LCA Case Studies

The Environmental Impact of Disposable Versus Re-Chargeable Batteries for Consumer Use*

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Abstract

Goal, Scope and Background. The most common system for powering small items of electronics by both consumers and industry in Australia is simply to repeatedly buy and use disposable alkaline batteries. A growing practice however is to invest in a small battery charger and buy more expensive re-chargeables such as nickel metal hydride batteries. This latter course is promoted as being better for the environment. This study evaluates this assertion to guide future practice by both consumers and industry.
The study compares re-chargeable AA batteries of both nickel cadmium (NiCd) and nickel metal hydride (NiMH) chemistry, each used either 400 times or 50 times with the number of AA alkaline batteries required to provide 1 kWh of energy to a device being powered. The scope of the analysis includes the materials and processes used in the production, distribution, use and disposal of the batteries and the battery charger and includes consideration of partial recycling and disposal to landfill.

Methods. The study is done by developing an inventory of the life cycle of each of the alternatives which in the case of re-chargeable batteries includes the charger and the discharge & re-charging process. Measurements were conducted of re-charging efficiencies of representative batteries and of battery charger energy efficiencies. Energy use in wholesale and retail parts of the distribution system are also accounted for. SimaPro LCA software and associated Australian databases are then used to analyse the data using the Eco Indicator 99 (E) model of environmental impact.

Results. The relative impacts of the three alternative systems on the categories human health, ecosystem quality and resource use showed little difference between the NiCd and NiMH batteries except for human health where the toxicity of cadmium gave a 20% advantage to NiMH batteries. When comparing re-chargeable batteries with alkaline batteries, the former caused less damage by factors varying from 10 to 131 for an optimistic scenario of 400 cycles of discharge and charge.
Significant factors in the impact of the re-chargeable batteries were the production of batteries themselves, the electricity used for wholesaling and retailing, the transport to landfill and the copper and other components in the battery charger. For the disposable alkaline batteries the dominant impacts came from the electrical energy used for wholesaling and retailing the batteries, followed by the production of the batteries.

Discussion. Most of the results are in line with expectations but somewhat surprisingly, the impact in most categories is dominated by the energy used in wholesaling and retailing, particularly for the alkaline batteries where the number involved is large. Also surprising is the fact that the cadmium present in the NiCd batteries was less significant than many other factors. The results however agree broadly with those of Lankey and McMichael (2000).

Conclusions. Analysis results were overwhelmingly in favour of the re-chargeable battery option. This was true for every impact criteria studied and for less than optimistic scenarios of battery use such as significant shelf life or high discharge rates.

Recommendations and Perspectives. Given the present very large market for disposable batteries in Australia, there is a need for education of the consumer population and, to a lesser extent, industry, of the environmental and economic advantages of moving to re-chargeable batteries.

Keywords: Alkaline batteries; Australia; batteries; charger; consumers; disposable batteries; nickel-cadmium batteries; nickel-metal-hydride batteries; re-chargeable batteries

Introduction

There is a huge and growing demand for small batteries in Australia to power all manner of electronic equipment from portable CD players to toys. Many batteries are simply thrown in the local rubbish bin when fully discharged because there is no practical alternative. There does however appear to be a growing demand for re-chargeables.

The global production of small re-chargeable batteries in 1999 was 2.9 x 10^9 following an annual growth rate of about 14% over the past ten years (Rydh and Karlstrom 2002). If for example it was assumed that all these batteries were AA cells of either NiCd or NiMh types, each containing about 10 g of nickel, then the global consumption of nickel would be 29,000 tonnes per year. **Fig. 1** shows the value of various battery imports into Australia in the year 2004 as an indication

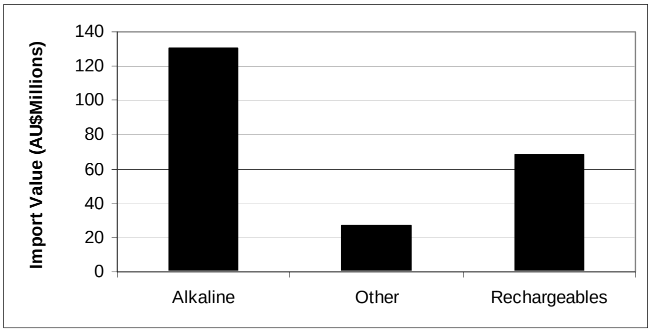

Fig. 1: Value of battery imports to Australia in 2004. Source: Australian Bureau of Statistics (2005)

*** ESS-Submission Editor:** Dr. Wulf-Peter Schmidt (wschmi18@ford.com) of the quantities involved. This data combines the import category 'Manganese dioxide' with 'alkaline' which together comprise the bulk of disposable batteries which most consumers use for their everyday purposes. It also combines nickel cadmium batteries with nickel metal hydride and other rechargeables. (The data includes industrial batteries). It can be seen that disposable batteries still dominate the situation.

1 Methods

1.1 Alternative systems

Two possible ways of powering portable consumer equipment are considered; buy numerous disposable batteries or buy a small number of re-chargeables and a battery charger. A study was done of the environmental consequences of each of these alternatives using life cycle assessment techniques with the aid of SimaPro software (Pre Consultants 2005). SimaPro has extensive banks of Australian data about materials and processes. The two systems (disposable and rechargeable) were compared including the production, packaging, transport, warehousing,and retailing, use and final disposal of the batteries and charger. **Fig. 2** and **Fig. 3** show the processes included in the study.

Lankey and McMichael (2000) conducted a similar study based on input-output data from the USA in 1992 and other related sources in that country. The present study aims to confirm their results in the Australian context and to add some measurements of battery and charger performance to the analysis. The functional unit for the study was the delivery of 1 kWh of energy to an item of equipment, which equates broadly to the energy available from two typical AA cells discharged and charged several hundred times. Three alternative battery systems were compared:

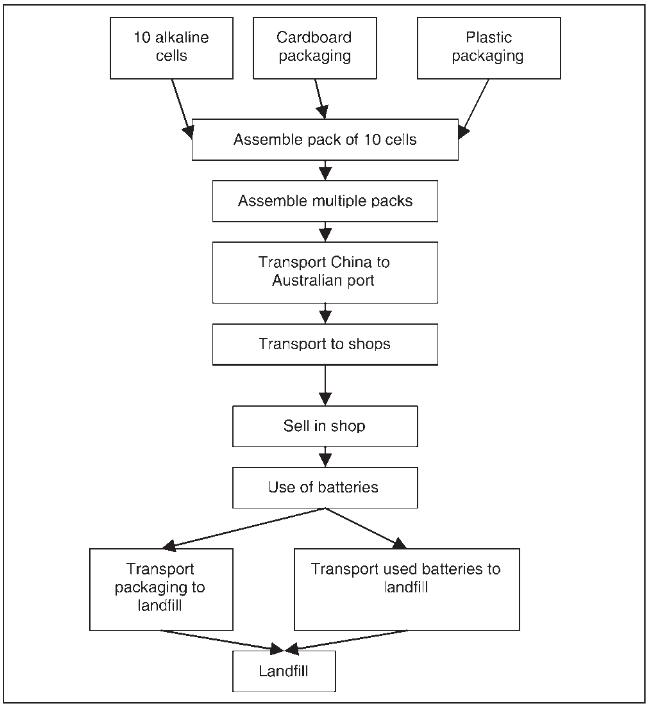

Fig. 2: Processes included in the alkaline battery life

1.1.1 System 1

This system comprised two nickel metal hydride (NiMH) AA cells of nominal capacity 1,200 mAh being charged and re-used.

Based on measurements taken on randomly selected samples of comparable cells (Choi 2005), these were capable of delivering about 72% of their nominal capacity under expected

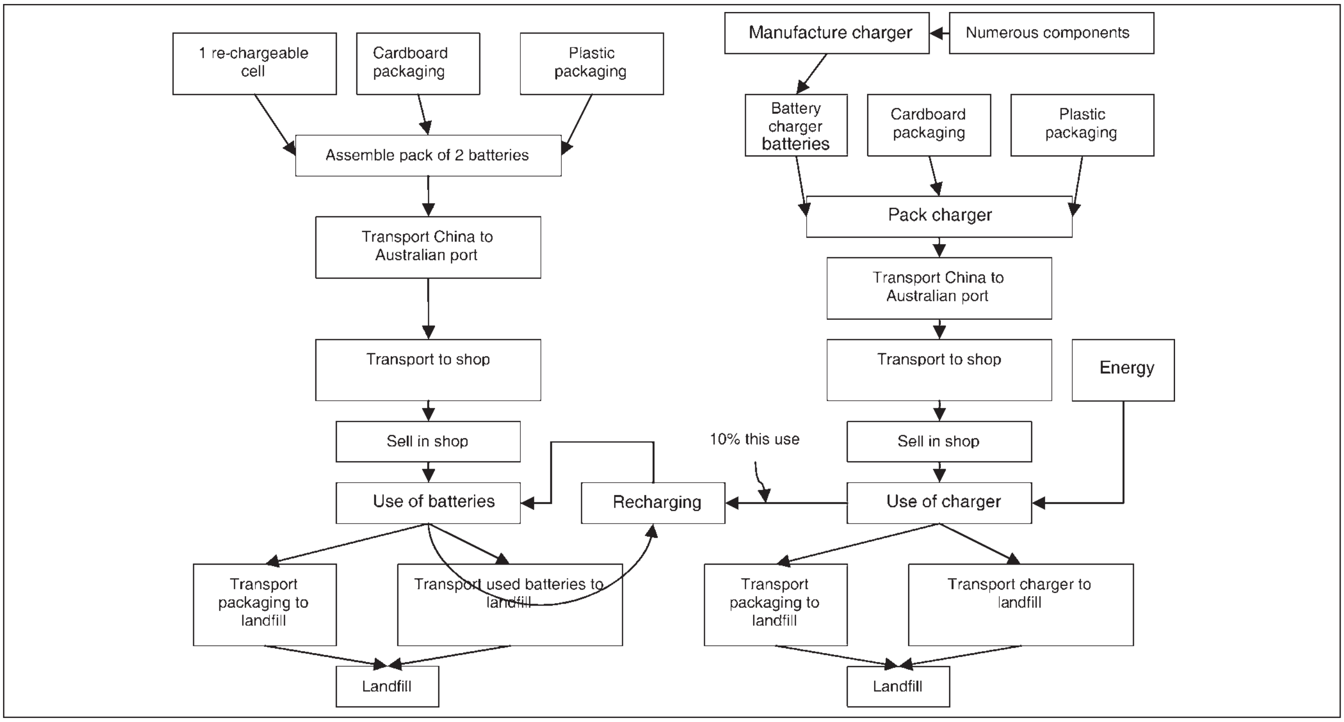

Fig. 3: Processes included in the re-chargeable battery life

operating conditions. Consequently the energy available from two of these cells was 2.16 Wh assuming an operating voltage of 1.25 V for each cell.

1.1.2 System 2

This system comprised two nickel cadmium (NiCd) AA cells of nominal capacity 800 mAh being charged and re-used. Based on measurements taken on randomly selected samples (Choi 2005), these were capable of delivering about 66% of their nominal capacity under expected operating conditions. Consequently the energy available from two of these cells was 1.32 Wh assuming an operating voltage of 1.25 V for each cell.

1.1.3 System 3

This system comprised a number of alkaline AA cells, which arrive at the consumer already fully charged. The energy available from the cells was measured by discharging a randomly selected pack and was 800 mAh. The energy available from two of these cells, assuming a voltage of 1.5 V per cell, was 2.4 Wh.

However NIMH and NiCd cells lose some capacity at higher discharge rates and also self-discharge significantly over times of the order of one month at rates dependent on their temperature. Alkaline cells do not self-discharge significantly over the same time periods but decline in capacity significantly at higher rates of discharge. In addition, the number of recharge cycles likely to be used for the rechargeable types can vary significantly depending on how they are managed. To allow for these variables, the range of scenarios shown in **Table 1** was studied with deterioration factors as given in the table (Energizer 2006). In order that each scenario deliver the functional unit of 1 kWh, the number of cells of each type which were required, allowing for the specified number of recharge cycles, is also given in Table 1.

All cells were assumed to have been transported by sea from China to Australia in a pack of two for the re-chargeables and a pack of 10 for the disposables. Local transport by road an average distance of 25 km was assumed. The charger was assumed to also have been transported from China in a cardboard box and samples of all packing material were weighed to determine their weight. When they had completed the specified number of cycles or were discharged, all cells were disposed of into both normal Australian municipal landfill via normal council garbage truck with a journey of 100 km, or recycled using Australian data which allows for the recycling of aluminium, copper, steel, various plastics and paper but not nickel or cadmium.

Some assumptions were made in order to model NiMH cells for which detailed inventory data was not available. An approximate inventory for NiMH batteries was derived by modifying the inventory for NiCd batteries by deleting all inclusions of cadmium and adjusting the mass of nickel and some other components according to the proportions given in Morrow (2001). A sample cell was also disassembled and the weight of major components determined. This weight data was used to confirm that the weights of the major components used in the inventory were realistic. All other components were assumed to be relatively minor in quantity or benign in impact and so left unchanged. Further pragmatic evidence for this approach is given by the fact that the retail price of the two battery types is very similar, suggesting that at least there were no major manufacturing processes of dramatically different type involved in one over the other.

1.2 Inventory of inputs and outputs

1.2.1 Charger

A specific model of battery charger (Energizer model CHM4FC) was used to analyse both the energy efficiency of the charging process and the environmental impact of the charger itself. This charger is typical of many on the Australian market and is a traditional transformer-rectifier-filter-regulator model. For this measurement, two AA cells of nominal capacity 1200 mAh were used. It was assumed that typically consumers would use the charger to re-charge only two batteries at a time, even though it could accommodate four. Measurements were made of the energy required into the charger and the energy put into the cells resulting in an efficiency of 77%. It was also noted that the harmonic content of mains current into the charger was a high 56%, because the current drawn by the charger varied with time in a pulsing pattern rather than being the ideal sinusoid. This non-sinusoidal pattern would have resulted in further difficult-to-quantify inefficiencies in the electric energy supply system such as heating losses in transformers and cables. These losses have been neglected in this study because it was not possible to quantify them in the present context but they are suspected of being less than 1% of the energy used by the charger.

Table 1: Range of battery types, scenarios and functional equivalents

	NiMH			NiCd			Alkaline	
	Optimistic case	Realistic case	Worst case	Optimistic case	Realistic case	Worst case	Optimistic/normal case	Worst case
Number of recharge cycles	400	50	50	400	50	50	–	–
Storage time and temperature	0	0	30 days at 37 degrees C	0	0	30 days at 37 degrees C	0	–
Discharge rate	Low	Low	High	Low	Low	High	Low	High
Percentage of capacity assumed	100	100	30	100	100	36	100	40
Number of cells to deliver 1 kWh	2.3	18.2	66.7	3.8	28.6	100	834	2085

Table 2: Major components of battery charger

Materials/Assemblies	Amount (g)	Item
Polypropylene	250	case
Copper	25	power chord conductor
PVC	7	power chord insulation
Polypropylene	38	power plug
Steel	5	screws
Spring steel	5	springs
Soft steel	8	contacts
'Magnetic' iron	150	transformer core
Steel	20	transformer frame
Copper	150	transformer windings
Cardboard	10	transformer insulation
Copper	3	internal cables
Printed circuit board	20	printed circuit board
Total weight	691	

The charger itself was then analysed by accumulating an inventory of the mass of all its component elements. It was assumed that 10% of the life of the charger would be devoted to the present charging tasks. The printed circuit board data available for the study was for a relatively high complexity board which includes the laminated board production plus integrated circuits. Since the board in the charger is significantly less complex, its effective weight was reduced to 20 g from the real weight of 70 g. Major material components of the charger are given in **Table 2**.

1.2.2 Energy use

Combining the efficiency figures given above, the electrical energy used to charge the re-chargeables over their lifetime while they deliver 1 kWh of energy was determined to be as given in **Table 3**. In addition, according to Norris et al. (2003), there is a significant energy cost associated with wholesaling and retailing consumer electronic equipment, amounting conservatively to about 4 TJ per million dollars of economic value, amounting to between about 20% and 50% of the total energy used in production and distribution, depending on the product. This significant energy use is common for consumer products (Grant 2006) even though it appears high. However the well-lit and air-conditioned shops in which most batteries are presented and sold are major energy consumers. Japanese input output data from 1995 shows that for batteries as a general category, the energy used in wholesaling and retailing as a percentage of the total energy in production and distribution is about 14%, but for products where a reasonably direct comparison may be made, the actual quantity of energy is significantly less than the USA data in Norris et al. (2003). Considering the age of the Japanese data and the likelihood of Australian conditions today matching those of the USA in 2003, a figure of 4 MJ per pair of cells was used for all types of battery. It was also assumed that such energy use would be the same for both alkaline and re-chargeable batteries in spite of their different economic cost because the data for the studies would have been dominated by the more common alkaline cells.

Table 3: Electric energy required to charge each type of battery to deliver 1 kWh of energy

Battery type	NiMH	NiCd	Alkaline
Lifetime charging energy	6.5 MJ	7.1 MJ	Nil

1.2.3 Resource inputs and emissions

Resource inputs and emissions are implied by the processes outlined in Fig. 2 and Fig. 3 and were dealt with by means of appropriate selections from the mainly Australian databases associated with SimaPro.

1.3 Analysis

A model of the alternative portable energy supply systems was then developed and analysed using SimaPro, and the Eco Indicator 99 (E) method. Luo et al. (2001) compare two electronic products, a telephone and a laptop computer plus a mechanical part using four different methods of analysis, including Eco Indicator 99 (E). Their results show that all four methods give broadly similar relative performance of the two products. This suggests that Eco Indicator 99 (E) is at least as credible as several other relatively current methods.

In the Eco Indicator model, the three categories chosen to measure impact and their units are:

1. Human Health. Unit: DALY= Disability Adjusted Life Years; (this means different disability caused by diseases are weighted);
2. Ecosystem Quality. Unit: PDF*m2yr; PDF= Potentially Disappeared Fraction of plant species; and
3. Resources. Unit: MJ surplus energy. Additional energy requirement to compensate for lower future ore grade.

2 Results of Life Cycle Assessment

2.1 Comparison of batteries

Table 4 shows the results for environmental damage due to the three battery systems using Eco Indicator 99 (E) and assuming the re-chargeable batteries are discharged and charged 400 times.

From the data in Table 4 it can be concluded that the recycling considered in the study produces about 20% less overall damage to resources than land-filling the re-chargeable batteries because of the re-use of some materials. Recycling

Table 4: Comparison of battery types with 400 cycles of discharge/charge and of recycling and landfill alternatives using Eco Indicator (E) 1999 methodology

Battery type	NiCd		NiMH		Alkaline
End of life scenario	Landfilled	Recycled	Landfilled	Recycled	Landfilled
Damage to human health DALY	6.14 E-6	6.42 E-6	5.03 E-6	5.26 E-6	482 E-6
Ecosystem quality PDF*m^{2}Yr	0.23	0.24	0.20	0.21	19.4
Resources MJ surplus	5.71	4.40	5.40	4.23	427

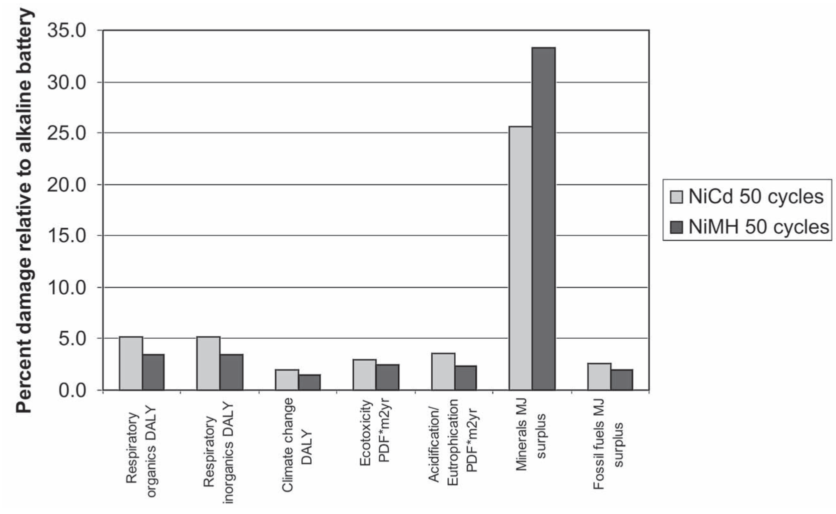

Fig. 4: The relative characterization performance of NiCd and NiMH batteries with 50 cycles of discharge and charge to that of Alkaline batteries

however makes little difference to the damage caused to ecosystem quality or to human health because that damage is overwhelmingly due to stages in the life cycle of the batteries prior to their disposal. For both damage categories, about 80% of the damage is due to the production of the battery itself, burning of coal for shop electricity and battery charging, and the production of the battery charger.

The use of NiMH batteries rather than NiCd batteries, considering only the recycled case, results in a significant benefit (18%) to human health, and (13%) to ecosystem quality plus a lesser (4%) benefit to resources. These benefits are due to two factors: the elimination of cadmium use from the system and the somewhat better energy efficiency (energy out divided by energy in) of the NiMH batteries compared to the NiCd batteries meaning that less of the former type were needed to supply the functional unit of 1 kWh of energy. The first of these factors is in line with the results of Rydh and Karlstrom (2002) who find that the only significant difference between the two battery types is due to the presence or absence of cadmium. According to Hawkins et al. (2006), there is little doubt that cadmium poses a health risk if released to the environment but end-of-life nickel cadmium batteries are not a major source of cadmium releases to the environment in the U.S.. However, given the low level of recycling of end-of-life batteries and the consequent likelihood of cadmium from this source ending up in landfill, the use of nickel cadmium batteries should be discouraged. The damage caused by the use of NiMH batteries compared to that caused by alkaline batteries is less by a factor of about 96 for each of the three damage criteria. **Fig. 4** shows the characterisation for the same comparison but with only 50 cycles of discharge and charge of the re-chargeable batteries. Again the performance of the NiCd and NiMH batteries are very similar to each other and the damage caused by the alkaline batteries varies from about 3 to 50 times greater than for the re-chargeables.

As outlined in Table 1, various other scenarios of battery use and management were also considered. The data given in **Table 5** shows the results of the same analysis as above applied to the NiMH battery assuming 400 cycles of use, 50 cycles of use, 50 cycles of use after 30 days of shelf life, normal alkaline battery use and alkaline battery use at a high discharge rate, with all batteries assumed to be landfilled at their end-of-life. From this data several additional conclusions can be drawn. For the less optimistic scenario of only 50 cycles of use for the NiMH batteries, the factors of advantage over alkaline cells ranged from 30 to 42 for the three damage categories, which can still be seen as a considerable advantage. For the less than optimistic scenarios of long shelf life for the NiMH batteries and a high discharge rate for the alkaline batteries, the factors of advantage range from 27 to 36 for the same three damage categories. Hence it is apparent that even if each type of battery was to be used under poor management conditions, there remains a considerable environmental advantage to using re-chargeable batteries. **Fig. 5** shows a comparison of the damage caused by NiMH batteries with 400 and 50 cycles of discharge/charge and with alkaline batteries, all used under optimum conditions. The damage caused by the re-chargeable batteries is greater if only 50 cycles of discharge and charge are achieved rather than 400 cycles but the increase is of the order of only two times. The damage caused by the alkaline batteries however is more than ten times that caused by the re-chargeables used for 50 cycles.

Table 5: Comparison of nickel metal hydride and alkaline batteries various management scenarios (landfill assumed)

Battery type and management	NiMH. 400 cycles	NiMH. 50 cycles	NiMH. 50 cycles, Long shelf life	Alkaline	Alkaline. High discharge rate
Damage to human health DALY	5.0 E-6	14.7 E-6	45.6 E-6	482 E-6	1210 E-6
Ecosystem quality PDF*m^2Yr	0.20	0.46	1.36	19.40	48.50
Resources MJ surplus	5.4	14.3	42.5	427.0	1070.0

Table 6: Factor of improvement for re-chargeable batteries over alkaline batteries according to both the present study and Lankey and McMichael (2000)

Characterisation of damage	Present study (400 re-charging cycles)	Characterisation of damage	Lankey & McMichael (2000) (200 re-charging cycles)
Carcinogens	42	Electricity	33
Respiratory organics	57	Water use	81
Respiratory inorganics	90	Coal use	56
Climate change	131	Iron use	190
Ecotoxicity	60	Lead and zinc use	6
Acidification/Eutrophication	108	Copper use	14
Land use	110	SO_2 releases	23
Minerals	10	NO_2 releases	46
Fossil fuels	115	Global warming potential	50

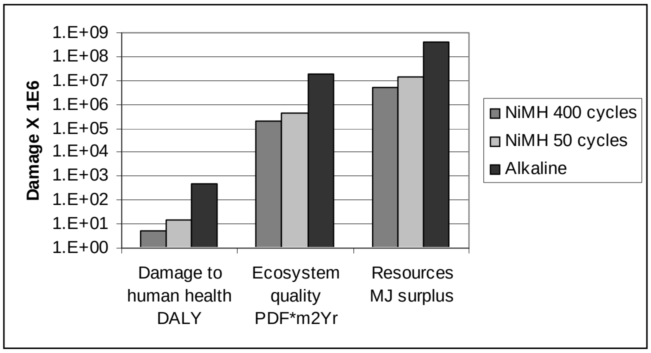

Fig. 5: Damage assessment of NiMH batteries with 400 cycles and 50 cycles and of Alkaline batteries, all used under optimum conditions

For the purpose of comparison of results with those of Lankey & McMichael (2000), **Table 6** shows the ratio of damage caused by alkaline batteries to that caused by NiMH batteries on a range of characteristics of the damage. The values range from 10 to 131 times. Table 6 also gives the ratio on slightly different criteria found by Lankey & McMichael (2000) where it can be seen that both sets of ratios are comparable in magnitude.

2.2 Analysis of major components of environmental impact

Analysis was also conducted to determine which components of the systems of use were the major contributory factors in the environmental impact. **Table 7** gives the major contributory factors for the less optimistic re-chargeable scenario of 50 cycles of discharge and charge for the NiCd and NiMH batteries and for the alkaline batteries used at normal discharge rates, with all batteries being land-filled.

The production of the batteries is the major damage factor for re-chargeable batteries accounting for about 70% of human health damage, 50% of ecosystem quality damage and 65% of damage to resources. The damage caused by the production of the alkaline batteries is much less as a percentage being about 15% for each category of damage.

Shop electricity and the coal used to produce it in Australia is the dominant cause of environmental impact for alkaline batteries because of the large numbers of batteries involved, accounting for about 70% of the damage in all three categories. It is also significant for the other types of battery being about 5%. The health impacts are caused mainly by the nitrogen oxides released by burning coal in the produc-

Table 7: Major sources of damage for three battery types with 50 cycles of discharge/charge and landfill of discarded batteries

		NiCd	%	NiMH	%	Alkaline	%
Human Health (DALY)	**Total**	**21.8 E-6**	**100**	**14.7 E-6**	**100**	**482 E-6**	**100**
	Battery	16.3 E-6	75	10.3 E-6	70	64.5 E-6	13
	Charging electricity	1.6 E-6	7.5	1.5 E-6	10	–	–
	Shop electricity	0.9 E-6	4.2	0.9 E-6	6.3	384 E-6	80
	Printed circuit board	0.6 E-6	2.8	0.6 E-6	4.1	-	-
	Transport to landfill	0.5 E-6	2.2	0.3 E-6	2.1	14.3 E-6	2.9
	Packaging	0.2 E-6	<1	0.1 E-6	<1	8.8 E-6	1.8
Ecosystem Quality (PDF*m2Yr)	**Total**	**0.675**	**100**	**0.463**	**100**	**19.4**	**100**
	Battery	0.37	55	0.24	51	3.23	17
	Charging electricity	0.055	8.1	0.051	11	–	–
	Shop electricity	0.031	4.6	0.031	6.7	12.9	66
	Transport to landfill	0.088	13	0.056	12	2.59	13
	Printed circuit board	0.045	6.6	0.045	9.6	–	–
	Packaging (plastic)		<<1		<<1	0.26	1.3
Resources (MJ surplus)	**Total**	**15.5**	**100**	**14.3**	**100**	**427**	**100**
	Battery	9.9	64	9.6	67	78.2	18
	Coal (for recharging)	1.4	8.9	1.3	8.8	–	–
	Coal (for shop electricity)	0.8	5.0	0.8	5.4	324	76
	Printed circuit board (in charger)	0.5	3.2	0.5	3.5	–	–
	Copper (in charger)	1.1	6.8	1.1	7.4	–	–
	Oil (for transport)	>0.3	>2	0.2	1.3	9.2	2.2
	Plastic packaging	0.2	1.5	0.15	1.0	10.9	2.6

tion of electricity and the ecosystem impacts are caused mainly by the release of nitrogen oxides and, to a lesser extent, sulphur oxides released by burning coal. This result is however based on an uncertain figure for energy consumption in warehousing and retailing from Norris et al. (2003) as described in section 2.2 above.

The damage caused by the generation of electricity for recharging the batteries is also significant, amounting to about 10% for the NiMH batteries.

The charger is significant to the extent of being less than 10% in all three damage categories for re-chargeable batteries. The significance of the battery charger in the re-chargeable system is related to the physical size of such units and to the fact that they contain a printed board the production of which is a complex and chemically-intensive process involving the use of both copper and lead, both toxic metals and the fact they may contain low technology integrated circuits. These impacts would be ameliorated by moves to lead-free solder and to smaller, lighter and more energy-efficient switched-mode chargers. It is also possible that this impact remains somewhat overemphasised in this study in spite of the deliberate down-grading figure applied, as described in section 2.1 above.

Transport at end-of-life is significant for ecosystem quality for all three battery types being about 12%. The result here is highly dependent on the battery collection and disposal scenario (Caudill and Dickinson 2004, Jofre and Morioka 2005). Rydh and Karlstrom (2002) also discuss the specific issue of battery collection in some detail. This analysis did not include costs for small volume users to physically take batteries for recycling to a depot (which is the main operating model at present in Australia). Had this been done and private cars assumed for this task, this transport impact would have been much greater.

3 Conclusions

This study reinforces what is probably the intuitive opinion of most experts that the environmental benefits of using rechargeable batteries rather than disposable batteries for consumer electronics are very significant. It also broadly confirms the results of Lankey and McMicheal (2000). More specifically, the benefits apply in all of the categories of impact which were analysed even in the relatively pessimistic case of only fifty cycles of discharge/charge for the re-chargeable batteries and even if the various battery types are used under less than ideal conditions such as storing re-chargeable batteries for a considerable time after charging.

The production of the batteries is the dominant source of damage from re-chargeable batteries so efforts to obtain maximum benefits in the form of the maximum number of discharge and charge cycles should be encouraged.

The environmental benefits of NiMH batteries over NiCd batteries are significant only in a minor way relative to the negative health impacts of cadmium and the chances that much of the cadmium will be released to the environment. However since NiMH batteries are generally as good as if not better performers than NiCd batteries in other respects, the use of NiCd batteries for powering consumer products should be discouraged.

Recycling of re-chargeable batteries produces benefits in the saving of resources. The value of recycling batteries however depends heavily on satisfactory battery collection arrangements where poor practice can produce significant damage, mainly to ecosystem quality.

4 Recommendations and Perspectives

Displaying and selling batteries in typical supermarket shops has a major impact for alkaline batteries because of the use of electricity and a minor impact for re-chargeable batteries. Possibly the best way to minimize this impact is to reduce the quantity of disposable batteries being sold. Beyond that, reducing the energy use in such shops will occur when community education about resource limitations reaches a sufficiently high level as to produce pressure on retailers to change practices, probably by attaching a marketing advantage to such changes.

Consumers should be encouraged to obtain and use a battery charger of the switching regulator technology in order to minimize the impact of the charger and to increase the energy efficiency of the charger in order to reduce the impact of the electricity used for re-charging batteries.

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