Residential and Commercial Carpet Case Study

The Potential Impacts of Extended Producer Responsibility (EPR) in California on Global Greenhouse Gas (GHG) Emissions

CalRecycle

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Contractor's Report

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Background

This case study supports responsibilities of the Department of Resources Recycling and Recovery (CalRecycle) under the California Air Resources Board Scoping Plan to address greenhouse gas emissions through an Extended Producer Responsibility (EPR) approach. Specifically, this case study assesses the extent to which product life-cycle greenhouse gas emissions might be reduced through possible product design, manufacturing, and end-of-life management strategies introduced under a producer's EPR initiatives.

EPR is a mandatory type of product stewardship that includes—at a minimum—that a producer's responsibility for its product extends to post-consumer management of that product and its packaging. In practical terms, this means that a producer (manufacturer, brand owner, or an organization that represents its interests) designs, manages, and implements a product stewardship and recycling program. While there is government oversight, the product stewardship and recycling program is financed and operated by the private sector. The goal is to provide incentives to producers to incorporate environmental considerations into the design of their products and packaging as they accrue the costs savings associated with design for recycling or end-of-life management.

The California Global Warming Solutions Act of 2006 (AB 32) requires greenhouse gas emissions to be reduced to 1990 levels by the year 2020. A primary aim of CalRecycle is to achieve high recycling rates and advance EPR to reduce emissions both in-state as well as within the connected global economy.

CalRecycle contracted with the University of California at Berkeley (UC Berkeley) and the University of California at Santa Barbara (UC Santa Barbara) with the objectives of developing several scientifically-based approaches to analyze life cycle environmental impacts of products, preparing case studies for selected products, and providing California-specific guidelines for determining if and when a product purchased with recycled content has reduced associated greenhouse gas emissions as compared to a similar product made from virgin materials. In this report, the only environmental impacts considered are energy demand (in MJ net calorific value) and greenhouse gas emissions (in kg CO_2-equivalent). The greenhouse gas emission estimates use the 100-year global warming potential (GWP100) approach. Other environmental impacts, such as air quality, toxicity, land, and water use, are not considered in the report, although they may have significant implications.

This report contains the case study for residential and commercial carpets, and was prepared by UC Berkeley and UC Santa Barbara under the aforementioned contracts. It uses life-cycle assessment methodology to estimate the greenhouse gas emission reductions that could be achieved through product stewardship approaches. There are two major methods for performing life-cycle assessments: process-based LCA and economic input-output (EIO-LCA). Process-based LCA uses a model of the sequence of processes involved in a product's life cycle to estimate environmental impacts, which are computed by summing the impacts of all the processes. Process LCA tends to be more accurate for specific product systems but often omits significant upstream impacts due to lack of data. In contrast, EIO-LCA uses an economic input-output model of the entire economy which has been extended with estimates of sector-wide environmental exchanges (such as sector energy use and emissions). Using the EIO model avoids the truncation error inherent to process LCA; however, it suffers from poor specificity and potentially poor accuracy for products that are not representative of their sector as a whole.

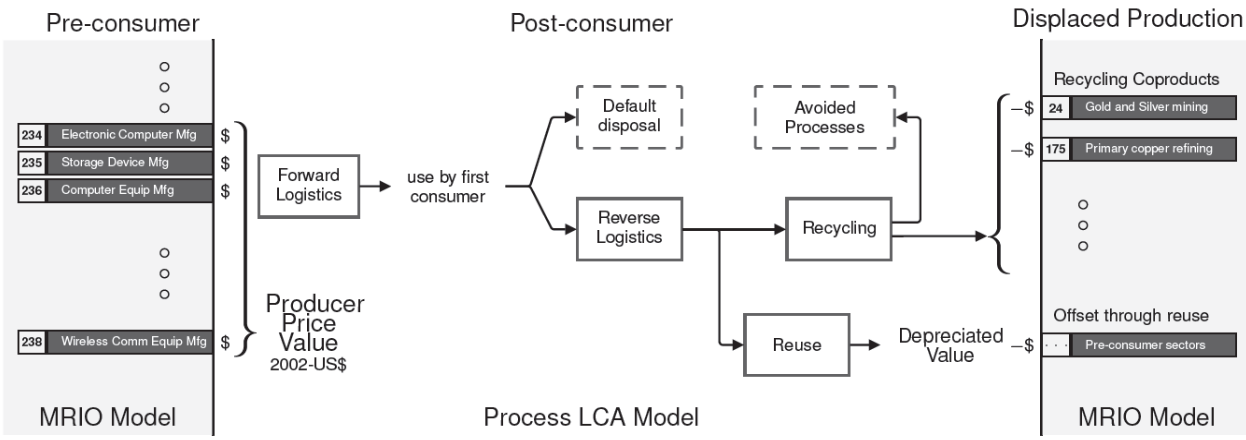

Figure 1: In the case studies, greenhouse gas emissions from product manufacturing and end-of-life management are calculated by combining MRIO-LCA with process-based LCA. The depiction shows a model of a desktop computer system as an example.

The only factors that determine environmental impact under an EIO-LCA model are economic sector and producer price, so comparisons between products within the same sector will depend strictly on their relative cost. Thus, economic sectors that vary widely in incurred environmental impacts per dollar value of product will tend to be more poorly modeled by the tool. Sectors with a relatively higher level of homogeneity in their included activities or produced outputs will be more aptly modeled (Hendrickson et al. 2005). EIO-LCA also does not take into account the use or post-consumer phases of a product life-cycle.

A hybrid approach is intended to take advantage of the strengths of both methods (Suh and Huppes 2002). In this project, a hybrid approach is used by employing EIO-LCA methods to account for upstream or "supply chain" impacts of producing a given product (and for which sectoral averages are an appropriate proxy) and process-based LCA to account for the impacts of forward logistics (i.e., transport from manufacturer to retailer), use (if applicable), and end-of-life management (i.e., collection, disposal, and processing).

The specific EIO-LCA model used in this study is the multi-region input-output (MRIO) LCA model developed by UC Berkeley and Carnegie Mellon University (Masanet et al. 2012). It employs economic input-output modeling techniques to separate purchases and greenhouse gas emissions into three regions; California, the rest of the United States, and the rest of the world. The model is based on the single-region U.S. national EIO-LCA model developed by Carnegie Mellon University, which can be found at http://www.eiolca.net. Documentation on this website may be beneficial to readers that are new to economic input-output modeling. Both models use the North American Industry Classification System (NAICS), for identifying the producing sector of a given product; NAICS codes are maintained by the U.S. Census Bureau. NAICS is the standard classification used by federal statistical agencies for the purpose of collecting, analyzing, and publishing statistical data related to the U.S. business economy. The MRIO model is based on the 2002 benchmark IO model maintained by the U.S. Bureau of Economic Analysis (Stevens, 2007). Figure 1 shows the relationship between the MRIO model and the process model used in the study series.

Process-based LCA is used to estimate the greenhouse gas emissions from forward and reverse logistics and product end-of-life management. Forward logistics refers to the shipment of products from the point of production to the point of consumption; reverse logistics indicates recovery of the products from consumers after the products' useful life. The process-based LCA model and approaches were developed by UC Santa Barbara in this case study series.

For each modeled process, the most appropriate process inventory data are chosen from a range of public and proprietary life cycle inventory databases, including Ecoinvent, GaBi, and the U.S. life-cycle inventory (LCI) database. In some cases UC Santa Barbara complemented these data sources by primary data collection. Generally, processes involved in product end-of-life management are landfill, reverse logistics, reprocessing operations such as disassembly, recycling and refurbishment, and the production processes avoided by secondary outputs from reuse and recycling activities. For example, the greenhouse gas emission reductions from materials recycling are calculated as the greenhouse gas savings from avoided landfill and avoided primary production reduced by the added greenhouse gas emissions from reverse logistics and reprocessing (Figure 2). In the general LCA methodology, this method is typically called the avoided burden approach or (consequential) system expansion. If it was unclear which exact process was avoided by the secondary resources, the MRIO-LCA model was used to assess displaced economic activity instead of avoided processes.

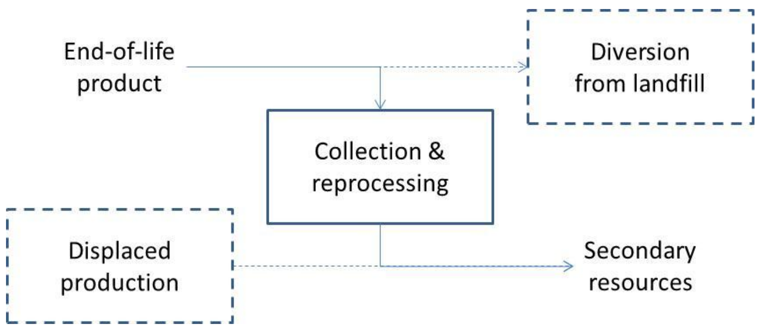

Figure 2: Analytical framework to assess greenhouse gas emissions reductions from end of life activities. Processes in dashed lines are avoided through collection and reprocessing of end-of-life products.

Product overview

In the United States, carpets are manufactured by the carpet and rug mills sector, which is classified under NAICS code 314110. While the production outputs from this sector are varied—including woven and tufted carpets, woven and tufted rugs, doormats, bath mats, and carpet and rug dyeing—tufted carpets and rugs represent the vast majority of production, accounting for 91 percent of the sector's 2002 value of shipments (U.S. Census 2004a).

In 2002, U.S. mills produced more than 1.4 billion square yards of tufted products, with an average 2002 producer price of $8.19 per square yard (U.S. Census 2004a). The producer price represents the net selling value of all products shipped from the producing sector prior to any price markups that occur for shipping, insurance, wholesale, or retail operations prior to purchase by the consumer.

A widely cited estimate is that 70 percent of U.S. floors are currently carpeted (Highbeam 2012), which underscores the high penetration of carpeting in U.S. homes and businesses. Assuming an average mass of 1.9 kg per square yard (NCDER 1998), the per-unit-mass 2002 U.S. producer price for U.S. carpet and rug mill products can be estimated at $4.31 per kg.

Table 1 summarizes the total value of U.S. shipments, exports, and imports of U.S. carpet and rug mill products in 2010 (U.S. Census 2011b, 2011c). These data suggest that majority of carpets and rugs purchased in the United States are domestically manufactured. Roughly half of all imports in 2010 came from China and India, while another one-third came from Egypt, Turkey, Canada, Belgium, and Iran (U.S. Census Bureau 2012). Considering the countries of origin, it is likely that the imports are predominantly area rugs, which are likely to have a much higher purchase price per square yard than carpets. However, no data on the product and mass composition (i.e., percent carpet versus percent rugs or mats) of U.S. production, imports, or exports could be found in the public domain, so there was no credible way of removing non-carpet products (i.e., those that are not covered by California's AB 2398) from the economic data in Table 1.

The inclusion of non-carpet products is an example of so-called aggregation error in input-output LCA (Hendrickson et al. 2005), which is a limitation to this study. However, given that carpets dominate the mass and economic flows from the carpet and rug mills sector, the study team expects that aggregation errors wouldn't affect the main conclusions of this study; namely, to identify broad areas of potential life-cycle greenhouse gas emissions reductions.

Table 1: Summary statistics of U.S. carpet production and apparent consumption.

Description	Producer price ($ million) in 2010
Value of product shipments, U.S. production	8,700
Value of exports	1,000
Value of imports	1,732
Apparent consumption (shipments – exports + imports)	9,432

In order to estimate the mass of carpet and rug mill products purchased in 2010, it is first necessary to convert from 2002 to 2010 producer prices. The producer price index (PPI) provides a means of converting producer prices between different years taking inflation into account. The U.S. Bureau of Labor Statistics provides a 2010: 2002 PPI ratio of 151:119 for U.S. carpet and rug mills (Bureau of Labor Statistics, 2012). Based on this ratio, we estimated a 2010 producer price $5.51 per kg of carpet. Multiplying this number by the apparent consumption value in Table 1 suggests that in 2010, the apparent consumption of carpet and rug mill products in the United States was 1.7 million metric tons (Mg).

Consistent primary data on the annual purchases of carpets in California could not be found in the public domain. As a result, we estimated in-state consumption by assuming that California's share of national consumption is proportional to its residential and commercial floor area. We further assumed that the apparent consumption of U.S. carpets was equal to the value of apparent consumption of all carpet and rug mill products. Clearly, this approach overestimates the total amount of carpets purchased in the United States. However, because available data only exist at the sector level (i.e., carpet and rug mills) and not at the product level (e.g., carpets), the study team had to adopt this method as the best approach in light of data limitations. As a result, the estimated mass flows and greenhouse gas emissions associated with carpet production and end-of-life in this case study should be interpreted as conservative (i.e., high) estimates of the total footprint. Future work should focus on identifying improved approaches to better identify purchases of carpets alone.

To estimate California's share of national consumption, we first use data from the U.S. Department of Energy on the floor area of the U.S. residential and commercial building stocks. These data suggest that there were 226 billion square feet of residential living space in 2005, and 71 billion square feet of commercial building space in 2003 (Department of Energy 2005, 2007). (These are the latest years for which credible national data are available in the public domain.) The data also indicate that the total residential living space in California was 19.4 billion square feet in 2005, or roughly 9 percent of the national total (Department of Energy 2007).

A study by Itron (2006) suggests that the total commercial floor space in California was 6.7 billion square feet in 2003, or 9 percent of the national total (Itron 2006).

Based on the Department of Energy and Itron data, we estimated that California accounts for 9 percent of total combined residential and commercial floor space in the United States.[*] Note that estimating California's share of national carpet consumption by floor area results in a lower amount (9 percent) than if one derived an estimate based on California's share of national population (12 percent) (U.S. Census Bureau 2011). However, given that it is floor area that drives carpet use, and not population, the study team feels that an allocation based on floor area is the more credible approach.

Figure 3 summarizes our estimates of 2010 mass flows of carpets in California. Based on the floor space share described above, we estimate that California purchased 153,000 metric tons of carpet in 2010 (which is 9 percent of 1.7 million metric tons). Assuming an average mass of 1.9 kg per square yard (NCDER 1998), 2010 California purchases would amount to roughly 80,530,000 square yards.

We compared this value to the only publicly available data point on California carpet purchases as a coarse "reality check." The Carpet America Recovery Effort (CARE) 2011 annual report (CARE 2012) reports shipments of carpet into California for July 1- December 31, 2011 of 50,059,517 square yards (or roughly 7,150,000 square yards per month if one assumes steady purchases throughout the reporting period). Extrapolating the monthly value to 12 months results in an estimated 85,800,000 square yards of shipments into California in 2011. This value compares favorably to our estimated value for 2010, which suggests that 2010 estimation approach gives credible approximate results.

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[*] The U.S. DOE's Commercial Building Energy Consumption Survey (U.S. DOE 2005) includes the following building types in its definition of commercial buildings: Education, Food Sales, Food Service, Health Care, Retail (Other Than Mall), Enclosed and Strip Malls, Office, Public Assembly, Public Order and Safety, Religious Worship, Service, Warehouse and Storage, Other, and Vacant. ITRON's California Commercial End Use Survey (Itron 2006) includes the following building types in its definition of commercial buildings: Small (<30K ft2) & Large Office, Restaurant, Retail, Food\Liquor, Refrigerated & Unrefrigerated Warehouse, School, College, Health Care, Hotel\Motel, Miscellaneous. Given differences in survey methods and documentation between these two data sources, it was not possible to assess the compatibility of building type definitions between them. Thus, the study team assumed that the commercial floor area totals in each source could be directly compared for the purposes of developing the preliminary estimates in this study. However, this assumption should be verified in future work.

In the absence of import/export mass data, we used value of imports as a proxy for mass flows from imports. Data on end-of-life disposition were obtained from CARE (2011), which documents detailed carpet waste recovery data for California.

The CARE (2011) report states that 410 million pounds (186,000 metric tons) of carpet were discarded in California in 2010, and that 29 million pounds (7 percent) and 47 million pounds (11 percent) of this mass went to recycling and thermal recovery, respectively.

The mass of annual discards exceeds the mass of annual purchases because carpets are typically used for anywhere from a few years to a few decades depending on consumer preferences. Thus, the stock of installed carpet in California is expected to be much greater than annual purchases and discards. As a rough estimate, if we assume that 70 percent of California's total residential and commercial floor space (26.1 billion square feet) is carpeted (Highbeam 2012), then the installed stock is roughly 18 billion square feet of carpet. Assuming 1.9 kg of carpet per square yard (NCDER 1998), we arrive at an installed stock estimate of 3.8 million Mg of carpet in California residential and commercial buildings.

Figure 4 summarizes how the recycled carpet flows in Figure 1 were further processed to produce different end use products, the most predominant of which is engineered resin pellets (CARE 2011). These data suggest that more than half of the materials reclaimed from end-of-life carpets in California are used in future carpet manufacture, and that a sizeable fraction (46 percent) can be used to offset a high-grade virgin material (i.e., engineered resins). The thermal recovery fraction is mostly through waste-to-energy recovery facilities, with a minor fraction used as fuel substitutes in cement kilns outside of the state (CARE 2011).

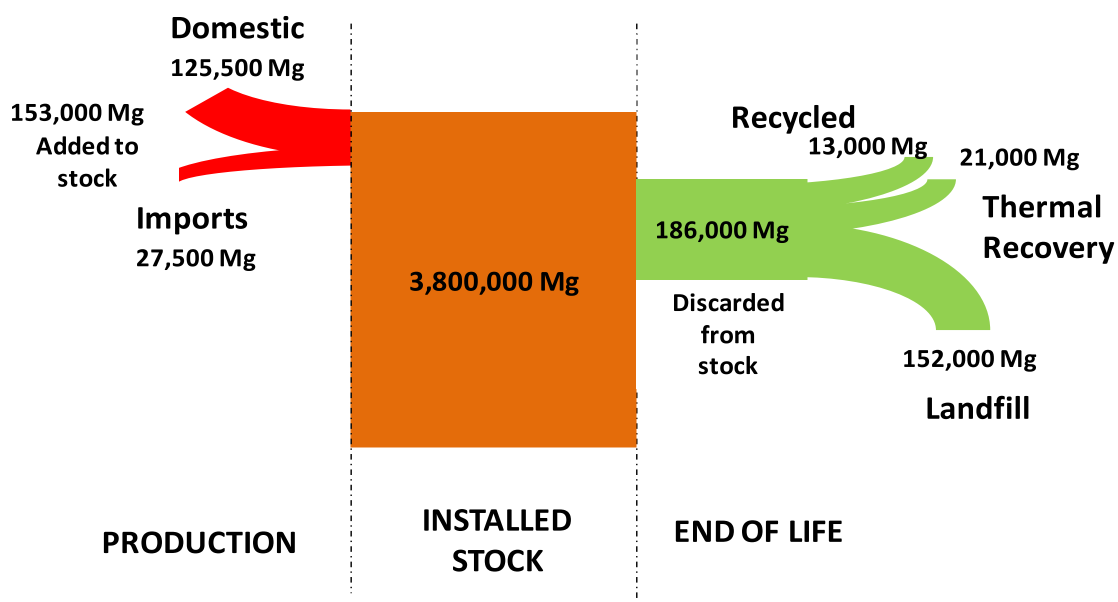
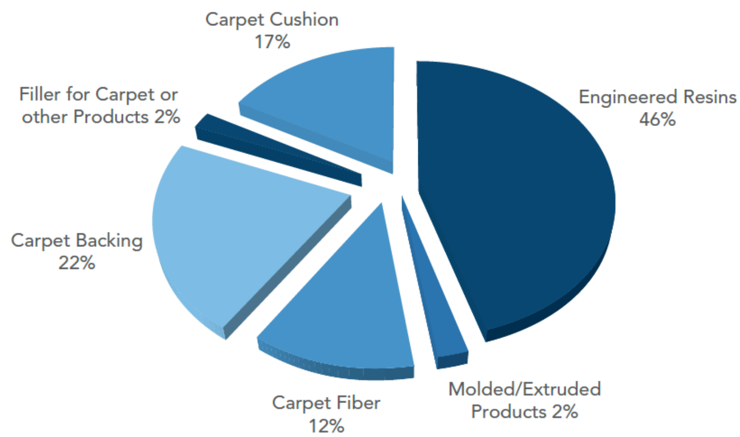


Figure 3: Estimated 2010 mass flows of residential and commercial carpet in California.



Source: CARE (2011)

Figure 4: Products manufactured from recycled carpets in California.

Emissions from production

Based on the stated assumption that 2002 producer prices for U.S. carpet and rug mill products was $4.31 per kg, we estimated that the 153,000 Mg of new carpet purchased in 2010 had a total 2002 producer price of $660 million. A conversion to 2002 producer price is necessary for compatibility with the MRIO model, which uses the 2002 U.S. input-output accounts as its basis (Masanet et al. 2012). The MRIO model estimates that the greenhouse gas emissions associated with $660 million of output from the carpet and rug mill sector (314110) amounts to roughly 780,000 Mg of carbon dioxide equivalents (CO_2E).

Figure 5 summarizes the MRIO greenhouse gas emissions estimates for the top 10 input-output sectors in the production chain for carpet and rug mill products, on a per dollar of production basis. The top emitter is the carpet and rug mills themselves, which attests to the significant energy expenditures in textile mill processes such as weaving mills and steam systems. Other major greenhouse gas emissions sources include the chemicals and fibers production sectors that provide the carpet and rug mills sector with its primary ingredients. The MRIO model also predicts that cotton farming is a key contributor; however, given that most carpets are made using synthetic fibers, the study team expects that predicted cotton inputs are a further example of aggregation error in the modeling approach.

The largest sources of emissions are electricity use (primarily for motor-driven systems in the fiber and textile mills), natural gas use for process heating and steam systems, and soil-related emissions in cotton farming. Transportation is the primary driver of emissions from petroleum combustion in the supply chain.

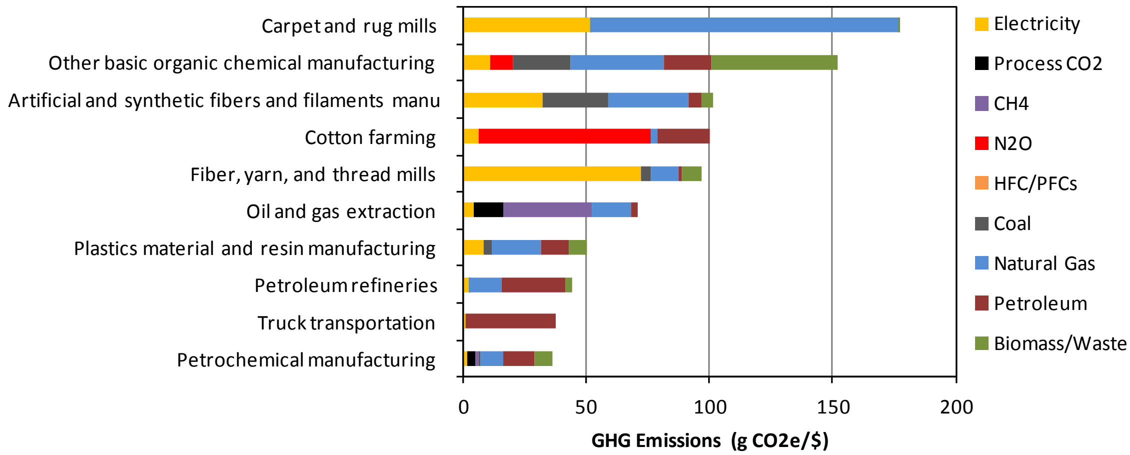


Figure 5: Top 10 sectors for greenhouse gas emissions in the carpet production chain.

Emissions from forward logistics

Forward logistics refers to the transportation of finished carpets from the manufacturer to wholesale and/or retail outlets for purchase by the final consumer. Emissions from forward logistics were estimated in four steps.

First, the typical energy and greenhouse gas emissions intensities of various U.S. freight modes were established from the U.S. LCI database (NREL 2011). These intensities are summarized in Table 2.

Table 2: Energy and greenhouse gas emissions intensities for common freight modes.

Mode	Energy (MJ/t-km)	CO2 (kg/t-km)
Transport, barge, diesel powered	3.49E-01	2.81E-02
Transport, combination truck, diesel powered	9.90E-01	7.99E-02
Transport, ocean freighter, residual fuel oil powered	2.06E-01	1.60E-02
Transport, train, diesel powered	2.36E-01	1.89E-02

Source: NREL (2011)

Second, the typical modes of domestic freight transport for carpets were estimated based on the U.S. Bureau of Transportation Statistics' Commodity Flow Survey (U.S. Census Bureau 2004b). The data from this survey suggest that of reported ton-miles for single-mode freight (24.6 billion), the vast majority of ton-miles (23.9 billion) were by truck, with most of the remainder of ton-miles by rail (0.4 billion).

Third, the average shipment distances occurring domestically and from imports were estimated based on regional economic data and online distance mapping software (Google Maps and PortWorld). For domestically produced carpets, data from the U.S. Census Bureau suggest that roughly two-thirds of U.S. employment in the carpet and rug mill sector is located in Georgia, followed by Alabama (6 percent), North Carolina (4 percent), and Virginia (4 percent) (U.S. Census Bureau 2012). Using an employment-weighted average of driving distances from the center of each state to the center of California produced an estimated domestic shipping distance of 3,600 km.

Import trade statistics suggest that half of all imports in 2010 (by value) came from China and India, while another one-third came from Egypt, Turkey, Canada, Belgium, and Iran (U.S. Census Bureau 2012). Based on these data, the value-weighted average shipping distances for imports to the United States were estimated at 14,500 km (to western ports from China and India) and 10,000km (to eastern ports from Egypt, Turkey, Belgium, and Iran). An additional 4,500km of domestic shipping by truck was assumed for transportation of imports from eastern ports to California.

Fourth, using the estimated shipping distances, modes, and purchased mass of carpets, the greenhouse gas emissions for forward logistics were estimated and summarized in Table 3. The total estimated greenhouse gas emissions of forward logistics for California-purchased carpets in 2010 is estimated at 45,440 Mg CO_2E, an amount equivalent to roughly 6 percent of the production emissions associated with purchased carpet (780,000 Mg CO_2E). Thus, while not insignificant, the emissions of forward logistics likely represent only a small fraction of the cradle-to-consumer system for carpets.

Table 3: Estimated 2010 emissions from forward logistics.

Transport activity	Mode	Distance (km)	Mass (Mg)	GHG emissions (Mg CO_2E)
Domestic shipments of domestically-produced carpets	Diesel combination truck	3,600	125,500	36,100
Ocean shipments of foreign-produced carpets to Western U.S. ports	Residual fuel ocean freighter	14,500	17,200	3,990
Ocean shipments of foreign-produced carpets to Eastern U.S. ports	Residual fuel ocean freighter	10,000	10,300	1,650
Domestic shipments of foreign-produced carpets from Eastern U.S. ports	Diesel combination truck	4,500	10,300	3,700
Total				**45,440**

Emissions from end-of-life operations

The study team adopted the UCSB end-of-life processed-based model for estimating the greenhouse gas emissions associated with different end-of-life pathways for discarded carpet in California. To estimate the average mass composition of a given ton of discarded carpets, we relied on publicly-available data from the U.S. EPA's WARM model (U.S. EPA 2011), which are summarized in Table 4. The mass compositions below were input into the UCSB model to generate the results summarized in Figures 6 and 7.

Table 4: Estimated average material composition of discarded carpets.

Material/Product	Application	% of Total Weight
Nylon resin	Face fiber	44.9%
Polypropylene	Woven for backing	15.0%
Styrene butadiene latex	Carpet backing adhesive	8.1%
Limestone	Filler in latex adhesive	32.0%
Total		**100.0%**

Source: U.S. EPA (2011)

Figure 6 shows how the various end-of-life disposition pathways compare on a per-kg basis, which are based on process-level EOL data in U.S. EPA (2011). Net landfill emissions include collection, transport, and landfill activities. Net recycling emissions include collection, transport, and recycling activities averaged across major end use products, and emissions avoided from substituting for virgin materials. Net waste-to-energy emissions include collection, transport, combustion, and emissions avoided from substituting for grid power.

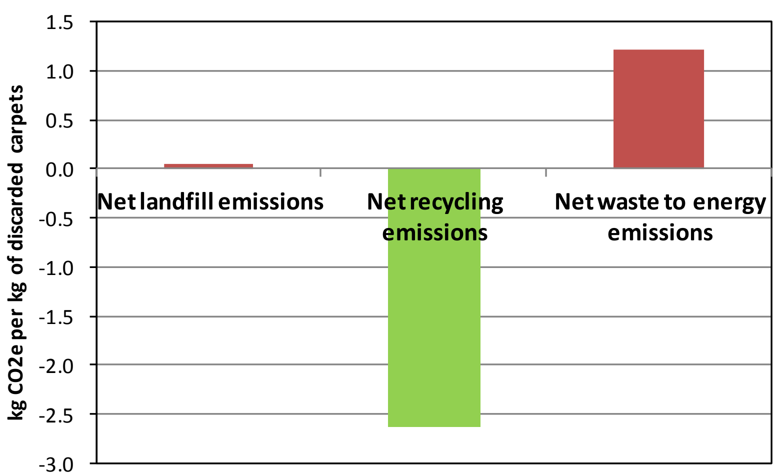


Figure 6: Per-kg comparisons of different end-of-life pathways for discarded carpet.

Figure 7 plots estimated total annual greenhouse gas emissions associated with California's end-of-life carpet mass flows in 2010, as depicted in Figure 3. Notable is that net emissions savings from current recycling slightly offset the combined net emissions outputs from current carpet landfill and thermal recovery operations in the state. The total net end-of-life emissions are estimated at -2,500 Mg CO_2E. While this is not a trivial amount of savings, it represents less than 1 percent of the 780,000 Mg CO_2E associated with the production of new carpets purchased in California in 2010.

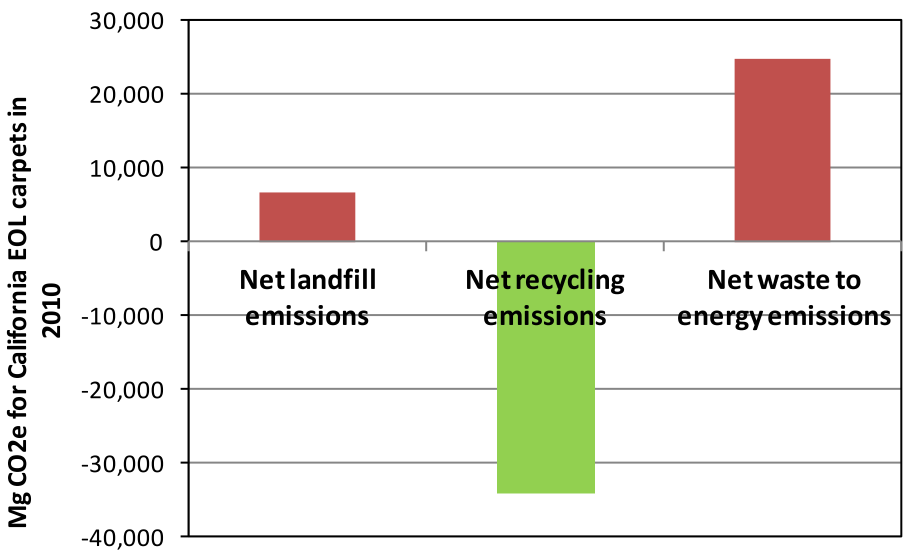


Figure 7: Estimated total greenhouse gas emissions associated with end-of-life recycling and disposal, 2010.

Opportunities for life-cycle emissions reductions

The study team conducted a global literature review to identify possible strategies for reducing the life-cycle impacts of carpets. As discussed above, the vast majority of current greenhouse gas emissions attributable to the carpet life-cycle are associated with its production phase. The identified recommendations for reducing life-cycle greenhouse gas emissions therefore centered on improved recycling infrastructures to provide more recycled content into the production process, improved design, and improved manufacturing and supply chain energy management. Specifically, we identified the following strategies, which are discussed in further detail in remainder of this section (see for example CARE 2011, 2012; INFORM 2012; Fishbein 2000):

- Design: modular design to extend carpet lifetime
- Design: increased use of post-consumer polymers for carpet feedstock
- Manufacturing: supply chain energy and emissions management to reduce upstream impacts
- Recycling: improved recycling rates

Modular design

Modular design refers to the use of carpet tiles in lieu of single wall-to-wall carpets. Modular design can extend the technical life of carpets, because individual tiles can be used to replace worn and/or stained areas rather than replacing the entire wall-to-wall carpet. A number of companies produce carpet tiles and offer refurbishment, recycling, and replacement of worn tiles (Helm 2011).

Carpet tiles are being used increasingly for both commercial and residential carpeting applications. Available data suggest that the market share of carpet tiles in U.S. commercial applications is around 15 percent (Helm 2011). No data could be found on the market share of carpet tiles in U.S. residential applications; thus, the study team assumed a similar penetration (15 percent) for U.S. homes.

No empirical data could be found in the public domain on the average technical lifetime extension of a carpet through the use of carpet tiles as opposed to wall-to-wall carpets. Furthermore, technical lifetime refers to the useful life based on technical parameters such as carpet resiliency, appearance, and cleanliness. Often, carpets are replaced due to reasons of aesthetics or style before the technical lifetime has been reached.

To estimate the potential life-cycle greenhouse gas emissions reductions associated with the use of carpet tiles, the study team assumed a maximum remaining market of 85 percent of California residential and commercial buildings, and potential range of lifetime extension of 25 percent to 50 percent based on engineering judgment. Future work can improve this estimated range by conducting interviews of carpet tile owners and soliciting data from major carpet tile manufacturers.

To approximate the effect of replacing carpet tiles to extend the life of carpets, we assumed that 20 percent of carpet area would be worn and replaced over the useful life of a carpet, and that new tiles would be used to replace the worn tiles. Annual purchases in the MRIO model were adjusted accordingly.

Increase post-consumer recycled content

Many companies are increasing the use of post-consumer polymers as a feedstock for new carpets. The post-consumer recycled content of carpets can vary widely by both manufacturer and carpet component (e.g., facing, backing, or fillers). Data from CARE (2012) suggest that the current range of post-consumer recycled content by carpet weight is 20 percent to 50 percent. In the absence of data on the average post-consumer content of currently installed California carpets and recent California carpet purchases, the study team used an estimate of 10 percent. We further assumed that this percentage could be increased from 20 percent to 50 percent based on data in CARE (2012).

To approximate the effect of increased post-consumer recycled content in carpets, we reduced the purchase of raw fibers for carpet production in the MRIO model, and increased purchases from the waste management and recycling sector, by the assumed marginal percentage increase in recycled content. This approach cannot distinguish between specific types of recycled resins (e.g., PET versus nylon), given that the MRIO model treats all recycled inputs as an aggregated sector. Thus, the results for this opportunity are treated as fairly rough, but nonetheless indicative of the general magnitude (i.e., big or small) of the opportunity associated with increased recycled resin content.

Maximum supply chain efficiency

To estimate manufacturing and supply chain energy efficiency improvement potentials, this study utilized the eSTEP modeling methodology that is summarized in Masanet et al. (2009a, 2009b). The model currently includes best practice technology energy savings data for a range of energy efficiency measures in different IO sectors, and for different energy end uses. It also contains key measures for non-energy related greenhouse gas emissions in several IO sectors. A summary of the broad IO sectors, fuels, and non-energy greenhouse gas emissions covered by best practice technology data in the eSTEP model is provided in Masanet et al. (2012).

The eSTEP model was used to generate potential reductions in fuel use and emissions for all manufacturing, commercial, agricultural, mining, and water treatment sectors in the MRIO model as a means of approximating the potential supply chain emissions reductions a final manufacturer might drive throughout its supply chain by sourcing its inputs only from "low carbon" supply chain partners. As such, it provides an upper bound estimate on best practice supply chain emissions savings, since it assumes that best practices will be adopted at all sectors in its supply chain, whether those sectors are primary or very distant suppliers. Use of renewable energy sources in the supply chain is not considered in eSTEP, but could represent an additional source of greenhouse gas emissions reductions via supply chain initiatives.

Detailed results on the estimated supply chain improvement potentials for the manufacture of $660 million in carpet are presented in Figure 8. The results show the top 10 emissions reduction opportunities across the supply chain in terms of estimated emissions saved by fuel and emissions reduction opportunity area (for energy efficiency) and by greenhouse gas emissions type and abatement opportunity (for greenhouse gas emissions abatement measures).

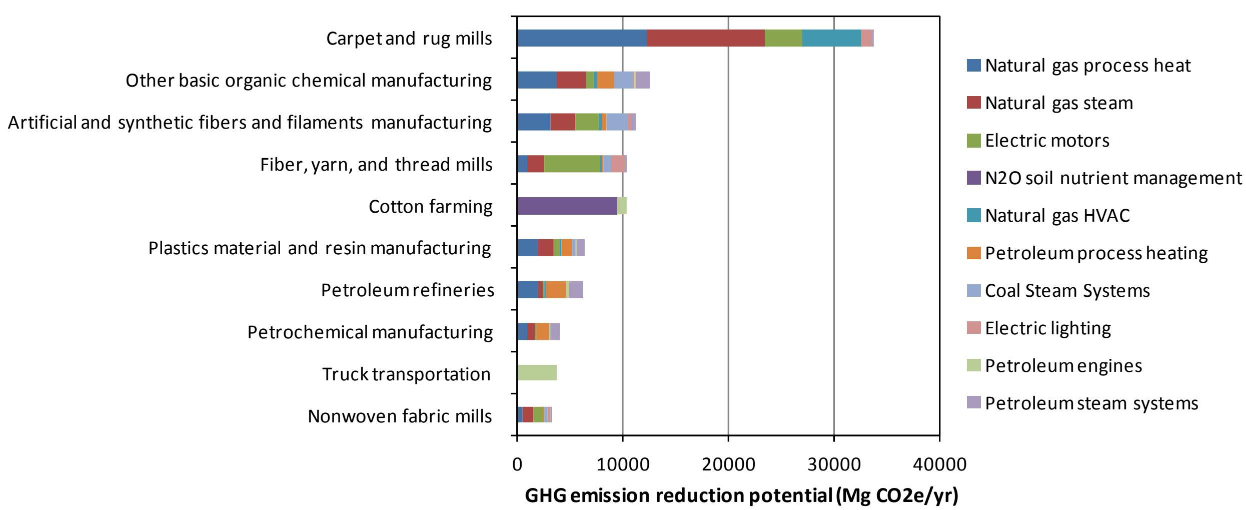


Figure 8: Supply chain greenhouse gas emissions reduction opportunities by sector and source.

Maximum end-of-life recycling

Lastly, for improved recycling we assumed a theoretically maximum-achievable end-of-life carpet diversion and recycling rate of 100 percent. The theoretical limit to this opportunity was explored to provide a rough upper bound estimate of the magnitude of this opportunity to assess its potential relative to the other opportunities; such an approach is consistent with methods used in technical potentials analysis (see for example Energetics 2006). This assumption was implemented in the process-based LCA model by reducing landfill and waste-to-energy flows to zero and assigning 100 percent of the end-of-life mass to the recycling route. As previously discussed, the current recycling rate of California carpets is 7 percent of annual end-of-life mass.

An important point is that this measure has overlap with the increased use of recycled content, in that the "credits" for materials recycling into new carpets are already accounted for in the methodology for estimating the emissions savings of increased recycled content. Thus, the emissions reductions associated with this measure account for the additional offsets of virgin materials that would occur beyond the amounts that are used in California purchased carpets.

Figure 9 and Table 5 summarize the estimated life-cycle greenhouse gas emissions associated with the opportunities described above under two cases compared to the 2010 base case (i.e., the current estimates of life-cycle greenhouse gas emissions). The first case (partial savings) considers more modest improvements in each opportunity area as coarse way of acknowledging potential technical, market, and economic barriers that might prevent realization of the full technical potential for greenhouse gas emissions reductions. For example, although it is theoretically possible to carpet all California residential and commercial buildings with carpet tiles, for reasons of cost, aesthetic preference, or awareness the penetration of carpet tiles may never reach 100 percent.

The second case (maximum savings) is based on the total estimated technical potential of the opportunity, and therefore represents an upper bound, best-case estimate for potential greenhouse gas emissions reductions. Note that all savings estimates within each case are additive, given that the opportunities were applied in cascading fashion to avoid double counting. Furthermore, subsequent opportunities within a case took into account relevant mass and product changes associated with previous opportunities within that case. For example, the mass of end-of-life carpets available for recycling takes into account the reduced mass purchases of new carpets associated with modular design for lifetime extension. Lastly, the savings estimates in the maximal savings case are inclusive of, not additive to, the savings in the partial savings case.

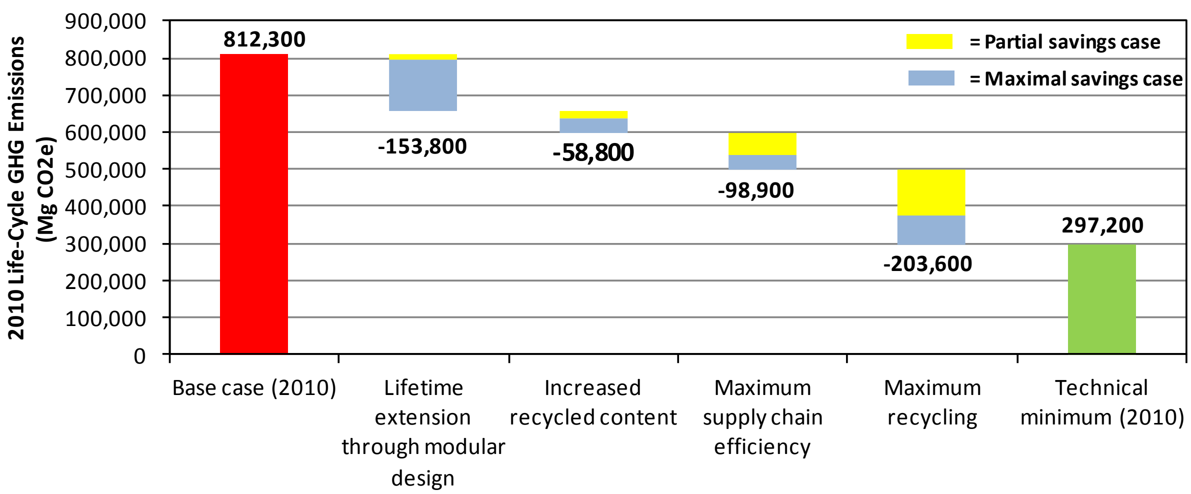


Figure 9: Estimated life-cycle greenhouse gas emissions reduction opportunities.

Considering the maximum savings case, the largest opportunity lie with extending the useful life of carpets, which has the effect of reducing overall annual purchases of carpets in California over time, and maximizing end-of-life recycling, which has the effect of offsetting virgin materials in the production of new products. Given that the results in this case study are based on data and estimates from a number of different sources, their absolute values should be treated as fairly uncertain. However, it is likely that even with increased data accuracy that the two largest opportunities would remain the same, given that their primary greenhouse gas emissions reduction mechanism (reducing primary materials use in production) typically results in environmental benefit. The use of increased recycled materials and minimizing supply chain greenhouse gas emissions through best practice supply chain efficiency may deliver smaller, but roughly equal savings. Supply chain efficiency serves to reduce the overall “embodied” greenhouse gas emissions in the product. Figure 6 suggests that the greatest supply chain savings are to be had at the carpet and rug mills themselves, and in particular through improved process heating, steam system, and motor system efficiency.

Table 5: Summary of analysis assumptions for life-cycle improvement opportunities.

Opportunity area	Analysis details	Analysis case		
		Base case	Partial savings	Maximum savings
Modular design	Key assumption(s)	Carpet tiles have 15% market penetration	Carpet tiles have 50% market penetration and extend life by 25%	Carpet tiles have 100% market penetration and extend life by 50%
	GHG emissions savings compared to base case (Mg/yr)	--	15,400	153,800
Increased recycled content	Key assumption(s)	Recycled content (total mass) = 10%	Recycled content (total mass) = 20%	Recycled content (total mass) = 50%
	GHG emissions savings compared to base case (Mg/yr)	--	23,500	58,800
Increased supply chain efficiency	Key assumption(s)	Current U.S. average supply chain efficiency	50% of supply chain efficiency potential is realized	100% of supply chain efficiency potential is realized
	GHG emissions savings compared to base case (Mg/yr)	--	63,800	98,900
Increased EOL recycling	Key assumption(s)	7% of annual EOL mass is recycled; 11% to thermal recovery; 82% to landfill	50% of annual EOL mass is recycled; 11% to thermal recovery; 39% to landfill.	100% of annual EOL mass is recycled
	GHG emissions savings compared to base case (Mg/yr)	--	124,600	203,600
All opportunities combined	GHG emissions savings compared to base case (Mg/yr)	--	227,300	515,100

Figures 10 and 11 plot the results for the 2010 base case and the 2010 technical minimum case (i.e., the base case minus the maximal savings case) by region of emissions as estimated by the MRIO model. Results are presented for California, the rest of the United States, and the rest of the world, as discussed in the background section.

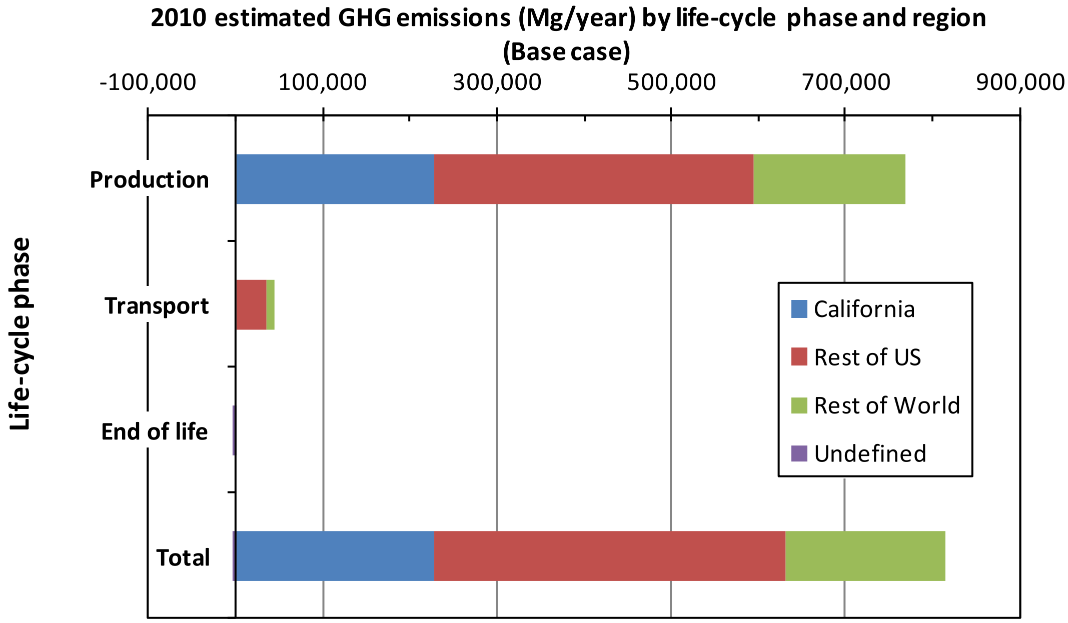


Figure 10: Regional breakdown of greenhouse gas emissions for the base case.

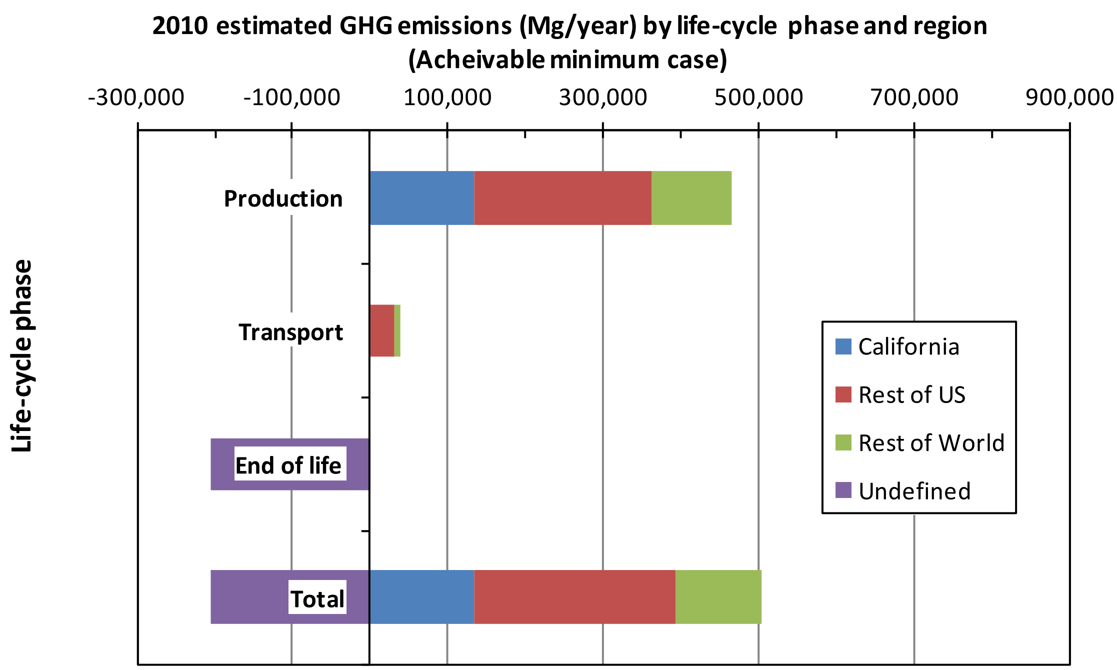


Figure 11: Regional breakdown of greenhouse gas emissions for the achievable minimum case.

Labor implications of increased recycling

A recent report by the Tellus Institute and Sound Resource Management (2011) attempted to estimate the job requirements of collection, recycling, and disposal systems for various components of municipal solid waste in the United States. The findings are reported in terms of jobs per 1,000 short tons (907 Mg) of material handled by collection, processing, manufacturing, and reuse/remanufacturing operations (for diverted waste) and by collection, landfill, and incineration (for disposed waste). While such estimates oversimplify the complex macroeconomic equilibrium analyses required to understand the job impacts of substituting materials and processes in an extended economic system, they can serve as a plausible estimate of potential job creation due to carpet recycling for the purposes of this study. The job creation estimates are summarized in Table 6.

Table 5: Summary of job requirements for textile waste processing.

Material	Diverted Waste				Disposed Waste		
	Collection	Processing	Manufacturing	Reuse/ Remanufacture	Collection	Landfill	Incineration
	Jobs per 1000 tons						
Textiles	1.67	2.00	2.50	7.35	0.56	0.10	0.10

Source: Tellus et al. (2011)

While data on the job requirements of carpet recycling (and materials recycling in general) are rare in the published literature, the study team compiled limited data from two additional sources for comparison to the values in Table 5. The CARE (2012) report states that in 2011, its survey respondents in California recycled 33 million pounds of carpet while its survey respondents in the United States recycled 250 million pounds. The report further states that respondents who collected and/or recycled California carpet reported employing 204 people in 2011, while U.S. respondents employed 1,462 people in 2011 in local communities across the United States (CARE 2012). Using these data for crude estimates results in 6.8 persons employed per 1,000 tons recycled (for California) and 8.8 persons employed per 1,000 tons recycled (for the United States).

Since the CARE (2012) data were not disaggregated by operation (e.g., collection vs. processing vs. reuse), it is not possible to compare them directly to the data in Table 5. While the CARE (2012) estimates are of the same order of magnitude as the Tellus et al. (2011) estimates, the differences between them underscore the critical point that such estimates are quite uncertain and the resulting job creation results should be interpreted in light of these uncertainties.

In the maximum savings case, the recycling rate was increased from its present rate of 7 percent of EOL mass to 100 percent of EOL mass. This rate increase raised the mass processed for recycling from 13,000 Mg/yr to 149,000 Mg/yr (note that the maximum savings case also reduced EOL mass generated by extending product life through modular design). It further reduced the EOL mass to landfill and incineration to zero from 152,000 Mg and 21,000 Mg, respectively. Assuming that all reclaimed materials from California’s end-of-life carpets would offset virgin materials use in new product manufacture (see Figure 2), the estimated job impacts associated with the increased recycling in the maximum savings case (nearly 800 jobs added) are summarized in Table 6.

Table 6: Estimated job impacts associated with increased EOL carpet recycling.

Case	Unit	Diverted Waste			Disposed Waste		
		Collection	Processing	Manufacturing	Collection	Landfill	Incineration
Base case	Mass (Mg)	13,000	13,000	13,000	173,000	152,000	21,000
	Jobs	24	29	36	107	17	2
Maximum savings	Mass (Mg)	149,000	149,000	149,000	0	0	0
	Jobs	274	329	411	0	0	0
Net change	Mass (Mg)	136,000	136,000	136,000	-173,000	-152,000	-21,000
	Jobs	250	300	375	-107	-17	-2

Conclusions

This case study estimated the life-cycle greenhouse gas emissions associated with the production, transport, and disposal of carpets consumed by California residential and commercial buildings, and the potential for reducing these emissions through improvements to product design, manufacturing, and end-of-life management. The considered improvements might reduce the annual greenhouse gas emissions “footprint” of carpets in California by up to 60 percent through product lifetime extension, increased use of recycled content, increased end-of-life recycling, and improved manufacturing energy and emissions efficiencies, while at the same time diverting thousands of metric tons of waste carpets from California landfills.

Each of the considered improvements is relevant to EPR programs, although the exact mechanism for inducing each improvement will vary by EPR program design and the stakeholders in charge of EPR compliance. For example, an EPR program designed to minimize waste might provide producers with financial incentive to offer more modular carpets, while an EPR program designed to reward “green” design and manufacturing features might provide motivation for improved manufacturing and supply chain energy and emissions efficiencies.

Regardless of the EPR program type, this case study has provided valuable quantitative estimates for scoping the potential emissions savings related to more sustainable carpets, which can provide guidance to policy makers and manufacturers on the most fruitful areas of improvement under various EPR initiatives. The maximum savings case results suggest that product lifetime extension and maximum end-of-life recycling might lead to the most significant life-cycle greenhouse gas emissions reductions, while improved manufacturing and supply chain efficiencies and greater use of recycled content can lead to additional savings.

The preliminary results for net job creation also suggest that improved recycling can have positive benefits on employment both inside and outside California. In summary, carpets represent an attractive opportunity for EPR programs due to the ready availability of environmental improvements through design, manufacture, and end-of-life strategies, which may offer California additional greenhouse gas emissions reductions beyond those expected under its current carpet EPR initiative.

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