Environmental Impact Assessment Review 31 (2011) 334–343

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar

Environmental impacts of lighting technologies — Life cycle assessment and sensitivity analysis

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ARTICLE INFO

Article history:
Received 19 October 2009
Received in revised form 25 August 2010
Accepted 31 August 2010
Available online 6 October 2010

Keywords:
Life cycle assessment (LCA)
Compact fluorescent lamp
Fluorescent lamp
Halogen lamp
Tungsten lamp
Sustainable lighting

ABSTRACT

With two regulations, 244/2009 and 245/2009, the European Commission recently put into practice the EuP Directive in the area of lighting devices, aiming to improve energy efficiency in the domestic lighting sector. This article presents a comprehensive life cycle assessment comparison of four different lighting technologies: the tungsten lamp, the halogen lamp, the conventional fluorescent lamp and the compact fluorescent lamp. Taking advantage of the most up-to-date life cycle inventory database available (ecoinvent data version 2.01), all life cycle phases were assessed and the sensitivity of the results for varying assumptions analysed: different qualities of compact fluorescent lamps (production phase), different electricity mixes (use phase), and end-of-life scenarios for WEEE recycling versus municipal solid waste incineration (disposal phase). A functional unit of "one hour of lighting" was defined and the environmental burdens for the whole life cycle for all four lamp types were calculated, showing a clearly lower impact for the two gas-discharge lamps, i.e. the fluorescent and the compact fluorescent lamp. Differences in the product quality of the compact fluorescent lamps reveal to have only a very small effect on the overall environmental performance of this lamp type; a decline of the actual life time of this lamp type doesn't result in a change of the rank order of the results of the here examined four lamp types. It was also shown that the environmental break-even point of the gas-discharge lamps is reached long before the end of their expected life-span. All in all, it can be concluded that a change from today's tungsten lamp technology to a low-energy-consuming technology such as the compact fluorescent lamp results in a substantial environmental benefit.

1. Introduction

In the Spring of 2009 the Commission Regulation EC No 244/, 2009 and Commission Regulation EC No 245/, 2009 entered into effect, dealing with eco-design requirements for non-directional household lamps (244/2009) and fluorescent lamps without integrated ballast, high intensity discharge lamps and ballasts and luminaries able to operate such lamps (245/2009). These regulations, annually banning from September 1, 2009, to September 1, 2016 more types of energy-wasting lamps, can be seen as the implementation of the EC Directive, 2005/32/EC for energy-using products (the so-called EuP directive). All lighting devices sold nowadays have to comply with these regulations — i.e. they have to achieve a minimal level of energy efficiency and they have to comply with restrictions concerning hazardous substances such as mercury.

The objective of this study was to assess the environmental impacts caused by lighting devices used in the domestic sector. Therefore several scenarios were used to identify the environmental burdens across the life cycle under varying assumptions. Although a variety of such life cycle assessment (LCA) studies of lighting devices for domestic use have been established in the last 20 years (see e.g. Hofstetter (1989), Gydesan and Maimann (1991), Ebersperger and Mauch (1992), Mani (1994), Pfeifer (1994, 1996), Rubic and D'Haese (1994), Parsons (2006)), we performed a new, broader comparison based on a more complete LCA framework and a more comprehensive inventory database. Most of those former studies discuss only the tungsten lamp and the compact fluorescent lamp; while our new study takes into account all four important technologies — i.e. the two filament lamp technologies of the incandescent or tungsten lamp and the low voltage halogen lamp, as well as two gas-discharge lamps, the conventional fluorescent lamp and the (newer) compact fluorescent lamp. Another important aspect is the lack of adequate inventory data in the old studies, especially in the area of electronics components. Here, the use of the most recent version of the ecoinvent database (ecoinvent Centre, 2007) made it possible to cover also the production step in a comprehensive and exact way, and thus, to provide a much more complete LCA study for the comparison of different lamp technologies. Furthermore, an important focus of this study is to give equal consideration to all life cycle phases of the various types of lamps examined by using the ecoinvent database as well as additional investigations. Due to the uniformity in the level of detail between the various life stages, the study allowed us to tackle further questions — e.g. the question as to the conditions under which the

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doi:10.1016/j.eiar.2010.08.004

production and disposal effects counterbalance the lamp's energy-saving potential in the use phase.

Additional weak points of the former studies include the fact that some of them define the functional unit in way that is not useable for further scenario analysis; some of them fail to discuss the influence of different electricity mixes or end-of-life options, and last but not least, there are obviously shortcomings in the impact assessment and the subsequent interpretation due to the earlier development status of the whole LCA framework at the time of publication of the older studies among them.

This new study pays special attention to all these points, in order to end up with a comprehensive ecological comparison of the four lamp technologies.

2. Methodology

The environmental aspects of four lamp types were evaluated with a Life Cycle Assessment (LCA) study. LCA is a structured, internationally standardised method for quantifying the emissions, resources consumed and environmental and health impacts associated with goods and services (see e.g. ISO, 2006). An LCA study is composed of four steps — goal and scope definition, inventory analysis, impact assessment, and interpretation.

2.1. Goal and scope

The overall goal of the study was to determine which of the four domestic lighting technologies examined had the best environmental performance. According to the European Union (EuPs, 2008a) the most common lamp type used today is the tungsten lamp with a power rating of 60 watts. This lamp was chosen as the reference for the study. For an appropriate comparison with the other three lamp types, corresponding wattages and luminance rated in lumens (l m) were applied — resulting in a comparison of a 35 watt halogen lamp, a 14 watt conventional fluorescent lamp and a 11 watt compact fluorescent lamp. In order to equalize the differences in lifetimes of the four lighting devices observed, the functional unit was defined as "one hour of lighting" (with the mentioned wattages).

Fig. 1 illustrates the life cycle phases considered. As shown, this is a "cradle to grave" study, taking into account all life cycle stages from manufacture (including the extraction of raw materials), to use and final disposal. However, within these boundaries only those aspects of the various lighting technologies were taken into account that differ due to the various technologies (e.g. the luminaire was not taken into account, as this part depends much more on one's personal liking than the lamp technology used). These measures have contributed to minimizing data uncertainty throughout the study.

As shown in Fig. 1, in addition to the four lighting technologies examined, several different electricity mixes (based on different amounts of renewable and non-renewable sources) were applied in the use phase in order to examine the sensitivity of the overall results for various electricity mixes.

In the use phase the specific infrastructure required to operate the lighting devices was examined. For the energy consumption in the use phase, only permanent flows of electricity were rated, but not short term flows such as the one generated by the ballast in the start up phase, mentioned in e.g. Ris (2008).

In the end-of-life phase detailed processes for disposal, recycling and incineration as municipal solid waste were taken into account. This phase was given special attention because earlier studies had suggested that improper disposal of small electronics parts can become an issue (see e.g. Hilty, 2005; Kräuchi et al., 2005; Wäger et al., 2005) and recycling of electronic components clearly pays off in environmental terms (see e.g. Hischier et al., 2005). Hence, this last life stage was modelled, based on appropriate disposal requirements for the investigated lamps as practised today in Western Europe.

The functional unit chosen here is based on the assumption of a functional equivalence between the four lamp types defined above;

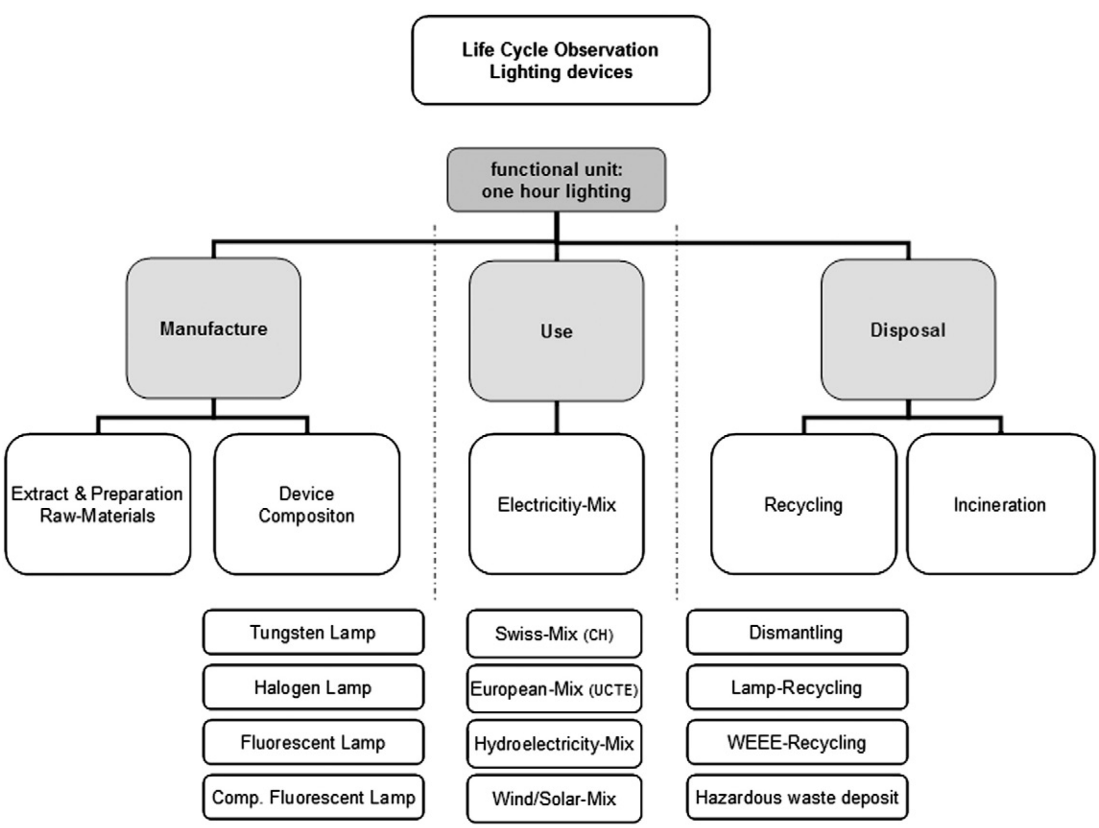

Fig. 1. Description of the investigated system of lighting devices in the domestic sector, according to the 'cradle to grave' approach.

arguments questioning this functional equivalence between tungsten, halogen and fluorescent lamps (e.g. concerning light quality or effects on the human organism by different light spectra emitted by the various lighting technologies) are explicitly not addressed within this study. Furthermore, we did not consider the argument that waste heat from lamps can be of any use, i.e. as a contribution to space heating. Then, according to the Swiss Society of Engineers and Architects (SIA), the heat requirement of a room in a house is about 50 kWh/m^2 (SIA, 2009) — a value that is already (for 1 m^2!) about 1000 times higher than the total heat emissions of a traditional light bulb. Differences in non-ionizing radiation and their potential effects on organisms were also excluded from the scope of this study.

2.2. Inventory analysis

Basic information was provided by the European Lamp Companies Federation (ELC), as well as the study by the European Commission 'European Directive on energy-using products' (see ELC, 2008; EuPs, 2008a, b). This basic data was complemented by our own data collection, our own measurements, literature study and expert interviews. The resulting key figures for the four light bulb types examined are summarized in Table 1.

For the end-of-life treatment, the current practice in Switzerland, based on in-house expert knowledge, was used as a default assumption for a state-of-the-art End-of-Life treatment. As mentioned above, in addition to the lamps themselves, the production and disposal of specific technical infrastructure for the operation of each of the lamp types were included in the study as well. Those inventories were compiled from our own measurements, as no public data was available. The *tungsten lamp* requires no such additional electrical equipment and its disposal is done exclusively in a municipal solid waste incinerator.

The *halogen lamp* requires a transformer to throttle its supply voltage. Disposal of the halogen lamp is similar to that for the tungsten lamp, namely via a municipal waste incinerator. The transformer, however, according to EU Directive 2002/96/EC on waste electrical and electronic equipment (WEEE), is recycled in an appropriate WEEE treatment process.

Conventional fluorescent lamps require an external ballast to generate the necessary voltage to start the light emission. In the disposal phase, these 69 grams of electronics have to be treated according to WEEE. This external ballast has an average lifetime of roughly 50,000 h and can therefore be assumed to outlast 2.5 tubes. The light tube itself has to be treated according to WEEE regulations due to the amount of hazardous substances it contains. A state-of-the-art recycling process for such lamps was used in our calculations.

For *compact fluorescent lamps*, no additional equipment is required for their operation. However, due to their electronics content (15.28 grams of microelectronics in the internal ballast) the disposal of this type of lamp is again regulated under the WEEE directive. For this study, we assumed disposal in a 'shredder' with a subsequent recycling of the various components extracted. One sensitivity analysis examined the influence of possible differences in the composition of various compact fluorescent lamps on the market. For this, a batch of sample lamps, including both the cheapest 'no name' and the most expensive 'premium' products, was purchased and investigated.

Based on the lamps' respective durability (see row "lifetime" in Table 1), the life stages of manufacture and end-of-life treatment were then allocated to one hour of lighting. In the use phase, no aspects other than electricity consumption were taken into account. All the materials of the lamp types examined, the electricity consumption in the use phase as well as the subsequent disposal activities were assessed based on data from the ecoinvent database, version 2.01 (ecoinvent Centre, 2007).

Table 2 shows an extract – listing some of the most important emission factors to water, air as well as resource fractions – of the resulting, cumulative life cycle inventory data for the four different lamp technologies, split up into the three life stages of manufacture, use (use in Switzerland and an average European use) and disposal (further split into efforts and recovery due to recycling).

The results of this investigation can also be used to analyse light bulbs with other wattages based on the same technologies. The flows of each phase have to be adjusted for their exact environmental performance. For the use phase, the flows grow proportionally with the wattage, whereas for production and disposal, they grow roughly proportionally with the physical mass of the device.

2.3. Impact assessment

Life cycle impact assessment (LCIA) distinguishes between 'endpoint' and 'midpoint' methods. Studies using the 'endpoint' methods can be interpreted easily, but generally exhibit greater uncertainties. The 'midpoint' methods, on the other hand, lead to smaller uncertainties in the results (see Zah et al., 2007); but such methods usually treat separate impact categories independently of others.

For this study the cumulative energy demand (CED), the global warming potential (GWP) and the Eco-Indicator'99 (EI99) were used. The first two methods belong to the 'midpoint' category and highlight just one specific environmental concern each: CED highlights the consumption of (in particular non-renewable) energy resources, expressed in MJ-Equivalents (MJ-Eq) (VDI 1997; Frischknecht et al., 2007) and the GWP (Albritton and Meira-Filho, 2001; IPCC and Climate Change, 2001) shows the 'carbon footprint' expressed in kg CO_2-Equivalents (CO_2-Eq), currently discussed very broadly (for a critical reflection see Weidema et al., 2008). EI99 is one of the most common 'endpoint' environmental assessment methods, aggregating all damages related to human health, ecosystem quality as well as resource consumption into one single indicator (Goedkoop and Spriensma, 2000a, b), expressed in Eco-Indicator points (EIP). All three approaches used here are widely accepted and applied LCIA methods.

Table 1
Basic data of Life Cycle Inventories used for various lighting devices as given by European Lamp Companies Federation and our own data acquisition.

Lamp type	Tungsten lamp	Halogen lamp	Fluorescent lamp	Comp. fluorescent lamp
Wattage	60 W	35 W	14 W	11 W
Net weight [g]	33.02	29.15	226.25	111.28
Lifetime [h]	1000	2000	20,000	10,000
Glass [g]	30.00	2.00	46.00	65.00
Metal [g]	3.00	4.63	95.56	4.00
Electronics [g]	–	12.92	69.13	15.26
Plastics [g]	–	9.94	13.97	25.00
Gases [g]	0.01	0.02	0.80	1.00
Pest [g]	0.01	0.01	0.80	1.00
Mercury [mg]	–	–	3	4

3. Results and discussion

3.1. The overall life cycle

Examination of the environmental impacts throughout the complete life cycle of the four lamp technologies specified here – partly documented in Table 2 – yielded the environmental impacts shown in Fig. 2. Based on the functional unit of one hour of lighting, the results for the Swiss and the average European electricity mix (i.e. the UCTE[1] mix) are shown, assessed with the EI99 method. As far as

[1] UCTE = Union for the Coordination of Transmission of Electricity.

Table 2
Extract of important emission and resource factors out of the cumulative life cycle inventory results for the life cycle of the various lighting technologies.

		Tungsten Lamp					Halogen Lamp				
		Manufacture	Use (CH)	Use (UCTE)	End-of-Life		Manufacture	Use (CH)	Use (UCTE)	End-of-Life	
					Efforts	Benefits				Efforts	Benefits
(i) Resources											
Energy, potential (in hydropower reservoir), converted	MJ	3.95E−05	9.25E−02	3.22E−02	1.76E−07	–	3.11E−04	5.39E−02	1.88E−02	3.03E−07	−1.53E−05
Coal, brown, in ground	kg	5.79E−06	2.23E−03	1.28E−02	2.24E−08	–	1.09E−04	1.30E−03	7.47E−03	7.77E−08	−1.07E−06
Coal, hard, in ground	kg	4.75E−06	1.74E−03	7.12E−03	3.13E−10	–	8.04E−05	1.01E−03	4.15E−03	3.44E−10	−2.23E−08
Gas, natural, in ground	Nm3	7.69E−06	7.18E−04	3.22E−03	1.11E−07	–	6.10E−05	4.18E−04	1.88E−03	1.29E−07	−3.16E−06
Oil, crude, in ground	kg	4.02E−06	2.43E−04	9.84E−04	3.47E−07	–	2.99E−05	1.41E−04	5.73E−04	1.51E−07	−2.96E−06
Calcite, in ground	kg	1.80E−05	2.16E−04	4.55E−04	6.75E−08	–	3.37E−05	1.26E−04	2.65E−04	3.14E−07	−1.04E−06
Gravel, in ground	kg	2.49E−05	1.01E−03	9.83E−04	8.83E−06	–	1.58E−04	5.86E−04	5.70E−04	3.22E−06	−2.98E−06
Aluminium, in ground	kg	1.40E−08	3.81E−06	4.24E−06	3.13E−10	–	5.76E−07	2.22E−06	2.47E−06	3.44E−10	−2.23E−08
Iron, in ground	kg	4.73E−07	1.08E−04	1.40E−04	4.54E−08	–	1.84E−05	6.30E−05	8.16E−05	2.59E−08	−4.25E−07
Copper, in ground	kg	1.05E−08	2.70E−05	2.73E−05	1.02E−10	–	1.95E−06	1.58E−05	1.59E−05	2.31E−10	−2.39E−06
(ii) Emission to air											
Carbon dioxide, fossil	kg	3.43E−05	7.38E−03	3.37E−02	9.51E−07	–	4.40E−04	4.28E−03	1.97E−02	2.09E−05	−1.35E−05
Sulfur dioxide	kg	2.27E−07	1.62E−05	1.17E−04	1.22E−09	–	1.79E−06	9.44E−06	6.85E−05	1.37E−09	−3.74E−07
Nitrogen oxides	kg	1.93E−07	1.20E−05	5.95E−05	1.72E−08	–	1.00E−06	7.00E−06	3.47E−05	1.88E−08	−8.68E−08
Methane, fossil	kg	7.30E−08	1.59E−05	5.86E−05	2.36E−09	–	1.35E−06	9.28E−06	3.42E−05	1.80E−09	−7.94E−08
PAH, polycyclic aromatic hydrocarbons	kg	8.94E−12	7.13E−10	2.04E−09	2.63E−13	–	7.07E−11	4.16E−10	1.19E−09	1.49E−13	
Mercury	kg	1.80E−12	2.63E−10	2.63E−09	6.07E−14	–	4.97E−11	1.53E−10	1.53E−09	1.43E−13	−1.91E−12
(iii) Emission to water											
COD, chemical oxygen demand	kg	8.15E−08	4.54E−06	1.56E−05	2.75E−09	–	1.23E−06	2.70E−06	9.1SE−06	1.38E−07	−3.99E−08
Chloride	kg	8.52E−07	3.77E−05	1.33E−04	2.07E−08	–	1.13E−05	2.19E−05	7.77E−05	1.49E−07	−6.51E−08
Sulphate	kg	9.89E−08	4.98E−05	1.97E−04	1.70E−08	–	3.71E−06	2.90E−05	1.15E−04	2.97E−08	−3.28E−07
Mercury	kg	3.16E−13	3.70E−11	3.37E−10	1.49E−14	–	1.70E−11	2.46E−11	1.99E−10	5.34E−13	−3.47E−13
Ammonium, ion	kg	3.54E−10	9.73E−08	7.65E−08	1.91E−12	–	2.42E−08	5.67E−08	4.46E−08	6.70E−12	−8.20E−10
Nickel, ion	kg	1.82E−10	4.66E−08	1.34E−07	3.16E−09	–	8.55E−09	1.16E−08	6.25E−08	1.96E−08	−1.64E−09
Cobalt, ion	kg	4.47E−11	1.39E−08	5.43E−08	1.71E−12	–	1.94E−09	7.92E−09	3.1SE−08	2.14E−10	−4.45E−10
Vanadium, ion	kg	8.15E−11	1.78E−08	1.10E−07	7.71E−11	–	2.09E−09	1.02E−08	6.43E−08	3.20E−10	−4.05E−11
		Fluorescent lamp					Compact fluorescent lamp				
		Manufacture	Use (CH)	Use (UCTE)	End-of-Life		Manufacture	Use (CH)	Use (UCTE)	End-of-Life	
					Efforts	Benefits				Efforts	Benefits
(i) Resources											
Energy, potential (in hydropower reservoir), converted	MJ	5.45E-05	2.16E−02	7.51E−03	4.21E−07	−2.44E−05	9.42E−05	1.70E−02	5.90E−03	1.12E−06	−1.55E−05
Coal, brown, in ground	kg	1.80E−05	5.21E−04	2.99E−03	1.44E−07	−2.07E−06	3.01E−05	4.09E−04	2.35E−03	3.93E−07	−1.29E−06
Coal, hard, in ground	kg	1.47E−05	4.06E−04	1.66E−03	4.36E−10	−1.22E−08	2.16E−05	3.19E−04	1.30E−03	1.02E−09	−1.80E−08
Gas, natural, in ground	Nm3	9.35E−06	1.67E−04	7.51E−04	5.26E−08	−1.84E−06	1.89E−05	1.32E−04	5.90E−04	1.32E−07	−3.31E−06
Oil, crude, in ground	kg	4.94E−06	5.66E−05	2.30E−04	9.19E−08	−1.38E−06	1.11E−05	4.51E−05	1.81E−04	2.66E−07	−2.77E−06
Calcite, in ground	kg	7.40E−06	5.03E−05	1.06E−04	3.56E−08	−3.91E−06	1.24E−05	3.96E−05	8.34E−05	6.74E−08	−4.12E−06
Gravel, in ground	kg	2.75E−05	2.37E−04	2.30E−04	3.99E−07	−5.76E−06	4.39E−05	1.89E−04	1.84E−04	1.07E−06	−6.62E−06
Aluminium, in ground	kg	1.64E−07	8.88E−07	9.88E−07	4.36E−10	−1.22E−08	3.44E−07	6.99E−07	7.77E−07	1.02E−09	−1.80E−08
Iron, in ground	kg	5.21E−06	2.52E−05	3.27E−05	2.03E−08	−2.57E−07	4.22E−06	1.99E−05	2.57E−05	5.31E−08	−3.73E−07
Copper, in ground	kg	3.72E−07	6.30E−06	6.37E−06	3.65E−10	−9.65E−07	5.08E−07	4.95E−06	5.OOE−06	9.72E−10	−1.68E−06
(ii) Emission to air											
Carbon dioxide, fossil	kg	7.26E−05	1.72E−03	7.87E−03	5.37E−06	−1.12E−05	1.25E−04	1.35E−03	6.18E−03	7.11E−06	−1.39E−05
Sulfur dioxide	kg	3.57E−07	3.77E−06	2.74E−05	1.62E−09	−1.94E−07	5.28E−07	2.97E−06	2.1SE−05	4.40E−09	−3.O1E−07
Nitrogen oxides	kg	1.74E−07	2.81E−06	1.39E−05	4.05E−09	−7.98E−08	3.06E−07	2.21E−06	1.09E−05	9.60E−09	−9.27E−08
Methane, fossil	kg	1.93E−07	3.71E−06	1.37E−05	1.12E−09	−2.78E−08	3.61E−07	2.92E−06	1.07E−05	3.01E−09	−6.59E−08
PAH, polycyclic aromatic hydrocarbons	kg	1.78E−11	1.66E−10	4.75E−10	7.69E−14	−5.34E−12	3.29E−11	1.31E−10	3.73E−10	1.94E−13	−2.84E−12
Mercury	kg	3.26E−11	6.14E−11	6.13E−10	5.56E−14	−4.15E−11	875E−11	4.83E−11	4.82E−10	1.34E−13	−4.99E−11
(iii) Emission to water											
COD, chemical oxygen demand	kg	2.23E−07	1.04E−06	3.62E−06	3.31E−08	−3.58E−08	3.60E−07	8.86E−07	2.91E−06	3.91E−08	−4.11E−08
Chloride	kg	1.87E−06	8.79E−06	3.11E−05	1.60E−08	−1.80E−07	2.48E−06	6.95E−06	2.45E−05	2.72E−08	−2.02E−07
Sulphate	kg	6.02E−07	1.16E−05	4.60E−05	5.00E−09	−1.53E−07	8.89E−07	9.14E−06	3.61E−05	9.33E−09	−2.42E−07
Mercury	kg	3.16E−12	8.74E−12	7.86E−11	9.20E−14	−1.53E−13	3.92E−12	8.29E−12	6.32E−11	1.14E−13	−2.83E−13
Arnmonium, ion	kg	3.45E−09	2.27E−08	1.78E−08	1.91E−12	−1.80E−10	5.68E−09	1.78E−08	1.40E−08	4.59E−12	−6.42E−10
Nickel, ion	kg	1.72E−09	1.29E−08	3.33E−08	7.64E−10	−7.07E−10	2.15E−09	8.75E−09	2.47E−08	8.69E−10	−1.18E−09
Cobalt ion	kg	3.81E−10	3.21E−09	1.26E−08	4.13E−11	−1.92E−10	5.03E−10	2.51E−09	9.92E−09	4.82E−11	−3.19E−10
Vanadium, ion	kg	3.82E−10	4.32E−09	2.59E−08	3.47E−12	−3.66E−11	6.35E−10	3.28E−09	2.03E−08	6.86E−12	−3.88E−11

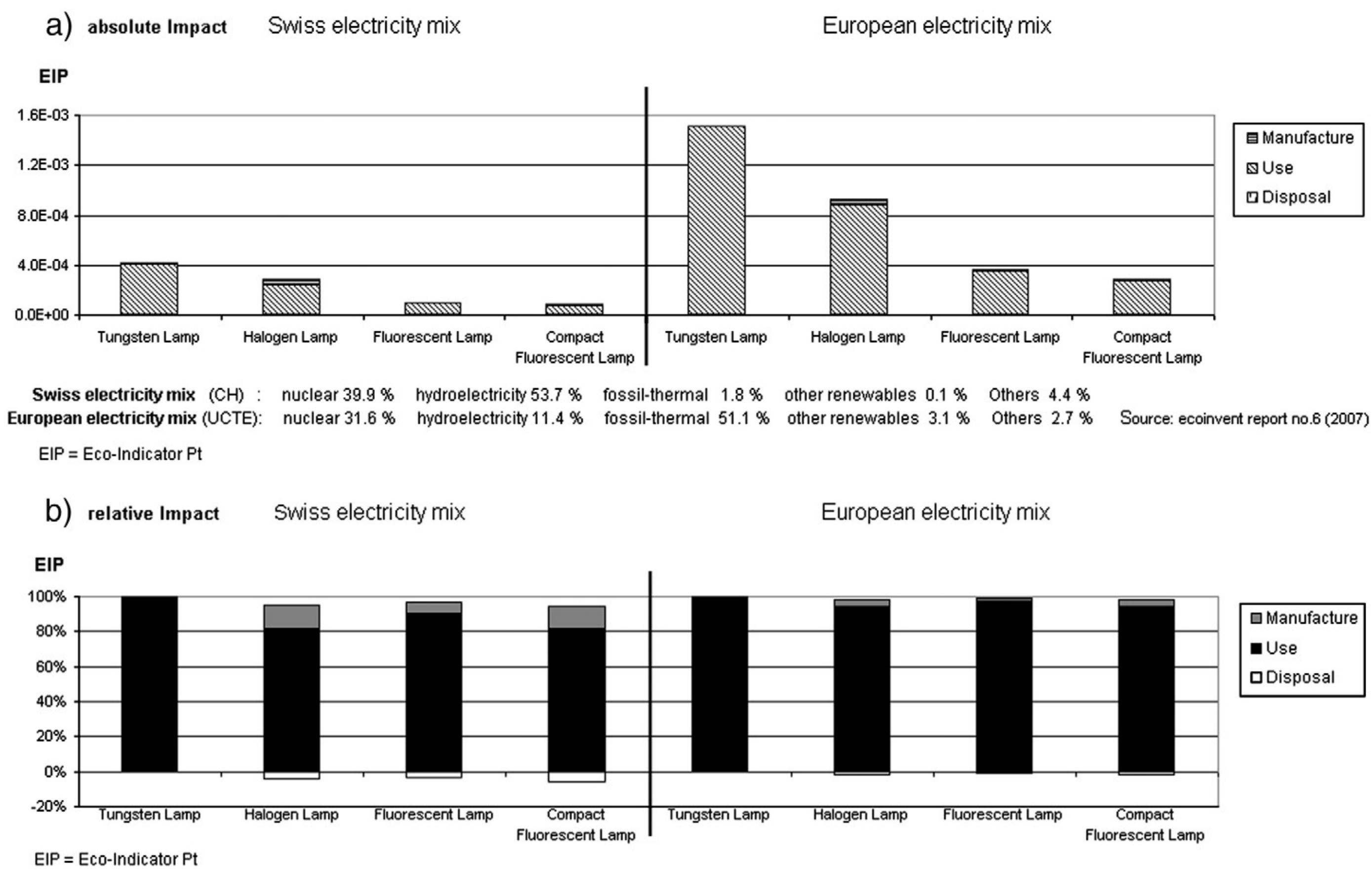

Fig. 2. Composition of environmental impacts by the light bulbs tested for the functional unit of one hour of lighting, expressed in Eco-Indicator Points (EIP).

electric energy is also involved in production and recycling, the electricity mix remained unchanged for these life cycle phases, assuming the European UCTE mix.

As illustrated in Fig. 2b, despite the comprehensive coverage of the manufacture of the various lamps, the use phase dominates by far the environmental burdens for all four technologies due to the environmental burdens of the electricity used. The burdens caused by the manufacturing of the tungsten lamp are very small (about 1% of the whole life cycle impact, assuming the Swiss mix for the use phase) and therefore not visible in Fig. 2. If the European UCTE mix is assumed in the use phase, the relative contribution of manufacture is even smaller (0.3%). In contrast, the relative impacts of the manufacture of the halogen and the two fluorescent lamps are visible, but still small (16%, 8% and 15% for the Swiss and 5%, 2% and 4% for the European UCTE mix, respectively) due to the amount of electronics used by the respective technology. One part of this impact can be compensated for by recycling in the end-of-life treatment due to the large share of electronics in these lamp types from which metals can be recovered. (The white bars below the zero line in Fig. 2b display this environmental benefit).

3.2. Sensitivity to life cycle impact methods

The same scenario was then also evaluated using the other impact assessment methods mentioned in order to check the robustness of the results. The result is shown in Fig. 3.

As shown in Fig. 3, the two used 'midpoint' methods ('global warming potential' and 'cumulative energy demand') deliver almost identical results as the 'endpoint' (EI99) method used. Then as shown in Fig. 2b, the use phase – i.e. the energy consumption of the lamp – is the dominating factor. We therefore decided to show for all further scenarios in this paper only the EI99 results.

3.3. Influence of disposal scenarios

A new element in this type of studies is the comprehensive integration of the end-of-life treatment (see also Section 1). For industrialized countries, a distinction is made here between the disposal of lamps via a 'municipal solid waste incineration' and the actual 'disassembly and recycling'. In the latter case, all subsequent treatment steps for the various fractions out of the disassembly activity were taken into account up to the supply as secondary material or its final disposal, e.g. in a landfill. The objective in this additional sensitivity analysis was to show the influence on the overall environmental performance by the variation of the disposal procedure. Its results are shown in Fig. 4.

As shown in Fig. 4a, the burden generated by incineration of the products containing a lot of electronics (halogen lamps and compact fluorescent lamps) is more than three times higher than the net environmental benefits that can be achieved by an appropriate recycling process. The resulting influence on the overall impact of each of the lamp types is, however, rather small (see Fig. 4b). An appropriate recycling technology can deliver a reduction of the life cycle impacts of a maximum of about 15% for the halogen and the compact fluorescent lamps. Hence, the choice of an appropriate disposal procedure displays some, but surely not a decisive effect on the overall impact of the halogen lamp and the compact fluorescent lamp.

3.4. Influence of product quality and of 'green electricity'

In a first sensitivity analysis, the environmental impacts for different models of lamps of the same type were examined. The goal was to examine variations in the environmental impact due to variations in technical composition. For this purpose the compact

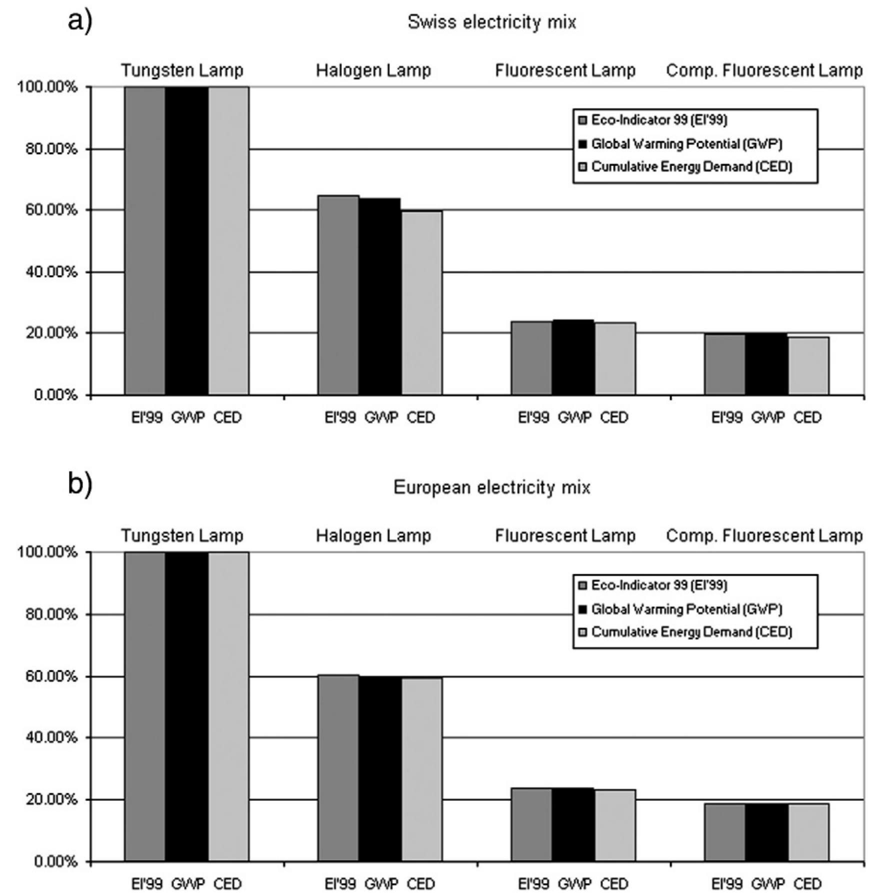

Fig. 3. Comparison of the environmental impacts assessed by applied 'endpoint' (EI'99) and 'midpoint' methods (GWP, CED) for all lamp types tested.

fluorescent lamp was chosen based on its rather high environmental impact in the manufacture phase and its expected future wide distribution in domestic use.

Eight different compact fluorescent lamps sold in Switzerland were selected in accordance with the specifications made in the scope (see Table 1), from a 'no name' product with the lowest price to a 'premium' product with the highest price. For all eight models the quantity of electronic components was analysed and each model was individually assessed, using the same functional unit (i.e. one hour of lighting).

Then, as shown in Fig. 5, the model with the lowest proportion of micro-electronic components (identical to the "premium product") was compared to the one with the highest proportion (identical to the "no name product") and to the median of all models ("generic samples") used in all other calculations for this lamp type. It turned out that the "premium product" (having the lowest share of electronics with 11.19 g per bulb) was hardly to be distinguished from the "no name product" (with its much higher amount of electronics of 19.36 g per bulb) or the median of all samples with regard to environmental impact. Differences in the outcome attributable to manufacture and disposal were only marginal (see Fig. 5). Thus, no significant differences in the overall environmental impact due to differences in product qualities could be identified.

In a second sensitivity analysis the influence of the life time of compact fluorescent lamps on the overall results was investigated. This is due to the fact that the real life time of a compact fluorescent lamp depends much from the actual use — e.g. the more often this type of lamp is turned on and off during a day, the shorter is its total life time (US-DoE, 2009). Hence, the influence of a lower life time (20 to 70% less than the value indicated in Table 1) on the overall result was calculated here. The results of these sensitivity calculations are shown in Table 3.

Table 3 shows clearly that the shortening of the life time has an influence on the overall impact of a compact fluorescent lamp. However this influence is of minor importance; even a reduction by 50% (from 10,000 to 5000 h) would result in an increase of the impact (per hour of use) of only 2.4 (with the UCTE electricity mix) resp. 8.2% (with the Swiss electricity mix); keeping the impact from the compact fluorescent lamp still clearly beyond the impact of the three other technologies.

Finally, due to the high influence of the electricity mix in the use phase, this point was investigated in a third sensitivity analysis. Two purely renewable electricity mixes, one based on wind power and photovoltaics, the other one based on hydro power only, were contrasted with the average European electricity mix. The results are shown in Fig. 6.

Fig. 6 shows clearly that these two renewable electricity mixes result in a significantly lower environmental impact, independent of the LCIA method used (shown is the result with EI99). Taking a closer look at the figure, we conclude that the use of 'green electricity' can induce greater environmental savings than the choice of lamp type. The same is true for national electricity mixes with a high portion of renewable energy. This point is exemplified for the tungsten lamp in Fig. 6. The tungsten lamp with hydro-generated electricity causes less environmental harm than the compact fluorescent lamp using the average European electricity mix. However, while most consumers can choose from a wide variety of different lighting devices on the market, choices concerning the source of the electricity consumed are still heavily constrained by availability and accessibility.

3.5. Environmental break-even points

As a new element for this type of study, the "environmental break-even point" of the various technologies was calculated. This is the

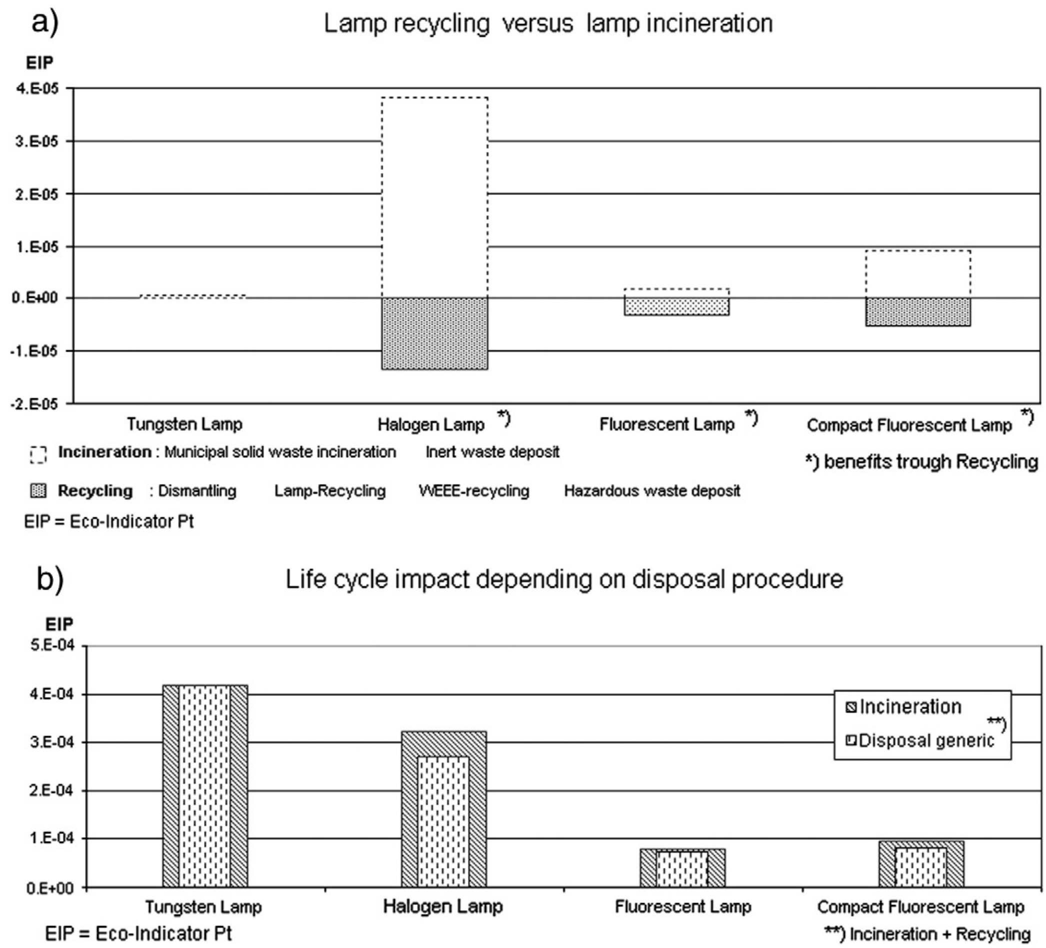

Fig. 4. Effects of the end-of-life treatment selected (incineration or recycling) on the environmental impacts of the four lamp types, expressed in Eco-Indicator points (EIP).

burning time (in hours) after which two lamp technologies have exactly the same overall environmental impact. As described in Section 2.2, the environmental impacts of manufacture and disposal are constant for each of the four lamp types, while in the use phase, the impact depends on the duration of use. Actually, the objective of this last step was to calculate the total burning period necessary to ensure that replacing a tungsten lamp by a lamp of any of the other types would result in a reduction in the overall environmental burden. In Fig. 7, this relationship is shown for the Swiss electricity mix.

The initial impact (for a burning time of 0 h) equals the sum of the manufacturing and disposal impacts of the lamp. This initial impact is highest for the normal fluorescent lamp because of its external ballast. It can be seen further that a compact fluorescent lamp already demonstrates environmental benefits compared to a tungsten lamp

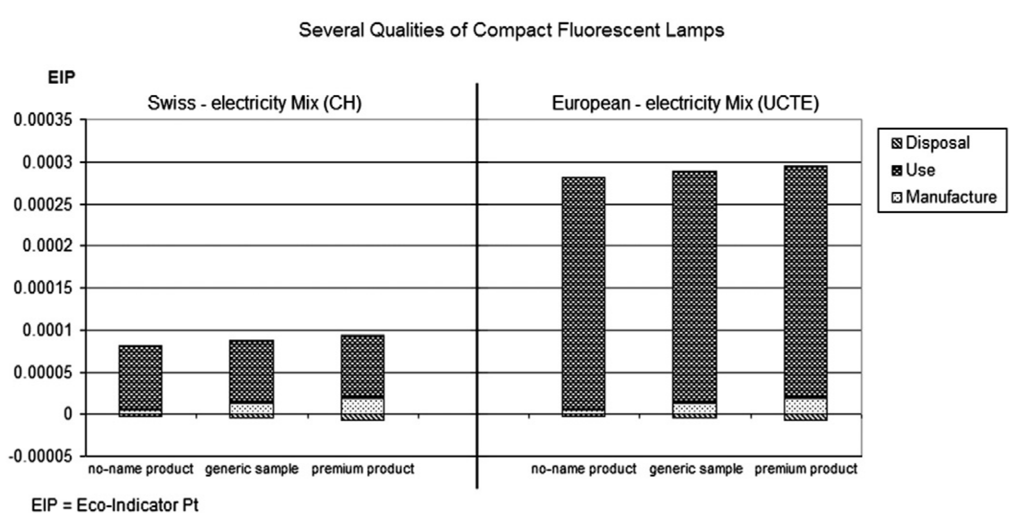

Fig. 5. Effects of different product qualities on environmental impacts, shown for the entire life cycle of compact fluorescent lamps. Investigation for Swiss and European average electricity mixes expressed in Eco-Indicator points (EIP).

Table 3
Influence of a change in the lifetime of a compact fluorescent lamp on the overall impact (i.e. the LCIA results).

Lifetime [jn h]		10,000		8000		5000		3000	
Used electricity mix		CH	UCTE	CH	UCTE	CH	UCTE	CH	UCTE
Impact	...of manufacture	1.22E−05	1.22E−05	1.53E−05	1.53E−05	2.45E−05	2.45E−05	4.08E−05	4.08E−05
	...of use	7.56E−05	2.76E−04	7.56E−05	2.76E−04	7.56E−05	2.76E−04	7.56E−05	2.76E−04
	...of disposal	−5.46E−06	−5.46E−06	−6.82E−06	−6.82E−06	−1.09E−05	−1.09E−05	−1.82E−05	−1.82E−05
Total		8.24E−05	2.83E−04	8.41E−05	2.85E−04	8.92E−05	2.90E−04	9.82E−05	2.99E−04
Change in %		–	–	2.1%	0.6%	8.2%	2.4%	19.2%	5.6%

for a burning period of only 187 h (intersection A). The periods are surprisingly short for the halogen lamp (intersection B) and the conventional fluorescent lamp (intersection C) as well. The figure shows that the environmental payback time of substitution is significantly affected by the initial impacts (i.e. the impact of manufacture and disposal). More important, all break-even points appear far below the life-span of a tungsten lamp, but also far below the average annual lighting duration of 1150 h in EU-27 countries (EuPs, 2008b).

Changing to the other electricity mixes examined above – i.e. the average European mix as well as the two renewable mixes – produces the results shown in Fig. 8.

With the European mix (Fig. 8a), the environmental payback times of the non-tungsten lamps shrink even more, while – as expected – the amortization period in the case of the use of renewable electricity (wind/photovoltaic mix in Fig. 8b, hydropower in Fig. 8c) is much longer. The latter is due to the fact that the low emission per kilowatt hour in the two renewable electricity mixes lead to lower variable impacts per hour of lighting. However, even in such extreme cases the amortization period turns out to be below one year of average operation.

4. Conclusion and outlook

Our study confirms the results from various old studies – i.e. that (compact as well as ordinary) fluorescent lamps result in a clearly lower environmental impact than the two other lamp types examined (i.e. tungsten and halogen lamp) – and this despite the new, much more comprehensive data available especially for the electronics components within the manufacturing phase. Our investigation thereby clearly confirms that the use phase, i.e. electricity consumption, is the main contributor to this impact — independent of the actual lamp type examined. The absolute environmental impacts of the life cycles therefore depend mainly on the electricity mix used. Impacts caused by manufacture and disposal can be neglected, except for the halogen and the compact fluorescent lamp due to their rather high content of electronic components. However, these respective impacts are still low in relation to the impact of power consumption

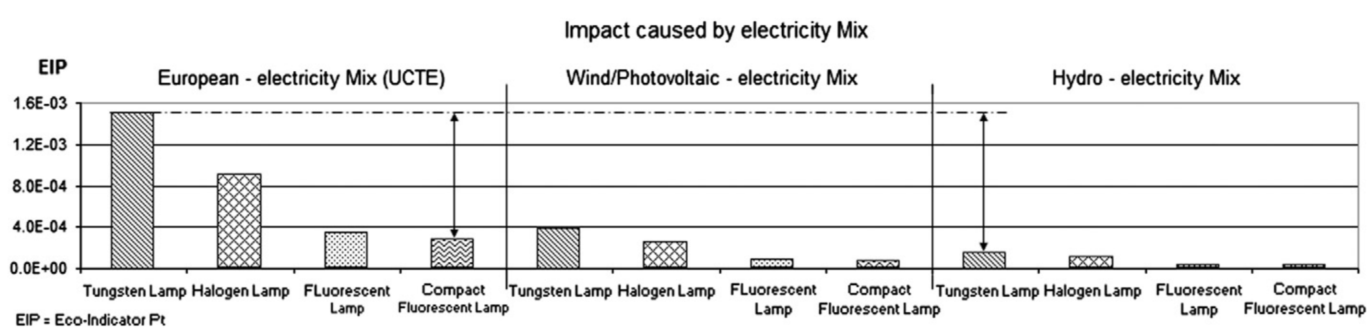

Fig. 6. Environmental performance for the functional unit of one hour of lighting under consideration of renewable and non-renewable electricity mixes, expressed in Eco-Indicator points (EIP).

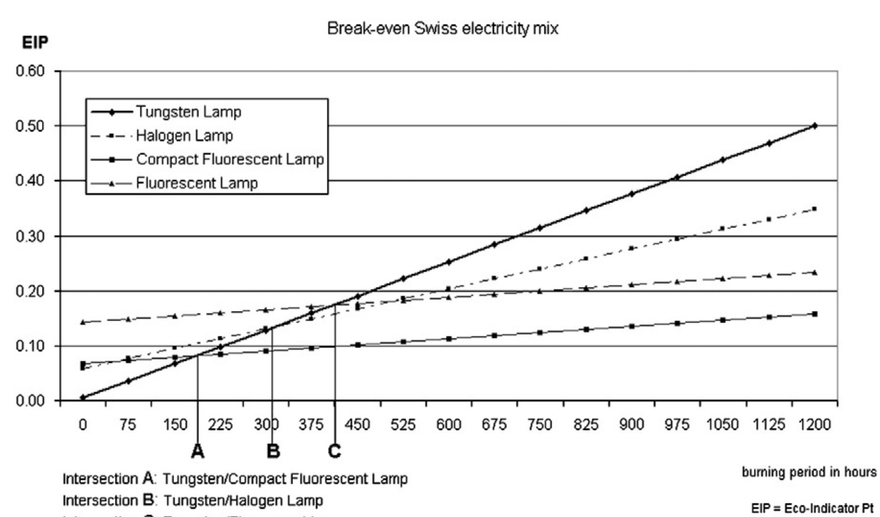

Fig. 7. Burning period of the non-tungsten lamp after which the overall environmental performance is better than that of a tungsten lamp (for the Swiss electricity mix and with EI99 LCIA method).

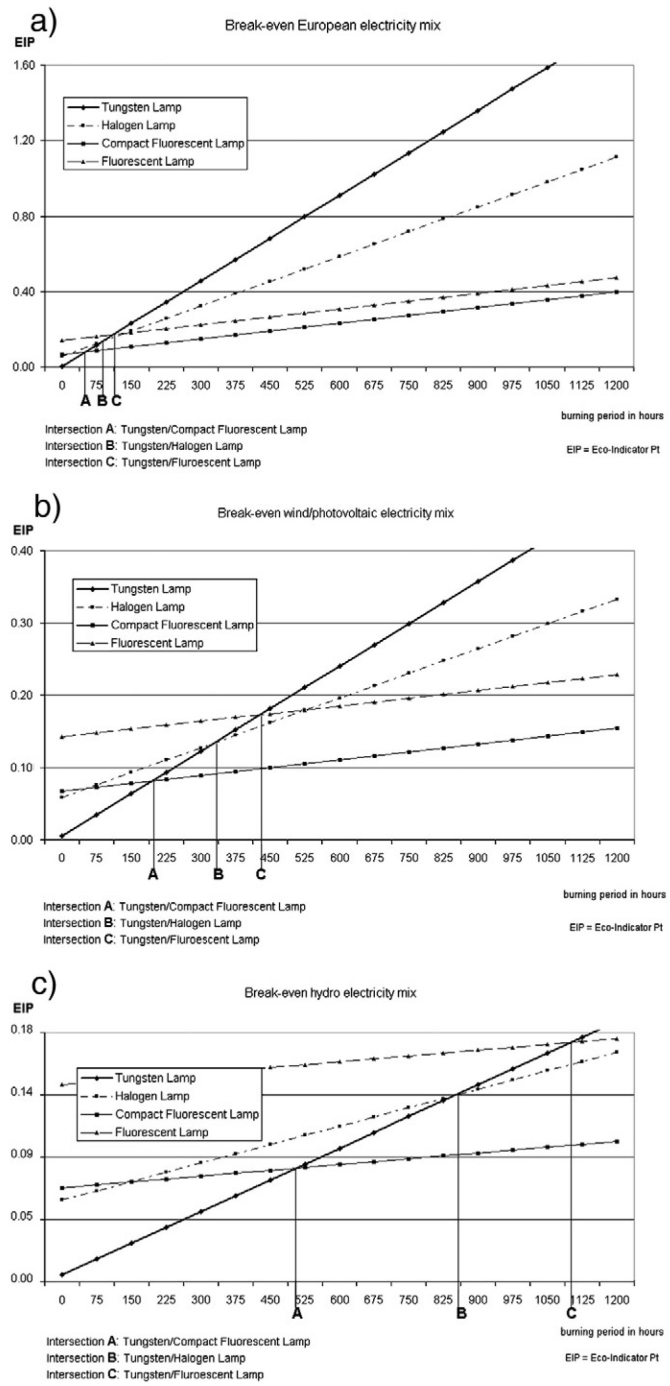

Fig. 8. Influence of the electricity mix on the environmental pay-off period. a) European electricity mix, b) wind/photovoltaic mix, c) hydro mix.

during use of the respective lamp type; so low that even a bisection of the life time of a compact fluorescent lamp results in a less than 10% increase of the environmental impact of 1 h of use.

A second important conclusion of this study is that differences in the product quality of compact fluorescent lamps did not reveal any relevant effect on the overall environmental performance of this lamp type, as was shown by the analysis of several different compact fluorescent lamps sold in Switzerland.

Recycling and incineration were compared as the two basic end-of-life procedures in this study. It turned out that an appropriate disposal process is important, but the difference between the two basic procedures still remains small compared to the use phase impacts. It should be noted that mercury, which is contained in the compact fluorescent lamp and which has toxic effects on the human organism, is predominantly emitted by fossil fuel power plants; a fact already shown by the study from Gydesan and Maimann (1991) — and confirmed in further studies (e.g. Ebersperger and Mauch, 1992; Parsons, 2006). Regarding environmental amortization, the substitution of compact fluorescent lamps for tungsten lamps appears to be the best alternative. The environmental pay-off period is longer wherever a “cleaner” electricity mix is available, but the break-even point is reached after less than one year of average use for all electricity mixes applied — even if 100% hydro power is assumed.

A comparison with the values from the various old studies appears rather difficult, as a broad variety of different impact indicators is used in the various studies. The oldest studies partially use LCIA indicators that are even not in use anymore today — making a comparison with today's result almost impossible. Another difficulty comes from the fact that the functional units vary considerably from one study to the other. Nonetheless, we were able to establish a comparison on the level of the cumulative energy demand as well as one on the level of the global warming potential; comparison summarized in Table 4.

As shown in Table 4, the values for the cumulative energy demand vary by a factor of more than 4 for the two lamp types shown in the various studies. The values from our study always fall into the upper level of the range. A similar observation can also be made for the GWP values — values that show an even higher variation due to the different electricity mixes used in the various studies. Due to the high importance of the use phase, and thus of the dominance of the electricity mix in the overall results, it can therefore be concluded from the results that not all examined studies use data of a similar level of completeness. Especially the studies with the very low values apparently used data of rather low quality, compared to today's data for electricity production.

Future research on the issue of lighting should include new, semiconductor based lighting technologies, such as LED (light emitting diode) and OLED (organic light emitting diode) devices and the electronics needed to operate them, as these technologies promise to be even more energy efficient than a compact fluorescent lamp. Further aspects to cover in such a future study would include efficiency improvements through product development on the basis of existing technologies, for example, by including krypton-filled

Table 4
Comparison of results from various LCA studies for tungsten lamps resp. compact fluorescent lamps.

Used electricity mix	Tungsten Lamp		Compact Fluorescent Lamp		Reference
	GWP [g C02/h]	CED [MJ — Eq/h]	GWP [g C02/h]	CED [MJ — Eq/h]	
Swiss electricity mix	*8*	*0.6*	*2*	*0.12*	*This study*
Swiss electricity mix	0.4		0.3		Mani (1994)
Swiss electricity mix		0.2			Hofstetter (1989)
Danish electricity mix		0.2			Gydesan and Maimann (1991)
German electricity mix		0.7		0.13	Ebersperger and Mauch (1992)
Coal-based electricity	99		19		Parsons (2006)
European electricity mix		0.9		0.02	Rubic and D'Haese (1994)
European electricity mix	*36*	*0.8*	*7*	*0.14*	*This study*

bulbs. This would then provide a comprehensive picture of the scope of viable environmental efficiency potential in domestic lighting.

It is also important to explore the issue of the functional equivalence of lighting devices more precisely. The light quality resulting from the light spectrum emitted may create differences in function; not all types of light may be suitable to all purposes and all groups of people. However, it would require objective testing methods to examine more precisely the qualitative factors involved in using compact fluorescent lamps.

Finally, it would be promising to model the total effects of domestic lighting in relation to other energy consuming devices and potential systemic interactions among the devices used in households.

Acknowledgements

We acknowledge Thomas Ruddy and Gregor Wernet, both from Empa, for their improvements of this article by their comments and corrections.

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