Life Cycle Assessment of Product Stewardship Options for Mercury-Containing Lamps in New Zealand: Final Report

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Executive Summary

Background

The Ministry for the Environment contracted ERM to undertake a life cycle impact assessment (LCA) study of mercury-containing lamps to assess the relative life cycle impacts of mercury-containing lamps when managed under the following scenarios:

- recycling at end-of-life,
- disposal in landfill at end-of-life,
- reducing mercury at-source, and/or
- some combination of the above.

The purpose of this study was to identify the potential environmental impact (environmental harm) of different types of lamps, and different end-of-life management options (in the context of the performance and applications of the lamps appraised). The results of this study will inform product stewardship policy.

A Working Group made up of representatives from the Ministry for the Environment, lighting industry, recycling sectors, local government, and lighting retailers has been investigating the potential for developing a product stewardship scheme for lighting products.

The group identified a three-phase approach to developing and implementing a product stewardship programme, as follows:

Phase 1. *New Zealand Lighting Industry Product Stewardship Scheme – Phase 1 Assessment and Review* (completed January 2008). An external consultant was commissioned to carry out Phase One funded jointly by the Ministry for the Environment and the Working Group. This work included an assessment of the current status of the lighting industry and its environmental impacts in New Zealand. More specifically, market characteristics of the lighting industry, potential harm to the environment and human health from lighting products, industry's ability to address issues, and a review of potential product stewardship models and best practices.

The Phase 1 report identified information gaps to be overcome prior to considering further work; a mercury inventory for New Zealand and a life cycle impact assessment of mercury-containing lamps for the lighting sector.

Phase 2. The need to understand the relative environmental impact of the mercury from mercury-containing lamps compared to the impact of mercury from other sources (anthropogenic or natural) in New Zealand is covered in the 'Mercury Inventory and Flow Analysis' report (completed May 2009). This information also helps to inform the development of New Zealand's policy on the reduction of mercury pollution for the proposed UNEP-led international initiative on mercury reduction.

Phase 3. This life cycle assessment report represents Phase 3. This ISO compliant study (completed June 2009) assesses the whole-life environmental impacts of mercury-containing lamps for the New Zealand lighting industry.

Scope of the LCA Study

The study has been conducted in compliance with international standards for LCA (ISO 14040/44) and has been externally reviewed by an expert panel of peer reviewers.

The study has assessed the whole-life environmental impacts that arise from mercury-containing lamps for New Zealand specific conditions, including overseas raw material manufacture, overseas lamp manufacture, lamp import, lamp distribution, lamp usage, disposal and recycling. Figure 1 on page 27 shows the generic life cycle of the lamps assessed.

The life cycle assessment study has assessed the environmental impact contributions of the following lamp types over 100,000 hours of operation:

- Fluorescent:
    1. Linear fluorescent lamp (LFL);
    2. Compact fluorescent lamp: external ballast (CFLe); and
    3. Compact fluorescent lamp: integral ballast (CFLi).
- High Intensity Discharge (HID):
    4. High pressure sodium (HPS);
    5. Metal Halide (MH); and
    6. Mercury Vapour (MV).

The lamps listed above represent the mainstream types used in New Zealand for residential, commercial and industrial applications.

The potential contributions of each system are assessed for the impact categories listed below. The listed impact categories address a range of environmental issues, and thorough methodologies have been employed for these categories.

- depletion of abiotic resources;
- global warming;
- stratospheric ozone depletion;
- human toxicity;
- freshwater and marine aquatic ecotoxicity;
- terrestrial ecotoxicity;

- photo-oxidant formation;
- acidification; and
- eutrophication.

The adequacy of human and ecotoxicity methods, are in general subject of international scientific discussion due to the need to employ assumptions and estimates regarding fate and exposure.

The results of the study are not comparable across lamp types, as they are not functionally equivalent, due to differences in lamp life, lamp output and application. However, the results are comparable within each lamp type for the different scenarios assessed in the study, as listed below.

Scenario 1. 50% recovery and recycling at end-of-life;

Scenario 2. 80% recovery and recycling at end-of-life;

Scenario 3. 100% disposal (to landfill) at end-of-life;

Scenario 4. Reducing mercury level to the technically feasible minimum and 50% recovery and recycling at end-of-life;

Scenario 5. Reducing mercury level to the technically feasible minimum and 80% recovery and recycling at end-of-life; and

Scenario 6. Reducing mercury level to the technically feasible minimum and 100% disposal (to landfill) at end-of-life.

The primary focus of the study has been to assess the whole-life environmental impacts from the use of mercury-containing lamps, and the trade-offs that arise from potential product-stewardship options for end-of-life management (by increasing recovery and recycling rates) and for lamp design (by reducing the lamps mercury content). In addition, the implications in relation to lamp lifetime and in-use efficiency improvements have also been tested.

Overall Study Conclusions for Mercury-Containing Lamps

The study has assessed and drawn conclusions for the environmental impacts of mercury-containing lamps in two main areas, as follows:

- *Whole life results*: which includes the environmental impacts associated with all stages of the lamp life cycle, from overseas raw material extraction through to overseas lamp manufacture, import into New Zealand, distribution, lamp usage, disposal and recycling.
- *End-of-life results*: which includes the environmental impacts only associated the end-of-life stages of lamp disposal and recycling. All other stages are excluded.

Whole Life Conclusions

When considering the whole-life environmental impacts, the results indicate that the use phase dominates the impacts across all impact categories, accounting for more than 90% of the total life cycle. The manufacturing phase represents around 5% of total impacts and the disposal phase represents around 1% of total impacts across the total life cycle.

The results demonstrate that an environmental benefit is achieved from increasing the recovery and recycling rates for mercury-containing lamps. However, in the context of the whole life cycle, the environmental benefits are relatively small.

In terms of mercury contribution to human toxicity impacts, the results indicate that mercury contributes a low amount to total impacts. Primarily, the contributions to human toxicity arise from generation of electricity in the use phase, resulting from combustion of gas and coal which releases emissions of PAH and NMVOC to air. The use phase contributes around 85% to 95% of the total human toxicity impact. This is the same across all lamp types (with the exception for integrated CFL where the use phase contributes around 65%, due to burdens associated with additional electronics).

When considering other lamp performance parameters, such as lamp lifetime and energy efficiency, it has been demonstrated that significant environmental benefit can be delivered by longer lifetimes and higher efficiencies. An increase in lamp lifetime reduces production burdens and waste management and results in significant benefits. Similarly, burdens reduce with reduced energy consumption in the use phase.

Conclusions when only End-of-Life is considered

When considering the end-of-life phase only, the results indicate that increasing recovery and recycling levels of lamps from 9%, in the baseline, up to 80%, then the environmental benefits for the end-of-life phase increase significantly. The benefits arise primarily from the benefit associated with avoiding the production of new materials that would have otherwise taken place if the lamps were not recycled in other materials.

In terms of the potential for mercury to contribute to human toxicity impacts, the results indicate that mercury releases from landfill contributes a significant proportion of the potential human toxicity impacts (ranging from around 25% to 90%) from end-of-life . Increasing the levels of recycling considerably reduces the contribution from mercury disposal at end-of-life.

When considering the influence other lamp characteristics have on end-of-life, such as lamp lifetime and mercury level in the lamps design, then significant environmental benefit can be achieved by longer lifetimes and reduced mercury-content, as these both deliver reduced quantities of material for disposal/management at end of life.

For end-of-life product stewardship options, overall, it can be concluded from the results that increasing the levels of recovery and recycling of mercury-containing lamps will provide benefits to the environment.

Summary of Main Results for Mercury-Containing Lamps

As mentioned above, the summary of results are presented here in two main sections, as follows:

- *Whole life results*: which includes the environmental impacts associated with all stages of the lamp life cycle, from overseas raw material extraction through to overseas lamp manufacture, import into New Zealand, distribution, lamp usage, disposal and recycling.
- *End-of-life results*: which includes the environmental impacts only associated the end-of-life stages of lamp disposal and recycling. All other stages are excluded.

Whole Life Impacts: Increased Recycling and Recovery

The results indicate that, for all lamps types, increased recovery and recycling levels reduces the contribution made to the human toxicity and ecotoxicity impact categories. These benefits are more prominent for domestic lamps (LFL, CFLi and CFLe), ranging from around 2% to 45%, when increasing from 0% to 80% for recycling and recovery. For industrial lamps the benefits relating to human toxicity and ecotoxicity range from around 2% to 35%, when increasing from 0% to 80% for recycling and recovery. An example for a compact fluorescent lamp with integral ballast (CFLi) is shown in Figure 5 on page 50.

For all other impact categories, such as global warming potential and resource depletion, the benefits achieved through increased recycling for they are relatively small, in the context of the whole life, due to the significance of the use stage. The benefits (i.e. reductions in impact) range from around 0% to 3% with increased recycling levels from 0% to 80%.

The primary driver for the reduction in ecotoxicity impacts is due to the environmental benefits that arise from avoided production of mercury material, and the associated emissions of mercury to air from the raw material production process.

The primary driver for the reduction in human toxicity impacts is due to the environmental benefits that arise from avoided production of nickel material, and associated emissions of heavy metals to air (which are non-mercury) from the raw material production process.

Whole Life Results: Reduced Mercury Levels

The study assessed a reduced mercury level of 20% for each lamp. Overall, the influence of reduced mercury levels of 20% provides an almost negligible reduction in environmental impact compared to typical mercury levels across all impact indicators, with the exception of terrestrial ecotoxicity impacts (as shown in Figure 15 on page 63 for a CFLi lamp), which gives a reduction of around 6% of the impact at an 80% recycling level (and 2% reduction at a rate of 9% recycling and recovery).

The benefits for terrestrial ecotoxicity impacts are almost entirely driven by the reduced need to manufacture as much mercury for the lamp, associated with reduction in release of mercury to air from raw material manufacturing process. Also smaller reductions occur at end-of-life landfill disposal which is primarily driven by a reduction in emissions of mercury to soil and to air, which results from reduced levels of mercury entering the landfill.

Whole Life Results: Contribution of Mercury to Human Toxicity Impacts

The contributions of different substance emissions (to air, water and land) that arise in the life cycle for each lamp were assessed for their potential contribution to human toxicity impacts. The results indicate that mercury emissions contribute under 0.5% of the calculated total potential human toxicity impact for all lamp types.

The most significant contributing substances relate to poly aromatic hydrocarbons (PAH) to air (contributing generally about 50% of impacts), non-methane volatile organic compounds (NMVOC) to air and other (non-mercury) heavy metals. These emissions arise primarily from the generation of electricity in the use phase, resulting from combustion of gas and coal. The results indicate that increased levels of recovery and recycling would reduce total human toxicity impacts and also reduce the levels of mercury release to the environment. The benefits achieved from changing from 9% to 80% recycling and recovery result in reduction of around 1.5% for human toxicity impacts over the life cycle.

Whole Life Results: Improved Energy Efficiency and Lamp Warm-Up

The study has assessed two areas in relation to lamp operating efficiency in the use phase, as follows:

- increased energy efficiency of 10% in the use phase (based on a theoretical estimate); and
- inclusion of reduced energy efficiency from potential warm-up effects (estimated at 0.5% reduction in efficiency).

The results show that for an increase in energy efficiency of 10% the change in environmental impacts across all indicators is significant. As previously mentioned, the use phase dominates the whole-life impacts, and a 10% reduction in energy consumption has the potential to deliver a similar reduction in impacts. This is the case for abiotic resource depletion, acidification, eutrophication, global warming potential and human toxicity, which reduce by 8% to 9%. Other impacts indicators reduce but to a slightly lesser extent (of around 2% to 4%).

The inclusion of warm-up effects would have a negligible influence on all the environmental impact categories appraised, Figure 22 on page 79 shows the results for a CFLi lamp.

Whole Life Results: Lamp Lifetime

The study has assessed a theoretical scenario of potential implications of extended and reduced lifetime of ± 50% of typical lifetime.

As would be expected, the environmental impacts reduce with extended lifetime, particularly in relation to human toxicity and ecotoxicity impact categories. This primarily arises due to the reduced requirements for manufacturing the product, as well as reduced waste disposal requirements. As would be expected, the opposite is true for reduced lifetime. Figure 21 on page 77 shows the results for a CFLi lamp.

End-of-Life Results: Increased Recycling and Recovery

The study assessed the environmental impacts that arise for increased recycling and recovery levels for the end-of-life stage alone (without considering impacts associated with other life cycle stages, i.e. for overseas raw material manufacture, overseas lamp manufacture, import distribution and usage).

The results indicate that significant environmental benefits across all impact indicators arise for all lamp types when recovery and recycling levels are increased. A negative number in the Figure indicates that there is an overall environmental saving.

These reductions in overall impact are dominated by the environmental benefits that arise through the avoided production of virgin raw materials, as a result of their displacement by materials recovered for further use by the recycling process.

End-of-Life Results: Reduced Mercury Levels

The study also assessed the potential change in environmental impacts that may arise from reduced mercury levels in the lamp for the end-of-life stage alone (without considering impacts associated with other life cycle stages i.e. for overseas lamp manufacture, import, distribution and usage).

Table 11 on page 62 shows that the influence of reduced mercury levels of 20% provides an almost negligible reduction in environmental impact compared to typical mercury levels across all impact indicators, with the exception of terrestrial ecotoxicity impacts, which gives a reduction of around 20% of total impact for a recycling and recovery rate of both 9% and 80%. This reduction results from a direct reduction in emissions from landfill disposal due to a reduced mass of mercury being disposed per lamp.

End-of-Life Results: Potential Contribution of Mercury to Human Toxicity Impacts

The potential contributions of different substance emissions (to air, water and land) that arise from the life cycle for each lamp were assessed for their contribution to human toxicity impacts.

When looking at end-of-life only, emissions are accounted for that cause both detrimental impacts, from direct emissions from waste management activities (e.g. heavy metals emissions to air, water and soil), and environmental benefits, through avoided emissions that arise from displaced production of virgin raw materials (recovered for further use by the recycling process). Negative numbers in the Table reflect the environmental benefits of the avoided emissions.

The results indicate that increased levels of recovery and recycling reduce total human toxicity impacts that result from mercury emissions from landfill. However, the primary driver for emissions reductions results from the environmental benefits delivered by avoided production of virgin raw materials. These avoided emission benefits mainly arise from avoided production of metals (nickel, brass and aluminium) in the lamps.

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- Dr. Barbara Nebel, Scion, Wellington; and
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1 Introduction

Environmental Resources Management (ERM) was commissioned by the Ministry for the Environment (MfE) to conduct a life cycle assessment (LCA) of Product Stewardship Options for Mercury-Containing Lamps in New Zealand. This report provides the results for the LCA study.

The LCA study conforms to the ISO 14040 and 14044 standards (2006 and 2006a) for LCA and has been externally reviewed by a panel of LCA experts as described by the standard.

The goal of the LCA study was to determine the environmental impacts of alternative lamp management options for different mercury-containing lamp types in order to inform the development of a product stewardship scheme for lighting in New Zealand.

The following typical lamp technologies have been assessed:

1. compact fluorescent lamps (CFL);
2. linear fluorescent lamps (LFL); and
3. mercury-containing gas discharge lamps (HID).

The LCA study assesses all life-cycle stages, from mining/production of raw materials to manufacture, distribution, product use and end-of-life waste management.

The results of the study are intended for both internal use and for external communications.

2 Goal of LCA

The international standard ISO 14040 (ISO, 2006) requires that the goal of an LCA study shall unambiguously state the intended application, the reasons for carrying out the study, the intended audience and whether the results will be used in comparative assertions intended to be disclosed to the public.

2.1 Goal

The goal of this study was to assess the potential life cycle environmental impacts associated with the production, use and end-of-life management options for individual types of mercury-containing lamps in New Zealand. This information will be used to interpret, for the purpose of informing product stewardship policy, the potential environmental impact of the different lamps, the different end-of-life management options in the context of the performance and applications of the lamps appraised.

The original scope of work as defined by the Ministry for the Environment was to focus on the end-of-life management options in the context of the performance and applications of the lamps appraised. In particular, this included an assessment of the relative Life cycle impacts of mercury-containing lamps when managed under the following product stewardship scenarios:

- recycling at end-of-life;
- disposal in landfill at end-of-life; and
- reducing mercury at source.

Although not part of the original scope for the LCA in the MfE objectives for the study, the LCA study as undertaken allows consideration of the implications of greater energy efficiency of the lamps in the use phase, as well as implications of changes in lamp lifetime.

The study assesses separately six typical types of lamps, as listed below:

- Fluorescent:
    1. Linear fluorescent lamp (LFL);
    2. Compact fluorescent lamp: external ballast (CFLe); and
    3. Compact fluorescent lamp: integral ballast (CFLi).
- High Intensity Discharge (HID):
    4. High pressure sodium (HPS);
    5. Metal Halide (MH); and
    6. Mercury Vapour (MV).

The lamps listed above represent the mainstream types used in New Zealand for residential, commercial and industrial applications. This study has not considered lamps that are integrated into other products, such as, those contained in fridges, LCD screens and projectors. Some of these lamps types are known to contain mercury; however, they are outside the scope of this study.

The primary focus of the study is to assess the whole life environmental impacts from the use of the mercury-containing lamps above, and the trade-offs that arise from potential product stewardship options for end-of-life management (by increasing recycling/ recovery rates) and for lamp design (by reducing the lamps mercury content). Additionally, use phase energy consumption and lamp lifetime are considered.

The product stewardship scenarios that have been assessed include the following:

Scenario 1. 50% recovery and recycling at end-of-life;

Scenario 2. 80% recovery and recycling at end-of-life;

Scenario 3. 100% disposal (to landfill) at end-of-life;

Scenario 4. Reducing mercury level[1] to the technically feasible minimum and 50% recovery and recycling at end-of-life;

Scenario 5. Reducing mercury level to the technically feasible minimum and 80% recovery and recycling at end-of-life; and

Scenario 6. Reducing mercury level to the technically feasible minimum and 100% disposal (to landfill) at end-of-life.

The above listed scenarios will be compared against the Baseline scenario of 9% recovery and recycling at end-of-life.

The study does not to provide comparative results across the different lamp types. This is because the lamps offer a different function and performance characteristics relating to lamp lifetime, lamp output (in terms of wattage) and in terms of lamp application (although application may be the same in many cases for CFLe and CFLi lamps). As such the lamps are not functionally the same and should not be directly compared. Each lamp may be assessed within each lamp type for the different scenarios assessed. Refer to Table 2 for specific details.

The results indicate baseline performance and comparative product stewardship options by individual lamp type for typical usage for New Zealand in 2007.

The study and subsequent results are intended to be communicated for internal and external use to inform the MfE of the development of a product stewardship scheme for lighting in New Zealand. The MfE is anticipated to use the study to support external communication relating to product stewardship of lamps.

Additionally, it should be noted that issues beyond those relating to environmental impacts of a product stewardship scheme, for example, relating to the wider context of

[1] It should be noted that the technical requirements for establishing mercury levels in the lamp will vary according to several parameters, for example, production technology and associated potential improvements, as well as the technical requirements for lamp design which affect, for example, light quality and lamp lifespan.

regulation, implementation, economics and issues of practicability (e.g. consumer engagement) are outside of the scope of this study.

3 Scope of the LCA

The scope of the study has addressed the following items:

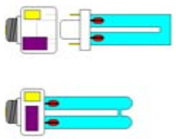
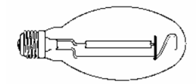
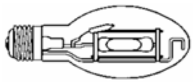
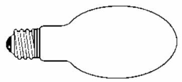
- the functions of the product systems and the functional unit;
- the product systems to be studied and system boundaries;
- allocation procedures;
- types of impact and methodology of impact assessment, and subsequent interpretation to be used;
- data requirements;
- assumptions and limitations;
- initial data quality requirements; and
- type of critical review.

3.1 Product Function

The function of the system describes the performance characteristics of the product systems being compared.

The general function of the lamps being studied is to provide lighting for different applications for private, commercial and industrial applications, in the visible light range 400nm to 800nm (ELCF, 2009). The lamp types and technology are summarised in Table 1.

Table 1 Summary of Lamps Assessed

Lamp family	Lamp type	Figure	Main uses	Brief Description
Fluorescent	Linear fluorescent lamp (LFL)		Commercial and Industrial	Uses electricity to excite mercury vapour in argon or neon gas, resulting in a plasma that produces short-wave ultraviolet light. This light then causes a phosphor to fluoresce, producing visible light. The blend of phosphors controls the colour of the light, and along with the lamp's glass, prevents the harmful UV light from escaping.
	Compact fluorescent lamp (CFL): external (CFLe) and integrated (CFLi)		Commercial Residential	Operate on the same principles as linear fluorescent, above. A compact fluorescent lamp may have a conventional ballast located in the fitting (CFLe) or they may have a ballast integrated (CFLi) in the lamp, allowing them to be used in fittings normally used for incandescent lamps.
High Intensity Discharge (HID)	High pressure sodium (HPS)		Public lighting Industrial	Uses sodium in an excited state to produce light. An amalgam of metallic sodium and mercury lies at the coolest part of the lamp and provides the sodium and mercury vapour in which the arc is drawn. Because of the extremely high chemical activity of the high pressure sodium arc, the arc tube is typically made of translucent aluminium oxide (alumina).
	Metal Halide (MH)		Industrial	An electric arc is passed through a mixture of gases. The compact arc tube contains a high-pressure mixture of argon, mercury, and a variety of metal halides. The mixture of halides affects the nature of light produced, influencing the correlated colour temperature and intensity.
	Mercury Vapour (MV)		Industrial	The arc discharge is generally confined to a small fused quartz arc tube mounted within a larger borosilicate glass lamp. The outer lamp may be clear or coated with a phosphor; in either case, the outer lamp provides thermal insulation, protection from ultraviolet radiation, and a convenient mounting for the fused quartz arc tube

Source: (Cited directly from Stewardship Solutions, 2008).

3.2 Functional Unit

The functional unit is the reference unit used to report the inventory analysis and impact assessment results for each lamp type. As the primary focus is to appraise each lamps life cycle with different end-of-life product stewardship options individually, the functional unit is defined as 100,000 hours of operation in the use phase, for the performance characteristics (of lamp life, output and application) as described in Table 2. Selecting a time period over which the lamps operate provides a fair basis for assessment of the product stewardship options. A period of 100,000 hours was chosen because this covers, for all lamp types, more than one total lamp lifespan and therefore includes the implications for variations at end-of-life and other phases of the life cycle.

The interpretation section of the study has considered findings in relation to, total national lamp usage, lamp performance and establishes where product stewardship messages are common across lamp types, or are in fact different for the individual lamps.

As mentioned, but highlighted here again, the functional unit does not provide for comparative results across the different lamp types. This is because the different lamp types offer different functions and performance characteristics relating to lamp lifetime, lamp output (in terms of wattage) and in terms of lamp application.

The typical performance parameters of the lamps assessed in the study are shown in Table 2 for product life span (measured in hours operation), power rating (measured in watts) and application.

Table 2 Typical Lamp Performance Parameters

Product System	Lamp Specification
Fluorescent:	
1. Linear fluorescent lamp (LFL)	• Life span: 8000 hours • Output: 35W, T8 • Application: Commercial and industrial • Mercury content: 4mg
2. Compact fluorescent lamp (CFL): external ballast	• Life span: 10, 000 hours • Output: 11W • Application: Commercial residential • Mercury content: 5mg
3. Compact fluorescent lamp (CFL): integral ballast	• Life span: 12, 000 hours • Output: 20W* • Application: Commercial residential • Mercury content: 5mg
High Intensity Discharge (HID):	

Product System	Lamp Specification
4. High pressure sodium (HPS)	• Life span: 20, 000 hours • Output: 150W • Application: Public lighting and industrial • Mercury content: 50mg
5. Metal Halide (MH)	• Life span: 20, 000 hours • Output: 400W • Application: Industrial • Mercury content: 50mg
6. Mercury Vapour (MV)	• Life span: 20, 000 hours • Output: 250W • Application: Industrial • Mercury content: 50mg

Source: Adapted from (Stewardship Solutions, 2008).

* This figure has been updated from that shown in the Stewardship Solutions (2008) report of 11W based on manufacturer feedback of which lamp wattages represent high volume sales in New Zealand.

Table 3 shows the number of lamps that are manufactured per 100,000 hours of in-use operation for each lamp.

Table 3 Number of Lamps Manufactured per 100,000 hours operation

		1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W
Number of lamps manufactured	each	12.5	10.0	8.3	5.0	5.0	5.0

Table 4 shows the typical lamp composition of each lamp type in New Zealand (Stewardship Solutions, 2008) that will be assessed in the study.

Table 4 Typical Lamp Composition (grams)

Product System	Total	Glass	Metals	Electronics	Plastics	Remainder
Fluorescent:	g	g	g	g	g	g
1. Linear fluorescent lamp (LFL)	120	115	3	--	--	2
2. Compact fluorescent lamp (CFL): external ballast	55	40	3	--	10	2
3. Compact fluorescent lamp (CFL): integral ballast	120	65	4	25	25	1
High Intensity Discharge (HID):						
4. High pressure sodium (HPS)	150	105	44.5	--	--	--
5. Metal Halide (MH)	240	195	42	--	--	3
6. Mercury Vapour (MV)	166	130	9	1	27	--

Note: The table indicates typical values for New Zealand (Stewardship Solutions, 2008, Sylvania, 2002).

The functional unit accounts for differences in the manufacture of the different lamp compositions, lamp use, lamp life, and disposal, as well as the impacts associated with alternate lamp recycling and recovery options and mercury-content.

3.3 Product Systems and System Boundaries

3.3.1 System Boundaries

The system boundary determines which life cycle stages and unit processes shall be included within the LCA. The boundary also determines the environmental releases and inputs to be included. The product system has been modelled in such a manner that the inputs and outputs at its boundary are elemental and product flows[2].

The lamp systems investigated include all significant processes, tracing material and energy flows to the point where material and energy are extracted or emitted to the natural environment. Waste management processes are also assessed, including the disposal of lamps via landfilling and recycling.

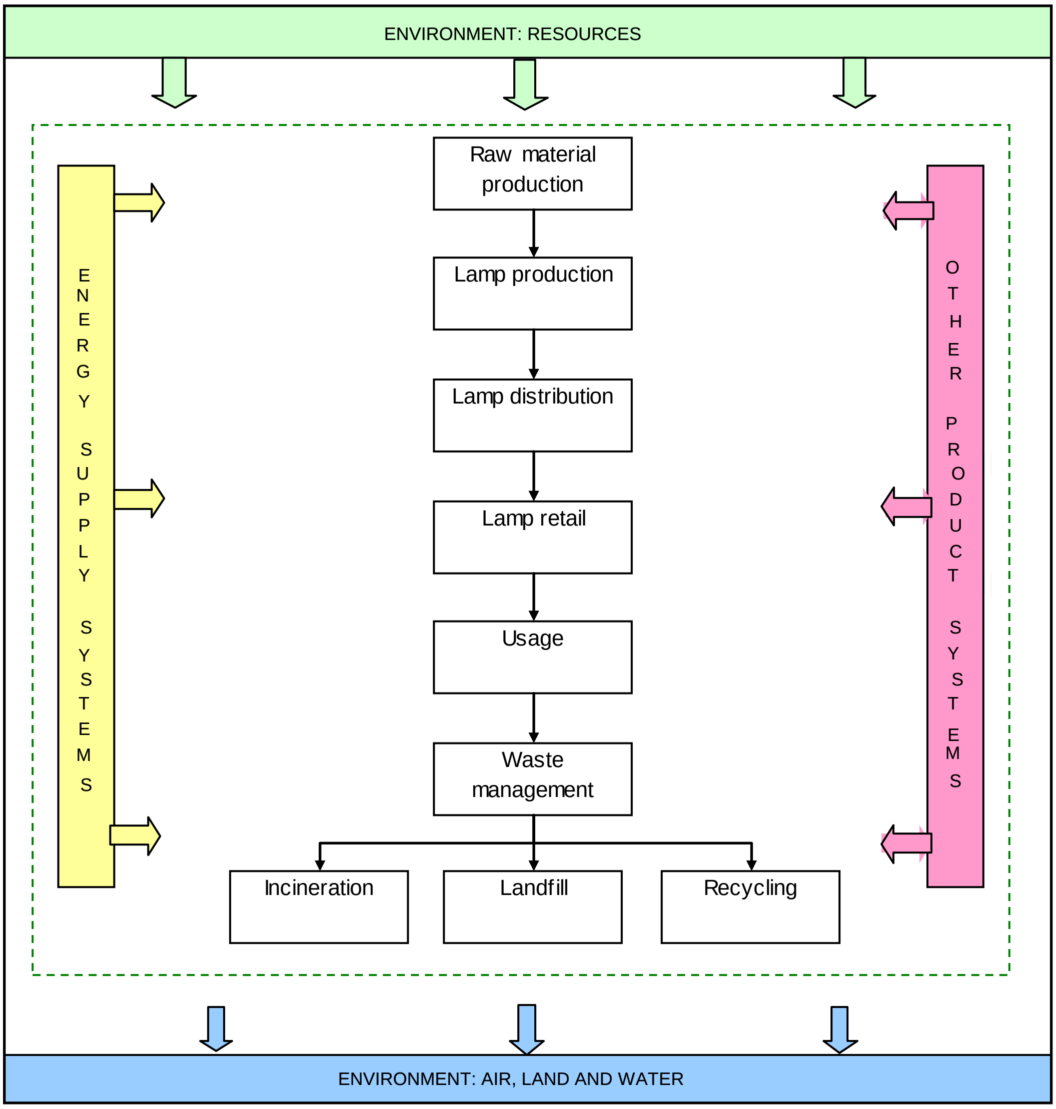
The following exclusions are made due to these being the same for each typical lamp type as described in further detail below in this Section:

- product fittings and control gear; and
- product packaging.

The activities that are included in the life cycle for each lamp system are shown in Figure 1.

[2] An elemental flow is material/energy entering the system being studied, which has been drawn from the environment without previous human transformation, or it is a material/ energy leaving the system being studied, which is discarded into the environment.

Figure 1 Summary Diagram of System Boundaries of the Lamp Systems Assessed



Note: Green dashed line indicates system boundary assessed.

The study has included the following life cycle stages:

- Raw material production, including:
    - *Mining of minerals.* The mining of metals, such as phosphor, mercury, sodium and aluminium, is included in the study. The materials and energy used for mining and transportation, as well as associated emissions, are assessed. The mining of metals is often associated with the extraction of more than one metal; as such the environmental burden is expected to be allocated between the different outputs associated with mining.

  - *Other raw materials.* The LCA study includes impacts of extraction and production of all other raw materials used in the lamp products, such as steel, glass and paper.

- *Transport of raw materials.* The transport of raw materials from the point of extraction to the point of use in lamp production is included.

- *Conversion processes.* The LCA study also includes the conversion processes associated with all raw materials used in lamp production. For example, conversion of the metal ores to forms suitable for lamp production. This includes processes such as metal purification and metal production.

- *Lamp production.* Processes for the manufacture of each of the lamp types (as listed in Section 2.1), have been assessed. For each lamp type, the inputs of energy and raw materials consumed, as well as emissions, solid waste and waste water treatment, are included. This study also accounts for any internal recycling of production waste.

- *Lamp distribution.* An average distribution distance for lamp distribution from production, via importers and distributors, to retail and to use is included in the assessment. This relates to domestic and commercial use in New Zealand.

- *Lamp consumer use.* The use of lamps is included in the study. Lamp use is defined by the specification for the functional unit, as described in Section 3.2. The study has accounted for New Zealand electricity generation mix.

- *Lamp collection and end-of-life management.* The impact of disposal of the lamps has been investigated in the study. Including the impacts associated with collection and sorting of the lamps prior to domestic and commercial disposal, and recycling and recovery operations in New Zealand and in Australia.

Those steps excluded from the study boundary were:

- *Fitting and control gear.* The production, packaging, use and disposal of fittings, and control gear that is associated with each lamp type have been excluded from the study. This is excluded because these components are identical within each lamp type when comparing alternative product stewardship scenarios. As mentioned in Section 2.1, the goal of the study is to assess the alternative product stewardship options within each individual lamp type. As such, those activities that are identical for each lamp type may be excluded from the study. Sensitivity analysis has been used to estimate the significance of this exclusion.

- *Manufacture, maintenance and decommissioning of capital equipment.* The manufacture, maintenance and decommissioning of capital equipment, such as buildings or machines, are not included in the investigated product systems. The reason for excluding capital equipment, besides the practical aspects, is that the environmental impact related to the functional unit is considered negligible. For example, the life time of the capital goods is usually much longer than the life time of the product under study. Furthermore one production machine or building will be used to mass produce multiple products. This means that environmental impacts associated with capital goods will need to be allocated across many products and many years of production, making the impacts of capital equipment insignificant.

- *Workforce burdens.* This study has assumed that the impact of the working environment (e.g. the impacts associated with human labour during production) will be insignificant for the studied scenarios and have, therefore, been excluded. Workforce burdens includes in the energy required for people to do manual work.

Section 3.5 describes the study limitations, inclusions and exclusions in detail.

3.4 Allocation Procedures

Some processes may yield more than one product and they may also recycle intermediate products or raw materials. Where this occurs, the LCA study has to allocate material and energy flows, as well as environmental releases, to the different products in a logical and reasonable manner.

According to the ISO standard, allocation should preferably be avoided, which can be achieved through system expansion. System expansion for recovery and recycling is further described below.

Where system expansion is not practicable, the inputs and outputs of the inter-related processes are allocated in a manner that reflects the underlying physical relationships between them. There may be certain circumstances where this is not appropriate or possible when carrying out an LCA study. In such cases, alternative allocation methods were used and these are documented in the inventory analysis.

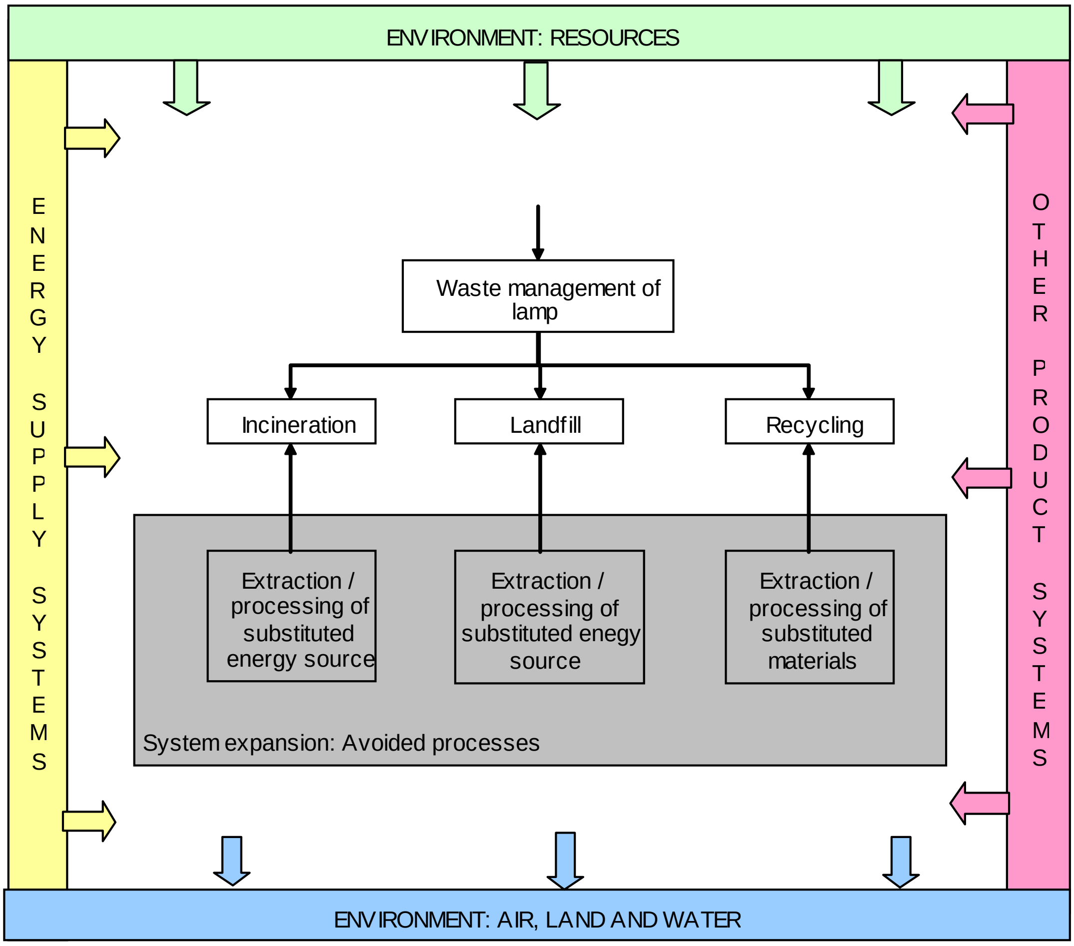
Where alternative allocation procedures are applicable then a sensitivity analysis has been conducted to illustrate the consequences of alternate approaches.

3.4.1 System Expansion for Recycling and Recovery

System expansion should be applied in the study when products are recovered, through recycling or energy recovery (ISO, 2006a). For instance, when recycling of lamps occurs, metals from the lamps are extracted and reused in the recycling process, and an 'avoided' production of metals has been included in the system. 'Avoided' production refers to materials not having to be generated from other sources, since the recycled material is used in its place.

Figure 2 shows the system boundaries of the expanded system. The processes shown in shaded grey indicate the additional activities that are included due to expansion of the system to include the benefit associated with avoided materials.

Figure 2 System Diagram Showing the System Expansion



Where closed loop recycling occurs (as is presented in sensitivity analysis section) the inventory data shall reflect those inputs and emissions arising from the product specific recycled material content or recycling rate, as shown in the calculation given below (PAS2050, 2008):

Emissions / unit = (1 - *R*1) x *EV* + (*R*1 x *ER*) + (1 - *R*2) x *ED*

Where:

R1 = proportion of recycled material input;

R2 = proportion of material in the product that is recycled at end-of-life;

ER = emissions arising from recycled material input per unit of material;

EV = emissions arising from virgin material input per unit of material; and

E_D = emissions arising from disposal of waste material per unit of material.

3.5 Inclusions, Exclusions and Assumptions

It is important to identify the main assumptions and limitations of the LCA so that the study results can be interpreted appropriately and in context.

The results contained in this report are based on the following main assumptions:

System boundary:

- *Life cycle stages.* The study includes all main phases of the life cycle from cradle-to-grave, as described previously.

- *Lamp composition.* The material composition of an average lamp varies due to the many different manufacturers and designs being available on the market. This study has defined a typical material composition of a mercury-containing lamp based on the report titled New Zealand Lighting Industry Product Stewardship Scheme PHASE 1: Assessment and Review (Stewardship Solutions, 2008) which provides estimated material compositions for New Zealand. That report provides a generic level material breakdown for lamps (as shown in Table3). That report also identifies the difficulty in determining an average lamp composition; however, through use of similar European studies and in agreement with the Lighting Council New Zealand (which represents the major New Zealand lighting importers) a typical material composition was determined which has been used for this study. Additionally, this composition has been supplemented by data from manufacturers material safety data sheets (MSDS) which identify levels of toxic ingredients in the lamp composition, such as heavy metals (Philips, 2001, 2002 and 2005 and Sylvania, 2002). Gases used in the lamps have been omitted from the study.

- *Lamp manufacture.* All the lamps are manufactured overseas. ERM has contacted all New Zealand based importers of mercury-containing lamps. However, there was a lack of specific data to describe the production of each lamp type. The results have therefore estimated electricity input for production based on a report by European Lamp Companies Federation (2008b) which provides a figure for electricity usage for CFL lamp manufacture. This is likely to be an overestimate. For other lamp types, this has been estimated based on mass of each lamp and electricity usage for a CFL. The electricity mix is based on the countries of origin of manufacture for each lamp type. Raw material inputs are included based on composition and 99% conversion efficiency.

- *End-of-life disposal and recycling.* This study has focused on lamp collection and disposal in New Zealand and Australia. For recycling, primary data has been gathered to describe the collection and transfer of waste lamps in New Zealand and the processes for recycling and recovery in Australia. All lamps that are not collected for recycling are sent for landfill disposal in New Zealand. The emissions from landfill have been generated by using ecoinvent (2007) landfill models which have been manipulated to reflect specific conditions for New Zealand and to account for lamp composition. No lamps are disposed of to incineration.

- *Avoided materials.* 'Avoided' materials refer to those raw materials that do not have to be produced from other sources, because the recycled material is used in its place. For lamps, avoided materials include the following that are produced from recycling processes in Australia: aluminium; glass granulate (for insulation); mercury (for dental amalgam); plastics; and phosphorus. The avoided impacts for these materials have been estimated using adapted ecoinvent (2007) datasets to represent location of material production and use.

- *Electricity generation.* Electricity generation in New Zealand is based on a generation mix from the Ministry of Economic Development (MED, 2007) and inventory data to describe these processes uses adapted datasets from ecoinvent (2007). The datasets account for the composition of coal in New Zealand, for efficiency of NZ coal fired power stations. Surrogate data were used for geothermal electricity generation in the absence of a specific inventory (refer to Appendix B for further details). Generation from gas accounts for generation efficiency and onshore/offshore gas supply. Coal generation is of particular interest due to the release of mercury from combustion of coal for electricity generation. For electricity generation in other countries, such as China and Thailand for lamp production and Australia for lamp recycling, the generation mix is based on International Energy Agency (IEA, 2009) data and ecoinvent datasets.

Lamp performance:

- *Lamp life.* This study has assumed for each typical lamp type an average lifetime (hours of operation) based on published sources, as shown in Section 3.2. However, differences in design, such as high-end or low-end products, will result in potential differences in lamp lifetime. Lamp lifetime has been tested in the sensitivity analysis, to indicate the change in impacts of a reduced or extended lamp lifetime of ±50%.

- *Lamp mercury level.* The study has assumed typical lamp mercury content based on published sources, as shown in Section 3.2. These levels may potentially vary depending on regulated levels in country of manufacture and on differences in lamp design. This assumption has been tested in the sensitivity analysis in order to indicate the change in impacts of increased or reduced mercury content in the lamp. It has been assumed that future technologies which deliver lower mercury level in lamps will provide the same functional performance (of lifetime, wattage and light quality). Refer to Appendix B, Section B11.1 for further details.

- *Lamp energy consumption.* Some research indicates (Parsons, 2006) that there is a warm-up effect for fluorescent lamps which increases power required in the initial period of operation compared to rated power. The study does not account for these effects, but uses the rated lamp wattage to determine energy consumption. Lamp warm-up effects have been considered in a sensitivity analysis in order to establish their potential significance for the environmental impacts appraised.

Cut-off criteria:

- *Process inputs.* In order to maintain a feasible scope for the study, and in conformance with the ISO standard, ERM has applied ‘cut-off criteria’ to ensure focus is directed at the major environmental contributors for each lamp type. In the case of individual life cycle stages and processes material inputs known to be less than 1% by mass of the product output of a particular process, and for which no appropriate inventory data are available, have been excluded. However, the total cut-off was not more than 5% of input of all materials in reference to the functional unit. Ideally, cut-off criteria should be based on environmental relevance. However, cut-off by mass has been applied as it is impractical to define cut-off criteria based on environmental impact, since data for a process need to be collected in order to understand the environmental impact of that process or the entire life cycle. Nonetheless, where considered relevant, such as in the case for potential ecotoxicity impacts, a test of environmental significance has been used based on professional judgement. Material inputs excluded through cut-off are documented and reviewed for significance.

Impact categories:

- *Land occupation.* The study excludes the environmental implications of land occupation and use, for example, we excluded the implications of alternative land use and the effects of land use changes between the options.

- *Litter.* Littering is a potential environmental impact. However, this is difficult to quantify both as an environmental impact but also as an aesthetic impact. Therefore, this impact has been excluded from the LCA study.

3.6 Data Collection

The data required to perform the LCA are listed in the following Sections, which describes:

- data categories to be collected;
- primary data requirements;
- secondary data requirements; and
- data quality requirements.

The lamp systems assessed in the study are representative of those available on the New Zealand markets. To ensure representative product systems, detailed questionnaires have been sent to lamp manufacturers and lamp collection and recycling companies. Where specific production processing data for a lamp were not available, secondary data has been used, together with estimates based on the data gathered for the other lamps.

Appendix B provides a summary of the data sources, assumptions and limitations used for the LCA study.

3.6.1 Data Categories

The following data categories are included in the study:

- raw materials;
- chemicals;
- transport;
- energy;

- other physical inputs (e.g. water);
- products and co-products;
- emissions to air, water and soil;
- solid waste; and
- waste water.

3.6.2 Primary Data Requirements

Specific data were collected for the production of the lamps and for the generation of wastes and emissions in each of the main life cycle stages.

Specific data were required for the following:

- lamp production operations (based on published data and questionnaires);
- transport distances of raw materials to the lamp production facilities, and types of transport;
- electricity generation mix for the relevant countries; and
- lamp collection and waste management.

As mentioned in Section 3.5, all lamps are manufactured outside of New Zealand and are imported into the country (primarily from China and Thailand). Primary data were not available relating to emissions, raw materials used; solid waste generated and waste water data from the production of lamps is anticipated to be limited for New Zealand conditions. Manufacturers have been contacted as part of the study, however, due to a lack of data this has been estimated based other published sources for Europe. Raw materials have been included using the composition of the lamps. Previous studies of fluorescent lamps, such as those published by European Lamp Companies Federation (2008) and Ramroth (2008) indicate that the manufacturing phase of the life cycle contributes approximately 5% of total life cycle impacts across the measured environmental indicators.

Transport distances have been determined based on specific country locations and estimated distances for retail and use in New Zealand.

Specific data on electricity mix in the geographical area where the lamp is produced, used and disposed of has been sourced from International Energy Agency (IEA, 2009) data and from the Ministry of Economic Development (MED) (2008) for New Zealand.

As mentioned in Section 3.5, waste management data for New Zealand and the recycling operations that occur in Australia have been sourced from questionnaires to waste operators. The availability of data to describe landfilling and incineration of lamps and processing wastes for New Zealand and Australia has been based on ecoinvent (2007) datasets that have been amended to reflect New Zealand and Australian conditions. The final results will describe specific conditions for New Zealand and account for lamp composition.

3.6.3 Secondary Data Requirements

For the production of commodity materials and energy, and the operation of transport processes, generic data were used where no specific information was made available by the data suppliers.

Secondary data has been used for the following:

- production of raw materials and chemicals;
- general waste management operations;
- electricity generation methods; and
- emission data from transport.

Secondary data have generally been sourced from relevant databases or published sources, such as the Ecoinvent (2007) database, International Journal for LCA, US life cycle inventory (LCI) databases (NREL, 2008, EPA, 2008) and the Australian LCI database (AusLCI, 2008). For example, the ecoinvent database contains international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services, including any offset benefits of avoided production through recycling operations.

The geographical base for most of the ecoinvent database is European, but for a limited number of inventory data, world data are available. The data represents the most up-to-date and available public inventory data. Where relevant, processes used from the generic databases have been adapted to represent the appropriate geography, by adjusting electricity generation mix and transportation steps to the appropriate country of origin.

For electricity generation relating to New Zealand conditions, published data which describes trace metal composition of coal in order to estimate the specific mercury-emissions from electricity generation from known fossil fuel combustion sources.

3.6.4 Data Quality Requirements

Data quality requirements specify in general terms the characteristics of the data needed for the study, based on the ISO 14044 (ISO, 2006a). Descriptions of data quality are important to understand the reliability of the study results and to interpret the outcomes of the study.

In general, the data collated for the study has been assessed on a qualitative robustness test as shown in Table 4.

Listed below are specific details of data quality requirements for the lamp types being assessed in the study:

- *Geographic boundaries.* All lamps are imported into New Zealand and must represent appropriate geographic locations of manufacture (e.g. China, Thailand, Germany, Hungary, Taiwan and others). Lamp distribution, use and waste management data are based on New Zealand conditions. All lamp recycling occurs in Australia and should reflect those conditions.

- *Technological boundaries.* The study has assumed that the data collated via questionnaires for specific manufacturing plants and data used from the secondary LCA databases are representative of New Zealand conditions and representative production technologies.

- *Time boundaries.* The systems investigated should represent the situation in 2007, as this represents the last full calendar year for which data were available for the study. With regard to landfilling, the decomposition of any biomass is assumed to take place within the time boundaries of the study.

In cases, where there are missing data, this has been identified and documented in the inventory analysis. The quality of surrogate data will be characterised and methods used to integrate the data explained.

Table 5 Data Quality Requirements for Inventory Data

Parameter	Description	Requirement
Time-related coverage	Desired age of data and the minimum length of time over with data should be collected.	Data should represent the situation in 2007 and cover a period representing that calendar year.
Geographical coverage	Area from which data for unit processes should be collected.	Data should be representative of the situation in the New Zealand.
Technology coverage	Technology mix.	Technology (for manufacture, product usage and end-of-life management) should be representative of New Zealand conditions and technology.
Precision	Measure of the variability of the data values for each data category expressed.	Not applicable.
Completeness	Assessment of whether all relevant input and output data are included for a certain data set.	Specific datasets will be compared with literature data and databases.
Representativeness	Degree to which the data represents the identified time-related, geographical and technological scope.	The data should fulfil the defined time-related, geographical and technological scope.
Consistency	How consistent the study methodology has been applied to different components of the analysis.	The study methodology will be applied to all the components of the analysis.
Reproducibility	Assessment of the methodology and data, and whether an independent practitioner will be able to reproduce the results.	The information about the methodology and the data values should allow an independent practitioner to reproduce the results reported in the study.
Sources of the data	Assessment of data sources used.	Data will be derived from credible sources and databases.

Source: (ISO 14044, 2006)

3.7 Inventory Analysis

As discussed in *Section 3.3*, all life cycle stages are included in the inventory analysis.

Inventory analysis involves data collection and calculation procedures to quantify all relevant inputs and outputs of a product system.

Section 3.6.2 and Section 3.6.3 detail that inventory data requirements. Where specific data for lamp production and disposal were not available, secondary data has been used, together with estimates based on the data gathered for the other lamps.

Data validation has been conducted using mass balances, energy balances or comparative analyses of release factors to verify the unit process data. Any anomalies will be checked to ensure that they comply with the data quality and selection requirements. No significant anomalies exist.

3.8 Impact Assessment

The impact assessment phase of a LCA provides a system-wide perspective of the environmental issues for the systems being assessed. The impact assessment quantifies the results of the inventory analysis in terms of several different impact categories.

The contributions of each system are assessed for the impact categories listed below. The listed impact categories address a range of environmental issues, and thorough methodologies have been developed for these categories.

The study employs the problem oriented approach for the impact assessment, which focuses on:

- depletion of abiotic resources;
- global warming;
- stratospheric ozone depletion;
- human toxicity;
- freshwater and marine aquatic ecotoxicity;
- terrestrial ecotoxicity;
- photo-oxidant formation;
- acidification; and
- eutrophication.

The contribution that lamp manufacture, use and waste management make on these categories is calculated for each system.

The impact categories listed above are further described in Annex A.

Generally within the science of LCA, for some impact categories, particularly human toxicity, a number of simplifying assumptions are made in the modelling used to derive characterisation factors, relating to fate and effects modelling. As a result, the adequacy of human toxicity in representing impact is still the subject of international scientific discussion.

However, this category is still widely used and has been accompanied by caveats describing the deficiencies. The impact assessment reflects potential, not actual, impacts and does not take into account the local receiving environment.

The modelling method used is that developed and advocated by CML (Centre for Environmental Science, Leiden University) and which is incorporated into the SimaPro LCA software tool. The version contained in the software is based on the CML (2007) spreadsheet version 3.2 as published on the CML web site.

The final results will evaluate impacts using the following alternative impact methods:

- TRACI, version 3.0, which is the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, developed by the US EPA (Bare, 2003); and
- IMPACT 2002+ (2003), version 2.04, which is mainly a combination between IMPACT 2002 (Pennington, 2005), Eco-indicator 99 (Goedkoop, 2000), CML (2000) and data from the Intergovernmental Panel on Climate Change (IPCC, 2000).

3.9 Interpretation

The Interpretation Section contains sensitivity analysis which considers lamp performance and addresses key assumptions and limitations within the study. Sensitivity analysis is essential to ensure the conclusions and recommendations made are supported by the results of the study.

The results have appraised the following:

- impact of assumed lifetime of the lamps – ± 50% lifetime;
- impacts of assumed power rating of the lamps, accounting for potential increases in energy usage from lamp start-up – +0.5%;
- impacts of improved energy efficiency in the use phase – +10% efficiency;
- impacts of closed loop recycling;
- impacts of not attributing offset benefits to avoided materials from lamp recycling operations; and
- potential impacts of packaging and fittings.

Further details of these sensitivity analyses can be found in Appendix B, Section B.11. The results of the LCA study are interpreted and conclusions are drawn on the difference in environmental impacts for the studied lamps in the context of the goals of the study.

General observations and lessons learned from all lamps studied are presented and discussed. These include elements such as comparisons between alternative options for end-of-life product stewardship and mercury levels in the lamps.

Additionally, the interpretation identifies improvement potentials in the individual life cycle stages of the lamp products.

3.10 Modifications to Initial Scope

Conducting an LCA is an iterative process and modifications to the initial scope may be necessary. Where this is the case, modifications were discussed, agreed upon with the Ministry for the Environment, and documented in the report. The only modification to the original goal and scope has included the following:

1. The power rating of 11W for a typical CFL with integral ballast has been updated from that reported in the Stewardship Solutions (2008) to 20W, based on manufacturer feedback that identified which lamp wattages represent mainstream products in New Zealand.

3.11 Optional Elements Under ISO 14044

ISO 14044 (2006a) provides optional elements for impact assessment relating to the following four areas:

- *normalisation:* calculating the magnitude of category indicator results relative to reference information;
- *grouping:* sorting and possibly ranking of the impact categories;
- *weighting:* converting and possibly aggregating indicator results across impact categories using numerical factors based on value choices (for an ISO compliant LCA, data prior to weighting must remain available); and
- *data quality analysis:* better understanding the reliability of the collection of indicator results.

In this study we have not carried out normalisation, grouping or weighting of impact indicator results. Although these methods can provide additional context to the results, especially in the case of normalisation, they also introduce subjectivity and value-based judgements, especially relating to grouping and weighting. Handling these value judgements can be an area of controversy and individual opinion. Weighting is prohibited by the International Standard for use in comparative assertions to be disclosed to the public. We have excluded these optional elements from the study.

In terms of data quality, the final results for the study will use sensitivity analysis to evaluate uncertainties relating to data, assumptions and methodological choices.

3.12 Critical Review

In accordance with the ISO standard for LCA, the study has been reviewed by an external review panel (as shown in Appendix E) consisting of three experts, as follows:

- Dr. Barbara Nebel, Scion, Wellington;
- Dr. Sarah McLaren, Landcare Research, Wellington; and
- Donald Hannah, ERMA, New Zealand.

The review panel's report, and ERM's responses, will be included in the final report.

The reviewers will address the issues below.

- For the goal and scope:
  - ensure that the scope of the study is consistent with the goal of the study, and that both are consistent with the ISO standard; and
  - include this in a review statement.
- For the inventory:
  - review the inventory for transparency and consistency with the goal and scope and with the ISO standard;
  - check data validation and that the data used are consistent with the system boundaries. It is unreasonable to expect the review panel to check data and calculations beyond a small sample; and
  - include this in a review statement.
- For the impact assessment:
  - review the impact assessment for appropriateness and conformity to the ISO standard; and
  - include this in a review statement.
  - For the interpretation:
  - review the conclusions of the study for appropriateness and conformity with the goal and scope of the study; and
  - include this in a review statement.
- For the draft final report:
  - review the draft final report for consistency with reporting guidelines in the ISO standard and check that recommendations made in previous review statements have been addressed adequately; and

- prepare a review statement including consistency of the study and international standards, scientific and technical validity, transparency and relation between interpretation, limitations and goal.

4 Inventory Analysis

Section 4 presents the life cycle inventory results for the six lamps types assessed, for the following:

- by life cycle stage for baseline scenario (i.e. 9% recovery and recycling);
- for whole life comparing different recovery and recycling rates (Baseline 9%, Scenario 1: 50%, Scenario 2: 80% and Scenario 3: 0%); and
- for end-of-life comparing different recovery and recycling rates (Baseline 9%, Scenario 1: 50%, Scenario 2: 80% and Scenario 3: 0%).

The inventories generated provide data on hundreds of internal and elemental flows for each lamp type. Appendix C shows the results Tables for the inventory analysis. The sections below provide a description and interpretation of these inventory results.

4.1 Inventory Data by Life Cycle Stage

Table to Table C1f in Appendix C present the inventory results by life cycle stage for each of the lamps assessed in the study.

The results indicate that in general the use phase dominates the inventory results across the life cycle. For example, for carbon dioxide emissions to air or non-renewable energy, the use phase accounts for around 90% to 99% of the life cycle, while the manufacturing phase accounts for around 0.5% to 10%. As would be expected, the lamps that have a higher wattage (HPS, MH and MV) show higher consumptions in the use phase compared to the lower wattage lamps (LFL, CFLe and CFLi).

The reason for the relatively higher inventory data for CFLi lamps in the manufacturing phase, compared to other lamp types, is due to the electronics incorporated into the lamp unit.

The results in relation to mass of mercury emissions to air, water and land show that emissions are very small in total mass, with the majority of emission being to land, followed by emission to water. Emissions to air are relatively minimal relative to land and to water. Of emissions to land and water, the disposal phase produces the majority of emissions (around 50% to 80%) followed by the use phase. For CFLi lamps the manufacturing phase contains a higher amount of mercury emissions, compared to other lamps types, due to the electronics incorporated into the lamp unit.

Please refer to Section 5 for details of the scale of environmental impacts of the mercury emissions.

Table 6 shows an example set of result for a CFLi lamp.

Table 6 Life Cycle Inventory – Baseline: 9% Recycling – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

	Unit	Manufacture	Import and distribution	Retail and use	Waste disposal NZ	Recycling	Displaced material benefits	Total
Total mercury use in lamp manufacture – internal flow	mg	5.0	0.0	0.0	0.0	0.0	0.0	5.0
Coal – resource	kg	17.6	0.0	83.4	0.0	0.0	0.0	101.0
Natural gas – resource	m^3	3.4	0.0	133.2	0.0	0.0	0.0	136.6
Oil – resource	m^3	1.5	0.1	2.5	0.0	0.0	0.0	4.1
CO_2 (fossil) to air	kg	40.9	0.2	415.4	0.0	0.0	-0.1	456.4
CO to air	kg	0.0	0.0	0.1	0.0	0.0	0.0	0.2
SO_x to air	kg	0.4	0.0	1.0	0.0	0.0	0.0	1.4
NOx species to air	kg	0.1	0.0	0.9	0.0	0.0	0.0	1.1
N_2O to air	kg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH_4 to air	kg	0.2	0.0	1.8	0.0	0.0	0.0	1.9
VOC to air	kg	0.0	0.0	0.2	0.0	0.0	0.0	0.2
Particulates to air	kg	0.1	0.0	0.3	0.0	0.0	0.0	0.4
Hg to air	mg	0.00000002	0.00000000	0.00000000	0.00000000	0.00000000	0.00000000	0.00000002
Hg to water	mg	0.00000057	0.00000000	0.00000015	0.00000078	0.00000000	-0.00000001	0.00000149
Hg to land	mg	0.00000000	0.00000000	0.00000001	0.00000182	0.00000000	0.00000000	0.00000183
Energy – Non renewable	Mj	600.8	2.9	6,839.1	0.4	0.7	-3.1	7,440.8
Energy – Renewable	Mj	33.7	0.0	756.2	0.0	0.1	-0.2	789.9

Note: a negative number represents an environmental benefit

4.2 Inventory Data for Whole Life

Table C2a to Table C2f in Appendix C presents the whole-life inventory results for each of the lamps assessed in the LCA for the following scenarios:

- Baseline performance for 2007: 9% recovery and recycling;
- Scenario 1: 50% recovery and recycling;
- Scenario 2: 80% recovery and recycling; and
- Scenario 3: 100% landfill.

The results indicate that environmental benefit arises from increasing the recycling levels for all lamp types. However, the benefits achieved are very small across the whole life cycle. For example, for carbon dioxide emissions to air or non-renewable energy, an increase in recycling rate from 9% to 80% provides a benefit of around 0.25% of the total life cycle.

Please refer to Section 5 for details of the scale of environmental impacts of the mercury emissions.

Table 7 shows an example set of results for a CFLi lamp.

Table 7 Life Cycle Inventory – Whole life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total mercury use in lamp manufacture – internal flow	mg	5.0	5.0	5.0	5.0
Coal – resource	kg	101.0	101.0	100.9	101.0
Natural gas – resource	m^3	136.6	136.5	136.4	136.7
Oil – resource	m^3	4.1	4.0	3.9	4.1
CO_2 (fossil) to air	kg	456.4	456.0	455.8	456.5
CO to air	kg	0.2	0.2	0.2	0.2
SO_x to air	kg	1.4	1.4	1.3	1.4
NOx species to air	kg	1.1	1.1	1.1	1.1
N_2O to air	kg	0.0	0.0	0.0	0.0
CH_4 to air	kg	1.9	1.9	1.9	1.9
VOC to air	kg	0.2	0.2	0.2	0.2
Particulates to air	kg	0.4	0.4	0.4	0.4
Hg to air	mg	0.00000002	0.00000001	0.00000000	0.00000002
Hg to water	mg	0.00000149	0.00000111	0.00000083	0.00000158
Hg to land	mg	0.00000183	0.00000101	0.00000042	0.00000201
Energy – Non renewable	Mj	7,440.8	7,429.9	7,421.9	7,443.2
Energy – Renewable	Mj	789.9	789.6	789.5	789.9

4.3 Inventory Data for End-of-Life Phase

Table C3a to Table C3f in Appendix C presents the end-of-life inventory results for each of the lamps assessed in the LCA for the following scenarios:

- Baseline performance for 2007: 9% recovery and recycling;
- Scenario 1: 50% recovery and recycling;
- Scenario 2: 80% recovery and recycling; and
- Scenario 3: 100% landfill.

The results show the environmental benefits from the end-of-life stage increase significantly with increasing recovery and recycling levels for all lamp types. For example, for a CFLi lamp, the carbon dioxide emissions benefit increases by ten-fold (from a saving of -0.06kg CO_2 to a saving of -0.75kg CO_2) by increasing the recovery and recycling rate from 9% to 80%. This similarly occurs for all other lamps types.

Please refer to Section 5 for details of the scale of environmental impacts of the mercury emissions.

Table 8 shows an example set of result for a CFLi lamp.

Table 8 Life Cycle Inventory – End-of-Life Only – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total mercury use in lamp manufacture – internal flow	mg	0.00	0.00	0.00	0.00
Coal – resource	kg	0.00	-0.02	-0.03	0.00
Natural gas – resource	m^3	-0.03	-0.16	-0.25	0.00
Oil – resource	m^3	-0.01	-0.11	-0.19	0.01
CO_2 (fossil) to air	kg	-0.06	-0.46	-0.75	0.03
CO to air	kg	0.00	0.00	0.00	0.00
SO_x to air	kg	0.00	-0.02	-0.04	0.00
NOx species to air	kg	0.00	0.00	0.00	0.00
N_2O to air	kg	0.00	0.00	0.00	0.00
CH_4 to air	kg	0.00	0.00	-0.01	0.00
VOC to air	kg	0.00	0.00	0.00	0.00
Particulates to air	kg	0.00	0.00	0.00	0.00
Hg to air	mg	0.00000000	-0.00000001	-0.00000002	0.00000000
Hg to water	mg	0.00000077	0.00000039	0.00000011	0.00000086
Hg to land	mg	0.00000182	0.00000100	0.00000041	0.00000200
Energy – Non renewable	Mj	-2.01	-12.92	-20.91	0.39
Energy – Renewable	Mj	-0.05	-0.26	-0.41	0.00

Note: a negative number represents an environmental benefit.

5 Impact Assessment

Section 5 presents the results of the life cycle impact assessment based on the CML 3.2 (2007) method for the following impact categories:

- depletion of abiotic resources;
- global warming;
- stratospheric ozone depletion;
- human toxicity;
- freshwater and marine aquatic ecotoxicity;
- terrestrial ecotoxicity;
- photo-oxidant formation;
- acidification; and
- eutrophication.

5.1 Whole Life Impacts

Figure 3 to Figure 8 presents the whole-life impact indicator results for each of the lamps assessed in the LCA for the following scenarios:

- Baseline performance for 2007: 9% recovery and recycling;
- Scenario 1: 50% recovery and recycling;
- Scenario 2: 80% recovery and recycling; and
- Scenario 3: 100% landfill.

The results indicate that, across all lamps types, increased recovery and recycling levels significantly reduces the contribution made to the human toxicity and ecotoxicity impact categories. These benefits are more prominent for domestic lamps (LFL, CFLi and CFLe), ranging from around 2% to 45%, when increasing from 0% to 80% for recycling and recovery. For industrial lamps the benefits relating to human toxicity and ecotoxicity range from around 2% to 35%, when increasing from 0% to 80% for recycling and recovery.

For all other impact categories, the benefits achieved through increased recycling for the other, such as global warming potential and resource depletion, are relatively small, in the context of the whole life, due to the significance of the use stage. The benefits (i.e. reductions in impact) range from around 0% to 3%.

The primary driver for the reductions in ecotoxicity impacts is due to the environmental benefits that arise from avoided production of mercury material and the associated emissions of mercury to air from the raw material production process.

The primary driver for the reductions in human toxicity impacts is due to the environmental benefits that arise from avoided production of nickel material, and associated emissions of heavy metals to air (which are non-mercury) from the raw material production process.

Figure 3 Life Cycle Impacts – Whole life – Linear fluorescent lamps (LFL), 35W, T8 (100,000 hours operation)

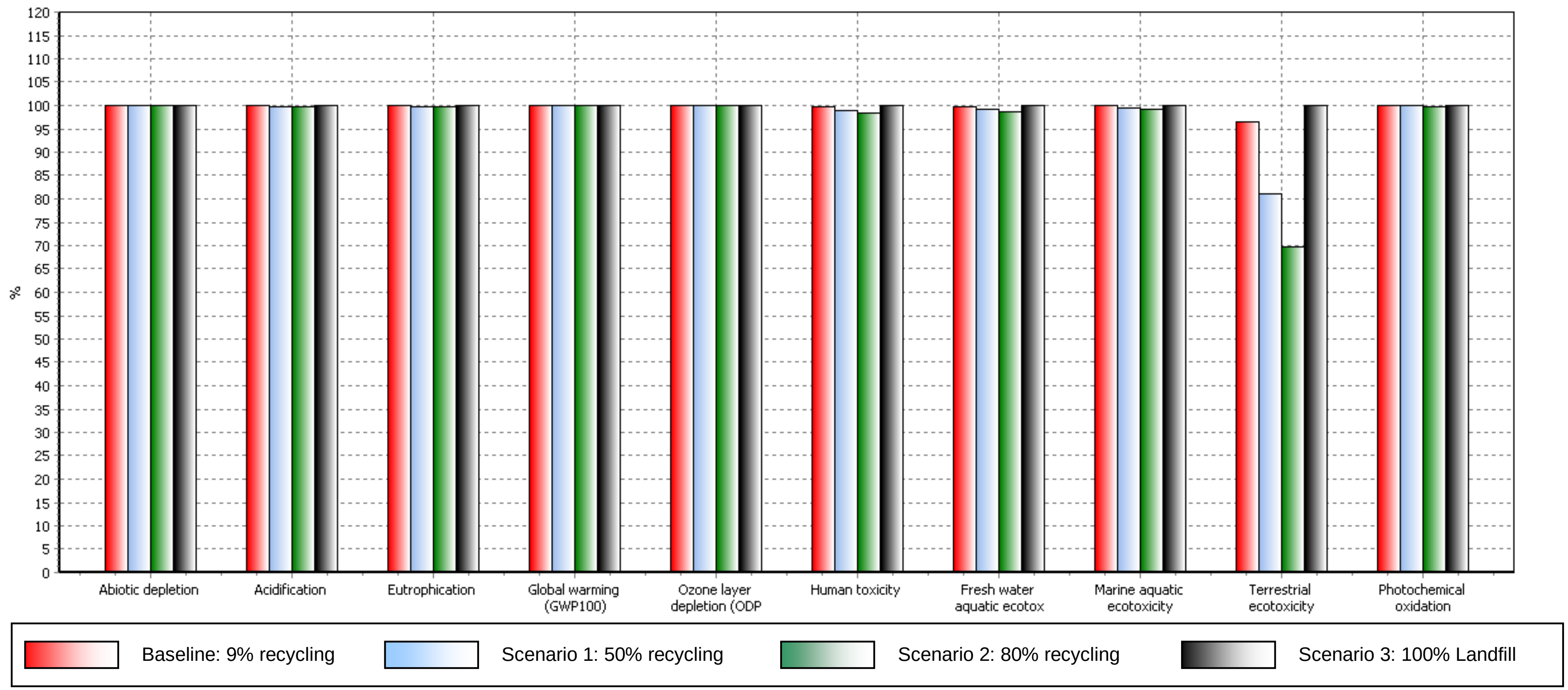


Figure 4 Life Cycle Impacts – Whole life – Compact fluorescent lamps (CFLe) 11W: external ballast (100,000 hours operation)

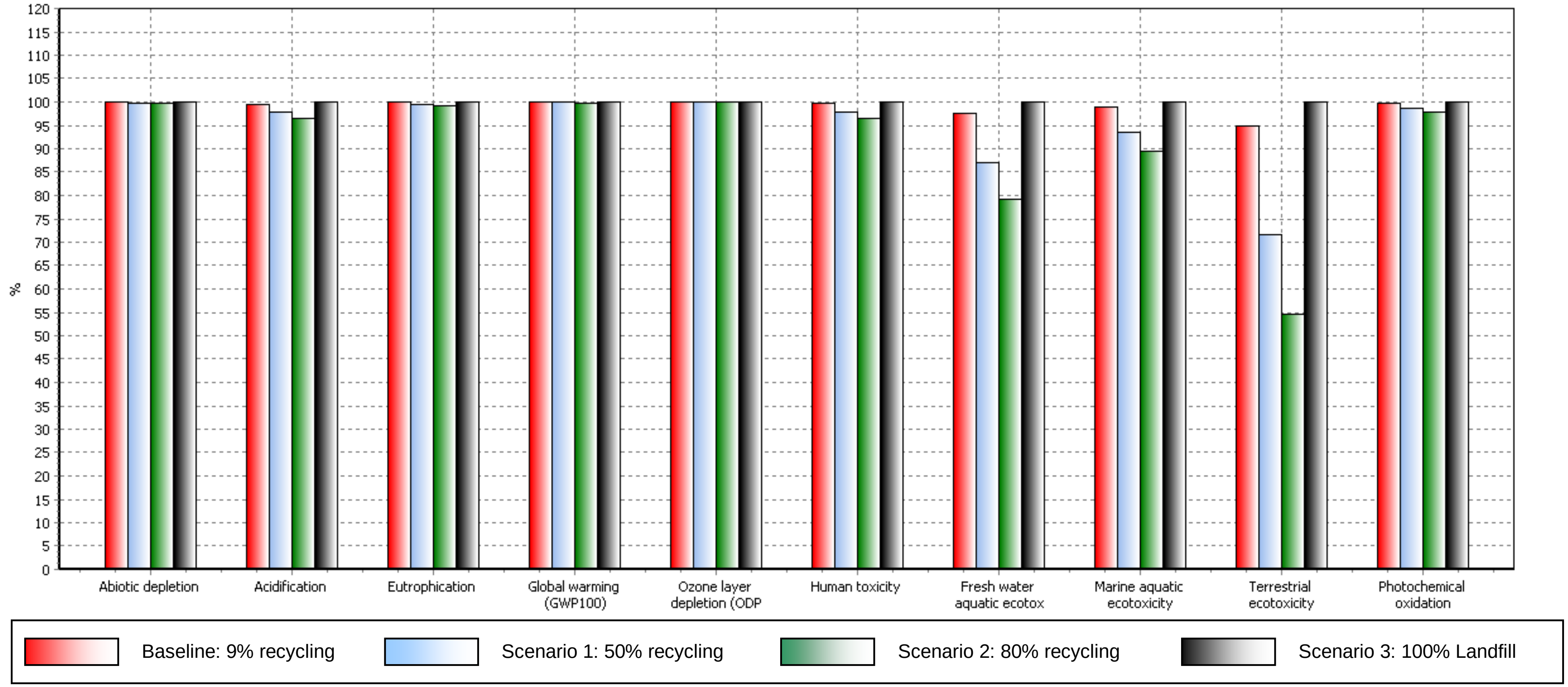


Figure 5 Life Cycle Impacts – Whole life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

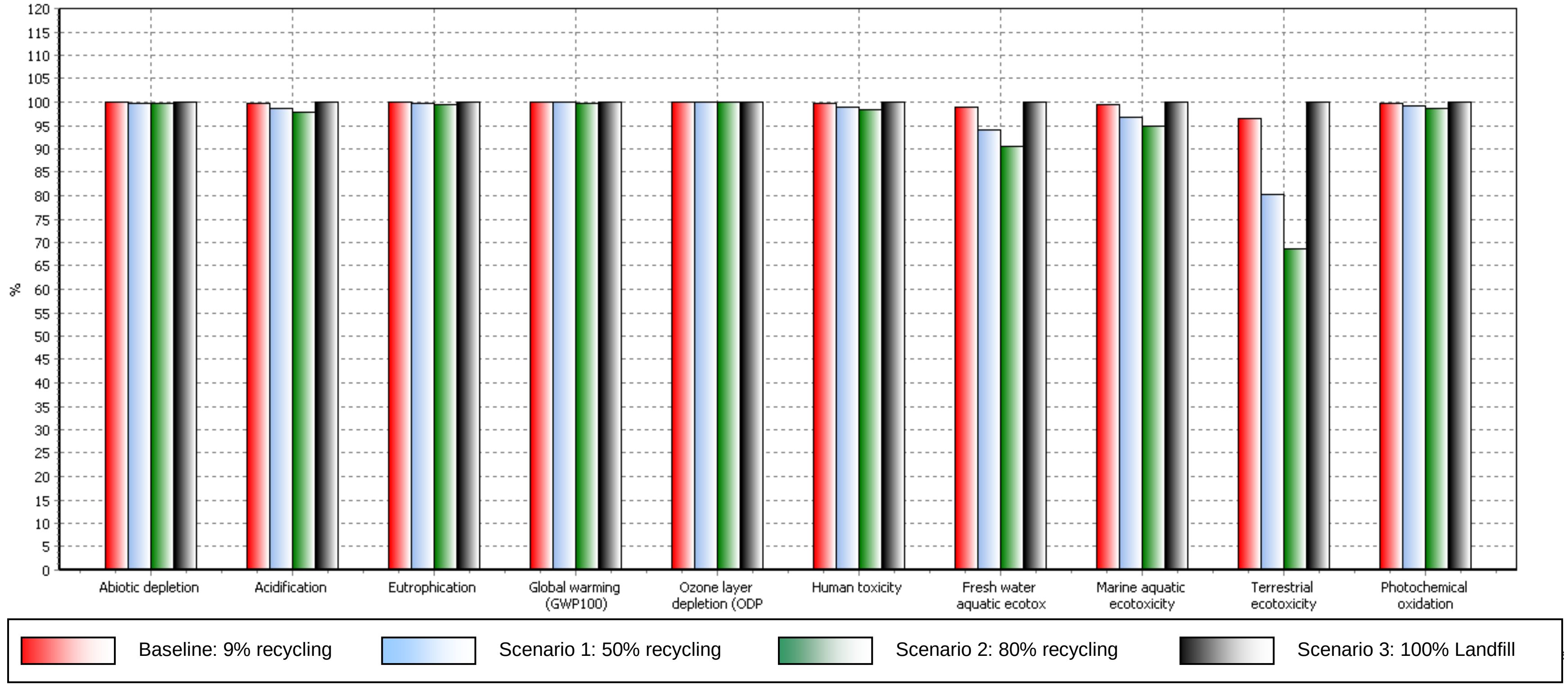


Figure 6 Life Cycle Impacts – Whole life – High pressure sodium (HPS) lamps, 150W (100,000 hours operation)

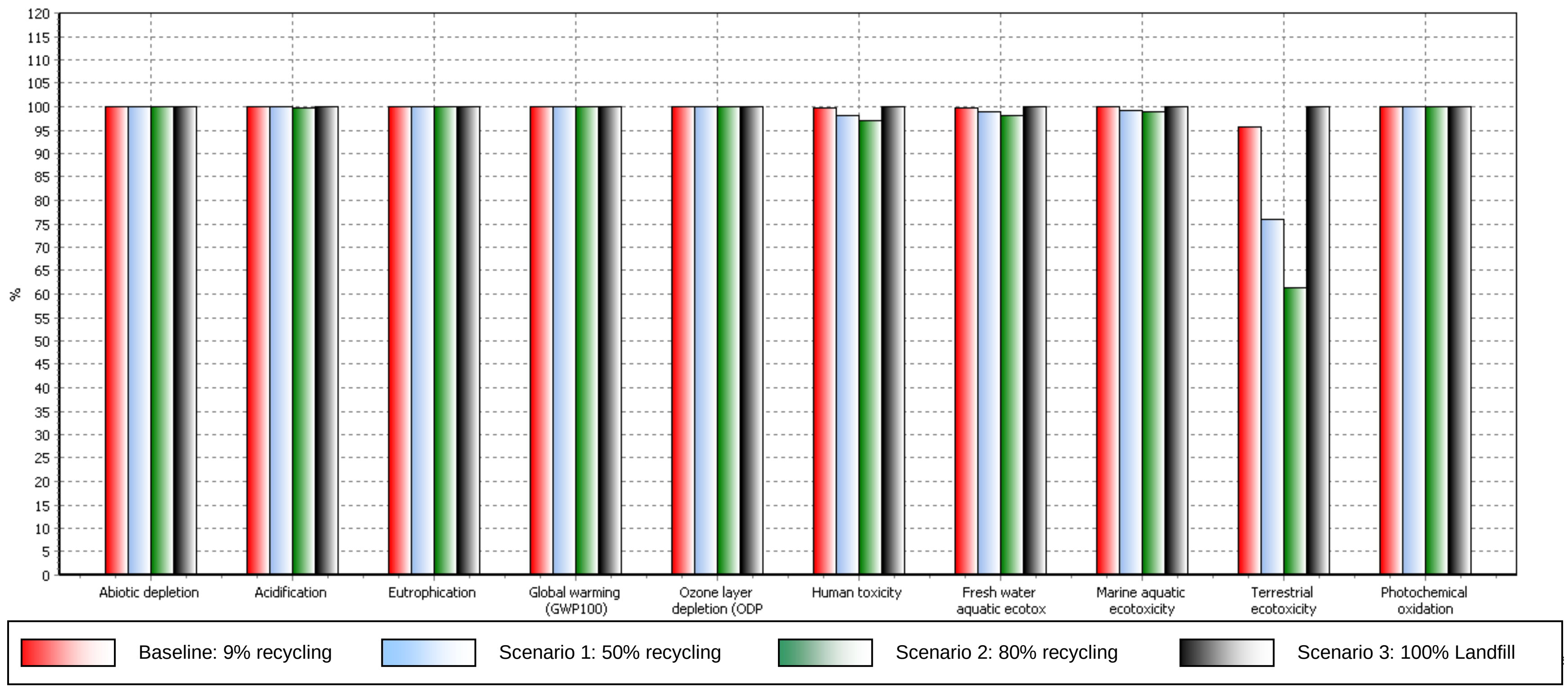


Figure 7 Life Cycle Impacts – Whole life – Metal Halide (MH) lamps, 400W (100,000 hours operation)

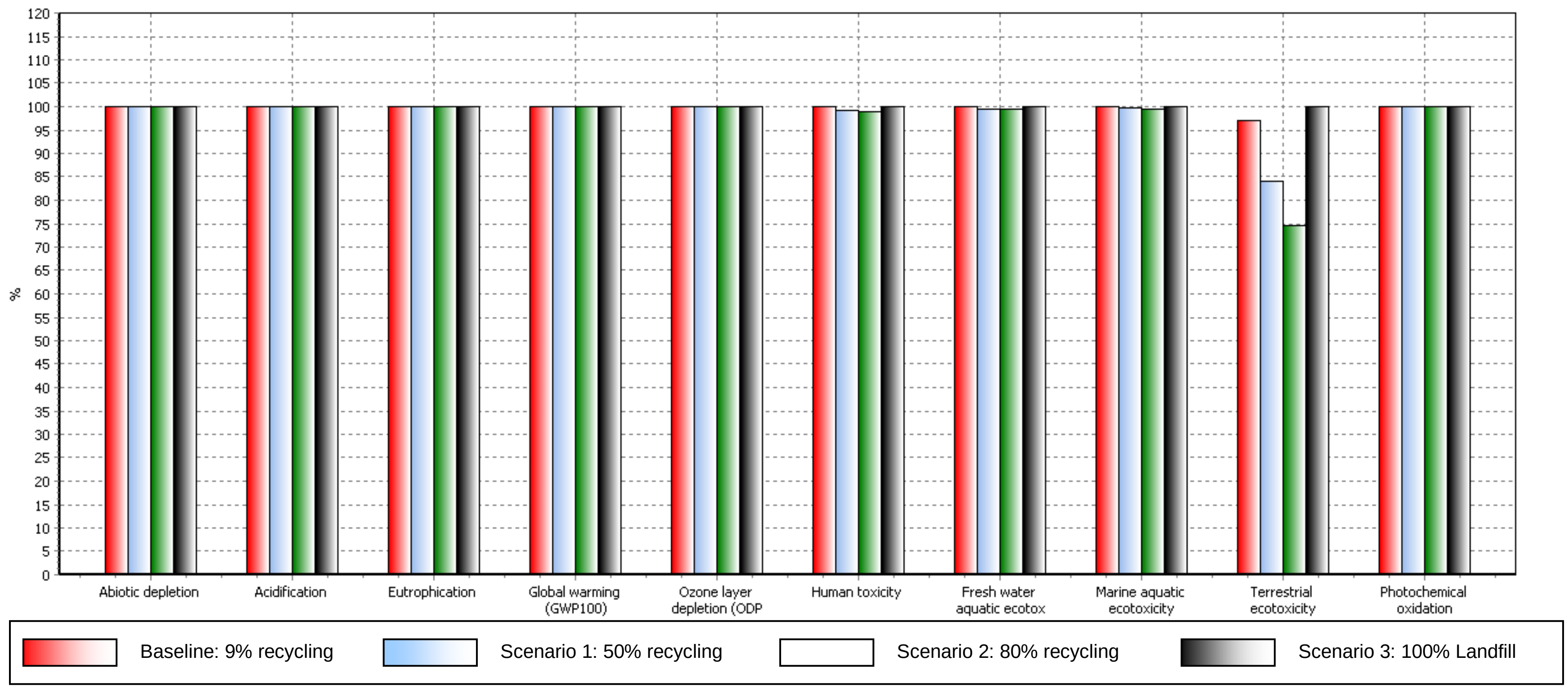
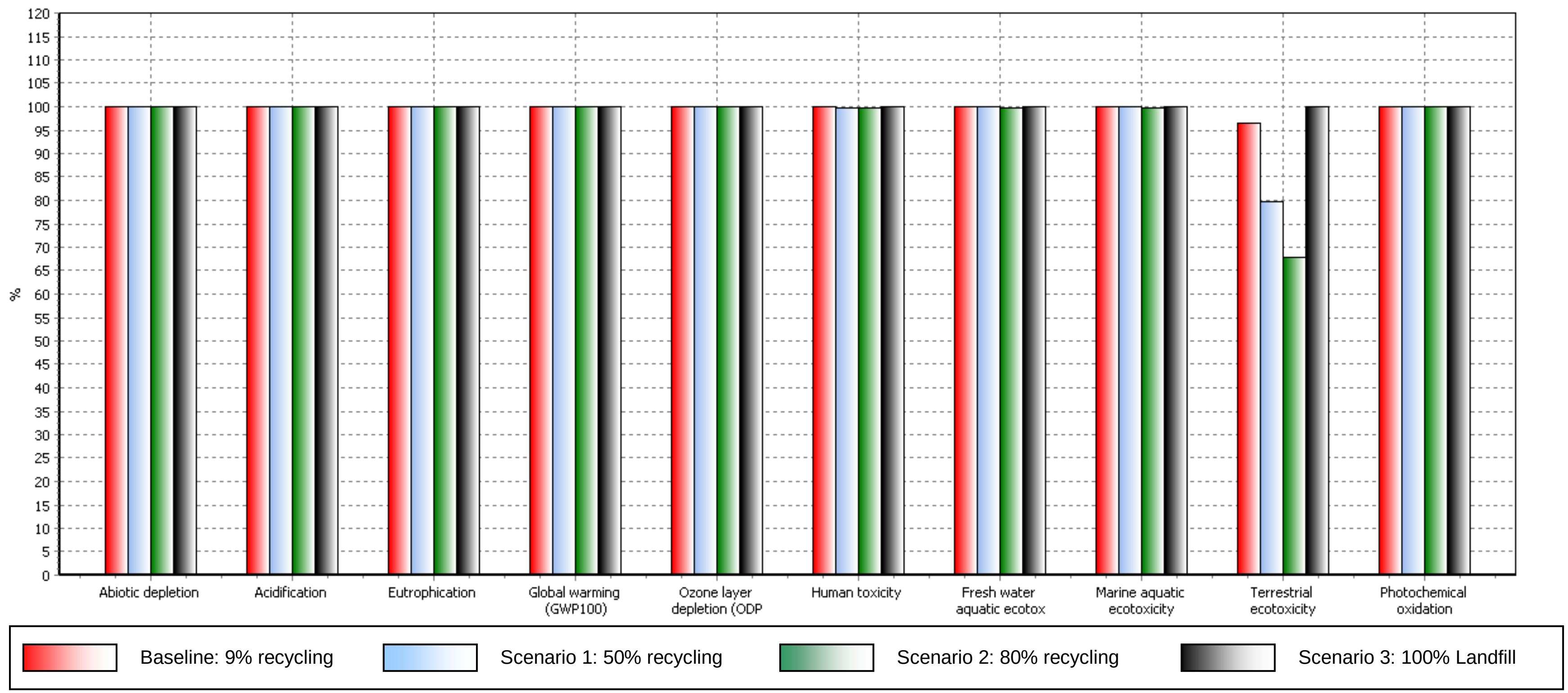


Figure 8 Life Cycle Impacts – Whole life – Mercury Vapour (MV) lamps, 250W (100,000 hours operation)



5.2 Impacts of End-of-Life Management

Section 5.2 focuses on end-of-life and the environmental impacts associated with the product stewardship options for end-of-life management.

The results shown in Figure 9 to Figure 14 indicate that increased levels of recycling and recovery increase the environmental benefits across all impacts indicators. The negative numbers in the chart indicate an environmental benefit.

The results indicate significant environmental benefits across all impact indicators and all lamps types for increased recovery and recycling levels.

These benefits, across impact indicators and all lamp types are dominated by the environmental benefits that arise through the avoided production of virgin raw materials, as a result of their displacement by materials recovered for further use by the recycling process.

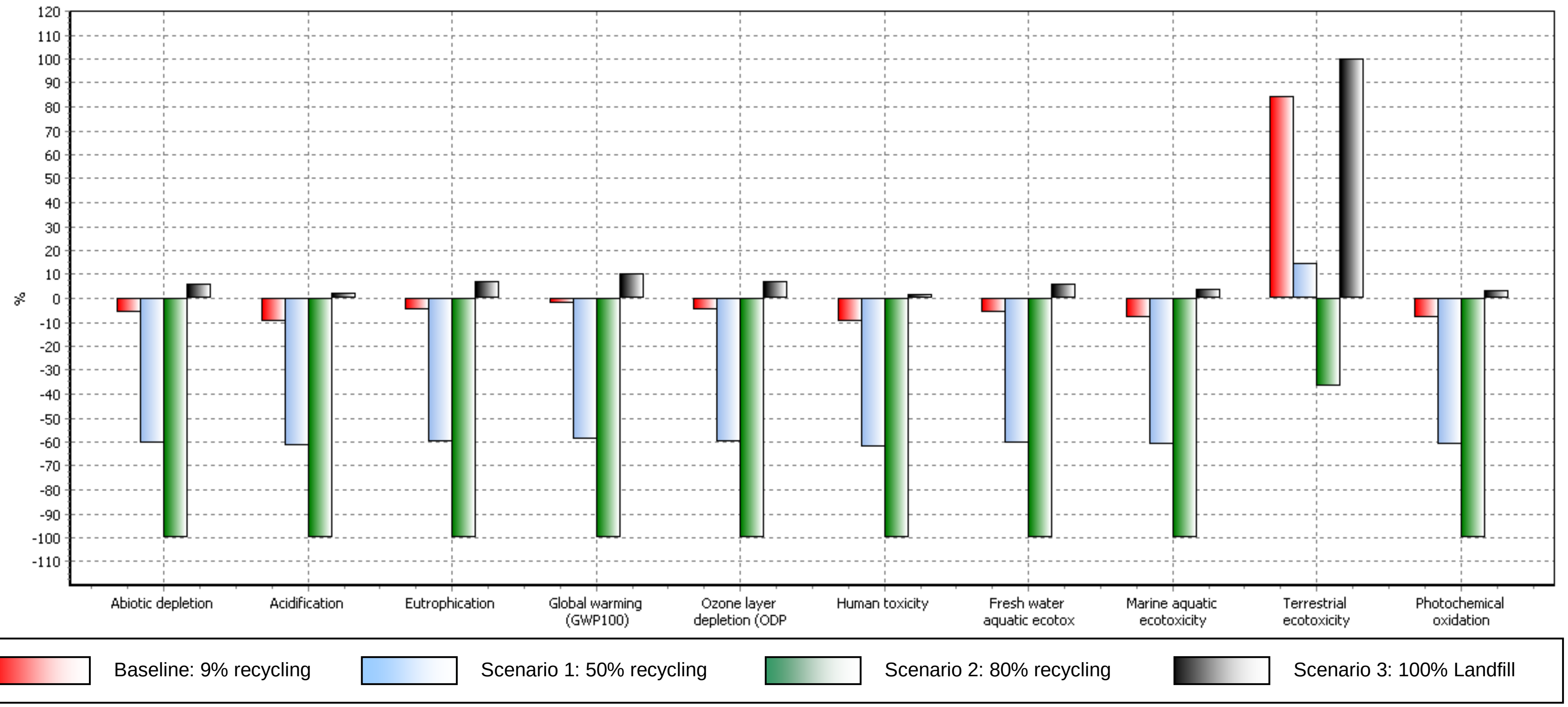
As an example the environmental impact results are shown numerically in Table 9 for a CFLi lamp. These indicate that benefits achieved from changing from 9% to 80% recycling and recovery, over the 100,000 hour operation time, result in savings of approximately 0.8kg CO_2 equivalents (which is equivalent to under 0.5% in the context of the whole life cycle).

Table 9 Life Cycle Impact Results – End-of-Life Only – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Abiotic depletion	kg Sb eq	-0.001	-0.005	-0.009	0.000
Acidification	kg SO_2 eq	-0.005	-0.030	-0.047	0.000
Eutrophication	kg PO_4^{-3} eq	0.000	-0.001	-0.001	0.000
Global warming	kg CO_2 eq	-0.075	-0.538	-0.877	0.027
Ozone layer depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	-0.111	-0.690	-1.113	0.016
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	-0.076	-0.441	-0.708	0.004
Marine aquatic ecotoxicity	kg 1,4-DB eq	-86.97	-502.16	-805.92	4.16
Terrestrial ecotoxicity	kg 1,4-DB eq	0.122	0.018	-0.058	0.145
Photochemical oxidation	kg C_2H_4	-0.0003	-0.0015	-0.0024	0.0000

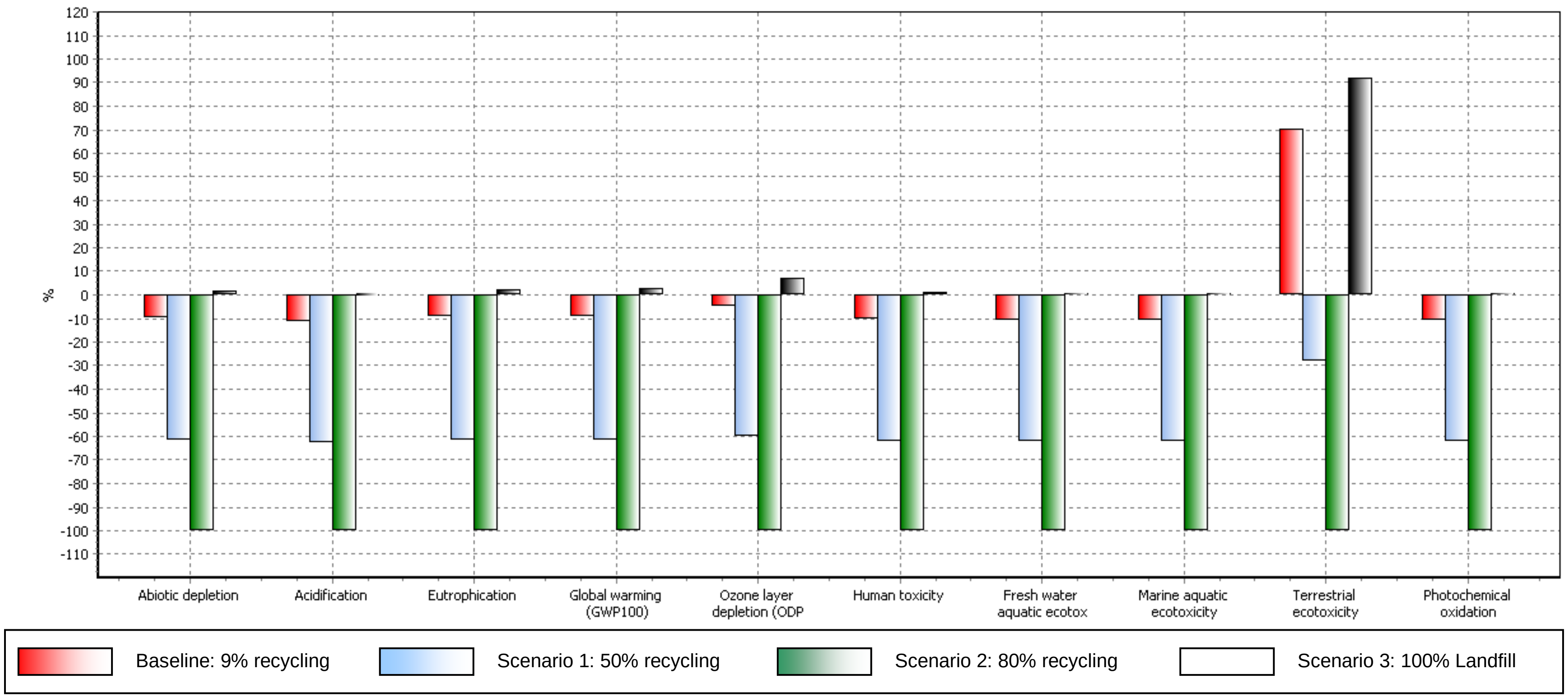
Note: a negative number represents an environmental benefit.

Figure 9 Life Cycle Impacts – End-of-Life Only – Linear fluorescent lamps (LFL), 35W, T8 (100,000 hours operation)



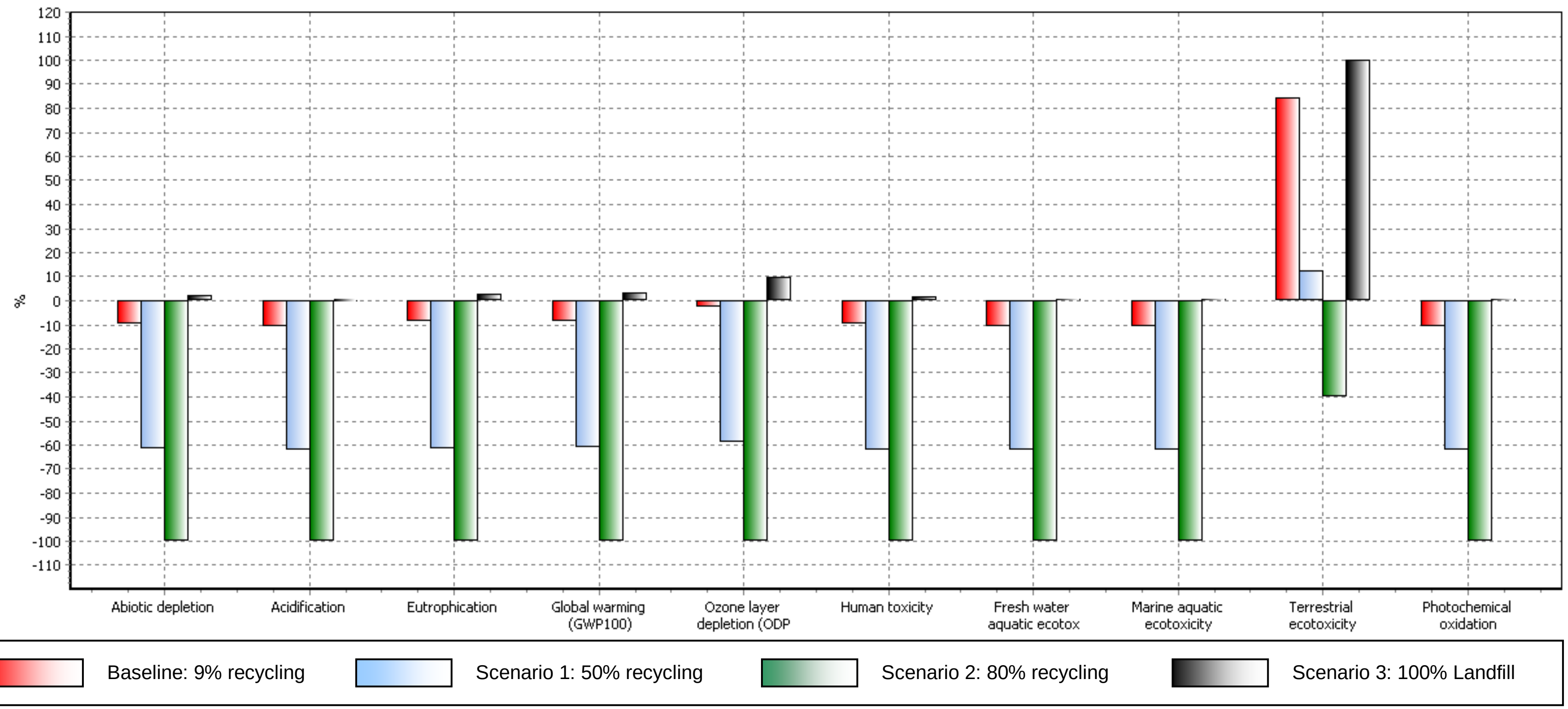
Note: a negative number represents an environmental benefit.

Figure 10 Life Cycle Impacts – End-of-Life Only – Compact fluorescent lamps (CFLe) 11W: external ballast (100,000 hours operation)



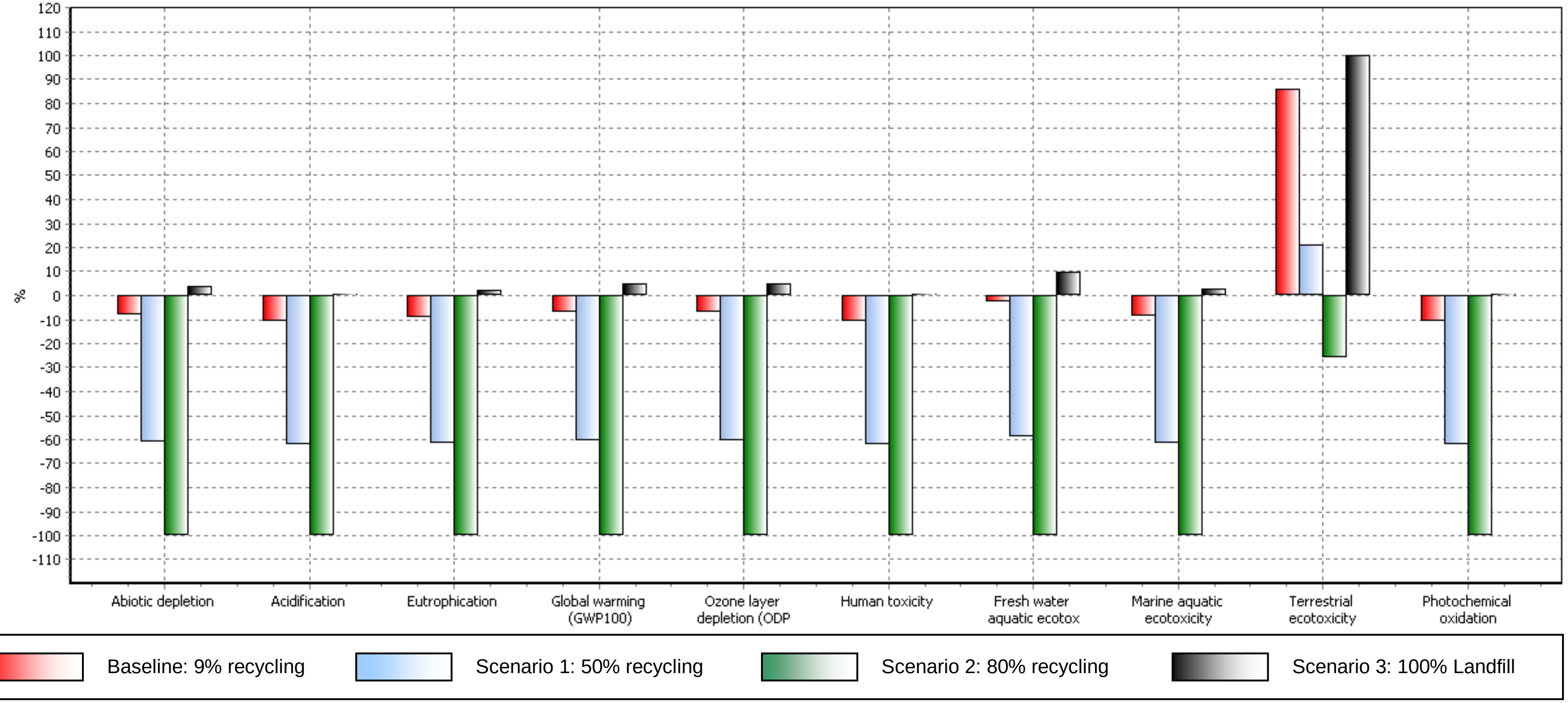
Note: a negative number represents an environmental benefit.

Figure 11 Life Cycle Impacts – End-of-Life Only – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)



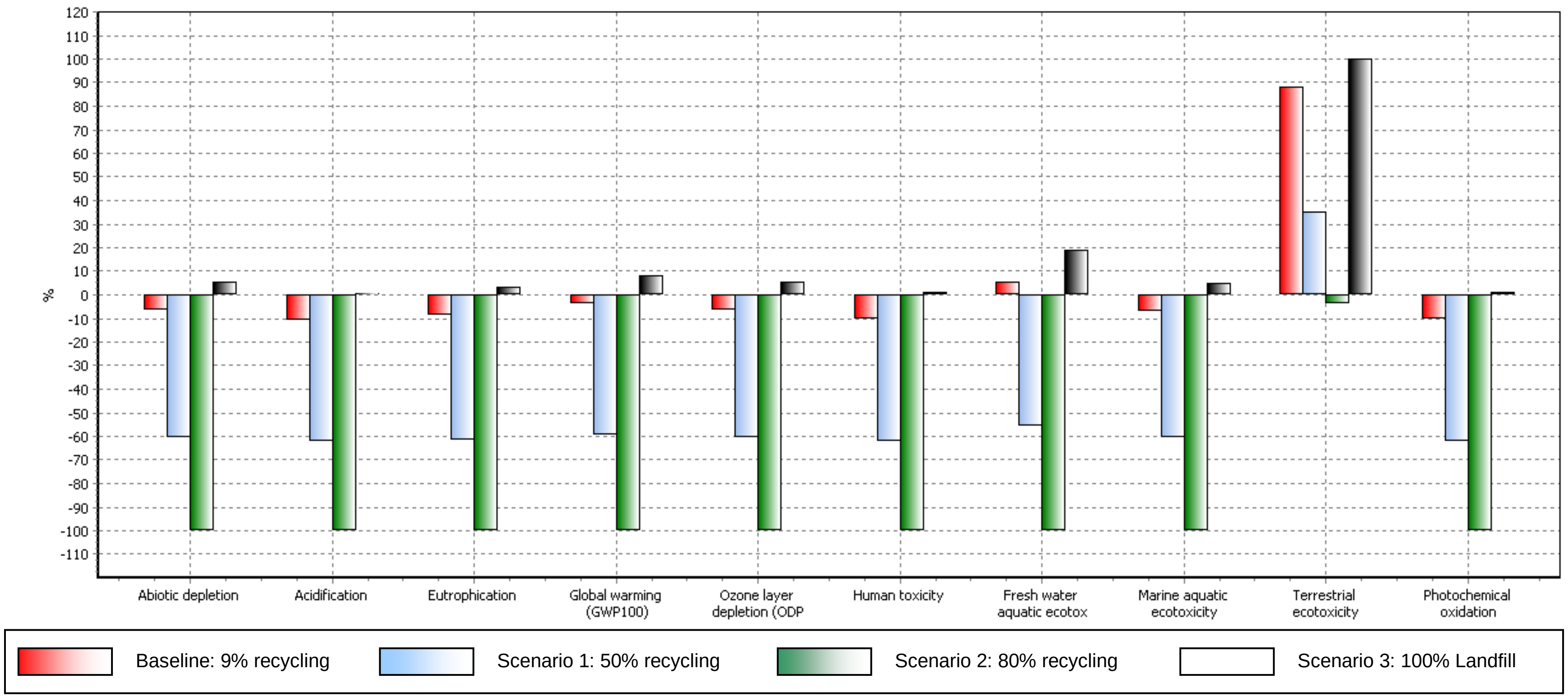
Note: a negative number represents an environmental benefit.

Figure 12 Life Cycle Impacts – End-of-Life Only – High pressure sodium (HPS) lamps, 150W (100,000 hours operation)



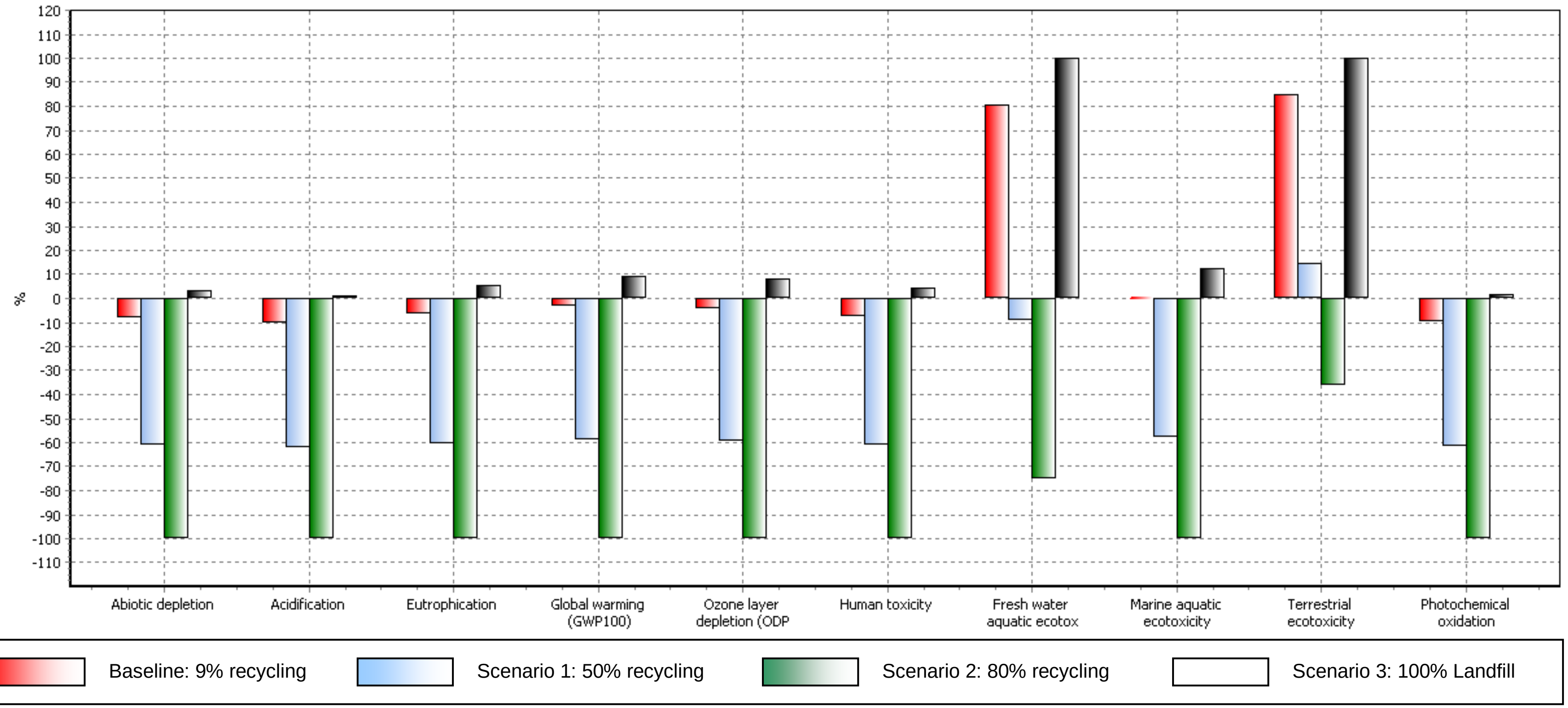
Note: a negative number represents an environmental benefit.

Figure 13 Life Cycle Impacts – End-of-Life Only – Metal Halide (MH) lamps, 400W (100,000 hours operation)



Note: a negative number represents an environmental benefit.

Figure 14 Life Cycle Impacts – End-of-Life Only – Mercury Vapour (MV) lamps, 250W (100,000 hours operation)



Note: a negative number represents an environmental benefit.

5.3 Impacts of Reduced Mercury Levels in Lamps

5.3.1 Whole Life Results: Reduced Mercury Levels

The whole-life results shown in Figure 15 to Figure 20 indicate that with a 20% reduction in lamp mercury content along with increased levels of recycling and recovery, then marginally reduced impacts arise.

The influence of reduced mercury levels of 20% provides an almost negligible reduction in environmental impact compared to typical mercury levels across all impact indicators, with the exception of terrestrial ecotoxicity impacts, as shown in Table 10, which gives a reduction of around 6% of the impact at an 80% recycling level (and 2% reduction at a rate of 9% recycling and recovery).

The benefits for terrestrial ecotoxicity impacts are almost entirely driven by the reduced need to manufacture as much mercury for the lamp. This reduction in impact results from a reduction in release of mercury to air that is associated with the mercury raw material manufacturing process. Also smaller reductions occur at end-of-life landfill disposal which is primarily driven by a reduction in emissions of mercury to soil and to air, which results from reduced levels of mercury entering the landfill.

Table 10 Life Cycle Impact Results – Whole life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Baseline: 9% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 5: 80% recovery and recycling
		Typical Mercury Level	Low Mercury Level	Typical Mercury Level	Low Mercury Level
Abiotic depletion	kg Sb eq	4.03	4.03	4.02	4.02
Acidification	kg SO_2 eq	2.21	2.21	2.17	2.17
Eutrophication	kg PO_4^{-3} eq	0.15	0.15	0.15	0.15
Global warming	kg CO_2 eq	516.9	516.9	516.1	516.1
Ozone layer depletion	kg CFC-11 eq	0.00	0.00	0.00	0.00
Human toxicity	kg 1,4-DB eq	68.96	68.95	67.95	67.95
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	7.53	7.53	6.90	6.90
Marine aquatic ecotoxicity	kg 1,4-DB eq	15,821	15,819	15,102	15,101
Terrestrial ecotoxicity	kg 1,4-DB eq	0.62	0.58	0.44	0.43
Photochemical oxidation	kg C_2H_4	0.19	0.19	0.18	0.18

Note: a negative number represents an environmental benefit.

5.3.2 End-of-Life Results: Reduced Mercury Levels

Section 5.3.2 focuses on end-of-life and the environmental impacts associated with the product stewardship options for end-of-life management.

Table 11 shows that the influence of reduced mercury levels of 20% provides an almost negligible reduction in environmental impact compared to typical mercury levels across all impact indicators, with the exception of terrestrial ecotoxicity impacts, which gives a reduction of around 20% of total impacts for a recycling and recovery rate of both 9% and 80%. This reduction in impact results from a direct reduction in emissions of mercury to air and to soil from landfill disposal due to a reduced mass of mercury being disposed per lamp.

Table 11 Life Cycle Impact Results – End-of-Life Only – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling Typical Mercury Level	Baseline: 9% recovery and recycling Low Mercury Level	Scenario 2: 80% recovery and recycling Typical Mercury Level	Scenario 5: 80% recovery and recycling Low Mercury Level
Abiotic depletion	kg Sb eq	-0.001	-0.001	-0.009	-0.009
Acidification	kg SO_2 eq	-0.005	-0.005	-0.047	-0.047
Eutrophication	kg PO_4^{-3} eq	0.000	0.000	-0.001	-0.001
Global warming	kg CO_2 eq	-0.075	-0.075	-0.877	-0.877
Ozone layer depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	-0.111	-0.112	-1.113	-1.110
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	-0.076	-0.077	-0.708	-0.708
Marine aquatic ecotoxicity	kg 1,4-DB eq	-87.0	-87.2	-805.9	-805.1
Terrestrial ecotoxicity	kg 1,4-DB eq	0.122	0.098	-0.058	-0.047
Photochemical oxidation	kg C_2H_4	0.000	0.000	-0.002	-0.002

Note: a negative number represents an environmental benefit.

Figure 15 Life Cycle Impacts – Whole life – Linear fluorescent lamps (LFL), 35W, T8 (100,000 hours operation) – 20% Reduced Mercury

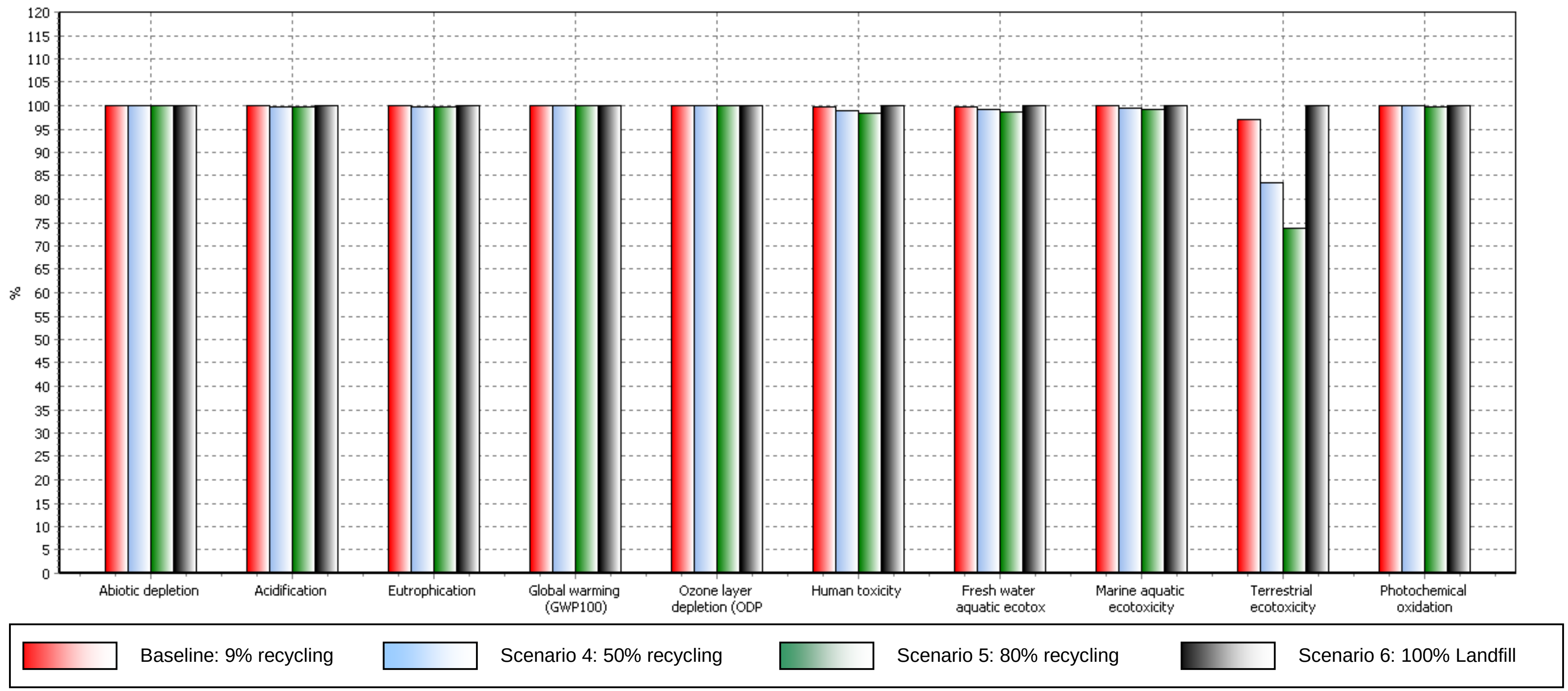


Figure 16 Life Cycle Impacts – Whole life – Compact fluorescent lamps (CFLe) 11W: external ballast (100,000 hours operation) – 20% Reduced Mercury

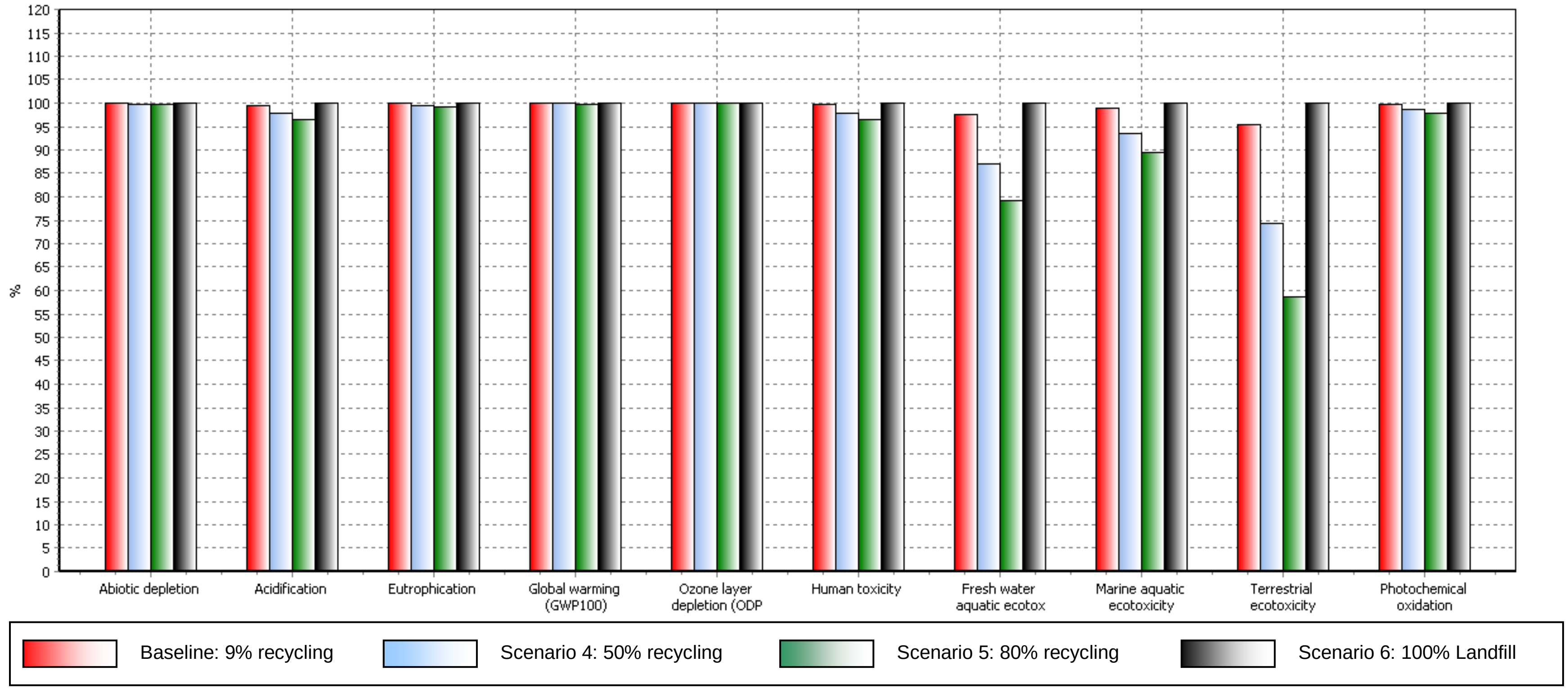


Figure 17 Life Cycle Impacts – Whole life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation) – 20% Reduced Mercury

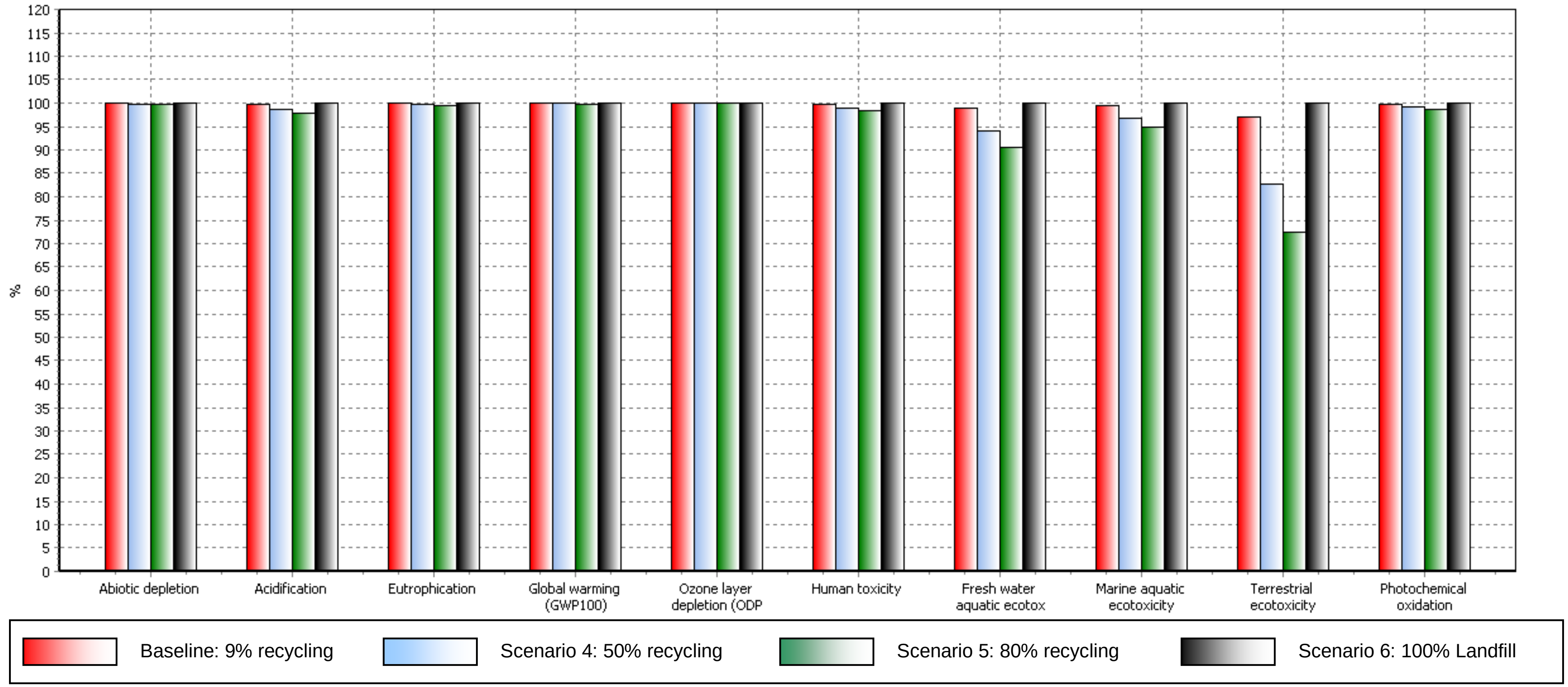


Figure 18 Life Cycle Impacts – Whole life – High pressure sodium (HPS) lamps, 150W (100,000 hours operation) – 20% Reduced Mercury

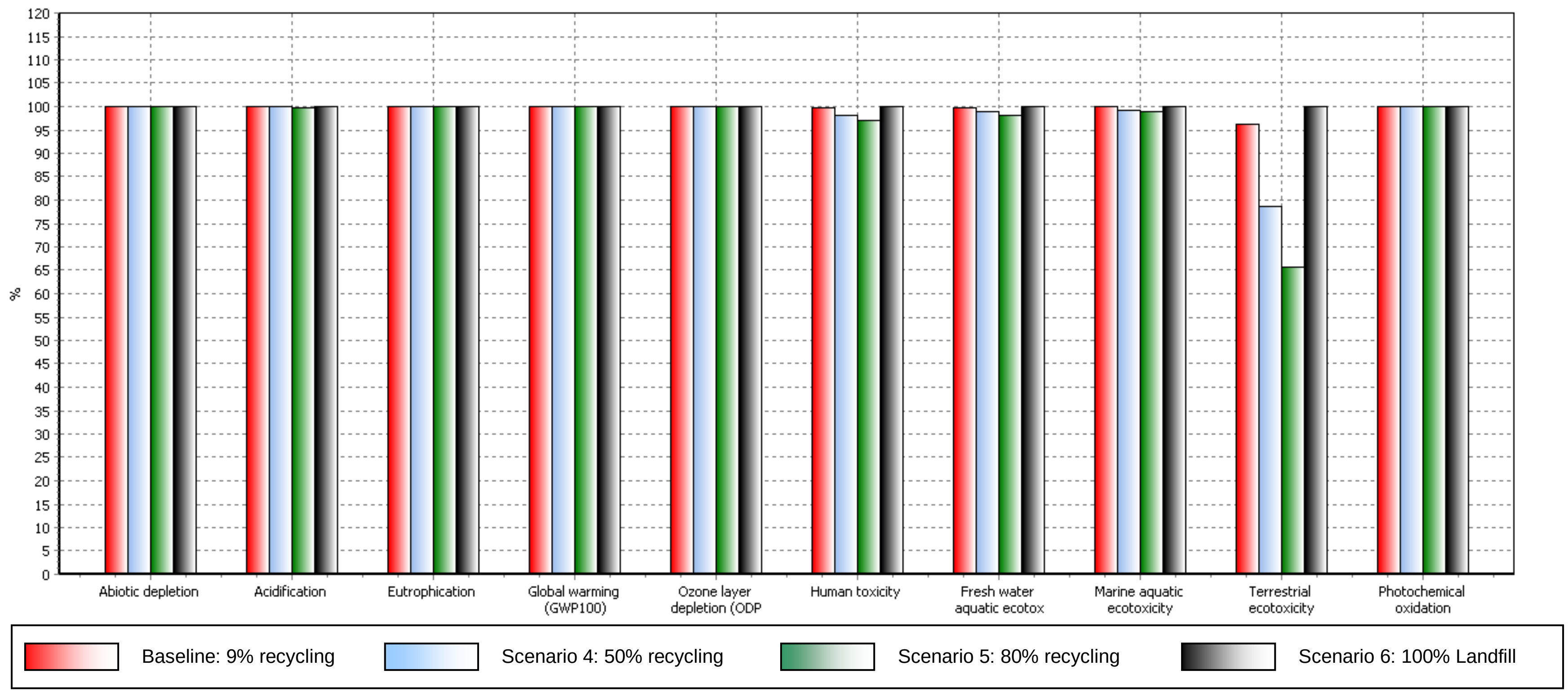


Figure 19 Life Cycle Impacts – Whole life – Metal Halide (MH) lamps, 400W (100,000 hours operation) – 20% Reduced Mercury

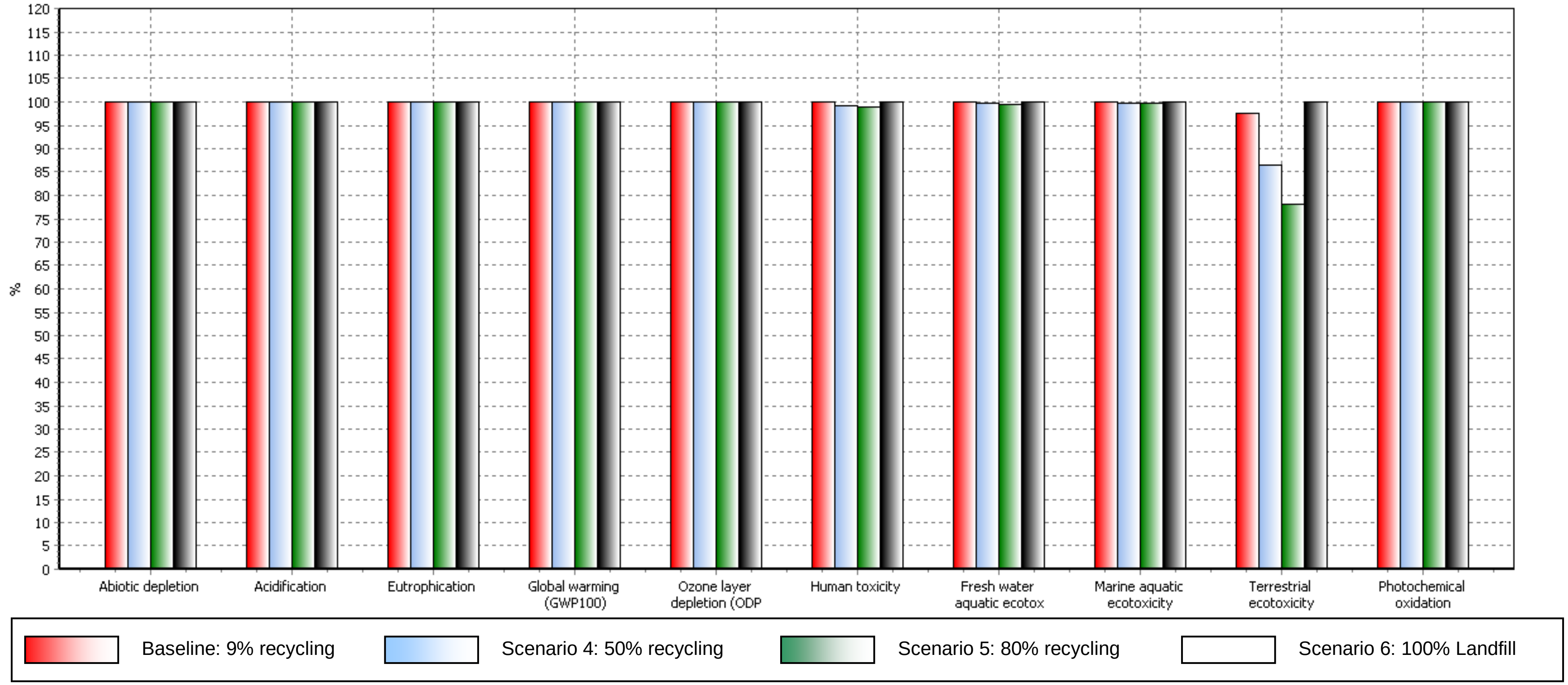
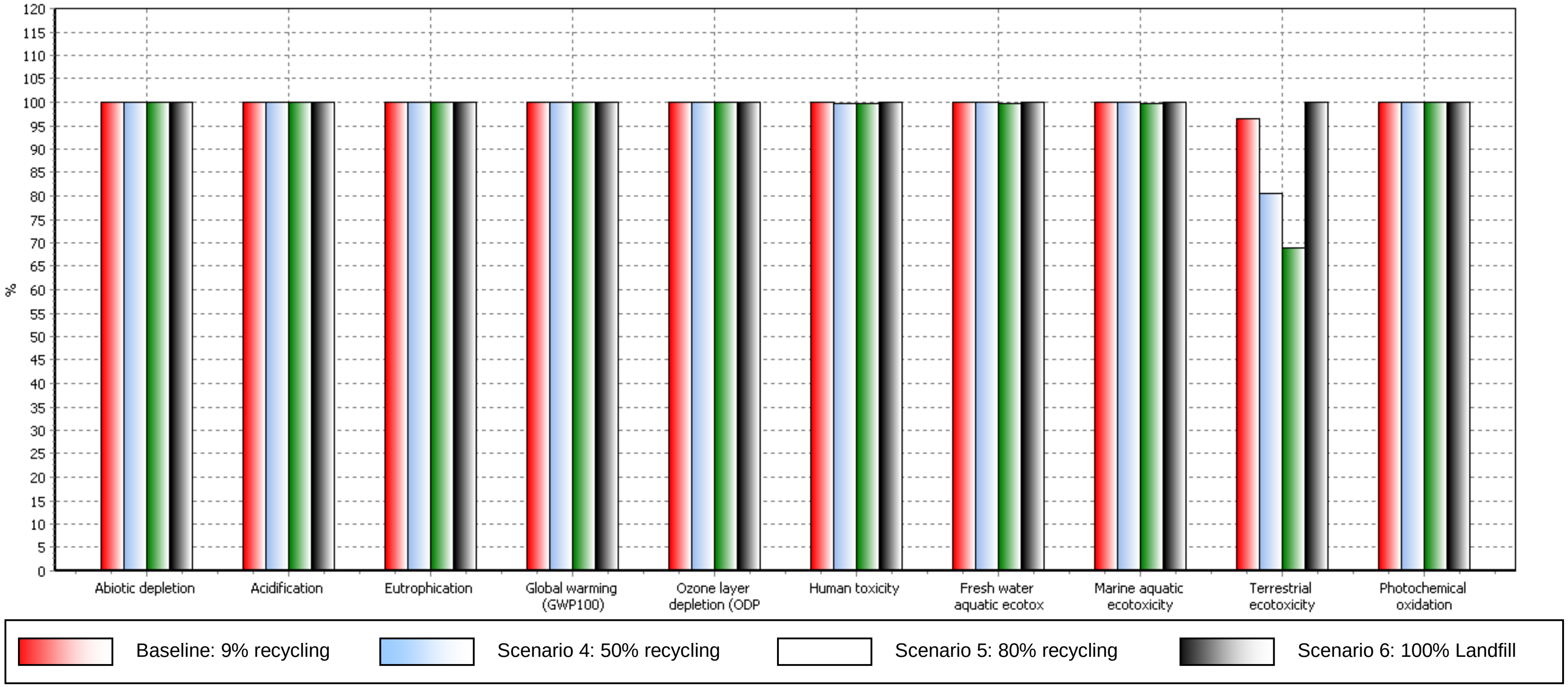


Figure 20 Life Cycle Impacts – Whole life – Mercury Vapour (MV) lamps, 250W (100,000 hours operation) – 20% Reduced Mercury



5.4 Contribution of Mercury to Human Toxicity Impacts

5.4.1 Whole Life Results: Contribution of Mercury to Human Toxicity Impacts

The results in Table 12 and Table 13 show the contribution of the most significant substances to human toxicity impacts over the complete life cycle for the six lamps assessed. The results indicate that mercury emissions contribute under 0.5% of the total impacts of human toxicity.

The results show the most significant contributing substances relate to poly aromatic hydrocarbons (PAH) to air (contributing generally around 50% of impacts), non-methane volatile organic compounds (NMVOC) to air and other (non-mercury) heavy metals that are released to air and to water.

Primarily, the contributions to human toxicity arise from generation of electricity in the use phase, resulting from combustion of gas and coal which release PAH and NMVOC to air with the use phase contributing around 85% to 95% of the total life cycle. This is the same across all lamp types, with the slight exception for the integrated CFL. For CFLi lamps the manufacturing phase results in additional human toxicity impacts resulting from the production of electronics and the use phase contributes around 65% from emissions of PAH and NMVOC to air from electricity generation.

The results indicate that increased levels of recovery and recycling reduce total human toxicity impacts and also reduce the levels of mercury release to the environment. The results indicate that benefits achieved from changing from 9% to 80% recycling and recovery result in reduction of around 1.5% for human toxicity impacts over the life cycle.

The Impact 2002+ (2003) assessment method also ranks the mercury contribution at a similar level for human health impacts.

The Impact 2002 method also confirms the use stage as being dominant, around 80% of total impacts. The generation of electricity is the primary contributory process; with the main substance contributions being nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM) released to air.

The TRACI method (Bare, 2003) also indicates similar results; however this is dependent on the impact category selected. It should be noted that the TRACI method considers mercury for non-carcinogenic impacts and ecotoxicity impacts, but is not characterised in relation to other impact categories. For respiratory effects, very similar results are shown. For carcinogenic and non-carcinogenic impacts the TRACI method indicates that heavy metals (but excluding mercury) are the primary contributory substances, from both generation of electricity in the use phase and some from raw material manufacture. For CFLi lamps, the method also identifies the production of electronics as being a significant contributor (representing around 70% for carcinogenic impacts and around 85% for non- carcinogenic impacts).

Table 12 Human Toxicity Impacts – Whole life – Substance Contributions (100,000 hours operation for baseline scenario of 9% recycling)

Substance	Fate	Unit	1. Linear fluorescent lamp (LFL)	2. Compact fluorescent lamp (CFL)	3. Compact fluorescent lamp (CFL)	4. High pressure sodium (HPS)	5. Metal Halide (MH))	6. Mercury Vapour (MV))
Total of all compartments		kg 1,4-DB eq	87.6	28.6	69.0	348.8	903.8	561.3
Remaining substances		kg 1,4-DB eq	0.4	0.1	0.9	1.5	3.8	2.3
PAH	Air	kg 1,4-DB eq	46.1	14.0	27.9	187.3	499.0	311.7
NMVOC	Air	kg 1,4-DB eq	13.2	4.2	8.3	55.7	148.5	92.9
Arsenic	Air	kg 1,4-DB eq	4.4	1.5	11.0	22.0	43.3	24.0
Chromium VI	Air	kg 1,4-DB eq	4.1	1.4	3.2	12.6	32.0	20.1
Nickel	Air	kg 1,4-DB eq	3.2	1.4	4.0	13.0	31.3	19.1
Benzene	Air	kg 1,4-DB eq	3.1	1.0	2.0	12.7	33.9	21.1
Selenium	Air	kg 1,4-DB eq	2.2	0.7	1.5	9.1	24.1	15.0
Nitrogen oxides	Air	kg 1,4-DB eq	2.1	0.7	1.3	8.5	22.4	14.1
Selenium	Water	kg 1,4-DB eq	1.5	0.5	1.1	3.4	8.5	5.4
Vanadium, ion	Water	kg 1,4-DB eq	1.4	0.5	1.1	2.7	6.7	4.3
Hydrogen fluoride	Air	kg 1,4-DB eq	1.2	0.4	0.7	4.7	12.5	7.8
Thallium	Water	kg 1,4-DB eq	1.1	0.4	0.7	1.8	4.5	2.9
Vanadium	Air	kg 1,4-DB eq	0.3	0.1	0.3	0.8	2.1	1.4
PAH	Water	kg 1,4-DB eq	0.3	0.1	0.3	1.2	3.3	2.1
Copper	Air	kg 1,4-DB eq	0.3	0.1	0.6	1.6	3.8	2.3
Cadmium	Air	kg 1,4-DB eq	0.3	0.1	1.4	2.2	3.9	2.0
Barium	Air	kg 1,4-DB eq	0.3	0.1	0.2	1.2	3.2	2.0
Barium	Water	kg 1,4-DB eq	0.3	0.1	0.3	1.0	2.8	1.7
Barium	Soil	kg 1,4-DB eq	0.2	0.1	0.1	1.0	2.6	1.6
Molybdenum	Water	kg 1,4-DB eq	0.2	0.1	0.2	0.4	1.0	0.6
Sulfur dioxide	Air	kg 1,4-DB eq	0.2	0.1	0.1	0.8	2.0	1.2
Particulates, < 2.5 um	Air	kg 1,4-DB eq	0.1	0.0	0.1	0.5	1.4	0.9
Chromium	Soil	kg 1,4-DB eq	0.1	0.0	0.1	0.5	1.4	0.9
Beryllium	Water	kg 1,4-DB eq	0.1	0.0	0.1	0.2	0.5	0.4
Arsenic, ion	Water	kg 1,4-DB eq	0.1	0.0	0.1	0.1	0.3	0.2
Dioxins	Air	kg 1,4-DB eq	0.1	0.0	0.1	0.5	1.2	0.8
Mercury	Air	kg 1,4-DB eq	0.1	0.1	0.1	0.5	1.0	0.7

Table 13 Human Toxicity Impacts – Whole life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

Substance	Fate	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total of all compartments		kg 1,4-DB eq	69.0	68.4	68.0	69.1
Remaining substances		kg 1,4-DB eq	0.3	0.3	0.3	0.3
PAH	Air	kg 1,4-DB eq	27.9	27.9	27.9	27.9
Arsenic	Air	kg 1,4-DB eq	11.0	10.9	10.9	11.0
NMVOC	Air	kg 1,4-DB eq	8.3	8.2	8.2	8.3
Nickel	Air	kg 1,4-DB eq	4.0	3.9	3.7	4.1
Chromium VI	Air	kg 1,4-DB eq	3.2	3.3	3.3	3.2
Benzene	Air	kg 1,4-DB eq	2.0	2.0	2.0	2.0
Selenium	Air	kg 1,4-DB eq	1.5	1.5	1.5	1.5
Cadmium	Air	kg 1,4-DB eq	1.4	1.4	1.4	1.4
Nitrogen oxides	Air	kg 1,4-DB eq	1.3	1.3	1.3	1.3
Selenium	Water	kg 1,4-DB eq	1.1	1.1	1.1	1.1
Vanadium, ion	Water	kg 1,4-DB eq	1.1	1.1	1.1	1.1
Hydrogen fluoride	Air	kg 1,4-DB eq	0.7	0.7	0.7	0.7
Thallium	Water	kg 1,4-DB eq	0.7	0.7	0.7	0.7
Cobalt	Air	kg 1,4-DB eq	0.7	0.5	0.3	0.8
Copper	Air	kg 1,4-DB eq	0.6	0.6	0.5	0.6
Benzene	Water	kg 1,4-DB eq	0.5	0.5	0.5	0.5
Vanadium	Air	kg 1,4-DB eq	0.3	0.3	0.3	0.3
Barium	Water	kg 1,4-DB eq	0.3	0.3	0.3	0.3
PAH	Water	kg 1,4-DB eq	0.3	0.3	0.3	0.3
Nickel, ion	Water	kg 1,4-DB eq	0.2	0.2	0.2	0.2
Molybdenum	Water	kg 1,4-DB eq	0.2	0.2	0.2	0.2
Barium	Air	kg 1,4-DB eq	0.2	0.2	0.2	0.2
Antimony	Water	kg 1,4-DB eq	0.1	0.1	0.1	0.1
Sulfur dioxide	Air	kg 1,4-DB eq	0.1	0.1	0.1	0.1
Barium	Soil	kg 1,4-DB eq	0.1	0.1	0.1	0.1
Dioxins	Air	kg 1,4-DB eq	0.1	0.1	0.1	0.1
Ethylene oxide	Air	kg 1,4-DB eq	0.1	0.1	0.1	0.1
Beryllium	Water	kg 1,4-DB eq	0.1	0.1	0.1	0.1
Arsenic, ion	Water	kg 1,4-DB eq	0.1	0.1	0.1	0.1
Particulates, < 2.5 um	Air	kg 1,4-DB eq	0.1	0.1	0.1	0.1
Lead	Air	kg 1,4-DB eq	0.1	0.1	0.1	0.1
Mercury	Air	kg 1,4-DB eq	0.1	0.1	0.1	0.1

5.4.2 End-of-Life Results: Contribution of Mercury to Human Toxicity Impacts

Section 5.4.2 focuses on end-of-life and the environmental impacts associated with the product stewardship options for end-of-life management.

The results in Table 14 and Table 15 show the contribution of the most significant substances to human toxicity impacts over the complete life cycle for the six lamps assessed.

When looking at end-of-life only emissions arise from disposal causing both detrimental impacts (e.g. heavy metals emissions to air, water and soil) and also environmental benefits of the avoided emissions that arise through the avoided production of virgin raw materials, as a result of their displacement by materials recovered for further use by the recycling process.

Considering only the detrimental impacts at end-of-life, the results show that mercury emissions from landfill contribute around 25% for LFLs and CFLs, while for industrial lamp types (HPS, MH and MV) mercury emissions from landfill contribute around 90% of the total impacts for human toxicity.

The results indicate that increased levels of recovery and recycling reduce total human toxicity impacts that result from mercury emissions from landfill. However, the primary driver for reducing emissions results from environmental benefits of the avoided emissions that arise through the avoided production of virgin raw materials, as a result of their displacement by materials recovered for further use by the recycling process. These benefits mainly arise from avoided production from metals (nickel, brass and aluminium) in the lamps.

Table 14 Human Toxicity Impacts – End-of-Life – Substance Contributions (100,000 hours operation for baseline of 9% recycling)

Substance	Fate	Unit	1. Linear fluorescent lamp (LFL)	2. Compact fluorescent lamp (CFL)	3. Compact fluorescent lamp (CFL)	4. High pressure sodium (HPS)	5. Metal Halide (MH))	6. Mercury Vapour (MV))
Total of all compartments		kg 1,4-DB eq	-0.1435	-0.1064	-0.1107	-1.1324	-1.0159	-0.1625
Remaining substances		kg 1,4-DB eq	-0.0005	-0.0519	-0.0591	-0.0198	-0.0176	-0.0027
PAH	Air	kg 1,4-DB eq	-0.1550	-0.0024	-0.0016	-0.0059	-0.0055	0.0000
Arsenic	Air	kg 1,4-DB eq	-0.0060	-0.0082	-0.0095	-0.8237	-0.7789	-0.1606
Vanadium, ion	Water	kg 1,4-DB eq	-0.0055	-0.0002	-0.0001	-0.0003	-0.0002	0.0001
Barite	Water	kg 1,4-DB eq	-0.0032	-0.0012	-0.0015	-0.0017	-0.0027	-0.0014
Selenium	Water	kg 1,4-DB eq	-0.0016	-0.0005	-0.0007	-0.0003	-0.0003	-0.0002
Cadmium	Air	kg 1,4-DB eq	-0.0008	-0.0008	-0.0009	-0.1146	-0.1083	-0.0224
Sodium dichromate	Air	kg 1,4-DB eq	-0.0006	0.0000	0.0000	-0.0003	-0.0003	-0.0001
Hydrogen fluoride	Air	kg 1,4-DB eq	-0.0006	-0.0001	-0.0001	-0.0001	-0.0002	-0.0001
Nickel	Air	kg 1,4-DB eq	-0.0003	-0.0365	-0.0407	-0.1577	-0.1486	-0.0305
NMVOC	Air	kg 1,4-DB eq	-0.0003	-0.0028	-0.0041	-0.0021	-0.0019	-0.0021
Thallium	Water	kg 1,4-DB eq	-0.0002	-0.0001	-0.0001	-0.0002	-0.0002	-0.0001
Nitrogen oxides	Air	kg 1,4-DB eq	-0.0002	-0.0003	-0.0003	-0.0005	-0.0005	-0.0002
Copper	Air	kg 1,4-DB eq	-0.0002	-0.0036	-0.0040	-0.0319	-0.0301	-0.0062
Barium	Soil	kg 1,4-DB eq	0.0002	0.0000	0.0001	0.0000	0.0000	0.0000
Vanadium	Air	kg 1,4-DB eq	0.0002	-0.0010	-0.0011	-0.0016	-0.0014	-0.0006
Nickel, ion	Water	kg 1,4-DB eq	0.0006	-0.0054	-0.0058	-0.0018	-0.0015	-0.0001
Benzene	Air	kg 1,4-DB eq	0.0006	0.0000	-0.0001	-0.0004	-0.0002	0.0000
Barium	Water	kg 1,4-DB eq	0.0010	0.0001	0.0003	-0.0003	-0.0001	-0.0002
PAH	Water	kg 1,4-DB eq	0.0012	0.0004	0.0009	0.0003	0.0007	0.0007
Mercury	Water	kg 1,4-DB eq	0.0013	0.0006	0.0011	0.0084	0.0134	0.0093
Barium	Air	kg 1,4-DB eq	0.0023	0.0005	0.0008	0.0006	0.0010	0.0000
Mercury	Soil	kg 1,4-DB eq	0.0024	0.0011	0.0020	0.0147	0.0236	0.0163
Mercury	Air	kg 1,4-DB eq	0.0052	0.0011	0.0043	0.0360	0.0661	0.0359
Chromium VI	Air	kg 1,4-DB eq	0.0165	0.0049	0.0099	-0.0292	-0.0221	0.0025

Table 15 Human Toxicity Impacts – End-of-Life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

Substance	Fate	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total of all compartments		kg 1,4-DB eq	-0.111	-0.690	-1.113	0.016
Remaining substances		kg 1,4-DB eq	-0.001	-0.006	-0.009	0.000
Cobalt	Air	kg 1,4-DB eq	-0.054	-0.302	-0.483	0.000
Nickel	Air	kg 1,4-DB eq	-0.041	-0.227	-0.363	0.000
Arsenic	Air	kg 1,4-DB eq	-0.009	-0.053	-0.085	0.000
Nickel, ion	Water	kg 1,4-DB eq	-0.006	-0.032	-0.052	0.000
NMVOC	Air	kg 1,4-DB eq	-0.004	-0.027	-0.044	0.001
Copper	Air	kg 1,4-DB eq	-0.004	-0.023	-0.037	0.000
Antimony	Water	kg 1,4-DB eq	-0.003	-0.019	-0.030	0.000
PAH	Air	kg 1,4-DB eq	-0.002	-0.019	-0.031	0.002
Barite	Water	kg 1,4-DB eq	-0.002	-0.008	-0.013	0.000
Vanadium	Air	kg 1,4-DB eq	-0.001	-0.006	-0.010	0.000
Cadmium	Air	kg 1,4-DB eq	-0.001	-0.005	-0.009	0.000
Selenium	Water	kg 1,4-DB eq	-0.001	-0.004	-0.007	0.000
Cobalt	Water	kg 1,4-DB eq	0.000	-0.003	-0.004	0.000
Sulfur dioxide	Air	kg 1,4-DB eq	0.000	-0.002	-0.004	0.000
Nitrogen oxides	Air	kg 1,4-DB eq	0.000	-0.003	-0.005	0.000
Hydrogen fluoride	Air	kg 1,4-DB eq	0.000	-0.001	-0.001	0.000
Vanadium, ion	Water	kg 1,4-DB eq	0.000	-0.001	-0.001	0.000
Barium	Water	kg 1,4-DB eq	0.000	-0.002	-0.003	0.001
Barium	Air	kg 1,4-DB eq	0.001	0.000	0.000	0.001
PAH	Water	kg 1,4-DB eq	0.001	0.003	0.004	0.000
Mercury	Water	kg 1,4-DB eq	0.001	0.001	0.000	0.001
Mercury	Soil	kg 1,4-DB eq	0.002	0.001	0.000	0.002
Mercury	Air	kg 1,4-DB eq	0.004	-0.007	-0.016	0.007
Chromium VI	Air	kg 1,4-DB eq	0.010	0.055	0.088	0.000

6 Interpretation

Section 6 contains the interpretation and sensitivity analysis which considers lamp performance and addresses key assumptions within the study in order to test the robustness of the conclusions and recommendations suggested by the results of the study.

The following analyses have been assessed:

- impact of assumed lifetime of the lamps – ± 50% lifetime;
- impacts of assumed power rating of the lamps, accounting for potential increases in energy usage from lamp warm-up – +0.5%;
- impacts of improved energy efficiency in the use phase – +10% efficiency;
- impacts of closed loop recycling;
- impacts of attributing offset benefits to avoided materials from lamp recycling operations;
- potential impacts of packaging and fittings.

No significant cut-off criteria have been applied to the study and are therefore not tested in the sensitivity analysis.

The results are presented only for the CFLi lamp in the report, although discussion is provided as to implications for the other lamp types.

Further details of these sensitivity analyses and assumptions made can be found in Appendix B, Section B.11.

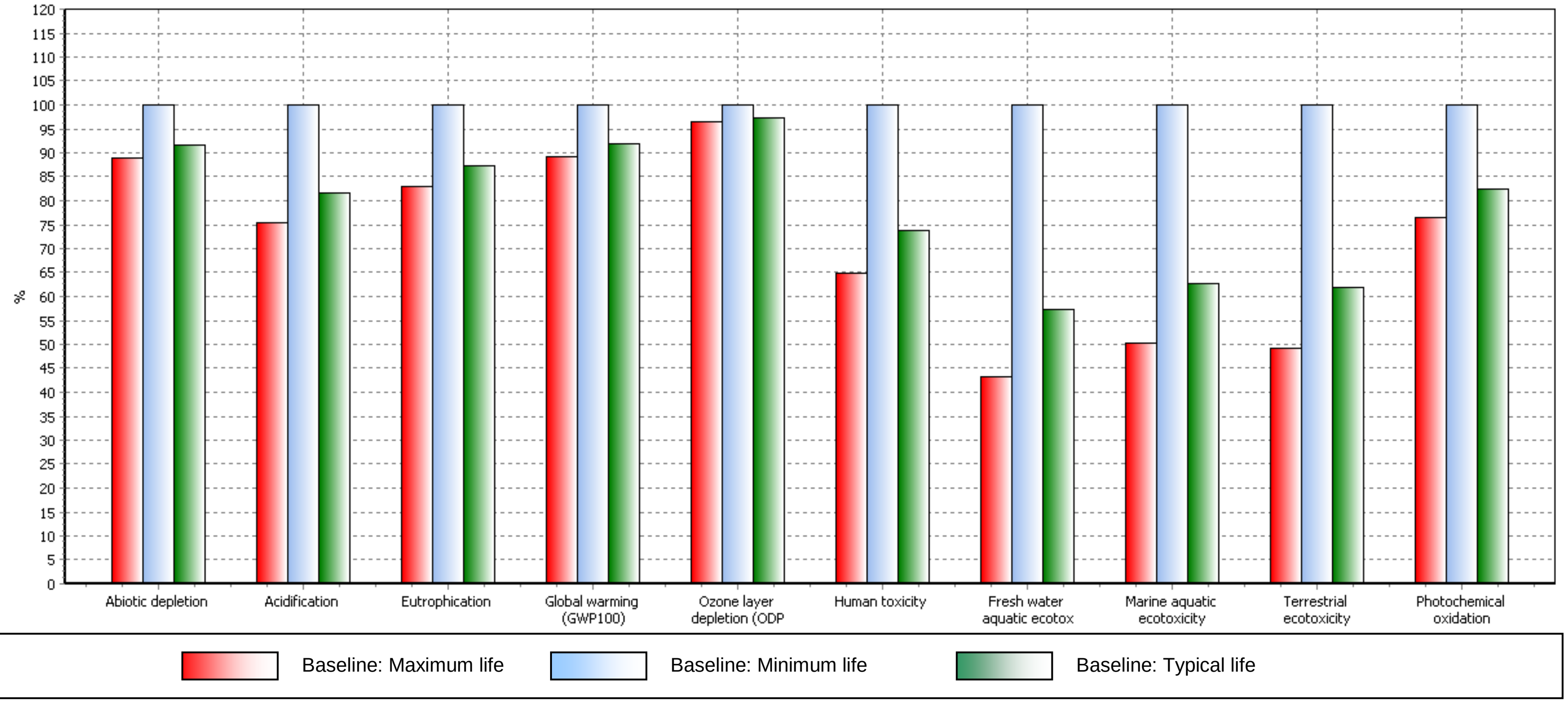
6.1 Impact of Assumed Lamp Lifetime

The sensitivity analysis has assessed the potential implications of both extended and reduced lifetime of ± 50% for each lamp type. The results are presented for the baseline scenario of 9% recycling for a CFLi lamp over 100,000 hours operation in Figure 21.

The results clearly indicate that significant benefits arise from extended product life, particularly in relation to human toxicity and ecotoxicity impact indicators. These benefits primarily arise due to the reduced requirements for manufacturing the product, as well as reduced waste disposal requirements. As would be expected, the opposite is true for reduced lifetime.

It should be noted that this is a theoretical sensitivity analysis and it does not account for the changes in lamp design or technical feasibility. Lamp manufacturers have indicated (Philips, 2009) that increased life requires increased mercury levels in the lamp. However, when considering the impacts of human toxicity and ecotoxicity the benefits of increased lifetime is likely to outweigh the impacts associated with increased mercury levels.

Figure 21 Life Cycle Impacts – Whole life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation) – ± 50% Lifetime



6.2 Impacts of Lamp Warm-Up and Impacts of Improved Energy Efficiency in the Use Phase

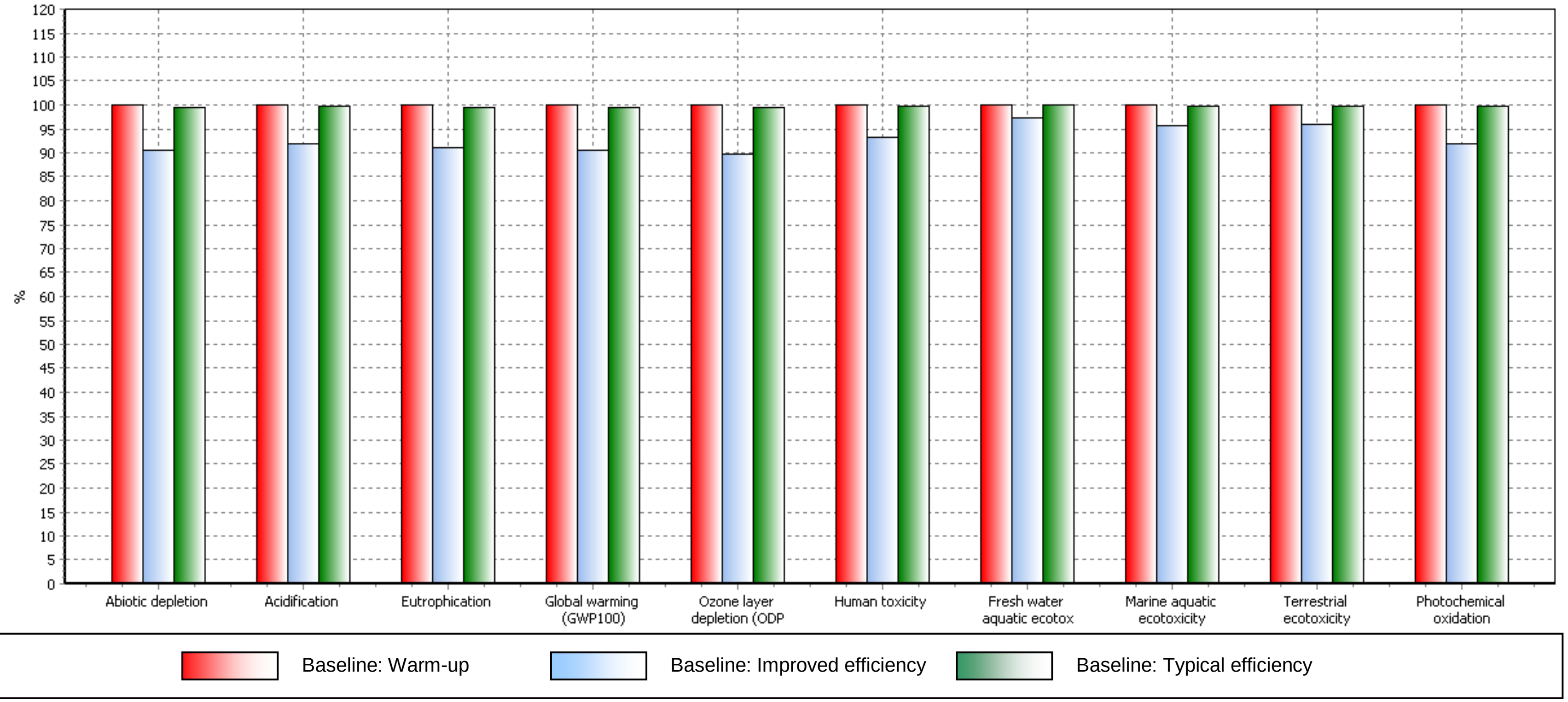
This sensitivity has assessed, individually, the consequence of reduced energy efficiency from potential warm-up effects, and a 10% increase in the use phase energy efficiency. The results are presented for the baseline scenario of 9% recycling for a CFLi lamp over 100,000 hours operation in Figure 22.

In relation to warm-up effect these are negligible across all impact indicators for the results presented. The impacts increase, marginally, due to the higher energy demand in the use phase.

Due to the significance of the use phase, for all lamp types, the efficiency change is reflected directly in the impact reductions witnessed. This is especially the case for abiotic resource depletion, acidification, eutrophication, global warming potential and human toxicity, where a 10% improvement in energy efficiency results in a nearly matched improvement for these indicators (of around 8% to 9%). Similarly, other impacts indicators reduce but to a slightly lesser extent (of around 2% to 4%).

It should be noted increased energy efficiency is a theoretical sensitivity analysis and it does not account for the changes in lamp design or technical feasibility.

Figure 22 Life Cycle Impacts – Whole life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation) – +0.5% increase in energy usage from lamp warm-up and improved energy efficiency in the use phase – +10% efficiency



6.3 Impacts of Closed-Loop Recycling

Whole Life Results: Closed-Loop Recycling

Closed loop[3] recycling has been appraised and includes the recycling process requirements, reduced virgin material requirement in lamp manufacture, and the additional oceanic transport of material and container back to place of manufacture.

The sensitivity compares the benefits of recycling and recovery of materials in a closed manner, versus material recycling and second use in Australia via open-loop[4] recycling.

The results shown in Figure 23 indicate that there is no significant environmental benefit of closed-loop recycling compared to open-loop. This is due to the recovered materials displacing the same quantities of virgin material in both open-loop and closed-loop recycling. A difference arises due to the additional oceanic transport, for closed-loop recycling, back to the original place of manufacture.

End-of-Life Results: Closed-Loop Recycling

The results for end-of-life only shown in Figure 24 indicate that closed loop recycling provides less benefit across all environmental impact indicators, although the results are not significantly different. Closed-loop recycling results in greater impacts due to the additional oceanic transport to return materials back to the original place of manufacture, versus Melbourne, Australia, for the open-loop recycling.

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[3] Closed-loop recycling can be generally defined as a recycling system in which a particular mass of material (possibly after upgrading) is remanufactured into the same product (e.g., aluminium from lamps returned back into use for aluminium into lamps).

[4] Open-loop recycling can be generally defined recycling system in which a product made from one type of material is recycled into a different product.

Figure 23 Life Cycle Impacts – Whole life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation) – Closed Loop Recycling

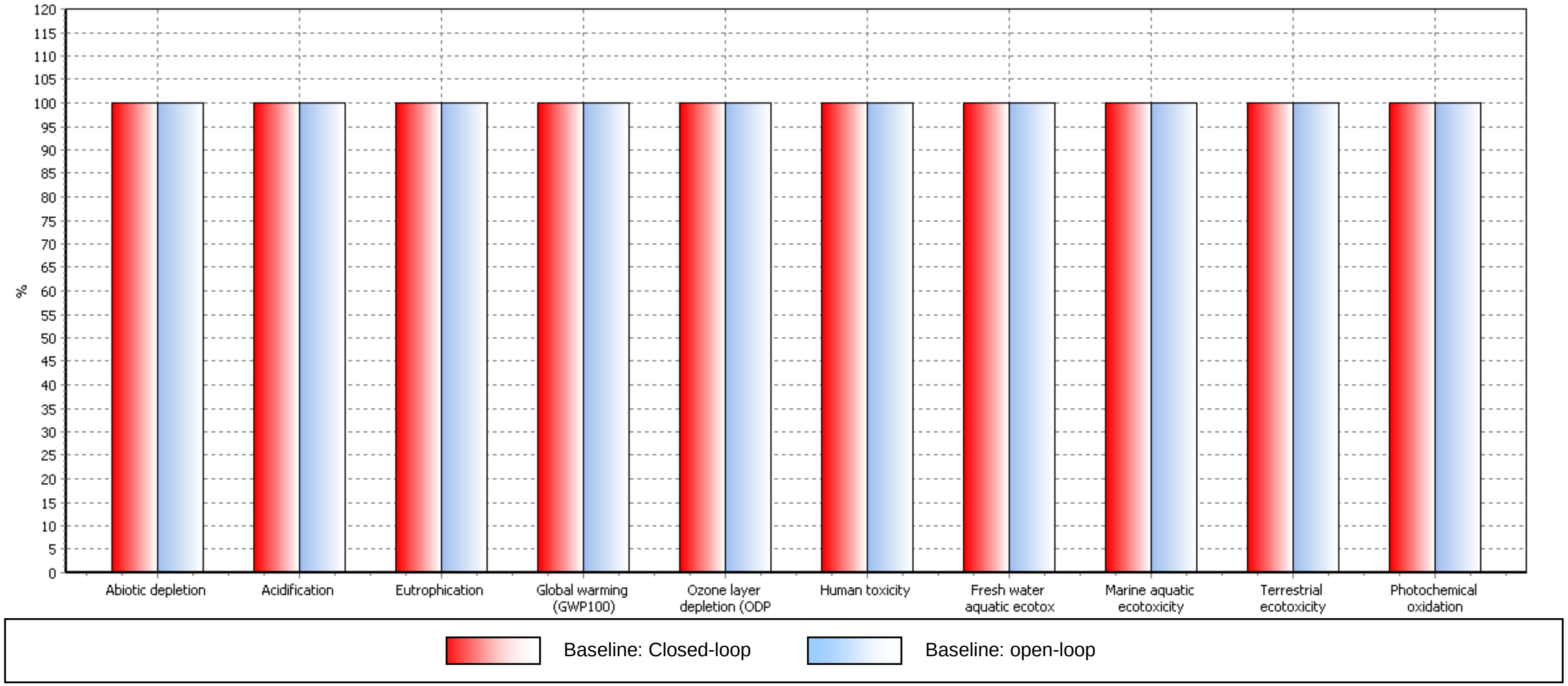
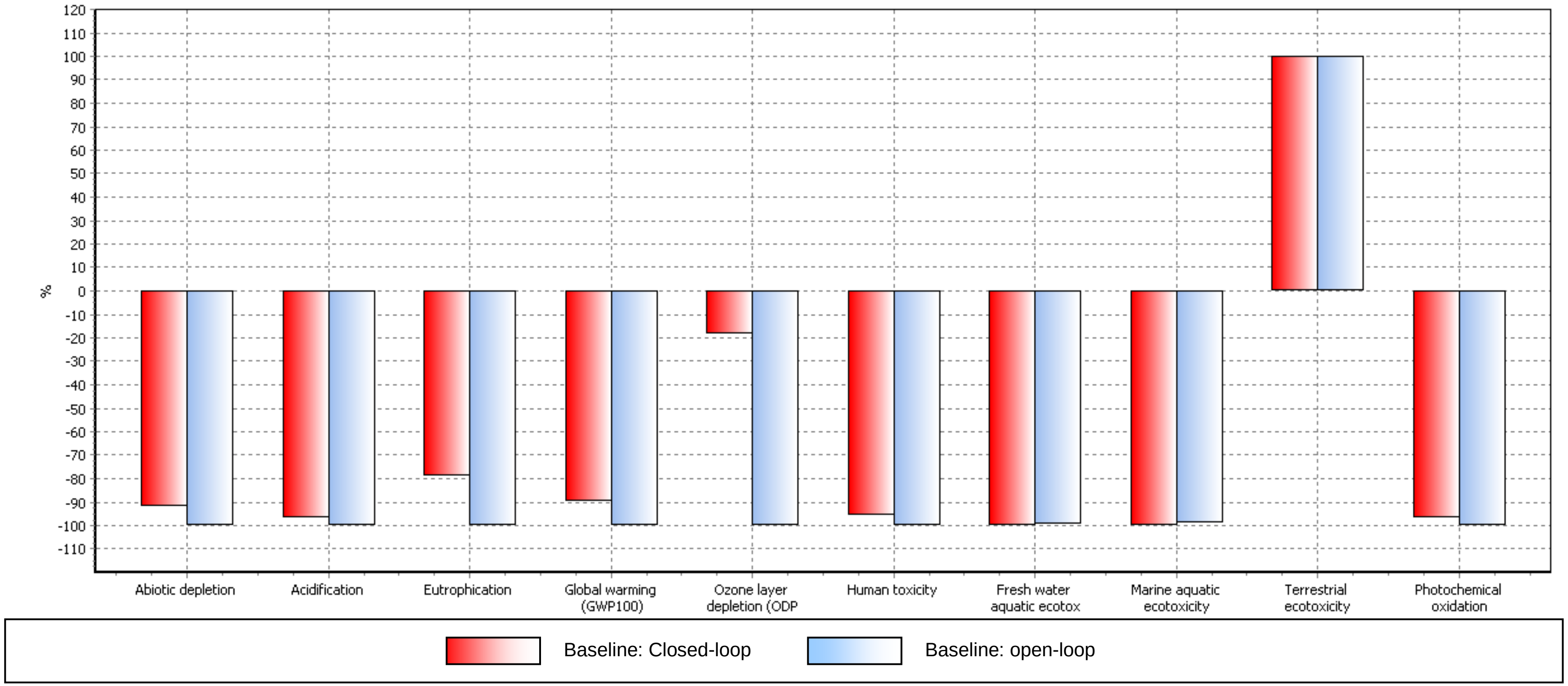


Figure 24 Life Cycle Impacts – End-of-Life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation) – Closed Loop Recycling



6.4 Impacts of Not Attributing Offset Benefits to Avoided Materials from Lamp Recycling and Recovery

Whole Life Results: Not Attributing Offset Benefits to Avoided Materials

The assumption that recovered materials will displace primary/virgin material production, on a weight for weight basis, is subject to some uncertainty.

As an extreme, the consequence of not expanding the system boundary and attributing an offset benefit to avoided primary material production is considered in this sensitivity analysis.

The results indicate, as shown in Figure 25, that the recycling route (without virgin material displacement), does not result in environmental benefit when compared to conventional disposal, with the exception of the terrestrial ecotoxicity impact categories.

The results indicate that the benefits of increased recycling and recovery are primarily driven by the benefits derived from avoided material production and of the reduced emissions resulting from avoided waste production.

End-of-Life Results: Not Attributing Offset Benefits to Avoided Materials

When considering the end-of-life impacts only of not including the benefits of virgin material displacement the results indicate, as shown in Figure 26, that decreased levels of recycling significantly improve environmental performance. This is primarily due to the reduced impacts associated with disposal phase.

Figure 25 Life Cycle Impacts – Whole life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation) – No Benefit Attributed to Avoided Products

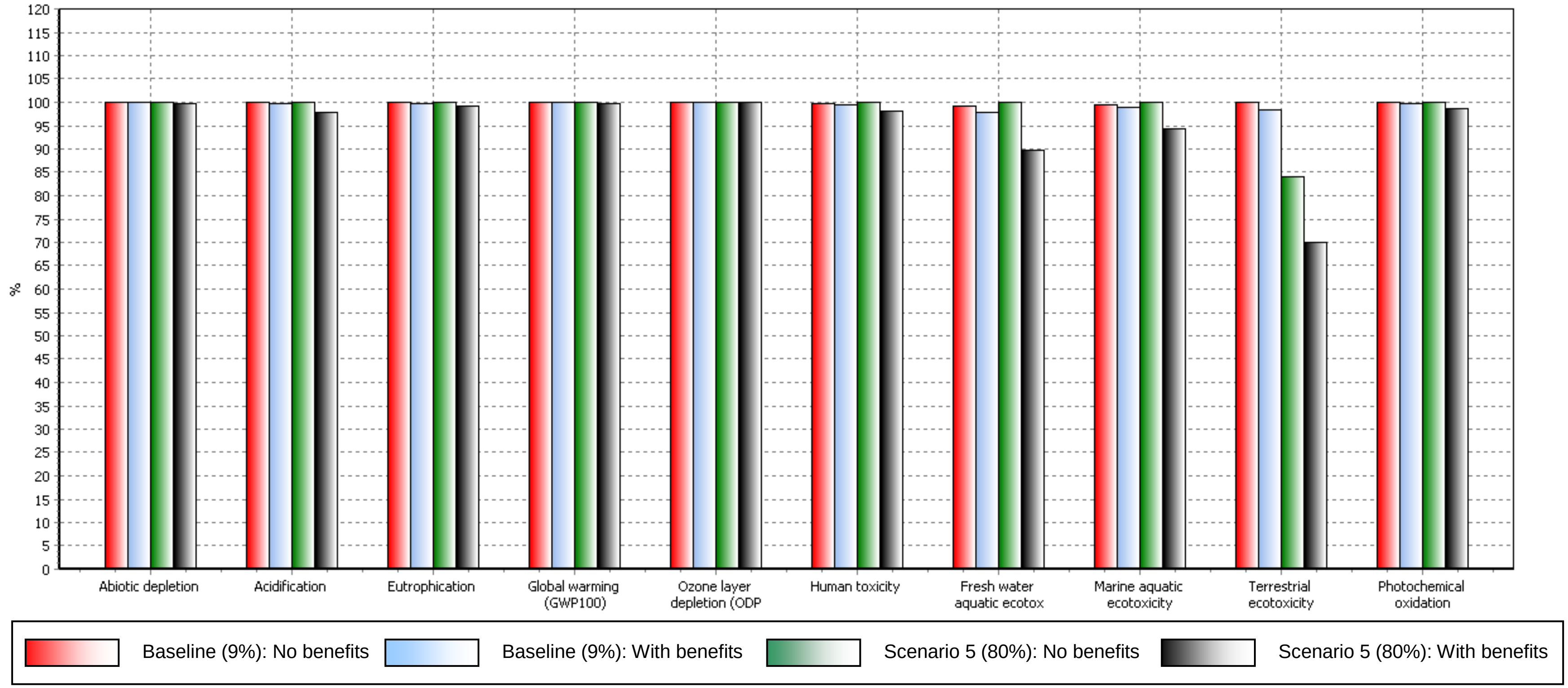
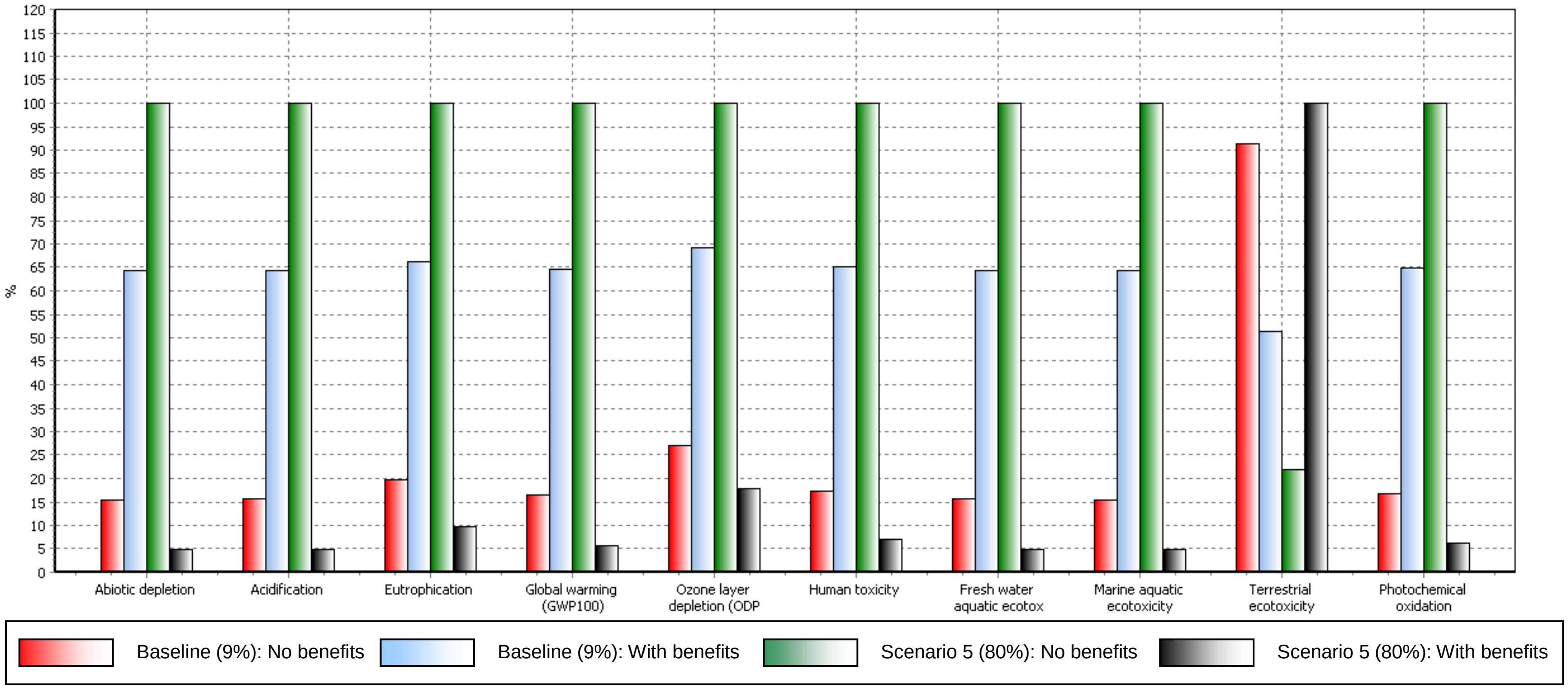


Figure 26 Life Cycle Impacts – End-of-Life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation) – No Benefit Attributed to Avoided Products

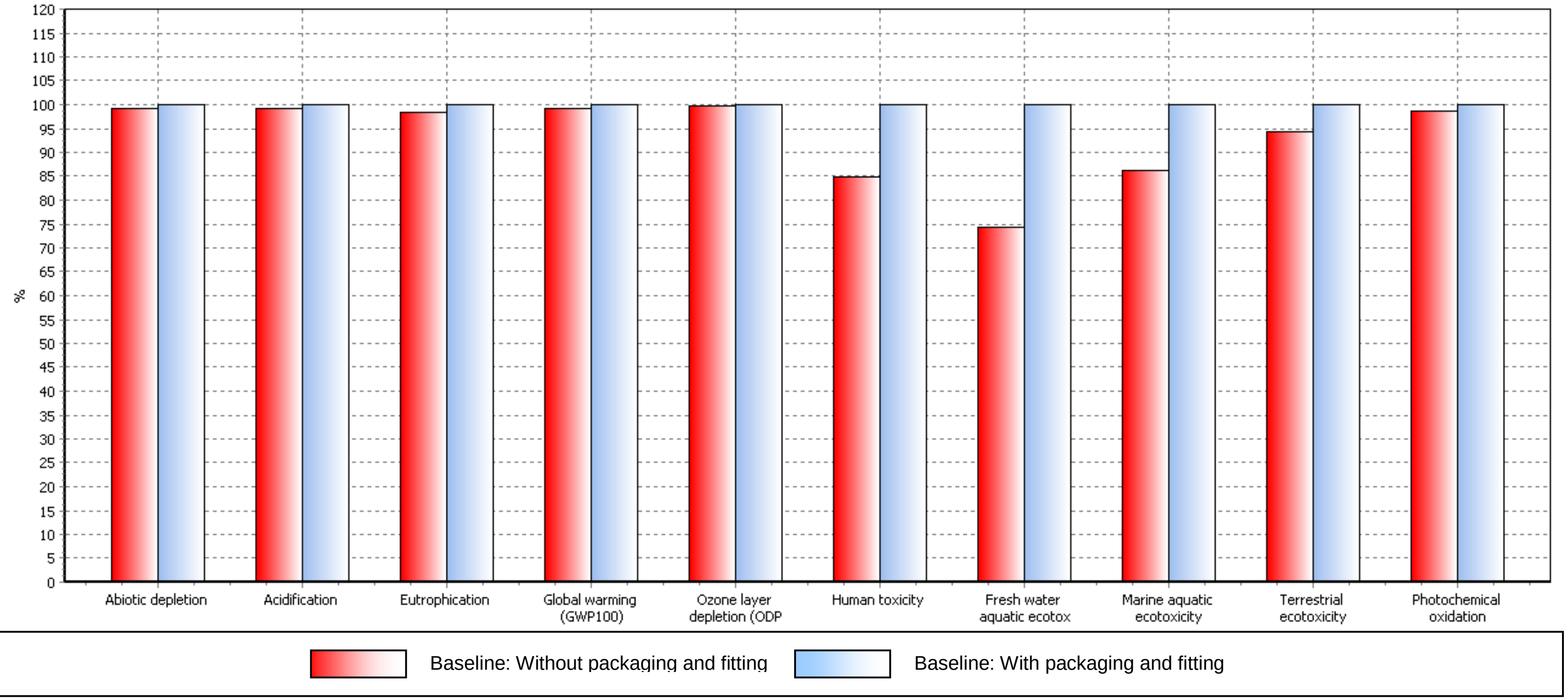


6.5 Potential Impacts of Packaging and Fitting

To test the original decision to exclude packaging and fittings, an estimate of their contribution has been made, based on secondary inventory data and estimates of weights.

The results of this sensitivity indicate, as shown in Figure 27, with the exception of human toxicity and fresh and marine water ecotoxicity, that the exclusion of these elements is insignificant. The increased impacts for these indicators are linked to the emissions associated with the production of the raw materials, in particular aluminium, used to fabricate the fittings. Packaging has a negligible effect. Refer to Appendix D for further details. A similar conclusion can be drawn for other lamp types. However, the inclusion of packaging and fittings would not change the conclusions of this study, only the relative magnitude of the contributing elements to the toxicity impact categories.

Figure 27 Life Cycle Impacts – Whole life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation) – Impacts of Packaging and Fittings



6.6 Summary of Interpretation

Section 6 contains the interpretation and sensitivity analysis which considers lamp performance and addresses key assumptions within the study. The following analyses were assessed:

- impact of assumed lifetime of the lamps – ± 50% lifetime;
- impacts of assumed power rating of the lamps, accounting for potential increases in energy usage from lamp start-up – +0.5%;
- impacts of improved energy efficiency in the use phase – +10% efficiency;
- impacts of closed loop recycling;
- impacts of attributing offset benefits to avoided materials from lamp recycling operations;
- potential impacts of packaging and fittings.

No significant cut-off criteria have been applied to the study and are therefore not tested in the sensitivity analysis.

The results indicate that lamp performance parameters, such as lamp lifetime and energy efficiency, have a significant effect on the environmental performance across all lamp types. An increase in lamp lifetime reduces production burdens and waste management and results in significant benefits. Similarly, a reduction in energy consumption through higher lamp efficiency would reduce the use phase burdens significantly.

The results indicate that the benefits of increased recycling and recovery are primarily driven by the benefits derived from avoided material production and of the reduced emissions resulting from avoided waste production. If zero benefit is attributed to avoided virgin materials then recycling does not result in an environmental benefit when compared to conventional disposal, with the exception of the terrestrial and fresh and marine water ecotoxicity impact categories.

An estimate has been made for the exclusion of packaging and fittings, which shows that this decision has a small effect on the overall results, with the exception of human toxicity and fresh and marine water ecotoxicity. The increased impacts for these indicators are linked to the emissions associated with the production of the raw materials, in particular aluminium, used to fabricate the fittings. Packaging has a negligible effect. A similar conclusion can be drawn for other lamp types. The inclusion of packaging and fittings would not change the conclusions of this study.

7 Conclusions and Recommendations

The results for the study provide a robust estimate of the scale and significance of alternate product stewardship mechanisms for the environmental profiles of the following mercury-containing lamp products:

- Fluorescent:
    7. Linear fluorescent lamp (LFL);
    8. Compact fluorescent lamp: external ballast (CFLe); and
    9. Compact fluorescent lamp: integral ballast (CFLi).
- High Intensity Discharge (HID):
    10. High pressure sodium (HPS);
    11. Metal Halide (MH); and
    12. Mercury Vapour (MV).

The lamps listed above represent the mainstream types used in New Zealand for residential, commercial and industrial applications and have been assessed for an operational period of 100,000 hours. It should be noted that results cannot be compared across lamp types, as they are not functionally equivalent, due to differences in lamp output and application.

The primary focus of the study has been to assess the whole-life environmental impacts from the use of mercury-containing lamps, and the trade-offs that arise from potential product stewardship options for end-of-life management (by increasing recovery and recycling rates) and for lamp design (by reducing the lamps mercury content). Through interpretation and sensitivity analysis, implications in relation to mercury content, lamp lifetime and in use efficiency improvements have also been investigated.

The results show the environmental implications for increased recovery and recycling, for the following scenarios:

- Baseline: 9% recovery and recycling;
- Scenario 1: 50% recovery and recycling of end-of-life lamps;
- Scenario 2: 80% recovery and recycling of end-of-life lamps; and
- Scenario 3: 100% disposal (to landfill) of end-of-life lamps.

Additional sensitivity analyses, have also considered the potential impact of lamp warm-up power, closed-loop recycling, inclusion of fixture and fitting and packaging.

7.1 Whole Life Conclusions

When considering the whole-life environmental impacts, the results indicate that the use phase dominates the impacts across all impact categories, accounting for more than 90% of the total life cycle. The manufacturing phase represents around 5% of total impacts and the disposal phase represents around 1% of total impacts across the total life cycle.

The results demonstrate that an environmental benefit is achieved from increasing the recovery and recycling rates for mercury-containing lamps. However, in the context of the whole life cycle, the environmental benefits are small.

Table 16 Life Cycle Impact Results – Whole Life – (100,000 hours operation)

	Unit	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W
Abiotic depletion	kg Sb eq	6.73	2.14	4.03	27.58	73.39	45.90
Acidification	kg SO_2 eq	3.41	1.14	2.21	13.04	34.51	21.64
Eutrophication	kg PO_4 eq	0.25	0.08	0.15	0.98	2.59	1.62
Global warming	kg CO_2 eq	874	278	517	3,553	9,450	5,912
Ozone layer depletion	kg CFC-11 eq	0.00	0.00	0.00	0.00	0.00	0.00
Human toxicity	kg 1,4-DB eq	88	29	69	349	904	561
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	6.82	3.05	7.53	16.42	41.23	26.23
Marine aquatic ecotoxicity	kg 1,4-DB eq	18,332	6,924	15,821	51,675	132,550	83,883
Terrestrial ecotoxicity	kg 1,4-DB eq	0.76	0.35	0.62	3.40	6.89	4.92
Photochemical oxidation	kg C_2H_4	0.28	0.09	0.19	1.11	2.96	1.85

Note: a negative number represents an environmental benefit.

7.1.1 Mercury Contribution

In terms of mercury contribution to human toxicity impacts, the results indicate that mercury contributes a low level of total impacts. Primarily, the contributions to human toxicity arise from generation of electricity in the use phase, resulting from combustion of gas and coal which release PAH and NMVOC to air. The use phase contributes around 85% to 95% of the total life cycle impact. This is the same across all lamp types, with the slight exception for the integrated CFL where the use phase contributes around 65% of whole life impact, due to the increased manufacturing burden associated with additional electronics.

Increasing the level of recovery and recycling of lamps reduces the levels of mercury released to the environment. A reduction in the human toxicity impact, in the order of 1.5% is observed when increasing from 9% to 80% recycling and recovery.

7.1.2 Lamp Performance

When considering other lamp performance parameters, such as lamp lifetime and energy efficiency, then significant environmental benefit can be achieved by longer lifetimes and higher efficiencies. An increase in lamp lifetime reduces production burdens and waste management and results in significant benefits. Similarly, reduction in energy consumption higher lamp efficiency reduces the use phase burdens significantly.

7.2 End-of-Life Conclusions

When considering the end-of-life phase only, the results indicate that increasing recovery and recycling levels of lamps from 9%, in the baseline, up to 80%, then the environmental benefits for the end-of-life phase increase significantly. The benefits arise primarily from the benefit associated with avoiding the production of new materials that would have otherwise taken place if the lamps were not recycled in other materials. Recycling of metals and glass offer the most significant benefits, primarily due to the proportionally larger mass of the lamp. Table 17 shows the results for a CFLi lamp with varying recycling and recovery rates.

Table 17 Life Cycle Impact Results – End-of-Life Only – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Abiotic depletion	kg Sb eq	0.000	-0.001	-0.001	0.000
Acidification	kg SO_2 eq	-0.001	-0.005	-0.005	-0.002
Eutrophication	kg PO_4 eq	0.000	0.000	0.000	0.000
Global warming	kg CO_2 eq	-0.009	-0.051	-0.075	-0.029
Ozone layer depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	-0.143	-0.106	-0.111	-1.132
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	-0.005	-0.071	-0.076	-0.007
Marine aquatic ecotoxicity	kg 1,4-DB eq	-12.89	-80.69	-86.97	-48.49
Terrestrial ecotoxicity	kg 1,4-DB eq	0.147	0.061	0.122	0.933
Photochemical oxidation	kg C_2H_4	0.000	0.000	0.000	0.000

Note: a negative number represents an environmental benefit.

The benefits from closed-loop recycling are negligible as the only real differences arise due to the additional oceanic transport, for closed-loop recycling, back to the original place of manufacture. The benefits associated with avoided virgin materials are almost equal for both open-loop and closed-loop recycling.

7.2.1 Mercury Contribution

In terms of mercury contribution to human toxicity impacts, the results indicate that mercury release from landfill contributes a significant proportion of the end-of-life impacts (ranging from around 25% to 90%). Increasing the levels of recycling considerably reduces the impacts from mercury at end-of-life.

For end-of-life product stewardship options, overall, it can be concluded from the results that increasing the levels of recovery and recycling of mercury-containing lamps will provide significant benefits to the environment.

7.2.2 Lamp Performance

When considering other lamp performance parameters, such as lamp lifetime and mercury level in the lamps design, then significant environmental benefit can be achieved by longer lifetimes and reduced mercury-content for end-of-life. An increase in lamp lifetime reduces burdens of waste management and results in significant benefits. Similarly, a reduction in mercury level reduces the human toxicity impacts associated with emission of mercury from landfill disposal.

7.3 Recommendations

The recommendations section outlines the areas where improvements could be made to the life cycle assessment study that has been conducted. For this study, the following improvements in relation to data could be made:

- Further clarification of potential future improvements that will increase lamp lifetime and the associated design changes. Currently, the study makes a theoretical assumption of ± 50% of total lifetime.
- Further clarification of potential future improvements for improved energy efficiency of the lamps and the associated design changes. Currently, the study makes a theoretical assumption of ± 10% improved efficiency.
- Improved life cycle inventory data for the production of raw materials. The study uses modified datasets (electricity and transport) to represent geographic locations of manufacture. Country specific datasets would improve the results.
- Further confirmation that recovered materials from the recycling process deliver the associated benefits of avoiding the virgin material production.

Whilst this would improve the robustness of the study, the additional data are unlikely to change the results in a material way.

Appendix A: Impact Category Descriptions

A.1 Impact Category Descriptions

The following impact categories, as used by CML2.7 (2007) method, are described below (SimaPro, 2007):

- depletion of resources;
- global warming;
- stratospheric ozone depletion;
- human toxicity;
- freshwater aquatic ecotoxicity;
- marine ecotoxicity;
- terrestrial ecotoxicity;
- photo-oxidant formation;
- acidification; and
- eutrophication.

A.2 Impact Categories

- Depletion of resources. This impact category is concerned with protection of human welfare, human health and ecosystem health. This impact category indictor is related to extraction of minerals and fossil fuels due to inputs into the system. The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on concentration reserves and rate of de-accumulation. The geographic scope of this indicator is at a global scale.

- Global warming can result in adverse affects upon ecosystem health, human health and material welfare. Climate change is related to emissions of greenhouse gases to air. The characterisation model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for development of characterisation factors. Factors are expressed as Global Warming Potential for time horizon 100 years (GWP100), in kg carbon dioxide/kg emission. The geographic scope of this indicator is at global scale.

- Stratospheric ozone depletion. Because of stratospheric ozone depletion, a larger fraction of UV-B radiation reaches the earth surface. This can have harmful effects upon human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and on materials. This category is output-related and at global scale. The characterisation model is developed by the World Meteorological Organisation

(WMO) and defines ozone depletion potential of different gasses (kg CFC-11 equivalent/ kg emission). The geographic scope of this indicator is at global scale. The time span is infinite.

- Human toxicity. This category concerns effects of toxic substances on the human environment. Health risks of exposure in the working environment are not included. Characterisation factors, Human Toxicity Potentials (HTP), are calculated with USES-LCA, describing fate, exposure and effects of toxic substances for an infinite time horizon. For each toxic substance HTP's are expressed as 1.4-dichlorobenzene equivalents/ kg emission. The geographic scope of this indicator determines on the fate of a substance and can vary between local and global scale.

- Freshwater aquatic ecotoxicity. This category indicator refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil. Ecotoxicity Potential (FAETP) are calculated with USES-LCA, describing fate, exposure and effects of toxic substances. The time horizon is infinite. Characterisation factors are expressed as 1,4-dichlorobenzene equivalents/kg emission. The indicator applies at global/continental/ regional and local scale.

- Marine ecotoxicity refers to impacts of toxic substances on marine ecosystems (see description freshwater toxicity).

- Terrestrial ecotoxicity. This category refers to impacts of toxic substances on terrestrial ecosystems (see description freshwater toxicity).

- Photo-oxidant formation is the formation of reactive substances (mainly ozone) which are injurious to human health and ecosystems and which also may damage crops. This problem is also indicated with "summer smog". Winter smog is outside the scope of this category. Photochemical Ozone Creation Potential (POCP) for emission of substances to air is calculated with the UNECE Trajectory model (including fate), and expressed in kg ethylene equivalents/kg emission. The time span is 5 days and the geographical scale varies between local and continental scale.

- Acidification. Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings). Acidification Potentials (AP) for emissions to air are calculated with the adapted RAINS 10 model, describing the fate and deposition of acidifying substances. AP is expressed as kg SO2 equivalents/ kg emission. The time span is eternity and the geographical scale varies between local scale and continental scale.

- Eutrophication (also known as nutrification) includes all impacts due to excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water and soil. Nutrification potential (NP) is based on the stoichiometric procedure of Heijungs (1992), and expressed as kg PO4 equivalents/ kg emission. Fate and exposure is not included, time span is eternity, and the geographical scale varies between local and continental scale.

A.2 Adaptations to CML 2.7 Impact Method

Please note the following adaptions made by ERM to the CML 2.7 method;

- VOC characterisation factor has been included. NMVOC & VOC are considered the same characterisation factor and included in GWP, human tox, fresh water tox, marine tox, terrestrial exotox and photochemical oxidation. Characterisation factors developed from speciation shown in "UK emissions of air pollutants 1970 - 2005" by UK emissions inventory team, Nov 2007, pg 67, table 2.13. Speciations were modelled and analysed using CML2001 method. This is based upon method suggested by leiden university. www.airquality.co.uk/archive/reports/cat07/0801140937_2005_Report_FINAL.pdf and www.leidenuniv.nl/cml/ssp/databases/cmlia/index.html

- Nitrogen oxides have been duplicated (by different naming convention) in CML 2.7 as they can be characterised under a number of different substances. All NOx is now characterised and added to Eutrophication and Photochemical oxidation categories.

- The characterisation factors for biogenic CO_2 emissions and carbon dioxide removals from air are set to zero.

- Carbon dioxide for land transformation and carbon in organic matter and in soil were considered to be removed as probably biogenic but left in for now as further research needed into this. See paragraph below copied from methodology report.

  A new elementary flow is introduced to account for the CO_2 emissions due to land transformation, in particular due to clear cutting of primary forests. Carbon losses from soil and carbon dioxide released by burning wood residues from clear-cutting are classified as "Carbon dioxide, land transformation".

  In line with the IPCC accounting rules, this elementary flow is treated like fossil CO2 emissions in life cycle impact assessment methods (see Jungbluth et al. 2007).

  Additionally, the elementary flow (resource) "Carbon, in organic matter, in soil" is introduced. It balances the carbon dioxide emissions caused by soil degradation.

Appendix B: Inventory Data

B.1 Lamp Composition

Table B1a provides a breakdown of the compositions used for each lamp type assessed in the study. These are based on data from the Stewardship Solution (2007) report for generic materials (glass, electronics, plastics, metals and other) and from material safety data sheets (MSDS) for hazardous materials (Philips 2001, 2002 and 2005 and Sylvania 2009). Compositions are for those lamps which represent the mainstream types used in New Zealand for residential, commercial and industrial applications.

Table B1a Lamp Composition Data

Component / Material	Unit	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W
Total Mass	g	120.0	55.0	120.0	150.0	240.0	166.5
Glass	g	115.0	40.0	65.0	105.0	195.0	129.5
Electronics	g	-	-	25.0	-	-	1.1
Plastics	g	-	10.0	25.0	-	-	-
Metals Total	g	3.0	3.0	4.0	44.5	42.0	8.5
*Other Total	g	2.0	2.0	1.0	-	3.0	27.3
Nuisance Dust	g	3.0	-	-	-	-	-
Cerium Terbium Magnesium Aluminate	mg	300	-	-	-	-	-
Barium Magnesium Aluminate	mg	600	-	-	-	-	-
Yttrium Oxide (1314-36-9)	mg	600	-	-	-	-	-
Antimony (7440-36-0)	mg	12	-	-	-	-	-
Manganese (7439-96-5)	mg	24	-	-	-	-	-
Mercury (7439-97-6)	mg	4	5	5	50	50	50
Iodine (7553-56-2)	mg	-	-	-	-	48	-
Sodium (7440-23-5)	mg	-	-	-	15	48	-

Sodium Iodide (7681-82-5)	mg	-	-	-	-	48	-
Yttrium Vanadate (7440-65-5)	mg	-	-	-	-	1.4	4.2
Vanadium (1314-62-1)	mg	-	-	-	-	-	1.7
Yttrium (7440-65-6)	mg	-	-	-	-	-	1.2
Lead (7439-92-1)	mg	-	-	-	-	-	8.3
Phosphor powder	mg	-	1.1	2.4	-	-	-

Source: Philips (2001, 2002 and 2005), Stewardship Solutions (2008), Sylvania (2009).

*Note: 'Materials Other' includes all those materials listed below that line which are shown in the table.

B.2 Raw Materials Production

Table B2a, B2b and B2c show the inventory datasets and assumptions used to represent raw material production. Datasets are primarily sourced from Ecoinvent 2.0 (2007), which represents European datasets. In some cases, where representative datasets were not available, estimates have been made using surrogate datasets. For some materials, the quantities of individual components have been estimated stoichiometrically based on the chemical formula. All datasets have been adjusted to account for the electricity generation mix associated with their country of manufacture. Additionally, for the main materials (glass, electronics, plastics and metals) the transport has been adjusted to reflect geographic conditions.

Table B2a Raw Materials Inventory Data

Material	Assumptions	Inventory Dataset
Glass	Glass used in lamp construction is assumed to be flat coated glass, represented by an Ecoinvent (2007) dataset.	• Flat glass, coated, at plant/RER SNI
Electronics	See Table B2b for breakdown of electronics materials and inventory datasets used.	
Plastics	All plastics used in lamp construction are assumed to be polyurethane, represented by an Ecoinvent (2007) dataset.	• Polyurethane, rigid foam, at plant/RER SNI
Metals	See table B2c for metal composition of lamp end caps and inventory datasets used.	
Others	All materials not identified in lamp construction are assumed to be HDPE, represented by an Ecoinvent (2007) dataset.	• Polyethylene, HDPE, granulate, at plant/RER SNI

Cerium Terbium Magnesium Aluminate	Cerium Terbium Magnesium Aluminate, (Ce,Tb)MgAl11O19:Ce,Tb, has been estimated stoichiometrically on the following basis: • 3% Mg • 32% Al • 15% Ce • 33% O • 17% Tb A data set for phosphate rock is assumed to represent cerium production, and uranium is assumed to represent terbium production. Magnesium, aluminium and oxygen have used representative datasets from Ecoinvent 2.0 (2007).	• Magnesium, at plant/RER SNI • Aluminium - Aluminium, primary, at plant/RER SNI • Cerium - Phosphate rock, as P2O5, beneficiated, dry, at plant/MA SNI • Oxygen - Oxygen, liquid, at plant/RER SNI • Terbium - Uranium natural, in uranium hexafluoride, at conversion plant/CN SNI
Barium Magnesium Aluminate	Barium Magnesium Aluminate, Al2Ba2Mg2O7, has been estimated stoichiometrically on the following basis: • 56% Ba • 10% Mg • 11% Al • 23% O A dataset for magnesium has been assumed to represent barium production. Magnesium, aluminium and oxygen have used representative datasets from Ecoinvent 2.0 (2007).	• Barium - Magnesium, at plant/RER SNI • Magnesium - Magnesium, at plant/RER SNI • Aluminium - Aluminium, primary, at plant/RER SNI • Oxygen - Oxygen, liquid, at plant/RER SNI
Cerium Magnesium Aluminate (67542-72-7)	Cerium Magnesium Aluminate, (Ce)MgAl11O19:Ce), has been estimated stoichiometrically on the following basis: • 3% Mg • 39% Al • 18% Ce • 40% O A dataset for phosphate rock is assumed to represent cerium production. Magnesium, aluminium and oxygen are represented by Ecoinvent (2007) datasets.	• Magnesium - Magnesium, at plant/RER SNI • Aluminium - Aluminium, primary, at plant/RER SNI • Cerium - Phosphate rock, as P2O5, beneficiated, dry, at plant/MA SNI • Oxygen - Oxygen, liquid, at plant/RER SNI
Yttrium Oxide (1314-36-9)	Yttrium oxide (Y_2O_3), has been estimated stoichiometrically on the following basis: • 79% Y • 21% O A dataset for phosphate rock is assumed to represent yttrium production. Oxygen is represented by an Ecoinvent (2007) dataset. Material weight represents up to 0.5% of total lamp.	• Yttrium - Phosphate rock, as P2O5, beneficiated, dry, at plant/MA SNI • Oxygen - Oxygen, liquid, at plant/RER SNI
Antimony (7440-36-0)	No dataset available for antimony. Material weight represents up to 0.01% of total lamp. This quantity is considered to be negligible therefore raw material production data has been omitted.	• No dataset available.

Manganese (7439-96-5)	Manganese is represented by an Ecoinvent (2007) dataset.	• Manganese, at regional storage/RER SNI
Mercury (7439-97-6)	Mercury is represented by the following datasets: • Primary mined uses an Ecoinvent (2007) dataset; • Recovered from vinyl chloride monomer facilities uses an Ecoinvent (2007) dataset; • Recovered from chlor-alkali facilities uses an Ecoinvent (2007) dataset; • Recycled via vacuum distillation process uses a datasets for battery recycling from ERM (2006); and • Recycled via pyrometallurgical process uses a datasets for battery recycling from ERM (2006).	• Mercury, liquid, at plant/GLO SNI
Iodine (7553-56-2)	A dataset for sodium sulphate is assumed to represent iodide production. Material weight represents up to 0.02% of total lamp.	• Sodium sulphate, from natural sources, at plant/RER SNI
Sodium (7440-23-5)	Sodium is assumed to be 100% sodium chloride represented by an Ecoinvent (2007) dataset.	• Sodium chloride, powder, at plant/RER SNI
Sodium Iodide (7681-82-5)	Sodium iodide (NaI) has been estimated stoichiometrically on the following basis: • 15.3% Na • 84.7% I A dataset for sodium sulphate is assumed to represent iodide production. A dataset for sodium chloride has been assumed to represent sodium production, represented by an Ecoinvent (2007) dataset.	• Sodium - Sodium chloride, powder, at plant/RER SNI • Iodide – Sodium sulphate, from natural sources, at plant/RER SNI
Yttrium Vanadate (7440-65-5)	Yttrium Vanadate (YVO_4) has been estimated stoichiometrically on the following basis: • 44% Y • 25% V • 31% O A dataset for phosphate rock is assumed to represent yttrium production. Vanadium is represented by a dataset from IDEMAT (2001) and oxygen using a dataset from Ecoinvent 2.0 (2007).	• Yttrium - Phosphate rock, as P2O5, beneficiated, dry, at plant/MA SNI • Vanadium - Vanadium I (IDEMAT, 2001) • Oxygen - Oxygen, liquid, at plant/RER SNI
Vanadium (1314-62-1)	Vanadium used in lamp construction is represented by a dataset from IDEMAT (2001).	• Vanadium I (IDEMAT, 2001)
Yttrium (7440-65-6)	A dataset for phosphate rock is assumed to represent yttrium production. Material weight represents up to 0.7% of total lamp.	• Yttrium - Phosphate rock, as P2O5, beneficiated, dry, at plant/MA SNI

Lead (7439-92-1)	Lead used in lamp construction is assumed to be primary lead, represented by an Ecoinvent (2007) dataset.	• Lead, primary, at plant/GLO SNI
Phosphor Powder	Phosphor used in lamp construction is assumed to be white phosphor liquid, represented by an Ecoinvent (2007) dataset.	• Phosphorus, white, liquid, at plant/RER SNI
Hydrogen	Hydrogen used in lamp construction is assumed to be liquid hydrogen, represented by an Ecoinvent (2007) dataset.	• Hydrogen, liquid, at plant/RER SNI

Table B2b Electronics Inventory Data

Material	Assumptions	Estimated percentage of composition (%)	Inventory Dataset
Inductor	Inductors used in lamp construction assumed to be unspecified inductors, represented by an Ecoinvent (2007) dataset.	35	• Inductor, unspecified, at plant/GLO SNI
PCB	PCBs used in lamp construction assumed to be passive electronic component, represented by an Ecoinvent (2007) dataset.	12	• Electronic component, passive, unspecified, at plant/GLO S
Electrolytic capacitor	Electrolytic capacitors used in lamp construction are assumed to be electrolyte type capacitors, represented by an Ecoinvent (2007) dataset.	16	• Capacitor, electrolyte type, < 2cm height, at plant/GLO SNI
Filter inductor	Filter inductors used in lamp construction are assumed to be unspecified inductors, represented by an Ecoinvent (2007) dataset.	7	• Inductor, unspecified, at plant/GLO SNI
Capacitor	Capacitors used in lamp construction are assumed to be unspecified capacitors, represented by an Ecoinvent (2007) dataset.	12	• Capacitor, unspecified, at plant/GLO SNI
Coil	Coil used in lamp construction are assumed to be low-alloyed steel, represented by an Ecoinvent (2007) dataset.	5	• Steel, low-alloyed, at plant/RER S
Transistor	Transistors used in lamp construction are assumed to be unspecified transistors, represented by an Ecoinvent (2007) dataset.	5	• Transistor, unspecified, at plant/GLO SNI
Diode	Diodes used in lamp construction are assumed to be unspecified diodes, represented by an Ecoinvent (2007) dataset.	3	• Diode, unspecified, at plant/GLO SNI
R0 (resistor)	R0 resistors used in lamp construction are assumed to be unspecified resistors, represented by an Ecoinvent (2007) dataset.	1	• Resistor, unspecified at plant/GLO SNI

Mainscord	Mainscords used in lamp construction is assumed to be a ribbon cable, 20-pin, with plugs, represented by an Ecoinvent (2007) dataset.	3	• Cable, ribbon cable, 20-pin, with plugs, at plant/GLO SNI
Resistor	Resistors used in lamp construction are assumed to be unspecified resistors, represented by an Ecoinvent (2007) dataset.	2	• Resistor, unspecified at plant/GLO SNI

Source: Philips (2009)

Table B2c Metals Inventory Data

Material	Assumptions	Estimated percentage of composition (%)						Inventory Dataset
		1. LFL	2. CFLe	3. CFLi	4. HPS	5. MH	6. MV	
Nickel	Nickel used in lamp composition assumed to be nickel 99.5%, represented by an Ecoinvent (2007) dataset.		94	94				• Nickel, 99.5%, at plant/GLO SNI
Aluminium	Aluminium used in lamp composition assumed to be primary aluminium, represented by an Ecoinvent (2007) dataset.				94	94	94	• Aluminium, primary, at plant/RER SNI
Brass	Brass used in lamp composition assumed to be brass, represented by an Ecoinvent (2007) dataset.	94						• Brass, at plant/CH SNI
Solder	Solder used in lamp composition assumed to be solder paste for electronics industry, represented by an Ecoinvent (2007) dataset.	6	6	6	6	6	6	• Solder, paste, Sn63Pb37, for electronics industry, at plant/GLO SNI

Source: Sylvania (2009)

In cases where surrogate datasets were not available, the original ore containing the raw material in question has been identified. An inventory dataset for another raw material mined from the same ore has been used, as the manufacturing process is assumed to be similar for both raw materials (Table B2d).

Table B2d Ores Containing Raw Materials Used in Lamp Manufacture

Material	Assumptions	Inventory Dataset
Cerium	Cerium is extracted from monazite ore – Ce (Ce, La, Pr, Nd, Th, Y)PO4. This ore also contains the minerals Lanthanum , Praseodymium, Neodymium, thorium, yttrium and, phosphate. A dataset for phosphate rock is assumed to represent cerium production. This is represented by an Ecoinvent (2007) dataset.	• Cerium - Phosphate rock, as P2O5, beneficiated, dry, at plant/MA SNI

Ytrrium	Yttrium is extracted from monazite ore – Ce (Ce, La, Pr, Nd, Th, Y)PO4. This ore also contains the minerals lanthanum , praseodymium, neodymium, thorium, cerium and, phosphate. A dataset for phosphate rock is assumed to represent yttrium production. This is represented by an Ecoinvent (2007) dataset.	• Yttrium - Phosphate rock, as P2O5, beneficiated, dry, at plant/MA SNI
Terbium	Terbium is extracted from xenotime ore – $YAsO_4$ or YPO_4. This ore also contains the minerals uranium, gadolinium, thorium, ytterbium, erbium, dysprosium, chernovite, and yttrium orthophosphate. A dataset for natural uranium is assumed to represent terbium production. This is represented by an Ecoinvent (2007) dataset.	• Terbium - Uranium natural, in uranium hexafluoride, at conversion plant/CN SNI
Iodine	Iodine is extracted from Caliche rock. This rock also contains potassium nitrate, sodium borate, sodium nitrates, sodium sulphate. A dataset for sodium sulphate is assumed to represent iodine production. This is represented by an Ecoinvent (2007) dataset.	• Iodine – Sodium sulphate, from natural sources, at plant/RER SNI

Source: Wikipedia (2009), Mineral Information Institute (2009).

Manufacturing processes are described below for raw materials that did not have corresponding inventories.

Mercury

Based on latest available data representing 2005/06 (COWI, 2008, Concorde, 2008, Claushius, 2009) for mercury recycling, recovery and mining internationally, the following estimates have been calculated for mercury sources that are used in lamp production, as shown in Table B2e. The countries listed below cover between 70% to 90% of sources of mercury for all lamp types, which is assumed to be sufficient coverage to represent an international average figure for this study. The data shown in Table B2e have been combined with import data (as shown in Table B4a) to generate an average production mix per lamp type.

Table B2e Sources of Mercury

Source	China	Thailand	Europe
Primary mined	89%	0%	0%
Recovered from non-ferrous metal smelting and natural gas cleaning	0%	32%	0%
Recovered from vinyl chloride monomer facilities	11%	0%	0%
Recovered from chlor-alkali facilities	0%	62%	10%
Recycled via vacuum distillation process	0%	6%	62%
*Recycled via pyrometallurgical process	0%	0%	28%
Total	100%	100%	100%

Source: (COWI, 2008, Concorde, 2008, Claushius, 2009)

*Within the EU Claushuis Metaalmaatschappij B.V. (The Netherlands) is the main recycler using the pyrometallurgical process. Other processes for hydrometallurgical and electrometallurgical are minimal in the EU and have been ignored.

Inventory datasets to describe production mercury from these processes are listed in Table B2a above. For allocation, of burdens to recovered mercury from chlor-alkali facilities, non-ferrous metal smelting and natural gas cleaning and vinyl chloride monomer, this is assumed to be burden free for mercury from these processes, with the exception of local transport to the point of manufacture which is estimated to be 500km by road. Data for recycling has been used for batteries to represent the pyrometallurgical process (ERM, 2006) and primary data gathered in this study for mixed waste for Australia (EcoCycle, 2009) for the vacuum distillation process. Input inventories for electricity have been adjusted accordingly to supply geography.

Cerium Terbium Magnesium Aluminate

A method of manufacturing a terbium activated cerium magnesium aluminate phosphor has been described by Fan et. Al. (1989). This is achieved by forming a uniform powder blend consisting essentially of aluminium oxide, cerium oxide, magnesium, fluoride, and terbium, then firing the blend in a non-oxidizing atmosphere at a temperature of approximately 1500 – 1800° C, for a sufficient time to produce the phosphor. The phosphor is then cooled and deagglomerated.

Yttrium

Yttrium deposits can be found in xenotime, euxenite and fergusonite. It can also be obtained as a by-product of some uranium ores processing.

After Yttrium separation from the whole bulk of rare earth metals, it is subject to reduction. The metal is produced commercially by reduction, transferring yttrium oxide into yttrium halogenide. During the process this compound is mixed with sublimated calcium and argon and heated in a furnace up to 1600°C. The slag material is split off and hard oxygen and tantalum extracted, to produce yttrium ingots (Chemical-elements.info, 2007).

Iodine

Iodine is extracted from water and oil deposits and from mother waters of saltpeter production. It may also be recovered from seaweeds ashes. Mineralized water contains 0.001–0.01% iodine in iodides. During production, it is acidified and treated to extract elemental iodine, using activated coal or anionites. Iodine is refined by sublimation or smelting (Chemical-elements.info, 2007).

Antimony

Antimony is sometimes found native, but more frequently it is found in the sulfide stibnite (Sb2S3) which is the predominant ore mineral (Wikipedia, 2009).

Antimony ores are concentrated by flotation and gravity methods. The element is extracted mostly by a pyrometallurgical method which is precipitation of the fusion with iron. Alternatively partially oxidized ores, or ores containing precious metals are subject of oxidizing roasting with sublimation. It may be applied for Sb_2O_3, which is then processed by reduction smelting (Chemical-elements.info (2007).

Barium

The most common naturally occurring minerals containing barium are barium sulfate, $BaSO_4$ (barite), and barium carbonate, $BaCO_3$ (witherite).

Barite concentrate is the main feedstock material for barium extraction. It is obtained by barite flotation using liquid glass as a dead rock depressor. After $BaSO_4$ reduction with lack coal, coke or natural gas, BaS is obtained which then is converted into other barium compounds. After roasting at 800, 1400 and 700°C BaO is produced which then is reduced with aluminium powder at 1100–1200°C (Chemical-elements.info, 2007).

Sodium

Naturally occurring sodium is bound to other elements in many minerals. The most common sodium-containing mineral is halite (or rock salt), chemically known as sodium chloride. Other minerals that contain sodium include cryolite (sodium aluminium fluoride), soda ash (sodium carbonate), and soda niter (or Chile saltpeter, sodium nitrate) (Wikipedia, 2009). Sodium is now produced commercially through the electrolysis of fused (liquefied) sodium chloride. In this process, known as the Downs process, calcium chloride is mixed with the sodium chloride to lower the melting point below 600 °C. Sodium, but not calcium, is deposited on the cathode (New World Encyclopaedia, 2008).

The transport of raw materials from point of extraction to the locations of lamp manufacture has been estimated in tonne kilometres, based on shipping distances from the website ‘Sea Rates’ (2009) and locations for worldwide mineral production data from Index Mundi (2009). Tonne kilometres were estimated for the top three countries of lamp manufacture and the top three countries of raw material production.

B.3 Lamp Manufacture

The European Lamp Companies Federation (2008b) reports that during the production phase of an 11W CFL, energy use is 143 MJ. Based on mass (kg), the electricity use for production of the five other lamp types was estimated as this information was not provided by lamp manufacturers, exact figures could not be obtained. It is likely that this could be an overestimate for the higher mass lamps. The study has not considered other material inputs from lamp production and has assumed a 1% material wastage in the production process. Table B3a shows the estimated electricity needed for production of each lamp type.

Table B3a Estimated Electricity Used to Manufacture Lamps

Lamp Type	Mass	Electricity Used	Electricity Used	Estimated Electricity
	g	Mj	kWh	kWh
1. Linear fluorescent lamp (LFL) 35W, T8	120			4.0
2. Compact fluorescent lamp (CFL) 11W: external ballast	55			1.8
3. Compact fluorescent lamp (CFL) 20W: integral ballast	120	143	4.0	-
4. High pressure sodium (HPS) 150W	150			5.0
5. Metal Halide (MH) 400W	240			7.9
6. Mercury Vapour (MV) 250W	166.5			5.5

Source: European Lamp Companies Federation (2008b)

B.4 Lamp Import into New Zealand

Table B4a shows a breakdown of the countries where lamps are manufactured, based on data provided by the Statistics New Zealand (2009) for the import of lamp products into New Zealand. This data has been used to determine the electricity generation mix, by country of origin, for the production of lamps and transportation distances of lamps imported into New Zealand.

Table B4a New Zealand Lamp Import Data

Lamp Type	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W
Country	%	%	%	%	%	%
Australia				1.4		
Belgium				15.4	21.4	3.4
Brazil				1.9		
China	60.3	60.3	60.3	51.1	38.4	60.3
Germany	9.1	9.1	9.1	3.9	12.9	
Hong Kong					1.0	
Hungary	2.4	2.4	2.4	10.5	8.3	
India					3.3	
Indonesia	1.4	1.4	1.4			
Italy	1.6	1.6	1.6			
Japan				2.8	3.1	28.1
Netherlands	1.1	1.1	1.1			3.6
Poland	1.1	1.1	1.1			
Slovakia				7.5		
Switzerland						1.1
Thailand	20.5	20.5	20.5			
United Kingdom				2.9		
United States of America				2.3	8.7	
Remainder	2.5	2.5	2.5	0.4	2.8	3.5
Total	100.0	100.0	100.0	100.0	100.0	100.0

Source: Statistics New Zealand (2008).

Table B4b shows the shipping distances from each country of lamp manufacture to Auckland, New Zealand. These distances have been calculated using the website 'Sea Rates' (2009). Road transport distances have been estimated from the place of manufacture to port in the country of origin as 400km and from Auckland port to the point of retail in New Zealand as 400km.

Table B4b Shipping Distances from Lamp Countries of Origin to New Zealand

Country	Shipping Distance	Shipping Distance	Estimated Trucking Distance – Place of Manufacture to Port	Estimated Trucking Distance – Auckland Port to Retail Point in New Zealand
	Nautical miles	km	km	km
Australia	1,638	3,034	400	400
Belgium	11,373	21,063	400	400
Brazil	6,780	12,557	400	400
China	5,197	9,625	400	400
Germany	11,627	21,533	400	400
Hong Kong	5,060	9,371	400	400
Hungary	10,658	19,739	400	400
India	7,169	13,277	400	400
Indonesia	4,549	8,425	400	400
Italy	10,353	19,174	400	400
Japan	4,883	9,043	400	400
Netherlands	11,379	21,074	400	400
Poland	11,968	22,165	400	400
Slovakia	10,658	19,739	400	400
Switzerland	10,785	19,974	400	400
Thailand	5,485	10,158	400	400
United Kingdom	11,327	20,978	400	400
United States of America	5,659	10,480	400	400

Source: Sea Rates (2009)

Table B4c shows the estimated tonne kilometres for each lamp type, based on the distances travelled above, and the proportion of lamps manufactured in each country. Inventory data to represent shipping and trucking are based on Ecoinvent (2007) datasets.

Table B4c Estimated Tonne Kilometres for Importing and Distribution of Lamps to Point of Retail

	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W
	tkm	tkm	tkm	tkm	tkm	tkm
Trucking Distance – Place of Manufacture to Port	0.05	0.02	0.05	0.06	0.10	0.07
Shipping – Place of Manufacture to New Zealand	1.38	0.63	1.38	2.14	3.54	1.71
Trucking Distance – Auckland Port to Retail Point in New Zealand	0.05	0.02	0.05	0.06	0.10	0.07

Source: Statistics New Zealand (2008), Sea Rates (2009).

B.5 Retail and Use

Table B5a presents the electricity consumption for typical lamp usage in New Zealand, based on the lamps rated wattage and lifespan. Typical lamp lifetimes have been sourced from Stewardship Solutions (2008).

For the purposes of the study, the environmental impacts associated with retail are assumed to be negligible.

Table B5a Typical Lamp Specifications

	Unit	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W
Lamp wattage	W	35	11	20	150	400	250
Lifespan	Hours	8,000	10,000	12,000	20,000	20,000	20,000

Energy use	Mj	1,008	396	864	10,800	28,800	18,000
	kWh	280	110	240	3,000	8,000	5,000

Source: Calculated by ERM from data provided in Stewardship Solutions (2008)

B.6 Lamp Disposal

B.6.1 Waste Disposal in New Zealand

The New Zealand Environment Report (MfE, 2007b) provides an overview of waste and disposal routes in New Zealand. This states that much of the solid waste generated in NZ is disposed of to landfills and cleanfills, although industrial waste such as that produced by agricultural, forestry, quarrying and mining activities is generally disposed of on site to dedicated industrial landfills.

Based on information provided by the Ministry for the Environment (MfE, 2007), it is considered that all mercury-containing lamps used for domestic and industrial purposes in New Zealand are disposed of to municipal landfill or are collected for recycling. A proportion may also be dumped but there is no data to clarify this and dumping has not been assessed as a disposal route. Based on data provided by Stewardship Solutions (2008), an estimated level of 9% recycling has been estimated for HID lamp types. In the absence of better data, the study assumes the same recycling rate for all other lamp types. The proportion of mercury-containing lamps being disposed of through other routes is considered to be negligible. Table B6a shows the current disposal routes for mercury-containing lamps in New Zealand for 2007 and for the product stewardship scenarios that have been assessed that represent increased recycling and recovery levels.

Mercury is defined as a class 6.1b substance (HSNO, 1996) which is classified as hazardous. According to the Hazardous Substances (Disposal) Regulations 2001 (HSNO 1996) in New Zealand the allowable treatment includes depositing the substance in a landfill, incinerator, or a sewage facility if this facility will treat the substance by changing its characteristics or composition so that the substance is no longer a hazardous. Dilution of the substance with any other substance before discharge into the environment is not permitted.

Under current NZ regulations, spent lamps are considered hazardous and are unacceptable for landfill when the concentration of mercury exceeds 0.2mg/L in a Toxicity Characteristic Leaching Procedure (TCLP) test (MfE, 2004; cited in Knapp B et al, unknown date). The TCLP limit is based on US Environmental Protection Agency (USEPA) guidelines in accordance with testing of mercury leaching characteristics. The regulations also prohibit the high-temperature incineration of hazardous waste, with the exception of some medical waste. Consequently, no lamps are disposed of by incineration in New Zealand.

Table B6a End-of-life Management for Mercury-Containing Lamps in New Zealand

	Unit	Baseline	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Domestic waste					
Municipal landfill	%	91%	50%	20%	100%
Cleanfill	%	0%	0%	0%	0%
Hazardous landfill	%	0%	0%	0%	0%
Industrial landfill	%	0%	0%	0%	0%
Municipal incineration	%	0%	0%	0%	0%
Hazardous incineration	%	0%	0%	0%	0%
Recycling	%	9%	50%	80%	0%
Industrial waste					
Municipal landfill	%	91%	50%	20%	100%
Cleanfill	%	0%	0%	0%	0%
Hazardous landfill	%	0%	0%	0%	0%
Industrial landfill	%	0%	0%	0%	0%
Municipal incineration	%	0%	0%	0%	0%
Hazardous incineration	%	0%	0%	0%	0%
Recycling	%	9%	50%	80%	0%

Source: MfE (2007)

B.6.2 Waste Disposal in Victoria, Australia

Waste is categorised as three types in Victoria:

- municipal solid waste, from households and council operations;
- construction and demolition waste; and
- commercial and industrial waste.

Of the total waste generated in 2006–2007, just under four million tonnes were disposed of to licensed landfills and over six million tonnes were recovered for reprocessing. Almost half of the recovered material came from the construction and demolition sector (Victorian Government Department of Sustainability and Environment, 2009).

In the absence of better data, the study assumes that all waste from recycling of lamps is waste disposed to sanitary landfill and there is no waste disposed to incineration. Refer to Section B.

B.6.3 Municipal Landfill Disposal in New Zealand and Australia

Sanitary landfill scenarios were constructed on the basis of the methods set out in Doka (2007) and Doka (2007a) from ecoinvent.

The sanitary landfill models for New Zealand and Australia account for short term emissions, which are those that are considered to occur in less than 100 years. Further assumptions, inclusions and exclusions are noted below.

Rainfall

The sanitary landfill models account for the average rainfall in the two regions. It is assumed that New Zealand (rainfall of 1102mm/year) has similar rainfall to Zurich (1089mm/year), which is the Ecoinvent default. Australian rainfall is based on average data for Victoria (654mm/year). The models account for the change in waste water treatment burdens (form reduced leachate) into account and change in release factors for each element. Revised element release factors were recalculated for Australia using the method presented in Doka (2007) associated with reduced values for rain infiltration rate and effective annual leachate.

Composition

Elemental lamp mass and composition is accounted for. This study has accounted for the release of metallic elements and compounds. All other materials e.g. glass and metal casing are assumed to be inert and have no impact.

Emissions of compounds are modelled as emissions of elements based on molecular mass. Yttrium and Yttrium compounds have been excluded. Cerium terbium magnesium aluminate and phosphor powder have been modelled as barium magnesium aluminate (BMA) due to lack of specific life cycle inventory data. BMA ($Al_2Ba_2Mg_2O_7$) is not fully accounted for, as oxygen is excluded.

Fate

Three pathways have been assumed for the fate of each metal in the model as follows::

- gas;
- effluent; and
- sludge resulting from the treatment of landfill leachate.

Gas is assumed to be flared with the emissions released to atmosphere, effluent is assumed to be released and sludge is assumed to be used in land applications. Transfer coefficients and burdens associated with sludge digestion have been excluded due to a lack of available data. Emissions of iodine to water and land modelled have been modelled as iodide.

Decomposition

A 100% decomposition rate is assumed for all trace metals. This means that the waste has 100% degradability and is completely decomposed in the first 100 years after the waste placement. According to Ecoinvent, this does not equate to total emission from the landfill, due to re-precipitation, storage deposits and delayed emissions. There is no uncertainty variation used in the model, as it is assumed that the uncertainty of the short-term transfer coefficients already covers possible variations in the decomposition process.

Release factors

Release factors are presented in Table B6b. It is possible for some elements to have a calculated release factor of greater than 100%; however, this is corrected to 100% to mass balance the equations.

Table B6b Calculated Release Factors for Municipal Landfill Disposal

Element / Chemical	Assumption	Release Factor (%)
Aluminium (Al)	ERM estimated.	5.00%
Antimony (Sb)	-	10.50%
Barium (B)	Assumed to be same as Mn	115.00%
Barium magnesium aluminate (BMA)	ERM calculated as release of individual elements by molecular mass.	82.00%
Cerium terbium magnesium aluminate	Assumed to be same as BMA	82.00%
Iodine (I)	Assumed to be same as Cl	255.00%
Lead (Pb)	-	0.59%
Manganese (Mn)	-	115.00%
Mercury (Hg)	-	9.59%
Phosphor (P)	Assumed to be same as BMA	82.00%
Sodium (Na)	-	414.00%
Vanadium (V)	Assumed to be same as Sb (soluble oxianion)	10.50%

Source: Calculated by ERM from Doka (2007).

Fraction of Element Released in Gas or in Leachate

The fraction of each element that is released as a gas or in the leachate is based on Ecoinvent data presented in Table B6c

Table B6c Fraction of Element Released in Gas or in Leachate

Element / Chemical	Assumption	% Released to Air	% Released to Leachate
Aluminium (Al)	-	0.025%	99.975%
Antimony (Sb)	-	0.025%	99.975%
Barium magnesium aluminate (BMA)	ERM calculated as release of individual elements by molecular mass.	52.000%	48.000%
Cerium terbium magnesium aluminate	Assumed to be same as BMA	52.000%	48.000%
Iodine (I)	-	1.380%	98.620%
Lead (Pb)	-	0.033%	99.967%
Manganese (Mn)	-	0.025%	99.975%
Mercury (Hg)	-	28.600%	71.400%
Phosphor (P)	Assumed to be same as BMA	52.000%	48.000%
Sodium (Na)	-	0.025%	99.975%
Vanadium (V)	-	0.025%	99.975%

Source: Calculated by ERM from Doka (2007).

Transfer coefficients

The transfer coefficient of an element to landfill gas is based on the product of the decomposition rate, release factor and fraction of the element released as a gas for a given element. The transfer coefficient of an element to leachate is based on the product of the decomposition rate, release factor and remaining amount of the fraction left (subtracting the amount released as gas).

It should be noted that parameters for compounds were modelled as a proportioned average of element parameters.

Metals in leachate are subject to waste water treatment and were apportioned between effluent and sludge using the Ecoinvent dataset presented in Table B6d

Figures are not available for some elements. For these elements estimates are made based on their aqueous chemistry.

Table B6d Transfer Coefficients for Metals in the Waste Water Treatment Process

Element / Chemical	Assumption	Transfer coefficient to raw sludge (%)	Transfer coefficient to effluent (%)

Aluminium (Al)	-	95%	5%
Antimony (Sb)	50% to each compartment is assumed.	50%	50%
Barium magnesium aluminate (BMA)	50% to each compartment is assumed.	50%	50%
Cerium terbium magnesium aluminate	50% to each compartment is assumed.	50%	50%
Iodine (I)	Iodine is assumed to be completely dissolved.	0%	100%
Lead (Pb)	-	90%	10%
Manganese (Mn)	-	50%	50%
Mercury (Hg)	-	70%	30%
Phosphor (P)	50% to each compartment is assumed.	50%	50%
Sodium (Na)	Sodium is assumed to be completely dissolved.	0%	100%
Vanadium (V)	50% to each compartment is assumed.	50%	50%

Source: Calculated by ERM from Doka (2007).

Landfill burdens

Process-specific burdens associated with the operation of a sanitary landfill, including infrastructure material, land transformation and occupation, are included in the model.

Waste water treatment plant burdens were sourced from Doka (2007)b. These burdens are associated with energy used for pumping and heating, the sewer and plant infrastructure, transport and disposal of grit waste. Only base plant burdens are accounted for; burdens for each individual element have not been included. Burdens associated with digestion have been excluded.

B.7 Lamp Collection for Recycling

Spent lamps are collected by Interwaste NZ Ltd (Interwaste) through the following five main collection routes:

1. electricians;
2. wheelie bins;
3. retail drop-off;
4. domestic post; and
5. one-off collections.

Lamps used by industry (HIDs, LFLs or CFLs) are either collected by electricians in recycling boxes (containing 50 or 100 lamps for LFLs) or delivered to Interwaste in wheelie bins. Domestic lamps (CFLs) are sent to Interwaste through a free post recycling system, dropped off at retail outlets, or collected on a one-off basis.

Interwaste has four collection depots in New Zealand, based in Auckland, Wellington, Christchurch and Dunedin, where waste lamps are deposited.

Spent lamps collected in the South Island are crushed in a mobile crushing machine and packed into 200 litre steel drums, at either the Christchurch or Dunedin depot. The 200 litre containers are then shipped to CMA Eco Cycle (Eco Cycle) in Melbourne for recycling and recovery of materials.

Waste lamps that are collected in Wellington are consolidated and transported in bulk to Auckland, where they are crushed along with the Auckland waste lamp collection, and shipped in 200 litre steel drums to Eco Cycle in Melbourne, Australia.

Primary data has been gathered from Interwaste to describe the number of lamps collected through each collection route to each depot, transport distances and vehicle types, process inputs and outputs for the lamp crushing machines, and specifications of packaging. These data were collated and tonne kilometres calculated for each transport stage for lamp collection and for the transfer of lamps to Melbourne for recycling, as shown in Table B7d. Where collection was part of another journey this has been allocated accordingly. Vehicles are assumed to 100% full on outbound journey and 50% full on return.

B.7.1 Material and Energy Inputs at Interwaste

Table B7a shows the quantity of electricity consumed for each lamp during the recycling process at Interwaste in New Zealand. This was based on estimated data provided by Interwaste and lamp mass.

Table B7a Electricity Consumption for Lamp Crushing Process at Interwaste

	1. Linear fluorescent lamp (LFL) 35W, T8	**2. Compact fluorescent lamp (CFL) 11W: external ballast**	**3. Compact fluorescent lamp (CFL) 20W: integral ballast**	**4. High pressure sodium (HPS) 150W**	**5. Metal Halide (MH) 400W**	**6. Mercury Vapour (MV) 250W**
	kWh	kWh	kWh	kWh	kWh	kWh
Electricity use per lamp	0.00069	0.00032	0.00069	0.00087	0.0014	0.00096

Source: Interwaste New Zealand Ltd 2009

Raw materials used in the crushers at Auckland and Christchurch/Dunedin are fuel for vehicles on site, plastic packaging, cleaning products, PPE, and replacement parts for equipment. Tables B7b and B7c show the amount of materials consumed per lamp type, based on lamp mass.

Table B7b Process Inputs at Interwaste's Auckland Crushing Machine

	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W
Propane (l)	2.6415E-05	1.21069E-05	2.6415E-05	3.30187E-05	5.283E-05	3.66398E-05
Packaging – Plastic wrap (kg)	1.98112E-05	9.08015E-06	1.98112E-05	2.47641E-05	3.96225E-05	2.74798E-05
Cleaning Product – Surfactant (l)	1.32075E-05	6.05344E-06	1.32075E-05	1.65094E-05	2.6415E-05	1.83199E-05

Source: Interwaste New Zealand Ltd 2009

Table B7c Process Inputs at Interwaste's Christchurch/Dunedin Crushing Machine

	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W
Diesel (l)	0.000398	0.000182421	0.000398	0.000497512	0.000796	0.000552
PPE – Polycarbonate goggles (Kg)	0.000239	0.000109453	0.000239	0.000298507	0.000478	0.000331
Chutes and Chains – Steel (kg)	6.63E-06	3.04035E-06	6.63E-06	8.29187E-06	1.33E-05	9.2E-06

Source: Interwaste New Zealand Ltd 2009

Table B7d Estimated Transport for Spent Lamp Collection by Interwaste and Shipping to Eco Cycle (Australia)

Transport Stage	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W	Assumptions	Inventory Dataset from Ecoinvent 2.0 (2007)
	tkm	tkm	tkm	tkm	tkm	tkm		
Transport by all collection routes to Christchurch depot	0	0	0	0.0034	0.0054	0.0037	Collection – 10t truck	• Transport, lorry 7.5-16t, EURO4/RER SNI
Transport by all collection routes to Wellington depot	0.0002	0.001	0	0	0	0	Collection – 3.5t van	• Transport, van <3.5t/RER SNI
Transport by all collection routes to Auckland depot	0.0006	0	0	0	0	0	Collection – 6t truck	• Transport, lorry 3.5–7.5t, EURO4/RER SNI
Transport by all collection routes to Dunedin depot	0	0	0	0	0	0	Collection – 4.9t truck	• Transport, lorry 3.5–7.5t, EURO4/RER SNI
Transport of crushed lamps from Wellington to Auckland depot	0.0086	0.0101	0.0220	0	0	0	Transfer – 44t truck (Wgtn to Akl depot)	• Transport, lorry >32t, EURO4/RER SNI
Transport of drums from Dunedin to Christchurch depot	0.0056	0.0005	0.0011	0.0005	0.4796	0.0006	Transfer – rail (Dun to ChCh depot)	• Transport, freight, rail/RER SNI
Shipping of drums from Auckland or Christchurch depots to Melbourne	0.1490	0.1144	0.2497	0.2997	0.4796	0.3326	Transfer – container ship (Akl or Chch to Melbourne)	• Transport, transoceanic freight ship/OCE SNI
Transport of drums from Melbourne port to Eco Cycle plant	0.0022	0.0010	0.0023	0.0027	0.0043	0.0030	Transfer – 44t truck (port to Eco Cycle)	• Transport, lorry >32t, EURO4/RER SNI

Source: Interwaste (2009)

B.7.2 Process Wastes at Interwaste

It is assumed that all wastes produced at Interwaste collection depots are disposed of as industrial waste.

Table B7e shows the types and weights of packaging associated with collection and transportation of waste lamps to Interwaste depots.

Cardboard boxes and wheelie bins used for lamp collection are sent back to customers for reuse if in good condition, otherwise they are recycled.

Table B7e Composition of Packaging used for Spent Lamp Collection

Material	Unit	LFL 100	LFL 50	CFL Globe Box	Wheelie Bin	Steel Drum
Cardboard	kg	1.500	1.00	0.800	-	-
Plastic Liner	kg	0.002	0.002	0.002	-	-
Plastic	kg	-	-	-	15.000	-
Steel	kg	-	-	-	-	12.000
Total		1.502	1.002	0.802	15.000	12.000

Source: Interwaste New Zealand Ltd (2009)

B.8 Lamp Recycling Process

When the crushed lamps reach Eco Cycle in Melbourne, they are mixed with other mercury-containing and hazardous waste products, such as batteries, switches, thermometers, military wastes and catalysts. Once the pure materials are extracted from these waste products, they are then distilled and recycled into marketable materials. The recycling process for the lamps involves the following stages:

B.8.1 Crushing and Dry Separation

Used or obsolete mercury-containing lamps are processed in a machine that crushes and separates the lamps into three categories: glass, end-caps and a mercury/phosphor powder mixture (Basel Convention, 2007).

This process involves crushing the spent tubes, and sieving and air stripping the large particles from the mercury-containing phosphor powder (The Solid Waste Association of North America, unknown date). During crushing, mercury vapours are contained and filtered to eliminate airborne mercury emissions (Conrad & Associates Ltd, 2000).

B.8.2 Mercury Distillation

The phosphor powder is then retorted under vacuum and heat. The mercury is volatilized and then distilled to the required purity. The recycling of mercury-containing lamps is a proven technology capable recovering greater than 99% of the mercury in the spent lamps (The Solid Waste Association of North America).

B.8.3 Production of Marketable By-products

At Eco Cycle, glass, aluminium, mercury and phosphor powder are produced as marketable by-products from the lamp recycling process. These by-products are described in more detail in Section B10 below. The estimated transportation (tonne kilometres) of these by-products from Eco Cycle to place of use is shown per lamp in Table B8a below.

Table B8a Transportation of Marketable By-Products from EcoCycle to Place of Use

	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W
	tkm	tkm	tkm	tkm	tkm	tkm
Trucking from EcoCycle to place of use	5.53E-02	5.16E-02	5.29E-02	5.69E-02	6.13E-02	5.64E-02

Source: EcoCycle (2009b)

B.8.4 Material and Energy Inputs at EcoCycle

Table B8b shows the amount of energy consumed by each lamp type during the recycling process at Eco Cycle. This was calculated using the mass of one lamp, divided by the total mass of lamps recycled per month, multiplied by the total energy consumption (kWh) used at the plant per month.

Table B8b Electricity Consumption for Lamp Recycling Process at EcoCycle

	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W

	kWh	kWh	kWh	kWh	kWh	kWh
Australia -Eco Cycle	0.039	0.018	0.039	0.049	0.079	0.055

Source: Eco Cycle (2009a)

The only additives used in the recycling process at Eco Cycle are nitrogen and oxygen gas. The amount of each gas used per lamp type is shown in Table B8c. This was calculated using the mass of one lamp, divided by the total mass of lamps recycled per month, multiplied by the total nitrogen and oxygen consumption (m^3) used at the plant per month.

Table B8c Gas Consumption for Lamp Recycling Process at Eco Cycle.

	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W
	kg	kg	kg	kg	kg	kg
Nitrogen	0.0032	0.0014	0.0032	0.0039	0.0063	0.0044
Oxygen	0.0062	0.0028	0.0062	0.0077	0.0123	0.0086

Source: Eco Cycle (2009b), Engineering Toolbox (2009)

B.8.5 Process Wastes at EcoCycle

The lamp recycling processes at Eco Cycle does not generate any emissions to air or water. The only solid wastes produced are packaging products, which are all recycled. Steel drums for example are reused locally, or flattened and shipped to China for recycling. Cardboard packaging is sent to the neighbouring paper recycling facility. Copper contained in crushing machine filters is extracted, recycled, and sold to overseas markets.

B9 Electricity Generation

Section B9 presents the life cycle inventory modelling used for electricity generation for New Zealand and for countries where electricity is used for overseas manufacture of lamps, as listed in Section B4.

B.9.1 Generation Mix

The electricity generation mix for each country that manufactures lamps were sourced from the International Energy Agency electricity statistics (IEA, 2007), which represents the generation mix for 2006.

The electricity mix for New Zealand, as shown in Table B9a, was sourced from the Ministry of Economic Development (MED) *Energy Data File June 2008* (MED, 2008), which represents the generation mix for 2007.

Table B9a Electricity Generation Mix for New Zealand in 2007

Generation Fuel	%
Hydro	54.9
Gas	26.4
Geothermal	7.7
Coal	6.9
Oil	-
Wind	2.2
Biogas	0.4
Biomass	1.4
Total	100

Source: MED (2008)

Further descriptions of each generation fuel type are described below.

B.9.2 Transmission and Distribution losses

Power losses arise during the transmission and distribution of electricity, due to resistive and inductive losses in transformers and overhead lines. High voltage (HV) losses are referred to as transmission losses and medium-voltage (MV) and low-voltage (LV) losses are referred to as distribution losses.

Based on data provided by the MED (2008), the New Zealand national loss ratio (which represents low voltage losses) was 7.7% in 2007. We have estimated HV and MV losses based on typical losses in other countries, where HV losses are often around 5% of total LV loss and MV losses around 10% of total LV loss. For New Zealand this equates to an estimated loss of 0.4% for HV and 0.8% for MV.

B.9.3 Imports and Exports

The effect of imports or exports of electricity for overseas countries has not been included in the generation mix to describe each country's profile. Imports or exports of electricity are not relevant for New Zealand.

B.9.4 Life Cycle Inventories – Overseas

Table B9b shows inventory datasets used for estimating electricity generation by fuel type for overseas countries where lamp manufacture occurs. These datasets have been estimated based on the Ecoinvent 2.0 (2007). Infrastructure has been excluded. These datasets represent average European technology.

Table B9b Inventory Datasets Used for Electricity Generation

Generation Fuel	Inventory Dataset from Ecoinvent 2.0 (2007)
Hydro	• Electricity, hydropower, at power plant/SK SNI
Gas	• Electricity, natural gas, at power plant/CENTREL SNI
Geothermal	• Electricity, hydropower, at power plant/SK SNI
Coal	• Electricity, hard coal, at power plant/SK SNI
Oil	• Electricity, oil, at power plant/SK SNI
Wind	• Electricity, at wind power plant/RER SNI
Biogas	• Electricity, at cogen ORC 1400kWth, wood, allocation exergy/CH SNI
Biomass	• Electricity, at cogen ORC 1400kWth, wood, allocation exergy/CH SNI

B.9.5 Life Cycle Inventories – New Zealand

Hydro Generation

Generation of electricity from hydro plants in New Zealand consists of around 50 generation plants, primarily from reservoir plant schemes and a small proportion of run-of-river and combined pumped storage (Wikipedia, 2009).

Generation of electricity from hydro in New Zealand has been assumed to be all from reservoir plant schemes and modelled using Ecoinvent 2.0 (2007) *Electricity, hydropower, at reservoir power plant/CH* which represents European data. The dataset represents a head height over 30m (which is analogous to New Zealand). It includes the area occupied, an estimation of greenhouse gas emissions (based on Swiss conditions from the water reservoir), maintenance and infrastructure.

Gas Generation

Gas used for electricity generation is supplied from several gas fields both onshore and offshore in New Zealand. Based on data from the *Energy Data File June 2008* (MED, 2008) approximately 71% is onshore and is 29% is offshore, based on delivered energy.

In terms of generators, Contact Energy Limited (operating Otahuhu B, Taranaki Combined Cycle and New Plymouth) and Genesis Power Limited (operating Huntly including the new e3p combined cycle plant) are the main electricity generators in New Zealand using natural gas. Based on the data shown in Table B9c which shows a summary for New Zealand, a national average generation efficiency of 48% is estimated, based on the proportion of generation (by energy delivered) for the different gas turbine technologies.

Table B9c Electricity Generation via Gas in New Zealand

Generator	Electricity Generated in 2007	Proportion of Electricity Generated in 2007	Generation Efficiency	Technology
Genesis Power	GWh	%	%	
Units 1–4	4239	33%	36%	Conventional boiler and steam turbine technology. Can burn coal, gas or mixture of both
Unit 5	3187	25%	57%	Closed cycle gas turbine
Unit 6	149	1%	41%	Open cycle gas turbine
Contact Energy				
Otahuhu B	2441*	19%	55.5%	Combined cycle gas turbine
Taranaki	2300*	18%	55.5%	Combined cycle gas turbine
New Plymouth (decommissioned part way through 2007)	610*	5%	35%	Steam Turbine
Otahuhu A (reactive power – used to balance electricity grid)	-	-	-	Gas fired power station

Source: (Contact, 2008, 2009, 2009a and Genesis, 2008)

*Note: estimated figures based on total thermal generation of 5351GWh and plant capacity (Contact, 2008).

Generation of electricity from gas in New Zealand has been modelled using Ecoinvent 2.0 (2007) *Electricity, natural gas, at power plant/UCTE* and adjustments have been made to account for onshore or offshore gas source along with average generation efficiency. No adjustments have been made for the emission of trace metals (including that for mercury) as data are not available for composition of gas in New Zealand. This provides a reasonable estimate for trace metals emissions based on European data.

Geothermal Generation

Generation of electricity from geothermal sources in New Zealand has been estimated based on life cycle inventory data for hydro generation, as described above. No dataset for geothermal generation was available for the study from published and licensed sources. The Ecoinvent dataset has been modified to include an estimate of fugitive methane emissions based on data for Contact Energy (2008), which reports 90tonnes of CO_{2e} per GWh, which is principally methane. The dataset assumes 90% methane and 10% carbon dioxide, based on global warming potential.

Coal Generation

Generation of electricity from coal in New Zealand is provided by Huntly power station operated by Genesis Power. This power station operates at a generation efficiency of 36% (Genesis, 2009). In 2007, coal used in electricity generation was supplied form Huntley coalfield (approximately 37%) and imports from Indonesia (approximately

67%), based on data from the *Energy Data File June 2008* (MED, 2008) and Genesis (2009). Transport of coal from these locations has been estimated in the inventory dataset.

Typical New Zealand coal composition has been accounted for in order to estimate trace metals emissions to air from coal generation. Table B9d shows the estimated average trace metals composition of coal supplied to Huntly power station based on elemental analysis data (CRL, 2004) proportion of coal supplied from New Zealand and Indonesia.

ERM has calculated air emissions of metals based on assumptions provided in Ecoinvent (Dones, 2007, Röder, 2007) which calculate emissions of trace metals to air from coal generation by accounting for elementary analysis of the coal, the element-specific emission factor to air and emission control equipment. Table B9d shows the estimated emission factors to air for electricity generation.

Table B9d Coal Composition for Trace Metals and Power Station Emission Factor to Air

Element	Estimated Concentration	Estimated release factor to air
	ppm	%
Aluminium	3293.6	10%*
Antimony	1.0	0%
Arsenic	5.2	1%
Barium	35.8	10%*
Bismuth	0.4	10%*
Boron	130.1	30%
Cadmium	0.2	0%
Caesium	0.4	10%*
Chromium	3.3	10%*
Cobalt	2.8	0%
Copper	3.9	10%*
Fluorine	22.9	90%
Iron	2329.0	10%*
Lanthanum	1.4	0%
Lead	3.2	10%*
Lithium	6.6	10%*
Manganese	24.1	10%*
Mercury	0.1	90%
Molybdenum	1.0	0%
Nickel	5.7	0%
Rubidium	2.3	10%*
Selenium	5.2	15%
Silver	0.4	10%*
Strontium	34.2	0%

Element	Estimated Concentration	Estimated release factor to air
Thallium	0.2	0%
Tin	2.2	10%*
Uranium	0.2	0%
Vanadium	5.9	0%
Zinc	7.8	0%

Source: (Röder, 2007, CRL, 2004)

* Note: These factors are estimated based on average of other metals shown.

Generation of electricity from coal in New Zealand has been modelled using Ecoinvent 2.0 (2007) *Electricity, hard coal, at power plant/UCTE* and adjustments have been made to account for trace metals emissions to air and transport of raw coal, as described.

Wind Generation

Based on data provided in the *Energy Data File June 2008* (MED, 2008) and NZWEA (2009) New Zealand constitutes approximately the following wind generation profile by turbine capacity:

- 53% are 3MW wind turbines;
- 18% are 2MW wind turbines;
- 28% are 1.65MW wind turbines; and
- 1% are 500kW wind turbines.

Generation of electricity from wind has been modelled using Ecoinvent 2.0 (2007) *Electricity, at wind power plant/RER*, which represents 800kW European technology. This provides a reasonable estimate based on plant capacity in New Zealand. The dataset includes the operation of the wind power plant with the necessary change of gear oil.

Biogas Generation

Generation of electricity from biogas represents combustion of biogas and landfill gas sources. The life cycle inventory is modelled using Ecoinvent 2.0 (2007) *Electricity, at cogen with biogas engine, allocation exergy/CH*, which represents European technology for use of biogas in a cogeneration unit. Included are emissions to air, biogas consumption and use, and disposal of operational supplements. This multi-output process delivers the co-products of heat and electricity. The allocation is based on the exergy values which allocates electricity as 1 and heat as 0.17.

Biomass Generation

Generation of electricity from biomass represents combustion of residential firewood wood and woody biomass from wood pellets (MED, 2008). This life cycle inventory is modelled using Ecoinvent 2.0 (2007) *Electricity, at cogen ORC 1400kWth, wood, allocation exergy/CH*, which represents European technology for combustion of natural wood chips, including, the wood input, emissions to air, transport of the fuel, and disposal of the ashes. This multi-output process delivers the co-products of heat and electricity. Allocation is based on the exergy.

B.10 Avoided Products

At EcoCycle the following by-products are produced from the lamp recycling process:

- **Nickel** end caps are assumed to be recycled and stored onsite.
- **Brass** end components are assumed to be recycled and stored onsite.
- **Aluminium** end caps are sent to another CMA recycling facility in New South Wales where they are processed into ingots for foundry application.
- **Glass** crushed into granules (2-3mm) and sent to a local business in Victoria where it is further processed into glass wool for insulation.
- **Mercury** is processed into ingots and sent to a local dental industry where it is reused in the manufacture of dental amalgam.
- **Phosphor powder** is produced in small volumes and supplied to the agricultural industry to use as a soil enhancer.
- **Plastics** are assumed to be recycled and stored onsite.

Table B10a shows the inventory datasets used for determining the environmental benefits associated with avoided materials from the cycling of lamps. Based on data provided by Eco Cycle, the study assumes that 99% of materials from the lamps are recycled. Adjustments are made for electricity generation and transportation, assuming all mercury is sourced from China and all other materials from within Australia.

Table B10a Avoided Products Resulting from Lamp Recycling at Eco Cycle

Avoided Product	Description	Inventory Dataset from Ecoinvent 2.0 (2007)
Nickel	Nickel is assumed to be 99.5% nickel, represented by an Ecoinvent (2007) dataset Dataset originally represents 2006 data of a global production mix. Some processes originate from European datasets. Amendments made by ERM include the change of input electricity mix to match the country of recovery and recycling. Processes includes: mining, beneficiation and disposal of overburden and tailings. Subsequently it includes the metallurgy step with the disposal of slag and the separation of the co-product copper, and the refining step yielding the desired Class I nickel. Production, application and emissions of most agents and additives used in beneficiation and metallurgy are also included. Overburden and tailings are disposed and partly re-filled. Sulphur dioxide in the off-gas is recovered.	• Nickel, 99.5%, at plant/GLO SNI
Brass	Brass is represented by an Ecoinvent (2007) dataset. Dataset originally represents 2003 technology of the EU average. Amendments made by ERM include the change of input electricity mix to match the country of recovery and recycling. Processes include copper and zinc, including their melting and casting of brass ingots.	• Brass, at plant/kg/CH
Mercury	Mercury is assumed to be liquid mercury, represented by an Ecoinvent (2007) dataset Dataset originally represents technology from no specific geographic origin. Amendments made by ERM include the change of input electricity mix to match the country of recovery and recycling. Processes include raw materials and energy consumption for production, estimated emissions to air from production. No water emissions. Technology uses data from lime mining, crushing and milling plus estimation of the additional furnace operation step. Refer to Appendix B.2 for description on the mix of mercury production used to offset this inventory.	• Mercury, liquid, at plant/GLO SNI
Glass	Glass is assumed to be flat glass, represented by an Ecoinvent (2007) dataset Dataset originally represents 2000 technology in Germany (EU). Amendments made by ERM include the change of input electricity mix to match the country of recovery and recycling. Processes include all measured in-and output materials and energy carriers reported for a glass coating plant during operation (coating process, internal transports, packing and administration). The flat glass coating technology includes the following stages: metal coating is applied to float glass by cathodic sputtering in vacuum.	• Flat glass, uncoated, at plant/RER SNI
Phosphor powder	Phosphor powder is assumed to be liquid white phosphorous, represented by an Ecoinvent (2007) dataset Dataset originally represents 2003 technology of no specific geographic origin. Amendments made by ERM include the change of input electricity mix to match the country of recovery and recycling. Processes include raw materials and chemicals used for production, by-products and waste produced, transport of materials to manufacturing plant, emissions to air and energy demand. Technology uses production from phosphate rock with the aid of the Wöhler process, with a yield of 91%.	• Phosphorus, white, liquid, at plant/RER SNI
Aluminium	Aluminium is assumed to be primary aluminium, represented by an Ecoinvent (2007) dataset Dataset originally represents 2003 technology for EU processes. Amendments made by ERM include the change of input electricity mix to match the country of recovery and recycling. Processes include cast aluminium ingot production, transport of materials to the plant and disposal of wastes.	• Aluminium, primary, at plant/RER SNI
Plastics	Plastics are assumed to be polyurethane, represented by an Ecoinvent (2007) dataset. Dataset originally represents 2003 technology for the EU. Amendments made by ERM include the change of input electricity mix to match the country of recovery and recycling. Processes include transport of the monomers as well as the production (energy, air emissions) of the PUR foam.	• Polyurethane, rigid foam, at plant/RER SNI

The transportation of these avoided products from place of extraction to EcoCycle are estimated in tonne kilometres (Table B10b). It is assumed that mercury is extracted from China and shipped to Melbourne. All other avoided products are assumed to be sourced from Australia.

Table B10b Transportation of Avoided Products from Place of Extraction to EcoCycle

	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W
	tkm	tkm	tkm	tkm	tkm	tkm
Shipping from country of extraction to Melbourne port	3.73E-05	4.66E-05	4.66E-05	4.66E-04	4.66E-04	3.54E-04
Trucking from place of extraction (within Australia) and from port to EcoCycle	1.60E-02	1.28E-02	1.82E-02	1.58E-01	1.54E-01	3.59E-02

Source: EcoCycle (2009b)

B11 Sensitivity Analysis

Section B11 provides inventory data in relation to sensitivity analyses conducted for the LCA study.

B11.1 Mercury Levels

Typical mercury levels have been assumed to increase or decease by 20 percent, depending on the design and quality of lamp, as shown in Table B11a. It is considered that the range selected will take into account any mercury reductions in future lamp designs. Specific data from manufacturers regarding lamp design and potential effects on lamp life and quality were not readily available for the study. Although Philips (Ross, 2009) indicated the following when discussing reduced mercury levels:

For fluorescent domestic lighting (LFL, CFLe and CFLi):

- Light quality. Light quality with regards to colour rendering (reproduction of colour) is unchanged. The colour appearance can also change. For example, low mercury levels may result in slight flickering of lamps and the tube shows a “pink” tinge. This effect can be noted in other brands towards end of life if the phosphorous coating on the inside glass of the tube is not thick/even enough, and mercury is absorbed into the glass.

- Lamp life. The two main indicators of lifetime are emitter coating level and mercury level. Excess levels of mercury allow longer life; however the production goal is to make market leading lifetime values for standard product with minimum mercury levels.

- Lamp outputs (W). Output unchanged. Although light output levels can decrease as electrons have less interaction with mercury molecules.

- Other design changes. Entry level lamps have all been optimised with lowest mercury levels, along with other material construction. Under current processes, any further minimisation of lamp components will result in reduced performance.

For HID lamp (HPS, MH and MV):

- Lamp life. Higher mercury levels lead to longer lifetime. It is not clear what relationship exists and if this relationship is linear.

For this sensitivity analysis, we have assumed that in the future (egg in 5 years time) technology improvements will have been made to allow a further 20% reduction in mercury level which will achieve the same functional performance of lamp life, light quality and output for the purposes of this sensitivity analysis. No changes have been made to this sensitivity beside mercury level.

Table B11a Mercury Content in Lamps

Mercury Content	Unit	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W
Minimum	mg	3.2	4	4	40	40	40
Maximum	mg	4.8	6	6	60	60	60

B11.2 Lamp Lifetimes

Maximum and minimum lamp lifetimes have been estimated at 50 percent above and below typical values (Table B11b). The selected range in lifespan is assumed to cover variance between potential lamp design and quality.

Table B11b Range of Lamp Lifespans

	Unit	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W

Lamp wattage	W	35	11	20	150	400	250
Lifespan Typical	Hours	8,000	10,000	12,000	20,000	20,000	20,000
Lifespan Minimum	Hours	4,000	5,000	6,000	10,000	10,000	10,000
Lifespan Maximum	Hours	12,000	15,000	18,000	30,000	30,000	30,000

Source: Calculated by ERM from data provided in Stewardship Solutions (2008) B.6 Lamp Disposal

B11.3 Light Fittings and Fixtures

The materials used in light fittings vary widely, depending on application and purpose. Examples of typical light fittings are shown below (Figure B11a), and typical construction materials and weights are provided in Table B11c. These materials do not include ballasts and additional lamp gear.

The sensitivity assumes one set of packaging per new lamp and one set of fittings per 100,000 hours of operation (or approximately 12 years for continuous operation). For domestic lamp this may represent an underestimate for impacts of fittings, while industrial lamps this may represent and over estimate. For CFL lamp two lamps are used in each fitting and for all other lamp types one lamp is sued per fitting.

Figure B11a. Examples of typical light fittings: General Use Luminaire (left), Fluorescent Batten Fitting (centre) and Low Bay HID fitting (right)

Table B11c Construction Materials and Estimated Weights of Typical Lamp Fittings

Fluorescent Batten Fitting	
Linear fluorescent lamp (LFL)	
Dimensions	L 1225mm X W 58 mm X H 48mm

Materials and Weights	Nylon end cap	0.2 Kg
	Cold rolled sheet	0.49 Kg
	Epoxy powder	0.02 Kg
Total weight of Fitting		0.7 Kg
General Use Luminaire		
Compact Fluorescent Lamps (CFLe and CFLi)		
Dimensions	W 297mm X L 297mm X H 83mm	
Materials and Weights	Sheet steel	1.2 kg
	Enamel	0.2 kg
	Anodised aluminium	0.4 kg
	Cold rolled sheet	0.99 kg
	Epoxy powder	0.001 kg
Total Weight of Fitting		2.85 kg
Low Bay HID Fitting		
High Pressure Sodium Lamps (HPS), Metal Halide Lamps (MH) and Mercury Vapour Lamps (MV)		
Dimensions	W 610mm x L 370mm x H 200mm	
Materials and Weights	Pressed steel sheet	3.5 kg
	Epoxy resin	0.001 kg
	Integral control gear	0.059 kg
	Aluminium reflector	1.0 kg
	Ceramic lamp holder	0.14 kg
	Steel press frame	1.0 kg
	Shock resistant glass	0.5 kg
Total Weight of Fitting		6.2 kg
High Bay HID Fitting		
High Pressure Sodium Lamps, Metal Halide Lamps (MH) and Mercury Vapour Lamps (MV)		
Dimensions	L 252mm X W 135mm X H 290mm	
	Bowl Diameter 475mm X H 270mm	
Materials and Weights	Cold rolled sheet steel	3.099 kg
	White powder finish	0.001 kg
	Aluminium spun reflector	0.9 kg
	Wire guard	0.09 kg
	Shock resistant glass	0.31 kg
Total Weight of Fitting		4.4 kg

Source: Estimated weights by ERM based on total weight data from All Products (2009)

B11.4 Packaging

Packaging used for lamp retail also varies widely depending on product brand. Lamps may be purchased individually or in bulk. Table B11d shows estimated typical packaging and material weights used for each lamp.

Table B11d Typical Packaging Types and Estimated Weights

	1. Linear fluorescent lamp (LFL) 35W, T8	**2. Compact fluorescent lamp (CFL) 11W: external ballast**	**3. Compact fluorescent lamp (CFL) 20W: integral ballast**	**4. High pressure sodium (HPS) 150W**	**5. Metal Halide (MH) 400W**	**6. Mercury Vapour (MV) 250W**
Packaging Type	Round cardboard tube	Cardboard box with cardboard inserts	Cardboard box with cardboard inserts	Cardboard box Corrugated cardboard sleeve	Cardboard box Corrugated cardboard sleeve	Cardboard box Corrugated cardboard sleeve
Dimensions of Packaging	L 1215mm X W 30mm X H 30mm	L 110mm X W 60mm X H 60mm	L 115 mm X W 65mm X H 65mm	L 215mm X W 50mm X H 50mm	L 292mm X W 123mm X H 123	L 228mm X W 93mm X H 93mm.
Cardboard weight	91 g	26 g	30 g	90 g	312 g	184 g

Source: Estimated packaging weights by ERM from based on data from Philips (2009), Eye Lighting (2009)

B11.5 Closed Loop Recycling

A closed loop recycling system assumes that all waste lamps are returned to their place of manufacture and recycled into new lamps. Under this assumption, transport measured in tonne kilometres has been estimated for each lamp type (Table B11e). These values are based on the transport for lamp import in Table B4c, with the addition of the weight of the steel drums used to contain crushed waste lamps. Inventory data to represent shipping and trucking are based on Ecoinvent (2007) datasets. Environmental benefit is attributed to 99% of the recovered materials for the avoided materials production that would have otherwise taken place. 1% represents a recycling process wastage.

Table B11e Estimated Tonne Kilometres for Transporting Crushed Lamps back to Place of Manufacture

	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W
	tkm	tkm	tkm	tkm	tkm	tkm
Trucking Distance – From Place of Use to Port in New Zealand	0.05	0.02	0.05	0.06	0.10	0.07
Shipping – From New Zealand Port to Port in Country of Manufacture	1.46	0.61	1.46	2.27	3.75	1.82
Trucking Distance – From Port to Place of Manufacture	0.05	0.02	0.05	0.06	0.10	0.07

Source: Statistics New Zealand (2008), Sea Rates (2009).

B11.6 Cut-offs for Material Production

Filling gases (argon and krypton) have been omitted from the study as the volume contained in lamps is considered negligible and due to a lack of data on the quantities contained in each lamp. These noble gases are naturally occurring in the earth's atmosphere. They are chemically unreactive gases. Environmental databases (Ecoinvent 2007) show low energy requirements for the production of argon and krypton. Based on this information and the substantially low amounts contained in lamps, it is considered acceptable to not take their environmental impact into account for the LCA study.

B11.7 Warm-up Effects

Some research indicates (Parsons, 2006) that there is a warm-up effect for fluorescent lamps which increases power required in the initial period of operation compared to rated power.

Based on data provided in (Parsons, 2006) for an 18W CFL lamp, ERM estimates that around 0.5% additional energy may be required for a CFL lamp operated over an a typical one hour period. The effect of increased power at warm-up is dependent on the increased power required for warm-up (rated at 19W over 10minutes for an 18W lamp), as well as the time operated between warm-ups. An increased time between warm-ups of more than one hour would reduce the additional energy requirements. Based on one hour between warm-ups we estimate an increased energy consumption of 0.5% in the use phase. We have assumed this is the case for all lamps, although this is an assumption for non-CFL lamp types.

Table B11f Lamp Electricity Consumption

	Unit	1. Linear fluorescent lamp (LFL) 35W, T8	2. Compact fluorescent lamp (CFL) 11W: external ballast	3. Compact fluorescent lamp (CFL) 20W: integral ballast	4. High pressure sodium (HPS) 150W	5. Metal Halide (MH) 400W	6. Mercury Vapour (MV) 250W
Lamp wattage	W	35	11	20	150	400	250
Lifespan	Hours	8,000	10,000	12,000	20,000	20,000	20,000
Typical energy use	kWh	280	110	240	3,000	8,000	5,000
Energy use with warm-up effects	kWh	281.4	110.6	241.2	3,015	8,040	5,025

Source: Calculated by ERM from data provided in Stewardship Solutions (2008)

Appendix C: Results of the Inventory Analysis

C.1 Inventory Data by Life Cycle Stage

Table to Table C1f in Appendix C present the inventory results by life cycle stage for each of the lamps assessed in the study.

Table C1a Life Cycle Inventory – Baseline: 9% Recycling – Linear fluorescent lamps (LFL), 35W, T8 (100,000 hours operation)

	Unit	Manufacture	Import and distribution	Retail and use	Waste disposal	Recycling	Displaced material benefits	Total
Total mercury use in lamp manufacture – internal flow	mg	4.0	0.0	0.0	0.0	0.0	0.0	4.0
Coal – resource	kg	19.1	0.0	145.9	0.0	0.0	0.0	165.0
Natural gas – resource	m^3	3.0	0.0	233.1	0.0	0.0	0.0	236.2
Oil – resource	m^3	0.8	0.1	4.4	0.0	0.0	0.0	5.2
CO_2 (fossil) to air	kg	43.9	0.3	726.9	0.0	0.1	-0.1	771.2
CO to air	kg	0.0	0.0	0.3	0.0	0.0	0.0	0.3
SO_x to air	kg	0.3	0.0	1.8	0.0	0.0	0.0	2.1
NOx species to air	kg	0.1	0.0	1.6	0.0	0.0	0.0	1.8
N_2O to air	kg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH_4 to air	kg	0.3	0.0	3.1	0.0	0.0	0.0	3.3
VOC to air	kg	0.0	0.0	0.3	0.0	0.0	0.0	0.3
Particulates to air	kg	0.1	0.0	0.5	0.0	0.0	0.0	0.6
Hg to air	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	554.3	4.3	11,969.0	0.5	1.3	-2.6	12,526.8
Energy – Renewable	Mj	28.6	0.0	1,323.4	0.0	0.8	-0.2	1,352.6

Note: a negative number represents an environmental benefit

Table C1b Life Cycle Inventory – Baseline: 9% Recycling – Compact fluorescent lamps (CFLe) 11W: external ballast (100,000 hours operation)

	Unit	Manufacture	Import and distribution	Retail and use	Waste disposal NZ	Recycling	Displaced material benefits	Total
Total mercury use in lamp manufacture – internal flow	mg	5.0	0.0	0.0	0.0	0.0	0.0	5.0
Coal – resource	kg	7.1	0.0	45.9	0.0	0.0	0.0	52.9
Natural gas – resource	m^3	1.2	0.0	73.3	0.0	0.0	0.0	74.5
Oil – resource	m^3	0.4	0.0	1.4	0.0	0.0	0.0	1.8
CO_2 (fossil) to air	kg	16.6	0.1	228.5	0.0	0.0	-0.1	245.2
CO to air	kg	0.0	0.0	0.1	0.0	0.0	0.0	0.1
SO_x to air	kg	0.1	0.0	0.6	0.0	0.0	0.0	0.7
NOx species to air	kg	0.1	0.0	0.5	0.0	0.0	0.0	0.6
N_2O to air	kg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH_4 to air	kg	0.1	0.0	1.0	0.0	0.0	0.0	1.1
VOC to air	kg	0.0	0.0	0.1	0.0	0.0	0.0	0.1
Particulates to air	kg	0.0	0.0	0.2	0.0	0.0	0.0	0.2
Hg to air	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	215.0	1.6	3,761.7	0.2	0.5	-2.0	3,977.0
Energy – Renewable	Mj	11.4	0.0	415.9	0.0	0.1	-0.1	427.3
Total mercury use in lamp manufacture – internal flow	mg	5.0	0.0	0.0	0.0	0.0	0.0	5.0

Note: a negative number represents an environmental benefit

Table C1c Life Cycle Inventory – Baseline: 9% Recycling – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

	Unit	Manufacture	Import and distribution	Retail and use	Waste disposal NZ	Recycling	Displaced material benefits	Total
Total mercury use in lamp manufacture – internal flow	mg	5.0	0.0	0.0	0.0	0.0	0.0	5.0
Coal – resource	kg	17.6	0.0	83.4	0.0	0.0	0.0	101.0
Natural gas – resource	m^3	3.4	0.0	133.2	0.0	0.0	0.0	136.6
Oil – resource	m^3	1.5	0.1	2.5	0.0	0.0	0.0	4.1
CO_2 (fossil) to air	kg	40.9	0.2	415.4	0.0	0.0	-0.1	456.4
CO to air	kg	0.0	0.0	0.1	0.0	0.0	0.0	0.2
SO_x to air	kg	0.4	0.0	1.0	0.0	0.0	0.0	1.4
NOx species to air	kg	0.1	0.0	0.9	0.0	0.0	0.0	1.1
N_2O to air	kg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH_4 to air	kg	0.2	0.0	1.8	0.0	0.0	0.0	1.9
VOC to air	kg	0.0	0.0	0.2	0.0	0.0	0.0	0.2
Particulates to air	kg	0.1	0.0	0.3	0.0	0.0	0.0	0.4
Hg to air	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	600.8	2.9	6,839.1	0.4	0.7	-3.1	7,440.8
Energy – Renewable	Mj	33.7	0.0	756.2	0.0	0.1	-0.2	789.9

Note: a negative number represents an environmental benefit

Table C1d Life Cycle Inventory – Baseline: 9% Recycling – High pressure sodium (HPS) lamps, 150W (100,000 hours operation)

	Unit	Manufacture	Import and distribution	Retail and use	Waste disposal NZ	Recycling	Displaced material benefits	Total
Total mercury use in lamp manufacture - internal flow	mg	50.0	0.0	0.0	0.0	0.0	0.0	50.0
Coal – resource	kg	8.4	0.0	625.4	0.0	0.0	0.0	633.9
Natural gas – resource	m^3	1.1	0.0	999.2	0.0	0.0	0.0	1,000.2
Oil – resource	m^3	0.3	0.1	18.9	0.0	0.0	0.0	19.2
CO_2 (fossil) to air	kg	18.9	0.2	3,115.4	0.0	0.0	-0.1	3,134.5
CO to air	kg	0.0	0.0	1.1	0.0	0.0	0.0	1.1
SO_x to air	kg	0.1	0.0	7.7	0.0	0.0	0.0	7.8
NO_x species to air	kg	0.1	0.0	7.0	0.0	0.0	0.0	7.0
N_2O to air	kg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH_4 to air	kg	0.1	0.0	13.1	0.0	0.0	0.0	13.2
VOC to air	kg	0.0	0.0	1.2	0.0	0.0	0.0	1.2
Particulates to air	kg	0.0	0.0	2.3	0.0	0.0	0.0	2.3
Hg to air	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	289.0	2.5	51,295.5	0.3	0.8	-1.6	51,586.4
Energy – Renewable	Mj	18.1	0.0	5,671.8	0.0	0.0	-0.1	5,689.8

Note: a negative number represents an environmental benefit

Table C1e Life Cycle Inventory – Baseline: 9% Recycling – Metal Halide (MH) lamps, 400W (100,000 hours operation)

	Unit	Manufacture	Import and distribution	Retail and use	Waste disposal NZ	Recycling	Displaced material benefits	Total
Total mercury use in lamp manufacture – internal flow	mg	50.0	0.0	0.0	0.0	0.0	0.0	50.0
Coal – resource	kg	13.0	0.0	1,667.8	0.0	0.0	0.0	1,680.8
Natural gas – resource	m^3	1.9	0.0	2,664.4	0.0	0.0	0.0	2,666.3
Oil – resource	m^3	0.5	0.1	50.3	0.0	0.0	0.0	50.9
CO_2 (fossil) to air	kg	29.2	0.3	8,307.7	0.0	0.1	-0.1	8,337.1
CO to air	kg	0.0	0.0	3.0	0.0	0.0	0.0	3.0
SO_x to air	kg	0.2	0.0	20.5	0.0	0.0	0.0	20.7
NOx species to air	kg	0.1	0.0	18.6	0.0	0.0	0.0	18.7
N_2O to air	kg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH_4 to air	kg	0.1	0.0	35.0	0.0	0.0	0.0	35.2
VOC to air	kg	0.0	0.0	3.1	0.0	0.0	0.0	3.1
Particulates to air	kg	0.0	0.0	6.1	0.0	0.0	0.0	6.1
Hg to air	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	469.6	4.0	136,788.1	0.4	1.3	-2.3	137,261.1
Energy – Renewable	Mj	23.6	0.0	15,124.9	0.0	0.0	-0.1	15,148.4

Note: a negative number represents an environmental benefit

Table C1f Life Cycle Inventory – Baseline: 9% Recycling – Mercury Vapour (MV) lamps, 250W (100,000 hours operation)

	Unit	Manufacture	Import and distribution	Retail and use	Waste disposal NZ	Recycling	Displaced material benefits	Total
Total mercury use in lamp manufacture – internal flow	mg	50.0	0.0	0.0	0.0	0.0	0.0	50.0
Coal – resource	kg	10.6	0.0	1,042.4	0.0	0.0	0.0	1,052.9
Natural gas – resource	m^3	1.1	0.0	1,665.3	0.0	0.0	0.0	1,666.4
Oil – resource	m^3	0.6	0.0	31.4	0.0	0.0	0.0	32.1
CO_2 (fossil) to air	kg	23.7	0.2	5,192.3	0.0	0.0	-0.1	5,216.2
CO to air	kg	0.0	0.0	1.8	0.0	0.0	0.0	1.9
SO_x to air	kg	0.2	0.0	12.8	0.0	0.0	0.0	13.0
NOx species to air	kg	0.1	0.0	11.6	0.0	0.0	0.0	11.7
N_2O to air	kg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH_4 to air	kg	0.1	0.0	21.9	0.0	0.0	0.0	22.0
VOC to air	kg	0.0	0.0	1.9	0.0	0.0	0.0	1.9
Particulates to air	kg	0.0	0.0	3.8	0.0	0.0	0.0	3.8
Hg to air	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	324.8	2.3	85,492.6	0.3	0.8	-2.0	85,818.7
Energy – Renewable	Mj	19.2	0.0	9,453.0	0.0	0.0	-0.1	9,472.2

Note: a negative number represents an environmental benefit.

C.2 Inventory Data for Whole Life

Table C2a to Table C2f the whole-life inventory results for each of the lamps assessed in the LCA for the following scenarios:

- Baseline performance for 2007: 9% recovery and recycling;
- Scenario 1: 50% recovery and recycling;
- Scenario 2: 80% recovery and recycling; and
- Scenario 3: 100% landfill.

Table C2a Life Cycle Inventory – Whole life – Linear fluorescent lamps (LFL), 35W, T8 (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total mercury use in lamp manufacture – internal flow	mg	0.0	0.0	0.0	0.0
Coal – resource	kg	165.0	165.1	165.1	165.0
Natural gas – resource	m^3	236.2	236.1	236.0	236.2
Oil – resource	m^3	5.2	5.2	5.1	5.3
CO_2 (fossil) to air	kg	771.2	771.0	770.8	771.2
CO to air	kg	0.3	0.3	0.3	0.3
SO_x to air	kg	2.1	2.1	2.1	2.1
NO_x species to air	kg	1.8	1.8	1.8	1.8
N_2O to air	kg	0.0	0.0	0.0	0.0
CH_4 to air	kg	3.3	3.3	3.3	3.3
VOC to air	kg	0.3	0.3	0.3	0.3
Particulates to air	kg	0.6	0.6	0.6	0.6
Hg to air	mg	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	12,526.8	12,520.6	12,516.1	12,528.2
Energy – Renewable	Mj	1,352.6	1,355.5	1,357.6	1,352.0

Table C2b Life Cycle Inventory – Whole life – Compact fluorescent lamps (CFLe) 11W: external ballast (100,000 hours operation)

	Unit	Baseline	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total mercury use in lamp manufacture – internal flow	mg	0.0	0.0	0.0	0.0
Coal – resource	kg	52.9	52.9	52.9	52.9
Natural gas – resource	m^3	74.5	74.4	74.3	74.5
Oil – resource	m^3	1.8	1.7	1.7	1.8
CO_2 (fossil) to air	kg	245.2	244.9	244.7	245.2
CO to air	kg	0.1	0.1	0.1	0.1
SO_x to air	kg	0.7	0.7	0.7	0.7
NO_x species to air	kg	0.6	0.6	0.6	0.6
N_2O to air	kg	0.0	0.0	0.0	0.0
CH_4 to air	kg	1.1	1.1	1.1	1.1
VOC to air	kg	0.1	0.1	0.1	0.1
Particulates to air	kg	0.2	0.2	0.2	0.2
Hg to air	mg	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	3,977.0	3,970.1	3,965.1	3,978.5
Energy – Renewable	Mj	427.3	427.4	427.4	427.3

Table C2c Life Cycle Inventory – Whole life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total mercury use in lamp manufacture – internal flow	mg	0.0	0.0	0.0	0.0
Coal – resource	kg	101.0	101.0	100.9	101.0
Natural gas – resource	m^3	136.6	136.5	136.4	136.7
Oil – resource	m^3	4.1	4.0	3.9	4.1
CO_2 (fossil) to air	kg	456.4	456.0	455.8	456.5
CO to air	kg	0.2	0.2	0.2	0.2
SO_x to air	kg	1.4	1.4	1.3	1.4
NO_x species to air	kg	1.1	1.1	1.1	1.1
N_2O to air	kg	0.0	0.0	0.0	0.0
CH_4 to air	kg	1.9	1.9	1.9	1.9
VOC to air	kg	0.2	0.2	0.2	0.2
Particulates to air	kg	0.4	0.4	0.4	0.4
Hg to air	mg	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	7,440.8	7,429.9	7,421.9	7,443.2
Energy – Renewable	Mj	789.9	789.6	789.5	789.9

Table C2d Life Cycle Inventory – Whole life – High pressure sodium (HPS) lamps, 150W (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total mercury use in lamp manufacture – internal flow	mg	0.0	0.0	0.0	0.0
Coal – resource	kg	633.9	633.8	633.8	633.9
Natural gas – resource	m^3	1,000.2	1,000.2	1,000.2	1,000.2
Oil – resource	m^3	19.2	19.2	19.1	19.2
CO_2 (fossil) to air	kg	3,134.5	3,134.2	3,134.1	3,134.5
CO to air	kg	1.1	1.1	1.1	1.1
SO_x to air	kg	7.8	7.8	7.8	7.8
NO_x species to air	kg	7.0	7.0	7.0	7.0
N_2O to air	kg	0.0	0.0	0.0	0.0
CH_4 to air	kg	13.2	13.2	13.2	13.2
VOC to air	kg	1.2	1.2	1.2	1.2
Particulates to air	kg	2.3	2.3	2.3	2.3
Hg to air	mg	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	51,586.4	51,582.5	51,579.6	51,587.3
Energy – Renewable	Mj	5,689.8	5,689.3	5,688.9	5,689.9

‘tbc’ means ‘to be confirmed’

Table C2e Life Cycle Inventory – Whole life – Metal Halide (MH) lamps, 400W (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total mercury use in lamp manufacture – internal flow	mg	0.0	0.0	0.0	0.0
Coal – resource	kg	1,680.8	1,680.8	1,680.8	1,680.8
Natural gas – resource	m^3	2,666.3	2,666.3	2,666.2	2,666.3
Oil – resource	m^3	50.9	50.8	50.8	50.9
CO_2 (fossil) to air	kg	8,337.1	8,336.9	8,336.8	8,337.2
CO to air	kg	3.0	3.0	3.0	3.0
SO_x to air	kg	20.7	20.7	20.7	20.7
NO_x species to air	kg	18.7	18.7	18.7	18.7
N_2O to air	kg	0.0	0.0	0.0	0.0
CH_4 to air	kg	35.2	35.2	35.2	35.2
VOC to air	kg	3.1	3.1	3.1	3.1
Particulates to air	kg	6.1	6.1	6.1	6.1
Hg to air	mg	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	137,261.1	137,256.4	137,253.0	137,262.2
Energy – Renewable	Mj	15,148.4	15,147.9	15,147.5	15,148.5

Table C2f Life Cycle Inventory – Whole life – Mercury Vapour (MV) lamps, 250W (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total mercury use in lamp manufacture – internal flow	mg	0.0	0.0	0.0	0.0
Coal – resource	kg	1,052.9	1,052.9	1,053.0	1,052.9
Natural gas – resource	m^3	1,666.4	1,666.3	1,666.3	1,666.4
Oil – resource	m^3	32.1	32.0	31.9	32.1
CO_2 (fossil) to air	kg	5,216.2	5,216.1	5,216.0	5,216.2
CO to air	kg	1.9	1.9	1.9	1.9
SO_x to air	kg	13.0	13.0	13.0	13.0
NO_x species to air	kg	11.7	11.7	11.7	11.7
N_2O to air	kg	0.0	0.0	0.0	0.0
CH_4 to air	kg	22.0	22.0	22.0	22.0
VOC to air	kg	1.9	1.9	1.9	1.9
Particulates to air	kg	3.8	3.8	3.8	3.8
Hg to air	mg	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	85,818.7	85,813.4	85,809.4	85,819.9
Energy – Renewable	Mj	9,472.2	9,472.0	9,471.9	9,472.2

C.3 Inventory Data for End-of-Life Phase

Table C3a to Table C3f presents the end-of-life inventory results for each of the lamps assessed in the LCA for the following scenarios:

- Baseline performance for 2007: 9% recovery and recycling;
- Scenario 1: 50% recovery and recycling;
- Scenario 2: 80% recovery and recycling; and
- Scenario 3: 100% landfill.

Table C3a Life Cycle Inventory – End-of-Life Only – Linear fluorescent lamps (LFL), 35W, T8 (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total mercury use in lamp manufacture – internal flow	mg	0.0	0.0	0.0	0.0
Coal – resource	kg	0.0	0.0	0.1	0.0
Natural gas – resource	m^3	0.0	-0.1	-0.2	0.0
Oil – resource	m^3	0.0	-0.1	-0.1	0.0
CO_2 (fossil) to air	kg	0.0	-0.2	-0.3	0.0
CO to air	kg	0.0	0.0	0.0	0.0
SO_x to air	kg	0.0	0.0	0.0	0.0
NO_x species to air	kg	0.0	0.0	0.0	0.0
N_2O to air	kg	0.0	0.0	0.0	0.0
CH_4 to air	kg	0.0	0.0	0.0	0.0
VOC to air	kg	0.0	0.0	0.0	0.0
Particulates to air	kg	0.0	0.0	0.0	0.0
Hg to air	mg	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	-0.8	-7.0	-11.5	0.6
Energy – Renewable	Mj	0.6	3.5	5.6	0.0

Note: a negative number represents an environmental benefit.

Table C3b Life Cycle Inventory – End-of-Life Only – Compact fluorescent lamps (CFLe) 11W: external ballast (100,000 hours operation)

	Unit	Baseline	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total mercury use in lamp manufacture – internal flow	mg	0.0	0.0	0.0	0.0
Coal – resource	kg	0.0	0.0	0.0	0.0
Natural gas – resource	m^3	0.0	-0.1	-0.2	0.0
Oil – resource	m^3	0.0	-0.1	-0.1	0.0
CO_2 (fossil) to air	kg	0.0	-0.3	-0.5	0.0
CO to air	kg	0.0	0.0	0.0	0.0
SO_x to air	kg	0.0	0.0	0.0	0.0
NO_x species to air	kg	0.0	0.0	0.0	0.0
N_2O to air	kg	0.0	0.0	0.0	0.0
CH_4 to air	kg	0.0	0.0	0.0	0.0
VOC to air	kg	0.0	0.0	0.0	0.0
Particulates to air	kg	0.0	0.0	0.0	0.0
Hg to air	mg	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	-1.3	-8.1	-13.2	0.2
Energy – Renewable	Mj	0.0	0.0	0.1	0.0

Note: a negative number represents an environmental benefit.

Table C3c Life Cycle Inventory – End-of-Life Only – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total mercury use in lamp manufacture – internal flow	mg	0.0	0.0	0.0	0.0
Coal – resource	kg	0.0	0.0	0.0	0.0
Natural gas – resource	m^3	0.0	-0.2	-0.3	0.0
Oil – resource	m^3	0.0	-0.1	-0.2	0.0
CO_2 (fossil) to air	kg	-0.1	-0.5	-0.7	0.0
CO to air	kg	0.0	0.0	0.0	0.0
SO_x to air	kg	0.0	0.0	0.0	0.0
NO_x species to air	kg	0.0	0.0	0.0	0.0
N_2O to air	kg	0.0	0.0	0.0	0.0
CH_4 to air	kg	0.0	0.0	0.0	0.0
VOC to air	kg	0.0	0.0	0.0	0.0
Particulates to air	kg	0.0	0.0	0.0	0.0
Hg to air	mg	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	-2.0	-12.9	-20.9	0.4
Energy – Renewable	Mj	0.0	-0.3	-0.4	0.0

Note: a negative number represents an environmental benefit.

Table C3d Life Cycle Inventory – End-of-Life Only – High pressure sodium (HPS) lamps, 150W (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total mercury use in lamp manufacture – internal flow	mg	0.0	0.0	0.0	0.0
Coal – resource	kg	0.0	0.0	0.0	0.0
Natural gas – resource	m^3	0.0	0.0	-0.1	0.0
Oil – resource	m^3	0.0	0.0	-0.1	0.0
CO_2 (fossil) to air	kg	0.0	-0.2	-0.4	0.0
CO to air	kg	0.0	0.0	0.0	0.0
SO_x to air	kg	0.0	0.0	0.0	0.0
NO_x species to air	kg	0.0	0.0	0.0	0.0
N_2O to air	kg	0.0	0.0	0.0	0.0
CH_4 to air	kg	0.0	0.0	0.0	0.0
VOC to air	kg	0.0	0.0	0.0	0.0
Particulates to air	kg	0.0	0.0	0.0	0.0
Hg to air	mg	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	-0.6	-4.5	-7.4	0.3
Energy – Renewable	Mj	-0.1	-0.6	-1.0	0.0

Note: a negative number represents an environmental benefit.

Table C3e Life Cycle Inventory – End-of-Life Only – Metal Halide (MH) lamps, 400W (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total mercury use in lamp manufacture – internal flow	mg	0.0	0.0	0.0	0.0
Coal – resource	kg	0.0	0.0	0.0	0.0
Natural gas – resource	m^3	0.0	-0.1	-0.1	0.0
Oil – resource	m^3	0.0	-0.1	-0.1	0.0
CO_2 (fossil) to air	kg	0.0	-0.2	-0.4	0.0
CO to air	kg	0.0	0.0	0.0	0.0
SO_x to air	kg	0.0	0.0	0.0	0.0
NO_x species to air	kg	0.0	0.0	0.0	0.0
N_2O to air	kg	0.0	0.0	0.0	0.0
CH_4 to air	kg	0.0	0.0	0.0	0.0
VOC to air	kg	0.0	0.0	0.0	0.0
Particulates to air	kg	0.0	0.0	0.0	0.0
Hg to air	mg	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	-0.6	-5.3	-8.7	0.5
Energy – Renewable	Mj	-0.1	-0.6	-1.0	0.0

Note: a negative number represents an environmental benefit.

Table C3f Life Cycle Inventory – End-of-Life Only – Mercury Vapour (MV) lamps, 250W (100,000 hours operation)

	Unit	Baseline: 9% recovery and recycling	Scenario 1: 50% recovery and recycling	Scenario 2: 80% recovery and recycling	Scenario 3: 100% landfill
Total mercury use in lamp manufacture – internal flow	mg	0.0	0.0	0.0	0.0
Coal – resource	kg	0.0	0.0	0.0	0.0
Natural gas – resource	m^3	0.0	-0.1	-0.1	0.0
Oil – resource	m^3	0.0	-0.1	-0.1	0.0
CO_2 (fossil) to air	kg	0.0	-0.1	-0.2	0.0
CO to air	kg	0.0	0.0	0.0	0.0
SO_x to air	kg	0.0	0.0	0.0	0.0
NO_x species to air	kg	0.0	0.0	0.0	0.0
N_2O to air	kg	0.0	0.0	0.0	0.0
CH_4 to air	kg	0.0	0.0	0.0	0.0
VOC to air	kg	0.0	0.0	0.0	0.0
Particulates to air	kg	0.0	0.0	0.0	0.0
Hg to air	mg	0.0	0.0	0.0	0.0
Hg to water	mg	0.0	0.0	0.0	0.0
Hg to land	mg	0.0	0.0	0.0	0.0
Other heavy metals to air, water and land	mg	0.0	0.0	0.0	0.0
Energy – Non renewable	Mj	-0.9	-6.2	-10.2	0.3
Energy – Renewable	Mj	0.0	-0.2	-0.3	0.0

Note: a negative number represents an environmental benefit.

Appendix D: LCIA Results

D.1 Impact Assessment Results for IMPACT 2002+ and TRACI Methods

Table D1a shows the whole-life inventory results for each of the lamps assessed in the LCA using the IMPACT 2002+ method for the baseline scenario for 2007: 9% recovery and recycling. Table D1b shows the IMPACT 2002+ results by life cycle stage for the CFLi lamp. Refer to Section 5.4 for discussion and interpretation of these results.

Table D1a Environmental Impacts for IMPACT 2002+ method – Whole life – (100,000 hours operation for baseline scenario of 9% recycling)

Impact Category	Unit	1. Linear fluorescent lamp (LFL)	2. Compact fluorescent lamp (CFL)	3. Compact fluorescent lamp (CFL)	4. High pressure sodium (HPS)	5. Metal Halide (MH))	6. Mercury Vapour (MV))
Carcinogens	kg C_2H_3Cl eq	0.81	0.28	0.70	2.74	7.26	4.45
Non-carcinogens	kg C_2H_3Cl eq	3.16	1.06	2.65	9.62	24.29	15.24
Respiratory inorganics	kg PM2.5 eq	0.56	0.18	0.35	2.18	5.76	3.61
Ionizing radiation	Bq C-14 eq	791	266	1,122	2,784	6,719	3,982
Ozone layer depletion	kg CFC-11 eq	0.00	0.00	0.00	0.00	0.00	0.00
Respiratory organics	kg C_2H_4 eq	0.20	0.06	0.14	0.85	2.26	1.42
Aquatic ecotoxicity	kg TEG water	52,468	16,859	38,222	222,878	591,677	369,422
Terrestrial ecotoxicity	kg TEG soil	14,609	4,710	9,319	62,768	165,789	103,518
Terrestrial acid/nutri	kg SO_2 eq	12.08	3.90	7.43	47.68	126.46	79.22
Land occupation	m2org.arable	2.33	0.74	1.34	9.77	26.01	16.26
Aquatic acidification	kg SO_2 eq	3.43	1.14	2.19	13.18	34.90	21.88
Aquatic eutrophication	kg PO_4 P-lim	0.01	0.00	0.00	0.03	0.07	0.04
Global warming	kg CO_2 eq	804	255	476	3,266	8,687	5,435
Non-renewable energy	MJ primary	12,972	4,117	7,697	53,503	142,374	89,014
Mineral extraction	MJ surplus	1.45	0.92	7.89	7.20	8.35	2.78

Table D1b Environmental Impacts for IMPACT 2002+ method – Whole life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

Impact Category	Unit	Manufacture	Import and distribution	Retail and use	Waste disposal NZ	Recycling	Displaced material benefits	Total
Carcinogens	kg C_2H_3Cl eq	51%	0%	49%	0%	0%	-1%	100%
Non-carcinogens	kg C_2H_3Cl eq	56%	0%	44%	0%	0%	0%	100%
Respiratory inorganics	kg $PM_{2.5}$ eq	19%	0%	81%	0%	0%	0%	100%
Ionizing radiation	Bq C-14 eq	75%	0%	25%	0%	0%	0%	100%
Ozone layer depletion	kg CFC-11 eq	3%	0%	97%	0%	0%	0%	100%
Respiratory organics	kg C_2H_4 eq	18%	0%	81%	0%	0%	0%	100%
Aquatic ecotoxicity	kg TEG water	23%	0%	77%	0%	0%	0%	100%
Terrestrial ecotoxicity	kg TEG soil	11%	0%	88%	1%	0%	0%	100%
Terrestrial acid/nutri	kg SO_2 eq	15%	0%	85%	0%	0%	0%	100%
Land occupation	m2org.arable	3%	0%	97%	0%	0%	0%	100%
Aquatic acidification	kg SO_2 eq	-	-	-	-	-	-	-
Aquatic eutrophication	kg PO_4 P-lim	-	-	-	-	-	-	-
Global warming	kg CO_2 eq	9%	0%	91%	0%	0%	0%	100%
Non-renewable energy	MJ primary	8%	0%	92%	0%	0%	0%	100%
Mineral extraction	MJ surplus	99%	0%	1%	0%	0%	0%	100%

Table D1c shows the whole-life inventory results for each of the lamps assessed in the LCA using the TRACI 2 method for the baseline scenario for 2007: 9% recovery and recycling. Table D1d shows the TRACI 2 results by life cycle stage for the CFLi lamp. Refer to Section 5.4 for discussion and interpretation of these results.

Table D1c Environmental Impacts for TRACI method – Whole life – (100,000 hours operation for baseline scenario of 9% recycling)

Impact Category	Unit	1. Linear fluorescent lamp (LFL)	2. Compact fluorescent lamp (CFL)	3. Compact fluorescent lamp (CFL)	4. High pressure sodium (HPS)	5. Metal Halide (MH))	6. Mercury Vapour (MV))
Global Warming	kg CO_2 eq	976	310	575	3,989	10,613	6,640
Acidification	H+ moles eq	181	60	115	695	1,839	1,153
Carcinogenics	benzene eq	0.20	0.07	0.37	0.83	1.80	1.05
Non carcinogenics	toluene eq	1,904	626	2,014	7,931	20,609	12,806
Respiratory effects	kg $PM_{2.5}$ eq	0.99	0.33	0.63	3.79	10.03	6.29
Eutrophication	kg N eq	0.09	0.03	0.06	0.37	0.97	0.61
Ozone depletion	kg CFC-11 eq	0.000139	0.000044	0.000081	0.000592	0.001578	0.000986
Ecotoxicity	kg 2,4-D eq	750	246	513	2,809	7,404	4,642
Smog	kg NOx eq	1.81	0.58	1.09	7.20	19.11	11.97

Table D1d Environmental Impacts for TRACI method – Whole life – Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation)

Impact Category	Unit	Manufacture	Import and distribution	Retail and use	Waste disposal NZ	Recycling	Displaced material benefits	Total
Global Warming	%	8%	0.0%	92%	0.0%	0.0%	0.0%	100%
Acidification	%	21%	0.1%	79%	0.0%	0.0%	-0.2%	100%
Carcinogenics	%	79%	0.0%	21%	0.0%	0.0%	-0.1%	100%
Non carcinogenics	%	50%	0.0%	50%	0.1%	0.0%	-0.2%	100%
Respiratory effects	%	21%	0.1%	79%	0.0%	0.0%	-0.2%	100%
Eutrophication	%	24%	0.3%	76%	0.0%	0.0%	-0.2%	100%
Ozone depletion	%	3%	0.0%	97%	0.0%	0.0%	0.0%	100%
Ecotoxicity	%	29%	0.0%	71%	0.0%	0.0%	-0.1%	100%
Smog	%	13%	0.2%	87%	0.0%	0.0%	-0.1%	100%

D.2 Impact Assessment Results for Offset Materials

Table D2a Life Cycle Impact Results for Offset Materials – Whole life – 1kg of each material

	Unit	Mercury	Flat glass	Aluminium	Brass	Nickel	Polyurethane	Phosphorus
Abiotic depletion	kg Sb eq	0.72	0.01	0.07	0.02	0.07	0.04	0.14
Acidification	kg SO_2 eq	0.48	0.01	0.06	0.12	1.71	0.02	0.07
Eutrophication	kg PO_4^{-3} eq	0.02	0.001	0.01	0.004	0.01	0.003	0.01
Global warming	kg CO_2 eq	64.72	0.69	12.04	2.65	11.84	4.38	15.12
Ozone layer depletion	kg CFC-11 eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Human toxicity	kg 1,4-DB eq	567.7	0.25	55.4	64.6	44.5	0.71	1.77
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	31.88	0.04	5.64	1.88	29.73	0.18	0.51
Marine aquatic ecotoxicity	kg 1,4-DB eq	134,236	108.2	6,708	3,327	32782.8	166.9	1103.2
Terrestrial ecotoxicity	kg 1,4-DB eq	2,461	0.002	0.14	0.32	0.25	0.01	0.07
Photochemical oxidation	kg C_2H_4	0.03	0.00	0.01	0.01	0.07	0.00	0.01

D.3 Impact Assessment Results for Packaging and Fittings

Table D3a Life Cycle Impact Results for Packaging and Fittings for Compact fluorescent lamps (CFLi) 20W: integral ballast (100,000 hours operation) – Whole life

	Unit	CFLi fittings	CFLi packaging
Abiotic depletion	kg Sb eq	0.06	0.00
Acidification	kg SO_2 eq	0.03	0.00
Eutrophication	kg PO_4^{-3} eq	0.005	0.00
Global warming	kg CO_2 eq	7.97	0.03
Ozone layer depletion	kg CFC-11 eq	0.00	0.00
Human toxicity	kg 1,4-DB eq	24.71	0.01
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	5.17	0.003
Marine aquatic ecotoxicity	kg 1,4-DB eq	4958.91	2.83
Terrestrial ecotoxicity	kg 1,4-DB eq	0.07	0.00
Photochemical oxidation	kg C_2H_4	0.005	0.00

Appendix E: Peer Review Panel Comments and Responses

Critical Review Panel

Life Cycle Assessment of Product Stewardship Options for Mercury-Containing Lamps In New Zealand

Review Statement on Draft Final Report

Members of Review Panel:	**Dr Sarah McLaren (Chair)**	**Landcare Research**
	Dr Barbara Nebel	**Scion**
	Dr Donald Hannah	**ERMA**
Date of meetings:	**Thursday 28th May 2009, 3.00 pm to 4.15 pm**	
	Tuesday 2nd June 2009, 9.00 am to 10.30 am	
	Friday 5th June 2009, 11.30 am to 12.40 pm	

Summary

The Ministry for the Environment has contracted ERM to undertaken an LCA study of mercury-containing lamps – in the context of development of a product stewardship scheme for these products in New Zealand. A Critical Review Panel for the study was set up by the Ministry for the Environment consisting of Dr Donald Hannah (ERMA), Dr Sarah McLaren (Landcare Research) and Dr Barbara Nebel (Scion). Dr Sarah McLaren was appointed Chair of the Panel.

This document provides a summary of the Critical Review Panel's assessment of the draft Final Report provided by ERM in May 2009. It is divided into: General Comments, Main Comments (for each section of the report), Minor Comments, and Reporting.

General Comments

Modelling use of mercury

Our understanding is that there is very little mercury now sourced from primary mining and that the mercury used in the fabrication of energy efficient lighting products is almost completely sourced from recycled mercury (either from recovery processes or from mercury from phased-out industrial processes). The UNEP Global Mercury Programme (http://www.chem.unep.ch/mercury/default.htm) is a good source and starting point for following this up. We think that, if this is taken into account, the conclusions of the report with respect to mercury are likely to be significantly different. ERM response (1): The study has been updated to reflect recycled and recovered sources of mercury in lamp production. This has been updated based on recently published and available data. Based on the predominant countries of lamp manufacture: mercury used in China is predominantly from primary sources; mercury used in Thailand relates to both primary and recycled sources; while in the EU, mercury is primarily from recycled sources. Further specific references and updates to the LCI/LCIA results are presented in the final report. In terms of effect on final results, the above changes do not affect the main focus and overall conclusions of the report in any material way. Overall, results in relation to the emissions and impacts of mercury have altered as follows:

- LCI flows and LCIA results remain almost unchanged for whole life results and end-of-life only results. Emissions of mercury to air and to land are dominated by the end-of-life stage. Emissions to water are dominated by end-of-life and the manufacturing stage (for manufacturing this is from other (i.e. non-mercury) material production and electricity generation).

- For whole-life human toxicity impacts mercury contribution reduces by around 10%; although, total mercury contribution still remains below 0.5% for whole life. For end-of-life only human toxicity impacts, mercury contribution to water and soil remain unchanged, but for emissions to water, these reduce by around 50%. This reduction is due to the changes in offset benefits of the above modifications. Nevertheless, the same overall conclusions are drawn from the results.

In general, it was difficult to check modelling calculations because insufficient data have been supplied in the report. ERM response (2): See responses below from ERM on specific areas where additional data have been requested.

We recommend that further details are provided throughout the text on quantities of mercury emissions released to different media. ERM response (3): Additional resolution of data has been added in where LCI results are presented in *Section 4* of the main report and *Appendix C*.

Modelling use of recycled aluminium, nickel and brass

Following on from the comment about use of recycled mercury above, we consider that further details should be provided about the modelling assumptions for avoided use of aluminium, nickel and brass. This is particularly in view of the fact that modelling of these metals appears to make a big contribution to the toxicity impact category results (as stated in Sections 5.4.2 and 6.4). ERM response (4): Additional descriptive text has been added for these inventories as presented in *Appendix B, Section B.10*.

Main Comments: Goal

Section 2.1

As per our comments in the earlier Review of the Goal and Scope Document, we consider that Section 2.1 should provide a fuller explanation of why there is a particular focus in the study on end-of-life management and mercury use in lamps. ERM response (5): The original scope of work as defined by the Ministry for the Environment in New Zealand was to focus only on these aspects. Additional descriptive text has been added in *Section 2.1* to this effect.

The different scenarios are listed in Section 2.1. We suggest that these are numbered as Baseline Scenarios 1 to 6, and that there is consistency in using these scenarios throughout the document. In the current report, a Baseline Scenario with 9% recovery and recycling appears in the Impact Assessment results, and it is not clear how this relates to the list of scenarios in Section 2.1. ERM response (6): Scenarios have been labelled as suggested, in order to ease interpretation and clarity of the results.

Also, for scenarios 4 to 6, what is the technically feasible minimum? ERM response (7): The technically feasible minimum has been estimated based on a 10% reduction in mercury content. This was estimated as the maximum mercury reduction that the manufacturers, which we were in contact with, felt could be achieved without significant changes in lamp design and unacceptable loss in performance. Appendix B, Section B.11 presents the lamp mercury levels assessed in the study. No additions or amendments to the report have been made.

Section 3.3.2

As indicated in our earlier comments on the Goal and Scope Definition, the packaging and fittings/gear are not the same across the different lamp types, and so the sentences in Section 3.3.2 (p.18 and p.20) stating that the packaging and fitting gear are identical for the different lamp types is incorrect. ERM response (8): The peer review panel has not read the text correctly as shown in the final report and this has been misinterpreted, as follows:

- the sentence on page 18 which states "*The following exclusions are made due to these being the same for each typical lamp type*".
- the sentence on page 18 which states *"This is excluded because these components are identical within each lamp type".*

This does not state "across" lamp types, but "within" each lamp type – meaning that "within" each of the six lamp types assessed the packaging and fittings/gear are identical.

In order to provide additional clarity, and as described in *Section 2.1* of the LCA report, the goal of the study was to "*…to assess the potential life cycle environmental impacts associated with the production, use and end-of-life management options for individual types of mercury-containing lamps in New Zealand. […] The study does not to provide comparative results across the different lamp types. This is because the lamps offer a different function and performance characteristics relating to lamp lifetime, lamp output (in terms of wattage) and in terms of lamp application (although application may be the same in many cases for CFLe and CFLi lamps). As such the lamps are not functionally the same and should not be directly compared.* "

Consequently, for the intended goal of the study, the "packaging and fittings/gear" are identical within each of the six typical lamp types assessed. The study therefore excludes these from the assessment when making a comparison "within" each lamp type. The comparison is made within each lamp type according to changes in recycling/recovery rates at end-of-life, alternate life times, alternate operating efficiency and alternate mercury levels in the product.

Also, we note that the current version includes the packaging, product fittings and control gear at sensitivity analysis, and so this section needs to be updated to reflect the current study. ERM response (9): The final report reflects the inclusion of a sensitivity analysis that addresses packaging and product fittings.

As an aside, we note from Figure 13 that the inclusion of packaging and fittings actually makes a 25% difference to the Freshwater Aquatic Ecotoxicity result (and a 15% difference to the Human Toxicity and Marine Aquatic Ecotoxicity results) for the compact fluorescent lamps with integral ballast. Therefore it is important to be take account of these ancillary items from a whole-of-life-cycle perspective. ERM response (10): Refer to *comment 8* above for their exclusion from the study.

Main Comments: Inventory Analysis

Data in Inventory Analysis (Section 3.7)

In general, it was difficult to check calculations because no data are supplied in this section. We feel the study would be more transparent if data on actual use of materials and energy are provided in this section. For example, Table 4 provides details on lamp composition; this could be moved to Section 3.7, and augmented with information on the specific datasets used for each of the materials. ERM response (11): All data are provided *Appendix B* of the report which clearly and logically identifies all assumptions and data sources. Please refer to *Appendix B* of the main report for these details. No additions or amendments to the report have been made.

More details are also required in this section on actual energy use for each lamp type and other data assumptions and datasets used for each scenario. A clearer description of each life cycle stage with associated assumptions and data would provide further clarity in this section. ERM response (12): All data are provided *Appendix B* of the report which clearly and logically identifies all assumptions and data sources. Please refer to Appendix B of the main report for these details. No additions or amendments to the report have been made.

Main Comments: Impact Assessment and Interpretation

Impacts of end-of-life

Informing end-of-life management options is stated specifically in the goal of the study. In this context it is valid to look at the end-of-life stage of the life cycle separately. However, the results need to be presented in a way that reflects the relative importance of this life cycle stage.

In order to allow an interpretation of the reported results, their relative importance should be stated. How significant is, for example, a saving of 0.8 kg of CO_2 equivalents? (Last paragraph in Section 5.2). ERM response (13): All results are presented initially as the entire life cycle which provides context for the end-of-life phase. Where numerical results have been presented in the interpretation for the end-of-life phase, these have also been shown as percentage in terms of whole-life, as the example suggested by the review panel in *Section 5.2*.

Impacts of reduced mercury in lamps

Based on our understanding that mercury used in the fabrication of energy efficient lighting products is almost completely sourced from recycled mercury (see General Comments above), the results for terrestrial ecotoxicity will change. ERM response (14): Refer to comment 1 from ERM for additions and amendments to the LCA study and effect on results that have been made. No additional amendments made to the LCA report.

Results using different Impact Assessment methodologies

The choice of Impact 2002+ and TRACI are in general regarded as appropriate by the Review Panel. However, it is stated that health impacts related to mercury are excluded in the TRACI methodology. It would be good to state if impacts related to mercury are included elsewhere in this methodology**.** ERM response (15): The LCA report in *Section 5.4* has been updated.

For the interpretation and transparency of the study, we recommend to include the results of the alternative Impact Assessments, i.e. to provide data related to the statements made in the last paragraph on p.61.

ERM response (16): The LCA report has been updated to provide some additional results tables of these two methods.

Section 5.4.2: End-of-life results

It is stated in Section 5.4.2 that nickel, brass and aluminium play an important role. We recommend quantifying the results for those metals in order to increase the transparency of the study. ERM response (17): The LCA report has been updated with some additional LCIA results tables of these materials, which includes material extraction, production and transportation to point of manufacture.

Brass is not mentioned in Appendix B.10. ERM response (18): Brass has been added to *Appendix B.10*.

Main Comments: Interpretation

Impacts of lamp warm-up and impacts of improved energy efficiency in the use phase

This scenario requires more detail with regard to the 'warm-up' effect. Quantifying the increased energy use as well as the increase in environmental impacts would help to clarify the second paragraph. ERM response (19): An additional Table has been added to *Appendix B.11* to show the changes in energy consumption from warm-up effects. The Figure shown in *Section 6.2* provides results which quantify the changes that result from warm-up effect sin relation to the baseline scenario.

Does the "0.5% scenario" in Figure 10 relate to the warm up effect? This needs clarification. ERM response (20): The 0.5% scenario relates to the scenario for warm-up effects. The 0.5% represents the percentage difference in energy usage compared to baseline, as described in *Appendix B.11*. The *Figure* in *Section 6.2* of the LCA report has been updated to identify this scenario more clearly.

The title of this scenario also does not correspond with the scenarios listed on page 67. ERM response (21): The *Figure* in *Section 6.2* of the LCA report has been updated to reflect same names as shown on page 67.

Section 6.3: Impacts of open- and closed-loop recycling

The terms 'open-loop' and 'closed-loop' recycling requires a short explanation.

The second sentence in the third paragraph needs clarification. ERM response (22): Additional text to clarify has been added to *Section 6.3* of the LCA report.

Section 6.4

The text in Section 6.4 does not correspond with the related Figures in all aspects. The second Figure 12 (see also minor comment related to p.75/76) shows environmental benefits for fresh and marine ecotoxicity - the words 'and fresh and marine water' therefore need to be deleted in the third paragraph. ERM response (23): Agreed. Interpretation of results should only relate to terrestrial ecotoxicity. Text shown in Section 6.4 has been amended.

The last paragraph is also not in line with the second Figure 12. The text states that increased levels of recycling improve the environmental performance. This is also what would be expected due to reduced emissions from the disposal stage. The second Figure 12, however, shows opposite results except for terrestrial ecotoxicity. ERM response (24): Agreed. Interpretation of results should have stated 'decreased' rather than 'increased' in the first sentence of last paragraph. The second sentence of the last paragraph has been updated to reflect the results correctly.

Section 6.5: Potential impacts of packaging and fittings

Providing separate results for packaging and fittings would increase the transparency of the results. Also this section states that packaging has a negligible effect, it would be good to provide the data for this. ERM response (25): The LCA report has been updated in the appendix to provide some additional LCIA results tables of the packaging materials, which includes material extraction, production and transportation to point of manufacture.

Figure 13 shows an approximate increase for fresh water ecotoxicity of 25%. As noted earlier in this Review, this seems to be a significant change and should be reflected in the text. ERM response (26): The text has been updated to reflect the scale of changes in the results compared to the baseline.

Main Comments: Conclusions

Mercury contribution

The first sentence of Section 7.2.1 needs some clarification. We realise that this section is within the section on ‘End-of-Life Conclusions’, but the reference to ‘total impacts’ in section 7.2.1 is slightly misleading. We recommend changing it to “end-of-life” impacts. ERM response (27): The LCA report text has been updated in *Section 7.2.1* to reflect recommendation.

Minor Comments

p.19 In Figure 1 it would be clearer to draw a labelled system boundary around the system under analysis i.e. it includes the “energy supply systems” and “other product systems” but excludes the “environment” categories at the top and bottom of the diagram. ERM response (28): The LCA report has been updated to reflect recommendation.

p.21 Section 3.4.1 first sentence, provide a reference to justify the source for stating that system expansion “should” be applied. . ERM response (29): The LCA report has been updated to reflect this comment.

p.22 The reference for the equation under Figure 2 should be stated. ERM response (30): The LCA report has been updated to reflect recommendation.

p. 23 Why does the second paragraph refer to ‘provisional’ results? . ERM response (31): Incorrect text shown in the LCA report. The LCA report has been updated to reflect this comment.

p.24 We do not understand the sentence in the second paragraph, “an estimate is used for geothermal electricity generation based on hydro generation.” ERM response (32): The LCA report has been updated to provide further clarification. Appendix B provides specific details and assumptions used.

p.24 Regarding the “Lamp energy consumption” paragraph, we note that the sensitivity analysis in Section 6.2 (p.70) considers a situation where there is both increased power required in the initial period of operation AND a 10% improvement in energy efficiency over the lifetime of the lamps. Is there a direct correlation between these two aspects? If not, why have the two been considered together at sensitivity analysis? ERM response (33): There is no direct correlation between these two sensitivities. Nor have the results been aggregated in any way as presented in Section 6.2. The results are simply shown in the same section and the same results figure in order to provide a useful comparison on the same results Figure to indicate scale of difference between these changes associated with baseline versus a 10% improvement in energy efficiency and lamp warm-up effects. No changes or updates made to the LCA report.

p.27 Section 3.6.3 The International Journal of LCA is not a database ERM response (34): The LCA report has been updated to reflect this comment.

p.29 Table 6 does not include PAH and NMVOC yet these groups of substances make the biggest contribution to Human Toxicity (Section 5.4.1). We are not sure of the overall value of Table 6. ERM response (35): The LCA report has been updated to reflect this recommendation. The Table has been deleted from the report.

p.31 Section 3.9 mentions “provisional results” but presumably these should be final results. ERM response (36): Incorrect text shown in the LCA report. The LCA report has been updated to reflect this comment.

p. 38 Add ‘abiotic’ in first bullet point (depletion of abiotic resources) ERM response (37): The LCA report has been updated to reflect this comment.

p. 46 Table 10 – change unit for Eutrophication potential to PO_4^{-3} ERM response (38): The LCA report has been updated to reflect this comment.

p. 47 Figure 9 – Abbreviations are only provided for GWP and ODP not for other impact categories. ERM response (39): No update made to LCA report.

Add ‘)’ after ODP abbreviation. ERM response (40): No changes have been made to the report. This minor formatting issue hasn’t been easy to resolve with the LCA software used.

p. 55 Numbering of Figures from here to the end of the report needs to be checked. Figure on page 55 is Figure 3 – there was already a Figure 3 on page 40. ERM response (41): The LCA report has been updated to reflect this comment.

p. 62 It is not obvious from the caption for Table 13 that is relates to the base scenario. This should be stated in the caption. ERM response (42): The LCA report has been updated to reflect this comment.

p. 64 4th paragraph – 2nd sentence. This sentence needs clarification. We assume that it should be ‘of mercury production’ instead of ‘of mercury emissions’. ERM response (43): Correct assumption. The LCA report has been updated to reflect this comment.

p. 67 First paragraph – change ‘reduce’ to ‘reduced’

second paragraph line 2 – change ‘sue’ to ‘due’

third paragraph – provide a reference for ‘research indicates’

ERM response (44): The LCA report has been updated to reflect these comments.

p.68 Last paragraph, reference research that indicates increased life requires increased mercury levels ERM response (45): The LCA report has been updated to reflect these comments.

p. 75/76 Numbering of figures - both figures are ‘Figure 12’ ERM response (46): The LCA report has been updated to reflect these comments.

Reporting

The requirements for reporting are specified in detail in Section 5 of ISO 14044. The Review Panel has reviewed this report for consistency with those guidelines and concludes that the report in general complies with those requirements once the comments from the Review Panel are addressed. ERM response (47): All peer reviewer comments have been addressed above.

The requirements of the Inventory Analysis specifically require a qualitative and quantitative description of the unit processes. Although the Review Panel acknowledges that the data are provided in the appendix, we suggest that key data for unit processes are presented in the main text. ERM response (48): All data is provided in the Appendix in order to maintain ease of reading the final LCA report. Reference to Appendix B should be made for further details.

ERM response (49): ERM would like to thank and acknowledge the peer review panel members for their thorough, concise and helpful comments supplied in their review of this ISO LCA study.

Dr Sarah McLaren

Dr Barbara Nebel

Dr Donald Hannah

15 June 2009

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