CHBE 484 – Green Engineering Principles

Textbooks on Paper or E-Reader: A Comparative Life Cycle Assessment

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Table of Contents

1.0 INTRODUCTION

From the first printed paper book dated back in the 1880's to the 21st Century, the publication sector has grown productive ever so rapidly, with approximately 5% annual increase in new book titles (Figure 1). Books have indeed served its purpose to increase literacy and information accessibility. However, this explosion of information has also shortened the lifespan of the books, where information needs to be updated at an ever increasing rate.

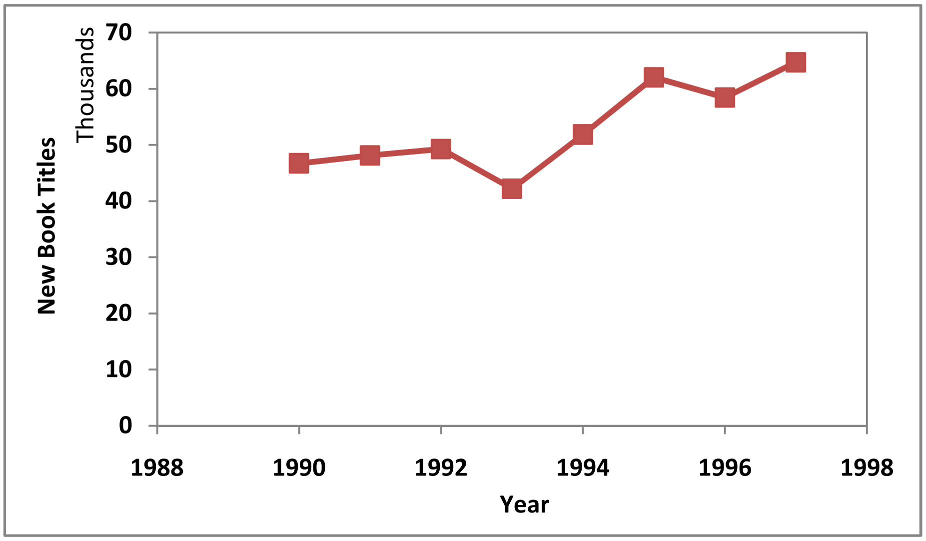

Figure 1. Increase in Book Titles in the US (IPA Geneva, 2001)

Craving for the most current information and knowledge, the university and its students are a major consumer in this material and energy intensive publishing industry. With 35,518 undergraduate and 8,368 graduate students (UBC Calendar, 2008), the University of British Columbia has a significant impact on the material and energy consumption as well as the environmental impacts associated with the production and use of books.

This paper compares two textbook options for the undergraduate students at UBC – the conventional printed paper books and the portable electronic book reading devices. The two options are evaluated on a life cycle basis by their material use, energy consumption, environmental impact, and economical profit.

The life cycle assessment (LCA) considers the material use, energy consumption, pollutant emission and waste generation involved in each step of a product's life, graphically represented in Figure 2. This paper divides the life cycles of each textbook option into five stages – raw material processing, product assembly, distribution, use, and disposal.

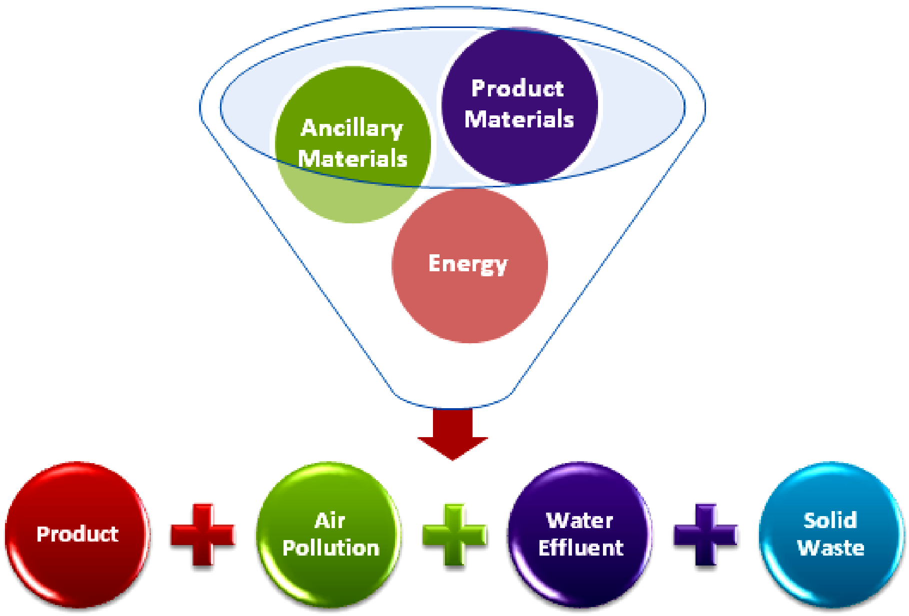

Figure 2. Process Framework

The comparison is established based on a typical undergraduate engineering student enrolled in a 4-year program with a full course load, where a portable 12" color LCD screen electronic device as well as electronic data stored on the publisher's computer network is proposed to replace the textbooks used during the undergraduate studies. Due to the renewal of textbook editions and the change of textbooks used from year to year and instructor and instructor, 50% of the textbook is assumed to be resold. The E-reader, if properly maintained, should have an expected lifespan of approximately 10 years; each E-reader is assumed to be resold once to the next student.

2.0 PRINTED TEXTBOOK LIFE CYCLE

Conventional textbook life cycle including raw material production, manufacturing, distribution, use and finally disposal are presented in this section. As can be seen on the process diagram, environmental burdens of raw material extraction such as wood harvesting and petroleum production are incorporated in material processing of paper and ink, respectively (Figure 3).

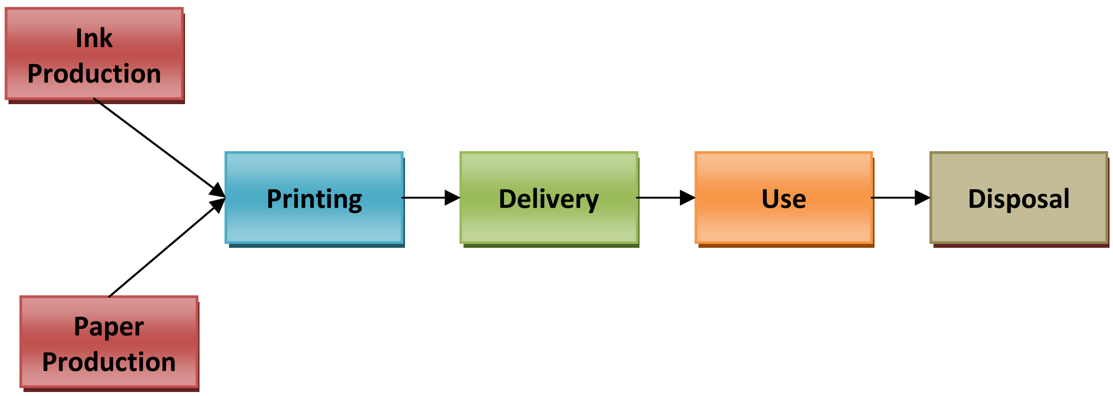

Figure 3. Life Cycle Process Flow Diagram for Conventional Textbooks

For the purpose of this study total number of textbooks used by an engineering student through out a 4-year undergraduate career is calculated based on the number of textbooks used in the first year and then multiplied by an appropriate factor for all consecutive years. It is assumed that freshmen use the most textbooks equal to about 8 textbooks per year with an average of approximately 1 textbook per each of the 8 courses in terms 1 and 2. In the second year students acquire approximately 80% of the amount of textbook they used in first year; 50% and 30% subsequently in their third and fourth years. Under this assumption total number of textbooks for one engineering student is slightly over 20 for all 4 year, and with each book weighing about 3.62 kg total mass of textbooks used is approximately 75.3 kg. Further assumption is made that 50% of the textbooks are reused in the following year such that each resold textbook is used by 2 students through out its life time before it is disposed of. A typical list of textbooks used by an undergraduate engineering student at UBC is presented in Appendix E.

2.1 Raw Material Production

Printed textbook primary components such as paper and ink are derived from harvested wood and petroleum stocks. For the purposed of this study impacts of the raw material extraction are incorporated under production of paper and ink.

Paper production includes the following steps: timber preparation, pulping, bleaching, refining, sheet forming, coating, drying, calendaring, cutting and finally packaging. Once the logs are delivered to the mill they are soaked in water, debarked and fed into the chipper. Pulping process separates lignin and other components from cellulose fibres used to make paper. For chemical pulping wood chips are treated with white liquor to dissolve lignin and digested pulp is then bleached with a combination of chlorine, chlorine dioxide, ozone and peroxide. Next pulp is refined using a series of rotating serrated metal disks to flatten individual cellulose fibres. Refined pulp is then mixed with clay or talc to form a paper web, which is then coated and dried. Finally paper roll is cut, boxed and wrapped for delivery.

Primary components of lithographic ink commonly used in textbook are pigments, vehicles and modifiers. To produce pigments, refined petroleum components are treated through a series of synthesizing and finishing stages. They are then filtered to remove impurities and finally washed such that the finished product contains only pigment and water. Vehicles are a type of oil-based lacquer films that are used to wet, carry and bond pigments in the ink to the paper. And modifiers are oil derivatives used to adjust ink press performance. Both vehicles and modifiers are additives produced prior to the ink manufacturing process.

To produce enough paper and ink for all textbooks of the 4-year engineering curriculum requires 218 kg of raw materials and about 2930 MJ of energy. Assuming 50% reuse rate these numbers are 145 kg and 1953 MJ of raw materials and energy, per engineering student, respectively.

2.2 Textbook Printing

Most common printing process used in textbook manufacturing, offset lithography, is described in this section. Images are put on plates and then damped by water and than ink. The process works on the principle that the ink is highly oleophilic, i.e. has greater affinity to oil than water, and as a result it adheres oil-based image areas and is repelled from wet non-image areas. Images are then transferred to a rubber blanket, and then finally from rubber blanket to paper. Overall printing process consists of pre-press, press and post-press stages outlined next. During pre-press digital files containing text and images are used to create negatives that are then transferred to printing plates. To transfer the image onto a plate, the plate is exposed to a controlled amount of light that activates ink-receptive coating in a similar way to the process of developing photographs. Next paper is pressed either continuously though a series of cylinders if it has not been previously cut or using sheet-fed presses for pre-cut paper.

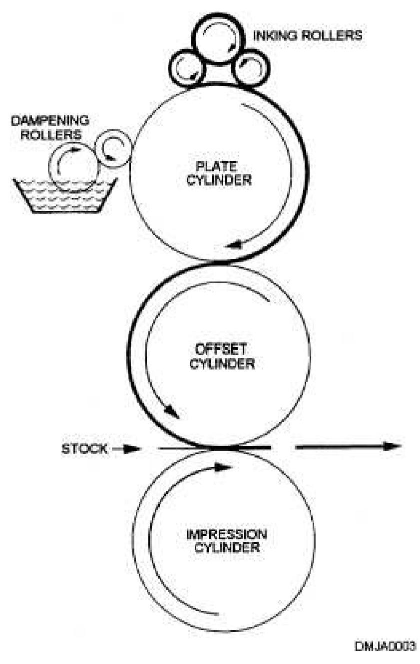

Figure 4. Offset Lithography Schematic

A schematic of offset lithography set up is shown on Figure 4 above. The plate cylinders are dampened by water and ink rollers such that the ink adheres to the image area and is repelled by wet non-image areas. The plate cylinder is then transfers the image to a rubber blanket of the offset cylinder, which in turn transfers the image to the paper. Next, to avoid smudging the paper is fed through an oven dryer and then a series of chill rollers to cool down the paper and set in the ink. Post-press production includes cutting paper into sheets, assembling them in the correct order, sewing and binding together. Most scholarly textbook are bound using Smyth sewn technique which is more durable than adhesive case binding, and has an added feature of the stitched being overlapped with one another, which allows the book to lie open flat.

Textbook manufacturing process utilizes 10 kg of raw materials and 209 MJ of energy to produce entire 4-year textbook supply for one undergraduate engineering student. As before, using a reuse rate of 50% 6.7 kg of raw materials and 139 MJ of energy are needed per student.

2.3 Distribution

Once manufactured textbooks are shipped from the printing location to the wholesaler warehouses and finally to thousands of retail locations through out the country. For the purpose of this study UBC Bookstore is considered the primary retail location where a vast majority of UBC undergraduate engineering students purchase their textbooks. Furthermore, all leading publishers of scholarly textbooks such as John Wiley & Sons Canada Limited, McGraw-Hill Ryerson Limited and Pearson Education Canada are located in Ontario. Therefore, environmental impacts of textbook distributions are calculated based on these assumptions. Furthermore, it is assumed that a typical heavy duty class 8 diesel tractor-trailer is used to deliver textbooks with an energy consumption of approximately 1465 Btu/mile per ton of carried weight.

Transportation of textbooks requires about 0.9 kg of raw materials and 51.8 MJ of energy for all 4 years of undergraduate engineering books, or about 0.6 kg and 34.5 MJ of raw materials and energy per student.

2.4 Use

For the purpose of this analysis environmental impact associated with the use of textbooks amounts to book storage and facility infrastructure required to maintain a collection of books. Facility infrastructure refers to the UBC Bookstore where, as mentioned above, the majority of textbooks are distributed. The calculated impact is considered negligible compared to the environmental burden of raw material extraction, processing, printing and distribution. Moreover, environmental effect of personal transportation to the bookstore is not included in the scope of this study.

2.5 Disposal

Environmental impact of textbook disposal is eliminated from this analysis based on the justification that scholarly books are purchased with the intent of keeping them indefinitely. It has been previously stated that printed books made from quality materials using offset lithography and Smyth sewn binding can survive up to 400 years under normal use. Aside from the reuse factor of 50% that is used to reduce the environmental burned of raw material production, textbook publishing and distribution per student, textbook disposition is excluded from this study.

2.6 Summary

A summary of material and energy inputs as well as total emissions is presented below for the life cycle of all required undergraduate engineering textbooks.

Table 1. Material and Energy Inputs of Undergraduate Engineering Textbooks

	Material (kg)	Energy (MJ)	Water Emissions (g)	Air Emissions (g)	Solid Waste kg)
Raw Material	218	2932	818	191229	4
Manufacturing	10	209	191	85919	164
Distribution	9	518	499	46018	3
Use	0	0	0	0	0
Disposal	0	0	0	0	0
Total	**237**	**3659**	**1508**	**323166**	**170**

Considering 50% reuse rate for textbook there is a shared burden for raw material production, textbook publishing and distribution stages of the life cycle. The average for each student is presented below.

Table 2. Material and Energy Inputs per Student (Textbooks)

	Material (kg)	Energy (MJ)	Water Emissions (g)	Air Emissions (g)	Solid Waste (kg)
Printed Book	158	2439	1005	215444	113

The life cycle inventories are presented in Appendix A. Environmental impacts on global warming, ozone depletion and acid rain formation are summarized in Table 3 below, and can be found in Appendix C.

Table 3. Environmental Impacts of Undergraduate Engineering Textbooks

	Raw Material	Manufacture	Distribution	Use	Disposal	Total
GW (eq CO2 kg)	213.50	145.33	6.95	0	0	366
OD (eq CFC-11 kg)	1.28E-07	1.77E-06	5.23E-09	0	0	1.91E-06
AR (eq SO2 kg)	1.07	0.66	0.35	0	0	2.08

Considering 50% reuse rate, the average for each student is presented below.

Table 4. Environmental Impacts per Student (Textbooks)

	Raw Material	Manufacture	Distribution	Use	Disposal	Total
GW (eq CO2 kg)	142.33	96.88	4.63	0	0	244
OD (eq CFC-11 kg)	8.52E-08	1.18E-06	3.48E-09	0	0	1.27E-06
AR (eq SO2 kg)	0.71	0.44	0.23	0	0	1.39

3.0 E-READER LIFE CYCLE

An E-reader is a portable electronic device dedicated to viewing electronic books. Although current E-reader industry is immature and the majority of E-reader screens on the market are less than 10” and mono toned, software and hardware giants such as Microsoft and Adobe have invested in the development of an e-book market system with appropriate software, hardware, and data management. This paper discusses the life cycle assessment of a 12” color screened E-reader, likely going to be commercialized in a few years. The life cycle has been divided into five stages outlined in Figure 5 below.

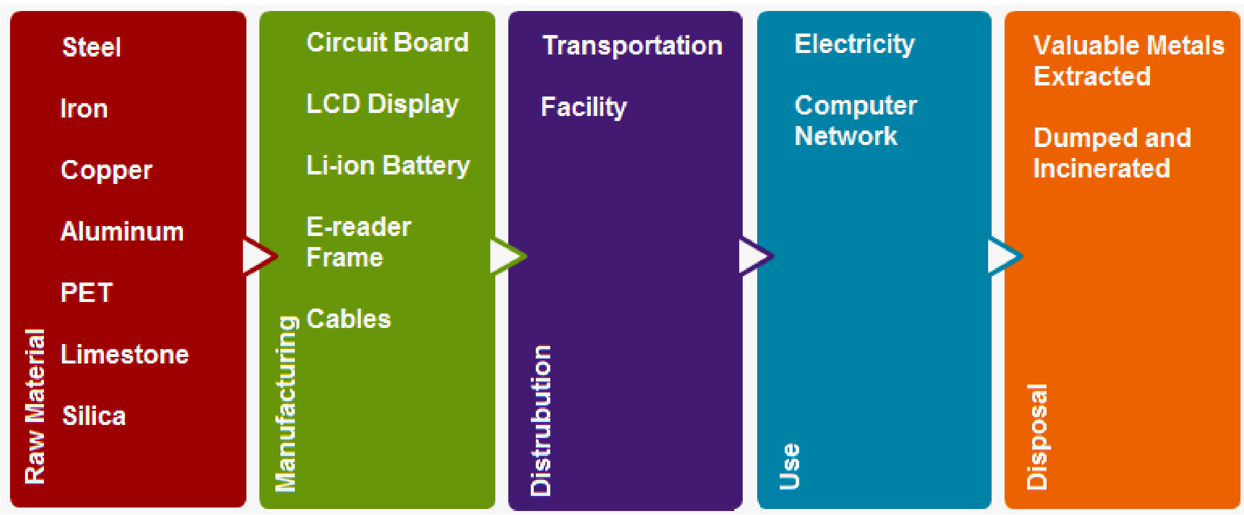

Figure 5. Life Cycle Stages for E-Books & E-Readers

The life cycle inventories for each life cycle stage can be found in Appendix B.

3.1 Raw Material Preparation

The primary sources of raw material for the making of one electronic E-reader are metals (0.504kg of iron, 0.063kg aluminum, 0.179kg copper, 0.015kg zinc and 0.030kg steel) and petroleum derived plastics (0.421kg of PVC, 0.257kg ABS), where the extraction and purification processes create burdens of 6.68kg and 97.8MJ of material and energy burdens.

As an example, steel is created from iron ore, sintered limestone and coked coal in an oxygen reactor vessel at around 3000°C where molten steel is created (Figure 6). After quenching, steel undergoes hot rolling mills where flat sheets are formed. These steel sheets are then cut, bent and welded to form the frame of the E-reader device.

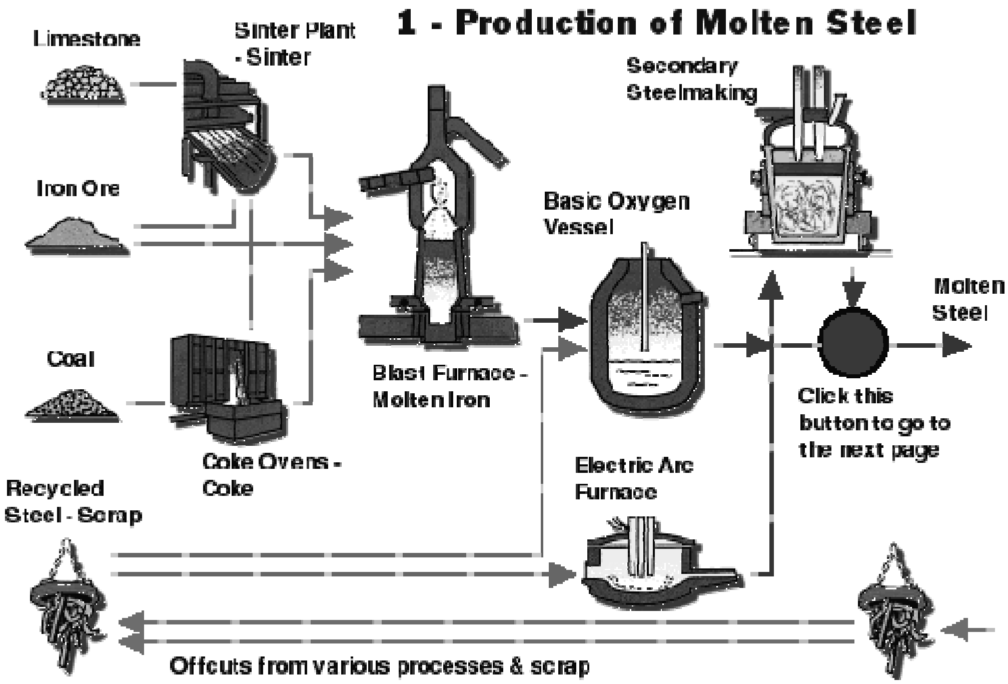

Figure 6. Production of Molten Steel

The E-reader body shell and buttons are made of polyvinyl chloride (PVC), derived from petroleum ethylene and from chlorine in the vinyl chloride monomer (VCM) process, and then the polymerisation of VCM in the S-PVC process (Figure 7).

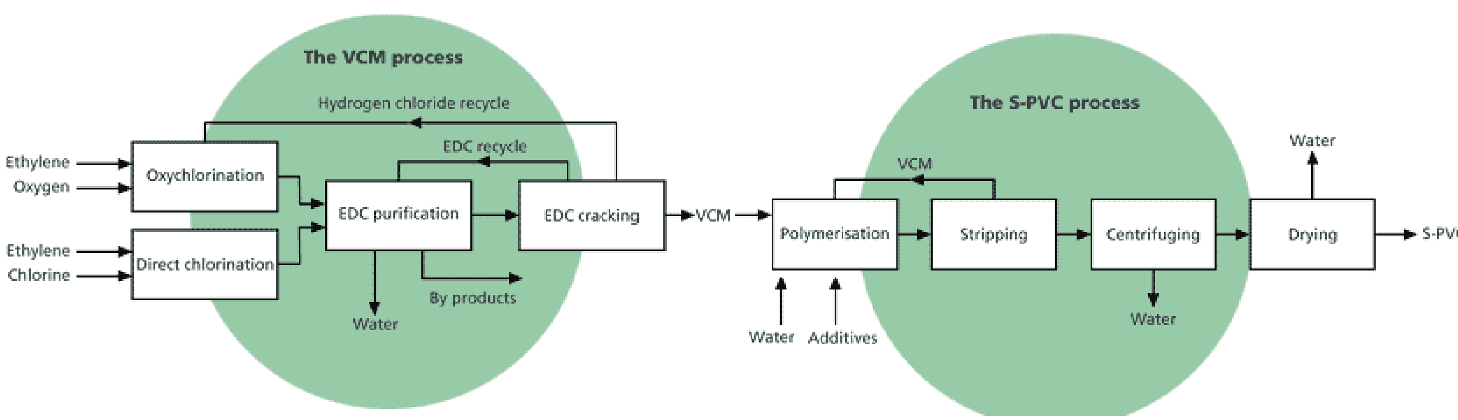

Figure 7. PVC Production (INEOS Vinyls, 2005)

3.2 Product Parts and Product Assembly

The major assemblies of an E-reader compose of – integrated circuit boards, liquid crystal display, rechargeable lithium ion battery, E-reader main body, and cables.

The integrated circuit board is a PET board coated by a layer of copper by physiosorption. The unnecessary copper is then removed using a computerized template by etching (circuit board printing). Conventionally, brominated flame retardants (BFR) are used to coat the circuit boards; however, halogen-free flame retardants are eagerly pursued by computer manufacturers (with Dell planning to completely eliminate BFR by 2009).

The liquid crystal display (LCD) screen is made by coating silicon oxide and indium tin oxide on the front and back of the glass support. Polyamides are applied to the glass surface for the alignment of liquid crystals. Finally the liquid crystal polymers are injected and sandwiched between the front and back glass (Advameg Inc, 2007).

The rechargeable lithium ion battery is made of a cobalt oxide anode and a graphite cathode with entrained lithium ions. The electrolyte is a lithium salt typically $LiPF_6$. A steel casing is employed to protect the battery cell stack. The average single charge battery life is roughly 5 hours. If properly maintained, the Li-ion battery should have a product lifetime of more than 10 years. Interests in direct methanol fuelled battery stacks are gaining interest with prolonged battery life and product lifetime.

The E-reader body is made of a steel frame mechanically bent and welded. The PET shell is made by thermal moulding and pieced together by screws. Electrical cables and wires are made from stranded thermal extruded and tensioned copper wires wrapped in a flexible insulating plastic.

A total of 45.1kg of material use and 455MJ of energy consumption is expected from the manufacturing processes of one E-Reader.

3.3 Distribution

After the E-reader production process, it is transported to the university bookstore. With a large volume of production, intermediate storage has relatively low energy intensity per footprint, and the environmental impacts are considered negligible. A 500 mile (800 km) travel distance from the E-reader factory to the university bookstore is assumed. A typical a heavy duty class 8 diesel tractor-trailer is used for the delivery, with an energy consumption of 1465 Btu/mile per ton of carried weight. The major pollutants from the burning of the diesel fuel include CO_2, NO_x, and SO_x. An E-reader weight of 1.5kg is assumed, consuming 0.00343gal of fuel, and emitting 40.7g of air pollutants.

3.4 Use

Electricity will be consumed during the use of E-readers, from the direct electricity use, and also from the data storage on publishers' computer network server (negligible). It is assumed that the student reads 1 hour a day during the school year (1270 hours in eight undergraduate school terms), and the E-reader consumes 24 watts of electricity per hour. 110 MJ of electrical energy is consumed in four years of academic studies. The electricity and computer network create burdens of 16.6kg and 493MJ in material and energy consumption.

3.5 Disposal

The disposal of E-reader to landfill is assumed, with no recycling, in the analysis. Burdens associated with electronic device disposal to landfills is estimated by Keep America Beautiful, Inc. However, the extend of many negative impacts associated with electronic devices such as heavy metals and brominated flame retardants are not known. Many electronic manufacturers are switching to a BFR replacement, Firemaster®550 (EPA, 2008), which is supposed to be safer and environmentally sound (EPA, 2003).

3.6 Summary

A summary of material and energy input as well as total emissions is presented below for the life cycle of one E-reader without recycle.

Table 5. Material and Energy Input for One E-Reader

	Material (kg)	Energy (MJ)	Water Emissions (g)	Air Emissions (g)	Solid Waste (kg)
Raw Material	7	98	62	4800	0
Manufacturing	45	455	266	12584	5
Distribution	0	1	0	41	0
Use	17	493	297	39514	79
Disposal	0	1	0	487	2
Total	**68**	**1047**	**626**	**57425**	**86**

Considering that each E-reader is used by 2 students, where each shares the burdens from all life cycle stages but the use stage. The average for each student is presented below.

Table 6. Material and Energy Input Per Student (E-Reader)

Material (kg)	Energy (MJ)	Water Emissions (g)	Air Emissions (g)	Solid Waste (kg)
43	**770**	**464**	**48470**	**83**

The life cycle inventories are presented in Appendix B. Environmental Impacts in global warming, ozone depletion and acid rain formation are summarized in Table 7 below, and can be found in Appendix D.

Table 7. Environmental Impacts for One E-Reader

	Raw Material	Manufacture	Distribution	Use	Disposal	Total
GW (eq CO2 kg)	**5.39**	**38**	**2.16**	**82.6**	**3.45**	**131**
OD (eq CFC-11 kg)	**7.42E-07**	**3.88E-08**	**5.00E-10**	**1.70E-06**	**0**	**2.49E-06**
AR (eq SO2 kg)	**0.0655**	**0.262**	**0.0436**	**0.502**	**0**	**0.873**

Considering that each E-reader is used by 2 students, where each shares the burdens from all life cycle stages but the use stage. The average for each student is presented below.

Table 8. Environmental Impacts Per Student (E-Reader)

	Raw Material	Manufacture	Distribution	Use	Disposal	Total
GW (eq CO2 kg)	2.69	19	1.08	82.6	1.72	107
OD (eq CFC-11 kg)	3.71E-07	1.94E-08	2.50E-10	1.70E-06	0	2.09E-06
AR (eq SO2 kg)	0.03	0.13	0.02	0.50	0	0.69

4.0 Comparative Assessment

In order to compare environmental impact of undergraduate engineering textbooks to a proposed 12” colour screen E-reader raw material consumption, energy requirements, water and air emissions and solid waste generation are normalized per student for both textbooks and the E-reader. As mentioned earlier a 50% reuse rate for textbooks is assumed, while the impact of one E-reader is shared by 2 students for all stages of E-reader life cycle, except for usage. The summary of raw material and energy consumptions as well as water and air emissions and the amount of solid waste generated for the entire life cycle of both the textbooks and the E-reader is presented in the Table 9 below.

Table 9. Material, Energy, Emissions Summary

	Material (kg)	Energy (MJ)	Water Emissions (g)	Air Emissions (g)	Solid Waste (kg)
Printed Book	158	2439	1005	215444	113
E-Book	43	770	462	48470	83
Score	3.7	3.2	2.2	4.4	1.4
Reduction	73.0%	68.4%	54.1%	77.5%	26.8%

The comparison is bases a score system, where amount of resources consumed during the life cycle of the E-reader is equal to unity. Then since the same resources used for the production and distribution of printed textbooks are typically number of times greater, dividing conventional book impact by that of the E-reader produces a dimensionless score number greater than 1, and thus the score is assigned. For example, amount of raw materials used through out the life cycle of undergraduate engineering textbooks per student is about 158 kg, while the E-reader consumption is only 43 kg of raw materials per student. As a result textbooks utilize 3.7 times more raw materials compared to the E-reader and thus results in a score of 3.7. The greater the score the lesser environmental burden of the E-reader compared to that of the conventional textbooks. Overall, the E-reader performed better in all categories with scores of 3.7, 3.2, 2.2, 4.4 and 1.4 for source depletion of raw materials and energy, water and air emissions, and solid waste generation, respectively. Another way to evaluate the environmental effect of the E-reader is to calculate percent reduction in the amount of resources depleted and emissions and waste produced compared to the printed books. These results are also presented in Table 9 above.

Air emissions are further classified into their effect on global warming potential, ozone depletion and acid rain potential for the life cycle of both printed textbook and the E-reader. The results are again normalized per student for comparison. Except for ozone depletion potential, E-reader life cycle resulted in about 50% reduction of both global warming and acid rain potentials, expresses as kilograms of CO_2 and SO_2 emitted, respectively (Table 10). These reductions produced scores of 2.3 and 2.0 compared to the conventional textbooks. Due to the types of chemicals used in the manufacturing of E-reader components ozone depletion effect of the E-reader is actually about 65% greater than printed books with a score of 0.6. Overall ozone depletion is expressed in equivalent kilograms of CFC-11 emitted per life cycle.

Table 10. Environmental Impact Summary

	GW (eq CO2 kg)	OD (eq CFC-11 kg)	AR (eq SO2 kg)
Printed Book	244	1.27E-06	1.39
E-Book	107	2.09E-06	0.69
Score	2.3	0.6	2.0
Reduction	56.1%	-64.9%	50.4%

Overall environmental performance of conventional textbooks and the E-reader used by one student are evaluated using a hierarchical ranking structure presented below (Figure 8).

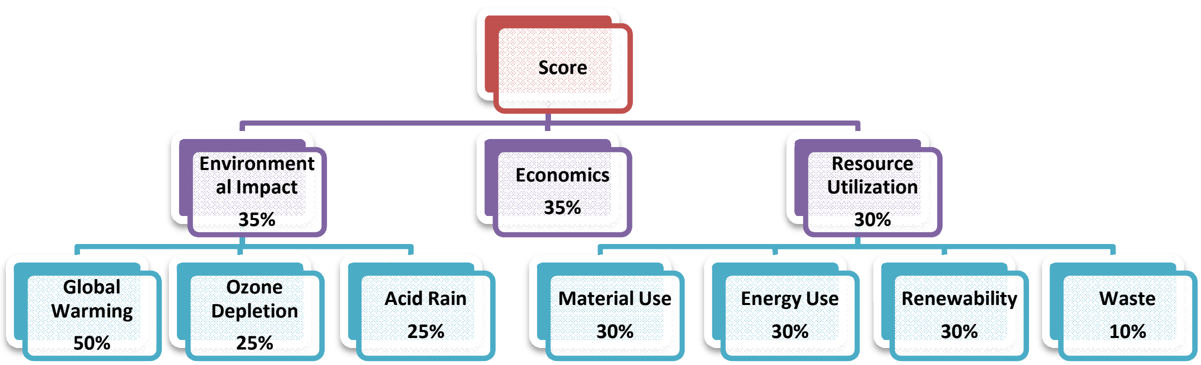

Figure 8. Weight Factor

Weight factors are arbitrarily assigned bases on the perceived importance of the contributing aspects. Environmental impact consisting of global warming potential, ozone depletion and acid rain potential is weighted at 35%, while economics and resource utilization are at 35% and 30%, respectively. The weight of environmental impacts is further distributed as 50% for global warming potential, and 25% for ozone depletion and acid rain potential each. Resource utilization is also broken down into material and energy uses, renewability and waste generation. It is assumed that the E-reader is non-renewable aside from the fact that is it recycled once through out its lifetime, as a result a renewability score for the E-reader is zero. Material and energy uses and renewability are then weighted at 30%, while waste generation is at 10%.

Overall score of 1.7 is calculated bases on the weighted sum of all individual scores presented in the Table 11 below. In other words, overall environmental impact of E-reader life cycle is about 58.8% compared to that of the conventional printed textbooks.

Table 11. E-Book vs. Printed Book Score

				Overall Score
Environment	Global Warming	2.3	1.8	**1.7**
	Ozone Depletion	0.6		
	Acid Rain	2.0		
Economics	Savings	1.1	1.1	
Resource Use	Material	3.7	2.3	
	Energy	3.2		
	Renewability	0		
	Waste	2.7		

5.0 Economical Assessment

The purpose of this paper is to convince the undergraduate students to recognize the potential of the electronic book system, and eventually to support the system. Therefore the economical assessment is evaluated from the students' point of view. A typical undergraduate engineering student is considered in the evaluation, for whom the amount of textbook needed declines to 80%, 50% and 30% of his freshman year needs in subsequent years of his/her education. Because textbooks may differ from year to year, 50% of the text will be purchased new and 50% used from the bookstore. The resell value is estimated at 75% of the new book cost, and the seller receives 50% of the new book value from the UBC Bookstore.

The E-reader device discussed has not currently been commercialized, thus an estimated cost of $600 is considered. The purchase cost of electronic books is approximately 50% of the paper book equivalent (Amazon). In recent years, major publishers have been less reluctant to release electronic copies of their publications, despite the fear that the e-book industry may experience copyright issues similar to the music industry. Software solutions are developed such as the Adobe PDF Merchant and Microsoft United DRM (Hilts, 2003) to manage copyrighted material and avoid invasion to intellectual property. Therefore students cannot resell or distribute e-books, but pay for each copy they acquire. If properly maintained, the E-reader should have a lifetime in excess of 10 years. A single time resell of the E-reader is considered where the resell value imitates the current UBC Bookstore buyback setup.

The following table outlines the non-discounted cash flow from the students' perspective, where an average saving of $147.10 per student is expected.

Table 12. Non-discounted Student Cash Flow

E-BOOK PRICE = -$ 600.00

	PRINTED BOOK				E-BOOK		
Year	**Person 1**		**Person 2**		**Person 1**		**Person 2**
	Book Cost	Resell Revenue	Book Cost	Resell Revenue	Cost	Resell Revenue	Cost
1	-$1,070.98	$267.75	-$937.11	$267.75	-$1,135.49	$300.00	-$985.49
2	-$856.78	$214.20	-$749.69	$214.20	-$428.39	$0.00	-$428.39
3	-$535.49	$133.87	-$468.55	$133.87	-$267.75	$0.00	-$267.75
4	-$321.29	$80.32	-$281.13	$80.32	-$160.65	$0.00	-$160.65
Total		**-$2,088.41**		**-$1,740.34**		**-$1,692.27**	**-$1,842.27**
			Average	**-$1,914.38**		**Average**	**-$1,767.27**
						Savings	**$147.10**

6.0 Conclusion

The objectives of this study are to investigate the life cycle environmental aspects of conventional printed textbooks and a hypothetical 12” colour screen E-reader and compare the two. The LCA considers the material use, energy consumption, pollutant emission and waste generation involved in each step of a product life cycle. For each option the life cycle is broken down into five stages – raw material processing, product assembly, distribution, use, and disposal. The comparison is established based on the total textbook requirement for a typical undergraduate engineering student enrolled in a 4-year program with a full course load, where a portable 12” colour LCD screen electronic device and electronic data stored on the publisher’s computer network are proposed to replace the textbooks used during the undergraduate studies. Due to the renewal of textbook editions and the change of textbooks used from year to year and different instructors, 50% of the textbook is assumed to be resold and reused. The E-reader, if properly maintained, should have an expected lifespan of approximately 10 years, and therefore each E-reader is assumed to be resold once to the next student.

Based on this comparison overall environmental impact of the E-reader per student is then calculated using a dimensionless score system and a number of weight factors assigned to resource depletion, emissions and waste generation. One of the greatest reductions for the E-reader life cycle impact compared to that of the conventional textbooks is observed in raw material and energy utilization with 73% and 68%, respectively. Moreover, a 78% reduction in total air emissions such as global warming and aid rain potentials is obtained when E-reader is substituted for the printed books.

It should be noted that for the scope of the study the environmental life cycle burden of the E-reader is only compared to the total number of required textbooks for one engineering student during their 4-year undergraduate career. Nonetheless, the overall environmental impact is reduced by about 41.1% compared to that of the conventional printed textbooks. However, if E-readers are actively integrated into student life they have the potential to reduce not only printed textbook use, but also the amount of paper that goes into printing lecture notes, course materials, journal articles and other study resources. The quantity of paper and ink that are used to produce scholarly textbooks is a mere fraction of the total that is consumed through out undergraduate studies of any particular student. As a result, the environmental impact reduction associated with the use of electronic devices such as E-readers to replace paper and ink can be considerably higher.

A change to the student textbook system involves more than just the environment and economics, but also social change and technological advancements in electronic hardware and e-book software. Since the use of computers is widespread in the academic community, integration of the E-Reader with a tablet laptop will reduce not only the material used but also additional environmental benefits in reduced material use. Some existing issues with intellectual property concerns and publishers' willingness to release electronic copies of books still persist. The evolution of the textbook system is an on-going project for the environmental engineers, computer and software engineers, and particularly the social scientists.

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Appendix A – Printed Book Life Cycle Inventory

Table A1. Raw Material Process Inventory

Textbook Paper mass = 75.31 kg		
Material	**kg per kg paper**	**kg**
Clay	6.46E-02	4.87E+00
Coal	7.64E-02	5.75E+00
Lignite	3.04E-02	2.29E+00
Limestone	3.45E-02	2.60E+00
Natural gas	2.03E-01	1.53E+01
Oil	7.81E-02	5.88E+00
NaCl	3.67E-02	2.76E+00
Sulfur	1.38E-02	1.04E+00
Wood	2.33E+00	1.75E+02
Others	2.25E-02	1.69E+00
Total	**-**	**2.18E+02**
Energy	**MJ per kg paper**	**MJ**
	3.89E+01	**2.93E+03**
Water emissions	**g per kg paper**	**g**
	1.09E+01	**8.18E+02**
Air emissions	**g per kg paper**	**g**
	2.54E+03	**1.91E+05**
Solid waste	**kg per kg paper**	**kg**
	4.65E-02	**3.50E+00**

*Updated and scaled up from Kozac, 2003

Table A2. Printing Process Inventory

Material	kg per kg paper	kg
Heavy Fuel Oil	5.98E-02	4.51E+00
Natural Gas	7.32E-02	5.51E+00
Total	**-**	**1.00E+01**
Energy	**MJ per kg paper**	**MJ**
Electricity	2.77E+00	**2.09E+02**
Water emissions	**g per kg paper**	**g**
	2.53E+00	**1.91E+02**
Air emissions	**g per kg paper**	**g**
	1.14E+03	**8.59E+04**
Solid waste	**kg per kg paper**	**kg**
	2.17E+00	**1.64E+02**

*Updated and scaled up from Kozac, 2003

Table A3. Textbook Delivery Inventory

Trip distance = 3000 miles

Fuel Efficiency = 9.4 gal/1000 mile.ton

Energy Consumption = 1465 But/mile.ton

Material	kg per kg paper	kg
Diesel	1.19E-02	**8.97E-01**
Energy	**MJ per kg paper**	**MJ**
	6.88E-01	**5.18E+01**
Water emissions	**g per kg paper**	**g**
	6.63E-01	**4.99E+01**
Air emissions	**g per kg paper**	**g**
	6.11E+01	**4.60E+03**
Solid waste	**kg per kg paper**	**kg**
	3.38E-03	**2.55E-01**

*Updated and scaled up from Kozac, 2003

Appendix B – E-Reader Life Cycle Inventory

Table B1. Raw Material Process Inventory

Zinc Process	5.15E-02	kg	**Aluminum Process**	6.33E-02	kg	**Steel Process**	3.01E-02	kg	**Iron Process**	5.04E-01	kg
Material =	2.10E-01	kg	Material =	4.73E-01	kg	Material =	7.13E-02	kg	Material =	1.67E+00	kg
Energy =	3.01E+00	MJ	Energy =	1.08E+01	MJ	Energy =	8.14E-01	MJ	Energy =	1.66E+01	MJ
Water emissions =	3.29E+00	g	Water emissions =	7.55E+00	g	Water emissions =	7.44E+00	g	Water emissions =	3.12E+00	g
Air emissions =	2.44E+02	g	Air emissions =	5.32E+02	g	Air emissions =	2.73E+00	g	Air emissions =	1.35E+03	g
Solid waste =	1.13E-02	kg	Solid waste =	1.34E-02	kg	Solid waste =	7.18E-02	kg	Solid waste =	2.40E-01	kg
Copper Process	1.79E-01	kg	**ABS Process**	2.57E-01	kg	**Styrene-Butandiene**	6.76E-02	kg	**PVC Process**	4.21E-01	kg
Material =	7.66E-01	kg	Material =	2.55E+00	kg	Material =	1.23E-01	kg	Material =	8.07E-01	kg
Energy =	1.33E+01	MJ	Energy =	2.25E+01	MJ	Energy =	5.28E+00	MJ	Energy =	2.55E+01	MJ
Water emissions =	1.15E+01	g	Water emissions =	5.78E+00	g	Water emissions =	3.08E-01	g	Water emissions =	2.27E+01	g
Air emissions =	9.64E+02	g	Air emissions =	8.09E+02	g	Air emissions =	1.39E+02	g	Air emissions =	7.61E+02	g
Solid waste =	1.03E-04	kg	Solid waste =	3.14E-02	kg	Solid waste =	1.31E-04	kg	Solid waste =	3.73E-02	kg
Total											
Material =	**6.68E+00**	**kg**									
Energy =	**9.78E+01**	**MJ**									
Water emissions =	**6.17E+01**	**g**									
Air emissions =	**4.80E+03**	**g**									
Solid waste =	**4.06E-01**	**kg**									

*Updated and scaled up from Kozac, 2003

Table B2. Manufacturing Inventory

E-Reader			**Cable**			**Battery**		
Material =	4.47E+01	kg	Material =	2.33E-01	kg	Material =	1.79E-01	kg
Energy =	4.43E+02	MJ	Energy =	6.89E+00	MJ	Energy =	5.30E+00	MJ
Water emissions =	2.66E+02	g	Water emissions =	1.50E-01	g	Water emissions =	1.15E-01	g
Air emissions =	1.04E+04	g	Air emissions =	9.18E+02	g	Air emissions =	1.24E+03	g
Solid waste =	2.66E+00	kg	Solid waste =	1.11E+00	kg	Solid waste =	8.51E-01	kg
Total								
Material =	**4.51E+01**	**kg**						
Energy =	**4.55E+02**	**MJ**						
Water emissions =	**2.66E+02**	**g**						
Air emissions =	**1.26E+04**	**g**						
Solid waste =	**4.62E+00**	**kg**						

*Updated and scaled up from Kozac, 2003

Table B3. Distribution Inventory

Fuel consumed =	**3.43E-03**	**gal**
Energy =	**5.60E-01**	**MJ**
Water emissions =	**6.23E-02**	**g**
Air emissions =	**4.07E+01**	**g**
Solid waste =	**2.07E-04**	**kg**

*Updated and scaled up from Kozac, 2003

Table B4. Use Inventory

Data Storage	5.10E+01	MJ	**Reading**	5.05E+01	MJ
Material =	8.37E+00	kg	Material =	8.28E+00	kg
Energy =	2.48E+02	MJ	Energy =	2.45E+02	MJ
Water emissions =	5.39E+00	g	Water emissions =	2.92E+02	g
Air emissions =	1.99E+04	g	Air emissions =	1.96E+04	g
Solid waste =	3.98E+01	kg	Solid waste =	3.94E+01	kg
Total					
Material =	**1.66E+01**	**kg**			
Energy =	**4.93E+02**	**MJ**			
Water emissions =	**2.97E+02**	**g**			
Air emissions =	**3.95E+04**	**g**			
Solid waste =	**7.92E+01**	**kg**			

*Updated and scaled up from Kozac, 2003

Table B3. Distribution Inventory

Material =	**0.00E+00**	**kg**
Energy =	**1.35E+00**	**MJ**
Water emissions =	**3.67E-01**	**g**
Air emissions =	**4.87E+02**	**g**
Solid waste =	**2.20E+00**	**kg**

*Updated and scaled up from Kozac, 2003

Appendix C – Printed Book Environmental Impact

Table C1. Global Warming Potentials

Chemical	GWP*
Carbon dioxide (CO_2)	1
Methane (CH_4)	23
Carbon tetrafluoride (perfluormethane)	5,700
Nitrous oxide (N_2O)	296
Sulfur hexafluoride	22,200
HFC-23	12,000
HFC-125	3,400
HFC-134a	1,300
HFC-143a	4,300
HFC-152a	120
HFC-227ea	3,500
HFC-236fa	9,400
Perfluoroethane (C_2F_6)	11,900

*Kozac, 2003

Table C2. Ozone Depletion Potentials

Chemical	ODP*
1,1,1-trichloroethane (methyl chloroform)	0.1
CFC-12 (dichlorodifluoromethane)	1
CFC-13 (chlorotrifluoromethane)	1
Carbon tetrachloride (tetrachloromethane)	1.1
HALON-1301	10
HCFC-225ca	0.025
HCFC-225cb	0.033
Bromomethane (methylbromide)	0.7

*Kozac, 2003

Table C3. Acid Rain Potentials

Chemical	AP*
Ammonia (NH_4)	1.88[a]
Hydrochloric acid (HCl)	0.88[a]
Hydrofluoric acid (HF)	1.6[a]
Nitric oxide (NO)	1.07[a]
Nitrogen dioxide (NO_2)	0.7[a]
Nitrogen oxides (NOx)	0.7[a]
Sulfur dioxide (SO_2)	1[a]
Sulfur oxides (SOx)	1[a]
Sulfur trioxide (SO_3)	0.8[b]
Nitric acid (HNO_3)	0.51[b]
Sulfuric acid (H_2SO_4)	0.65[b]
Phosphoric acid (H_3O_4P)	0.98[b]
Hydrogen sulfide (H_2S)	1.88[b]

*Kozac, 2003

Table C4. Global Warming

	Raw Material	Manufacture	Distribution	Use	Disposal	Total
CO2 (g)	212389	136252	6080	0.0	0.0	**354720**
CH4 (g)	45.9	245	26.40	0.0	0.0	**317**
N2O (g)	0.22	12	0.53	0.0	0.00	**12.3**
FC 14 (g)	0.00	0.00	0.00	0.00	0.00	**0.0**
SF6 (g)	0.00	0.00	0.00	0.00	0.00	**0.00**
CO2 eq (kg)	**214**	**145**	**6.95**	**0.0**	**0.00**	**366**

*Updated and scaled up from Kozac, 2003

Table C5. Ozone Depletion

	Raw Material	Manufacture	Distribution	Use	Disposal	Total
Chlorothene (g)	5.40E-07	3.11E-04	4.36E-07	0.00E+00	0.00E+00	**3.12E-04**
Benziform (g)	1.13E-04	0.00E+00	2.46E-06	0.00E+00	0.00E+00	**1.16E-04**
Halon-1301 (g)	2.03E-09	2.71E-09	2.36E-09	0.00E+00	0.00E+00	**7.10E-09**
HCFC-225ca (g)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
HCFC-225cb (g)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Bromomethane (g)	4.31E-08	2.49E-03	3.49E-06	0.00E+00	0.00E+00	**2.50E-03**
CFC-11 eq (kg)	**1.28E-07**	**1.77E-06**	**5.23E-09**	**0.00E+00**	**0.00E+00**	**1.91E-06**

*Updated and scaled up from Kozac, 2003

Table C6. Acid Rain Formation

	Raw Material	Manufacture	Distribution	Use	Disposal	Total
NH4 (g)	5.12E+00	6.13E-01	1.76E-01	0.00E+00	0.00E+00	**5.91E+00**
HCl (g)	1.51E+01	1.87E+01	2.64E-01	0.00E+00	0.00E+00	**3.40E+01**
HF (g)	1.88E+00	2.34E+00	0.00E+00	0.00E+00	0.00E+00	**4.22E+00**
NOx (g)	9.95E+02	3.73E+02	3.03E+02	0.00E+00	0.00E+00	**1.67E+03**
SOx (g)	3.56E+02	3.73E+02	1.10E+02	0.00E+00	0.00E+00	**8.39E+02**
HNO3 (g)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
H2SO4 (g)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
H2S (g)	2.19E-02	4.38E-02	8.80E-02	0.00E+00	0.00E+00	**1.54E-01**
SO2 eq (kg)	**1.07E+00**	**6.56E-01**	**3.52E-01**	**0.00E+00**	**0.00E+00**	**2.08E+00**

*Updated and scaled up from Kozac, 2003

Appendix D – E-Reader Environmental Impact

Table D1. Global Warming

	Raw Material	Manufacture	Distribution	Use	Disposal	Total
CO2 (g)	4979	11581	2090	76416	347	**95413**
CH4 (g)	10.9	22	2.18	133	135	**303**
N2O (g)	0.13	0.35	0.00	10.4	0.00	**10.9**
FC 14 (g)	0.02	0.00	0.00	0.00	0.00	**0.02**
SF6 (g)	0.00	1.16	0.00	0.00	0.00	**1.16**
CO2 eq (kg)	**5.39**	**38**	**2.16**	**82.6**	**3.45**	**131**

*Updated and scaled up from Kozac, 2003

Table D2. Ozone Depletion

	Raw Material	Manufacture	Distribution	Use	Disposal	Total
Chlorothene (g)	8.07E-08	6.20E-06	4.01E-08	2.99E-04	0.00E+00	**3.05E-04**
Benziform (g)	5.69E-08	5.52E-08	2.44E-07	0.00E+00	0.00E+00	**3.57E-07**
Halon-1301 (g)	7.40E-05	6.44E-11	2.17E-10	5.67E-10	0.00E+00	**7.40E-05**
HCFC-225ca (g)	0.00E+00	5.91E-05	0.00E+00	0.00E+00	0.00E+00	**5.91E-05**
HCFC-225cb (g)	0.00E+00	5.91E-05	0.00E+00	0.00E+00	0.00E+00	**5.91E-05**
Bromomethane (g)	6.46E-07	4.97E-05	3.21E-07	2.40E-03	0.00E+00	**2.45E-03**
CFC-11 eq (kg)	**7.42E-07**	**3.88E-08**	**5.00E-10**	**1.70E-06**	**0.00E+00**	**2.49E-06**

*Updated and scaled up from Kozac, 2003

Table D3. Acid Rain Formation

	Raw Material	Manufacture	Distribution	Use	Disposal	Total
NH4 (g)	2.18E-02	9.88E+00	8.73E-02	0.00E+00	0.00E+00	**9.99E+00**
HCl (g)	3.49E-01	1.08E+01	4.36E-02	1.80E+01	0.00E+00	**2.91E+01**
HF (g)	2.18E-02	8.31E+00	0.00E+00	2.25E+00	0.00E+00	**1.06E+01**
NOx (g)	1.65E+01	2.31E+02	1.83E+01	2.84E+02	1.11E+00	**5.51E+02**
SOx (g)	4.35E+01	5.92E+01	2.26E+01	2.75E+02	1.53E-01	**4.00E+02**
HNO3 (g)	0.00E+00	4.36E-02	0.00E+00	0.00E+00	0.00E+00	**4.36E-02**
H2SO4 (g)	2.18E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**2.18E-04**
H2S (g)	3.71E-03	2.18E-04	6.55E-04	6.33E-03	0.00E+00	**1.09E-02**
SO2 eq (kg)	**6.55E-02**	**2.62E-01**	**4.36E-02**	**5.02E-01**	**0.00E+00**	**8.73E-01**

*Updated and scaled up from Kozac, 2003

Appendix E – Textbook Estimation

Table E1. Typical Undergraduate Chemical Engineering Student's Textbook Use

Year	Course	Amazon List Price (New)	Weight (kg)	pages	size (cm^2/pg)	Paper (m^2)
1	APSC 122	$0.00	0	0	0	0
	APSC 150	$37.95	0.32	200	349	3
	CPSC 152	$113.00	1.98	976	435	21
	CHEM 154	$112.95	2.84	1152	530	31
	ENGL 112	$66.85	0.70	432	348	8
	MATH 100	$144.95	2.39	936	549	26
	MATH 101	$0.00	0.00	0	0	0
	MATH 152	$0.00	0.00	0	0	0
	PHYS 153	$184.00	4.40	1714	552	47
	PHYS 170	$278.33	6.30	1390	973	68
	ECON 101	$132.95	1.42	568	537	15
	Sub-Total	**$1,070.98**	**20.36**	**7368**	-	**219**
2	APSC 201	$102.00	1.67	720	499	18
	APSC 262	$55.95	0.61	352	374	7
	CHBE 230	$130.94	1.24	608	439	13
	CHBE 241	$0.00	0.00	0	0	0
	CHBE 242	$157.50	2.50	1018	528	27
	CHBE 251	$149.38	2.00	864	497	21
	CHBE 262	$0.00	0.00	0	0	0
	CHEM 250	$0.00	0.00	0	0	0
	CHEM 251	$0.00	0.00	0	0	0
	CHEM 260	$190.95	3.29	1296	546	35
	MATH 253	$129.95	1.53	576	573	16
	MATH 256	$163.95	1.89	800	508	20
	APSC 278	$167.95	1.99	832	515	21
	Sub-Total	**$1,248.57**	**16.75**	**7066**	-	**180**
3	CHBE 344	$217.04	2.07	982	452	22
	CHBE 345	$0.00	0.00	0	0	0
	CHBE 346	$184.94	1.76	840	449	19
	CHBE 351	$134.95	2.49	1024	523	27
	CHBE 356	$159.95	1.81	736	528	19
	CHBE 362	$0.00	0.00	0	0	0
	CHBE 376	$0.00	0.00	0	0	0
	CHBE 363	$0.00	0.00	0	0	0
	CHBE 381	$119.95	1.12	576	418	12
	CHBE 357	$0.00	0.00	0	0	0
	STAT 251	$0.00	0.00	0	0	0
	ECON 102	$132.95	1.44	583	531	15
	Sub-Total	**$949.78**	**10.69**	**4741**	-	**115**
4	APSC 450	$0.00	0.00	0	0	0
	CHBE 455	$147.50	2.23	1120	428	24
	CHBE 457	$129.95	2.00	820	523	21
	CHBE 459	$0.00	0.00	0	0	0
	CHBE 464	$0.00	0.00	0	0	0
	CHBE 454	$0.00	0.00	0	0	0
	CHBE 456	$0.00	0.00	0	0	0
	CHBE 474	$0.00	0.00	0	0	0
	CHBE 477	$0.00	0.00	0	0	0
	CHBE 484	$0.00	0.00	0	0	0
	EECE 263	$214.53	2.24	901	535	24
	Sub-Total	**$491.98**	**6.47**	**2841**	-	**70**
	Total	**3761.3**	**54**	**22016**	-	**583**

Table E2. Typical Undergraduate Chemical Engineering Student's Textbook Use

APSC 122	NONE
APSC 150	9780195422177 DUNWOODY ET AL FUNDAMENTAL COMPENTENCIES FOR ENGINEERS
APSC 160	9780135007051 ETTER / LARSON PKG (2 BKS) UNIVERSITY PHYSICS & ENG PROB SOLVING W/ C
CHEM 154	FINE. CHEMISTRY FOR SCIENTISTS & ENGINEERS
ENGL 112	Birks. Landmarks: A Process Reader for Canadian Writers
MATH 100	Stewart. Single Variable Calculus
MATH 101	Same as MATH 100
MATH 152	Course Notes
PHYS 153	University Physics
PHYS 170	9780132307413 HIBBELER ENGINEERING MECHANICS 11/E W/ STATICS & DYNAMICS
ECON 101	9780176448691 MANKIW PKG PRINCIPLES OF MICROECONOMICS 4TH CDN EDN (W/APLIA)
APSC 201	281000001851B 1001 APSC 201 CCM BERNDT / ALL
	9780536489685 PFEIFFER * CUSTOM * TECHNICAL COMMUNICATION UBC 3RD & 4TH ED
APSC 262	9780534602772 TEICH TECHNOLOGY & FUTURE 10/E
	9780944583197 ELDER MINIATURE GUIDE ON ANALYTIC THINKING
CHBE 230	9780073132907 CHAPRA APPLIED NUMERICAL METHODS W/MATLAB
CHBE 241	None
CHBE 242	9780073305370 CENGEL THERMODYNAMICS 6TH ED W/DVD - AN ENGINEERING APPROACH
CHBE 251	9780073309200 WHITE FLUID MECHANICS 6/E (W/CD)
CHBE 262	NONE
CHEM 250	None
CHEM 251	None
CHEM 260	McMurry, Organic Chemistry
MATH 253	9780536498946 PCP/TRIM/KUSKE *CUSTOM* MULTIVARIATE & VECTOR CALCULUS FOR ENGINEERS (BK ONLY)
MATH 256	9780471433385 BOYCE / DIPRIMA ELEMENTARY DIFFERENTIAL EQUATIONS & BOUNDARY VALUE PROBLEMS W/ODE CD 8/E
APSC 278	9780471736967 CALLISTER MATERIALS SCIENCE & ENGINEERING 7/E
CHBE 344	Coulson. Chemical Engineering Vol2
CHBE 345	Same as CHBE 344
CHBE 346	Smith. Introduction to Chemical Engineering Thermodynamics
CHBE 351	Incropera. Foundamentals of Heat and Mass Transfer
CHBE 356	9780471000778 SEBORG / EDGAR PROCESS DYNAMICS & CONTROL
CHBE 362	None
CHBE 376	None
CHBE 363	None
CHBE 381	9780130819086 SHULER BIOPROCESS ENGINEERING 2/E
CHBE 357	None
STAT 251	None
ECON 102	9780070741140 FRANK / PKG PRINCIPLES OF MACROECONOMICS 2/E W/LYRYX
APSC 450	None
CHBE 455	Fogler. Elements of Chemical Reaction Engineering
CHBE 457	Seider. Product & Proces Design Principles: Synthesis, Analysis, and Evaluation
CHBE 459	None
CHBE 464	None
CHBE 454	None
CHBE 456	Same as CHBE 455
CHBE 474	Same as CHBE 356
CHBE 477	None
CHBE 484	NONE
EECE 263	9780073301150 ALEXANDER FUNDAMENTALS OF ELECTRIC CIRCUITS 3/E