

Emissions and economic costs of cycling compact fluorescent lamps with integrated ballasts

FG Rosillo

F Castejón

MA Egido

This paper proposes a way to quantify the emissions of mercury (Hg) and CO₂ associated with the manufacture and operation of compact fluorescent lamps with integrated ballasts (CFLi), as well as the economic cost of using them under different operating cycles. The main purpose of this paper is to find simple criteria for reducing the polluting emissions under consideration and the economic cost of CFLi to a minimum. A lifetime model is proposed that allows the emissions and costs to be described as a function of degradation from turning CFLi on and their continuous operation. An idealized model of a CFLi is defined that combines characteristics stated by different manufacturers. In addition, two CFLi models representing poor-quality products are analyzed. It was found that the emissions and costs per unit of time of operation of the CFLi depend linearly on the number of times per unit of time it is turned on and the time of continuous operation. The optimal conditions (lowest emissions and costs) depend on the place of manufacture, the place of operation and the quality of the components of the lamp/ballast. Finally, it was also found that for each lamp, there are intervals when it is turned off during which emissions of pollutants and costs are identical regardless of how often the lamp is turned on or the time it remains on. For CO₂ emissions, the lamp must be off up to 5 minutes; for the cost, up to 7 minutes and for Hg emissions, up to 43 minutes. It is advisable not to turn on a CFLi sooner than 43 minutes from the last time it was turned off.

Nomenclature

a	interval between the time the lamp is turned on and the next time it is turned off in a cycle	b_{opt}	time the lamp remains off such that the costs are identical in any cycle
b	time that the lamp remains off in a cycle	$C_{a,n}$	cost per unit of time of the CFLi in cycling characterized by (a,n)
$b_{opt}^{CO_2}$	time the lamp remains off such that CO ₂ emissions are identical in any cycle	$C_{b,n}$	cost per unit of time of the CFLi in cycling characterized by (b,n)
b_{opt}^{Hg}	time the lamp remains off such that Hg emissions are identical in any cycle	C^c	cost of electricity in the country in which the lamp is being used
		C_l	cost of acquiring the lamp
		c_m	mercury content dumped into the environment per lamp
		e	E/P

E number of particles emitted by the electrode each time it is turned on
 E'_{CO_2} amount of CO₂ emitted by the electricity consumed in country c' where the CFLi is operating
 $E^c_{CO_2}$ amount of CO₂ emitted by the electricity consumed in country c where the CFLi is manufactured
 $E^{CO_2}_{a,n}$ CO₂ emissions during cycling characterized by (a,n) per unit of time of reference
 $E^{CO_2}_{b,n}$ CO₂ emissions during cycling characterized by (b,n) per unit of time of reference
 $E^{Hg}_{a,n}$ Hg emissions during cycling characterized by (a,n) per unit of time of reference
 $E^{Hg}_{b,n}$ Hg emissions during cycling characterized by (b,n) per unit of time of reference
 $E^{T,CO_2}_{a,b}$ CO₂ emissions during reference time T with CFLi operating in cycling characterized by (a,b)
 f F/P
 F number of particles emitted by the electrode during normal operation per unit of time
 i discount rate
 l_{on} lifetime of the lamp (the time the lamp remains on before it stops working)
 l_{on+off} lifetime of the lamp including the time that the lamp remains off
 LWF_p correction factor for power quality of CFLi
 $MC_{a,n}$ cost of acquisition with CFLi operating in cycling characterized by (a,n)
 $ME^{CO_2}_{a,n}$ CO₂ emissions from manufacturing the lamp with CFLi operating in cycling characterized by (a,n)
 $ME^{Hg}_{a,n}$ Hg emissions from manufacturing the lamp with CFLi operating in cycling characterized by (a,n)
 N number of starts during time T
 n number of times turned on per unit of time
 $OC_{a,n}$ cost of operation with CFLi operating in cycling characterized by (a,n)
 $OE^{CO_2}_{a,n}$ CO₂ emissions from operating the lamp with CFLi operating in cycling characterized by (a,n)

$OE^{Hg}_{a,n}$ Hg emissions from operating the lamp with CFLi operating in cycling characterized by (a,n)
 P number of particles susceptible to being detached from the electrode by sputtering or by evaporation
 $P_{elec}(t)$ number of particles present in the electrode at time t
 P_l lamp power consumption
 P_{lpf} product of P_l and LWF_p
 r_c portion of the CFLi that are used and returned to the recycle chain
 T reference time including on and off times
 T_e time in years the discount rate covers
 u_m energy consumed in manufacturing a CFLi

1. Introduction

The use of any technological device is associated with polluting emissions and economic costs. This study estimates the CO₂ and mercury (Hg) emissions of several compact fluorescent lamps with integrated ballasts (CFLis) and the economic cost associated with their lifecycle.

There is a widely spread mythology related to turning on and operating fluorescent lamps such as that turning on and off the lamp should be avoided because it consumes an exorbitant amount of energy. There are a limited number of studies that analyze in more or less detail the polluting emissions or the cost associated with the use of fluorescent lamps in general compared to other light source technologies.¹⁻¹⁶ From the studies mentioned, it is difficult to extract any standards of use that enable CFLi emissions and costs to be made easily communicable to experts interested in illumination, much less to the final user.

This paper makes an estimation of some of the polluting emissions associated with CFLi and the economic cost of their use based on an easily understandable lifetime model which has been compared with experimental data. The calculations are made for the use of CFLi

in Spain, discussing the parameters that could influence these calculations. Emissions during the production and use stages are included, attributing an amount of Hg to the production stage which is impossible to recover because many CFLi are disposed of outside the recycling chains. We attempt to compare the results with some of the recommendations made in previous studies and in manufacturers' technical documents.^{1,17} Finally, the results are used to provide a guide for the final user.

The case under study is residential application of the CFLi because of its social and educational interest. Furthermore, the choice of a CFLi instead of a compact lamp without integrated ballast or a fluorescent tube allows the whole problem to be dealt with, because in the CFLi, the fluorescent lamp itself and its ballast are inseparable. The emissions evaluated (CO₂ and Hg) were chosen for their paradigmatic character, CO₂ as an emission indicative of climate change and energy efficiency, and Hg because it is specifically associated with fluorescent lamps. It should be emphasized that the comparison made in this paper is between different ways of cycling CFLi and qualities but not different illumination technologies.

2. Lifetime model

In two studies similar to this, other authors have used an empirical model based on a Weibull distribution.^{1,15} Application of this distribution requires knowledge of three parameters whose relationship to the phenomena that influence lamp lifetime is not easy to establish. A lifetime model is proposed based on two parameters, one that describes the effect of turning them on and the other describing the effect of continuous operation. In spite of its simplicity and of consisting of only two parameters instead of three, the model proposed is based on physical parameters and provides fits of similar quality.

Before it starts to operate, the electrode of a fluorescent lamp is characterized by having a certain number of particles susceptible to being detached from the electrode by sputtering or by evaporation¹⁸ and able to emit electrons, which we shall call P . Each of these particles is defined as the average particle object of evaporation, sputtering, and in general, any physical phenomenon which causes loss of material from the electrode. To simplify, in the following, the average particle emitted by the electrode in any of the processes mentioned is assumed to be identical. Instantaneous variation of particles present in the electrode is given by the equation:

$$\frac{dP_{elec}(t)}{dt} = F + \frac{E}{a} \quad (1)$$

where $P_{elec}(t)$ represents the number of particles present in the electrode at time t . $P_{elec}(t)$ is a function of time, since the electrode undergoes the loss of material due to continuous operation and to start-up. According to this definition, $dP_{elec}(t)/dt$ represents the number of particles per unit of time emitted by the electrode at time t due to different physical phenomena, F represents the number of particles emitted by the electrode during normal operation per unit of time and E is the number of particles emitted by the electrode each time it is turned on, and has been divided by a , the interval between the time the lamp is turned on and the next time it is turned off. The approach considers F and E constant throughout the lifetime of the lamp and characteristic of each ballast for a given fluorescent lamp. At any time t after the first start-up, the following equation which describes the conservation of matter must be met:

$$P = P_{elec}(t) + \int_0^t \left(F + \frac{E}{a} \right) dt \quad (2)$$

The lifetime of the lamp is designated by lt_{on} . This number represents the time the lamp remains on before it stops working because the electrodes are exhausted. It should be stressed that this does not include the time the lamp remains off between start-ups. $P_{elec}(lt_{on}) \approx 0$, since at the end of its useful life, the lamp will have lost most of its electron emission coating. Substituting generic time t in Equation (2) with lifetime lt_{on} and solving we have:

$$lt_{on} = \frac{P}{F + \frac{E}{a}} \quad (3)$$

To solve Equation (3) from experimental data, since it is impossible to know P explicitly, new variables $f = F/P$ and $e = E/P$ are defined with which Equation (3) can be rewritten in the following manner:

$$lt_{on} = \frac{1}{f + \frac{e}{a}} \quad (4)$$

The variables f and e supply measures of the reduction of lifetime due to normal operation and starting, respectively.

It is useful to define the lifetime of the lamp including time b that the lamp remains off lt_{on+off} given by the following equation:

$$lt_{on+off} = \frac{a+b}{a} lt_{on} \quad (5)$$

This model coincides completely with a previous proposal by two authors of this article.^{19,20} Defining lt_0 as the nominal lifetime of the lamp, the variables used in the original model (A and B) are linearly related to those in the present proposal, in which the following relationships may be established immediately:

$$e = -\frac{A}{lt_0} \quad (6)$$

$$f = \frac{1-B}{lt_0} \quad (7)$$

The advantage of the version of the lifetime model presented here is that it is based on physical principles down to the level of the particles that make up the electrodes and that understanding of the meaning of e and f is more direct than of A and B .

Although this deduction was made considering the degradation mechanisms of fluorescent lamps, in a previous study,¹⁹ it was found that the fit of the model (based on A and B) to experimental data available for CFLi²¹ was acceptable with an R^2 of 0.86 for the fit of experimental data and model. In this application, f describes the effect of continuous operation during the lifetime of the lamp/ballast pair, while e does the same for turning it on.

3. Equations describing emissions and costs

CO₂ emissions associated with the use of a CFLi are essentially produced by consumption of electricity during lamp production and during its operation.⁹ A reference time T corresponds to the time a user keeps the CFLi in use, including both the time the lamp remains on and the time it remains off. T can be compared to the lifetime in years that manufacturers assign to their CFLi in the basic technical documents directed at the final user for his orientation.²²

During time T , the lamp may break and have to be replaced. The lamp is subjected to cycling during which it remains on for time a and off for time b . The time the lamp remains on when it is subjected to the cycling described is given by $aT/(a+b)$. $E_{a,b}^{T,CO_2}$ is defined as CO₂ emissions during reference time T with CFLi operating in cycling characterized by (a,b) as given by the following equation:

$$E_{a,b}^{T,CO_2} = \frac{T}{lt_{on+off}(a)} E_{CO_2}^c u_m + \frac{aT}{a+b} E_{CO_2}^c P_{lpf} \quad (8)$$

where $lt_{on+off}(a)$ is the lifetime, including time off, in cycling characterized by a , $E_{CO_2}^c$ is the amount of CO_2 emitted by the electricity consumed in country c where the CFLi is manufactured, u_m is the energy consumed in manufacturing a CFLi, $E_{CO_2}^{c'}$ is the amount of CO_2 emitted by the electricity consumed in country c' where the CFLi is operating. $P_{lpf} = P_l LWF_p$ is the product of lamp power consumption P_l and a correction factor for the CFLi power consumption quality, LWF_p , that accounts for the low power factor of CFLi.¹⁶ In this study, a value of 1.05 is assigned to LWF_p that represents a 5% increase of P_l .¹⁶ $T/lt_{on+off}(a)$ is the number of CFLi used during time T , and the first term in Equation (8) shows the emissions from manufacturing the number of lamps necessary to provide service during time T . Taking into account that $aT/(a+b)$ is the time that the CFLi remains on during time T , the second term gives the emissions associated with CFLi operation.

As the number of starts during time T is given by $N = T/(a+b)$, n is defined as the number of times turned on per unit of time:

$$n = \frac{N}{T} = \frac{1}{a+b} \quad (9)$$

This study evaluates the emissions and costs by normalizing the unit of time T , so that $E_{a,n}^{CO_2} = E_{a,b}^{T,CO_2}/T$ are defined as the CO_2 emissions during cycling characterized by (a,n) per unit of time of reference. Taking into account Equations (4) and (8), it is expressed as follows:

$$E_{a,n}^{CO_2} = an \left(E_{CO_2}^c u_m \left(f + \frac{e}{a} \right) + E_{CO_2}^{c'} P_{lpf} \right) \quad (10)$$

The relationship between CO_2 emissions from manufacturing the lamp $ME_{a,n}^{CO_2}$ and

from its operation $OE_{a,n}^{CO_2}$ may be evaluated as:

$$\frac{ME_{a,n}^{CO_2}}{OE_{a,n}^{CO_2}} = \frac{E_{CO_2}^c u_m}{E_{CO_2}^{c'} P_{lpf}} \left(f + \frac{e}{a} \right) \quad (11)$$

Based on Equation (10), and keeping in mind that $a = 1/n - b$, making $E_{a,n}^{CO_2}$ the same for any n , and with a few operations, a time may be found when the lamp remains off, $b_{opt}^{CO_2}$, such that the emissions are identical in any cycle, regardless of the time on, a , and the number of starts per unit of time, n :

$$b_{opt}^{CO_2} = \frac{e E_{CO_2}^c u_m}{E_{CO_2}^{c'} P_{lpf} + f E_{CO_2}^c u_m} \quad (12)$$

A version of Equation (10) may also be used in which a is substituted by b through the expression $a = 1/n - b$ called $E_{b,n}^{CO_2}$.

The deduction and equations for Hg emissions $E_{a,n}^{Hg}$ and $ME_{a,n}^{Hg}/OE_{a,n}^{Hg}$ are similar. In this case, a portion r_c of the CFLi that are used are returned to the recycle chain so that a portion $1 - r_c$ and its Hg content c_m is dumped into the environment. Under these conditions, the equations are the following:

$$E_{a,n}^{Hg} = an \left(\left(E_{Hg}^c u_m = c_m(1 - r_c) \right) \left(f + \frac{e}{a} \right) + E_{Hg}^{c'} P_{lpf} \right) \quad (13)$$

$$\frac{ME_{a,n}^{Hg}}{OE_{a,n}^{Hg}} = \frac{E_{Hg}^c u_m + c_m(1 - r_c)}{E_{Hg}^{c'} P_{lpf}} \left(f + \frac{e}{a} \right) \quad (14)$$

and

$$b_{opt}^{Hg} = \frac{e \left(E_{Hg}^c u_m + c_m(1 - r_c) \right)}{E_{Hg}^{c'} P_{lpf} + f \left(E_{Hg}^c u_m + c_m(1 - r_c) \right)} \quad (15)$$

It should be emphasized that the accounting of emissions from manufacturing $ME_{a,n}^{Hg}$ includes both Hg emitted by consumption of electricity during lamp manufacture from fuels used for generating electricity, and the Hg in the composition of gas in the fluorescent lamp not recycled.

Finally, the equations and concepts are analogous for the economic cost to the final user. $C_{a,n}$ is defined as the cost per unit of time of the CFLi in cycling characterized by (a,n) :

$$C_{a,n} = an \left(C_l \left(f + \frac{e}{a} \right) + C^C P_{lpf} \right) \quad (16)$$

where C_l is the cost of acquiring the lamp and C^C the cost of electricity in the country in which it is being used. In a somewhat different manner, a similar economic assessment was previously developed by Carriere and Rea,¹ with the main difference being that in the study cited, the lifetime was evaluated based on a Weibull distribution. Following the cost assessment methodology that includes the discount rate i as an annual percentage, and T_e , the time in years the discount rate covers and which allows the value of money to be updated to the present time,^{4,5} a somewhat more complicated expression is used:

$$C_{a,n} = an \left(C_l \left(f + \frac{e}{a} \right) \left(1 + \frac{i}{100} \right)^{T_e} + C^C P_{lpf} \frac{\left(1 + \frac{i}{100} \right)^{T_e} - 1}{\frac{i}{100}} \right) \quad (17)$$

The ratio between the cost of acquisition $MC_{a,n}$ and the cost of operation $OC_{a,n}$ of the lamp is given by the following equation:

$$\frac{MC_{a,n}}{OC_{a,n}} = \frac{C_l}{C^C P_{lpf}} \left(f + \frac{e}{a} \right) \frac{\left(1 + \frac{i}{100} \right)^{T_e} - 1}{\left(1 + \frac{i}{100} \right)^{T_e} - 1} \frac{100}{i} \quad (18)$$

If the discount rate is not considered, we have:

$$\frac{MC_{a,n}}{OC_{a,n}} = \frac{C_l}{C^C P_{lpf}} \left(f + \frac{e}{a} \right) \quad (19)$$

The optimal economic value of the time off b_{opt} is given by:

$$b_{opt} = \frac{eC_l \left(1 + \frac{i}{100} \right)^{T_e}}{C^C P_{lpf} \frac{\left(1 + \frac{i}{100} \right)^{T_e} - 1}{\frac{i}{100}} + fC_l \left(1 + \frac{i}{100} \right)^{T_e}} \quad (20)$$

Or, if the discount rate is ignored:

$$b_{opt} = \frac{eC_l}{C^C P_{lpf} + fC_l} \quad (21)$$

It is possible to evaluate the emissions and cost per lumen-hours² just by dividing Equations (10), (13) and (16), respectively, by the integral of the luminous flux generated during CFLi lifetime. In general, this calculation would involve the time integration due to the reduction of the luminous flux emitted during lamp lifetime (lumen maintenance). This parameter is especially useful for performing comparisons of different technologies as, for example, CFLi, incandescent and light-emitting diodes (LEDs) and for comparison of models of the same technology.² However, it does not supply simple rules of use to the final user. The purpose of the present work is not to calculate this quantity but to investigate rules that make it possible to evaluate selected scenarios of use of some models of CFLi that supply a criterion for switching on and off the lamps, independently of the cost and emission per lumen generated for the lamp during its life. For this reason, this quantity has not been evaluated in the present work. On the other hand, a simple estimation of this quantity can be performed

easily with the data supplied here, as will be stated in the chapter of results.

4. CFLi model

There is no complete set of data related to a specific CFLi that makes this study possible. It was decided to define an ideal fluorescent lamp model that combines manufacturers' data for similar models in an average range of CFLi qualities. Table 1 shows the data used for the CFLi model. The CFLi described does not exist, but it is also true that it could perfectly well exist and be equivalent to one of the models found in major manufacturers' catalogues.

The origins of the data selected are specified below. The model proposed is considered a good-quality CFLi in the average commercial range of features and prices. It is usually possible to find the lifetime of a CFLi in the conventional 2 hours 45 minutes on/15 minutes off (or similar) test. But to infer e and f from Equation (4), the lifetime in at least two different cycles must be known. The e and f in Table 1 were calculated based on the manufacturer's data for the CFLi.²³ CFLi Hg content estimates by manufacturers differ^{3,8,10,24-28} from 1 mg to 27 mg of Hg per CFLi, which makes it difficult to select one concrete value. It was decided to choose one for the CFLi quality considered with low Hg content, but somewhat higher than the minimums stated for that quality of lamp. Electricity used in manufacturing the lamp

somewhat higher than the most similar reference was taken for a 15 W CFLi.^{9,29} Finally, we took the rounded price of a CFLi with consumption and lifetime described for Spain according to prices published by one of the major manufacturers.³⁰

Consumption of 18 W was selected as equivalent to the 100 W incandescent lamp commonly used in Spain and prohibited by European regulation in 2009.³¹ As described elsewhere,¹⁶ a correction factor for power quality, LWF_p , that accounts for the CFLi low-power factor must be considered.

The luminous flux of the model of CFLi described is 1000 lm, a value in the lower range of the luminous flux of real CFLi of a similar category.

In addition to the model described, which is a state-of-the-art good-quality CFLi (G Start-G Cont.oper), another two models of CFLi are used: One is poor quality (B Start-B Cont. oper) and one very poor (VB Start-VB Cont.oper). The three models are characterized by having different e , f and price. Reference 21 shows that there are CFLi with much shorter lifetimes than the nominal. As we have no additional data, it is assumed that the rest of the characteristics (power consumed, Hg content, correction factor for power quality, electricity in manufacture and luminous flux) are identical in all the samples. Although this approximation could seem questionable, it happens to be useful in order to perform an initial approach to the problem. For the two poor-quality models, lower prices and higher e and f are proposed,

Table 1 Characteristics of the CFLi model analyzed in this study.

Power consumed P_l	18 W
Purchase price C_l	10 Euro
Lifetime/ a	10 000 h/3 h and 12 500 h/12 h
e	8.000 E-05
f	2.037 E-08 (s ⁻¹)
Hg content c_m	3 mg
Electricity in manufacture u_m	4 kWh

CFLi: compact fluorescent lamps with integrated ballasts; Hg: mercury.

which result in a reduction of lifetime (Figure 1). Table 2 shows the data for the three models analyzed in this study. In the case of the two poor-quality lamps, prices are typical of shops in Madrid. The reference model is called G and the poor-quality and very poor-quality models are called B and VB, respectively.

Figure 1 shows the lifetime of the three models of CFLi compared to continuous operation time a and the manufacturer's data, which make it possible to determine the coefficients of lifetime e and f for the good-quality model.

5. Description of cycling

It was decided to evaluate the magnitudes considered for an arbitrary time T , which includes both the time the CFLi remain on and the time they are off. Cycles are defined by the number of times turned on per unit of time designated by n (h^{-1}), by time a (m) that the lamp remains on between the time it is turned on and the following time it is turned off, and finally by time b (m) that the lamp is off between the time it is turned off and the following time it is turned on. The real time of operation when the CFLi is on is given by

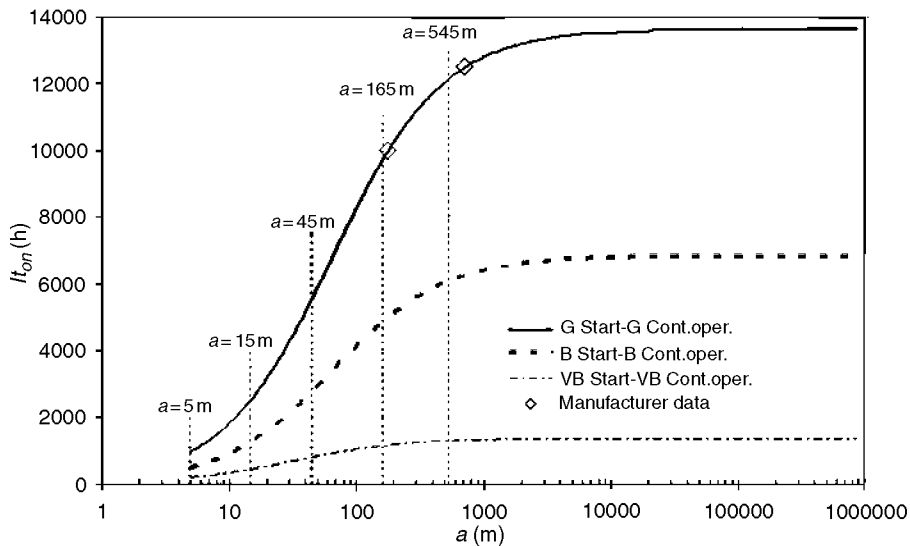


Figure 1 Compact fluorescent lamps with integrated ballasts (CFLi) lifetime data according to the manufacturer's technical specification sheets. The lifetime of a good-quality CFLi model (G Start-G Cont.oper) poor-quality CFLi model (B Start-B Cont.oper) and very poor-quality CFLi model (VB Start-VB Cont.oper) for different a . The vertical dotted lines show several a used to make some of the estimates

Table 2 Prices and coefficients that determine the lifetime of CFLi models analyzed

Model	Purchase price C_i (Euro)	e	f (s^{-1})
G	10	8.000 E-05	2.037 E-08
B	6	1.600 E-04	4.074 E-08
VB	3	4.000 E-04	2.037 E-07

CFLi: compact fluorescent lamps with integrated ballasts.

$aT/(a+b)$. In homes, CFLs are turned off at night, which is equivalent to every 24 hours, one of the periods characterized by b is longer than the value computed. This really has no effect on the calculations of interest for this study, except if it is necessary to estimate the time in years the user is going to use the CFLi. It can be demonstrated that if b' is the time that the CFLi remains off every night, that is every 24 hours, the ratio between the computation time T in the cycle (a,b) and the computation time T' in the cycle (a,b,b') is given by $T' = T(1 + (b' - b)/((a + b)24 \times 60))$ with a , b and b' expressed in minutes.

Figure 2 shows graphically some of the cycles for which the polluting emissions and the economic cost were estimated. Each cycle is repeated until the end of time T , although it might be necessary to replace a CFLi that breaks, in which case, the emissions from manufacturing the new lamp have to be added. $b = 15$ minutes in the first cycle up to cycle $n = 3/1 \text{ h}^{-1}$. For example, cycle $n = 1/9 \text{ h}^{-1}$

(that is turned on every 9 hours) can correspond to $a = 525$ minutes as shown in Figure 2, but also to any a , as long as $a = 1/n - b$, for example, $a = 240$ minutes and $b = 300$ minutes.

No attempt was made to identify the cycles with real use profiles, which would have been less demanding, but to cover a wide range of cycles that make it possible to understand what happens in very different cycles. The extreme cycles of being turned on nine times per hour and of being turned on once every 9 hours provide a wide range of possibilities.

6. Emission and cost framework

It is assumed that the lamps used in Spain may have been manufactured in Germany or Slovakia. This assumption is based on checking shops in the city of Madrid and in the manufacturer's reference to the place of manufacture of his lamps.³²

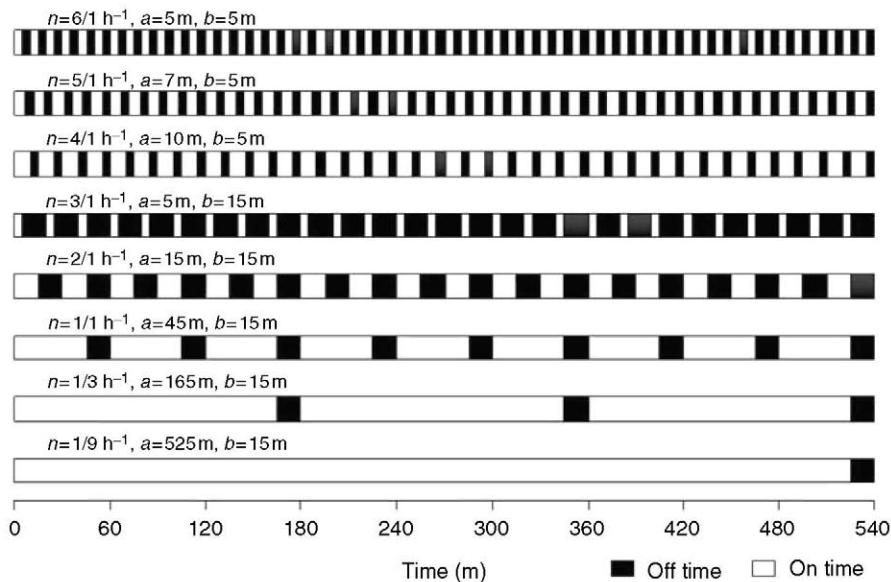


Figure 2 Diagram of some of the lifecycles for which the polluting emissions and economic cost of compact fluorescent lamps with integrated ballasts (CFLi) are estimated. $b = 15$ minutes up to cycle $n = 3/1 \text{ h}^{-1}$, for faster cycles, $b = 5$ minutes

Table 3 shows the CO₂ equivalent and Hg emissions from electricity consumed in Germany, Slovakia and Spain³³ for 2007. Lower emissions are observed in Slovakia because of the higher component of nuclear energy in the electricity mix. The costs of radioactive waste management or safety problems are not evaluated in this study. In Germany and Slovakia, emissions are from manufacture of the lamp, while in Spain emissions are due to the electricity consumed during lamp use.

With reference to CO₂ equivalent, the data used correspond to a Life Cycle Assessment (LCA) emission factors assessment scheme, which evaluates all the emissions generated for the production of the lamp and the consumption of electricity, and that include not only the CO₂ emissions but also the equivalent ones due to the emissions of CH₄ and N₂O. Further details of the methodology and origin of data can be encountered in Reference 33, the source of the data presented in Table 3.

To simplify, it is assumed that recycled lamps do not emit the Hg in the gas into the environment and that, on the contrary, lamps not recycled end up emitting all of the Hg that was originally contained in the gas into the environment. Table 3 shows an estimate of the number of residential CFLi

recycled in Spain, which only comes to 2 out of 10 lamps.³⁴ The price of electricity considered for Spain is for the residential sector and the year of reference is 2008.³⁵

The selection of the discount rate i and computation time T_e is essentially an arbitrary exercise. The discount rate is especially subject to economic fluctuations difficult to forecast that often depend on international events such as the attack of September 11th. It is estimated that the value of i is between 7% and 12%.⁴⁻⁶ This study considers an annual discount rate of 7% for 3 years. The choice of 3 years for T_e is based on the 3-year replacement warranty for broken CFLi given by manufacturers of CFLi, such as those analyzed in this study.²² Further below, b_{opt} is computed for 12% discount rates and periods up to 10 years. b_{opt} is also found without considering the discount rate and is expressed by Equation (21).

7. Results and discussion

7.1. Emissions and costs of manufacture and operation

Figures 3 and 4 present the ratio of CO₂ equivalent and Hg emissions from CFLi manufacturing to emissions from operation,

Table 3 CO₂ equivalent emissions ($E_{CO_2}^c$) and Hg (E_{Hg}^c) from electricity consumption in countries of manufacture (Germany and Slovakia) and operation (Spain) of the CFLi. Portion of lamps recycled (r_c) and price of electricity (C^c) in Spain. Discount rate (i) and time considered (T_e) for the economic calculations

Country	Emissions from electricity consumption	
	$E_{CO_2}^c$ (tCO ₂ equ/MWh)	E_{Hg}^c (kgHg/kWh)
Spain	0.639	9.55 E-09
Germany	0.706	3.02 E-09
Slovakia	0.353	7.60 E-10
	Portion of CFLi recycled r_c	Price of electricity C^c (cEuro/kWh)
Spain	0.2	15.6
	Discount rate, i (%)	Period of discount rate, T_e (years)
	7	3

CFLi: compact fluorescent lamps with integrated ballasts; Hg: mercury.

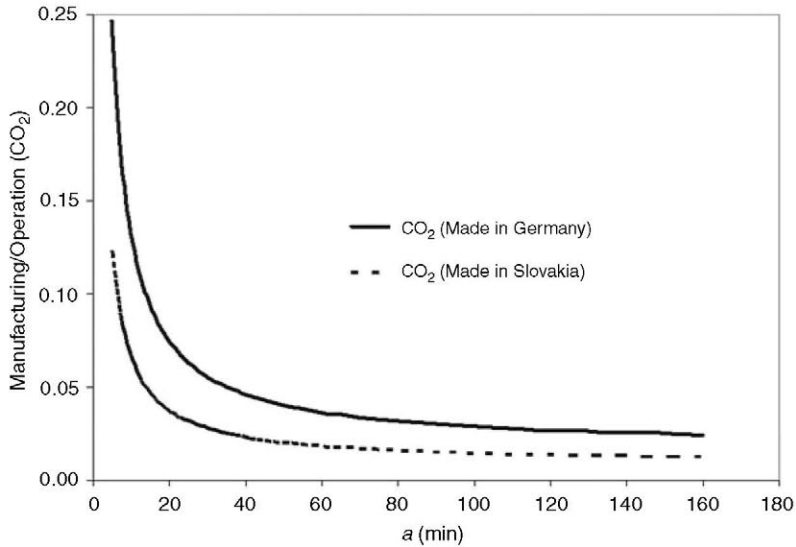


Figure 3 Ratio of CO₂ equivalent emissions from manufacturing and from operation over time of continuous operation of the compact fluorescent lamps with integrated ballasts (CFLi)

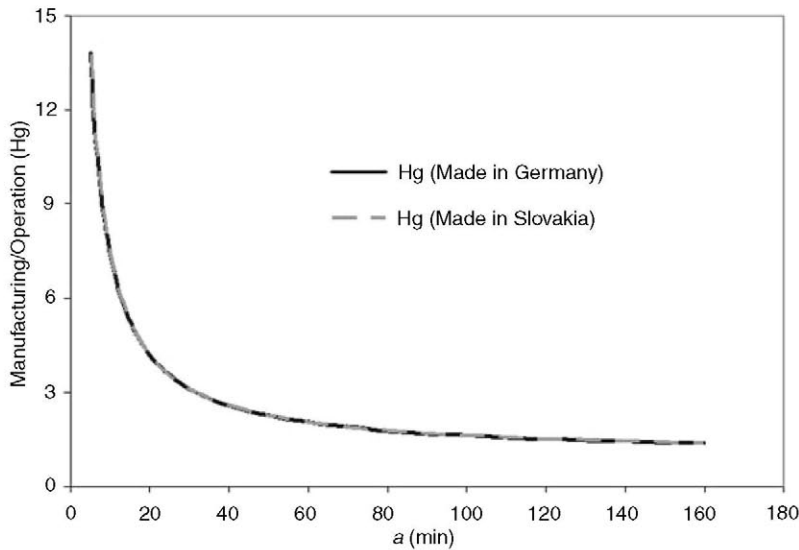


Figure 4 Rate of mercury (Hg) emissions from manufacture and from operation over time of continuous operation of the compact fluorescent lamps with integrated ballasts (CFLi)

over time of continuous operation a . Hg emissions are accounted as manufacturing emissions.

In the case of CO₂ equivalent emissions, operation predominates over manufacturing.

Since the electricity mix in Germany is more coal-intensive than in Slovakia, a lamp manufactured in Germany emits more CO₂ equivalent during manufacturing than one manufactured in Slovakia. However, as the

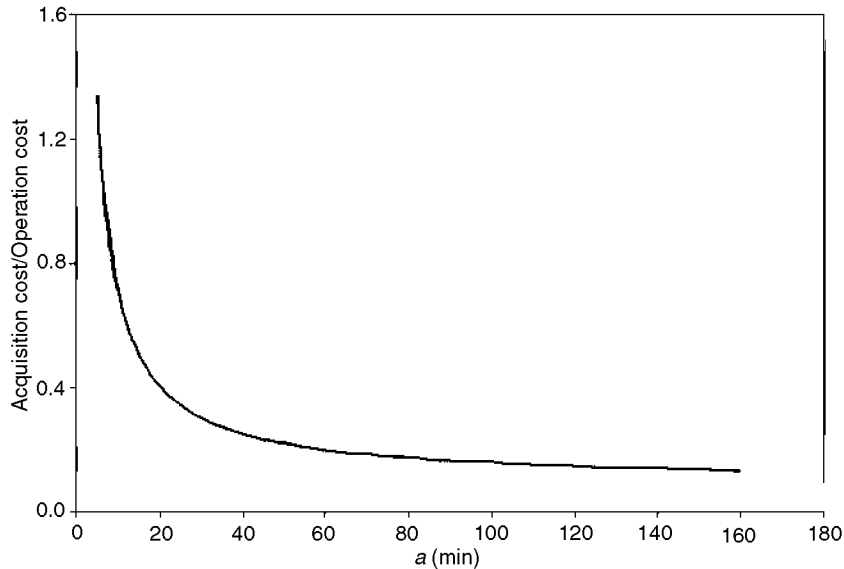


Figure 5 Ratio of the purchase price to the cost of operation at different continuous operation times, a , of the compact fluorescent lamps with integrated ballasts (CFLi)

emissions from operation in Spain are higher in both cases, the total CO₂ equivalent emissions are similar, regardless of the country manufactured or the value of a .

In the case of Hg emissions, the situation is the contrary: As a consequence of the original Hg content in the CFLi and its low recuperation rate in Spain, the Hg emissions due to manufacturing clearly dominate over operation. Only at high a are the emissions due to operation an appreciable portion of the total emissions.

The purchase price of the lamp represents an important part of the total cost of the CFLi. Both costs are equivalent for an a near 7 minutes. Above this, cost of operation gains weight, and below it, purchase price gains weight as may be observed in Figure 5. If the discount rate had not been considered and Equation (19) had been used, a at which the cost of operation and the purchase price are identical would be around 22 minutes.

7.2. Influence of the number of times turned on and the time the CFLi remains on

Figures 6 and 7 show the CO₂ equivalent and Hg emissions per hour over the time of continuous operation, a , of the CFLi. The data given are for a lamp manufactured in Germany and purchased and used in Spain, as the figures for a lamp manufactured in Slovakia are similar.

The emissions during the lifecycle are proportional to n as seen in Equations (10) and (13) and in Figure 6. There is also a term that depends on the product an . It is therefore impossible to find an ideal situation for reduction of emissions and costs, except if the CFLi are subjected to the lowest operation time possible with the minimum number of times turned on.

This extreme would be the absurd situation of not using the lamp. However, neither would it be reasonable to assume that leaving the lamp on is a good option. As an example, and insofar as CO₂ emissions are concerned,

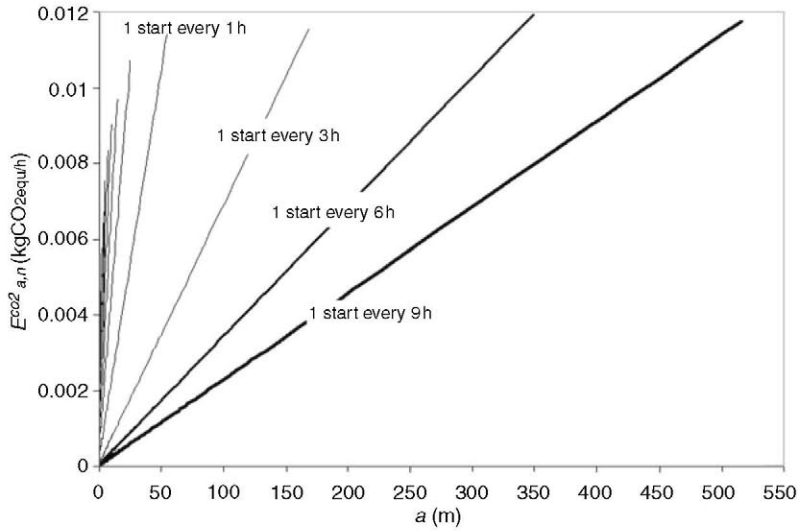


Figure 6 CO₂ emissions for a compact fluorescent lamps with integrated ballasts (CFLi) manufactured in Germany in operation in Spain over operating time

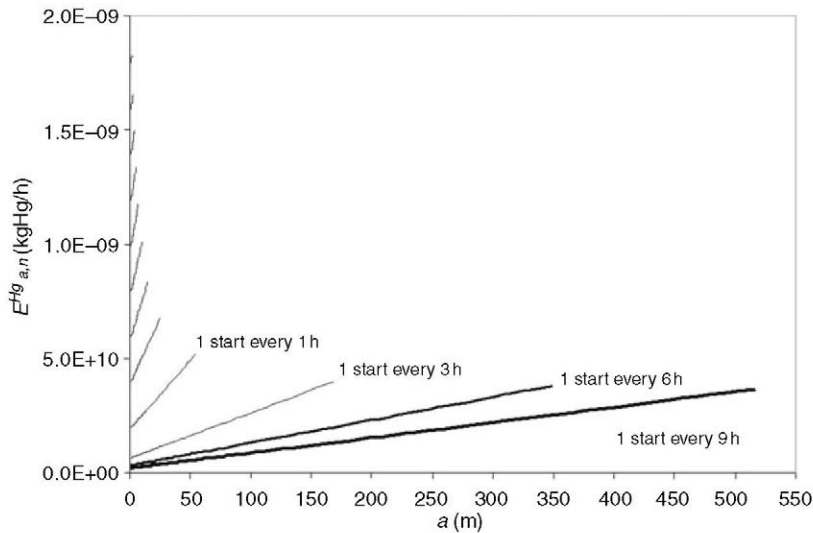


Figure 7 Mercury (Hg) emissions for a compact fluorescent lamps with integrated ballasts (CFLi) manufactured in Germany in operation in Spain over time of operation

if the user is going to devote an hour to reading, it is not reasonable for the lamp to stay on longer. Cycling with starts once every 6 hours with an a below 60 minutes means lower emissions than leaving it on for a longer

time. Concerning the number of times turned on, the cycle in which it is turned on once every 3 hours with an a of 60 minutes will always have higher CO₂ emissions than the cycle before. Therefore, the valid criterion for

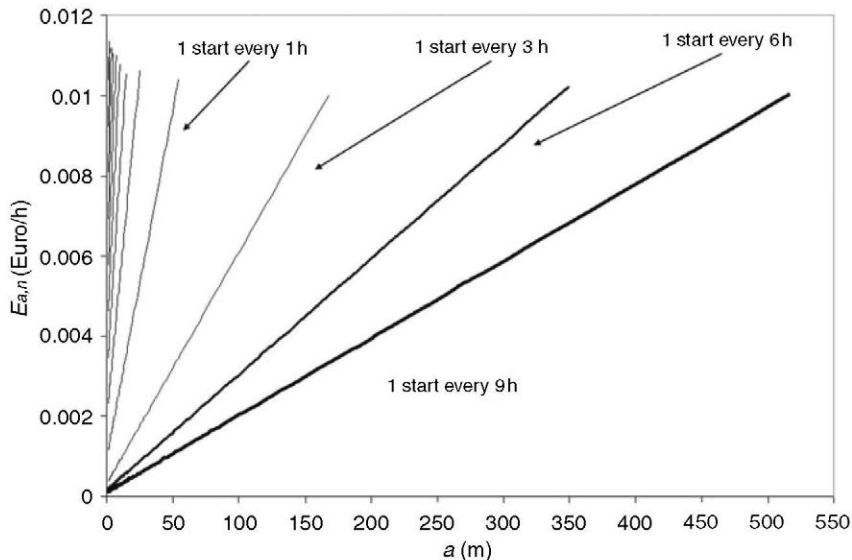


Figure 8 Costs of a compact fluorescent lamps with integrated ballasts (CFLi) manufactured in Germany or Slovakia in operation in Spain over time of operation

reducing CO₂ emissions is to use the lamp when needed, turning it on a minimum number of times and for the shortest operating time possible.

The Hg emissions depend more strongly on the lifetime of the lamp due to the high original content in the CFLi, and therefore, on the number of times turned on. Figure 7 shows that, compared to CO₂ emissions where all the lines converge practically at zero emissions at very low a (Figure 6), the lines that represent Hg emissions for very low operation times, a , are scaled on the ordinate axis and do not converge at zero emissions.

The cost of the lamp is reflected in Figure 8 and shows intermediate behaviour between CO₂ and Hg emissions: The purchase price has an important role starting at an a of 7 minutes, so the cost lines are scaled similar to Hg but less exaggerated. The number of starts and the consequent reduction in lifetime of the lamp increase the cost noticeably, especially for a under 7 minutes.

As it is not possible for the residential user to predict the cycling he is going to subject the CFLi to, or for him to have a calculator at hand to check whether it is worthwhile to turn off the lamps, the only valid criteria that makes common sense is to minimize the number of starts and the time the lamp is in operation, as long as it still fits the need for illumination. Only in the case of a business or industry with formal hours when it has to remain on in a room or workplace would it be possible to establish a more specific criterion of use.

Furthermore, while a higher number of starts leads to higher Hg emissions and economic costs due to the reduction in lifetime of the sample and the need for its replacement, a longer continuous operation time a has a similar effect on CO₂ emissions.

7.3. Optimal time off

The analysis of data up to now can hardly be made use of by the final user beyond what

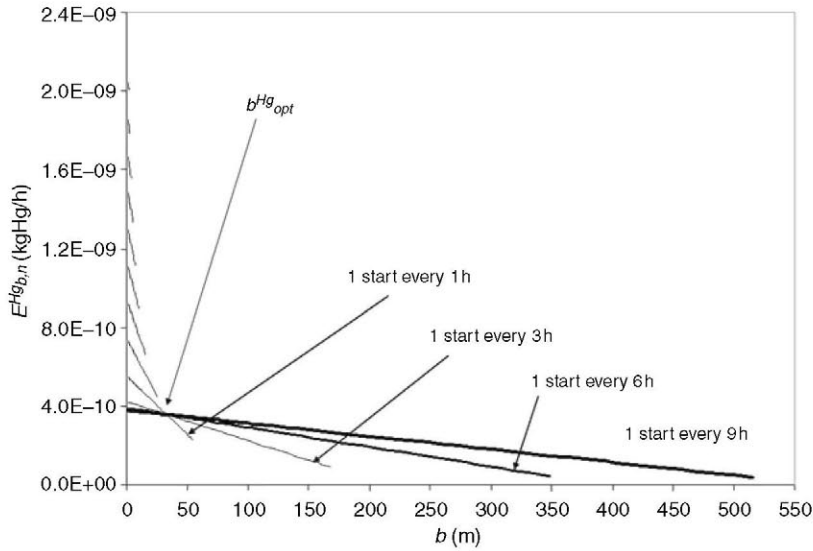


Figure 9 Mercury (Hg) emissions for a compact fluorescent lamps with integrated ballasts (CFLi) manufactured in Germany and in operation in Spain over time off

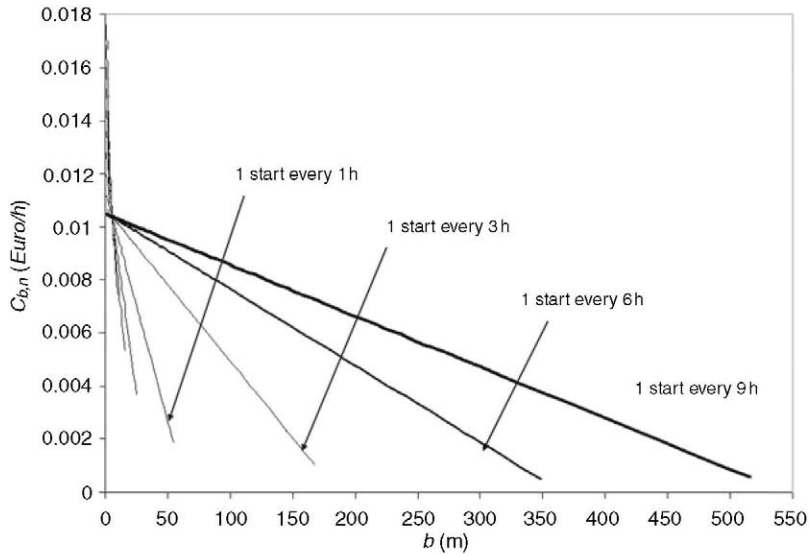


Figure 10 Cost of a compact fluorescent lamps with integrated ballasts (CFLi) manufactured in Germany or Slovakia in operation in Spain over time off

common sense dictates with regard to operating the lamp for the least time possible with the lowest number of starts.

However, the representation of emissions and cost over time b , the time the lamp

remains off, provides additional information. Figures 9 and 10 represent the emissions of Hg and costs, respectively, for a CFLi manufactured in Germany and in operation in Spain over time off b . The families of

curves that appear in each graph are observed to have a radial point where they cross. This point is given by Equations (15) and (20) for Hg and cost considering the discount rate (and in Equations (12) and (21) for CO₂ and the economic cost without considering the discount rate) and represent times off b_{opt}^{Hg} and b_{opt} for which Hg emissions and cost, respectively, are identical in any combination of a and n . If the CFLi is operated such that it respects the optimal b , it at least ensures that the highest emissions cost zones are avoided, whatever the number of starts and length of a . If, in addition, one takes the precaution of increasing b over the optimum, the emissions and costs are lowered considerably.

In the case of CFLi manufactured in Germany, the optimal $b_{opt}^{CO_2}$ for CO₂ equivalent emissions does not exceed 68 seconds, that is, all the emissions and costs lines arise from almost zero b . The value of $b_{opt}^{CO_2}$ for a CFLi manufactured in Slovakia is 34 seconds.

b_{opt}^{Hg} is 32 minutes for Hg emissions (nearly the same for CFLi manufactured in Slovakia and in Germany) and b_{opt} is up to 6 minutes for the cost of the lamp. If the discount rate is not considered, b_{opt} is 13 minutes. Some recommendations suggest that fluorescent lamps not be turned off for a time under 5 minutes to 15 minutes.^{17,36} In one case, the recommendation is based on the definition of lifetime¹⁷ and in another case on cost reduction.³⁶ However, there is no additional information on the calculation method.

As observed in Figure 9, there is a critical maximum b for each cycle after which the cycle does not exist, since the sum of a and b makes the corresponding n impossible.

The analysis of optimal b provides a more concrete criterion than that based on the choice of a or n . If the user is interested in reducing the environmental impact of his CFLi, he should keep in mind that it is not a good idea to turn the lamp off if he plans to turn it on again before b_{opt}^{Hg} . If the user wishes to lower the cost of his CFLi, he should keep

in mind that it is inadvisable to turn off the lamp, if he plans to turn it on again before b_{opt} . If he uses the environmental criterion under the current conditions of the Hg cycle an acceptable efficiency can also be reached for the economic cost.

7.4. Effect of quality and price of the CFLi

The above analysis is based on the use of a CFLi of reasonable quality, and price and quality similar to those of the major brands. However, there are a multitude of products of doubtful quality at a much lower price than have been considered up to now.

This section analyzes the effect on lamp lifetime of assuming different times of turning it on and off using different e and f , respectively, and lower purchase prices. Figure 1 shows the lifetime of the CFLi considered over a . The a at which the calculations are made are also shown. Table 2 shows e and f , the purchase prices considered and the names of the CFLi models proposed: G, B and VB (good, bad and very bad, respectively). The prices of poor-quality CFLi (B and VB) are typical of presumably low quality that may be found in super centres and low-cost product stores in Madrid. As in the case of Model G, the poor-quality models do not correspond to specific products found on the market. It is possible for low-price, good-quality models to be found and vice versa. However, practical experience of the authors as users and of other users consulted suggests that it is more likely to find low-price, low-quality models than the contrary.

The Hg content in the gas in the lamp and the electricity used in its manufacture is still as shown in Table 1. CO₂ and Hg emissions during manufacturing take Germany as a reference. However, it is assumed that low-quality models may also worsen both the energy used in manufacturing them and their Hg content, while the price of labour is very low.

Emissions and costs and optimal time off for a selection of cycles are analyzed: Cycle A with 545 on/15 off, Cycle B with 165 on/375 off, Cycle B' with 165 on/15 off, Cycle C with 45 on/15 off, Cycle D with 15 on/15 off and Cycle E with 5/5, which provides an idea of the effect of starts and operating time in specific cases. Figure 1 shows the values of a mentioned. Cycle B' represents conventional cycling and it may be compared with Cycle B, which is continuous operation for a similar time but with long intervals turned off. Cycle E corresponds to very short periods of on and off. The problem with this type of cycling^{37,38} is that the lifetime of the lamp is hard to predict: It is possible for Equation (4) not to be able to describe the lifetime of the CFLi adequately. The analysis is included because it is considered that the lifetime model is the

best estimate available and to characterize what could happen in the extreme case of using the CFLi in places with traffic where users with a sense of saving turn it on and off very frequently.

Table 4 shows the CO₂ ($E_{a,n}^{CO_2}$) and Hg ($E_{a,n}^{Hg}$) emissions and the cost ($C_{a,n}$ computed for $T_e = 3$ years and $i = 7\%$) as result of introducing the values of the variables (in particular Cycles A, B, B', C, D and E) in Equations (10), (13) and (17). It also shows the ratio of maximums and minimums (Max/Min row) for each model of CFLi and for each operating cycle considered (Max/Min column). Max/Min row correspond to the rows in the table giving information on the sensitivity of emissions and costs of a certain CFLi to different cycles. The Max/Min column corresponds to columns in the table that give information on

Table 4 CO₂ and Hg emissions and economic cost of several different models of CFLi in a selection of cycles. The last column shows the optimal minimum time off for each emission and economic cost. The row and column labelled Max/Min shows the ratio between the worst and the best case per model in each cycle and per cycle for each model, respectively

		a (m)/ b (m)							
		A	B	B'	C	D	E		
		545/15	165/375	165/15	45/15	15/15	5/5		
		Starts/number of hours (on + off)							
		1 Start/9 h	1 Start/9 h	1 Start/3 h	1 Start/1 h	2 Start/1 h	6 Start/1 h		
Model		$E_{a,n}^{CO_2}$ (g/h)						Max/Min row	$b_{opt}^{CO_2}$ (m)
G	12.43	3.78	11.34	9.45	6.61	7.53	3	1	
B	12.67	3.87	11.61	9.84	7.17	9.02	3	2	
VB	14.45	4.46	13.39	11.79	9.40	14.01	3	5	
Max/Min column	1.2	1.2	1.2	1.2	1.4	1.9			
Model		$E_{a,n}^{Hg}$ (ng/h)						Max/Min row	b_{opt}^{Hg} (m)
G	382	131	392	461	565	1337	10	32	
B	582	206	618	787	1039	2583	13	43	
VB	2075	703	2109	2427	2905	6764	10	30	
Max/Min column	5	5	5	5	5	5			
Model		$C_{a,n}$ (cEuro/h)						Max/Min row	b_{opt} (m)
G	1.058	0.328	0.984	0.876	0.715	1.107	3	6	
B	1.079	0.336	1.007	0.909	0.763	1.233	4	7	
VB	1.245	0.388	1.165	1.060	0.903	1.491	4	7	
Max/Min column	1.18	1.18	1.18	1.21	1.26	1.35			

CFLi: compact fluorescent lamps with integrated ballast; Hg: mercury.

the sensitivity of emissions and costs in a certain cycle to the quality of CFLi used.

It is observed in the Max/Min rows in Table 4 that the use of one cycle or another has a strong influence on emissions and costs for any quality of lamp. Multiplication factors of three and four were found for CO₂ emissions and cost. That is, the cycles with the highest CO₂ emissions and the highest costs may triple or quadruple emissions and costs. The Hg emissions are even more dramatic, since the selection of the cycle can multiply Hg emissions up to 10 to 13 times.

For a same cycle, the Max/Min columns in Table 4 show that the sensitivity to CFLi quality is rather lower than the choice of cycle. However, the effect is not in the least negligible and the choice of a poor-quality CFLi can raise CO₂ emissions from 16% to 86%, costs from 18% to 35% and Hg emissions can be multiplied five times.

The most important factor in lowering CO₂ equivalent emissions is using the proper cycle, which in the examples in Table 4 lead to an increase of up to three times compared to the cycle with the most emissions and the cycle with the least emissions. This is explained by the heavier weight of CO₂ emissions during lamp operation than during manufacturing (Figure 3). For each cycle, although not negligible, the quality of the lamp has a secondary role. The $b_{opt}^{CO_2}$ for which the CO₂ emissions are identical regardless of cycling of a specific CFLi is relatively low up to 5 minutes for a poor-quality CFLi.

For Hg emissions, $E_{a,n}^{Hg}$ both CFLi quality and cycling lead to very important factors in the proportion of emissions of up to 5 and 13, respectively. In this case, the Hg content in the gas of the CFLi has a determining role (Figure 4), emissions skyrocket with the reduction in lifetime associated with short cycles (Cycles D and E) compared to cycles characterized by fewer starts (Cycles A, B, B' and C). The quality of the CFLi also plays an important role in Hg emissions, multiplying

Hg emissions five times for the same cycle. The minimal time off b_{opt}^{Hg} at which the Hg emissions for a specific lamp are identical in any cycle are up to 30 minutes and 43 minutes. It is important to keep in mind that a relatively low Hg content has been assigned to the CFLi. One study²⁵ shows that there are CFLi models with a much higher Hg content than used in this one. It is reasonable to assume that such cases correspond to lower quality, lower priced models and higher e and f . Under these assumptions, the Hg emissions skyrocket over what appears in Table 4.

The cost of operation of the CFLi, $C_{a,n}$ is similar to CO₂ emissions. The choice of cycle can multiply the cost by four, instead of by three as in the case of CO₂. The reason is that the purchase price has a weight comparable to the operating cost, at least in cycles with a below 7 minutes (Figure 5). The minimum time off b_{opt} at which the CFLi costs are identical regardless of cycling is from 6 minutes to 7 minutes depending on the quality of the CFLi. Figure 11 shows the influence of assuming different discount rates and periods of calculation for Model G, giving values of b_{opt} in the range 2 minutes to 14 minutes. If the discount rate is not considered, the b_{opt} found is 13 minutes. This coincides with prior information available.^{17,36}

Again, the reduction in polluting emissions and costs of manufacture and use of the CFLi require the minimum possible number of starts and number of hours of operation to satisfy the demand for light. This conclusion is obvious and is common sense; there is no general basic rule to orient the user based on the number of starts or the time the lamp has to remain on because Equations (10), (13) and (16) contain terms that are proportional to a and n .

A more specific criterion for deciding the best cycle for a certain CFLi is given by the optimal time off, which is different for the two polluting emissions considered and for the cost of the lamp. If this is respected, it at least

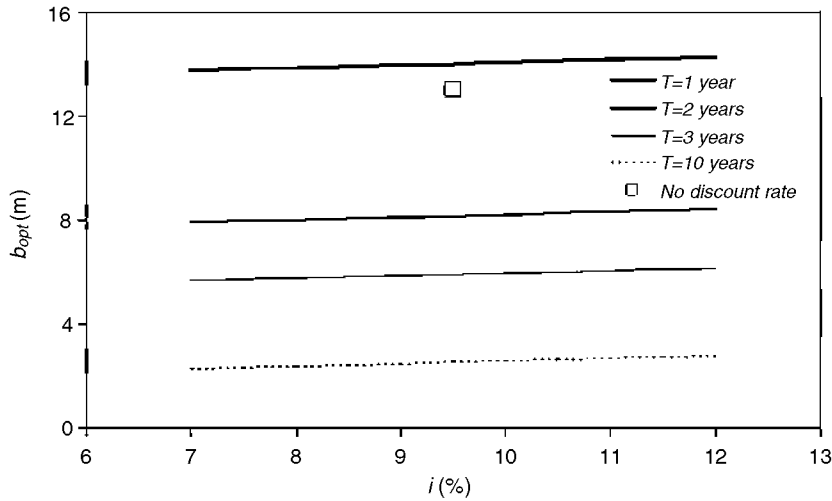


Figure 11 Optimal time off for model G over the discount rate and for different calculation periods. The figure not including discount rate is also shown

ensures that the cost of generating light is identical in any cycle. If, in addition, b is higher than b_{opt}^{Hg} , $b_{opt}^{CO_2}$ and b_{opt} , it can be ensured that the emissions and cost diminish with respect to the optimum as shown in Figures 9 and 10. It is important to observe that the information available up to now and based on economic considerations advises that it be left off from 5 minutes to 15 minutes.^{17,36} This study found that this is true for the economic cost, while reduction in Hg emissions requires noticeably higher b of at least 30 minutes to 43 minutes depending on the quality of the CFLi.

Finally, as the luminous flux of the CFLi considered is 1000 lm, a simple division of the emissions and costs of Table 4 by 1000 supplies, an estimation of the emissions and costs per lumen at each cycle. The analysis of the results is identical to that performed above. As stated in “Equations describing emissions and costs”, we do not consider that this quantity supplies rules of use for CFLi suitable for the final user and an estimation of the effect of lumen maintenance have not been performed in the present work.

7.5. Time frame of validity of results

Contaminating emissions in the three countries included, purchase price and electricity in Spain, manufacturing recycle rate, Hg content of the CFLi and discount rate that appear in this study will all indubitably undergo temporary changes. For example, it might be mentioned that in super centres, there may be sales on packs of two or three good-quality lamps at a price per unit two or three times lower than the one used for the economic calculations made in this study. It should therefore be taken into account that the calculations made and the conclusions they lead to provide results that are approximately valid only at the present time, and provide criteria and methods that allow the concrete values to be updated to the time it is intended to consider.

The optimal b calculated makes CFLi use criteria possible, which if publicized and applied are useful even considering any reduction in carbon content of the electricity mix, reduction of energy in manufacturing the lamps, reduction in purchase price or

reduction in Hg content in the CFLi and electricity mix.

8. Conclusions

Evaluation of polluting emissions and economic cost of the CFLi should take the time the lamp remains on and off, how often it is turned on and its quality into account. Optimization of operating time and the number of starts requires specific calculation to be made. The basic criteria must be to lower the number of hours of operation and the number of starts, as well as the choice of a good-quality CFLi.

CO₂ and Hg emissions, purchase price and operation of CFLi depend on lamp quality and cycling. This is especially applicable to Hg emissions which may vary widely depending on the quality of the model used and especially on the cycling the lamp is subjected to.

The analysis shows that for any values of a and n there are values of b for which the cost and emissions are always the same for a specific CFLi. The practical implication for the final user of CFLi is that the user can choose to reduce cost and emissions by increasing b – the time the lamp is off – over the calculated values. A specific criterion is given by the minimum time the CFLi has to remain off before turning it on again, and which in this study is called the optimal b . In the case of the models proposed, optimal b is rather low for CO₂ emissions (up to 5 minutes), higher for the cost of the CFLi (up to 7 minutes) and even higher for Hg emissions (up to 43 minutes). The higher b is the lower emissions and costs will be. It is therefore advisable not to turn on a CFLi sooner than 43 minutes from the last time it was turned off.

Of the three parameters studied, CO₂ emissions, Hg emissions and cost, the second is the most sensitive to cycling and CFLi quality. Implementation and improvement of CFLi recycling procedures

and reduction in the amount of Hg in the lamps have the most important role in reducing Hg emissions during CFLi use. These improvements make it possible to reduce the relationship of Hg content in the gas in the lamp plus what is emitted during fabrication and what is emitted during lamp operation.

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