LIFE CYCLE ANALYSES OF INTEGRAL COMPACT FLUORESCENT LAMPS VERSUS INCANDESCENT LAMPS
Energy and Emissions

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Abstract

This paper analyses various environmental effects of compact fluorescent lampscompared to incandescent lamps. The environmental effects are evaluated bycarrying out life cycle analyses for the lamps. In these life cycle analyses the maine mphasis is placed on energy consumption and emissions linked to this during the production, operating and scrapping phases of the lamps. Health and safety aspects during the life cycle are also assessed. The emissions due to electricity consumption are calculated assuming that the electricity is supplied from a coalfired power plant. Finally the environmental impacts of the lamps over their whole lifetime are compared, and it is evaluated if the compact fluorescent lamps can be characterized as a cleaner technology. Aspects such as lighting quality, problems with installing compact fluorescent lamps in existing luminaires etc. are not dealt with in this paper.

The life cycle analyses show that the use of compact fluorescent lamps instead of incandescent lamps, as expected, leads to reduced emissions of CO_2, SO_2 and NO_x, methane and solid waste. The most interesting conclusion is, however, that he compact fluorescent lamps, even though they contain a certain amount of mercury, will reduce emissions of mercury. Another finding is that the energy consumption to produce compact fluorescent lamps is of the same magnitude as the energy consumption to produce incandescent lamps when lifetime of the lamps and luminous intensity is taken into consideration. The energy consumption to produce each type of lamp is very small (about 1%) compared to their energy consumption during their operating lifetime.

ENVIRONMENTAL ASSESSMENT

Due to the increasing pollution of the environment, and the fact that energy production and consumption cause a great deal of the damaging emissions, it is necessary to implement energy technologies which have smaller environmental impact than technologies ordinarily used. To describe the environmental effects from a certain technology it is necessary to make a comprehensive assessment, covering the whole life cycle of the technology.

This implies studies of the environmental impact during the production, operating and scrapping phases of the technology. This type of analysis is named *life cycle analysis*. The life cycle analysis is an essential tool for the assessment of a techno- logy from a cleaner technology point of view. Cleaner technology is a term used for technologies with low overall environmental effect.

In the energy area, life cycle analyses are used to compare the environmental effects of different energy technologies providing the same sort of energy service[1]. An energy service is e.g. the benefit of using energy to light in our homes, warm meals, clean clothes etc., and not the energy consumption in itself. These energy services can be provided with a larger or smaller amount of energy, depending on the choice and use of the technology.

In this paper the environmental effects of two different types of lamps (compact fluorescent lamps and incandescent lamps), providing the energy service lighting by using the energy input *electricity* (during the operating phase), are compared. Depending on how the electricity is produced (technology, efficiency and energy source) the electricity consumption of the lamps will result in certain emissions to the environment. The compact fluorescent lamps use much less electricity to provide a certain illumination than the incandescent lamps, and therefore they cause much lower emissions during the operating phase than the incandescent lamps.

The analyses focus on the emissions of CO_2, SO_2, NO_x, methane (CH_4) and mercury because these emissions are seen as representing the most significant environmental hazards. In addition the generation of solid waste is investigated.

Compact fluorescent lamps contain mercury and certain other chemicals, which may cause problems during the production and scrapping phases, especially if the worn out tubes end up in an incinerator and the mercury is emitted to the air. However, coal also contains mercury, and if the electricity is supplied from a coal power plant (as normally in Denmark) the use of compact fluorescent lamps will result in lower mercury emissions, due to the reduced electricity consumption, than the incandescent lamps. This problem among others will be analysed in the following life cycle analyses.

The compact fluorescent lamp is a more complex technology than an incandescent lamp, due to electronic ballast, phosphor coating of the glass, and more complex manufacturing processes, and thus the energy consumption for the production of compact fluorescent lamps could be of a significant size. To investigate this a comparison is made of the energy used to produce compact fluorescent lamps and incandescent lamps.

LIFE CYCLE ANALYSES

To describe the environmental effects from the energy service lighting with the two different types of lamps, it is necessary to estimate the emissions from the techno- logy during its whole lifetime. This can be done by means of a life cycle analysis of the technology, where emissions and other environmental effects are calculated for the production, operating and scrapping phases. The principles of a life cycle analysis of an energy technology are shown in figure 1[1]. The most important aspects of each phase and of the comprehensive assessment are briefly described below.

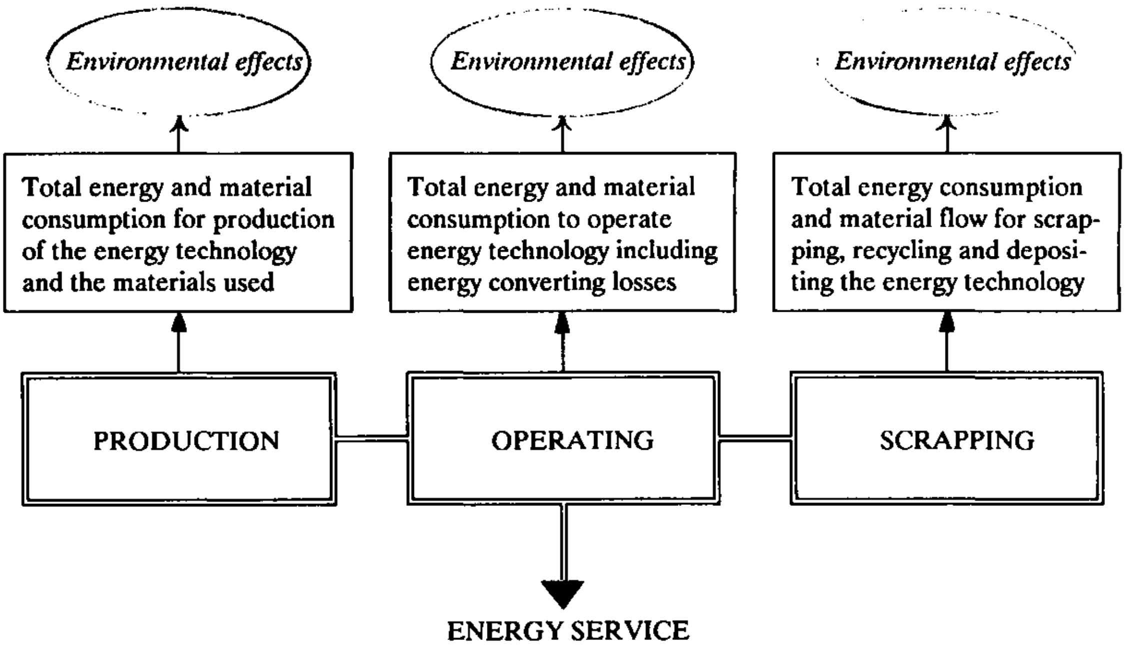

Figure 1. Principles of a life cycle analysis for an energy technology.

Production phase:
The materials used producing the technology are listed, and the energy consump- tion to extract and process these materials and to produce the technology are estimated. The emissions following from the energy consumption are calculated. In addition it is important to investigate whether the materials used may cause health and safety risks and environmental damage.

Operating phase:
The operating phase is the period during which the technology contributes its energy service, and for the lamps it is the lighting period. It is important to include all significant environmental aspects of the operation of the technology. For energy production technologies it is important to include the energy demand for mining and transportation of fuels, for conversion losses, and for carrying through the energy production processes. For the

end use technologies compact fluore- scent and incandescent lamps the effects of the operation phase are almost exclusively limited to the energy consumption for the operation and the emissions following from this.

Scrapping phase:
The scrapping phase is the period in which the technology is worn out. The technology can be treated in different ways, for instance: incineration, depositing or recycling. The energy consumption for scrapping the technology is estimated, and the significance is evaluated. The emissions following from the energy consumption and from residual products from the technology are calculated. Furthermore it is evaluated which kind of scrapping has the lowest environmental impact.

Comprehensive assessment:
The total energy consumption to produce, operate and scrap the technology is calculated. The significance of the energy consumption producing the technology compared to the energy consumption during the whole lifetime is assessed. The emissions from both the energy consumption and the technology itself to the environment are calculated. The environmental impact of the technology is evaluated, and options for improvement from a cleaner technology point of view investigated.

Life Cycle Analyses for Compact Fluorescent Lamps versus Incandescent Lamps

To compare the environmental effects from compact fluorescent lamps with incandescent lamps, life cycle analyses have been made for the two types of lamps. One analysis is made for an OSRAM 15 W compact fluorescent lamp with integrated socket and electronic ballast, with a luminous intensity of 900 lumen and a lifetime of 8000 hours[2]. The second analysis is made for an ordinary 60 W incandescent lamp, which has a luminous intensity of 730 lumen and a lifetime of 1000 hours[2]. The compact fluorescent lamp with integrated socket and electronic ballast is chosen for this analysis, because it is possible to replace an incandescent lamp directly with this compact fluorescent lamp. The same analysis with a modular lamp with separate socket and electronic ballast would result in less energy consumption during the production phase and less solid waste, as the ballasts can be used for several modular lamps.

The life cycle analyses follow the above mentioned principles. As the two types of lamps do not have the same luminous intensity, the energy consumption and the emissions are calculated per 10^6 lumen hours.

Production phase:
The compact fluorescent lamp consists of 2 glass tubes containing mercury gas. With electrodes at each end of the glass tubes, the mercury atoms are stimulated to emit UV-light. A phosphor coating on the inner surface of the glass tubes transforms the UV-light into visible light[3]. The compact fluorescent lamp contains certain chemicals[3] which can be critical to the environment and to the health of workers. These are antimony, barium, lead, various lanthanides and mercury. Especially the mercury content (5 mg in the actual lamp) has given rise to criticism of the compact fluorescent lamps for not being a cleaner technology. This aspect is evaluated below.

The material content in the two types of lamps is listed in table 1. Also the energy content (primary energy) in the materials is listed, and the energy content in the lamps calculated. The reference[4] concerning the energy content in the materials is old (1979), and the extraction and processing of the materials are probably more efficient today

Table 1:Material and energy content in compact fluorescent lamps (CFL) and incandescent lamps.

Material	Energy[4] content	weight ofl CFL	energy content	weight of incand.	energy content
Glass	5.2 Wh/g	33 g	0.17 kWh	22 g	0.11 kWh
Plastic	20 Wh/g	34 g	0.68 kWh		
Electronic	20 Wh/g	33 g	0.66 kWh		
Brass	20 Wh/g	9 g	0.18 kWh	9 g	0.18 kWh
TOTAL			1.7 kWh		0.29 kWh

A different analysis[2] of the energy consumption to extract and process the materials and assemble the lamps gives 1.4 kWh for a 15 W compact fluorescent lamps with integrated electronic ballast and 0.15 kWh for a 60 W incandescent lamp (the energy consumption refers to electricity). In primary energy the energy consumption is 3.5 kWh to assembling and finishing of compact fluorescent lamps and 0.4 kWh for incandescent lamps, when a efficiency of 40% of electricity generation is used. Thus the energy used for producing the two types of lamps (in primary energy), that is 3.5 - 1.7 kWh = 1.8 kWh for compact fluorescent lamps and 0.4 - 0.29 kWh = 0.11 kWh for the incande- scent lamps. This indicates that there is a much higher energy consumption for both material and processing of the compact fluorescent lamps. In the following analyses the electricity consumption for the production phase is assumed to be 1.4 kWh for a compact fluorescent lamp and 0.15 kWh for an incandescent lamp.

To produce 10^6 lumen hours, 0.14 CFL or 1.37 incandescent lamp is necessary. The energy consumption to produce 0.14 CFL is 0.19 kWh and to produce 1.37 incandescent lamps 0.21 kWh is needed. In other words the production of compact fluorescent lamps does not require more energy than producing incandescent lamps, if the comparison is - as it should be - based on similar provision of light.

Operating phase:
The compact fluorescent lamp consumes much less electricity during operation than the incandescent lamps as shown in table 2. This is also the reason why it is attractive to use compact fluorescent lamps instead of incandescent lamps from a cleaner technology point of view, because of the reduced emissions from electri- city production.

Table 2:Energy consumption of compact fluorescent and incandescent lamps.

	compact fluorescent	incandescent lamps
rated effect	15 W	60 W
luminous intensity	900 lumen	730 lumen
lifetime	8000 hours	1000 hours
energy consumption in 10^6 lumen hours	16.7 kWh	82.2 kWh

Table 2 shows that the incandescent lamps use 5 times as much energy as compact fluorescent lamps providing the same energy service. The assumption this result is based on, namely that the two types of lamps have the same usage pattern, does not always apply in reality. Often people leave the compact fluorescent lamps on for longer periods than incandescent lamps because of a widespread perception that a high number of on/off cycles reduces the lifetime of the compact fluore- scent lamps. For compact fluorescent lamps with electronic ballast there is no such link, and therefore the same usage pattern has been assumed.

Scrapping phase:
No quantitative calculation has been made of the energy consumption needed for scrapping the lamps, but a qualitative assessment support that it is negligible compared to the energy consumption during the operating phase. There are, however, various environmental impacts beside those connected to the energy consumption.

In a traditional waste disposal system the compact fluorescent lamp typically ends up in an incinerator, from which its content of chemicals such as mercury may be emitted to the atmosphere and cause environmental damage. Instead the compact fluorescent lamps may be subjected to some sort of collection, and maybe recyc- ling, system, which would lead to the damages being reduced, or even removed completely. In this analysis all of the mercury are assumed to be emitted.

Emissions Caused by Electricity Production

To calculate the total emissions caused by using the lamps it is necessary to establish the source of the electricity generation. To determine the emissions to the environment caused by the use of electricity the following emission factors have been used: 0.85 kg CO_2/kWh, 6.4 g SO_2/kWh, 4.3 g NO_x/kWh, 0.003 g CH_4/kWh, 48.6 g fly ash/kWh and 0.059 mg mercury/kWh. These emission factors are based on the assumption that the electricity production takes place on coalfired power plants, as is 95% of electricity generation in Denmark. The emission factors are calculated assuming 40%[9] efficiency of electricity generation and that the emissions from coal burning are 95 kg CO_2/GJ[6], 0.714 kg SO_2/GJ[6], 0.48 kg NO_x/GJ[6], 0.3 g CH_4/GJ[6], 5.4 kg fly ash/GJ[7] and 6.54 mg mercury/GJ[8]. Of the mercury emission about 60% is attached to the fly ash, and is gathered with this. The rest of the mercury emission is gaseous and very difficult to purify from the air. Other heavy metals and trace elements include lead, cadmium, arsen and uran, but the greater part of these emissions are collected with the fly ash[7]. The emissions from electricity production would naturally be different if the electricity were produced from a different fuel, like natural gas, or by non-fossil electricity production technologies such as windmills. Still the energy supply system in many countries is based on coal power plants, and often it is electricity generated by coal power plants that is eliminated by using an electricity saving technology. It is therefore reasonable to use the emission figures for a coal power plant to calculate the emissions from the electricity consumption of the lamps.

COMPREHENSIVE ASSESSMENT

Energy Consumption

The energy consumption during the lifetime of the two types of lamps is shown in table 3.

Table 3:Energy consumption in the life cycle of a compact fluorescent lamp and an incandescent lamp.

	15W comp. fluorescent	60 W incandescent
per lamp:		
production phase	1.4 kWh	0.15 kWh
operating phase	120 kWh	60 kWh
scrapping phase	0 kWh	0 kWh
Total	121 kWh	60 kWh
energy service	$7.2*10^6$ lumen hours	$0.73*10^6$ lumen hours
per 10^6 lumen hours:		
production phase	0.19 kWh	0.21 kWh
operating phase	17 kWh	82 kWh
scrapping phase	0 kWh	0 kWh
Total	17 kWh	82 kWh

Table 3 shows that the energy consumption to produce both types of lamps is about 1 % or less of the energy consumption during their lifetime. Also it shows that there is no further energy consumption to produce compact fluorescent lamps to meet the same lighting standard compared to incandescent lamps, and that providing a specific quantity of light requires 5 times as much energy when incandescent lamps are used instead of compact fluorescent lamps.

Emission Statement

The emissions during the life cycle of compact fluorescent and incandescent lamps are shown in table 4. The emissions are calculated per 10^6 lumen hours. As the emissions during both production and operating phases are limited to emissions from energy production, these two phases are treated together. The output to the environment during the scrapping phase is assumed to be solid waste and, for the compact fluorescent lamps, gaseous mercury.

Table 4:Emissions during the life cycle of the lamps per 10^6 lumen hours.

Emissions	Comp. fluorescent	Incandescent	Reduction
prod. and operating			
CO_2	14.4 kg	70.0 kg	55.6 kg
SO_2	0.11 kg	0.53 kg	0.42 kg
NO_x	0.07 kg	0.35 kg	0.28 kg
CH_4	0.05 g	0.25 g	0.20 g
fly ash	0.82 kg	4.00 kg	3.18 kg
mercury	1.00 mg	4.86 mg	3.86 mg
(gaseous/solid split)	*(0.40/0.60)*	*(1.94/2.92)*	*(1.54/2.32)*
scrapping			
mercury	0.69 mg	–	- 0.69 mg
solid waste	0.015 kg	0.042 kg	0.027 kg
Total mercury	1.69 mg	4.86 mg	3.17 mg
(gaseous/solid split)	*(1.09/0.60)*	*(1.94/2.92)*	*(0.85/2.32)*
Total solid waste	0.83 kg	4.04 kg	3.21 kg

The use of compact fluorescent lamps leads to reduced emissions of both gaseous mercury and mercury attached to the fly ash. The damaging effects of the mercury in the compact fluorescent lamps, when emitted to the air, ash is considered less dangerous to health and environment than gaseous mercury, though this depends on the treatment of the fly ash. Breakage of compact fluorescent lamps can result in high local concentrations of mercury vapour[10].

The above calculations are for the worst options with respect to the scrapping of the compact fluorescent lamps. If the lamps are collected and the mercury is seperated and recycled, the emissions of gaseous mercury are reduced.

It is interesting to notice that even though the compact fluorescent lamp contains mercury, its application reduces the overall emissions of mercury, because electri- city production based on coal power plants causes mercury emissions with the exhaust gas.

Furthermore the use of compact fluorescent lamps instead of incandescent lamps reduces the contribution to the greenhouse effect of providing the energy service lighting, because the emissions of CO_2, CH_4 and NO_x (greenhouse gases[11]) are reduced. Also the contribution to acid rain is reduced by avoiding emissions of SO_2 and NO_x. The generation of solid waste, in the form of both fly ash and scrap, is reduced.

Cleaner Technology Initiatives

Through the emission calculations it has been shown that compact fluorescent lamps are a cleaner technology than incandescent lamps. But still there is scope for further improvement of the technology of the lamps.

Mercury content in compact fluorescent lamps

The worn out compact fluorescent lamps can be collected and the mercury either deposited, or better recycled, to prevent emissions to the atmosphere.

The content of mercury can be reduced. In this specific OSRAM 15 W lamp the content of mercury is about 5 mg per lamp[2]. The theoretical minimum of the mercury content can be calculated from the equation for ideal gases[5]:

$$p * V = n * R * T$$

In this equation p is the saturated vapour pressure at the operating temperature T. V is the volume of the glass tube, calculated from the dimensions of the glass tube (V = p/4 * d2 * L), and n is the number of moles calculated from the weight of mercury in the glass tube (m) and mercury's molar mass (M). R is the universal gas constant. For a glass tube with diametre d and length L this leads to the following equation:

$$m = \frac{\pi * d^2 * L * p * M}{4 * R * T}$$

In the CFL the temperature of the mercury vapour is 50 degree C = 323 K[3]. The saturated vapour pressure at this temperature is 1.69 Pa. The glass tube of a Osram 15 W CFL has a diametre of 12 mm and total length of 480 mm. Using the above equation this leads to a theoretical minimum amount of mercury in the CFL of 0.007 mg. Comparing this to the actual amount of 5 mg there seems to be a large potential for reducing the content of mercury in the compact fluorescent lamps.

Efficient utilization of electricity

The efficiency of converting electricity to light is increased from about 6 to 30 % by using compact fluorescent lamps instead of incandescent lamps, but still there is scope for further increasing the efficiency by development of other types of lamps.

As the essential objective of the energy service lighting is to illuminate places it is important to design luminaires with high efficiency and reflectors which guide the light to the place where it is needed. Some luminaires retain as much as 80% of light within the luminaire.

Last but not least the most important issue is to use lamps as effectively as possible and turn off unnecessary lamps - which is the state in which even low energy lamps use the least electricity.

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