The Environmental Impact of Paper Waste Recycling: A Comparative Study

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Abstract

This paper aims to quantify the environmental impact of recycling paper in Canada versus other paper waste management options using the indicators of energy consumption and greenhouse gas emissions. Analysis was carried out comparing recycling to landfill, landfill with methane capture, energy-from-waste, cogeneration, and the use of conserved timber for energy. A review was done of existing paper life cycle analyses, as well as original calculations using data from refereed and Canadian government sources. It was found that recycling, based on energy consumption and greenhouse gas emissions, does reduce environmental impact, but that this benefit can be increased by recycling fibre multiple times, and through the integration of more than one management method.

Keywords

Paper waste management, paper recycling, energy-from-waste, cogeneration, landfill methane

Table of Contents

Introduction……………………………………………………………………………4
Energy……………………………………………………………………………………6
Energy from Waste…………………………………………………………………7
Transportation………………………………………………………………………8
Methane Recovery…………………………………………………………………8
Cogeneration……………………………………………………………………..9
Conserved Fibre……………………………………………………………………10
Option Comparisons……………………………………………………………..11
Analysis……………………………………………………………………………..13
Greenhouse Gases…………………………………………………………………..14
Forest Carbon………………………………………………………………………15
Emissions from Energy…………………………………………………………..15
Emissions Reductions……………………………………………………………18
Analysis……………………………………………………………………………..21
Discussion……………………………………………………………………………..21
Conclusion……………………………………………………………………………23

Index of Tables

Table 1: Net Energy from Paper Waste Management Options (one cycle)……………...12
Table 2: Sources of Fossil Fuel Energy in Pulp and Paper Production in Canada………16
Table 3: Inputs of Fossil Fuel Energy per Tonne of Virgin Pulp and Paper Production...17
Table 4: Energy based CO2 Emissions per Tonne of Virgin Paper by Fuel Type………17
Table 5: Greenhouse Gas Reductions for Paper Waste Management Options….………19

Index of Figures

Figure 1: Net energy surplus from combinations of paper disposal options (four cycles)….13
Figure 2: Net Greenhouse Gas Emission Reductions from combinations of paper disposal options (four cycles)…………………………………………...20

Index of Appendices

Appendix 1: Energy Recovery from Landfill Methane………………………………….31
Appendix 2: Electrical Energy Yield from Paper Waste from EFW…………………….31
Appendix 3: Cogeneration Energy Yield from Paper Waste…………………………….31
Appendix 4: Cogeneration Energy Yield from Conserved Fibre………………………..31
Appendix 5: Virgin and Recycled Paper Energy Costs in Canada………………………32
Appendix 6: Net Energy yields from Waste Paper Management Options, Multiple Cycles…………………..……………………………………...32
Appendix 7: Proportion of Electrical Consumption for Virgin and Recycled Paper (using Schmidt et al. energy sources)……………………………….33
Appendix 8: Sources of Fossil Fuel Energy in Pulp and Paper Production in Canada, by feedstock (using Schmidt et al. energy sources)………………33
Appendix 9: Greenhouse Gas Emissions from Fossil Fuel Production and combustion…...33
Appendix 10: Greenhouse Gas Emissions Reductions from Waste Paper Management Options, Multiple Cycles……………………………………34

Introduction

In the 21st century, recycling has become a part of life for those living in Canada. Statistics Canada reports that almost 90% of households have access to at least some sort of diversion system for the reprocessing and reuse of solid wastes, and that among these, almost 95% make use of recycling services or facilities (Statistics Canada 2007). These measures give two results: the reduction of pollution released into the environment, and a lessened need for raw materials (and their associated ecological disturbance) to produce new goods.

The most commonly recycled waste is paper. This follows naturally, since nearly half of household waste is paper, making it the most critical waste product to manage in order to reduce landfill volumes (Stilwell and Kopf 1992). Also, given the sheer mass of raw materials required for its production, the recycling of paper reduces the pressure placed on forests by demand for feedstock. This is an essential component of the recycling debate, since excluding fuelwood, 42 percent of wood harvested globally is used for paper production (Abramovitz and Mattoon 1999).

Paper as a material has a long history of recycling, beginning with the collection of discarded linens for the earliest Chinese paper mills in the 2nd century C.E. (CEPI 2009). In Canada, the origins of paper recycling date back to the use of pre-consumer waste as mill feedstock in the 1930s (Bourdages 1993). However, it was not until the latter part of the 20th century, that the driving force behind the reprocessing and reuse of raw materials became the protection of the environment.

Paper recycling has particular significance for Canada, since it is the world's 4th largest producer of paper, responsible for the milling of over 30 million tonnes of paper annually (NRCan 2008a), a full 6% of the global total (Earth Trends 2003). Of this, almost 7 million tonnes are consumed domestically, representing a per capita consumption of almost 250 kg, trailing only the United States and Japan, and easily surpassing the approximately 30 to 40 kg required for education and communication (Abramovitz and Mattoon 1999). Despite the widespread access to recycling in Canada, only an estimated one-quarter is recovered for remanufacturing, (PPPC 2007), well below the global average of 40% (Earth Trends 2003). This indicates a great deal of potential for improvement in recycling paper waste in the country.

There is no argument as to whether or not paper recycling reduces the demand for virgin timber. Since wood paper waste can be recycled up to seven times, even the reprocessing of small amount of fibre can have a significant impact on the need to harvest wood (TAPPI 2001). Similarly, it is safe to assume that recycling paper reduces the amount of solid waste being deposited in landfills. Diverting fibre for any use (e.g. incineration, composting, recycling, etc.) will obviously reduce the imprint of physical waste on the environment.

However, there remain real questions about the efficacy of paper recycling in reducing other forms of environmental degradation. New York Times journalist John Tierney publicly raised some of these questions in the article ‘Recycling is Garbage’, challenging the environmental benefits of the practice (Tierney 1996). So strong was the cultural resistance to criticism of recycling that the article spurred more negative responses than had ever before been received by the newspaper (Sanchez 2005). Despite the unpopularity of his message, Tierney’s question was valid and important: Is recycling actually beneficial for the environment?

The answer to the latter question depends on what it is to which recycling is being compared. This is no longer the era of the simple recycle-or-landfill dichotomy. In addition to these conventional methods, landfill with methane capture, incineration and cogeneration are also waste management options for paper. Methane capture from landfills represents a potential source of energy, while concurrently reducing greenhouse gas emissions. Incineration, the disposal of solid waste through high temperature combustion to produce electricity, is becoming more common as competing land use pressures and environmental concerns render landfills less feasible. Cogeneration, the combustion of a fuel to generate both electricity and useable heat, can be applied to waste paper as well. Also, if paper is recycled, the conserved timber can potentially be used as an energy source. These options, as well as various combinations of them should be considered as potential alternatives to recycling and landfill alone.

In comparing waste paper management option, conclusions regarding the effectiveness of recycling will depend upon how environmental indicators are weighted. By examining the indicators of energy and greenhouse gases, it is possible to obtain an initial picture of whether or not recycling paper does, in fact, reduce the ecological impact paper consumption in Canada.

Energy

One of the most fundamental measurements of the effectiveness of recycling is its ability to reduce energy consumption, either by limiting transportation costs for waste products, or by using preprocessed feedstock that is more readily refined into finished products. Energy, simply the ability to do work, is itself is not damaging to the environment. However, the manner in which energy is rendered into a useable form, by generating electricity, or extracting and refining petroleum, etc., will almost certainly entail some sort of environmental impact. This may involve the disturbance of fish spawning *via* hydroelectric dams, the creation of nuclear waste from reactors, the seepage of tailings from tar sand processing, or any number of other potential ecological side effects. In order to limit this, conservation of energy is a primary goal in the environmental movement, and a driving force behind recycling.

Energy from Waste

When determining the comparative energy efficiency of recycling, the equation is not simply one of how much less energy it consumes versus other options. Because numerous waste management options result in energy production, this gain represents a 'savings' that can be subtracted from energy consumption throughout the product's life cycle. Modern incineration facilities, for example, capture the heat of waste combustion to turn turbines, generating electricity. These plants, known as energy-from-waste (EFW) facilities, are widespread throughout Europe, and are becoming increasingly common in North America (CEFWC 2009). As a source of electricity, compared to fossil fuels, EFW plants emit fewer greenhouse gases and less fly ash, and use at least partially renewable fuel (as in the case with paper) (Ruth 1998). However, from an energy balance standpoint, EFW facilities are net losers. Because the energy recovered from incineration is significantly less than that required to produce the paper fuel (2.6 vs. 26.2 gigajoules per tonne (GJ/T)), energy-from-waste is seen as a disposal option with an energy bonus, rather than a true source of energy (Morris 1996, NRCan 2008a).

It is important to note the efficiency level of EFW generation. Because these plants operate by burning all household wastes: organics, plastics, glass, aluminum, etc. as well as paper, it is difficult to optimize plant design for generation due to the variability of the combustibles (Ekvall and Finnveden 2000). As a result of this, and the normal inefficiencies involved in energy conversion, burning garbage to produce electricity is able to capture only 15% of the waste's intrinsic energy (Morris 1996), significantly lower than other fuels (such as coal, which averages approximately 38% efficiency) (Taylor *et al*. 2008). This could be improved if further sorting were carried out in the waste-fuel stream, with specific incinerators for different fuels, but this would largely undermine the simplicity advantage conferred by such a catch-all disposal method.

Transportation

Regardless of whether it is incinerated, recycled or placed in landfill, all waste paper disposal involves transportation to some extent. Comparatively there is no clear advantage to any method. Since it is assumed that all waste paper must be collected from households and be transported to a recycling facility, an incinerator, or a landfill site, the energy saved by any one of these trips over another has only a small bearing on the overall energy cost. In general, the energy cost of transportation for waste paper is low, approximately 0.3 GJ/T (Morris 1996). Compared to the cost of processing and remanufacturing, this is marginal. Tillman *et al*. (1991) conclude that transportation has an overall energy impact of 2%, whereas Frees *et al*. (2005) indicate that transportation represents only 0.4% of the total energy use in the processing of paper waste. Because of this, the energy involved in collecting and transporting waste paper to any sort of facility is typically discounted entirely from comparative studies.

Methane Recovery

Of the studies examined, only one (Denison 1996) included the energy recoverable from landfill sites *via* the capture of methane gas. Although facilities to do this exist, few are in operation in Canada, so the baseline for landfills is established without them. However, methane capture can represent an energy source, since up to 0.09 tonnes of CH_4 can be emitted per tonne of decomposing paper (Micales and Skog

1997). Given an energy density of 50 GJ/T (Thomas 2000), and a 91% recovery rate (O'Brien 2008) this results in a possible energy gain of 4.1 GJ/T of paper (see Appendix 1). Furthermore, energy contained in methane, unlike that of paper, requires no conversion to be rendered useful.

Cogeneration

A further omission in most paper life-cycle analyses is the possibility of more than one disposal option. Because the fibres within paper shorten with increased processing, there is a maximum number of times that paper can be recycled. Beyond this, the stock becomes useless for new material production (Leach *et al*. 1997). At this point it is most efficient to incinerate the unusable fibres for energy recovery once the maximum energy savings have already been attained through recycling. Although this waste is often placed in landfill in the absence of integrated facilities (Dhir *et al*. 2001), where there exist suitable facilities at pulp and paper mills, the practice is both technically feasible and economical (Hogland and Stenis 2000).

In fact, due to the energy requirements of paper production, combustion of unusable fibre can be used even more effectively when integrated into milling. Because a significant portion of the energy required for paper production is thermal, combustion of waste paper can be used directly to fuel the process. Wood fibre cogeneration plants, which generate both electricity and useable thermal energy, obtain efficiencies of 25-30% for electrical generation (mean of 27.5%), and up 75% overall when heat is recovered (FAO 1990). So if the average thermal content of paper is assumed to be 17.3 GJ/T (Morris 1996), a maximum of 2.60 GJ/T could be recovered as electricity through EFW, but 4.76 GJ/T could be recovered through cogeneration, plus an additional 8.23 GJ/T in thermal energy (see Appendices 2, 3). This represents an improvement of 2.16 GJ/T in electrical production, and 10.4 GJ/T overall.

However, there is a limit to the amount of paper-derived thermal energy that can be used in new paper production. Currently, 55.1% of the energy used within the sector in Canada is derived from wood wastes with 20.2% coming from other combustible fuels (electrical generation excluded), and 5.0% from purchased steam (NRCan 2008a). This means that a maximum of 6.60 GJ/T of thermal energy could further be derived from fibre wastes for use in the milling process. Though surplus electricity can easily be sold back onto the electrical grid, any thermal energy beyond that used for paper production (a potential 1.63 GJ/T) would require infrastructure development in order for it to be sold to an external user (e.g. a district heating system). Regardless, there is still potential for the generation and sale of heat and power from paper wastes through in-house cogeneration.

Conserved Fibre

Another related factor rarely considered is the opportunity cost in energy from cutting virgin timber for use in paper. Since wood itself can be used as a fuel, if trees are felled for the production of paper, then the potential energy contained within them cannot be accessed until the end of the product life cycle, if the paper is then incinerated. However, if paper is recycled, the fibre saved could potentially be used as a feedstock for biomass electrical generation. Understandably, if recycling is used as a device to cut timber for energy production, it would defeat the ecological conservation component of the practice. In Canada, approximately 50% of paper is derived from lumber production tailings (OFIA 2005), so only half of the fibre preserved would be in trees. The use of the former for energy would simply represent an alternative use of a waste product.

Because of this, the surplus fibre obtained through recycling should be considered as a potential energy source.

For one tonne of paper, approximately 3.64 T of wet softwood are required (Morris 1996), a dry weight of 1.64 T (at 55% moisture) (Kofman 2006), containing an approximate 31.5 GJ of energy (at 19.2 GJ/T) (Welling and Shaw 2007). Using the same conversion efficiencies as above, minus harvest costs of 0.95 GJ/T for dry wood (Börjesson 1996), this yields a net value of 8.27 GJ of electricity, and 14.6 GJ of thermal energy per tonne of paper recycled (see Appendix 4). Again, the usefulness of the thermal yield will depend on the proximity and accessibility of external users. The harvesting of surplus timber for electricity, though practically feasible, may not be economically *via*ble, depending on region and the sale price for power. However, should market conditions be appropriate, this may indeed be an option for tenure holders substituting recycled paper for timber feedstock.

Option Comparisons

In the literature, the focus for waste paper disposal is typically limited to comparing recycling and energy-from-waste to a conventional landfill baseline. Within these studies, there is variance in the in the amount of energy consumed to produce paper, from a low of 21.0 GJ/T for newsprint (Hindle and Franke 1999), to a high of 58.0 GJ/T for virgin sulphite paper (Habersatter 1991). Energy recoverable *via* incineration ranges from 6.11 GJ/T (Denison 1996) to 7.86 GJ/T (Morris 1996), while energy saving much greater from recycling falling between 7.1 GJ/T (Porter and Roberts 1985) to 30.3 GJ/T (Morris 1996).

This trend is echoed is almost all articles. Finnveden and Ekvall (1998) found that recycling paper packaging results in less net energy consumption than incineration.

Eriksson *et al*. (2005) report that for corrugated cardboard, recycling results in the lowest energy consumption, followed by incineration, then landfills. Finnveden *et al*. (2005) found that for newsprint, corrugated cardboard, and mixed cardboard, the results were the same. Denison (1996) conducted a survey of four commissioned studies with similar conclusions, and Morris (1996) carrying out an exhaustive report on twenty-five studies, reports that all but one found recycling to be more energy efficient than incineration. If all paper management options are considered, the net energy benefits vary significantly (see Table 1).

Table 2: Net Energy from Paper Waste Management Options (one cycle)

Management Type	Net Energy (GJ/T)
Methane from Landfill capture	4.10
Energy From Waste	2.60
Recycling*	12.6
Cogeneration Electrical	4.76
Cogeneration Thermal	8.23
Conserved Fibre Electrical Potential	8.27
Conserved Fibre Thermal Potential	14.6

*see Appendix 5

However, since certain management options can be combined, higher energy savings can be attained than from simply recycling or incinerating alone. It should be noted, as well, that recycling and conserved fibre use are not limited to one cycle. Given that paper can be recycled up to 7 times, greater energy savings can be obtained (see Appendix 6). Although not all fibre can be reused, even at a recovery rate of 85% (Leach *et al*. 1997), energy benefits can be multiplied significantly. Figure 1 shows the comparative energy saving of combinations of management options based on a mean of four cycles.

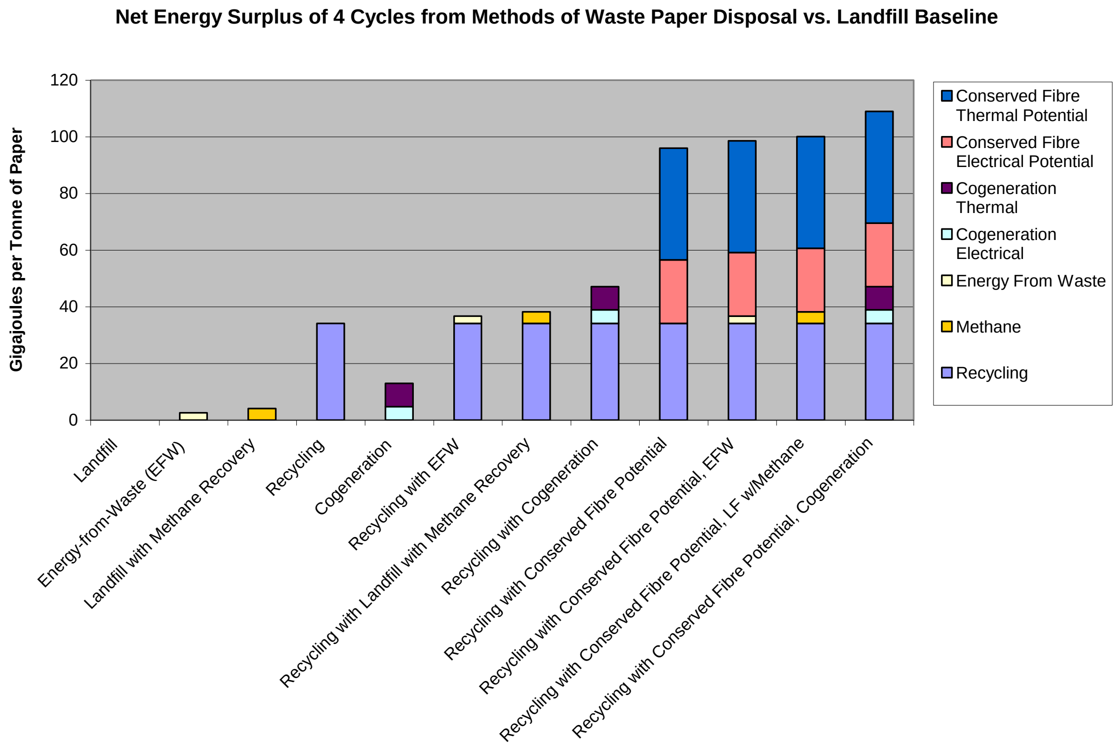

Figure 1: Net energy surplus from combinations of paper disposal options (four cycles)

Analysis

It is apparent from an energy standpoint that the optimal paper waste disposal option is recycling, with combustion for cogeneration at the end of the life cycle, and the use of conserved timber for biomass cogeneration. Even in the absence of energy from conserved timber, recycling followed by cogeneration of wastes is the most energy efficient option. Energy-from-waste, one of the more common waste disposal choices, provides among the lowest energy benefits, yielding more comparatively than only the baseline of landfill.

Overall, it can be seen that recycling paper does result in significant energy savings over the catch-all methods of landfill and energy-from-waste incineration, especially when coupled with other energy reclamation activities. However, recycling differs from EFW and landfills in the sense that it requires the sorting and streaming of waste products, which entails some organization and cost. Considering the energy benefits, though, these costs are ones that most communities are willing to bear, especially if some compensation can be obtained for the feedstock provided.

Although energy is not the only indicator of environmental impact, it is a primary indicator of the ecological disturbance associated with an activity. Because of this, recycling shows an environmental advantage for the disposal of paper wastes.

Greenhouse Gases

Given the current threat caused by global climate change, one of the more important measures of the ecological impact of an activity is the extent to which it emits greenhouse gases (GHGs). Carbon dioxide (CO_2) and methane (CH_4) are the two major greenhouse gases produced in the paper life cycle linked to climate change. Carbon dioxide, the primary anthropogenic greenhouse gas, is a normal part of the carbon cycle necessary for life on earth. However, the excess of CO_2 caused largely by fossil fuel combustion, has been correlated with an increase in global temperature (NASA 2003). Following CO_2 in importance is methane, which, though produced in lower quantities, has a higher rate of solar thermal conversion, and is thus a major contributor to the greenhouse effect (USEPA 2007).

Significant improvements have been made in the pulp and paper industry in Canada regarding greenhouse gases, indicated by a 45.9% reduction in GHG emissions between 1990 and 2006. These reductions largely result from increased use of biomass energy within the sector offsetting the need for fossil fuel derived power. Nonetheless, the pulp and paper industry remains one of the largest emitters of greenhouse gases, accounting for 12.9% of emissions in the manufacturing sector (Environment Canada

2008). This is independent of the methane released through paper waste decomposition if uncollected at landfills.

Forest Carbon

Because paper is a forest product, it is important to explore the role of forests in the carbon balance. There is currently a degree of controversy regarding the extent to which carbon in forests plays a role in climate change. Certainly permanent deforestation reduces the carbon sequestration capacity of an area, and the reforestation of a previously denuded landscape increases its ability to store carbon. But assuming that virtually all pulp and paper in Canada comes from managed forests, it is in a real sense carbon neutral. This is because trees cut will be rapidly replaced by growing stock, and the CO_2 released through the decomposition of forest products will be taken up by these new trees. For this reason the potential carbon stored in conserved timber is not calculated as a reduction in emissions for this report.

Emissions from Energy

Discounting methane, the greenhouse gas emissions of paper are almost exclusively due to the consumption of energy throughout the production process, and electricity is a large contributor to this. Although most electricity in Canada is generated from falling water, almost one quarter is derived from fossils fuels: 16.5% from coal, 5.2% from natural gas, and 1.9% from petroleum (NRCan 2009), which produce 17% of the country's GHG emissions (Gunter *et al*. 2005). Although the production of electricity from other sources does produce a carbon footprint, this is largely due to the construction of facilities, and not the fuel to power them (POST 2006). For the sake of this analysis, emissions related to these are ignored, as are those related to the construction of generation facilities in mills.

Electrical production aside, a significant amount of fossil fuel is used directly in pulp and paper production in Canada. Of the total energy used to produce a tonne of paper, 5.6% is derived from oil, 14.4% from natural gas, and 0.08% from coal. Atop this is the 5.0% of energy used in the form of purchased steam, derived largely from natural gas (NRCan 2008b). When combined with the amount from electrical production, a total 29.5% of the energy used in pulp and paper production in Canada results from fossil fuel combustion (see Table 2).

Table 3: Sources of Fossil Fuel Energy in Pulp and Paper Production in Canada

	Coal	Natural Gas	Petroleum	Total
Electricity*	3.04%	0.96%	0.35%	*4.34%*
Direct Fossil Fuel	0.08%	14.4%	5.64%	*20.1%*
Steam	-	5.00%	-	*5.00%*
Total	*3.12%*	*20.4%*	*5.99%*	**29.5%**

*absolute proportion based on 18.4% electrical energy use (NRCan 2008a)

There are, however, differences in the source of energy inputs between virgin and recycled paper production. The International Institute for Environment and Development, states that greater fossil fuel inputs are required for the use of recycled materials (1995). However, a study conducted by Schmidt *et al*. in Denmark shows lower heat requirements in the pulping of waste paper, which result in a higher proportional consumption of electricity by 7.1% (2007) (see Appendix 7). The impact this amount would on the overall fossil fuel proportion in Canada is marginal, though, constituting only a 0.44% difference between the two types of feedstock, and is discounted (see Appendix 8).

Due to the inefficiency of energy conversion, the amount of fossil fuel energy required to generate electricity and steam is greater than the simple amount of electrical and steam energy that go into paper production. For example, it requires 2.96 GJ of energy to produce the 1.14 GJ of fossil fuel derived electricity that goes into paper production, assuming 38%, 40%, and 39% efficiency for coal, natural gas, and petroleum, respectively (Taylor *et al*. 2008). Industrial steam boilers obtain better efficiencies than electrical generators (70-75%), but still involve greater inputs than outputs (CIBO 2003). This is why 11.3 GJ of fossil fuel energy are required to make the 8.67 GJ of fossil fuel derived energy in virgin paper production. These energy inputs are shown in Table 3.

Table 4: Inputs of Fossil Fuel Energy per Tonne of Virgin Pulp and Paper Production

	Coal (GJ/T)	**Natural Gas GJ/T)**	**Petroleum (GJ/T)**	**Total (GJ/T)**
Electricity	2.36	0.71	0.26	*3.32*
Direct Fossil Fuel	0.02	4.25	1.66	*5.93*
Steam	-	2.03	-	2.03
Total	*2.38*	*6.98*	*1.93*	**11.3**

The amount of greenhouse gases emitted by these energy inputs in paper production is dependent on the energy source. The extraction and combustion of coal, which derives all of its energy through the formation of carbon dioxide, emits 97 kg of CO_2 per GJ, while petroleum averages 83 kg per GJ, and natural gas, which derives the majority of its energy from the formation of water (H_2O), emits 67 kg of CO_2 per GJ (see Appendix 9). Applied to the energy inputs by type, these yield an average of 858 kg of carbon dioxide equivalent (CO2e) per tonne of paper (see Table 4).

Table 5: Energy based CO_2 Emissions per Tonne of Virgin Paper by Fuel Type

	Coal (kg CO_2e/T)	**Natural Gas (kg CO_2e/T)**	**Petroleum (kg CO_2e/T)**	**Total (kg CO_2e/T)**
Electricity	228	47.2	21.9	*297*
Fossil Fuels	2.19	284	138	*424*
Steam	-	135	-	*135*
Total	*230*	*467*	*160*	**858**

Emissions Reductions

Assuming an energy reduction of 43% if paper is recycled, there is a corresponding reduction in carbon dioxide emissions. This represents an emissions reduction of 369 kg of CO_2e per tonne of recycled paper. However, based on the scenarios presented in the energy section, energy based carbon offsets can be made through methane capture, energy-from-waste, and cogeneration, and the use of conserved timber.

However, when comparing these options against the baseline, it must be noted that a landfill is not simply a zero emissions scenario. Because paper in landfills emits methane, this must be factored into the greenhouse gas baseline. One tonne of decomposing paper emits up to 90 kg of methane. If uncaptured, this would be released into the atmosphere, where it acts as a greenhouse gas with a solar thermal conversion over 21 times that of carbon dioxide (NEB 2006). In terms of carbon dioxide equivalence, this equals 1890 kg of CO_2e.

However, not all of this can justifiably be counted against paper in landfills. This is because there an expected amount of CO_2e released based on the natural decomposition of forest products through the carbon cycle. If, as before, we assume a 3.64 T of wet wood per tonne of paper, a softwood density of 400 kg/m^3 (Zhang and Morgenstern 1995), and a carbon content of 175 kg/m^3, this represents 1592 kg C. In processing, 52% of carbon is lost, leaving 764 kg C in one tonne of paper (Krcmar and van Kooten 2005). Within the 90 kg of methane, 67.4 kg of carbon are 'sequestered', albeit it in a more greenhouse contributing form. An equivalent of 67% of this amount of carbon (44.9 kg) is emitted as CO_2 from the remaining carbon through normal decomposition (Mikales and Skog 1996). The remaining 652 kg of carbon (2457 kg of CO_2e) are effectively sequestered, due to the anaerobic conditions inside landfills. The net result is that paper in a landfill actually constitutes a carbon sink, sequestering 567 kg of CO_2e per tonne. Because of this, the zero baseline for emissions is set as the level from virgin production, followed by free aerobic decomposition, such as would occur if paper were left to decay uncompacted in the open.

In the case of methane capture within a landfill setting, only 9% (8.10 kg) of the CH_4 released from decomposition reaches the atmosphere (assuming high-efficiency capture design). The remainder of the methane is combusted upon use, and returned to the carbon cycle. Also, this paper-derived methane is able to offset the CO_2 from the combustion of an equivalent amount of fossil fuel methane. Overall, this results in 170 kg of CO_2e emitted from methane release, 275 kg offset from fossil derived methane, and 2457 kg sequestered in the form of paper, for a total reduction of 2561 kg CO_2e/T. The net carbon reductions of all examined options can be seen in Table 5.

Table 5: Greenhouse Gas Reductions for Paper Waste Management Options

	Net Energy Reduction (GJ/T)	Fossil Fuel Energy Reduction (GJ/T)	Total Emissions Offset (kg CO_2e/T)
Landfill	0	0	567
Recycling	12.6	6.44	369
Methane from Landfill capture	4.10	4.10	2561
Energy From Waste	2.6	1.59	195
Cogeneration Electrical	4.77	2.92	261
Cogeneration Thermal	8.23	11.4	760
Conserved Fibre Electrical Potential	8.27	5.07	454
Conserved Fibre Thermal Potential	14.6	20.1	1346

As before, methods of disposal can be coupled to yield better management solutions. Added to the potential of multiple cycles of recycling, large emission reductions can be obtained. Figure 2 shows the net carbon dioxide emissions for combined management options, based on four cycles.

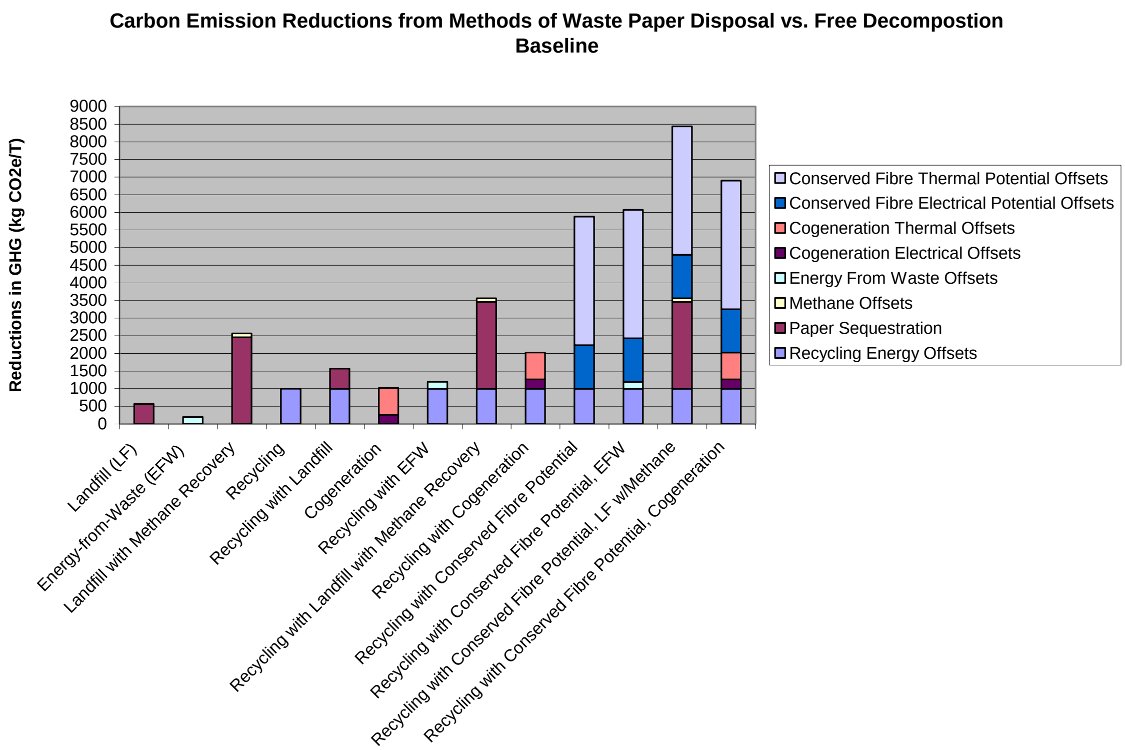

Figure 2: Net Greenhouse Gas Emission Reductions from combinations of paper disposal options (four cycles)

Analysis

From the perspective of greenhouse gases, it can be seen that recycling falls short of landfill with methane recovery in limiting emissions. In fact, paper would have to be recycled over six times before it would result in less greenhouse gas than landfill with captured methane. Over four cycles, it is not unless recycling is coupled with the use of conserved fibre for cogeneration that it becomes a preferable option to depositing in a landfill with methane recovery. Compared to energy-from-waste, however, recycling fares well, with 804 kg less CO_2e emitted. Recycling falls just short of the carbon offsets derived from cogeneration of paper wastes, assuming that all combined heat and power can be used. Of course, the most likely scenario is that paper recycling would be followed by conventional landfill, which places it higher than EFW and cogeneration.

In the absence of recycling, landfill with methane recapture is the best waste paper management option. Aside from preventing the release of methane into the atmosphere, the use of this tree derived methane as a fuel offsets the use fossil derived methane. This means that 'new' carbon is not released into the atmosphere, since the carbon from paper is already actively part of the carbon cycle. Because of this, landfill with methane capture is able to offset a large amount of carbon dioxide equivalent, especially when combined with recycling, or the use of conserved fibre for energy. Again, the recycling of paper can be carried out up to 7 times, which would yield higher emission reductions (see Appendix 10).

Discussion

If looking simply at the net energy benefit of waste paper disposal, recycling shows an obvious advantage over both landfill and energy-from-waste, but the highest benefit comes from following recycling with cogeneration, and using surplus timber for cogeneration. However, this optimal yield can only be accomplished in a situation where there exists the capacity to make use of the surplus heat from cogeneration. Otherwise, this thermal energy is simply waste, and contributes no addition to the energy balance. The highest overall benefit, understandably, comes from recycling the maximum number of times possible, each time using the conserved timber for energy, and when the waste fibre has become too degraded for use in paper, using it as an energy source. If this is carried out for seven cycles, the total energy benefit could reach 149 GJ per tonne of paper.

Other options, such as energy-from-waste and landfill with methane capture have much lower energy yields, and though they may constitute *via*ble options in regions that lack recycling facilities, are comparatively energy poor next to recycling and cogeneration. In cases such as this, it is likely a better option to transport waste paper to the nearest recycling facility, given the comparatively low energy cost of transportation.

From a greenhouse gas standpoint, recycling compares reasonably well to landfill alone, but poorly if the landfill is equipped to capture methane. In a conventional landfill, there are significant emissions from decomposing waste, but due to the capacity of a landfill to sequester the carbon in paper, landfills are able to store more carbon dioxide equivalent than they emit. But because recycling must be coupled with a final end of life disposal, recycling with landfill presents a good method of limiting greenhouse gas emissions. This benefit is amplified with methane recovery, resulting in the highest greenhouse gas reductions when combined with conserved fibre cogeneration.

Again it should be noted that this is based on four cycles. The optimal solution is to recycle as many times as possible, offsetting fossil fuel energy by using conserved timber in cogeneration, and sequestering the carbon of the unuseable fibre in landfill with methane capture. If using the same 85% recovery rate over seven cycles, this could offset 10913 kg CO_2e per tonne of paper, the equivalent annual emissions of two average automobiles (USEPA 2009).

Another note is that this analysis was based on a generalized average for energy sources in Canada, and there is significant regional variation across the country. In Manitoba, for example, 98.4% of electricity is generated by hydroelectric dams, whereas in Alberta, 73.6% of energy is derived from coal combustion (GoC 2008). This means that recycling paper in Alberta would offset considerably more carbon than it would in

Manitoba. The result is that recycling may not be the preferred option in Manitoba if the criterion was carbon emissions alone.

Overall, although the optimal scenarios may be somewhat optimistic, attempts we made to derive reasonable average data, and these scenarios represent attainable possibilities if waste management systems are designed ideally. Although there may be losses in transportation of electricity, steam, or waste fibre, these are far outweighed by the potential gains through waste stream optimization. However, these sorts of systems require a high degree of organization and cooperation between municipalities, pulp and paper manufacturers, and utilities. Nonetheless, in an energy constrained world that is trying to mitigate climate change, this sort of organization may not be a choice, but could in fact become a necessity.

Conclusion

Although there are certainly other environmental factors to be considered, such as thermal pollution, particulate emissions, chemical wastes, habitat disturbance and others, energy consumption and greenhouse gas emissions are primary indicators of the environmental impact of an activity. Although the two are related, they both represent opposite sides of the production equation; energy being an input to drive industry, and greenhouse gases being waste by-products of the manufacturing process. The former is an indicator of what can be done, the latter, of what has to be undone. For pulp and paper production, recycling can result in a lower demand for energy, and lower outputs of greenhouse gases; but not always.

The most important factor is the process of which recycling is part. Recycling alone confers far fewer benefits than when coupled with other waste management alternatives. The goal is to extract the full amount of benefits from a resource (i.e. paper fibre) by applying the optimal management option at the right time in the product's life cycle. The majority of time, the mantra 'recycle, recycle, recycle…' is appropriate to extract maximal benefits. However, when the fibre has sufficiently degraded, and truly represents waste, it is then that other waste management options should be considered. Until that time, using the term 'waste management' is a misnomer. What is normally dubbed 'waste paper' is not in fact waste at all. It is a resource, and should be treated as such.

However, when the life has been exhausted from paper fibre, the most environmentally conscious use of the waste will depend on management objectives, and proximity to appropriate facilities. If the goal is limit greenhouse gases, landfill with methane capture is the best alternative. If the goal is to save energy, and lower the need for new dams or nuclear power plants, then combustion for combined heat and power is the better option.

But to answer Tierney's question: Is recycling actually beneficial for the environment? For pulp and paper, when used with other appropriate waste management techniques, from an energy and greenhouse gas standpoint, the answer is almost certainly yes.

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Appendices

Appendix 1: Energy Recovery from Landfill Methane

Potential Methane Emissions = 0.09 T/T (Micales and Skog 1997)
Energy Density = 50.0 GJ/T (Thomas 2000)
Recovery Factor = 0.91 (O'Brien 2008)
Energy Recovery (*ER*) = $0.09\ T/T \times 50.0\ GJ/T \times 0.91$
***ER* = 4.10 GJ/T**

Appendix 2: Electrical Energy Yield from Paper Waste from EFW

Energy Density of Paper = 17.3 GJ/T (Morris 1996)
Electrical Efficiency = 15% (Morris 1996)
Electrical Yield (*EY*) = $17.3\ GJ/T \times 0.15$
***EY* = 2.60 GJ/T**

Appendix 3: Cogeneration Energy Yield from Paper Waste

Electrical Efficiency = 27.5% (FAO 1990)	Thermal Efficiency = 47.5% (FAO 1990)
Energy Density of Paper = 17.3 GJ/T (Morris 1996)	Thermal Yield (*TY*) = $17.3\ GJ/T \times 0.475$
Electrical Yield (*EY*) = $17.3\ GJ/T \times 0.275$	***TY* = 8.22 GJ/T**
***EY* = 4.76 GJ/T**	

Appendix 4: Cogeneration Energy Yield from Conserved Fibre

Electrical Efficiency = 27.5% (FAO 1990)	Thermal Efficiency = 47.5% (FAO 1990)
Energy Density of Wood Fibre = 19.2 GJ/T (Welling and Shaw 2007)	Wood Fibre Input = 1.64 T/T (Morris 1996; Kofman 2006)
Harvest Energy Cost = 0.95 GJ/T	Harvested Fibre Proportion = 50%
Electrical Harvest Proportion = 50%	Thermal Harvest Proportion = 50%
Electrical Yield (*EY*) = $1.64(19.2\ GJ/T \times 0.275 - (0.95\ GJ/T \times 0.5 \times 0.5))$	Thermal Yield (*TY*) = $19.2\ GJ/T \times 0.475 - (0.95\ GJ/T \times 0.5 \times 0.5)$
***EY* = 8.27 GJ/T**	***TY* = 14.6 GJ/T**

Appendix 5: Virgin and Recycled Paper Energy Costs in Canada

R = Energy Cost of Recycled Paper	V = Energy Cost of Virgin Paper
Mean Energy Consumption = 26.2 GJ/T (NRCan 2008a)	Energy reduction *via* recycling = 43% (Bourdages 1993)
Proportion Recycled = 0.251 (PPPC 2007)	Proportion Virgin = 0.749 (PPPC 2007)
$0.251R + 0.749V = 26.2\ GJ/T$	***V* = 29.4 GJ/T**
$R = (1 - 0.43)V$	$R = 0.57V$
$R = 0.57V$	$R = 0.57(29.4\ GJ/T)$
$0.251(0.57V) + 0.749V = 26.2\ GJ/T$	***R* = 16.7 GJ/T**
$0.143V + 0.749V = 26.2\ GJ/T$	$V - R = 29.4\ GJ/T - 16.7\ GJ/T$
$0.892V = 26.2\ GJ/T$	***V* - *R* = 12.6 GJ/T**
$V = \frac{26.2\ GJ/T}{0.892}$	

Appendix 6: Net Energy yields from Waste Paper Management Options, Multiple Cycles

Management Method	**Net Energy Surplus (GJ/T)**		
	1 Cycle	4 Cycles	7 Cycles
Landfill (LF)	0.00	0.00	0.00
Energy-from-Waste (EFW)	2.60	2.60	2.60
Landfill with Methane Recovery	4.10	4.10	4.10
Recycling	12.6	34.1	48.5
Cogeneration	13.0	13.0	13.0
Recycling with EFW	15.2	36.7	51.1
Recycling with Landfill with Methane Recovery	16.7	38.2	52.6
Recycling with Cogeneration	25.6	47.1	61.5
Recycling with Conserved Fibre Potential	35.4	96.0	136
Recycling with Conserved Fibre Potential, EFW	38.0	98.6	139
Recycling with Conserved Fibre Potential, LF w/Methane Recovery	39.5	100	141
Recycling with Conserved Fibre Potential, Cogeneration	48.4	109	149

Appendix 7: Proportion of Electrical Consumption for Virgin and Recycled Paper (using Schmidt *et al*. energy sources)

Proportion Recycled = 0.251	Proportion Virgin = 0.749
r = Proportion Electrical Energy Consumption of Recycled Paper	v = Proportion Electrical Energy Consumption of Virgin Paper
$0.251r + 0.749v = 0.184$ (NRCan 2008a)	**$v = 0.18$ (Δ from mean = -2.6%)**
$r = 1.10v$ (Schmidt *et al*. 2007)	$r = 1.10v$
$0.251(1.10v) + 0.749v = 0.184$	$r = 1.10(0.18)$
$0.276v + 0.749v = 0.184$	**$r = 0.197$ (Δ from mean = 7.1%)**
$1.03v = 18.4\%$	$\Delta = 0.18 - 0.197$
$v = \frac{0.184}{1.03}$	**$\Delta = -0.0174$**

Appendix 8: Sources of Fossil Fuel Energy in Pulp and Paper Production in Canada, by feedstock (using Schmidt *et al*. energy sources)

	Coal		**Natural Gas**		**Petroleum**		**Total**		**Change**
	Virgin	**Recycled**	**Virgin**	**Recycled**	**Virgin**	**Recycled**	**Virgin**	**Recycled**	
Electricity	2.96%	3.26%	0.93%	1.03%	0.34%	0.38%	4.24%	4.66%	*-9.98%*
Fossil Fuels	0.08%	0.08%	14.48%	14.17%	5.67%	5.55%	20.24%	19.80%	*2.18%*
Steam	-	-	5.03%	4.92%	-	-	5.03%	4.92%	*2.18%*
Total	*3.04%*	*3.34%*	*20.45%*	*20.11%*	*6.01%*	*5.92%*	*29.50%*	*29.37%*	**0.44%**

Appendix 9: Greenhouse Gas Emissions from Fossil Fuel Production and Combustion

Emission Origin	**Coal ($kg\ CO_2/GJ$)**	**Natural Gas ($kg\ CO_2/GJ$)**	**Petroleum ($kg\ CO_2/GJ$)**
Combustion (Roarty 1998)	91	55	68
Refining and Transportation (Wang *et al*. 2004, Jaramillo *et al*. 2007)	6	12	15
Total	*97*	*67*	*83*

Appendix 10: Greenhouse Gas Emissions Reductions from Waste Paper Management Options, Multiple Cycles

Management Method	GHG Reductions (kg CO2e/T)		
	1 Cycle	4 Cycles	7 Cycles
Landfill (LF)	567	567	567
Energy-from-Waste (EFW)	195	195	195
Landfill with Methane Recovery	2562	2562	2562
Recycling	369	999	1421
Recycling with Landfill	936	1566	1988
Cogeneration	1021	1021	1021
Recycling with EFW	564	1194	1616
Recycling with Landfill with Methane Recovery	2931	3561	3983
Recycling with Cogeneration	1390	2020	2442
Recycling with Conserved Fibre Potential	2169	5875	8351
Recycling with Conserved Fibre Potential, EFW	2364	6070	8546
Recycling with Conserved Fibre Potential, LF w/Methane Recovery	4731	8437	10913
Recycling with Conserved Fibre Potential, Cogeneration	3190	6896	9372