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Life Cycle Assessment and Comparison of Power, Light, and Content Options for the SunEdu Project

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In this thesis I inventory, assess, and compare the environmental impacts of light, power, and content devices for the SunEdu project. SunEdu seeks to provide solar chargers, lamps, and eReader devices to rural schoolchildren in Tanzania. The project also investigates the suitability and sustainability of modern technologies-- most prominently, electronics-- in rural areas with no access to grid electricity. The project will determine if the eReader is an appropriate way to distribute reading materials in the cultural and environmental paradigm of rural east Africa.

Environmental impact assessment is done using the IMPACT2002+ assessment method, openLCA software, and data from the EcoInvent database and product manufacturers. I offer sensitivity and uncertainty analyses of the included products and an interpretation of the final results. As much as is practical, the assessment is done in accordance with the ISO 14040 standard on life cycle assessment.

Keywords	Life cycle assessment, LCA, Life cycle inventory, LCI, life cycle inventory analysis, environmental engineering, product design, environmental impact assessment, SunEdu

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1 Introduction

The SunEdu project is a TEKES-funded public-private partnership formed to create opportunities for Finnish education export through eReader technology and to improve lighting, and thereby educational opportunities, for students in rural Tanzania. Partners include Helsinki Metropolia University of Applied Science, Suntrica Oy, LeiaMedia Oy, and Adamana Oy. The pilot project will consist of 75 solar chargers provided by Suntrica Oy, 10 eReaders provided by Leia Media, and a mobile telephone for data access and distribution. The goal of the pilot is to develop a usable and marketable product or set of products for the Tanzanian market.

The SunEdu team travelled to Tanzania in the beginning of 2013 and discussed with possible user groups to determine the customer requirements and possible use of the devices for and beyond schoolwork. They also described a status quo of kerosene burned in handmade tin lamps. By the time the life cycle assessment process began, the design processes for the charger and eReader products were already underway.

Aside from the development of a marketable product, the SunEdu project is expected to positively impact the health and social opportunities of participants. Fuel based lighting, in particular kerosene, is the primary cause of unacceptable incidence of house fires, burns, and poisonings, as well as respiratory illnesses and deaths [1;2;3]. Lighting and educational resources which depend on solar power are disconnected from the volatility of the fossil fuel market and the on-going costs to the user of quality PV products are much lower [4].

Life cycle assessment (LCA) is an established method of quantifying probable environmental impacts of a product, process, or activity by building an inventory of material and energy inputs and outputs, assigning characterization factors to each inventory item, and calculating the impacts in categories of concern. Life cycle comparison can help provide guidance for decision-making processes in the development and use of these products, processes, and activities.

The life cycle assessment project took place between April and September of 2013. The university library did not contain the ISO 14040 and 14044 standards and no computer lab had any particular LCA software nor database, so open-source software and database information available on the internet were used. Information on ISO standards was obtained through secondary sources only. This study is limited by necessity to data provided by partner organizations and information that could be adapted from the EcoInvent 1.2 database. OpenLCA was used due to practical and economical ease of access and abundance of technical support.

1.1 Review of Literature

Many of the questions initially posed by the manufacturers of the equipment under consideration have already been examined in depth by life cycle practitioners with greater data access than I have. Impact analyses of different types of solar cells, energy generation methods, e-readers, and battery types are already readily available in existing literature [5;6;7;8;9;10;11;12;13]. There are articles addressing the economic and environmental impacts of solar lamps in rural east Africa, the health effects of kerosene lighting, the lack of e-waste disposal facilities in Tanzania, and the effects of informal e-waste disposal [1;2;3;14;15;16;17;18]. This area is already well-studied; as a result, some of the more obvious comparisons are given only passing attention in this study, and more time is devoted to project-specific design choices and measuring the magnitude of the project's impact.

2 Goal and Scope

The goal of this life cycle assessment is to find ways to minimize the environmental impacts of the set of products used in the SunEdu pilot by identifying high-impact components and suggesting low-impact alternatives. A secondary goal of the life cycle inventory analysis is to determine how to provide light and educational content with the lowest environmental impact and the magnitude by which the possible product sets differ. Impact-based break-even points for electronic replacements of fuel lighting and paper books will be identified. A tangential benefit of this assessment will be the identification of areas with missing data that could use more attention and propose future studies.

In pursuit of these goals, data gathering began in April of 2013 on a variety of photovoltaic panel and laminate types, device chargers, batteries, and alternative energy generation techniques. Scenarios were built around the concept of 'learning days,' or days with enough light and content to study for three hours. The kerosene and paper books were included as the status quo scenario to provide a frame of reference and a rationale for proceeding or not proceeding with the project, based on comparative impacts.

The system boundaries include raw material extraction processes through final product manufacture, the most likely modes of transport for each product from closest port in the country of manufacture to Dar Es Salaam, Tanzania, likely emissions from use, and several scenarios for end of life including recycling methods and informal incineration. A diagram is provided for each system and indicates the type of information available. Fugitive and accidental emissions were impossible to measure without site visits, and therefore were excluded. Cotton wicks and tin lamps are assumed to be made of informally recycled materials and disposed of by informal landfill. Electricity, heat, water, and other process considerations were unavailable for assembly of the solar chargers and eReaders, but approximations for printed wiring board assembly were made based on PWB surface area.

System boundaries and data requirements depended dynamically on one another; where data was scarce, it was necessary to redraw system boundaries to exclude the missing or low quality data in such a way that the comparisons were still tenable. For example, exact information about the methods and impacts of transportation within Tanzania are not available for the Solar Strap and eReader equipment, therefore transportation within Tanzania is excluded for all systems. Data which was not available from product vendors and manufacturers was estimated from the EcoInvent 1.2 database, which provides high quality data for Europe and some other locations [19;20;21]. However, as most of the information is for Europe and Switzerland, the uncertainty for various elements such as electricity mix and transportation is considerable. Wherever possible, location has been adjusted within the OpenLCA program to reflect conditions at the actual locations in question.

Assumptions include the compliance of all electronics with the Restriction of Hazardous Substances legislation, as the electronics products are assembled in the European Union. Control circuitry for the diesel generator is excluded due to lack of data and small surface area. Emissions from informal incineration are approximated from a previous simulation of e-waste rudimentary recycling by Gullett et al. [18] with RoHS-forbidden substances removed from emissions.

2.1 Devices

2.1.1 Suntrica SS-W20432X Solar Strap

The Solar Strap is a small, flexible photovoltaic laminate in a durable foam case formed into a strap, with Velcro to attach to clothing, backpacks, or other convenient objects. There is a small box with voltage regulation for charging devices such as phones. Indicator LEDs tell the user about the status of the device, so it is possible to determine charge and error states. It comes with a set of adaptors for popular mobile telephones as well as USB. Packaging includes one paperboard box, several small plastic bags, various stickers and tapes, and an instruction manual. The battery capacity is listed as 1500 mAh. Its approximate lifetime is required by Finnish law to be two years, as guaranteed by warranty. The device is RoHS compliant, components are manufactured in China, and the device ships from Finland. Transport is assumed to be from Helsinki-Vantaa International Airport in Finland to Dar es salaam, Tanzania by air freight, though an alternative of transoceanic freighter will also be modeled. End of life for this product includes several scenarios; ideally, the product would be transported to the nearest e-waste recycling facility in Mombasa, Kenya, and copper, zinc, and the photovoltaic element fully recovered. In a less than ideal situation, the product would be transported to Iringa and recycled for copper recovery; other parts would be incinerated in a semi-controlled environment. In the most likely situation, the product will be informally incinerated in a fire pit on land which would potentially be used for agriculture in the future. All three end of life scenarios are modeled in this study.

2.1.2 Diesel generator

A 1 kWh diesel generator weighing 20 kilograms is modeled from the data given by Schleisner [8] and diesel fuel data from raw extraction to gate is estimated from data in the EcoInvent 1.2 database. The generator and fuel are used in two different scenarios, as described below. Control circuitry for the generator is not inventoried. Diesel generator efficiency is taken as 0.53 L/kWh, from the mean of several diesel generators at 50% and 100% efficiencies, as measured by Fleck and Huot [7]. Fuel transport is assumed to be from Durban, South America to Dar es Salaam, Tanzania via ocean tanker. Generator transport is assumed to be from Guangzhou, China to Dar es Salaam, Tanzania via transoceanic freight ship. End of life is modeled as transport by light truck to Dar es Salaam for metal recycling.

2.1.3 Kerosene lamp

A handmade, 10 gram tin lamp with replaceable cotton wicks is the status quo for provision of light. Kerosene data from raw extraction to gate is estimated from data in the EcoInvent 1.2 database. Fuel transport is assumed to be from Durban, South America to Dar es Salaam, Tanzania via ocean tanker. Lamp transport is assumed to be human-powered, and is not inventoried. The end of life for this lamp is modeled as the informal landfilling of 10 grams of tin on land which would potentially be used for agriculture in the future.

2.1.4 LeiaMedia eReader

The eReader is comparable in area to a letter-sized notebook, weighs considerably less than a traditional paper notebook or tablet computer (about 500 grams), and uses a color electronic ink to display still images. It is designed for durability. The internal battery is rated at 1500 mAh. The reading materials can be downloaded from a cloud server by the instructor using a smart phone or tablet computer, then sent to students' eReaders via Bluetooth. The instructor's device, the cloud server, and the mobile tower used to access the cloud server are outside the system boundary for the eReader life cycle inventory, as it is expected that the school's use of these resources is likely to be a small fraction of their total use, and the LCI information for these devices is not available within the time and cost restraints of the SunEdu project. The electricity required by the device was inventoried in the Power and Light scenarios, and therefore is outside the system boundary for this section. Transport is from Helsinki-Vantaa International Airport in Finland to Dar es Salaam, Tanzania by air freight, though transoceanic freight ship is also modeled. End of Life disposal methods are modeled in the same way as for the Solar Strap: ideal disposal in Mombasa, less than ideal disposal in Iringa, and informal disposal in a fire pit.

2.1.5 Books

The books used by the partner school are color-printed paperbacks. A selection of four storybooks and four course books were sent to the SunEdu project manager by the publisher; these books were weighed on a laboratory scale to obtain a mean mass of 120.9 kilograms. Approximately 90% of the weight is uncoated, color-printed paper; the remaining 10% is coated, color-printed paper which makes up the cover. LCI information for the books was estimated using data in the EcoInvent 1.2 database.

Transport is modeled from Dar es Salaam to Iringa by lorry, and end of life is modeled as informal incineration in a fire pit on land which could be used for agriculture in the future.

2.2 Scenario Definitions

Scenarios were built around the existing device choices made for the pilot project. It is assumed that the solar charger would also be used to charge mobile phones, the eReader would also be used for viewing periodicals. An estimated three hours of light and content use per day for 200 days per year is the basic requirement for each product set. Four scenarios were created to fill this requirement. Device numbers were based on the original intended pilot project size, but assessment results will be given in impact units per learning day.

The inventory and comparison of educational content devices was conducted separately from the inventories of power and light, as they are separate devices and not necessarily dependent upon one another. For example, an eReader could be charged at a kiosk and used in the home in conjunction with a kerosene lamp, or charged at the school and used at home with an LED lamp, or charged by the Solar Strap. Books could be used in conjunction with any of the methods of providing light. Therefore, the most relevant comparison is of the eReader device to the status quo, paper books. The functional unit for comparisons of the eReader and the paper book is, as with the light and power scenarios, one learning day.

2.2.1 Scenario 0 - Solar charger for power and light

One SS-W20432X Suntrica Solar Strap charger with the future design addition of three light emitting diodes— also inventoried— will provide both electricity and light for a total lifetime of 400 learning days, or approximately two academic years.

2.2.2 Scenario 1 - Diesel generator, smart phone case

One 1 kWh diesel generator and 27.3 kg of diesel fuel will provide 31 kWh of electricity for charging 17 eReaders, 17 battery-powered LED lamps (lamps not inventoried) and

17 student-family mobile phones, which were modeled as Nokia 1202 for electricity demand but not inventoried as part of this study [22]. The instructor's mobile phone, used for distributing educational content to the eReaders, will also be charged using this system. A Nokia Lumia 820 smart phone was used as the model for the instructor's mobile phone electricity demand in this scenario, and was also not inventoried in this study [23]. This combination of products is expected to provide a total of 6800 learning days.

2.2.3 Scenario 2 - Diesel generator, tablet case

One 1kWe diesel generator and 30.0 kg of diesel fuel will provide 34.0 kWh of electricity for charging 17 eReaders, 17 battery-powered LED lamps (lamps not inventoried) and 17 student-family mobile phones (phones not inventoried), which were modeled as Nokia 1202 for electricity demand [22]. The instructor's tablet, used for distributing educational content to the eReaders, will also be charged using this system. A Samsung Galaxy Tab II 7.0 Plus was used as the model for tablet electricity demand in this scenario but was not inventoried here [24]. This combination of products is also expected to provide a total of 6800 learning days.

2.2.4 Scenario 3 - Kerosene in handmade tin lamps

The current status quo is the burning of kerosene in handmade lamps with cotton wicks. The lamps are modeled as 10 grams of tin from recycled materials. Kerosene demand for 6800 learning days totals 584.5 kg, with the assumption that the lamp is burned for 3 hours per day at 15.7 grams per hour [3]. The fuel is assumed to be produced in Durban, South Africa and shipped by tanker to Dar es Salaam, Tanzania. The production of the tin lamps is not included in the model, as data for tin scrap and handmade tin products are not available at this time. The disposal of the lamp is modeled as informal landfilling to agricultural land. Kerosene residue on lamps at end-of-life is not modeled. This combination of items is expected to provide a total of 6800 learning days.

2.2.5 eReader

The scenario includes 1 eReader, providing a total of 400 learning days over two academic years.

2.2.6 Books

Seven to nine course books and an unknown number of storybooks are used per academic year. The scenario is modeled as 12 total books per academic year, each book providing 16.7 learning days. This number of learning days per book will be used to determine a break-even point with the eReader.

3 Inventory and Impact Assessments

For the Solar Strap and eReader, data for inputs has been taken from the vendors' bill of materials. Other information has been estimated from data in the EcoInvent 1.2 database, adjusted for actual component mass as measured on a laboratory scale [19;20;21]. Fuel quality data is not available due to the difficulty of transporting flammable substances; it is assumed that diesel and kerosene fuels meet the standards required for export to the EU.

3.1 IMPACT2002+

Quantitative impact assessments were conducted in OpenLCA using the IMPACT2002+ assessment method. This method was chosen because the categories assessed are relevant to the goals and easy to understand. It is a combined midpoint and damage-oriented approach, with several midpoints leading to several relevant damage categories, as seen in Figure 1. Classical impact assessment methods do not proceed past the early stages of cause-effect when categorizing impacts from life cycles; impacts are allotted to midpoint categories and characterization factors are calculated there. Damage-oriented methods attempt to model causes and effects until damage to the environment occurs; the environmental damage is then expressed in relevant characterization factors. IMPACT2002+ works on both levels to give a more specific understanding of damages [25]. However, damage categories are normalized into 'points,' which are only of use when comparing impacts across phases; therefore, characterization factors were multiplied by the impact points in order to obtain useful units of impact.

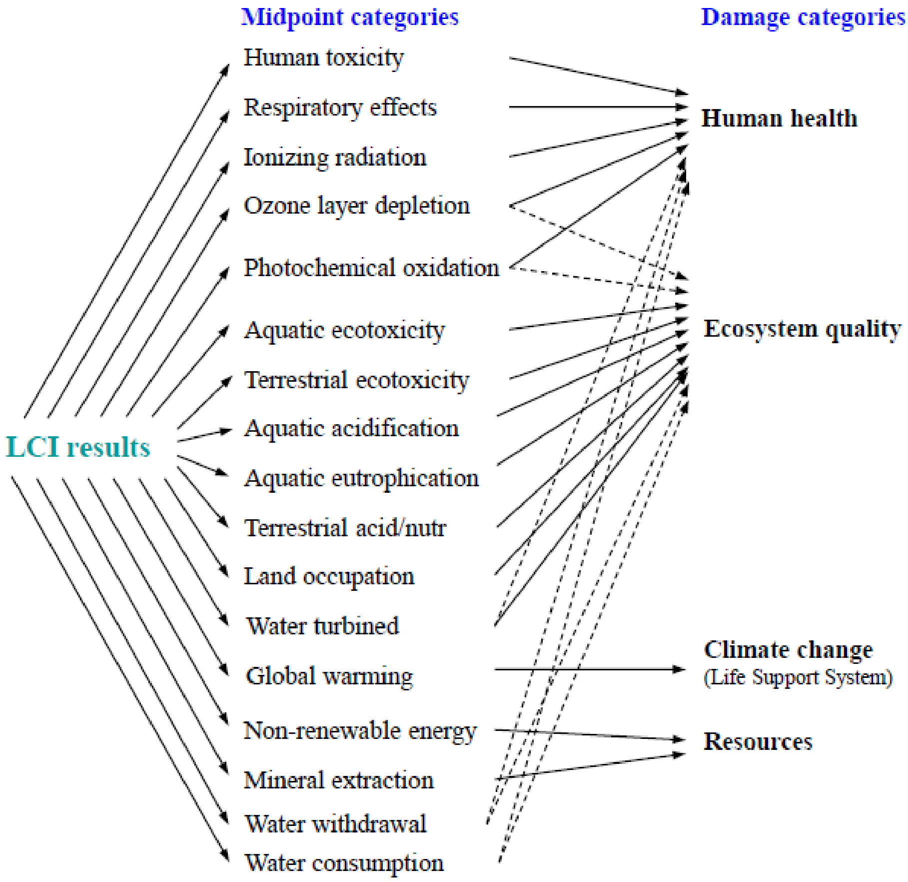


Figure 1. Overall scheme of IMPACT2002+, taken from IMPACT2002+ USER GUIDE [25]

Un-normalized units are:

- Human Health - in Damage Adjusted Life Years (DALY)
- Ecosystem Quality - in Percent Disappeared (PDF-m2-y)
- Climate Change - in kilograms of CO2 equivalent (kg CO2-eq)
- Resources - depletion in megajoules (MJ)

In this assessment, damage category scores are expressed for each product system and in all sensitivity analyses and comparisons. Midpoint categories may be discussed to characterize the type of damage dominating each endpoint damage category.

It is also worth noting that there are no site-dependent emission factors or impact factors for Africa at this time. It has been recommended that these factors be developed in future studies, but for now the IMPACT2002+ site-generic factors are suitable for this report [26].

3.2 Uncertainty Analysis

Uncertainty analysis is used to convey the quality of results from a life cycle assessment. It allows the reader of LCA reports to understand the results' dependability or lack thereof.[27] As all of these individual assessments were complex and involved tens of variables, statistical analysis by hand would be burdensome. Uncertainty analysis has been simplified by use of pedigree matrices to describe data quality and Monte Carlo simulations to generate a probable range and distribution of impact values returned by the model. The range and distribution of each impact value will help the reader understand how specific or how vague the results are, and help understand how reliably each product or scenario can be compared to others; for example, a scenario which returns a wide range of values may not be reliably defined as 'better' or 'worse' than a scenario that returns a narrow range which is neither completely above nor below the first scenario.

4 Light & Power Scenario Inventories

4.1 Suntrica SS-W20432X Solar Strap

The vendor provided a bill of materials which included component names and quantities. A single unit was dissembled and individual components were weighed. It is not possible to list the component names and details due to the non-disclosure agreement. Component mass was used to model most components with data from the EcoInvent 1.2 database [19;20;21]. Lithium polymer battery life cycle inventory data is not yet available and may affect actual environmental impacts. The battery was modeled as a lithium ion battery, which uses materials similar but not identical to lithium polymer. These impacts are for 400 learning days. A flow chart of included processes and data sources is included below as Figure 2.

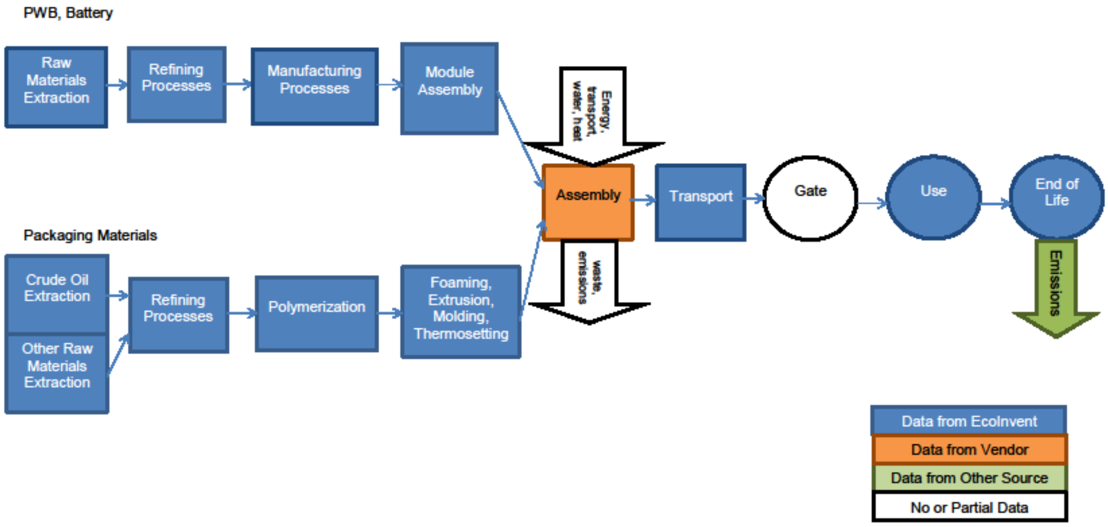


Figure 2. Solar Strap life cycle flow chart

A complete life cycle impact assessment was performed for the Solar Strap. Sensitivity to changes in modes of transportation, photovoltaic element type, and end of life disposal methods were tested using a one-at-a-time method. Mean results of a linear analysis of the model for one Solar Strap unit is presented in Table 1.

Table 1. Suntrica Solar Strap Life Cycle Impacts - 1 Unit

Impact Category	Impact	Unit
Climate Change	13.6617	kg CO_2 eq
Ecosystem Quality	93.6998	PDF.m^2.yr
Human Health	1.8713e-05	DALY
Resources	235.7621	MJ

It is common that the production phase of a photovoltaic product has the highest share of environmental impacts when compared to other phases of the product's life cycle; the use phase commonly has the lowest share of impacts [5;24]. This may be due to the lack of data about photovoltaic end of life impacts. In the SunEdu pilot project, the most likely end of life scenario is informal incineration in a fire pit on land near the user's home. This has a magnitude of impact not seen in other life cycle assessments of photovoltaics. A chart describing the breakdown of impacts by phase is included below as Figure 3.

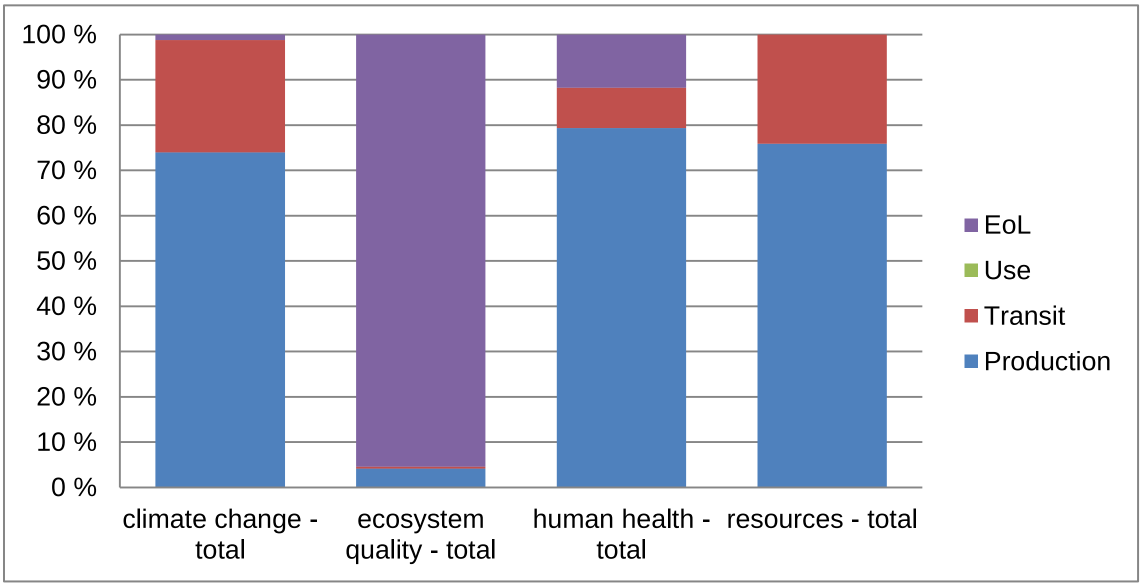


Figure 3. Scenario 0 Life Cycle Impacts by Phase

The largest impact in the category of climate change is the electronics assembly, which includes the printed wire board and all components on it but not, notably, the battery. The production of electronic components is energy-intensive, and the electricity mix in China is heavily dependent upon fossil fuels. Thirty-six percent of the climate change impact comes from electricity production for the manufacture of the Solar Strap's electronics. The production of the battery is another 18%, and 25% of the climate change impact is from aircraft use during both production and transportation phase. Only 1% of the climate change impact comes from burning the product informally at the end of its useful life.

The majority of damages to ecosystem quality are in the terrestrial ecotoxicity subcategory, caused by incineration of electronics on or near land which is likely to be used for agriculture in the future. Of the total impact, 57% is from the incineration of the electronics assembly, 30% is from the incineration of wires, and 6% is from the incineration of the battery. Other contributions in this category amount to less than 5% each. The contribution in the production phase is due to the electronics assembly.

Of the human health impact, 63% is from the production of the electronics assembly, the largest fraction of this from the mining and refining of palladium for electronic components. Twelve percent of impact is from the production of the battery, and 11% is from informal incineration of the electronics assembly. Approximately 8% of the human health impact is from air transportation in the production and transit phases. The remaining 1% of transit phase impact is from lorry transportation.

Resource depletion occurs not surprisingly in the production and transit phases. The production of the electronics assembly accounts for 52% of resource impact, followed by 11% for battery production and 8% for the production of LEDs. The large impact in this category is due to the electricity mix in China and its dependence on fossil fuels. Forty-four percent of the resource impact comes from the electricity used to extract raw materials for and produce the electronics assembly; only 8% is from the actual materials themselves. Twenty-four percent of the resource impact is from the transit phase; 22% from aircraft and 2% from lorry transportation.

4.1.1 Sensitivity Analyses

Several sensitivity analyses were performed; photovoltaic element types, transportation methods, and end of life disposal methods are compared both to choose the most beneficial as well as to determine the magnitude of impact reductions possible.

4.1.1.1 *Type of Photovoltaics*

At the request of the manufacturer, the unit was modeled using different types of photovoltaic elements. The photovoltaic element, while it is the centerpiece of the product, does not have a large share of the overall product's impacts in any category. Figure 4 is a graphical comparison of the results.

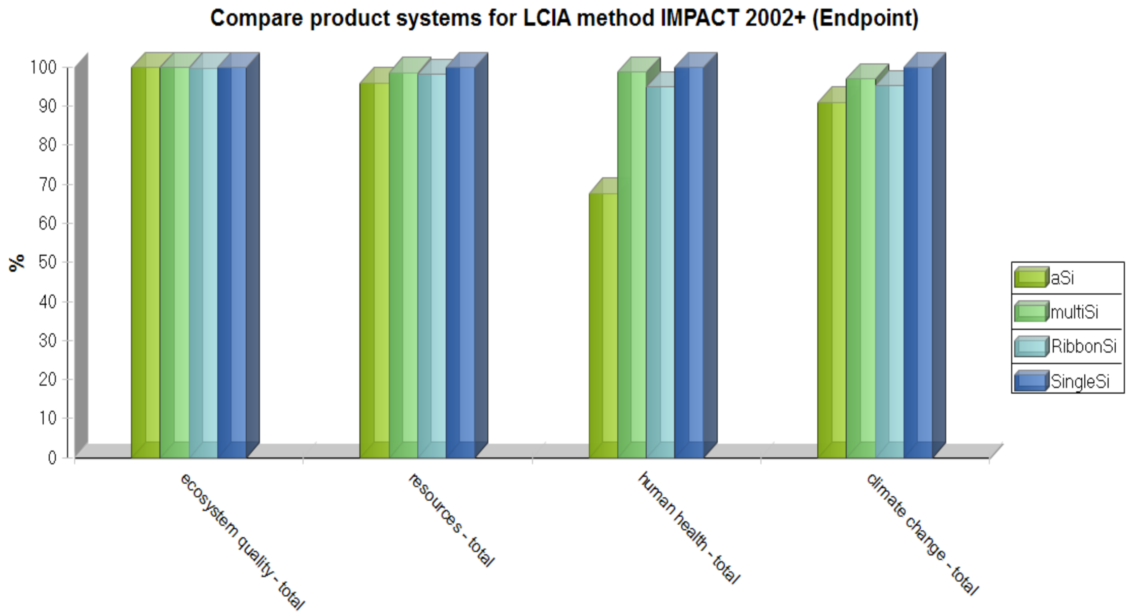


Figure 4. Sensitivity analysis of different photovoltaic element types

Different choices for photovoltaic element types create a difference of less than 10% in most categories. In the category of human health, the amorphous silicon PV element causes a significantly lesser impact than other types. Amorphous silicon is the environmentally wisest choice of the photovoltaics examined here.

The new version of the EcoInvent database would allow a comparison of photovoltaics manufactured in China and those manufactured in the EU. Unfortunately, the updated database was not available at the time of this report.

4.1.1.2 *Transportation methods*

The noticeable impact of transportation in the total impacts of the Solar Strap suggested it may be interesting to model the product using transoceanic freight as the mode of transport between electronics production and unit assembly, and between unit assembly at factory and gate at Dar es Salaam. The results of such a model are displayed below in Figure 5.

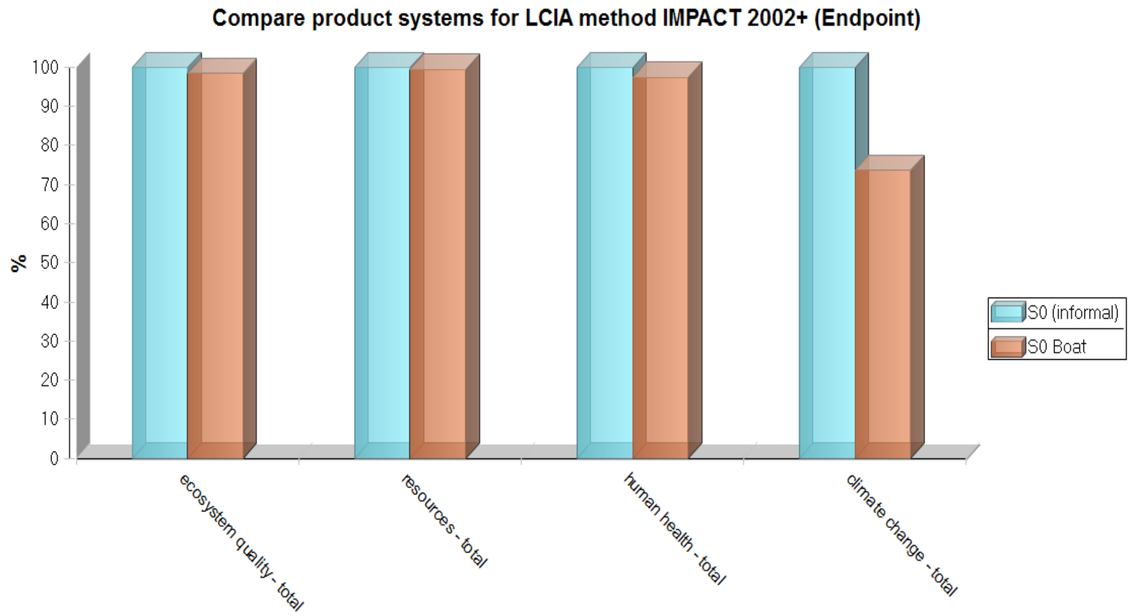


Figure 5. Sensitivity analysis of different transportation types

Transportation by boat overall creates little reduction in most categories. It does notably the climate change impact by about twenty-eight percent-- remembering that transportation happens also in the production phase. While the size of the shipment for the pilot project does not lend itself to transit by container ship, it may be interesting to consider ocean freight for future product shipments.

4.1.1.3 *End of Life*

Three possible end of life scenarios were modeled. The informal case is the one taken to be most likely; the device is informally incinerated on agricultural land. A ‘likely’ case in which the object is transported to Dar es Salaam and shredded to recover copper is also modeled. Recovery is modeled as 100% for this metal, even though recycling processes cannot deliver that recovery rate. Other materials are modeled as incinerated. An ‘ideal’ case in which the device is transported to the nearest e-waste recycling facility in Mombasa, Kenya is also modeled. Ideal recycling is modeled as returning 100% of copper, nickel, and the photovoltaic element, as there was no data on the recovery rates for photovoltaics of this type as of the writing of this report. A second model of ideal recycling is modeled as returning 50% of copper, nickel, and the photovoltaic element, in order to test sensitivity to recycling return rates. Other materials are modeled as incinerated. The recycling models include transportation by lorry from Iringa to the city where treatment occurs. Table 2 shows values from linear analysis of the Scenario 0 models, named after their end-of-life options.

Table 2. Scenario 0 End of Life Models

Impact Category	Informal	Ideal 100%	Ideal 50%	Likely	Unit
Climate Change	13.6617	12.1698	12.3306	13.7041	kg CO_2 eq
Ecosystem Quality	93.6998	5.3597	5.4111	93.7133	$PDF.m^2.yr$
Human Health	1.8713e-05	1.5900e-05	1.6000e-05	1.8800e-05	DALY
Resources	235.7621	212.1127	215.0050	236.4848	MJ

Figure 6 is a graphical comparison of the above values.

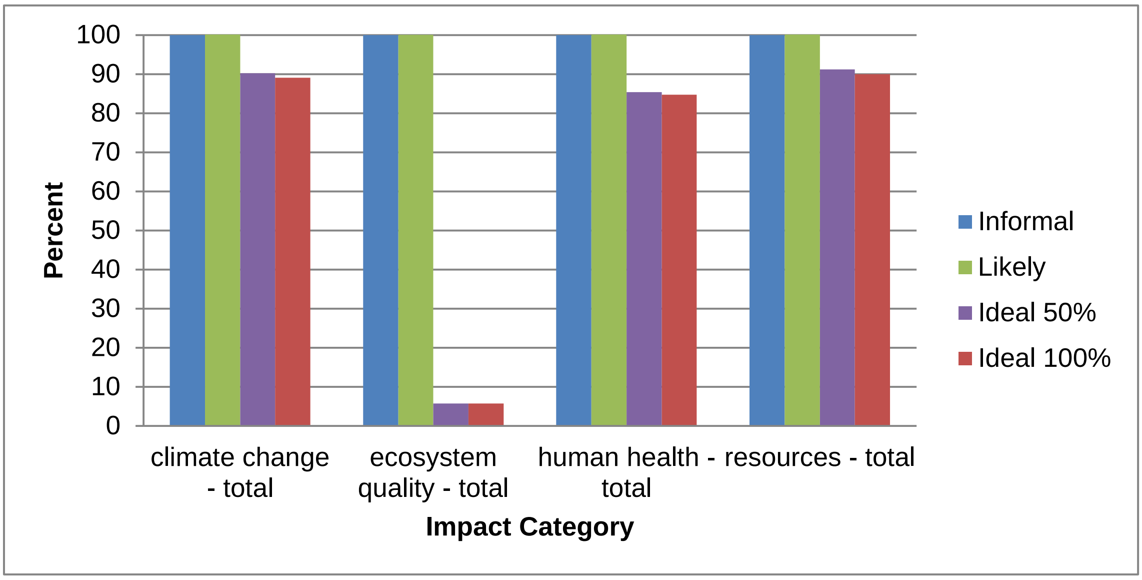


Figure 6. Scenario 0 End of Life Options, Informal as 100% Impact

The reduction in the category of resources is to be expected for any comparison of resource recovery scenarios. It is worthy to note that the benefits of recycling the product for copper in the ‘likely’ recycling method are outweighed by transporting the product to the recycling facility by lorry.

The largest benefits are in the ‘Ideal’ scenario, but after a certain recovery rate there are diminishing environmental returns. Further study would be required to determine theoretical recovery rates for each substance which would make transporting the unit to Kenya a worthwhile effort.

The significant reduction of ecosystem quality impacts when moving from end of life disposals which incinerate the electronics components to end of life scenarios which do not indicate the sensitivity of the model of metal emissions to agricultural land. An individual case of burning this product does not cause severe ecological damage on its own, but more units receiving the same treatment will cause cumulative damage.

4.1.2 Uncertainty Analysis

The Solar Strap is a pre-existing product acting as a reference for a device still in production, which will be specifically designed for the SunEdu project. Some parameter uncertainty is due to design changes taking place between materials measurement for LCA purposes and the finalization of the SunEdu device. Another source of uncertainty is the lack of information on electronic component manufacturing impacts from the specific country where the SunEdu components are manufactured, which would have been available in the newer version of the EcoInvent database. Vendors of solar cells and batteries did not have any information about the manufacturing processes behind their products; those who did have relevant information were largely uninterested in sharing, even after non-disclosure agreements were signed.

A Monte Carlo simulation was performed with 5000 iterations to propagate uncertainty throughout the model and generate probable return values. Uncertainties were defined using the pedigree matrix at the earliest occurrence of each item or process. Linear analysis and Monte Carlo simulation means are presented in Table 3; values are in their normalized form, wherein the units are points.

Table 3. Scenario 0 Informal, Monte Carlo Simulation Results

Impact Category	Linear Mean	Monte Carlo Mean	Standard Deviation
Climate Change	1.372e-03	6.518e-04	4.103e-05
Ecosystem Quality	6.839e-03	2.652e-04	6.554e-05
Human Health	2.636e-03	1.903e-03	2.076e-04
Resources	1.551-03	-6.738e-04	8.382e-05

Below is a visual representation of the Monte Carlo simulation data, with median, maximum, minimum, and 5th and 95th percentiles shown, in Figure 7.

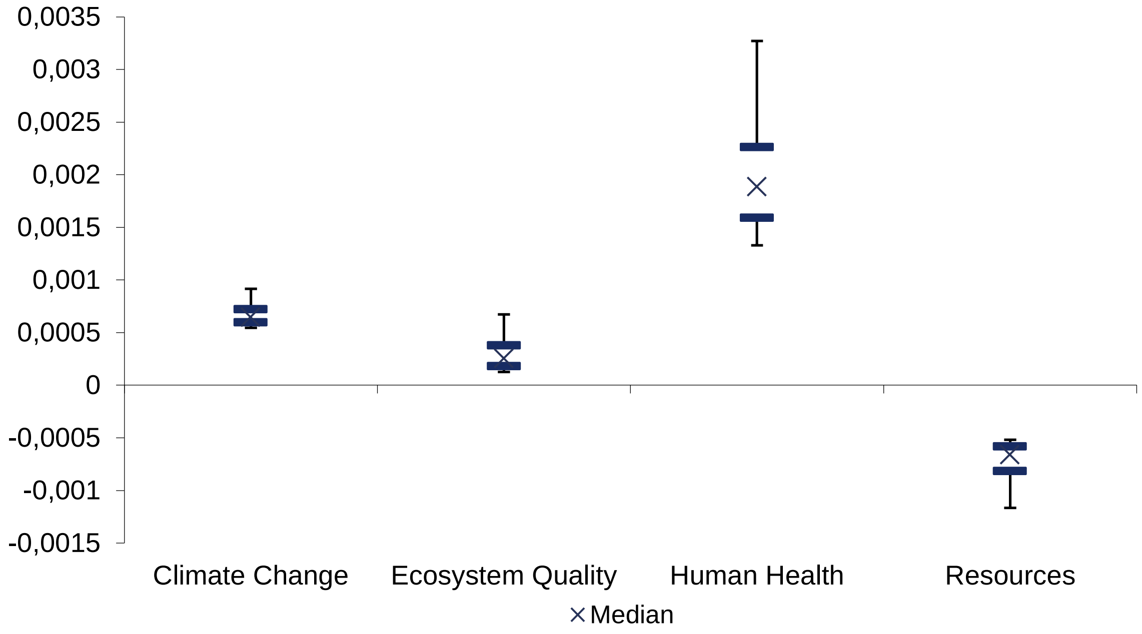


Figure 7. Scenario 0 Informal, Life Cycle Impacts in Points, Box & Whisker Chart

The Monte Carlo simulation gave a negative mean value in the resources category, inexplicably, though linear analysis did not.

4.2 Diesel Generator

Generator manufacturers were unwilling or unable to share a Bill of Materials, so generators were modeled with information from Fleck and Huot's study comparing a small wind turbine to other power solutions [7]. Data for fuel from crude extraction to gate is from EcoInvent. As before, a flow chart depicting included processes and data sources is included below, in Figure 8.

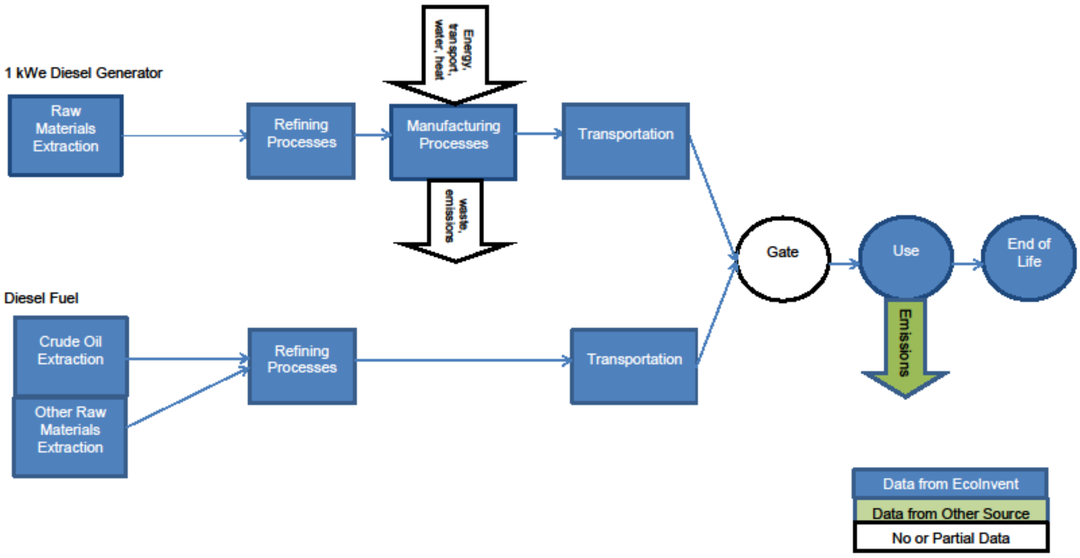


Figure 8. Diesel and Generator life cycle flow chart

Two diesel-powered scenarios were modeled to reflect possible power demand scenarios. It is expected that the generator will be installed at the school and the electricity will be used to charge students' solar lamps, mobile phones, and eReaders as well as a lamp, smart phone or tablet, and eReader for the teacher's use. The generator and additional diesel fuel would most likely be used for other purposes such as lighting the school or cooking, but the generator does not currently exist at the school, so it is assumed that it would be installed specifically for this project. With that assumption, the scenarios include 100% of the impacts from the generator and impacts from the fuel specifically demanded for the uses listed above. These impacts represent 6800 learning days. Table 4 shows mean life cycle impacts from linear analysis of each model.

Table 4. Scenarios 1 and 2 Life Cycle Impacts

Impact Category	S1 Result	S2 Result	Unit
Climate Change	201.3407	211.2063	kg CO_2 eq
Ecosystem Quality	44.3752	45.7085	PDF.m^2.yr
Human Health	2.6437e-04	2.8100e-04	DALY
Resources	2975.4005	3123.4280	MJ

Figure 9 is a graphical representation of life cycle impacts by phase. It is expected that the use phase impacts will be larger than in the solar charger scenario.

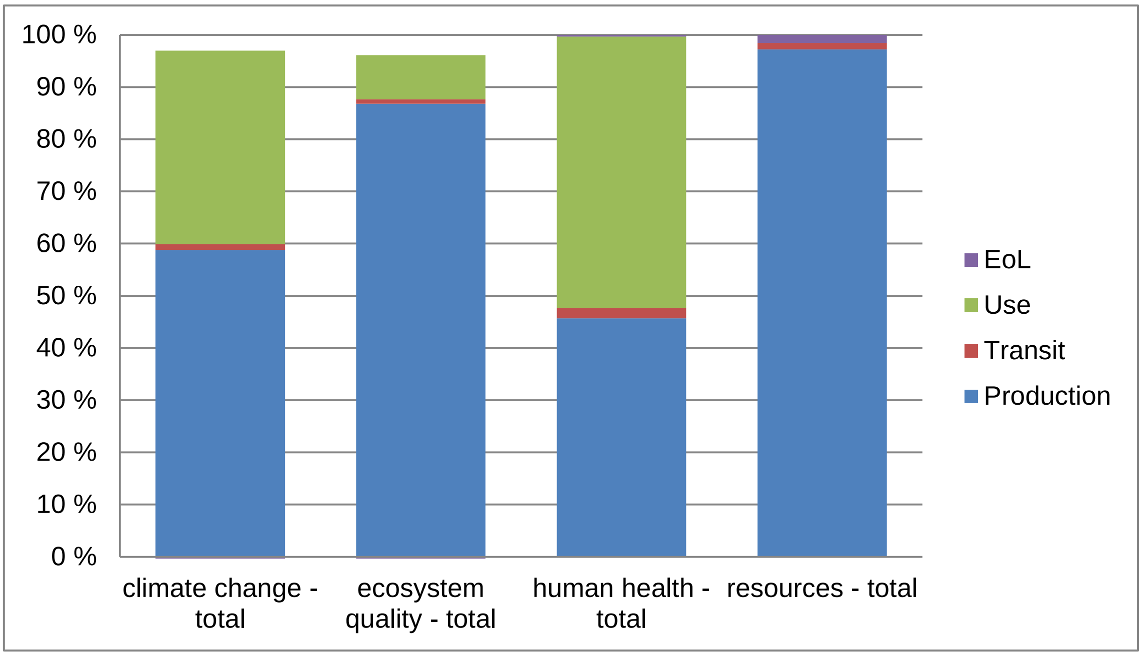


Figure 9. Scenario 1 Life Cycle Impacts by phase

The largest single impact in the category of climate change comes from the combustion of diesel in the generator, which is the entire Use phase. Other components of this category include aluminium production which accounts for 39% of the impact due to its energy intensive process, steel production which accounts for 9%, diesel fuel production at 6%, and production of LEDs at a little over five percent. Generator recycling prevents impacts from mining of new materials, equal to about 3% of the total climate change impact of this product set, and causes a negative value for climate change impact and ecosystem quality in the End of Life phase, thus the absence of graphical representation and the value below 100% in these categories in the figure above.

Ecosystem quality impact is mostly in the production phase. The production of aluminium accounts for 34% of the impact, production of copper is 21%, and production of steel is 17%. Blasting to extract raw ore is 18% and disposal of drilling waste from crude extraction is 13% of the impact. Diesel production accounts for 12% of the impact, and only 8% is caused by fuel combustion for energy. Recycling the generator prevents impacts from mining new materials, equal to about 4% of the total ecosystem quality impact of this product set.

Human health impact is largely from the combustion of diesel fuel in the Use phase. In the production phase, impact components include aluminium production which is 23% of total impact, steel production for 8%, copper production for 5%, and diesel fuel production for another 5%. Other production phase impacts account for less than 5% each. Transit phase impacts are 2% and due to the operation of freight and tanker ships.

Resource impacts are 45% from the extraction and production of diesel fuel, 34% from the production of aluminium, 10% from the production of steel, and 7% from the production of the LED lamp. It is notable that recycling the generator causes more impacts on resource depletion than it prevents, as the generator must be transported to Dar es Salaam.

Total impacts are not significantly different when a few extra kilowatt hours must be generated. It is reasonable to suspect that the percentage shares of each impact are not significantly different between Scenario 1 and Scenario 2.

4.2.1 Uncertainty Analysis

The diesel generator numbers are taken from literature. Some parameter uncertainty would be due to the difference between a measurement of average generator material contents and emissions, and the actual material contents and emissions of the generator chosen for the purpose. Other sources of uncertainty are the lack of information on electronic components used for generator controls, fuel quality in Tanzania, the method and capacity of fuel transportation from fueling station to schools with generators, and the location of the fueling station closest to the school.

A Monte Carlo simulation was performed with 5000 iterations to propagate uncertainty throughout the model and generate probable return values. Uncertainties were defined using the pedigree matrix at the earliest occurrence of each item or process. The Monte Carlo simulation again gave a negative mean value in the resources category, inexplicably, though linear analysis did not. Results in Table 5 are in their normalized form, wherein the units are points.

Table 5. Scenario 1 Monte Carlo Simulation Results

Impact Category	Linear Mean	Monte Carlo Mean	Standard Deviation
Climate Change	2.024e-02	3.545e-01	1.008e-01
Ecosystem Quality	3.216e-03	1.099e-01	4.338e-02
Human Health	3.724e-02	4.535e-01	1.486e-01
Resources	1.958e-02	-4.371e-01	1.321e-01

Figure 10 is a visual representation of the Monte Carlo simulation data, with median, maximum, minimum, and 5th and 95th percentiles shown.

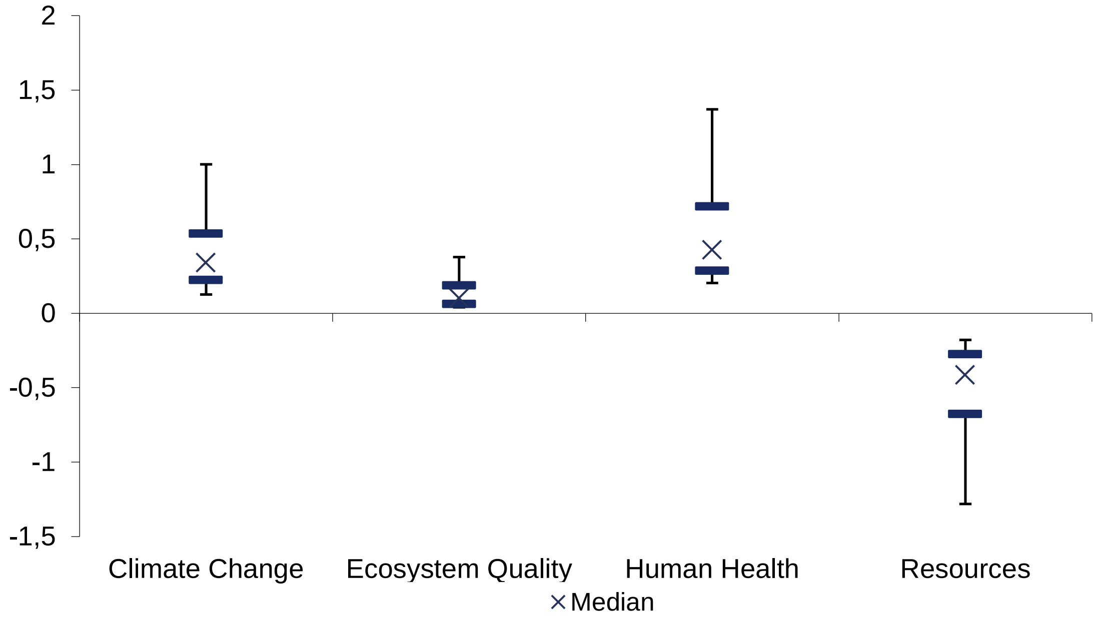


Figure 10. Scenario 1. Life Cycle Impacts in Points, Box & Whisker Chart

4.3 Kerosene lamp - Status Quo

Data for kerosene consumption in handmade lamps is taken from Fan & Zhang [3]. Emissions factors for Carbon monoxide, Carbon dioxide, and particulate matter from 0.1 to 10 µm diameter are also taken from Fan & Zhang. It seems likely that these are not the only substances emitted from handmade kerosene lamps, but further study on the matter is needed before dependable emissions factors can be determined. Figure 11 is a flow chart of included processes and data sources.

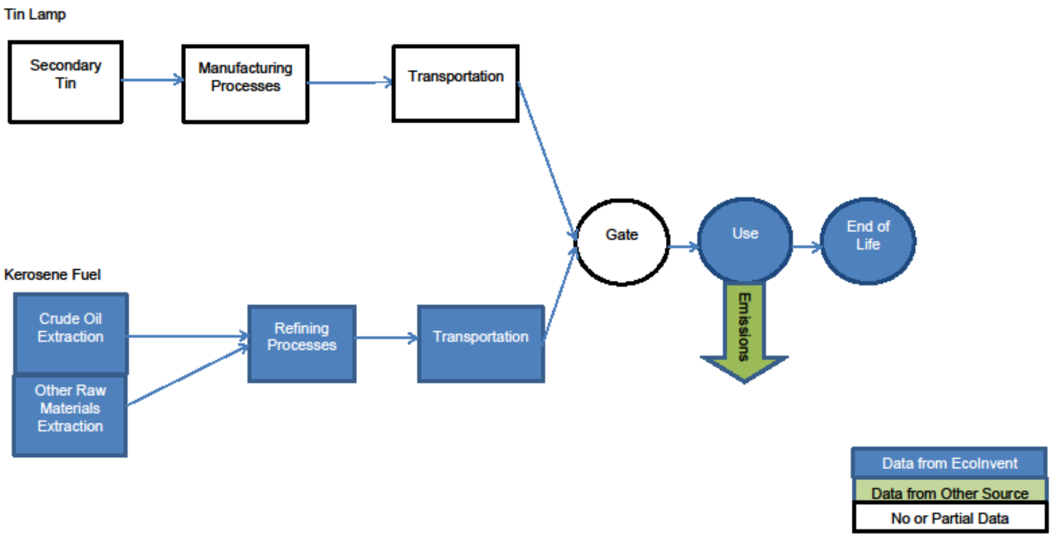


Figure 11. Kerosene and Tin Lamp flow chart

The kerosene scenario was designed to reflect the status quo situation of students before the pilot project. The model represents 6800 learning days, or two school years for seventeen students. Table 6 shows life cycle impacts from a linear analysis of the Scenario 3 model.

Table 6. Scenario 3 Life Cycle Impacts

Impact Category	Result	Unit
Climate Change	837.5475	kg CO_2 eq
Ecosystem Quality	164.8543	PDF.m^2.yr
Human Health	3.41e00-04	DALY
Resources	31861.3100	MJ

Figure 12 is a graphical representation of life cycle impacts by phase.

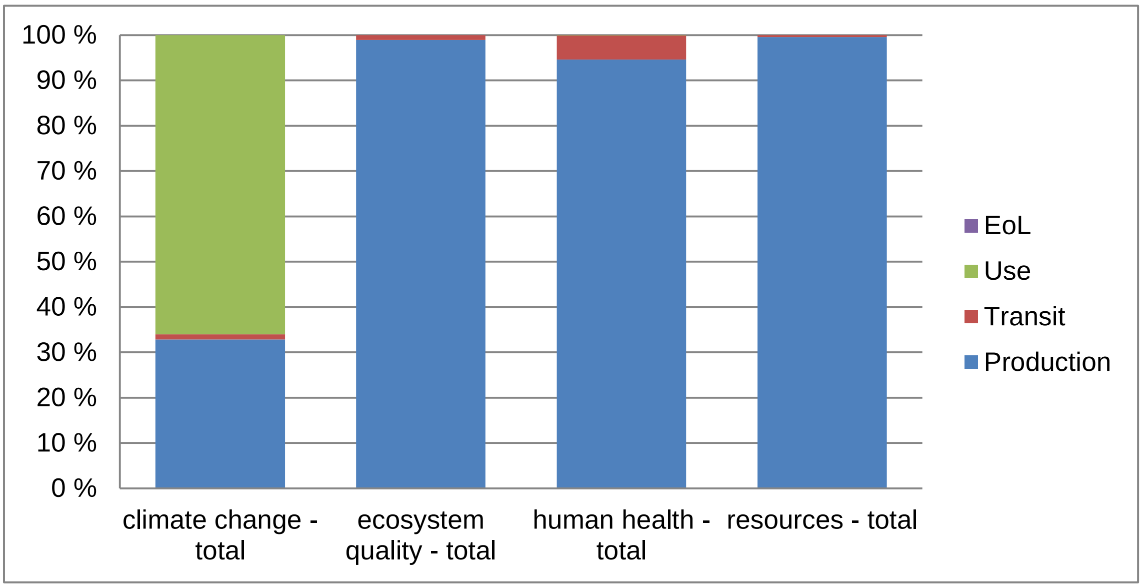


Figure 12. Scenario 3 Life Cycle Impacts by phase

The largest contribution in the category of climate change is from burning kerosene. This is the entire 66% impact from the Use phase. Kerosene production accounts for 33% of the total impacts; 8% is from crude oil extraction, 6% from electricity use, and 11% from flared refinery gas. The impact of the transit phase is only 1% of total climate change impact.

Human health impacts are overwhelmingly from the production of kerosene; natural gas flaring is 24% by itself. Other processes related to crude oil extraction and refining make up the remaining 71 percent. Five percent of the impact is from the transit phase. Less than 1% of the impact is allotted to the use phase, though further study on the emissions of kerosene burned in handmade lamps could affect this number. About 1%

is caused in the transit phase. Human health metrics used in LCA do not measure the burns, poisonings, and other human injuries related to kerosene.

Ecosystem quality impacts are also mostly from the production of kerosene. The extraction of crude oil causes 89% of the total impact and electricity use causes 7% of the impact.

Resource impact is 96% from crude oil extraction and 4% from the fuel and energy used for transit within the production phase and fuel processing.

4.3.1 Uncertainty Analysis

The kerosene emissions are modeled from factors taken from literature. Some uncertainty is due to the difference between the conditions of the test and the conditions of actual kerosene lamp use. Other sources of uncertainty are the lack of information on kerosene quality in Tanzania, the method and capacity of fuel transportation from market to homes, and the location of the market closest to the users' homes.

A Monte Carlo simulation was performed with 5000 iterations to propagate uncertainty throughout the model and generate probable return values. Uncertainties were defined using the pedigree matrix at the earliest occurrence of each item or process. The Monte Carlo simulation gave a negative mean value in the resources category, as before, but the Monte Carlo and linear analyses have returned results more similar than other light & power scenarios. Results in Table 7 are in their normalized form, wherein the units are points.

Table 7. Scenario 3 Monte Carlo Simulation Results

Impact Category	Linear Mean	Monte Carlo Mean	Standard Deviation
Climate Change	8.418e-02	8.041e-02	3.871e-03
Ecosystem Quality	1.203e-02	2.087e-02	3.342e-02
Human Health	4.802e-02	6.101e-02	2.659e-02
Resources	2.096e-01	-2.048e-01	8.620e-03

Below, in Figure 13, is a visual representation of the Monte Carlo simulation data, with median, maximum, minimum, and 5^{th} and 95^{th} percentiles shown.

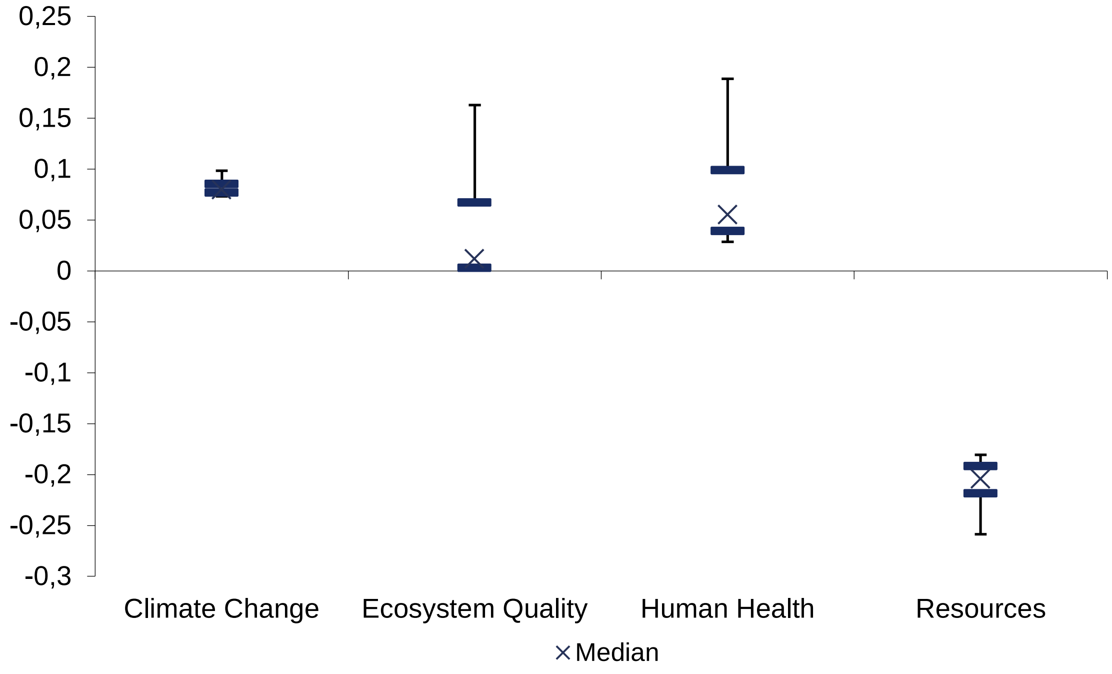


Figure 13. Scenario 3. Life Cycle Impacts in Points, Box & Whisker Chart

5 Comparison of Light & Power Scenarios

In order to conduct a comparison of these scenarios, impacts were divided by Learning Days and produced the results depicted in Figure 14.

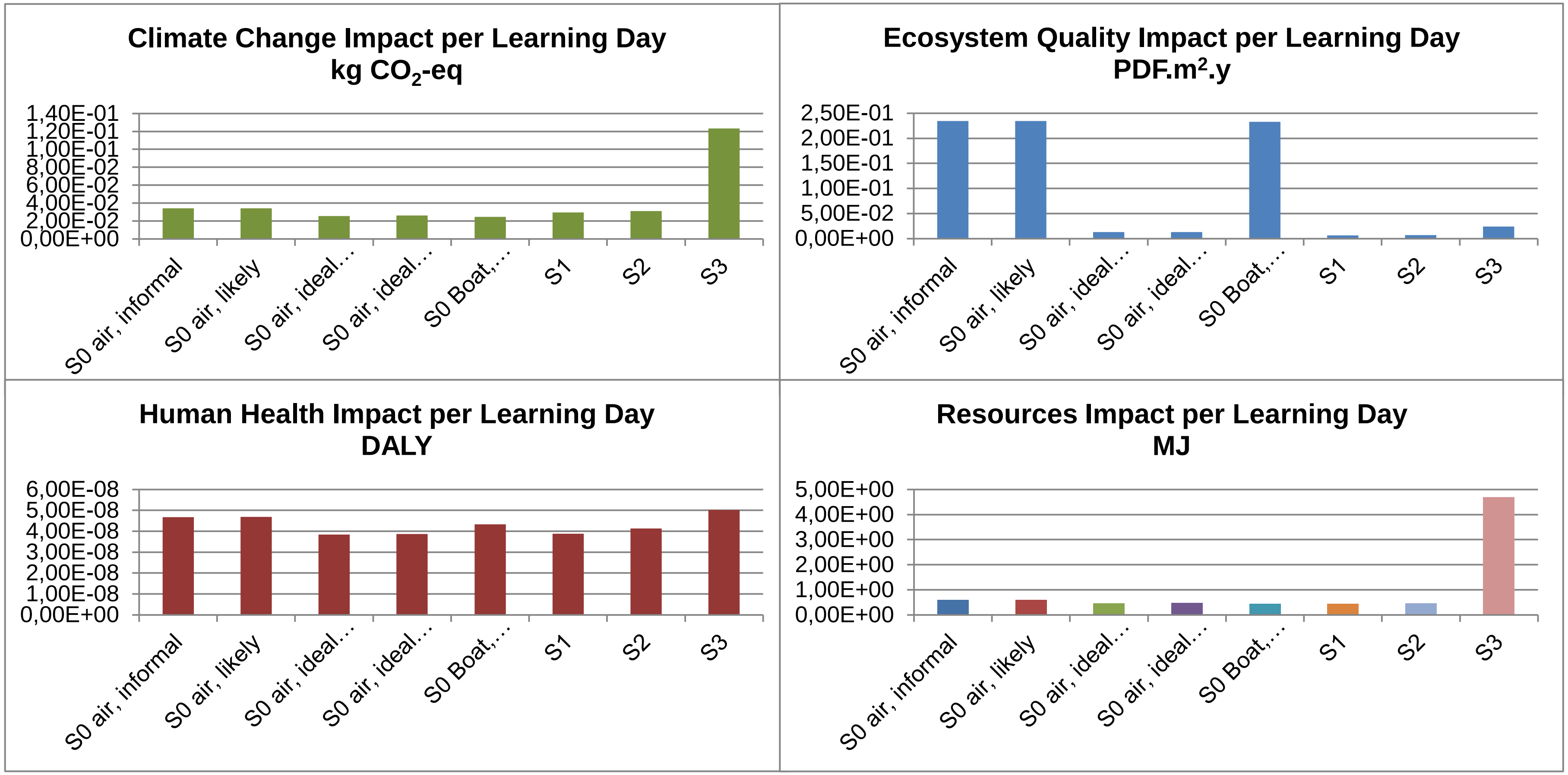


Figure 14. Comparison of impacts per learning day

In most categories, kerosene has the greatest impacts. The exception to this is the category of ecosystem quality, where Solar Straps which are partially or entirely incinerated have the largest impact. When compared only to *responsibly* recycled devices, kerosene has the greatest impacts per learning hour. The responsibly recycled Solar Straps and the diesel generator scenarios all have impacts within the same order of magnitude. The uncertainty of the model suggests that these product sets may not be significantly different.

6 Content Scenario Inventories

6.1 eReader

Data for color eInk screens is unavailable due to the proprietary nature of the information and the great secrecy that inventors and manufacturers observe. In past studies, Liquid Crystal Displays (LCDs) are used to model eReader displays [11;12]. LCDs are assumed to have two glass plates and enable input; in the LeiaMedia eReader used for the SunEdu project, these features are not present. Glass is excluded to reduce weight, replaced by a plastic protective film. The screen is not used for input; instead, input is from buttons on the frame of the device. Therefore, parameter uncertainty for the eInk screen is considerable. Table 8 shows life cycle impacts returned by a linear analysis of the eReader model.

Table 8. eReader Life Cycle Impacts

Impact Category	Result	Unit
Climate Change	103.75	kg CO_2 eq
Ecosystem Quality	271.81	PDF.m^2.yr
Human Health	1.01e-04	DALY
Resources	1768.27	MJ

Figure 15 is a graphical representation of impacts by phase.

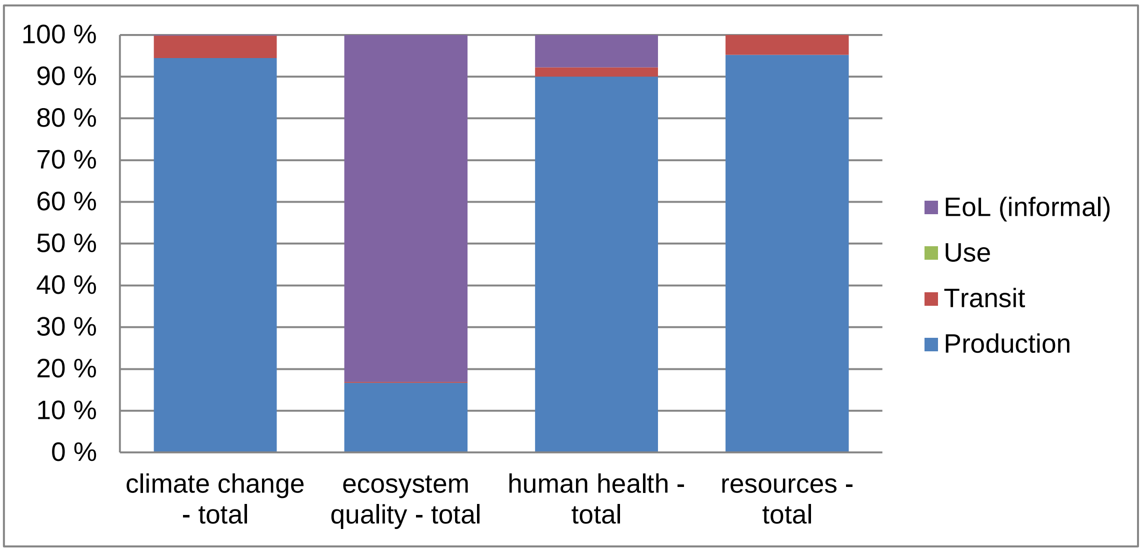


Figure 15. eReader (informal) Life cycle impacts by phase

Climate change impact is overwhelmingly centered in the production phase; major contributors include the production of integrated circuits, of which logic is 20.9% and memory is 56.5% of the total impact. The production of these circuits requires a lot of electricity, much of which is generated by fossil fuels. Production of the battery is about 7.5% of total climate change impact. Transportation by aircraft causes 7.3% of total climate change impact. Use and end of life phases cause less than 1% altogether.

As with the Solar Strap, the ecosystem quality impact is mostly from the end of life of the eReader, as it is burned in a fire pit on agricultural land. Production phase owns 16.7% of the ecosystem quality impact, 5.9% due to blasting and refining of metals and 5.1% due to generation of electricity from fossil fuels. Transit and use cause less than 1% of the ecosystem quality impact. Incineration of the electronics assembly causes 76.1% and incineration of the battery causes 6.9% of the total impact.

Human health impact is caused mostly in the production phase. Large shares of the total are held by processes related to electronics; disposal of waste silicon wafers, electricity generation, and blasting and refining metals contribute to the impact caused by electronic component production. Logic type ICs cause 19.9%, memory type ICs cause 42.5%, and resistors and capacitors each cause about 7% of the total impact. Battery production causes 7.2% of the impact. Transit causes about 2% of the impact; use phase contributes nothing. At end of life, incineration of the electronic parts causes about 7.7% of the total impact. All other processes contribute less than 1% of the total.

Resource depletion impacts are mostly from the generation of electricity from fossil and nuclear fuels, which accounts for about 68% of the total impact. Other impacts come from gold, natural gas and fuel oils used for the production of electronic components--mostly for logic and memory components. Altogether, these contributions are about 13% of the total. Production of the battery contributes 4.5% of the total impact. Transit by aircraft in both production and transit phases contributes 6.6% of the total; 4.8% in the transit phase itself. Use and end of life phases contribute very little to resource depletion, but neither do they return any materials to use.

6.1.1 Sensitivity Analyses

Sensitivity Analyses are performed for modes of transportation and different end of life scenarios, as these are of particular interest for partner organizations.

6.1.1.1 *Transportation*

Two modes of transportation are considered for both component transport from place of manufacture in China to place of assembly in Finland, and from Finland to Dar es Salaam; a comparison is shown in Figure 16. Air freight and oceanic freight are compared, with distances estimated using Air Distances and Sea Distances web tools [28;29].

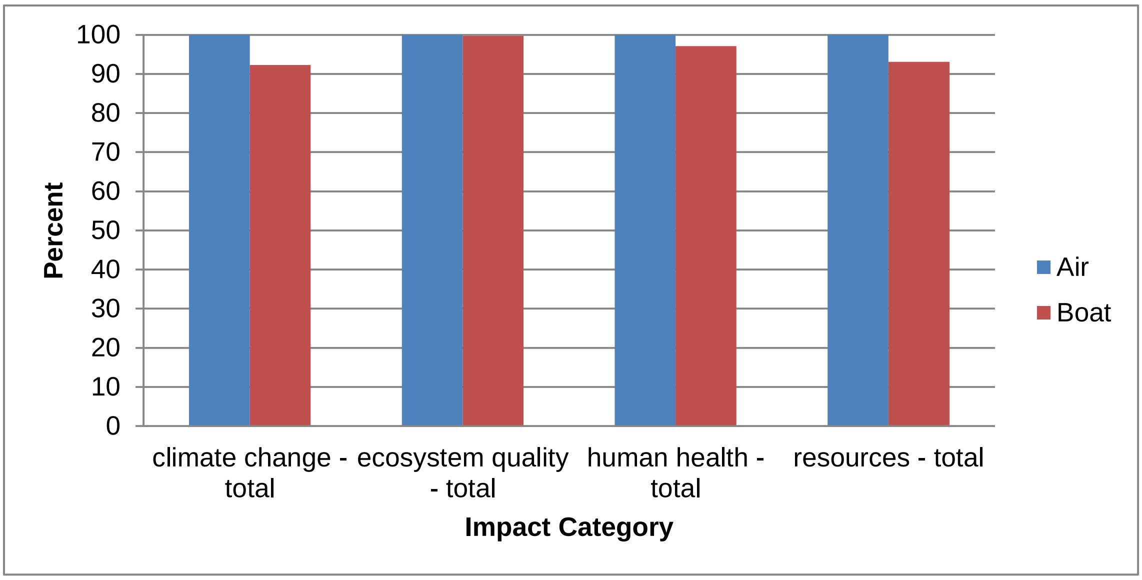


Figure 16. Sensitivity analysis of different transportation types

Transport by boat rather than air freight provides a 7.8% reduction in climate change impact, 2.9% reduction in human health impact, 6.9% reduction in resource impact, and less than 1% reduction in resource depletion impact. As with the Solar Strap, these impact reductions are not significant for the pilot project, but may be more significant once large quantities of the unit are required.

6.1.1.2 *End of Life*

Three end of life scenarios were considered: informal incineration in a fire pit on land which is likely to be used for agriculture in the future; shredding and recycling the unit for steel and copper in Dar es salaam, all other components incinerated; and the idea scenario being transport of the unit to the e-waste facility in Mombasa for 100% recovery of steel, nickel, and copper, treatment of PWB and eInk screen for further metallurgical treatment, and all other components incinerated. A comparison of results is shown in Figure 17.

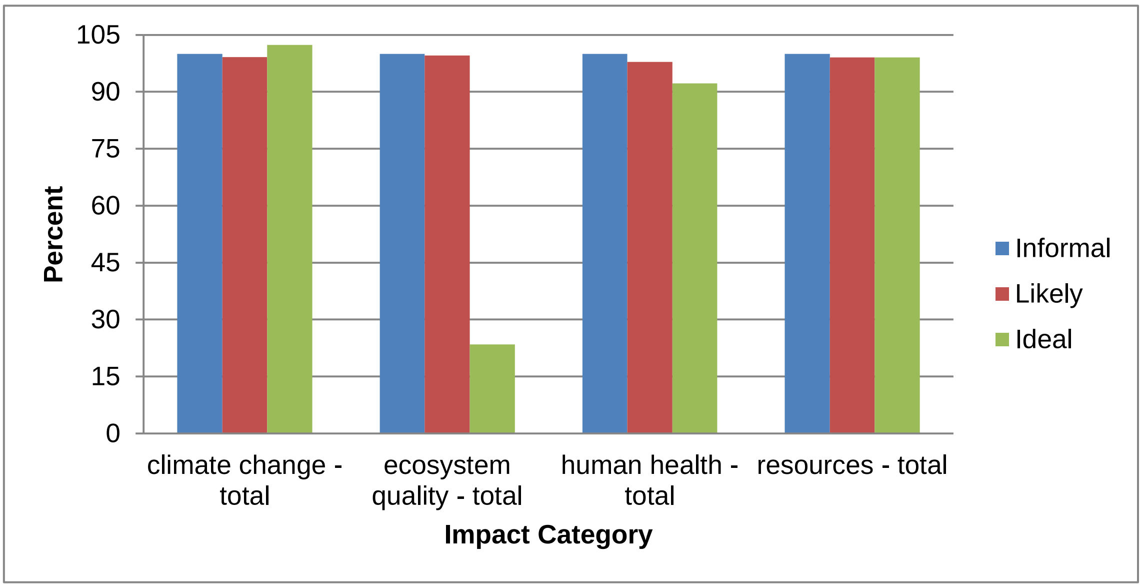


Figure 17. Sensitivity analysis of different end of life scenarios, Informal as baseline

Impacts from the transport of the unit to Dar es Salaam are offset by the impact reductions of reclaiming the steel and copper pieces; however, impact reduction totals are less than 1% in climate change, ecosystem quality, and resource depletion categories. Impact reduction is less than 3% in the category of human health. Ideal recycling increases the climate change impact by a little over 2% but reduces ecosystem quality impacts by over 76 percent. The impact on human health is reduced by almost eight percent. Resource depletion is decreased less than one percent.

6.1.2 Uncertainty Analysis

The eReader was specifically designed for the SunEdu project, and thus some parameter uncertainty is due to design changes taking place between materials measurement for LCA purposes and the final product release. Another source of uncertainty is the lack of information on electronic component manufacturing impacts from the specific country where the eReader components are manufactured, which would have been available in the newer version of the EcoInvent database. Further significant uncertainties are due to lack of information about the eInk display; the substitution of a weight-adjusted LCD screen is popular in similar reports, but unfortunate.

A Monte Carlo simulation was performed with 5000 iterations to propagate uncertainty throughout the model and generate probable return values. Uncertainties were defined using the pedigree matrix at the earliest occurrence of each item or process. Results in Table 9 are in their normalized form, wherein the units are points.

Table 9. Monte Carlo Simulation Results - eReader

Impact Category	**Linear Mean**	**Monte Carlo Mean**	**Standard Deviation**
Climate Change	1.043e-02	4.328e-03	3.193e-04
Ecosystem Quality	1.984e-02	1.895e-02	5.758e-04
Human Health	1.423e-02	1.083e-02	2.245e-03
Resources	1.163e-02	-3.520e-03	6.062e-04

The Monte Carlo simulation gave a negative mean value in the resources category.

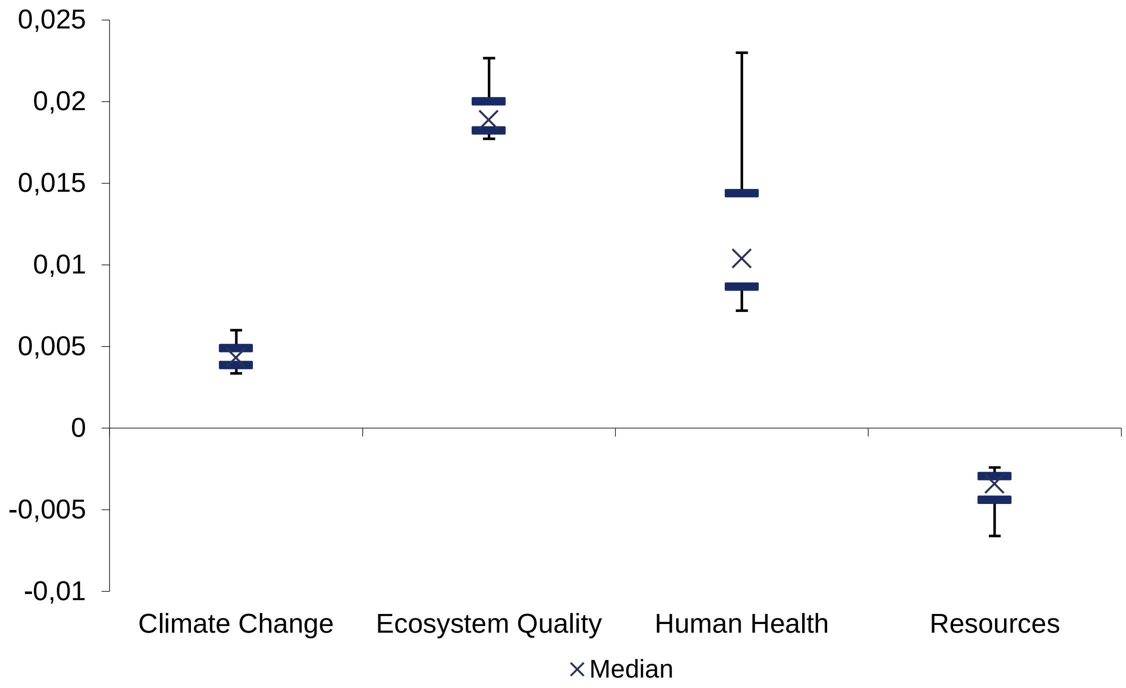


Figure 18. eReader Life Cycle Impacts, Box & Whisker Chart

6.2 Books

Due to complete lack of communication from any of the Tanzanian printing facilities contacted, books were modeled using data from the EcoInvent database; unfortunately, this leads to high spatial and temporal uncertainty, as the data is from Europe while the actual books to be modeled are printed and bound in Africa. The book model includes raw materials for both paper and ink, electricity, and machinery needed to produce a complete book. Paper is modeled as transported approximately 20 kilometers from the mill to the print facility, as both are assumed to be located in Dar es Salaam. The finished book is then transported to Iringa by light truck. Transport from Iringa to the users is not modeled due to lack of data on locations of schools or markets. With such high uncertainty and numerous assumptions, this is the least reliable part of the analysis.

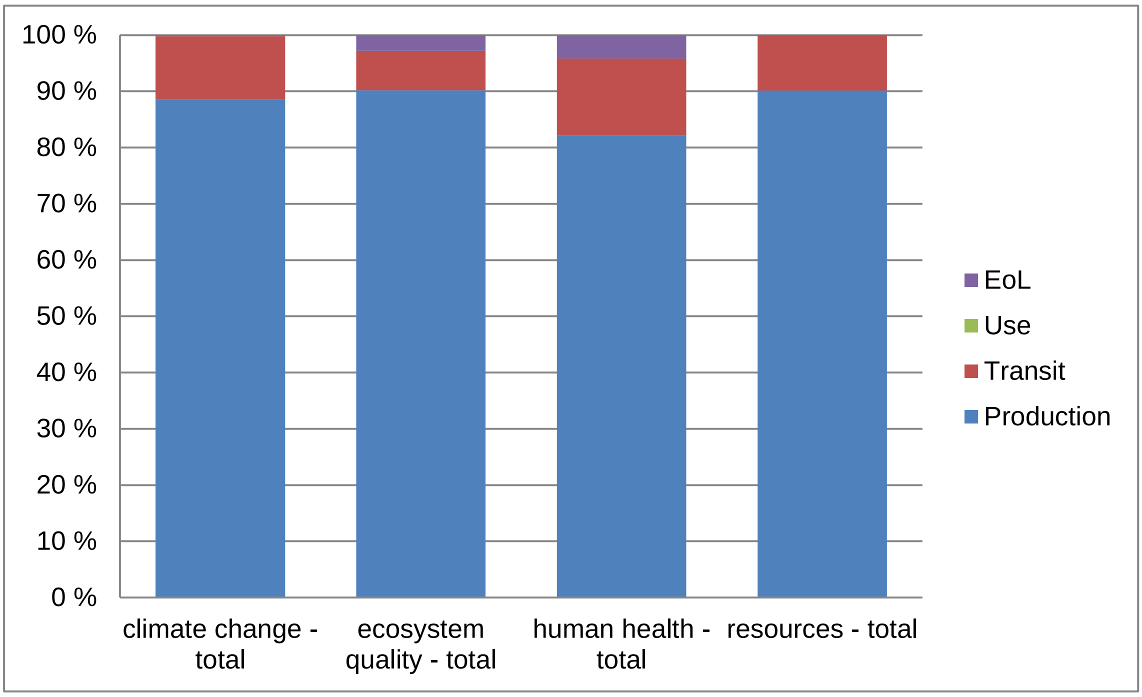
In Table 10, mean values for life cycle impacts of one book are given.

Table 10. Book Life Cycle Impacts, 1 unit

Impact Category	Result	Unit
Climate Change, total	0.1725	kg CO_2 eq
Ecosystem Quality, total	0.0900	PDF.m^2.yr
Human Health, total	1.5856e-07	DALY
Resources, total	3.3914	MJ

Figure 19 below shows the life cycle impacts of a book by phase.

Figure 19. Book life cycle impacts by phase



Most impacts are from the raw material through production phase. Climate change impact is 32.8% from the generation of electricity; because this is modeled as a European power mix, this number could significantly change the total impact if adjusted for Tanzania's power mix. Ten point one percent of climate change impact is from transportation by lorry and 5.5% from transportation by rail freight of raw materials to the paper mill. This is also likely to be significantly different with Tanzanian transport data. Excluding electricity, the production of the newsprint and wood-free coated paper required for the book accounts for 53.3% of total climate change impact. Transportation in the transit phase accounts for 11.4% of total climate change impact. Informal incineration of the book causes less than 1% of total impact.

A little more than a quarter of total ecosystem quality impact is from the harvesting of trees for paper. Another 8.4% is from the sulfate bleaching process, and 7.6% is from transport by lorry of raw materials and of paper from mill to printing press. Electricity generation creates 21.3% of the ecosystem quality impact. The transit phase impact share is 7.4%, and informal incineration causes 2.8% of the total impact. All other impacts are less than 5% of the total.

Electricty generation causes 29.4% of the human health impact; another 17.5% is from transportation during the production phase-- 12.2% by lorry and 5.3% by rail freight-- and 4.5% is from the sulfate bleaching process. Transit phase share of impacts is 14.5% and end of life is 4.2 percent. All other human health impact contributions are less than 5% of the total.

Resource depletion impact is divided into two categories: non-renewable energy and mineral extraction. As such, it is important to note that the temporary depletion renewable resources, such as trees, are not accounted for in this category. Of the total resource depletion impact, 55.8% is from uranium and fossil fuel use in electricity generation. This is likely to change significantly if data could be obtained for the Tanzanian power mix. Natural gas used at the paper mill accounts for 10.4% of the resource depletion impact; heavy fuel oil used at the plant is another 5.8% of the total. Ten point four percent is from lorry transportation and 5.2% is from rail freight in the transit phase. No resources are depleted during use and end of life phases. All other impacts are less than 5% of the total, individually.

6.2.1 Uncertainty Assessment

A Monte Carlo simulation was performed with 5000 iterations to propagate uncertainty throughout the model and generate probable return values. Uncertainties were defined using the pedigree matrix at the earliest occurrence of each item or process. Results here are in their normalized form, wherein the units are points.

Table 11. Monte Carlo Simulation Results - Book

Impact Category	Linear Mean	Monte Carlo Mean	Standard Deviation
Climate Change	1.734e-05	9.306e-06	1.224e-06
Ecosystem Quality	6.569e-06	-5.376e-08	9.806e-07
Human Health	2.233e-05	1.778e-05	2.561e-06
Resources	2.231e-05	-1.062e-05	1.674e-06

The Monte Carlo simulation gave negative mean values in the cases of ecosystem quality and resources categories. This appears to be a problem with the software, observed by others in the technical support forums on the OpenLCA website.

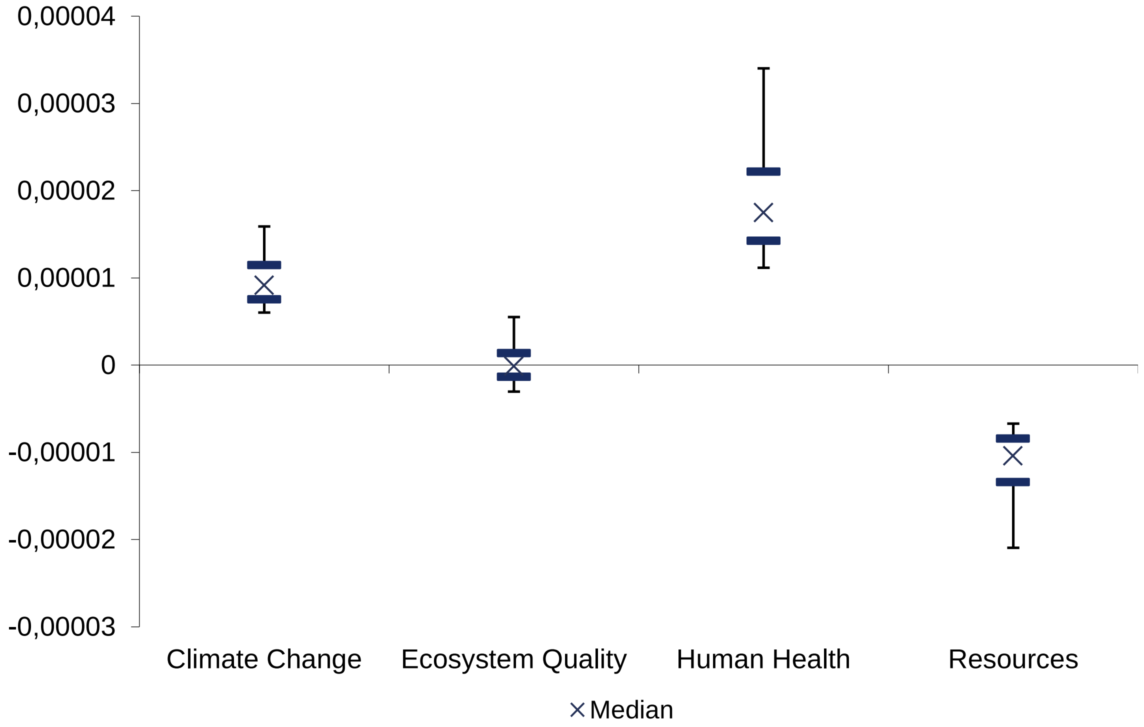


Figure 20. Book Life Cycle Impacts, Box & Whisker Chart

7 Comparison of Content Scenarios

As with the power and light scenarios, impacts were divided by the provided learning days for both content objects. The break-even point of the eReader is calculated as both the number of books the eReader would have to replace and the Learning Days the eReader would have to provide in order to have the same impact score in each category. In order to estimate the number of learning days a book ought to provide, the total number of learning days in an academic year was divided by the number of books used in one academic year-- 9 subject books and 3 story books. This yields 16.67 learning days per book. For initial comparison purposes, lifetime of the eReader is assumed to be two years, giving 400 learning days.

7.1 Impacts per Learning Day

Impacts per learning day provide the following comparison:

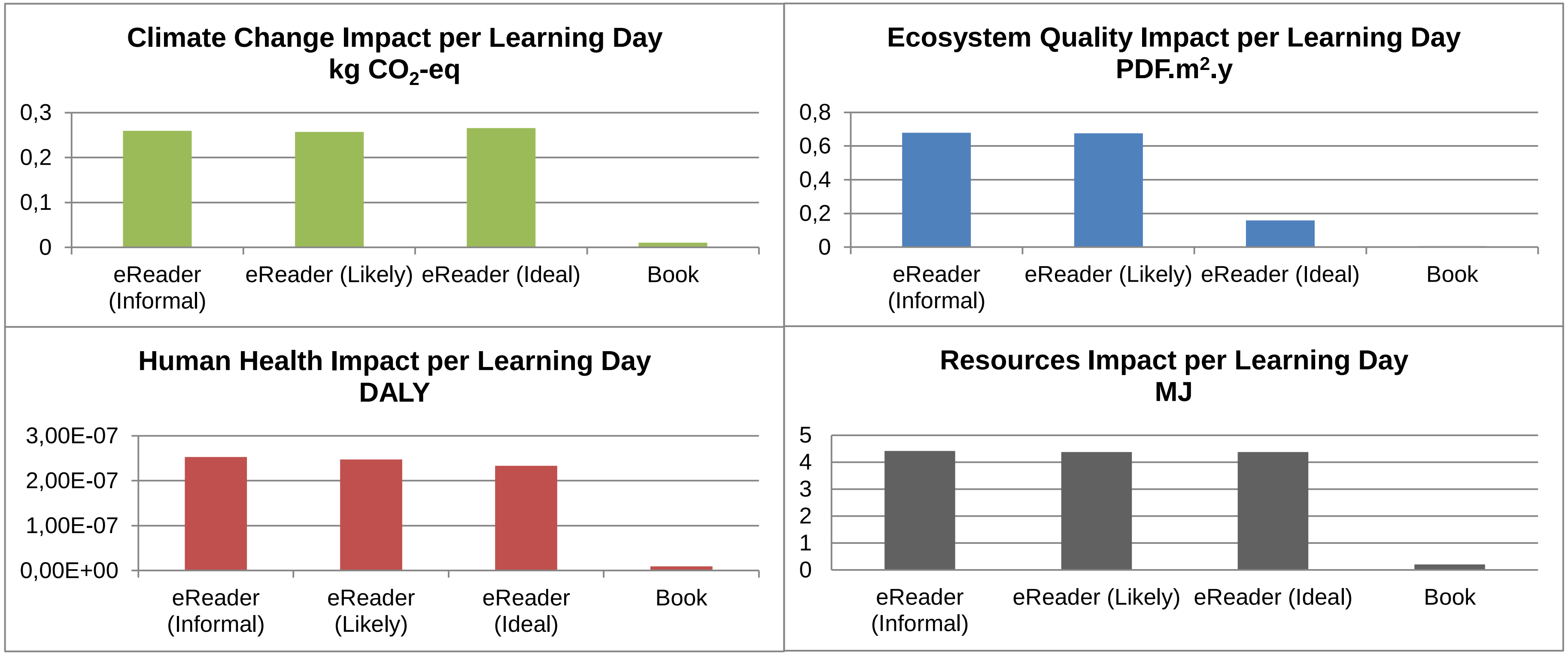


Figure 21. Impacts per Learning Day of Content Devices

Even comparing amongst impacts per learning day, the eReader has significantly higher impacts than the locally produced, locally printed books. As more is learned about the production of books in Tanzania, this could change, but electronic devices are likely to always have a higher impact than books.

7.2 Break-even Points

Break-even points are calculated for both the number of books and the number of learning days the eReader would have to replace in order to create equal environmental impacts.

Table 12. Break-even Points for eReader

	eReader (informal)	**eReader (informal)**	**eReader (Ideal)**	**eReader (Ideal)**
	# of Books	Learning Days	# of Books	Learning Days
Climate Change	601	10 017	616	10 267
Ecosystem Quality	3020	50 334	707	11 784
Human Health	637	10 617	588	9 800
Resources	521	8 683	517	8 617

The E-reader would have to be in service for 252 academic years in order to replace the books required in the same amount of time. This is not technically feasible in any imaginable universe. If the eReader were in use every day, rather than every learning day, the impacts per day would be significantly lower, but in that case the eReader would not replace only school books, but also newspapers and other content devices not modeled for this report.

8 Interpretation

Interpretation is not required by the ISO 14040 standard on Life Cycle Assessment, but if present it is recommended to include the identification of issues based on the inventory and analysis phases, evaluation of the study for completeness, sensitivity, consistency, and limitations, and any conclusions or recommendation [30].

8.1 Interpretation of Light & Power Scenarios

The impacts of burning kerosene make clear that the status quo is the least sustainable of all the light and power scenarios. Any one of the other scenarios would be an improvement. Due to the uncertainty of the model, it is not clear which of the other scenarios is the best, or if any of them is significantly better than any other. Responsible recycling practices provide a clear environmental benefit over informal incineration, but recycling only for copper is not environmentally beneficial. Responsible recycling may provide an even bigger benefit, were a facility for e-waste treatment located nearer to the product users, i.e. in Tanzania. The smaller benefit of oceanic shipping is shown; this benefit will be more significant after the pilot project, if the product is to be shipped in larger quantities. However, production of any of the devices closer to or even in Tanzania would provide an even greater impact reduction.

If the Solar Strap were assumed to be used at home every day, rather than only on school days, a two year life span would be 730 days. Increasing the Solar Strap product life without significantly altering the product would decrease the impact per learning day. Two years of product life would then yield impacts shown in Figure 22.

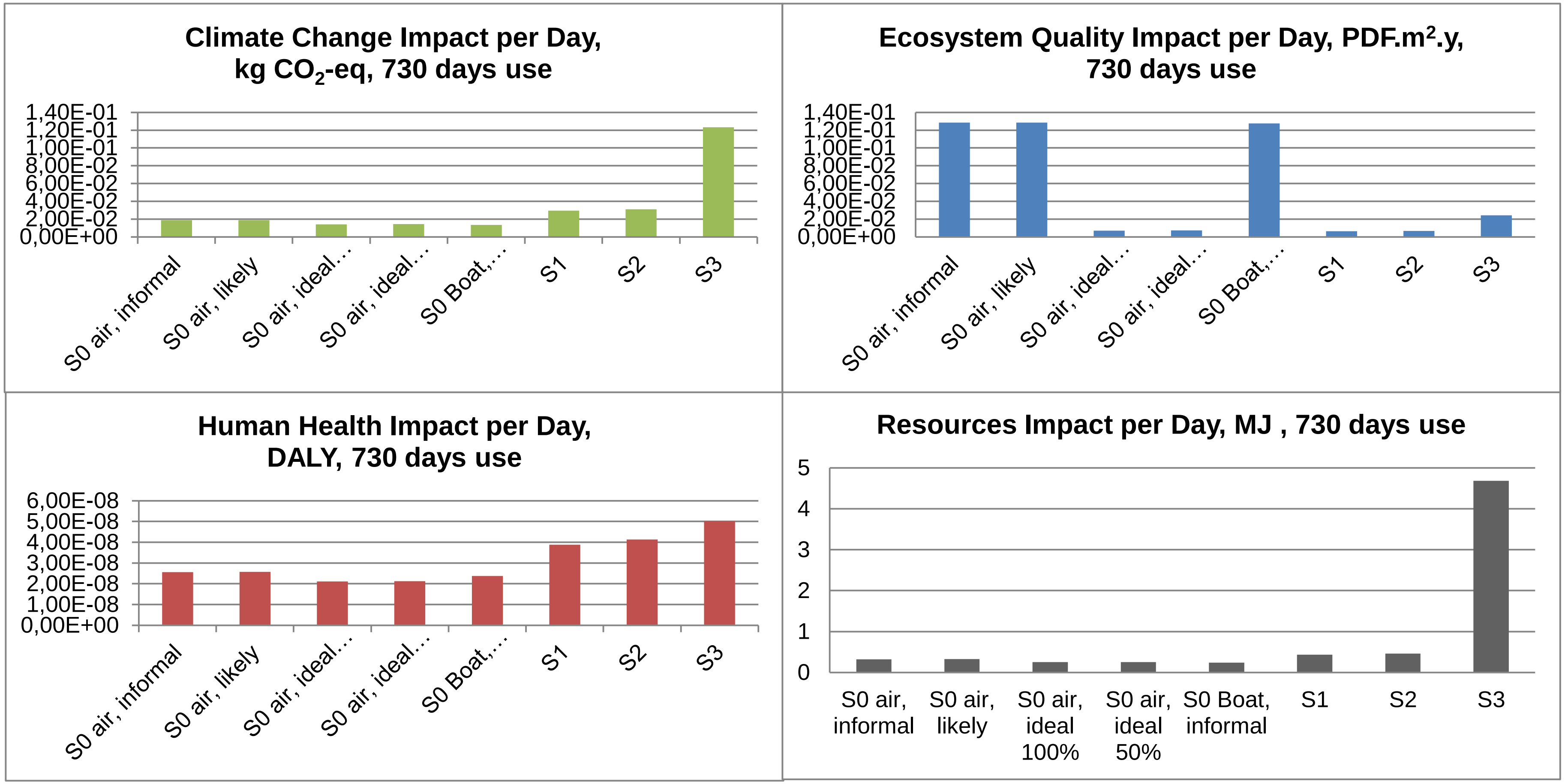


Figure 22. Impacts per day with everyday use of Solar Strap

8.2 Interpretation of Content Scenarios

Changing mode of transport would not significantly reduce the eReader's impact per unit, but could provide significant net reductions if units were mass produced. Production closer to the 'gate' would likely have greater reductions than changing the mode of transportation, and should be considered for the future. Ideal recycling would provide greater impact reductions if a responsible e-waste facility were located closer to the end user, eliminating the need for lengthy lorry journeys to Mombasa and eliminating the additional climate change impact that results from that trip. The lack of e-waste recycling facilities in Tanzania has become a recurring theme in this report; some enterprising parties may consider establishing such a facility.

Books still have a lower impact in spite of the advances made in technology and compliance with the Restriction on Hazardous Substances. It is not technically feasible to make the life of the eReader sufficiently long to close this gap. Reduction of materials used, particularly electronic components, and production in a facility receiving or generating its own clean electricity supply would reduce the impacts of the device.

8.3 Interpretation of Combined Scenarios

As an academic exercise as well as for building policy recommendations, what follows are the combined impacts per learning day for a variety of device combinations, regardless of feasibility in the target area. All electronics are assumed to be recycled as described in the Ideal end of life situations. The last combination represents the status quo, already in use.

Table 13. Combinations of Impacts per Learning Day

Impact Category	S0 + eReader	S0 + book	S1 + eReader	S1 + book	S3 + book
Climate Change	2.795e-01	2.437e-02	2.951e-01	3.996e-02	1.335e-01
Ecosystem Quality	1.662e-01	1.248e-02	1.656e-01	1.188e-02	2.964e-02
Human Health	2.541e-07	3.057e-08	2.719e-07	4.839e-08	5.965e-08
Resources	4.630	4.540e-01	4.817	6.410e-01	4.889

If the choice of devices were based solely upon environmental concerns, a combination of the solar charger and books would be the most likeable. Due to the uncertainties of these models, it is not possible to know if that combination is significantly better than the diesel generator and books, but it seems clear that the use of kerosene generates high environmental impacts that, with consideration of model uncertainties, may negate the impacts from the eReader in the best cases. However, responsible e-waste recycling and production closer to the users would be necessary for that to be true. With further changes in both solar charger and eReader design, it could be that together, they create little or no net increase in environmental impacts when replacing kerosene and books, while easing distribution of information and providing significant benefits to the user’s health.

8.4 Completeness, Sensitivity, Consistency, Limitations

This study has been as complete as possible without access to records of emissions, materials and energy flows, and other documents; it has been limited by the cooperation-- or lack thereof-- of related industries. It is also limited by lack of information from the region in question. Life cycle assessment is not as popular in Africa as in Europe, and data from specific regions in Africa was not available. As the models are all dependent in some way on electricity from the grid and raw materials from non-European regions, this could have a significant effect on the forecasted impact values’ distance from true values. The study has also been limited by either software or user error; the systematic problem with negative resource category values returned by simulations leaves both the author and her advisors somewhat befuddled.

It is recommended that future studies concentrate on regional impact characterization factors and building a database of life cycle inventory information for industries and activities in Africa, subdivided by region. Climatic conditions and population distribution should be taken into account when developing a set of regional factors. There is also a need for some legal protection for IPR holders, industrial partners, and LCA practitioners, so that all three parties may share information freely without fear of espionage, legal penalties for (previously unreported) excessive emissions, bad press, loss of business, or other consequences. The non-disclosure agreement does not seem to be sufficient, and life cycle assessment cannot take place without reliable, accurate, and useful data. It is not possible to build bricks without clay.

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