Mattress and Box Spring Case Study

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

California Department of Resources Recycling and Recovery

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Contractor's Report

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Acronyms

BEA	Bureau of Economic Analysis
BF	Blast furnace (converts iron ore to pig iron)
BLS	Bureau of Labor Statistics
BOF	Basic oxygen furnace (converts pig iron to primary steel)
CalRecycle	California Department of Resources Recycling and Recovery
CO_2E	Carbon dioxide equivalent
EAF	Electric arc furnace (converts scrap to secondary steel)
EIOLCA	Economic input output life-cycle assessment
EOL	End-of-life
EPR	Extended Producer Responsibility
GHG	Greenhouse Gas
GJ	Giga Joule (= 10^9 Joules, 1 BTU = 1055 Joules)
ISO	International Organization for Standardization
Kg	Kilogram (1 metric ton = 1,000 kg, 1 short ton = 907.185 kg, 1 kg = 2.205 lbs)
LCA	Life-Cycle Assessment
MJ	Mega Joule (= 10^6 Joules, 1 BTU = 1055 Joules)
MRIO	Multi-Region Input-Output Energy Use and GHG Emissions Model for California
NAICS	North American Industry Classification System
NCV	Net calorific value (same as lower heating value LHV)
PPI	Producer Price Index
UCSB	University of California at Santa Barbara
UCB	University of California at Berkeley

Glossary

Cradle-to-gate	This includes all upstream economic activities, from drilling and mining, shipping, beneficiation and processing, including the actual manufacturing of the product.
Unit	One mattress or one box spring (foundation) is called a unit.
Set	One mattress and one box spring is called a set.

Introduction

Background

This case study supports responsibilities of the Department of Resources Recycling and Recovery (CalRecycle, formerly the California Integrated Waste Management Board) under the California Air Resources Board Scoping Plan to address greenhouse gas emissions through an Extended Producer Responsibility (EPR) approach.

EPR is a mandatory type of product stewardship that specifies, 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. EPR is also meant 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 (EOL) 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. On Dec. 11, 2008, the California Air Resources Board approved the Scoping Plan to reduce the state's greenhouse gas emissions to 1990 levels by 2020. This plan includes a Recycling and Waste Management Measure for EPR. The aim of this climate action mitigation measure is to achieve high recycling and advance EPR to reduce emissions both in-state as well as within the connected global economy. This measure also aligns with the CalRecycle's policy priority of advancing industry-led product stewardship (also known as Extended Producer Responsibility) in accordance with the EPR Framework adopted by the Waste Board in September 2007 and modified in January 2008 (CIWMB 2008). One goal of product stewardship is to increase reuse and recycling of end-of-life products, which, in turn, can reduce greenhouse gas emissions by reducing the substantial energy use associated with the acquisition of raw materials in the early stages of a product's life cycle.

CalRecycle contracted with the University of California at Berkeley (UC Berkeley) and the University of California at Santa Barbara (UC Santa Barbara) with the objective of developing several scientifically-based approaches to analyze life cycle environmental impacts of products, prepare case studies for selected products, and provide 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. The four product case studies cover carpet, clamshells, mattresses and box springs, and single-use batteries.

Scope

This report assesses mattress and box spring production and end-of life management in terms of energy and greenhouse gas implications. Landfills are the final destination for most of the millions of mattresses and box springs disposed of in California every year, even though 85 percent of their mass can be readily recycled through simple manual disassembly. Their bulkiness makes them difficult to handle during waste pickup and transport, their low density makes them undesirable landfill material, and their springs have a tendency to disable landfill and transfer station equipment (ISPA 2004). Another problem with end-of-life mattresses is illegal dumping. While mattress and box spring recycling is perfectly feasible and has few technical challenges, its poor economics has so far hindered the natural growth of the collection and recycling industry. The mattress and box spring energy and greenhouse gas implications for different end-of-life management routes can inform the corporate and public environmental policy debate. This study assesses the energy and greenhouse gas implications of using different end-of-life management methods for mattresses and box springs. It does not study which EPR approaches and mechanisms would bring about which changes in mattress and box spring design and end-of-life management.

The study uses both types of life cycle assessment (LCA) methodology, economic input-output LCA and process-based LCA (see Appendix A), to estimate the greenhouse gas emission reductions that could be achieved through increased reuse and recycling of end-of-life products.

Economic input-output LCA is used to calculate the cradle-to-gate greenhouse gas emissions of manufacturing the product. 'Cradle-to-gate' here includes the greenhouse gas emissions of all upstream, or supply chain, activities and ends with the actual manufacturing of the product. The specific model used is the multi-region input-output life cycle assessment (MRIO-LCA) model developed by UC Berkeley. 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 economic input-output life cycle assessment (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 who are new to economic input-output modeling. Both models use the North American Industry Classification System (NAICS), maintained by the U.S. Census Bureau, to partition the U.S. economy. 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. economy. The economic data that underlies the models is the 2002 benchmark input-output model maintained by the U.S. Bureau of Economic Analysis (Stewart et al. 2007).

Process-based LCA is used to estimate the energy demand and greenhouse emissions from product manufacturing (cradle-to-gate), forward 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. 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 each modeled process, the most appropriate process inventory is chosen from a wide range of public and proprietary life cycle inventory databases, including Ecoinvent, PE, and U.S. LCI, and literature. In some cases this has been complemented by primary data collection.

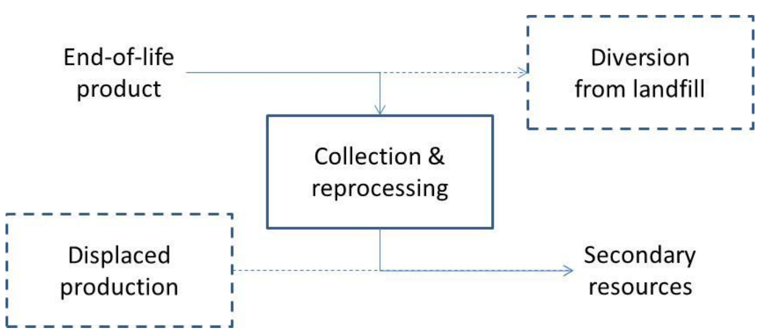

Figure 1: Analytical framework to assess greenhouse gas emissions reductions from reuse and recycling.

The greenhouse gas emission reductions from reuse and 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 1). In life cycle assessment methodology, this method is typically called avoided burden approach or (consequential) system expansion. Avoided burdens can be calculated with both the process model (as avoided processes) and the MRIO-LCA tool (as displaced economic activity). Avoided processes are modeled as negative energy requirements and greenhouse gas emissions. Displaced economic activity is modeled as negative economic demand in the MRIO-LCA tool. Because of the uncertainty inherent in estimating avoided burdens, the reported emissions reductions should be regarded as approximate. The way in which MRIO-LCA and process-based LCA is combined in the case studies is illustrated in Figure 2.

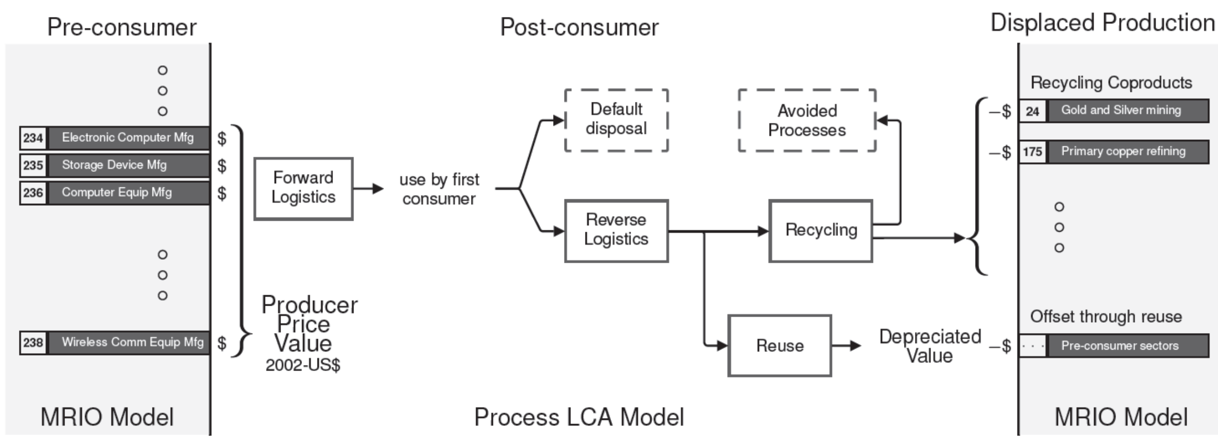

Figure 2: In the case studies, greenhouse gas emissions from product manufacturing and end-of-life management are calculated by combining MRIO-LCA with process-based LCA.

Product Description and Analysis

We will first use economic input-output life cycle assessment (EIO-LCA) to estimate the cradle-to-gate primary energy demand and greenhouse gas emissions of mattress and box spring production. The input-output tables are organized by sectors according to the North American Industry Classification System (NAICS). The relevant 2007 NAICS Code is 337910 (Mattress Manufacturing). This industry comprises establishments primarily engaged in manufacturing innerspring, box spring, and non-innerspring mattresses, including mattresses for waterbeds. Apparent U.S. consumption of products from NAICS sector 337910 in 2010 was $6.2 billion in 2010 producer price (see Table 1).

Table 1: Apparent U.S. consumption of products from NAICS sector 337910 in 2010.

	Value in $2010 producer price	Source
U.S. production	6,040,834,000	U.S. Census 2011a
Exports	117,863,000	U.S. Census 2011b
Imports	289,437,000	U.S. Census 2011b
Apparent U.S. consumption	6,212,408,000	

According to trade and industry statistics, around 38 million mattresses and box springs were sold in the U.S. in 2010 (ISPA 2012). According to this data, the average 2010 mattress and box spring set had a 2010 producer price of $326. The EIO-LCA model is based on the 2002 benchmark input-output tables. Between 2002 and 2010 the producer price index (PPI) for NAICS Code 337910 rose from 139.7 to 176.5 (BLS 2012). A 2010 producer price of $326 is thus equivalent to a 2002 producer price of $258. According to UC Berkeley's Multi-Regional Input Output Model (MRIO), the production of goods from sector 337910 worth $258 measured in 2002 producer price has cradle-to-gate greenhouse gas emissions of 129 kg of CO_2E and energy requirements of 1,745 MJ. Table 2 below shows the top five contributing sectors.

Table 2: The five sectors with the highest greenhouse gas and energy contributions to mattress production.

NAICS Code	Sector Name	GHG emissions in kg CO2eq	Energy Requirements in MJ
331111	Iron and Steel Mills	21.1	173.1
2211	Power Generation and Supply	26.1	447.9
484	Truck Transportation	5.6	80.1
21111	Oil and Gas Extraction	32.4	25.8
32519	Other Basic Organic chemical manufacturing	9.2	129.2

Energy demand and greenhouse gas emissions of mattress and box spring material production can also be calculated using process-based life cycle assessment (LCA), which is described in detail in ISO standards (ISO 14040, ISO 14044). An innerspring mattress consists of the innerspring unit, the insulator pad, the cushioning layers, and the cover. The core is the innerspring unit, which typically contains 250 to 1,000 steel coil springs. An insulator pad sits directly on top of the innerspring unit to prevent the next layer, the cushioning, from molding to the coils. The cushioning varies widely by material type and thickness. Currently, the most frequently used material is polyurethane foam, followed by cotton. Innerspring unit, insulator, and cushioning are encased by a quilted cover, which can be made from a variety of materials. Today, mattresses come in standard sizes, the most common of which are called Twin, Double, Queen, and King. The box spring interior is a wooden frame with wooden slats or metal springs. Similar to the mattress, the box spring is encased by a quilted cover.

Table 3: Material composition of an average mattress and box spring set (DR3 2012).

	Mass	Mass percent
Entire mattress and box spring	54.4 kg	100%
Steel	27.2 kg	50%
Wood	5.44 kg	10%
Foam	5.44 kg	10%
Cover (Toppers)	5.44 kg	10%
Cotton	2.72 kg	5%
Unspecified	8.16 kg	15%

One mattress disposal operation estimates that 125 mattresses of mixed sizes weigh about 10,000 pounds, which translates into 36.3 kg per average mattress (ISPA 2004). In 2010, North America's largest mattress recycler processed about 55,000 mattresses and 55,000 box springs, which together weighed 3,300 tons (DR3 2012). This translates into 54.4 kg per mattress and box spring set.

shows the average material composition of a mattress and box spring set processed by DR3 in 2010.

Table 4: A process-based assessment of the energy demand and greenhouse gas emissions from mattress and box spring production (see Appendix B for inventory data sources).

Component	Mass in kg	GHG intensity in kg CO_2E/kg	Energy intensity in MJ NCV/kg	GHGs in kg CO_2E	Energy in MJ NCV
Steel wire rod (Global EAF-BF/BOF mix)	27.2	2.16	21.8	58.7	593
Wood (pine, 40% water content)	5.44	-0.99	3.5	-5.4	19
Polyurethane flexible foam	5.44	4.74	91.8	25.8	499
Polyester fiber	5.44	4.54	106	24.7	577
Cotton fiber (U.S.)	2.72	1.52	34	4.1	92
Total				108	1,780

The unspecified fraction of the mattress and box spring material composition in the table above goes to landfill. The majority of this material consists of the insulator pads, frequently made of felt, and foams, fabrics, and covers which cannot be recycled.

multiplies the five main material fractions of a mattress and box spring set with their greenhouse gas and primary energy intensities, in order to determine the average embodied greenhouse gas emissions and primary energy.

The greenhouse gas and energy intensities are derived from life cycle inventory data for product systems that most closely resemble those present in California mattresses and box springs. The greenhouse gas emissions embodied in the five main material fractions of an average mattress and box spring set are 108 kg of CO_2E, which is close to the 129 kg CO_2E from the MRIO model. At 1,780 MJ NCV the embodied primary energy per average mattress and box spring set is essentially the same as the 1,745 MJ from the MRIO model. The MRIO model encompasses many more processes than those in Table 4 and should thus be expected to yield significantly larger greenhouse and energy results.

One reason for this not being the case is due to the fact that MRIO and process-based models make different assumptions about steel production. Steel can be made exclusively from scrap using electric arc furnace technology, or predominantly from ore through the blast furnace/basic oxygen furnace route. The blast furnace/basic oxygen furnace route has more than twice the greenhouse gas emissions and energy requirements per kg of steel than the electric arc furnace route. The process-based data set is based on the global production mix between the two routes, which is significantly lower than the U.S. production mix, which is around 50 percent electric arc furnace and 50 percent blast furnace/basic oxygen furnace. Also, the process-based data reflects the energy mix of global steel production, while the MRIO data is U.S. specific.

Around 3 million of 38 million mattresses and box springs sold in the U.S. in 2010 were imports (ISPA 2012). The domestically produced shipments were made up of roughly 17 million innerspring mattresses, 2 million non-innerspring mattresses, and 16 million box springs (ISPA 2012). According to our previous calculations, goods from NAICS code 337910 (Mattress Manufacturing) worth $326 in 2010 producer price require 1,745 MJ of primary energy and generate cradle-to-gate greenhouse gas emissions of around 129 kg CO_2E. With an average unit having a 2010 producer price of $163, the cradle-to-gate greenhouse gas emissions of all 38 million mattress and box spring units were on the order of 2.4 million metric tons of CO_2E, while the cradle-to-gate primary energy requirements were around 33 billion MJ NCV. If we assume that California, which has 12 percent of the U.S. population, also has 12 percent of the U.S. mattress and box spring sales, we obtain the following estimates: In 2010, around 4.6 million mattress and box spring units were sold in California, the production of which generated cradle-to-gate greenhouse gas emissions of 294,000 metric tons CO_2E and required 4 billion MJ NCV of primary energy. All this data is summarized in Table 5.

Table 5: 2010 sales data, production energy, and greenhouse gas emissions for the U.S. and California.

	Sales in 10^6 units	Sales in 10^6 kg	GHGs in 10^6 tons of CO_2E	Energy in 10^9 MJ NCV
U.S. (reported data)				
Innerspring mattresses	17	-	-	-
Non-innerspring mattresses	2	-	-	-
Box springs (foundations)	16	-	-	-
Imports	3	-	-	-
Total for all units	38	1,034	2.4	33
California (estimated as 12 percent of U.S.)				
Total for all units	4.6	125	0.29	4

Product End-of-Life Management

Once mattresses and box springs reach the end of their useful lives, their most likely fate is to end up in a landfill (ISPA 2004). Primary energy demand and greenhouse gas emissions come from the transportation of the mattress and box spring from their pickup location to the landfill, as well as the construction, maintenance, and operation of the landfill itself. Additional greenhouse gas emissions come from chemical and biological degradation processes of the mattress and box spring materials in the landfill. The transportation and landfill data that have been used to calculate primary energy demand and greenhouse gas emissions from landfilling an average mattress and box spring set are listed in Appendix B. An estimated 69.3 MJ and 8.3 kg CO_2E are avoided whenever an entire set is reused instead of landfilled (see Table 7). Recycling diverts at least 85 percent of the mattress and box spring mass from landfill (DR3 2012). The estimated energy and greenhouse gas savings are 58.8 MJ and 7.1 kg CO_2E, around 15 percent less than in the mattress and box spring reuse scenario (see Table 7).

Mattress and box spring reuse and recycling requires transportation as well as reprocessing of the end-of-life products into secondary outputs. The energy demand and greenhouse gas emissions from the reverse logistics are estimated in Table 7. Currently, around three quarters of the collected end-of-life mattresses and box springs are first driven to a transfer station or other nearby collection site in a private vehicle, and the maximum length of a round-trip to collect each mattress and box spring set in a combination truck is 320km (200 miles) (DR3 2012). Together with energy and greenhouse gas data for light duty vehicles and combination trucks, this results in primary energy demand for reverse logistics of around 60 MJ and cradle-to-gate greenhouse gas emissions of roughly 4 kg CO_2E per mattress and box spring set.

Table 6: Disposal processes avoided by mattresses and box spring recycling or reuse (see Appendix B for inventory data sources).

Disposal processes	Mass in kg	GHG in kg CO_2E/kg	Energy in MJ NCV/kg	GHGs in kg CO_2E/set	Energy in MJ NCV/set
Transport of entire set to landfill	54.4	0.067	0.963	3.6	52.4
Transport of 85 wt% of set to landfill	46.24	0.067	0.963	3.1	44.5
Steel in landfill	27.2	0.012	0.305	0.3	8.3
Wood in landfill	5.44	0.085	0.308	0.5	1.7
Foam in landfill	5.44	0.089	0.314	0.5	1.7
Cover in landfill	5.44	0.089	0.314	0.5	1.7
Cotton in landfill	2.72	0.82	0.334	2.2	0.9
Remaining 15 wt% in landfill	8.16	0.089	0.314	0.7	2.6
Transportation and landfill of 85 wt% of set				**-7.1**	**-58.8**
Transportation and landfill of entire set				**-8.3**	**-69.3**

Table 7: Reverse logistics data and assumptions for all reuse and recycling scenarios (see Appendix B for inventory data sources).

Reverse logistics	% of units	Mass	Distance	GHG intensity	Energy intensity	GHGs in kg CO_2E/set	Energy in MJ NCV/set
Private vehicle	75%	N/A	8 km	0.285 kg CO2eq/km	4.3 MJ/km	1.7	25.8
Combin-ation truck	100 %	54 kg	320 km	0.14 kg CO2eq/t·km	2.0 MJ/t·km	2.4	34.6
Total						**4.1**	**60.4**

The reprocessing at the recycling facility is limited to manual disassembly of the mattresses and box springs, as well as manual separation and baling of the secondary material outputs. While several technologies for automated disassembly exist, they don't appear to be used in actual recycling operations. The shredding of end-of-life mattresses and box springs is discussed in literature, but appears to be too costly to be viable in practice (ISPA 2004). Shredding would have to be followed by automated material separation, which is also very costly. It is also noted that the innerspring units can jam shredders and wear their blades quickly. We thus conclude that, for the foreseeable future, reprocessing of mattresses and box springs will predominantly consist of manual labor assisted by some basic equipment such as forklifts and balers. As a result, the energy demand and greenhouse gas emissions from mattress and box spring reprocessing are minimal. Energy consumption data from the largest mattress recycling facility in the U.S. results in 8 MJ of primary energy per mattress and box spring set, and 0.55 kg CO_2E (DR3 2011).

Table 8: Primary energy demand and greenhouse gas emissions from mattress and box spring reprocessing (see Appendix B for inventory data sources).

Reprocessing	MJ/set	GHG intensity in kg CO_2E/MJ	Energy intensity in MJ/MJ	GHGs in kg CO_2E/set	Energy in MJ NCV/set
Electricity	1.2	0.164	2.52	0.20	3.1
Gas/LPG	4.2	0.082	1.16	0.35	4.9
Total				**0.55**	**8.0**

Reuse and recycling activities divert end-of-life products from landfill and generate secondary resources (Geyer & Jackson 2004). When these secondary materials, components, and products are used, the demand for new materials, components, and products is reduced. It is thus typically assumed that recycling and reuse avoids the production of equivalent amounts of competing primary resources. In mattress and box spring recycling there are secondary markets for the steel of the innerspring unit, the polyurethane foam, the cover (toppers), the cotton, and the wood. The steel and the polyurethane foam generate the most significant revenue streams, while the income from the cover and the cotton is at best modest. It appears that the wood is typically given away for free. The steel scrap is used for steel making.

One of the main uses of recycled polyurethane foam is rebond carpet cushion, while a variety of uses are reported for the cotton fibers (DR3 2012, Legget & Platt 2012). The net benefits of recycling are calculated as the environmental burdens of the additional recycling processes minus the environmental burdens of the avoided production processes. In the case of steel recycling we follow Worldsteel's open loop recycling methodology (Worldsteel 2011). We assume that recycled polyurethane foam and cotton displace their virgin counterparts. Mechanical cotton recycling has about one-third of the primary energy demand and greenhouse gas emissions of virgin cotton production (PE 2012, Ecoinvent 2007).

Based on this and data for mechanical recycling of polymers, we assume that mechanical polyurethane foam recycling, which also involves some bonding, requires 40 percent of the primary energy demand and greenhouse gas emissions of primary polyurethane foam production. It is unclear what the recycled covers are used for. The benefits of cover recycling are therefore calculated as avoided economic production from the NAICS sector 32615 (foam product manufacturing) of an amount equal to the revenue from recycled cover sales. No recycling benefit is calculated for the wood. Per mattress and box spring unit, the combined net primary energy savings are 735 MJ and the combined net greenhouse gas savings are 59.9 kg CO_2E (see Table 9).

Table 9: Primary energy and greenhouse gas emission savings from avoided primary production processes (see Appendix B for inventory data sources).

Net avoided burdens	Mass in kg	Net GHG savings in kg CO_2E/kg	Energy savings in MJ NCV/kg	GHGs in kg CO_2E/set	Energy in MJ NCV/set
Recycling					
Steel recycling	27.2	-1.51	-13.4	-41.1	-364
PU foam recycling	5.44	-2.8	-55	-15.1	-297
Cover recycling	5.44	N/A	N/A	-1.0	-13
Cotton recycling	2.72	-1.0	-22.7	-2.7	-61
Total				**-59.9**	**-735**
Component reuse					
Spring unit reuse	27.2	-2.16	-21.8	-58.8	-593
PU foam reuse	5.44	-4.74	-91.8	-25.6	-496
Cover recycling	5.44	N/A	N/A	-1.0	-13
Cotton recycling	2.72	-1	-22.7	-2.7	-61
Total				**-88.1**	**-1,163**
Mattress and box spring reuse (100 percent displacement)					
Mattress and box spring reuse	54.4			**-129**	**-1,745**
Mattress and box spring reuse (50 percent displacement)					
Mattress and box spring reuse	54.4			**-64.5**	**-872**

For mattresses, a viable alternative to the recycling of the steel innerspring unit and polyurethane foam is their reuse, given that they are in suitable condition. They are most likely rebuilt into mattresses and therefore used instead of new innerspring units and the polyurethane foams. If we assume that such component reuse avoids the production of new components, its environmental benefits are larger than those from recycling their materials. In this component reuse scenario, the cover, cotton, and wood are still recycled in the same manner as in the recycling scenario. Per mattress and box spring unit, the resulting net primary energy savings are 1,163 MJ and the resulting net greenhouse gas savings are 88.1 kg CO_2E.

The third and final end-of-life management route is the reuse of entire mattresses and possibly box springs, with varying degrees of renovation and refurbishment. Such mattress renovation and reuse is already taking place in the U.S., but the exact nature and extent of these activities is unknown, even though ISPA suggests in one estimate that the market for reused mattresses has a substantial size (ISPA 2004). Manufacturers of new mattresses and box springs are concerned that the resale of used products cannibalizes the sale of new ones (ISPA 2004). However, there is little evidence of this, and some industry experts think that buyers of refurbished mattresses would otherwise sleep on the floor (Agha 2008).

Mattress reuse also faces significant hygienic issues, such as bacteria, mold, mites, and bed bugs (PSI 2011, ISPA 2004). The energy and greenhouse gas implications of necessary chemical or heat treatments have not been included in this analysis. If the reuse of a mattress and box spring set would indeed avoid the production of a new set, like the mattress industry fears, the primary energy and greenhouse gas savings would be those of producing a new set, that is, on the order of 1,745 MJ and 129 kg CO_2E. If only half of the reused sets avoid the production of a new set, the energy and greenhouse gas savings would be around 872 MJ and 64.5 kg CO_2E. In other words, product reuse with 50 percent displacement has energy and greenhouse gas benefits that are similar to those of recycling (see Table 9).

We can now estimate the maximum annual primary energy and greenhouse gas savings for each end-of-life management route by multiplying the savings per mattress and box spring set with the total amount of mattresses and box springs that are disposed of each year. For the last 10 years California's population has grown by about 314,000 each year (U.S. Census 2012). We estimate mattress disposals in California by subtracting California's annual population growth from the estimated 2010 sales of 4.554 million units, which yields 4.2 million units, or 2.1 million sets. Table 10 shows the cradle-to-gate energy demand and greenhouse gas emissions of producing 2.3 million average mattress and box spring sets, as well as the potential energy and greenhouse gas savings from recycling them, reusing their reusable components, or reusing them in their entirety. For illustration purposes we show the product reuse results with the assumptions of 100 percent displacement and 50 percent displacement. The totals for 2.1 million sets shown in
are, of course, upper limits, since it is unlikely that any EPR measures would achieve collection rates close to 100 percent and it is equally unlikely that component or product reuse would be feasible for all collected mattresses and box springs. The results can easily be adjusted to any given set of collection rates and recycling and reuse yields.

Table 10: Energy and greenhouse gas results per mattress and box spring set and per 2.1 million sets.

	GHG emissions in kg CO_2E/set	Energy demand in MJ NCV/set	GHGs in tons CO_2E per $2.3 \cdot 10^6$ sets	Energy in GJ NCV per $2.3 \cdot 10^6$ sets
Production & landfill				
Production	129	1,745	273,503	3,699,714
Landfill	8	69	17,597	146,928
Total	137	1,814	**291,101**	**3,846,643**
Recycling				
Avoided landfill	-7	-59	-15,053	-124,667
Reverse logistics	4	60	8,755	127,974
Reprocessing	1	8	1,155	16,861
Avoided production	-60	-736	-126,982	-1,560,177
Total	-62	-726	**-132,125**	**-1,540,009**
Component reuse				
Avoided landfill	-7	-59	-15,053	-124,667
Reverse logistics	4	60	8,755	127,974
Reprocessing	1	8	1,155	16,861
Avoided production	-88	-1,163	-186,678	-2,465,918
Total	-90	-1,154	**-191,821**	**-2,445,750**
Mattress and box spring reuse (100 percent displacement)				
Avoided landfill	-8	-69	-17,597	-146,928
Reverse logistics	4	60	8,755	127,974
Avoided production	-129	-1,745	-273,503	-3,699,714
Total	-133	-1,754	**-282,346**	**-3,718,669**
Mattress and box spring reuse (50 percent displacement)				
Avoided landfill	-8	-69	-17,597	-146,928
Reverse logistics	4	60	8,755	127,974
Avoided production	-65	-873	-136,752	-1,849,857
Total	-69	-881	**-145,594**	**-1,868,811**

Comparing the differences between the different end-of-life management routes, however, yields some important insights. First, the greenhouse gas benefits of mattress and box spring recycling are 45 percent of the production and landfill burdens, that is to say, very significant. Reusing instead of recycling innerspring unit and polyurethane foam increases those benefits to 66 percent of the production and landfill burdens. In other words component reuse offers a significant improvement over material recycling. While the reuse of a whole unit would offset almost the entire production and landfill burdens if it displaced the production of a new unit, this appears very unlikely. Assuming that only 50 percent of the reused units displace new ones reduces greenhouse gases saving to 50 percent of the production and landfill burdens, which is similar to those of recycling. According to some industry experts even 50 percent displacement seems highly unlikely (Agha 2008).

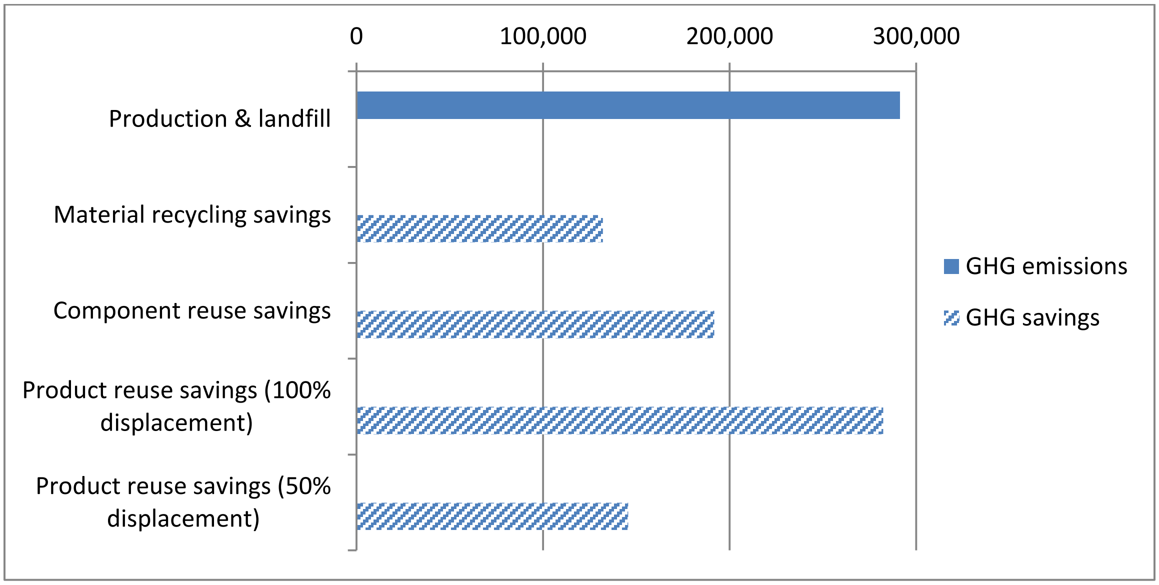

Figure 3: Greenhouse savings (in tons of CO_2E) of material recycling, component reuse, and product reuse for 2.1 million mattress and box spring sets, compared to the greenhouse gas emissions of producing and landfilling 2.1 million mattress and box spring sets.

All this suggests that EPR measures should aim at maximizing collection rates on one hand, and material recycling and component reuse yields on the other. The environmental benefits of product reuse hinge on the ability to displace the manufacturing of new products, which is highly uncertain. This also creates a dilemma for the mattress industry, since it is, of course, in its economic interest to minimize such displacement. On the other hand, product reuse without displacement may still have significant social value by making mattresses affordable to very low-income households.

EPR strategies for mattresses and box springs

Collection and reprocessing

The main objective of EPR initiatives is to increase manufacturers' financial and operational responsibility for the take-back, recycling, and final disposal of their products (Geyer 2004). In the previous section we concluded that mattress and box spring recycling and component reuse generates significant energy and greenhouse gas benefits. We also learned that the vast majority of end-of-life, or end-of-use, mattresses and box springs are not collected for recycling and therefore likely to end up in landfills. The most important part of any EPR initiative for mattresses and box springs should therefore be to increase the end-of-life or end-of-use collection rate. In fact, setting minimum collection rates and recycling yields is a common part of many EPR policy measures (see e.g. Europe's ELV and WEEE Directives). While collection rates are extremely low in California and the rest of the U.S., the recycling yields achieved by the recyclers are already 85 percent or higher. We think that only product redesign would be able to push recycling yields much higher than they already are.

Because recycling operations are mostly manual, their environmental impact is minimal. As a result, the environmental impacts from mattress and box spring collection are more than five times higher than those of reprocessing. While the collection burdens are over an order of magnitude smaller than the avoided primary production burdens, EPR initiatives should make sure that collection is done as efficiently as possible. This essentially means to establish or support a collection and recycling infrastructure that uses efficient transportation modes, achieves high utilization rates, and keeps distances low, especially for low-efficiency transportation modes, like light duty vehicles. Picking up the old mattresses and box springs when new ones are delivered by retailers would be one obvious way to achieve high collection rates and efficient reverse logistics.

Product design

An additional objective of EPR initiatives is to provide incentives to the producers to redesign their products in order to improve the operational, economic, and environmental performance of their end-of-life management. In the previous section we concluded that mattress and box spring recycling and component reuse generates significant energy and greenhouse gas benefits. We are therefore interested in identifying redesign opportunities that would increase the operational and economic feasibility of recycling and component reuse and increase the recycling and reuse yields.

An important aspect of both recycling and component reuse is the disassembly of the mattresses and box springs into their individual components. Ease of disassembly affects the costs of recycling and reuse operations as well as their yields, which, in turn, affects the revenues of the recyclers. Mattress and box spring producers, as well as their suppliers, should thus be encouraged to consider end-of-life disassembly in the product and component design process. Overall it appears that mattress and box spring disassembly is already fairly easy, but there might be room for improvement, such as alternative joining and fastening technologies instead of staples. This should also increase the value of the wood, whose reuse and recycling is currently hampered by the staples. The reuse of the innerspring unit and the polyurethane foam might be facilitated by considering designs that increase the protection of those two components from in-use damage that would make reuse unfeasible.

The one mattress component that currently does not have a secondary market is the insulator pad, which makes up a considerable part of the non-recycled material fraction that recyclers send to landfill. It would thus be environmentally beneficial to redesign the insulator pad in a way that makes it valuable as a secondary material or component once the mattress reaches the end of its life. Overall, redesigning mattresses and box springs for improved disassembly and recyclability should be able to increase their recycling yields from currently 85 percent to close to 100 percent. Redesign for component reuse might be able to increase the component reuse yield, which would further increase the energy and greenhouse gas savings from mattress and box spring take-back.

Incentives from EPR programs would only be one of many drivers for product redesign and new product development, many of which are directly related to maintaining or growing the product market and maintaining or gaining market share. These other drivers may lead to product designs that make end-of-life management more challenging rather than easier. One example would be the widespread diffusion of electronic devices in mattresses and box springs.

Not all EPR measures generate real incentives for product redesign, such as financial rewards that accrue only to those companies that increase the reusability or recyclability of their products. However, the question of which EPR program structures and details create what type and strength of redesign incentive is outside the scope of this study. This study only addresses the question of which product redesigns would help to increase end-of-life collection rates and recycling and reuse yields.

Labor implications

In 2010, North America's largest mattress recycler processed about 55,000 mattresses and 55,000 box springs with a staff of 15 fulltime employees (DR3 2012). This translates into one fulltime employee to process around 7,300 units (mattress or box spring) per year. We estimate that 4.2 million units of either mattresses or box springs are discarded in California every year, but less than 5 percent are recycled. This means that currently fewer than 30 fulltime employees work in mattress recycling. The recycling of all 4.2 million units would require around 575 fulltime employees. Additional jobs would be created in the industries that process the secondary outputs of the mattress recyclers, i.e. the steel scrap, the polyurethane foam, the cotton, the cover (toppers), and the wood. EPR measures that lead to the collection and recycling of 4.2 million mattress and box spring units per year are therefore estimated to generate in the order of 1,000 jobs, most of which are entry-level positions.

As we described earlier, the environmental benefits of reuse and recycling activities come from avoided landfill and, more importantly, from displaced primary production activities. So, while increased collection, reuse, and recycling of mattresses and box springs will create jobs in those sectors, avoided landfill and primary production activities could potentially reduce the number of jobs in the affected sectors. However, while reuse and recycling activities are very labor-intensive, activities like landfill operation, steel, foam, and cotton production are highly automated and have very high labor productivity. We thus estimate that the labor loss from displaced economic activities due to increased collection, reuse, and recycling of mattresses and box springs would be negligible.

Conclusions

Currently, most end-of-life mattresses and box springs are landfilled or dumped illegally, even though at least 85 percent of their mass can be readily reprocessed into useful secondary resources. Current reprocessing practices focus on material recycling, which is estimated to offset roughly 45 percent of greenhouse gas emissions from production and landfill of mattresses and box springs. About two-thirds of the greenhouse gas benefits come from the recycling of the steel innerspring unit, and another 25 percent from the recycling of the polyurethane foam. Reusing instead of recycling the innerspring unit and polyurethane foam would increase the offset to around two-thirds of the greenhouse gas emissions from the production and landfilling of mattresses and box springs. The reuse of entire mattresses and box springs faces significant hygienic issues and would also only generate significant greenhouse gas savings if the reused products would successfully compete with new ones, which is not in the economic interest of original mattress and box spring manufacturers.

The current economics of mattress and box spring recycling are not sufficient to lead to their widespread and large-scale recovery. It is estimated that around 4.2 million mattresses and box springs reach the end of their lives in California every year. EPR measures that lead to the collection and recycling of 4.2 million mattress and box spring units per year are estimated to generate in the order of 1,000 jobs and greenhouse gas savings of between 130,000 and 190,000 metric tons.

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Appendix A: Process versus Economic Input-Output LCA

There are two major methods for performing Life Cycle Assessment (LCA): process and economic input-output (EIO-LCA). Process LCA uses a model of the sequence of processes involved in a product's life cycle to estimate environmental impacts.

The life cycle impact is calculated as the sum of the impacts of all the individual processes. Process LCA enables very accurate modeling of individual processes, but suffers from the fact that for practical reasons and data limitations only the most important processes of a product life cycle are included, while the rest is excluded. This is also called the cut-off problem in process LCA.

In contrast, EIO-LCA uses a standard input-output model of the entire economy which has been extended with estimates of sector-wide environmental interventions. Using the EIO model avoids cut-off problem 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. 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 (Lenzen 2000). 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 & Huppes 2002). Input-output LCA is used to account for upstream or "supply chain" impacts for which sectoral averages are an appropriate proxy, and process LCA is used to describe detailed processes pertaining to the product system under study where greater specificity is needed than input-output LCA provides.

Appendix B: Sources of Process Inventory Data

Table 11: Unit process inventory data used in this case study.

Process	Reference year	Data source
Steel wire rod (Global production mix)	2007	World Steel Association
Wood (pine, 40% water content)	2010	PE Professional Database
Polyurethane flexible foam	2005	Plastics Europe
Polyester fiber	2010	PE Professional Database
Cotton fiber (U.S.)	2001	Ecoinvent v2.2
Transport to landfill	2010	Own survey
Steel: Inert material (0% water) to sanitary landfill	2000	Ecoinvent v2.2
Untreated wood (20% water) to sanitary landfill	2000	Ecoinvent v2.2
Foam & Cover: Plastics mixture (15.3% water) to sanitary landfill	2000	Ecoinvent v2.2
Cotton: Newspaper (14.7% water) to sanitary landfill	2000	Ecoinvent v2.2
Remaining 15 wt%: Plastics mixture (15.3% water) to sanitary landfill	2000	Ecoinvent v2.2
Private vehicle	2005	U.S. LCI
Combination truck	2005	U.S. LCI
Mattress and box spring recycling	2011	DR3 Recycling
Electricity production and transmission (WECC)	2005	U.S. LCI
Propane/LP gas production and combustion	2005	U.S. LCI
Value of steel scrap	2007	World Steel Association
Cotton fibers from recycling clothes	2010	PE Professional Database

More information about the data sources is available on:

PE databases: http://www.gabi-software.com/america/databases/gabi-databases/

Ecoinvent database: http://www.ecoinvent.ch/

U.S. LCI database: http://www.nrel.gov/lci/

Plastics Europe data: http://www.plasticseurope.org/plastics-sustainability/eco-profiles.aspx

World Steel Association data: http://www.worldsteel.org/steel-by-topic/life-cycle-assessment