The role of using carpet as a fuel in carpet recovery system development

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Systems and technologies to recover and process post-consumer carpet and post-industrial carpet by-products represent an exciting opportunity to reduce fossil fuel consumption and the production of virgin materials derived from fossil resources. An important concern for the economic health of these systems is the development of outlets for all the materials that are collected. This paper examines the use of discarded carpet and by-products as an alternative fuel as one option for fractions of the collected stream that do not have outlets as economically viable recycled commodities. Carpet has different face fibers, backings and grades that leads to variations in its value as a fuel. This paper develops a model for the heat of combustion of carpet, and a value of 8,800 btu/lb lower heating value is found for a representative carpet construction. This compares well with the limited experimental data on carpet combustion from the literature. For comparison the values of the lower heating value for bituminous coal is 11,230 btu/lb and natural gas 20,267 btu/lb. The emissions of CO_2 from thermal processing of carpet are estimated at 194 lb CO_2/mmbtu. For comparison the values for bituminous coal and natural gas are 208 and 119 lb CO_2/mmbtu respectively. This means that carpet is competitive with coal from a carbon emissions perspective, but emits more CO_2 than natural gas. However, of key importance is the second use of the discarded carpet which avoids (i.e., displaces) the need for these virgin fossil fuels and materials derived thereof. The energy required to transport and convert discarded carpet into a fuel is negligible compared to its eventual thermal energy. The paper concludes with a more detailed discussion of the role of discarded carpet as a fuel from a recycling systems perspective and presents a more detailed analysis of the CO_2 emissions for a collection and fuel generating system in Georgia.

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Introduction

This report examines the value that discarded carpet has as an alternative fuel. It does this quantitatively from the perspective of the energy and emissions that are generated by thermal processing of carpet compared to the fuels most likely to be displaced by its use, coal and natural gas. However, it is extremely important to recognize that the use of carpet as a fuel could have very beneficial impact on the overall carpet recycling system, irrespective of its relative fuel value compared to other fossil fuels. The key to successful recycling is deriving the highest possible value from all components of the incoming recovered carpet stream, and use of some components of the recovered stream as an alternative fuel is a viable strategy to help drive the total volume of the system and maximize the total amount recovered.

Carpet Composition

Carpet is constructed from a combination of layers of polymers such as latex, polyesters, polypropylene and nylon and in some cases inorganic fillers. At this point the polymers are almost all fossil hydrocarbon derived. The resulting composite material therefore has value from a recycling perspective due to its polymer content, but this is diluted by the presence of inorganic fillers such as calcium carbonate from crushed rock. Recovered carpet has a variable composition, partly due to the inherently different types of carpet that are manufactured and partly because during its use it will have seen different soiling conditions. The level of soiling in the discarded carpet will determine the degree of that soil or other inert materials are present during thermal processing which can dilute the fuel value. The major architectural components of carpet are listed below in Table 1 along with the typical materials that are used to make these components.

Carpet Architectural Component	Typical Materials used	Representative % Composition (mass of new carpet)
Face Fiber	Nylon 6, Nylon 6,6, polyester (PET), polypropylene (PP)	45-50%
Primary Backing Fabric	Polypropylene	4-6%
Backing Polymer	Styrene-butadiene latex	8-10%
Backing Filler	Calcium carbonate $CaCO_3$	30-40%
Secondary Backing Fabric	Polypropylene	4-6%

Table 1 Carpet architectural components with typical materials and representative compositions.

Heat Available from Carpet Combustion

The variation in carpet composition will lead inevitably to differences in the heat of combustion and so it is useful to have a theoretical model of the heat available from thermal processing of carpet based on the heats of combustion of the individual components. It is extremely unlikely that the observed heat of combustion will be substantially (+/- 25%) different from this theoretical calculation.

The most obvious sources of variation are the differences in the construction, and particularly whether the face fiber is made of a polyolefin, polyester or polyamide, and the relative weight of the face compared to the backing. We can use the estimates of the weight of these different components along with their heats of combustion, listed in Table 2 to find theoretical values of heat of combustion in Table 3. The values in the table have been found from two different sources indicated with superscripts. Several polymers values were found from both sources to confirm that they were consistent, the values are different by less than 10%. There is limited public data available for thermal processing of carpet and the theoretical calculations are compared to this in Table 4.

Carpet Material	Heat of Combustion (kJ/kg H2O(v))	Heat of Combustion (btu/lb H2O(v))
Nylon 6,6 (N66)	-32000[1]	-13800
Polypropylene (PP)	-43200[1]	-18600
Polyethylene (PE)	-46500[1]	-20000
Polyurethane	-45000[1]	-19300
Polyvinyl Chloride (PVC) Flexible	-15700[1]	-6700
Styrene-butadiene Copolymers (SBR)	-44000[1]	-18900
Polyethylene terephthalate (PET)	-20500[2]	-9500
Nylon 6 (N6)	-33100[2]	-14200
Polyethylene (PE) film	-43500[2]	-18700
Polyethylene (PE)	-43600[2]	-18700
Polypropylene (PP) film	-43600[2]	-18700
Calcium Carbonate	1800[2]	800

Table 2 Heats of combustion of selected materials found in carpets, calculated from heats of formation, with water as a vapor, negative values indicate that heat is released.

[1]Values taken from Nuclear Regulatory Commission, Estimating the Burning Duration of Combustible Solids, Chapter 8.

[2]Values calculated from heat of formation data presented by Purdue School of Aeronautics and Astronautics (2010).

Architecture	Carpet 1	Carpet 2	Carpet 3	Carpet 4
Face Fiber	N6 45%	N66 45%	PP 45%	PP 40%
Primary Backing Fabric	4% PP	4% PP	4% PP	4% PP
Backing Polymer	8% SBL	8% SBL	8% SBL	10% SBL
Backing Filler	39% $CaCO_3$	39% $CaCO_3$	39% $CaCO_3$	42% $CaCO_3$
Secondary Backing Fabric	4% PP	4% PP	4% PP	4% PP
Heat of Combustion (btu/lb clean carpet)	-9,100	-9,200	-11,100	-10,600
Heat of Combustion (20% soiled)	-7,600	-7,700	-9,200	-8,800

Table 3 Theoretical Calculation of Carpet Heat of Combustion for different face fiber types, and an assumed inert soiling level of 20%, negative values indicate that heat is released.

Source of Carpet Combustion Estimate	Value (btu/lb)
Carpet Combustion (Konopa 2008)	-7400
Carpet Fines Combustion (Lemieux 2004)	-12600
Carpet Backing Combustion (Lemieux 2004)	-5600
Carpet Combustion (Morris 2008)	-13900

Table 4 Comparison of Carpet Combustion Values from different sources

The paper by Lemieux et al. (2004) used the material from DuPont's process of generating a fines and backing fraction through its recycling process that was running in Calhoun, GA, at this time. If these values are combined in proportion to how much fines (25%) and backing (75%) were thought to be generated by the process, a value of -7300 btu/lb would be found. The theoretical values are consistent with the value from Konopa (2008). The value from Morris (2008) was taken from USEPA’s Waste Reduction Model (WARM) technical documentation, EPA (2003) and seems high. Closer examination of the WARM documentation shows that the composition of carpet assumed for the calculations is 100% nylon. The table of values for pure components, nylon 6 and nylon 6,6, shows that the value in Morris (2008) is consistent with this assumption.

A key component of some carpet construction is the calcium carbonate filler, this has two significant impacts on the value of carpet as a fuel. First, it reduces the fossil derived components in the carpet, and hence the overall heat of combustion. Second, during a combustion process the calcium carbonate will convert to calcium oxide, this conversion consumes energy (it is endothermic) and it releases CO_2. Thus it further reduces the energy available for use and releases CO_2. This is essentially the same reaction that happens in a cement kiln. The release of carbon dioxide can be reversed at lower temperatures but it is a relatively slow process. However, if the material is then used as in a cement kiln as an input material, this additional CO2 release would not be any different from that seen in the regular cement making process. Furthermore, thermally treated material may also see use as part of inorganic fillers in carpet backing.

Overall, the theoretical heat of combustion shows reasonable agreement with the experimental values of Konopa (2008). A component that has been left out of this calculation is any flame retardant that might have been added, such as an aluminum trihydrate, $Al(OH)_3$. This would have a similar impact to the calcium carbonate, and would displace it as another component of the filler. For carpets with different face weights and filler levels the theoretical model could be used to make predictions. Similarly if a fraction of the carpet is recovered by a process, such as shearing the face fiber, the residual fraction could have its heat of combustion estimated by this model.

In summary it is expected that recovered carpet will have significant (+/- 25%) variation in heat of combustion based on the level of soiling and exact carpet composition. Carpets with higher polymer face content (residential carpets) will have higher heat of combustion and those that have polypropylene face fiber will have the highest, and these are also the carpets with the lowest value in terms of their recycled face fiber.

Comparisons to other fuels

The two fuels that are most likely to be displaced by carpet are coal and natural gas. The reason that coal might be displaced is that both carpet and coal are solid fuels and therefore require similar handling. The modifications required to a fuel system using recovered carpet could therefore be less than that required to displace natural gas. Secondly, coal is widely used as a fuel in cement kilns where recovered carpet could be used because of its calcium carbonate content. A reason that carpet could displace natural gas is that new facilities at carpet mills that are constructed to take recovered carpet as a fuel are likely to be replacing natural gas boilers.

A key issue is how to compare the different fuels in terms of their environmental impact. All fuels have three significant impacts. The first is the impact of resource extraction, e.g., coal mining, natural gas wells, or oil exploration. The impact of resource extraction should not be underestimated, not only because of the on-going environmental impacts of the extraction, but also because of the risks associated with the extraction, such as coal mining accidents, natural gas pipeline leaks, or oil spills. The quantity of fuel that carpet represents is relatively small and so will not significantly change the amount of mining or drilling activity, but extracting a second use out of the fossil resource is desirable. The second impact is in the production of the fuel, or fuel supply chain. The energy used for producing coal or natural gas is a relatively small percentage of its fuel value, and carpet will turn out to be very similar. Lastly, and often the focus of attention is the impact of the emissions from combusting the fuel. For coal the major impacts are carbon dioxide, nitrogen oxides, sulfur oxides, particulates and mercury. For natural gas they are mainly the methane associated with the production and distribution and the carbon dioxide emissions. The next sections quantify the amounts of CO2 and NOX emissions from carpet as well as review the evidence for other emissions from carpet combustion.

Carpet Emissions

Carpet has no sulfur compounds or mercury in its construction. Contamination from these substances through normal carpet use is unlikely to be present in recovered carpet since any significant spills would require clean up and, potentially, required to be disposed through a regulated process. Therefore the main emissions from carpet are from the carbon and any nitrogen content. Potential emissions of non-halogenated dioxins or furans could result from incomplete combustion or combustion at intermediate temperatures, along with particulate emissions. Non-halogenated dioxin emissions could occur from any fuel, and chlorinated dioxins only when chlorine-containing compounds (e.g., polyvinyl chloride) are combusted in inappropriate combustion temperature ranges. Carpet has been combusted in a cement kiln and in a rotary kiln and dioxin and furan emissions monitored (Lemieux 2004, Realff 2007, Konopa 2008) In none of these cases were these dioxin or furan emissions significant. Particulate matter emissions were also measured for typically regulated particle sizes (10 microns or less particle size) and found to be well below regulatory limits.

Carbon Dioxide Emissions

Morris (2008) chooses CO2 emissions and other greenhouse gas (GHG) emissions, as the basis for comparing carpet as an alternative fuel to other fuels. Coal does not have a single composition, and its carbon content can vary significantly from 60-95% of the mass. The coal from a specific mine or mining region does tend to have relatively stable composition and so the U.S. Energy Information Administration (EIA) has produced information about the specific btu and carbon emissions of coals going to specific regions.

Natural gas has some variation in composition, but this is less significant in terms of carbon content than coal. The typical components are methane and other low number carbon alkanes such as ethane, propane and butane. The carbon dioxide emissions factors are available from the EIA (Hong 2010) but these are for higher heating values and it is assumed that lower heating values (LHV) will be about 5% lower for coals and 10% lower for natural gas. Representative values for the heating value of coal and the CO2 emissions for coal and Natural Gas is given in Table 5 below. The carpet values are derived from the transportation and a size reduction process; transportation numbers for coal and natural gas taken from the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model, Wang (2008), coal and natural gas emissions EIA (2007) and Hong (2010).

Quantity	Coal	Natural Gas	Carpet to boiler clean	Carpet to cement kiln
Energy Content HHV	12764 btu/lb	20267 btu/lb	10,600 btu/lb	10,600 btu/lb
Carbon Content	76%	75-80%	41% organic	41% organic
gCO2/mmBtu HHV	208 lb/mmBtu	119 lb/mmbtu	194 lb/mmbtu	174 lb/mmbtu
Supply chain Energy btu/btu	0.02	0.07	0.01	0.04

Table 5 Comparison of coal, natural gas and carpet as fuels along the dimensions of energy and CO2 emissions and the energy required to produce the fuel.

These data indicate that carpet falls somewhere between coal and natural gas as a fuel regarding CO2 emissions. It is substantially less "energy dense" on a per lb basis, because of typical polymeric material available for combustion and the fraction of inorganic backing filler. However, the filler does contribute marginally to the overall carbon dioxide emissions, about 20 lb/mmbtu around 10% of the total. The final ratio of energy to carbon emissions for carpet is not very different from fossil energy sources.

This suggests that the displacement of natural gas as a fuel by carpet could result in higher carbon dioxide emissions of approximately 75 lb CO2/mmbtu. Similarly if carpet displaces coal as a fuel then the emissions will be roughly the same, differing by 14 lb/mmbtu or less than 10% of the total which makes it within the margin of error. If it displaces coal as a fuel in a cement kiln and the emissions from the calcium carbonate are attributed to the product, then carpet does improve over coal because the inorganic emissions are no longer allocated to the fuel, this makes it about 34 lbs/mmbtu improved over coal. Later in this paper, in the section CO2 Emissions Comparison - carpet vs. coal~~CO2 Emissions Comparison - carpet vs. coal~~ a more detailed analysis of carpet versus coal emissions will be described, but the conclusions are still the same.

Nitrogen Oxide Emissions

Nylon carpet has a fraction of nitrogen as part of its composition, approximately 12% of the nylon fiber is nitrogen, which translates to about 6% of the final carpet being nitrogen compared to 0.7% for coal. This has been an area of concern for the thermal recycling of carpet because of the potential for this nitrogen to make it into nitrogen oxides, NO, N2O and NO2. The major source of nitrogen oxide emissions from combustion is the conversion of the nitrogen in air to those oxides because of temperature excursions in the combustion reaction, so-called "thermal NOX". Fuel nitrogen conversion is often much less than stochiometric, and much of the fuel nitrogen goes to N2 because there is insufficient oxygen present at the point of combustion to convert to oxides. The evidence from trials in a controlled combustion environment (Lemieux 2004, Konopa 2008) and from an industrial trial (Realff 2007) is that although the nitrogen emissions from combustion of carpet could be above those of natural gas, the most important factor is the control of combustion temperatures, rather than the nitrogen in the fuel. In the industrial trial at a cement kiln there was essentially no increase in NOX observed over the duration of the trial (Table 6 below). The Table indicates that first, for both coal and carpet co-fire, the emissions are significantly below the limits allowed for both NOX and SOX. Second, the nitrogen oxide emissions are not significantly different for carpet relative to coal. Third, the SOX emissions for carpet do appear higher than those for coal. This was thought to have occurred because the temperature profile in the kiln was not optimized for carpet and led to too hot conditions at the flame end of the kiln, and hence a shift in the equilibrium of the oxidation of the sulfur in the feed towards SO_2 and away from the solid SO_3^- components. However, there was significant variability in the SO_2 results from run to run, for example during some calibration and testing runs prior to the tests conducted in November 2010, the ppm vd of SO_2 was as high as 2129 and as low as 39, this variability is not due to the instrumentation but the kiln conditions, which take a long time to stabilize and which can be strongly affected by the exact oxidizing conditions.

Test data	Units	Coal Only 11/9-11/10	Coal Only 11/10	Coal Only 11/11	Carpet Co-Fire 11/8	
NOx	ppmvd	1177	805	857	884	884
NOx Emission Rate	Lb/hr	452.3	285.1	323.8	355.7	339.2
NOx Emission Rate	Lb/ton clinker	6.07	4.06	4.40	4.84	4.62
NOx Allowed Emission Rate	Lb/ton clinker	8.83	8.83	8.83	8.33	8.33
SO_2 Conc.	ppmvd	19.7	20.5	16.9	42.1	42.1
SO_2 Conc. Allowed	ppmvd	500	500	500	500	500
SO_2 lb/hr	Lb/hr	15.15	14.54	12.82	33.95	32.38
SO_2 lb/ton clinker	Lb/ton	0.203	0.207	0.174	0.462	0.441

Table 6 Carpet fuel emissions from a cement kiln, Lehigh Cement, Evansville PA.

Summary - Carpet as an alternative fuel

Overall, recovered carpet as an alternative fuel is intermediate between coal and natural gas. It has a heat content that is similar to that of coal but has somewhat lower CO_2 emissions because its carbon content is typically less on a percentage basis than that of coal. It may contain a significant amount of inorganic filler, calcium carbonate, that increases its CO_2 emissions and reduces its heat value and its heat value can be further diluted by soiling during use. From an emissions perspective this would be of limited concern if the carpet were used in a cement kiln or similar environment where the calcium carbonate in the carpet is replacing raw material. Greenhouse gases emissions and other environmental emissions such as mercury, are not significant and, overall, carpet represents a very clean combusting fuel whose fibrous nature leads to good behavior in combustion environments. If anything, characteristic of carpet combustion is that it is too good a fuel and tends to lead to high combustion temperatures, if not properly controlled.

The evaluation of carpet as an alternative fuel depends on which impacts are focused upon. If CO_2 emissions per unit of energy produced are the sole concern then carpet does not look as attractive compared to natural gas. However, if the depletion of fossil fuels is considered, then getting the second use from the embodied energy of the hydrocarbons in carpet rather than generating any new joules of fossil energy is beneficial. There is no reason to forgo the opportunity to use the carpet as an alternative fuel and dispose of it into a landfill. This argument is strengthened when the carpet that is to be used as an alternative fuel is a by-product of collecting carpet for recycling, where the investment in the transportation has already been made. The overall carpet recovery system will be significantly strengthened, from an economic perspective, by allowing a certain carpet diversion to alternative fuel uses. The markets for the commodities that can be generated from certain face fiber types, particularly mixed fiber types, and backing materials can be limited. Avoiding or lowering disposal costs, can make a positive difference to the overall carpet recovery economics. These systems issues will be the focus of the rest of this paper.

Recovery system discussion - connections to carpet as an alternative fuel.

At the core of the benefits of recovering carpet lie two important questions that are unrelated to the actual recycling process itself and its associated transportation.

What is the recovered carpet material displacing? There are two sorts of activities that could be displaced, 1) the production of materials and, 2) the production and consumption of fuels for energy. This is critical because it is this material creation, or any displaced fuel, that is avoided and hence the benefit from recycling is determined by it. Hence it is important to estimate the cradle-to-gate impact of the displaced material or fuel. This is critical because the benefit from the avoided activity is the supply chain in the case of the material, and the supply chain and the fossil carbon use and release in the case of a fuel.

In the case of displacing a material, or materials, what is avoided is the resource, the extraction of the resources and the cradle-to-gate supply chain that creates the materials from the resources. If the emission of greenhouse gas (GHG) expressed in carbon dioxide equivalents (CO2 Eq) is the measure being computed then the fate of the material that is being displaced must be considered. If the material would have been landfilled, or recycled, then the GHG emissions associated with the fossil resource itself cannot be considered avoided, because it would never have been released. If fossil resource use is the measure, then both the supply chain energy and the fossil energy of the resource should be considered avoided. Instead, what is substituted for the displaced materials is the supply chain of recovering and reprocessing the recovered carpet.

In the case of displacing a fossil fuel, what is avoided is the use of the resource itself, the supply chain to produce the fuel, and the emissions from the fuel combustion. Instead, what is substituted for the displaced materials is the supply chain of recovering and reprocessing the recovered carpet and then the GHG emissions of the carpet from combustion. There is no additional fossil resource use because that has been assumed to be accounted for in the first use of the resource as carpet.

In both of these cases the assumption is that carpet is essentially inert in a landfill and that therefore there are no GHG emissions from the carpet itself in the landfill. Thus, in the case of using carpet as a fuel, the GHG emissions of carpet combustion must be counted, because otherwise the carbon would have been sequestered in the landfill. The supply chain of making the carpet in the first place should not be counted against its use as a fuel, since this supply chain was required to make the carpet and achieve its function as a floor covering.

The above discussion follows the principle of "system expansion" for life cycle assessment. We are expanding the system such that the goals of the systems, and the functional units provided, are the same. The system is expanded to include the forward elements of the supply chains for the materials and fuels that carpet recycling is displacing.

The second important question is what is the volume and mix of the activities that are undertaken? This is a subtle issue that relates to the economics and emissions of the recovery activities as a whole. In other words, it might be the case that a specific activity, such as using a fraction of the recovered carpet as a fuel, has higher impact than using a fossil based fuel, but that without undertaking this activity the amount of carpet that is recycled into other materials might be reduced, and therefore the overall change in environmental impact would be less. Or, it might be that the mix of activities that can be undertaken has an overall lower environmental burden, if some portion of the carpet is used as a fuel rather than if the use as a fuel was excluded.

The idea of "system expansion" was introduced above as a way to compare alternatives where the immediately created functional units were not the same. The system is expanded to include the additional functional units so that the boundaries, goals and functional units of the two alternative systems are the same. In Table 8 lists some of the recovery options being pursued today by different carpet companies and entrepreneurs.

Recovery Activity	Commodities Generated	Commodities Displaced
Carpet Shearing-A	Baled Nylon Sheared Material Shoddy Fiber Calcium Carbonate rich stream	Nylon Engineered Resins Nylon Fiber Shoddy Fiber Virgin calcium carbonate
Carpet Shearing-B	Baled Nylon Sheared Material "carpet carcass" (i.e., backing)	Nylon Engineered Resins Nylon Fiber Coal for cement kiln
Carpet Shearing-C	Baled Nylon Sheared Material Ground PVC Backing	Nylon Engineered Resins Virgin PVC Backing
Depolymerization	Caprolactam Energy Calcium carbonate filler	Caprolactam Natural Gas Virgin calcium carbonate filler
Carpet Separation-A	Nylon Pellets Polypropylene Pellets Calcium carbonate filler	Nylon Engineered Resins Virgin Calcium carbonate filler
Carpet Separation-B	Nylon face fiber Polyolefin backing	Caprolactam Nylon 6 polymer Virgin polyolefin backing
Carpet Alternative Fuel-A	Energy	Coal or Natural Gas
Carpet Alterative Fuel-B	Energy Calcium carbonate filler	Coal or Natural Gas Virgin calcium carbonate

Table 7 Recovery system options for carpet.

What should be noted about each of these recovery pathways is that there is a high value component, such as nylon engineered resins or caprolactam and other lower value materials. Table 8 shows the energy in the recycled commodities that are potentially displaced by recycling carpet. The table has two columns of energy values. The first, Process Energy in mega joules per kilogram (MJ/kg) represents the energy required to take the natural materials, crude oil, natural gas, unmined calcium carbonate etc., and turn them into the commodities that would be displaced by recycled materials. The second column shows the Feedstock Energy, this is the fossil energy embedded in the materials due to the crude oil and natural gas that is in the material itself. This is a substantial fraction of the overall energy, and reflects the fossil resources that will not be mined to make the material. The allocation and reconciliation of any emissions associated with the feedstock energy as a "credit" to the recycling activity is not considered since it would not be released.

The recovery of this higher value component has to be accompanied by the creation of other commodities because of the composition of carpet. There is no notion that the system should be penalized for generating these lower value commodities such as fillers, even though mining calcium carbonate would be cheaper and less energy intensive. In the case of the carpet these materials are physically connected, whereas in the overall recovered carpet stream the carpets are physically mixed. The ability to reuse components of the mixed stream as energy as opposed to materials follows the same principle. Even though we may be able to find fuels that have a lower impact than carpet as an alternative fuel, the system has a lower overall impact because of the creation of other higher value commodities. When other activities for recovering higher value from the carpets that are currently not feasible due to complexity or scale, become feasible, then these will most likely become adopted, provided the growth of the system is not constrained by lack of investment.

Material	Process Energy (MJ/kg)	Feedstock Energy (MJ/kg)	Data Source
Nylon 6,6	93	49	Boustead, 1999.
Nylon 6	81	38	Boustead, 1999.
Polypropylene (PP)	45	49.5	Carpet LCI Db, 2010
Polyethylene terephthalate (PET)	43	40	Boustead, 2005
Calcium Carbonate Filler	0.8	0	Carpet LCI Db, 2010

Table 8 Values of Process Energy and Feedstock Energy for polymers most likely replaced by recycled carpet polymer fraction and calcium carbonate filler.

Recovery System Evolution, Change & Growth

It is important to recognize that carpet recovery and recycling is dynamic and that a snapshot of activities at any one time may not be how the system will be operating six months to a year later. The dynamics are almost all externally driven by market variations, typically in the amounts of recycled commodities that are demanded. Recycled commodities are often on the "margins" of the consumption curves for many manufacturers. This is driven by the fact that virgin material commodity contracts (supply agreements) are typically for large volume transactions and longer term than recycled materials contracts and hence it is easier for companies to adjust material volumes through changing recycled commodity contracts or purchases from recycled commodity spot markets. This means that recyclers have to have flexibility with respect to their outlets and systems may not develop linearly, with increasing volumes and increasing commodity values.

Figures 1 to 4 show different states of a carpet recycling system that could be experienced over an economic cycle and over the growth of the system. In Figure 1, at initiation, all the commodities are provided by virgin sources. Figure 2 shows often this can be followed by one or two specific commodities that can be extracted from the recovered carpet stream, such as recovered nylon fiber and recovered nylon or other plastic elements of carpet for general shoddy fibers. The rest of the recovered carpet stream, both the separated material from the carpet itself, calcium carbonate and small polymer fractions, as well as carpet with face fiber such as PET and PP that are not as valuable or, where markets for such materials from carpet are not developed, is landfilled. Later the system may develop the ability to use these materials as markets develop and demand increases, as depicted in Figure 3 or, they may be used as alternative fuels, as in Figure 4. The system may shift between the patterns shown in these figures as different end users and material demand influence the market. What is important is that a diversity of end markets be maintained with the ability to increase materials into them as they grow and as the system grows. If one stream has no outlet this may distinctly curtail the growth of the overall system as the economic cost of its disposal may be prohibitive. The inability to reach a higher scale of activity may prevent investment in more efficient equipment, which in turn keeps the recycled commodity costs higher and prevents further market penetration of recycled materials.

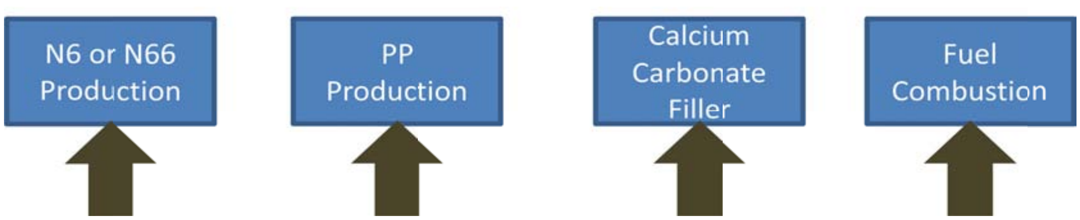

Figure 1 All virgin production system.

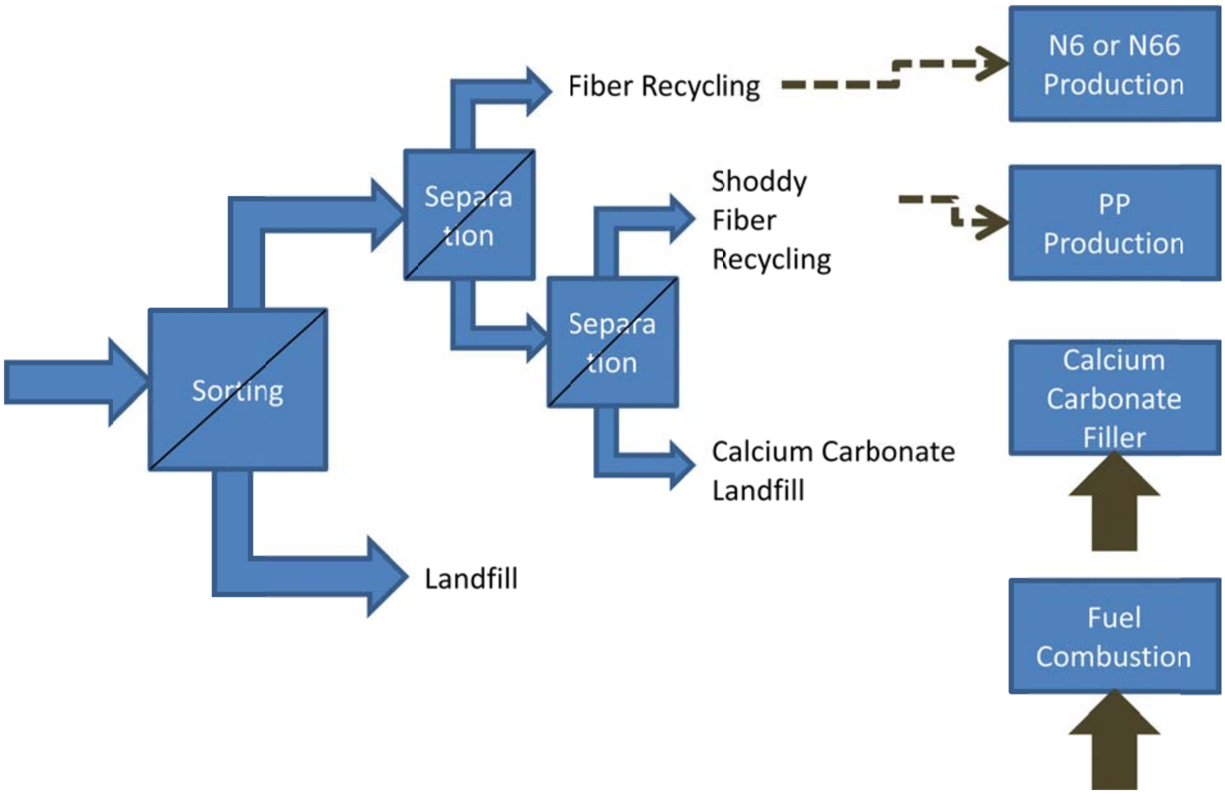

Figure 2 Limited recycling of the most valuable fiber fraction of carpet

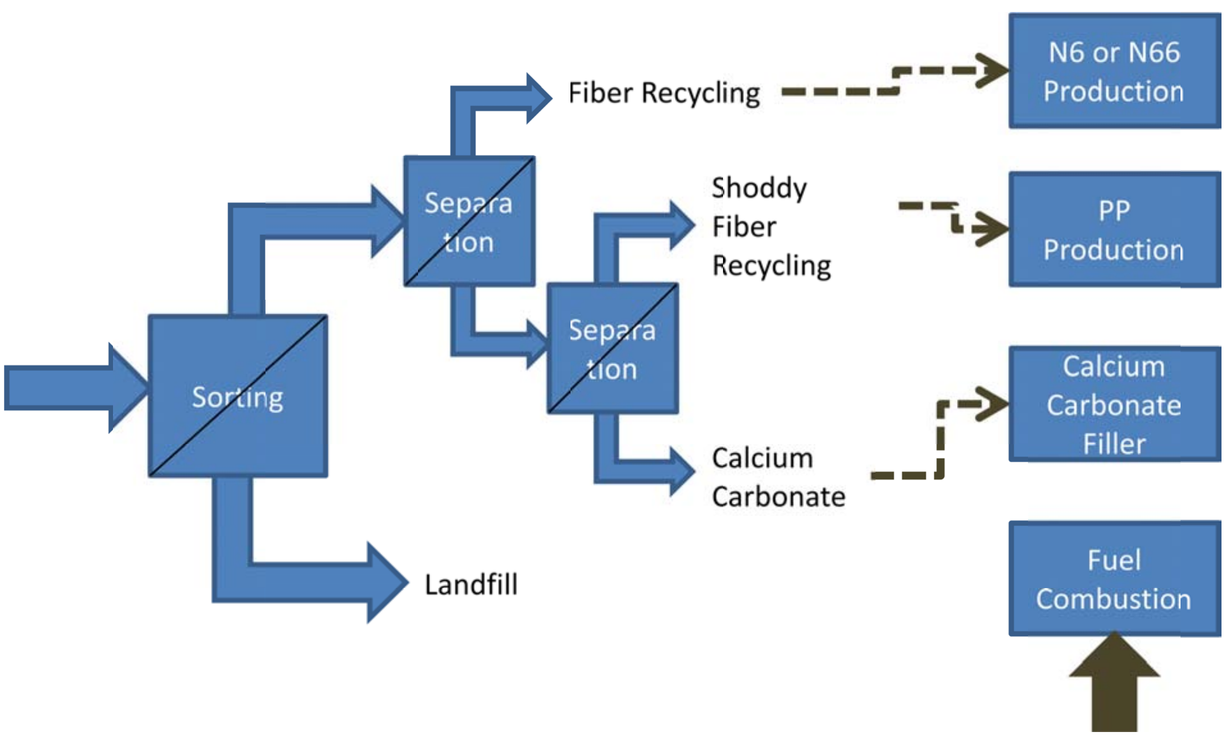

Figure 3 More intense use of a given carpet stream, but a significant fraction of the collected material still landfilled.

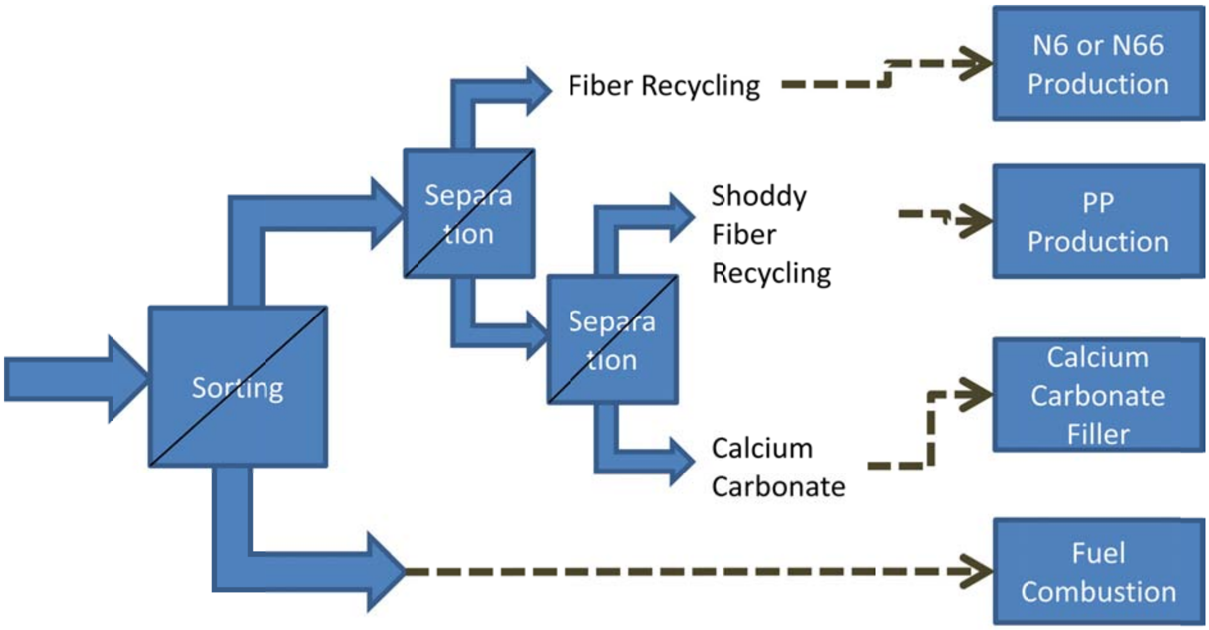

Figure 4 The landfilling of certain carpet face fiber streams is replaced by use as a fuel.

Carpet Transportation

The recovery supply chain of carpet has three main transportation components. The first is the local transportation to an initial collection and sorting point. The second is the transportation of the sorted fractions to the point where they are processed into fractions, such as the face fiber and backing, and third is the transportation from the processing to final end-use. For example using the GREET model of transportation energy use, given in Table 5 we can assume the following transportation model, which is conservative in the sense that the distances are probably overestimated.

- Local transportation of approximately 25 miles of all the recovered carpet in a loose form. We assume that this is mostly in Class 1 trucks powered by gasoline engines (such trucks as a Ford F150 fall in this category). It is assumed that the hauling is approximately 1500 lbs/trip, representing four carpet jobs of 100 square yards per job. This is a highly variable component of the transportation component of the system, and it is about 1/3rd of the total.
- Processor truck and rail transportation. For distances less than 400 miles, trucks are used, for distances over 400 miles rail is used. It is assumed that the mix of modes is about 70% truck and 30% rail and that the average rail distance is 1500 miles. These are full truck and rail loads. It is assumed that 65% of the carpet is transported beyond the locality. The other 35% stays locally and is transported 50 miles to a landfill by truck.

- Final production transportation. The final transportation of products takes place mostly by truck and represents about 50% of the material that is brought to the processor and travels about 500 miles, on average, to an end-use.

Energy of Transportation for recovery of carpet to final products						
Mode	MJ/ton -mile	Local Transport MJ per ton	Processor Transport MJ per ton	Final transport per final ton	MJ/input ton	mmbtu/short input ton
Local Truck	4.47	297.67				
Truck	0.90		281.25	225		
Rail	0.36		540			
Barge	0.54					
		297.67	462.38	225	906.29	0.94

Table 9 Representative Transportation input energies per recovered ton for carpet recycling based on assumed modes and distances given above the Table.

Thus the transportation input is 0.94 mmbtu/short ton which is less than 1% of the virgin supply chain energy as a reference. This also demonstrates that even though the local component of the transportation might be quite variable it is unlikely this will change the overall conclusion of the minimal impact of transportation on the overall system profile.

As in the Morris (2008) study the conclusion is that transportation is not a major factor in the overall impact of carpet recovery and recycling. Similarly changes in the transportation in order to use carpet as an alternative fuel or, to connect the material to final end markets should be of minimal concern to the overall recycling assessment from a GHG emissions or any energy based perspective.

Preparation of carpet for use as a fuel

Carpet will readily combust in appropriate fuel environments. A major issue is preparation and conveyance so that a consistent heat production is achieved. This can be done by size reducing the carpet into reasonably coarse material of approximately 0.25 to 0.5 inch maximum dimension. The energy requirements employed in this process are very dependent on the size reduction technology but trials indicate that about 0.1 - 0.2 MJ/kg is a reasonable estimate of the electrical energy consumption, or about 0.5 MJ/kg in natural resource energy assuming a

38% generating efficiency. This results in about a 3% use of the MJ in recovered carpet to produce the fuel, which needs to be added to the transportation energy.

Carpet Recovery System Emissions - the role of carpet as a fuel

The nylon component of the nylon carpet recovery stream is the most valuable from a materials perspective and hence is the fraction the least likely to be combusted. The component of the recovered carpet stream that is currently less valuable as material is the polypropylene or polyethylene terephthalate (i.e., polyester) face fiber carpet. These have minimal nitrogen content, and hence if the combustion temperature is appropriately controlled it will not change the nitrogen emissions. The goal of admitting carpet as an alternative fuel from a "systems" perspective is to enable a wider recovery of nylon faced carpet to occur because of the less favorable economic value of other recovered carpet streams.

CO2 Emissions Comparison - carpet vs. coal

The calculation of greenhouse gas and other emissions from the input of energy into the system is complicated by the differences in the electrical generation profiles of different parts of the country. For the purposes of simplicity, this analysis assumes that all the electrical energy consumed is the same as the state of Georgia average. This has been obtained from the eGRID system (2006) and was used in a recent Master's thesis at the Georgia Institute of Technology, Guidry (2008) from which other data on the transportation impacts of different vehicle modes has been taken. The basis of comparison is the production of 1 mmbtu of delivered energy. The assumptions for the carpet system are:

1. Local transportation of 25 miles by class 1 truck, 1500 lbs/trip to take initially removed carpet to a local collection point.
2. Further local transportation of 50 miles by a class 4 truck to get to a local processing site.
3. Sorting at the local processing site and sending the appropriate fraction of carpet that is to be used as a fuel to that location in a Class 8A truck for a distance of 150 miles.
4. Processing, by size reduction, the carpet at the location where it is to be used as an alternative fuel into a form suitable for feeding to the combustion utilizing approximately 43 btu/lb.
5. Combustion with a lower heating value (LHV) of 8800 btu/lb.

For comparison bituminous coal is used. The assumptions are:

1. A 0.01 mmbtu/mmbtu energy input for mining coal, Wang (2009).
2. A 0.01 mmbtu/mmbtu energy input for transporting coal.
3. Combustion with a LHV heating value of 11,230 btu/lb.

These energy inputs were converted to CO2 emissions by assuming national fuel emissions for gasoline and diesel inputs and Georgia electricity emissions reproduced from Guidry (2008) below.

Fuel	NOx [g/kWh]	SO2 [g/kWh]	CO2 [g/kWh]	Hg [g/kWh]
Bituminous Coal	1.32	7.51	892.76	0.000014
Sub bituminous Coal	0.71	3.11	997.96	0.000030
Natural Gas	0.01	0.0004	24.84	0
Annual Output GA Average	0.77	4.13	629.74	0.000012

Table 10 Pollution Rates for Electricity Generating Facilities in Georgia (eGRID 2006) from (Tables 4.3,4,6 Guidry 2008)

Figure 5 compares the two supply chains and final CO2 emissions for bituminous coal and recovered carpet. They are very similar in value, with coal emitting more on a direct basis, and recovered carpet more in the supply chain. This is because coal supply chains have been highly optimized to deliver coal to power plants and so have less emissions, whereas recovered carpet has to be handled in smaller quantities. It is again important to point out that we are assigning transportation inputs to this fraction of the recovered carpet in the same proportion as would be for any other use; this is the mass allocation method.

Summary of recovery systems and connections carpet as an alternative fuel

The robustness and health of the carpet recovery system depends upon finding markets and end uses for all the collected fractions of carpet. The effort of collecting and then re-disposing of a significant fraction will eventually undermine the whole system and potentially lead to its collapse. **This paper presents the business, economic and environmental case, from a systems perspective, that using certain fractions of carpet as an alternative fuel makes sense.** Carpet as an alternative fuel supports the robustness of the current carpet recovery and recycling network, providing a layer of potentially high demand that does not require a high level of purity of the recovered carpet stream, and which can take a mixed composition of fibers, backings and fillers. Carpet as an alternative fuel provides a valuable equilibrating component to the system when markets contract due to macroeconomic conditions, available materials and their economics or specific businesses' collapse. This perspective is important because, if carpet as an alternative fuel is viewed narrowly along the dimension of CO_2 emissions only, carpet is not significantly different from coal, and emits more CO_2 than natural gas. This ignores the benefit of avoiding the recovery and processing of the fossil fuel, but carpet will only ever have a very small impact on fuel quantities. Accepting that carpet can play a role as an alternative fuel will encourage carpet recovery to grow, and will allow a discovery of higher value material outlets in consistent with the waste management hierarchy. It is not today, or unlikely to be, the only terminal for the carpet recovery business, but will be a useful intermediate destination.

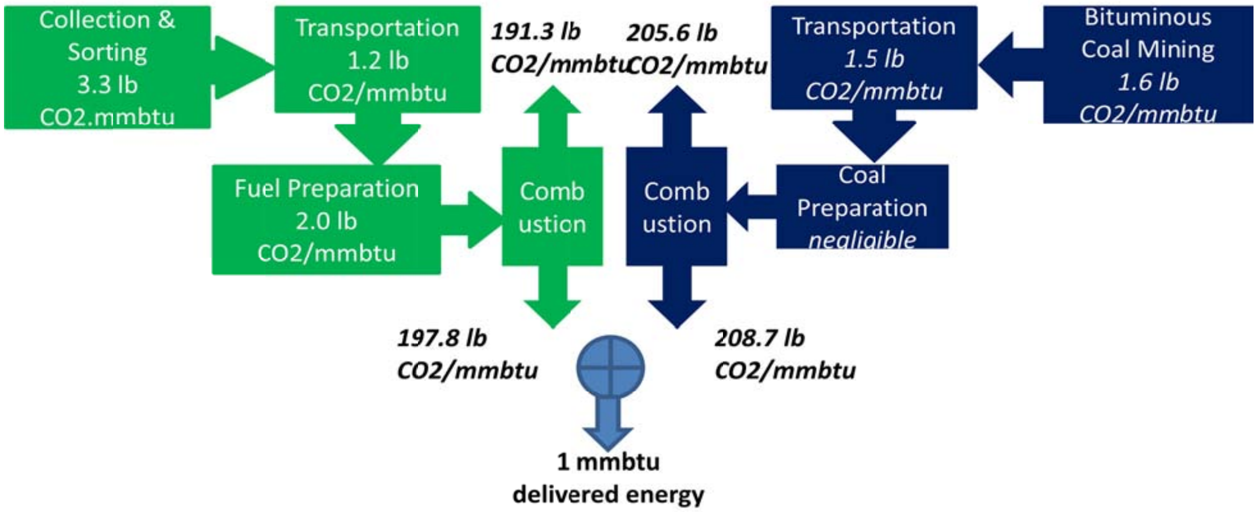

Figure 5 Comparison of CO2 emissions from carpet and coal supply chains and final combustion.

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Appendix

Abbreviation	Definition or Explanation
Al(OH)3	**Aluminum Trihydrate**, carpet filler used to suppress fires by release of water during combustion.
CaCO3	**Calcium Carbonate**, carpet filler
N6	**Nylon 6**, polymer, repeat unit (C6H11NO), carpet face fiber
N66	**Nylon 66**, polymer, repeat unit (C12H22N2O2), carpet face fiber
PE	**Polyethylene**, polymer, (C2H4),
PET	**Polyethylene terephthalate,** polymer, (C10H8O4), face fiber, backing fabric polymer
PP	**Polypropylene**, polymer, (C3H6), backing or face fiber
PVC	**Polyvinylchloride**, polymer, (C2H2Cl2), backing polymer
SBL	**Styrene-Butadiene Latex**, polymer, representative repeat unit, (C8H8C4H4), backing polymer mixed with filler

Table A1 Abbreviations Chemical Formulae - Materials

Abbreviation	Unit and relation to other units
Btu	British Thermal Unit = 0.9478 kilojoules (kJ)
GHG	Greenhouse Gas
HHV	Higher Heating Value, water produced as liquid =LHV+44kJ/mole of water produced.
kJ	Kilojoule=1000Joules=1.055 Btu
LHV	Lower Heating Value, water produced as vapor = HHV - 44kJ/mole of water produced.
MJ	MegaJoule = 1000KiloJoules=1055Btu
mmBtu	Million Btu's = 947.8MegaJoules
NOX	Nitrous Oxides
Ppmvd	Parts per million volume dry basis
SOX	Sulfur Oxides

Table A2 Abbreviations Combustion Related