ESTIMATING GREENHOUSE GAS EMISSION REDUCTIONS FROM RECYCLING RESIDENTIAL AND COMMERCIAL CARPETS

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Executive Summary

The greenhouse gas emission reduction benefits associated with recycling residential and commercial carpet were quantified by using the Recycling Emission Reduction Factor (RERF). The RERF and percentage emission reduction was calculated for broadloom and tile carpet for residential and commercial applications. A RERF was estimated for each combination of recycled product manufactured, such as engineered resins, carpet cushion and carpet tile backing, and materials used for manufacturing the face fiber, such as Nylon 6, Nylon 6-6, Polyethylene terephthalate (PET) and Polypropylene. The avoided emissions from manufacturing using recycled materials, transportation emissions, and recycling efficiency were incorporated in the life cycle analysis.

Because carpet components are recycled separately, RERF and percentage emission reductions can be stated for either the whole carpet or only the carpet fiber as the basis. The percentage reduction benefit and the RERF depend largely on the type of carpet recycled and the type of product manufactured from the recycled carpet. The estimated RERF ranged from 0.05 metric tons of CO_2 equivalents per short ton of recycled material ($MTCO_2e$/ton) to 4.86 $MTCO_2e$/ton with only the carpet fiber as the basis, and from 0.02 $MTCO_2e$/ton to 1.97 $MTCO_2e$/ton with the entire carpet as the basis. The corresponding reduction benefit ranged from 3% to 83% for carpet fiber and from 1% to 33% for the entire carpet. Manufacturing of engineered resin from the recycling of broadloom nylon 6 and nylon 6-6 carpets provided larger emission benefits compared to recycling of other carpet types.

1. Introduction and background

The process of recycling transforms materials that have reached the end of life into the same product or secondary products. When a material is recycled, it is used in place of virgin inputs in the manufacturing process of the new materials, instead of being treated as a waste product. The process of using the recycled materials in place of virgin materials can provide greenhouse gas emission reduction benefits. It offsets a part of upstream emissions in the manufacturing process and transportation of the virgin materials. If the emissions from transporting and processing the recycled materials into new products are less than the avoided emissions from not using virgin materials to make the new products, recycling is considered to have an emission reduction benefit.

Recycling processes are either closed loop or open loop. In a closed loop process, end-of-life materials are recycled into the same materials. For example, aluminum cans are recycled to make aluminum. Carpets are recycled both in closed and open loop processes. In closed loop process, polycaprolactam (nylon 6) is depolymerized into caprolactam monomer which is then mixed with virgin caprolactam monomer to produce new nylon 6. In open loop process, secondary products are manufactured from recycled carpet such as engineered resins, carpet cushions and carpet backing.

This assessment estimates the amount of greenhouse gas (GHG) carbon dioxide (CO_2) emissions that are avoided by recycling carpet. The emission reduction benefit is calculated in terms of a recycling emission reduction factor (RERF). The method for estimating RERF is described in the documentation for the Waste Reduction Model (WARM) by USEPA (2011) and follows the framework previously used by the Air Resources Board (ARB) in the *Method for Estimating Greenhouse Gas Emission Reductions from Recycling* report (ARB 2011). In the 2011 ARB report, the analysis was limited to recycling products such as aluminum, steel, glass and paper, and did not include carpet.

Carpets are used in residential and commercial buildings. Residential buildings use broadloom carpet while commercial buildings use broadloom or tile carpets. Each type of carpet consists of different components such as face fiber and attached backing. The amount of face fiber and backing varies depending on the carpet type and its application. Approximately 40% and 30% of the average weight of residential and commercial carpet, respectively, is made of face fiber (CARE, 2014a). Carpet face fiber can be made from Nylon 6, Nylon 6-6, Polyethylene terephthalate (PET) Polypropylene (CRI, 2014), and wool

The type of face fiber is an important factor that determines the type and amount of product manufactured after recycling. This assessment calculates the RERF for different carpet types based on the type of fiber as well as based on the type of recycled products manufactured. The following section explains the calculation methodology in detail.

2. Methodology

This section describes the methodology used to calculate the RERF for carpet. The life cycle stages of the carpet, including manufacturing, recycling efficiency and transportation emissions associated with moving the recycled material from its processing location to remanufacturing location are considered in the following method.

Life cycle greenhouse gas emissions associated with a manufactured material may be calculated as follows:

$$LCA = MS + US + EOLS \quad (1)$$

where,

LCA = Life cycle greenhouse gas emissions of the material
MS = Emissions associated with the manufacturing stage of the material
US = Emissions associated with the use stage of the material
EOLS = Emissions associated with the end of life stage of a material

The emissions associated with the mining, extraction, processing and transportation of the material inputs are included in the manufacturing stage. The energy required to use the material or transform it into usable products is included in the use stage. The emissions related to landfilling, recycling, composting, or combusting the material are included in the end-of-life stage.

The following equation describes the life cycle emission reductions due to recycling:

$$LCA_{Total} = (MS_{Virgin}+US_{Virgin}+EOLS_{Virgin}) – (MS_{Recycled}+US_{Recycled}+EOLS_{Recycled}) \quad (2)$$

where,

LCA_{Total} = Total life cycle emissions associated with recycling
MS_{Virgin} = Emissions associated with using virgin inputs for manufacturing the material
US_{Virgin} = Emissions associated with the use stage of the virgin material
$EOLS_{Virgin}$ = Emissions associated with the end of life stage of the virgin material
$MS_{Recycled}$ = Emissions associated with using recycled inputs for manufacturing the material

$US_{Recycled}$ = Emissions associated with the use stage of the recycled material
$EOLS_{Recycled}$ = Emissions associated with the end of life stage of the recycled material

For carpet material, assuming $US_{Virgin} = US_{Recycled}$ and $EOLS_{Virgin} = EOLS_{Recycled}$, then

$$LCA_{Total} = MS_{Virgin} – MS_{Recycled} \qquad (3)$$

The ARB published a paper (ARB 2011) that established a life cycle assessment framework for calculating greenhouse gas emission reduction factor for recycled materials. The framework quantified material-specific emission reduction benefits associated with recycling. The following equation calculates the recycling emissions reduction factor (RERF):

$$RERF = ((MS_{Virgin} – MS_{Recycled}) – T_{Remanufacture}) * R_{Use} \qquad (4)$$

where,

RERF = Recycling Emission Reduction Factor ($MTCO_2e$/ton of material)
MS_{Virgin} = Emissions at manufacturing stage when virgin materials are used ($MTCO_2e$/ton of material)
$MS_{Recycled}$ = Emissions at manufacturing stage when recycled materials are used ($MTCO_2e$/ton of material)
$T_{Remanufacturing}$ = Transportation emissions associated with moving materials from recycling location to remanufacturing destination ($MTCO_2e$/ton of material)
R_{Use} = Recycling efficiency (Fraction of material remanufactured from recycled material)

2.1 Emissions in the manufacturing stage

The datasets used for the estimation of RERF comprised of process and transportation emissions for virgin and recycled materials, recycled transport distances from California, and the amount of carpet transported. The process emissions included emissions associated with manufacturing a material, and transportation emissions included the emissions associated with transporting a material to a recycling facility.

The RERF before applying the transportation correction and recycling efficiency is calculated as:

$$RERF = MS_{Virgin} – MS_{Recycled} \qquad (5)$$

where,

MS_{Virgin} = Emissions associated with using 100% virgin inputs for manufacturing the material

$MS_{Recycled}$ = Emissions associated with using 100% recycled inputs for manufacturing the material

The emissions estimation includes using process energy associated with each fuel used in the manufacturing process and then applying the CO_2e emission factors to estimate GHG emissions. Datasets were evaluated and used to obtain manufacturing emissions. For virgin emissions, the data were obtained from the updated version of the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model (GREET 2012). The model documentation included raw material production data used to calculate environmental impacts of each material. The data included process and transportation emissions as well as energy inputs for the production of each product including nylon 6, nylon 6-6, polypropylene, PET and PVC. For the recycled inputs, emission data were gathered from the updated version of the Waste Reduction Model (WARM) developed by USEPA (USEPA 2015, USEPA 2012, USEPA 2011).

2.2 Transportation correction factor

The transportation correction factor ($T_{Remanufacturing}$) accounts for the transportation emissions associated with moving the recycled material from the location it was recovered to its remanufacturing destination. Estimation of the transportation correction factor involves gathering information about average load transported to remanufacturing facilities, the distance travelled to reach those facilities and the mode of transportation.

The transportation emissions were estimated using the distance travelled to many carpet processing facilities across the US. Nylon 6, nylon 6-6, and PET carpets that are delivered to recovery facilities in California are manually separated by fiber type and then shredded in a shredding machine. The fiber is then separated, and the calcium carbonate and some of the carpet backing is landfilled. The rest of the carpet backing is sent to landfills or to waste-to-energy (WTE) plants. The carpet processing facilities in California separate carpet components and shred the carpet. The shredded and whole carpet is sent to remanufacturing plants mostly by freight containers on railway. Additionally, a small amount of intermodal transportation is also done by common carrier trucks. The shredded nylon 6-6 is shipped mostly by common carrier trucks to resin compounders on the East Coast and Midwest. In 2014, about 9% of carpet collected in CA was exported to overseas markets. However, exported carpet is not included in the scope of this assessment and hence not accounted for in the transportation correction factor.

$T_{remanufacturing}$ addresses the emissions associated with moving recycled materials to their remanufacturing destinations. In some cases, these emissions may also be included in the emissions at the manufacturing stage (MS_{Virgin} and $MS_{Recycled}$). However, the data for emissions at the manufacturing stage often do not disaggregate the transportation emissions between transportation to recovery facilities and to remanufacturing facilities. There could be some overlap between the two emissions. However, this leads to a more conservative RERF. This approach is also consistent with the one ARB (2011) applied for estimating RERFs.

The following table provides the list of carpet processors in US (CARE, 2014b).

Table 1. Locations of Carpet Processors in US (CARE, 2014b)

Location	
City	**State**
Atlanta	Georgia
Calhoun	Georgia
Dalton	Georgia
Dalton	Georgia
LaGrange	Georgia
Augusta	Georgia
Dayton	Ohio
Hazelwood	Missouri
New Castle	Delaware
Indianapolis	Indiana
Portland	Oregon
Vernon	California
Carson	California
Pomona	California

The distances between transporting carpets from California to the various destinations were estimated and the appropriate emission factors were applied to calculate the transportation correction. See Section 3.2 of this report for more details on transportation emissions calculation.

2.3 Recycling efficiency

Recycling efficiency accounts for the amount of material that actually gets converted into recycled products. It accounts for any material losses that occur in the recycling, recovery, and remanufacturing process and accounts for the material that is sent to landfill. A material-specific recycling efficiency factor needs to be applied to the RERF, in order to account for the collection and use efficiency. The amount of recycled carpet that is converted into new product and the amount that goes to landfills are shown in Table 2. The table shows information by different types of carpet based on their application (such as commercial or residential, broadloom and tile) and the type of fiber (such as nylon 6, nylon 6-6, polyester (PET) and polyethylene). The percent market share that goes into waste stream is shown in the table. For residential carpet, the average weight per square yard is 4.2 pounds and for commercial carpet, it is 8.0 pounds (CARE, 2014b). The table also shows the amount of each recycled product formed from each carpet type and the amount that goes into landfills and to waste-to-energy facilities.

Table 2 also shows products made from recycled carpet. Monomer resulting from de-polymerization replaces virgin caprolactam, which is petroleum based. In the depolymerization process, nylon is broken into small chips, melt extruded and then depolymerized to caprolactam monomer. The caprolactam monomer is mixed with virgin caprolactam monomer to produce the polycaprolactam polymer (nylon 6). Then the polymer is extruded through spinneret to form either bulk continuous filament or staple yarn to be used in the production of carpets.

Because engineered resin produced from recycled nylon 6 and nylon 6-6 can withstand high temperature due to its high melting point, it is predominantly used in black plastic products used under the hood in cars. Nylon 6-6 is processed by heating the fiber and extruding it to form chips that can be processed further into engineered resin in-house or shipped to other companies that produce engineered resins. There is less waste produced in this process compared to de-polymerization because the final product can contain a certain amount of acceptable impurity.

Most of the tile is recycled into carpet backing. A small amount of face fiber that is considered contaminated with the backing is landfilled. Polyethylene terephthalate (PET) commercial tile is relatively new and has not yet been identified in the waste stream. The shredded PET is used to make carpet cushion. Most broadloom commercial carpets are installed in hotels, and some of the cushion used in this case is made from PET. Polypropylene is a relatively flexible thermoplastic polymer that replaces virgin polypropylene when recycled. Its use in commercial broadloom is very limited because it wears more quickly than PET or nylon. Polypropylene is not as heat resistant as nylon 6-6. It is mainly used in automobile parts as reservoir, such as windshield fluid, brake fluid. It replaces virgin polypropylene. Commercial polypropylene has not yet been identified in the waste stream. Carpet as an alternative fuel (CAAF) and cement kiln use is negligible.

Table 2. Types of carpet and products manufactured from recycled carpet

Carpet Type (Fiber Type and Application)	**Percent Market Share**[1]	**Average Weight per Sq. Yds. (Pounds)**[2]	**Recycle Product(s) Produced from Carpet type**[3]			**Pounds of Carpet Residuals**[2]	
			Product 1	**Product 2**	**Product 3**	**Landfilled**	**WTE**
Residential Broadloom Nylon 6	17.5	4.2	De-polymerization (0.4 pounds)	Engineered Resin (1.1 pounds)	Carpet Cushion (0.2 pounds)	2.45	0.05
Commercial Broadloom Nylon 6	7.5	4.2	Engineered Resin (1.1 pounds)	Carpet Cushion (0.2 pounds)	CAAF (Carpet as Alternative Fuel) & Cement Kiln	2.85	0.05
Commercial Tile Nylon 6		8.0	Carpet Tile Backing (7.0 pounds)	NA	NA	0.9	0.1
Residential Broadloom Nylon 6-6	24.1	4.2	Engineered Resin (1.5 pounds)	Carpet Cushion (0.2 pounds)	CAAF & Cement Kiln	2.45	0.05
Commercial Broadloom Nylon 6-6	10.3	4.2	Engineered Resin (1.1 pounds)	Carpet Cushion (0.2 pounds)	CAAF & Cement Kiln	2.85	0.05
Commercial Tile Nylon 6-6		8.0	Carpet Tile Backing (7.5 pounds)	NA	NA	0.4	0.1
Residential Broadloom Polyester (PET)	22.0	4.2	Carpet Cushion (0.4 pounds)	NA	NA	3.8	
Commercial Broadloom Polyester (PET)	1.8	4.2	Carpet Cushion (0.4 pounds)	NA	NA	3.8	
Commercial Tile Polyester (PET)		8.0	See Footnote[4]				
Residential Broadloom Polypropylene (polyolefin)	8.0	4.2	Extruded Polypropylene Yarn (1.5 pounds)	Carpet Cushion (0.1 pounds)	Engineered Resin (0.1 pounds)	2.5	
Commercial Broadloom Polypropylene (polyolefin)	3.4	4.2	Extruded Polypropylene Yarn (1.2 pounds)	Carpet Cushion (0.1 pounds)	NA	2.9	
Commercial Tile Polypropylene (polyolefin)		8.0	See Footnote[5]				

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[1] Market share assumptions based on Carpet America Recovery Effort (CARE) 2012 Annual Report [CARE (2012)] and personal communications between CalRecycle and LA Fiber [LA Fiber (2012)]. It is assumed that 70% of Nylon and Polypropylene carpets are residential broadloom, while 90% of PET carpet is residential broadloom (LA Fiber, 2014). The percentage breakdown of commercial broadloom and commercial tile for all fiber types is unknown, and therefore have been combined. The remaining 5.4% of market share unaccounted for in this table is comprised of mixed fibers and natural fibers such as wool.

[2] CARE (2014)

[3] LA Fiber (2014)

[4] Polyethylene terephthalate (PET) and Polypropylene commercial tile is relatively new and has not yet been identified in the waste stream.

3. Results and Discussion

This section gives a description of how the RERF was calculated and the intermediate steps. The intermediate steps include estimating the difference between the emissions from manufacturing virgin and recycled materials, the estimation of transportation correction and recycling efficiency. The final RERF was determined using Equation (4). Following sections describe the details of each step.

3.1 Emissions from virgin and recycled inputs

When carpet is recycled, it is separated into different components such as face fiber, cushion and backing. Some of the components are then recycled and remanufactured into other products. Because carpet components are recycled separately, it is necessary to estimate the emission reduction for individual components.

Following table gives emission reduction by component in the unit of $MTCO_2e$ of greenhouse gas emissions per short ton of material recycled. The GHG benefits of carpet recycling were calculated by comparing the difference between the emissions related to manufacturing a ton of material by its virgin inputs and manufacturing the same material using recycled inputs. The carpet face fiber is typically made of four types: nylon 6, nylon 6-6, PET and polypropylene. For all four fiber types, the emissions from virgin and recycled inputs are included in the analysis. A small amount of face fiber is converted back into caprolactam by depolymerization. Hence, the emissions from manufacturing virgin caprolactam and the emissions from manufacturing it using recycled carpet are included separately. Most of the tile backing is made of PVC hence the emissions from manufacturing PVC from virgin materials and manufacturing it from recycled carpet backing are included. Table 3 shows the emissions from manufacturing different fiber and tile materials, using virgin and recycled inputs. The difference between the two is the recycling emission reduction for each material type.

Table 3. Emissions from virgin and Recycled Inputs

	Emissions from Virgin inputs (MTCO2e/ton)	Emissions from Recycled Inputs (MTCO2e/ton)	Recycling Emission Reduction (MTCO2e/ton)
Nylon 6	7.90[1]	3.99[2]	3.91
Nylon 6-6	5.89[1]	0.35[2]	5.54
PET	2.31[1]	0.07[2]	2.24
Polypropylene	1.61[1]	0.56[2]	1.05
PVC	2.08[1]	1.44[3]	0.64
Caprolactam	1.61[4]	1.39[4]	0.22

[1] GREET (2012), [2] USEPA (2015), [3] USEPA (2011), [4] Binder et al (2010)

The recycling reduction or the GHG reduction benefits vary by type of fiber. The highest reduction is obtained by recycling of nylon 6-6 fiber, with more than 5.5 $MTCO_2e$/ton. The other face fibers such as nylon 6 and PET also result in 2.2 to 3.9 $MTCO_2e$/ton of reduction. The depolymerization process that converted the caprolactam back into caprolactam resulted in a small RERF of 0.2 $MTCO_2e$/ton. The manufacturing emissions include the emissions occurred in the manufacturing process as well as any transportation emissions occurred while transporting the materials to a recycling facility. These are the initial reductions before applying the transportation correction. These emissions may also be included in the transportation correction ($T_{Remanufacturing}$). However, a clear disaggregation of these emissions was not provided in the data listed in Table 3. Hence, there may be some overlap between the two terms. However, this approach is consistent with the RERFs previously estimated (ARB, 2011) and provides a conservative estimate. The following section describes the calculation of the transportation correction factor.

3.2 Transportation Correction Factor

In 2013, 44.4 million pounds of carpet was processed (CARE, 2014c). Out of that, 24 million pound was processed in California and from the remaining 20.4 million, approximately 90 percent was transported to Georgia. The information on the individual amount of carpet transported to each plant was not available. Hence it was assumed that the remaining 10 percent was transported equally in 5 other states shown in Table 1.

Table 4 shows the transportation emissions estimated for transporting the carpet to the remanufacturing facilities in different states. The weighted emissions are calculated based on the percentage of carpet transported to each state. To calculate transport distances, this assessment arbitrarily uses Sacramento, the capitol of California that is also geographically not far from the centroid of the state, as the starting point for calculating distances. The distances between destinations are estimated using Google Maps software (Google Maps, 2014). The two major carpet processing plants in California are in Vernon and Carson. For transport within California, the distance between Sacramento and the midpoint between Vernon and Carson was used as the assumed transport distance in state. For transport to the out-of state cities, the distance from Sacramento to each city was estimated.

About 95% of the carpet transported interstate is by rail and the remaining amount is transported by common carrier trucks (LA Fiber, 2014). Hence, the total miles were further divided into “rail miles” and “truck miles”. The emission factor for the on-road emissions by carrier trucks for transportation of materials was obtained for class 7 and class 8 freight trucks from Vehicle Technologies Market report (Davis et al. 2012). An average of the emission factors for class 7 and class 8 was estimated as 126 gCO_2/ton-mile. The emission factor of 20.78 gCO_2/ton-mile was applied to rail miles (USEPA, 2013). The total transportation emissions were estimated by adding the truck and rail emissions calculated for individual states.

Table 4. Estimation of Transportation Correction

	million pounds	Percentage	Total Miles	Truck miles	Rail Miles[7]	Truck emissions ($MTCO_2e$/ton)	Rail Emissions (MTCO2e/ton)	Total Emissions ($MTCO_2e$/ton)
Total Carpet processed	44.4[1]							
Carpet processed in California	24[1]	54%	400[4]	20	380	1.4E-03	4.3E-03	5.6E-03
Carpet processed Outside of California	20.4	46%						
Carpet processed in Georgia	18.36[2]	41%	2205[5]	110	2095	5.7E-03	1.8E-02	2.4E-02
Carpet processed in Ohio	0.41[3]	0.9%	2189[6]	109	2080	1.3E-04	4.0E-04	5.2E-04
Carpet processed in Missouri	0.41[3]	0.9%	1835[6]	92	1743	1.1E-04	3.3E-04	4.4E-04
Carpet processed in Delaware	0.41[3]	0.9%	2701[6]	135	2566	1.6E-04	4.9E-04	6.5E-04
Carpet processed in Indiana	0.41[3]	0.9%	2072[6]	104	1968	1.2E-04	3.8E-04	5.0E-04
Carpet processed in Oregon	0.41[3]	0.9%	978[6]	49	929	5.7E-05	1.8E-04	2.3E-04
Total Carpet processed	44.40	100%					Total	0.03

1 CARE (2014c)

2 LA Fiber (2014)

3 CARE (2014b)

4 Distance between Sacramento and midpoint of LA fiber at Vernon and Carpet Solutions at Carson

5 Average distance between midpoint of LA fiber at Vernon and Carpet Solutions at Carson; and each processing plant in Georgia

6 Average distance between midpoint of LA fiber at Vernon and Carpet Solutions at Carson; and processing plant in each state

7 LA Fiber (2014)

8 Davis et al. (2012)

3.3 Recycling Efficiency

Table 5 shows the recycling efficiency calculated for different recycled products made from each type of carpet. The weight of each recycled product manufactured from the recycled carpet is an important factor in determining the recycling efficiency. For residential carpet, approximately 40% of the average weight is made of face fiber (1.7 lb recycled out of 4.2 lb of a square yard of carpet). For commercial carpet, approximately 30% of the average weight is made of face fiber (1.3 pounds recycled out of 4.2 lb of a square yard of carpet). However, for commercial carpet tile, a majority of the backing, and not the face fiber, gets recycled to produce new backing. Hence recycling efficiency for commercial tile was calculated only based on entire carpet weight and not based on face fiber. The recycling efficiency for commercial PET tile and commercial polypropylene tile could not be calculated as these are not defined in the waste stream.

The recycling efficiency for entire carpet and for fiber was calculated separately. The recycling efficiency was calculated as:

Recycling efficiency for fiber = weight of recycled product/weight of fiber in the carpet

Recycling efficiency for entire carpet = weight of recycled product/total weight of carpet

Table 5. Recycling efficiency by fiber and by total carpet

Carpet and Fiber Types	Recycled Products	Recycling Efficiency	
		For Carpet	For Fiber
Residential Broadloom Nylon 6	Depolymerization	10%	24%
	Engineered Resin	26%	65%
	Carpet Cushion	5%	12%
Commercial Broadloom Nylon 6	Engineered Resin	26%	85%
	Carpet Cushion	5%	15%
Commercial Tile Nylon 6	Carpet Tile Backing	88%	
Residential Broadloom Nylon 6-6	Engineered Resin	36%	88%
	Carpet Cushion	5%	12%
Commercial Broadloom Nylon 6-6	Engineered Resin	26%	85%
	Carpet Cushion	5%	15%
Commercial Tile Nylon 6-6	Carpet Tile Backing	94%	
Residential Broadloom Polyester (PET)	Carpet Cushion	10%	24%

Commercial Broadloom Polyester (PET)	Carpet Cushion	10%	31%
Residential Broadloom Polypropylene	Extruded polypropylene yarn	36%	88%
	Carpet Cushion	2%	6%
	Engineered Resin	2%	6%
Commercial Broadloom Polypropylene	Extruded polypropylene yarn	29%	92%
	Carpet Cushion	2%	8%

3.4 Final RERF

The final RERFs are calculated using equation (4). The manufacturing emissions from using virgin and recycled inputs (MS_{Virgin} and $MS_{Recycled}$) are summarized in Table 3. The transportation correction ($T_{Remanufacturing}$) is summarized in Table 4. The recycling efficiency factors for different recycled products and carpet types are summarized in Table 5. Based on all the intermediate steps described above, the final RERFs are calculated for each combination of carpet type and recycled product, and are shown in Table 6. The RERFs indicate the emission reduction benefit of using recycled materials over virgin inputs in the manufacturing stage. Hence the percentage emission benefit is also quantified based on the RERF and the emissions from virgin inputs. Table 6 summarizes the RERF and the percentage emission reduction benefit for all the carpet types and recycled products included in this assessment. The emission benefit ranges widely from 1% to 83%. Using the approach described in this assessment, manufacturing engineered resin from broadloom nylon 6-6 carpet results in the highest RERF and emission reduction benefits among all the combination of carpet types and recycled products evaluated. Re-use of carpet tiles and recycling of natural fiber carpets (e.g. wool) were not included in this analysis.

Table 6. Final RERF for carpet types and recycled products.

Carpet and Fiber Types	Recycled Products	for carpet fiber		for entire carpet	
		RERF (MTCO2e/ton of Fiber)	Percentage Emission Benefit	RERF (MTCO2e/ton of carpet)	Percentage Emission Benefit
Residential Broadloom Nylon 6	Depolymerization	0.05	3%	0.02	1%
	Engineered Resin	2.51	32%	1.02	26%
	Carpet Cushion	0.46	6%	0.18	5%
Commercial Broadloom Nylon 6	Engineered Resin	3.29	42%	1.02	13%
	Carpet Cushion	0.60	8%	0.18	2%
Commercial Tile Nylon 6	Carpet Tile Backing			0.54	26%
Residential Broadloom Nylon 6-6	Engineered Resin	4.86	83%	1.97	33%
	Carpet Cushion	0.65	11%	0.26	4%
Commercial Broadloom Nylon 6-6	Engineered Resin	4.66	79%	1.44	24%
	Carpet Cushion	0.85	14%	0.26	4%
Commercial Tile Nylon 6-6	Carpet Tile Backing			0.57	27.5%
Residential Broadloom Polyester (PET)	Carpet Cushion	0.52	22%	0.21	9%
Commercial Broadloom Polyester (PET)	Carpet Cushion	0.68	29%	0.21	9%
Residential Broadloom Polypropylene	Extruded polypropylene yarn	0.90	56%	0.37	23%
	Carpet Cushion	0.06	4%	0.02	1.5%
	Engineered Resin	0.06	4%	0.02	2%
Commercial Broadloom Polypropylene	Extruded polypropylene yarn	0.94	58%	0.29	18%
	Carpet Cushion	0.08	5%	0.02	2%

3.5 Comparison to existing studies

The following section evaluates the RERF for each combination of carpet type and recycled product compared to the USEPA WARM Model. Table 7 compares the RERF values generated in this assessment to the Waste Reduction Model (WARM) developed by the United States Environmental Protection Agency. The WARM values listed in Table 7 are not relative to other waste alternatives. Instead, the values listed in Table 7 reflect only the recycling component of the WARM model. The section is designed to explain the differences between the RERFs in this method and the results from the WARM model. The differences are due to variety of factors including WARM only including residential carpet, differences in electricity mix, industrial location, life-cycle boundaries, assumed weight of face fiber in residential carpet, market share of various fiber types as shown in Table 8, and differences in recycling efficiencies. For instance, the WARM model assumes that face fiber comprises 45% of a residential broadloom carpet by weight while this method assumes face fiber comprises 40% of weight of residential carpet.

Table 7. Comparison of RERFs to other recycling studies

Carpet and Fiber Types	Recycled Products	This Method	WARM
Residential Broadloom Nylon 6	Depolymerization	0.02	1.35
	Engineered Resin	1.02	NA
	Carpet Cushion	0.18	NA
Commercial Broadloom Nylon 6	Engineered Resin	1	NA
	Carpet Cushion	0.18	NA
Commercial Tile Nylon 6	Carpet Tile Backing	0.54	NA
Residential Broadloom Nylon 6-6	Engineered Resin	1.97	0.7
	Carpet Cushion	0.26	NA
	Depolymerization	NA	0.21
Commercial Broadloom Nylon 6-6	Engineered Resin	1.44	NA
	Carpet Cushion	0.26	NA
Commercial Tile Nylon 6-6	Carpet Tile Backing	0.57	NA
Residential Broadloom PET	Carpet Cushion	0.21	0.06
Commercial Broadloom PET	Carpet Cushion	0.21	NA
Residential Broadloom Polypropylene	Extruded polypropylene yarn	0.37	NA
	Carpet Cushion	0.02	0.03
	Engineered Resin	0.02	NA
Commercial Broadloom Polypropylene	Extruded polypropylene yarn	0.29	NA
	Carpet Cushion	0.02	NA

Table 8: Market Share of Fiber Types

Fiber Type	This Method[5]		WARM v13
	Residential carpet market share from Table 2 (as % of all commercial & residential carpets)	Normalized residential carpet market share (as % of residential carpet only)	Market share of residential carpet types from WARM exhibit 6 (residential carpet only)
Residential Broadloom Nylon 6	17.5%	24.4%	40.0%
Residential Broadloom Nylon 6-6	24.1%	33.7%	25.0%
Residential Broadloom Polyester (PET)	22.0%	30.7%	15.0%
Residential Broadloom Polypropylene	8.0%	11.2%	20.0%

3.5.1 Residential Broadloom Nylon 6

This method assumes that Residential Broadloom Nylon 6 is recycled primarily into engineered resins with lesser amounts being depolymerized back to Nylon 6 and recycled into carpet cushion. The WARM model assumes that all Residential Broadloom Nylon 6 is depolymerized back to Nylon 6. The WARM model used life-cycle data for the virgin production of Nylon 6 from PlasticsEurope in the European context as a proxy for production in the United States. This method obtained the GHG emissions for the production of Nylon 6 from the GREET model which utilized life cycle inventory data from PlasticsEurope.

3.5.2 Residential Broadloom Nylon 6-6

This method assumes that Residential Broadloom Nylon 6-6 is recycled primarily into engineered resins with a small amount recycled into carpet cushion. The WARM model assumes that Residential Broadloom Nylon 6-6 is recycled primarily into engineered resins with a lesser amount recycled back into Nylon 6-6 fibers. The WARM model used life-cycle data for the virgin production of Nylon 6-6 from PlasticsEurope in the European context as a proxy for production in the United States. This method obtained

[5] The remaining market share unaccounted for in this table is comprised of mixed fibers and natural fibers such as wool.

the GHG emissions for the production of Nylon 6-6 from the GREET model which utilized life cycle inventory data from PlasticsEurope.

3.5.3 Residential Broadloom PET

Both this method and the WARM model assume that residential broadloom PET is recycled exclusively into carpet cushion. This method assumes that PET comprises a larger percentage residential broadloom carpet market than the WARM model.

3.5.4 Residential Broadloom Polypropylene

This method assumes that Residential Broadloom Polypropylene is recycled primarily into extruded polypropylene yarn with lesser amounts recycled as carpet cushion and engineered resin. The WARM model assumes that Residential Broadloom Polypropylene is recycled into carpet cushion.

4. Summary

This assessment estimated recycling emission reduction factors for various combinations of carpet type and recycled products. Carpet recycling is most often an open loop process where the recycled carpet materials are made into other secondary products; therefore, emission reduction factors for each recycled product manufactured from different carpet types are separately calculated. The RERFs are based on the emission reduction benefit of using recycled materials over virgin inputs in the manufacturing stage, the transportation associated with moving the recycled material to the point of remanufacturing, and the recycling efficiency. The percentage emission reduction benefits are also calculated based on the recycling emission reduction factors. The percentage emission reduction benefit and the RERF depend largely on the type of carpet recycled and the type of product manufactured from the recycled carpet. The estimated RERF ranged from 0.05 $MTCO_2e$/ton to 4.86 $MTCO_2e$/ton using carpet fiber as the basis, and from 0.02 $MTCO_2e$/ton to 1.97 $MTCO_2e$/ton using the entire carpet as the basis. The corresponding emission reduction benefit ranged from 3% to 83% for carpet fiber and from 1% to 33% for entire carpet. Manufacturing of engineered resin from the recycling of broadloom nylon 6 and nylon 6-6 carpets provided the largest emission reduction benefits.

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