ecosystems benefits of carpet recycling by a substantial amount. This is because virgin carpet production causes significant releases of metals such as copper and zinc to the environment; these metals have serious negative impacts on ecosystems.

Table 5
Economic Value of Upstream Benefits for Recycled- vs. Virgin-Content Carpet

Environmental Impact	Impact Indicator Pollutant	Value for One Ton of Indicator Pollutant Reduction	Pounds of Upstream Emissions Reductions Per Ton of Recycled-Content Carpet	Total Value
Climate Change	eCO2	$36	5,281.3	$95.06
Human Health				
-- Respiratory Pollutants	ePM2.5	$10,000	4.9	$24.43
-- Toxics	eToluene	$118	1,795.4	$105.48
-- Carcinogens	eBenzene	$3,030	0.1	$0.18
Eutrophication	eN	$4	0.4	$0.00
Acidification	eSO2	$661	16.2	$5.34
Ecosystems Toxicity	e2,4-D	$3,280	1.0	$1.66
				$232.16

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