What is the real efficiency of bulbs?

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Abstract
Bulbs are considered to be very inefficient sources of light. Bulbs give light and heat. As we use them for a long time, especially in winter, a large part of the heat produced by bulbs lowers the power consumption of the heating system.

In this paper the problem of the real efficiency of a bulb is solved when both the lighting and heating effect of illumination of the interior of buildings is taken into account. It is analyzed from the viewpoints of the energy consumed and the price of that energy. The real efficiency of bulbs and savings obtained by replacing them with fluorescent lamps are calculated for various locations.

1. Preface

Since 2009 the sale of bulbs has gradually been forbidden in the European Union. The reason for this is that the efficiency of bulbs as sources of light is low. It is assumed that the (forbidden) bulbs will be replaced by fluorescent lamps or possibly by lighting diodes.

In this paper the problem of calculating the real energy efficiency of a bulb will be solved when both the lighting and heating effects of illumination of building interiors is taken into account.

Currently only the consumption of energy for electric lighting in terms of performance and the cost of that energy are taken into account. The acquisition costs of the source of light and its lifetime are not dealt with.

2. Periods of a year

The calendar year can be divided into several periods – in view of the thermal regimes in the interior of buildings. We are only interested in the total duration of the electric lighting per year t and time of electric lighting for individual periods.

2.1. Thermal neutral period

It is a period in which people do not intentionally influence the temperature of interiors.

Heat produced by an electric light in this period is energy without any useful gain.

2.2. Heating period

The period in which people intentionally increase the temperature of interiors.

Heat produced by an electric light in this period contributes to the heating of interiors. If we assume that the energy given to an electric light is fully converted into heating the interior whereas the efficiency of the utilization of the energy by the heating system is $\eta, \eta \leq 1$, then heating by an electric light of input P allow us to lower the input of the heating system by $\frac{P}{\eta}$.

If the duration of electric lighting in the heating period is t_h, the change of energy consumption of the heating system per year caused by the electric lighting of input P is

$$\Delta E_h = -t_h \frac{P}{\eta}. \qquad (1)$$

1.3. Period of air conditioning

The period in which the temperature of an interior is higher than desirable and people intentionally decrease the temperature of the interior.

Heat created by an electric light must be taken out by the expenditure of extra amounts of energy. To take out the thermal input P corresponding to an electric light it is necessary to increase the input of air conditioning by $\frac{P}{l}$, where l is the ratio between the heat taken out by the air conditioning and the electric energy consumed by the air conditioning. The usual value is $l = 3$.

If the duration of the electric lighting during air conditioning is t_c, the change of energy consumption of air conditioning per year caused by electric lighting of input P is

$$\Delta E_c = +t_c \frac{P}{l}. \qquad (2)$$

Note - approximation of little correction
We assume that the total heat given off by an electric light is much smaller than the heat given off by a heating system or taken out by the air conditioning. If this is not valid, this analysis is not accurate or is totally false.

3. Energy view

Direct energy consumption of electric lighting during a year is the energy actually consumed by an electric light $E_d = tP$ (3)

We define the **effective** energy consumption of electric lighting during a year, E_e, as the addition of the direct energy consumption of electric lighting and the change of energy consumption of heating and air conditioning caused by electric lighting

$$E_e = E_d + \Delta E_h + \Delta E_c$$

We substitute values from (3), (1) and (2)

$$E_e = tP - t_h \frac{P}{\eta} + t_c \frac{P}{l} = \left(1 - \frac{t_h}{t}\frac{1}{\eta} + \frac{t_c}{t}\frac{1}{l}\right) tP$$

The effective energy consumption can be expressed as $E_e = \kappa E_d$

where $\kappa = 1 - \tau_h \frac{1}{\eta} + \tau_c \frac{1}{l}$ (4)

and $\tau_h = \frac{t_h}{t}, \tau_c = \frac{t_c}{t}$ (5)

are relative durations of lighting in the heating period and air conditioning period.

4. Price view

It is necessary to determine the price of energy consumption of electric lighting during a year. Price of energy M will be given by the product of unit price of energy c and energy consumption E

$$M = c \cdot E.$$

The type of energy must be distinguished. Lighting and air conditioning use electric energy. Its unit price is given as c_e. Heating usually uses different types of energy. Its unit price is given as c_h. Energy for heating is k-times cheaper than electric energy, $c_h = \frac{c_e}{k}$ (6)

Price of **direct** energy consumption of electric lighting during a year is

$$M_d = c_e E_d$$

Price of **effective** energy consumption of electric lighting during a year is the addition of the price of direct energy consumption of electric lighting and change of price of energy consumption of heating and air conditioning caused by electric lighting

$$M_e = c_e E_d + c_h \Delta E_h + c_e \Delta E_c \qquad (7)$$

The price of effective energy consumption can be expressed as $M_e = \lambda M_d$; using (1), (2), (3), (5), (6), (7) we obtain $\lambda = 1 - \frac{\tau_h}{k\eta} + \frac{\tau_c}{l}$ (8)

Note. Price could very approximately correlate with consumption of primary energy – if this is true, coefficient k should represent a multiplying factor of primary energy needed to produce electric energy.

5. Saving of energy and saving of price of energy

The saving of energy consumption and savings in the cost of energy consumption during a year if we replace bulbs with fluorescent lamps (or other source with higher efficiency) will be evaluated.
It is assumed that a user demands for lighting of a specific intensity which can be obtained by

i) a bulb with input P or
ii) a fluorescent lamp with input P/s; usual value of coefficient of light efficiency is $s \approx 5$.
Energy consumption and price of energy consumption are marked by double indexes
i) first index determines type of evaluation d - direct, e - effective (energy consumption, price)
ii) second index determines type of lighting b - bulb, f - fluorescent lamp

Table 1: Consumption of electric lighting during a year

	Energy	Price
Direct consumption of bulb (I)	$E_{d,b} = Pt$	$M_{d,b} = c_e \cdot Pt$
Effective consumption of bulb	$E_{e,b} = \kappa Pt$	$M_{e,b} = \lambda c_e Pt$
Effective consumption of fluorescent lamp	$E_{e,f} = \kappa \frac{P}{s} t$	$M_{e,f} = \lambda c_e \frac{P}{s} t$
Coefficients κ, λ – expression (4) and (8)	$\kappa = 1 - \tau_h \frac{1}{\eta} + \tau_c \frac{1}{l}$	$\lambda = 1 - \frac{\tau_h}{k\eta} + \frac{\tau_c}{l}$
Effective saving fl. lamp vs. bulb – def.	$\Delta E_e = E_{e,b} - E_{e,f}$	$\Delta M_e = M_{e,b} - M_{e,f}$
Effective saving fl. lamp vs. bulb – expression	$\Delta E_e = \kappa \left(1 - \frac{1}{s}\right) Pt$	$\Delta M_e = \lambda \left(1 - \frac{1}{s}\right) c_e Pt$
Taking as comparative base direct energy consumption of bulb*, we obtain		
Relative effective saving – definition (II)	$\varepsilon = \frac{\Delta E_e}{E_{d,b}}$	$\mu = \frac{\Delta M_e}{M_{d,b}}$
Relative effective saving - expression	$\varepsilon = \kappa \left(1 - \frac{1}{s}\right)$	$\mu = \lambda \left(1 - \frac{1}{s}\right)$
Using (I) and (II) we obtain		
Effective saving	$\Delta E_e = \varepsilon Pt$	$\Delta M_e = \mu c_e Pt$

* It is not the only possible comparative base, but, when savings are discussed, it is commonly used.

6. Computing of duration of lighting

6.1. Demand for lighting during a day

It is assumed that a user demands some lighting of the interior of buildings every day of the year for a fixed time interval $\langle t_1, t_2 \rangle$, for example 6 h – 22 h. This lighting is assured by the sun or by an electric light; electric lighting is used when the elevation angle of sun is lower than a given limit value ψ_m; usually $\psi_m = 0°$. The elevation angle of the sun is the angle between the solar ray and the horizontal plane.

Space with only electric lighting
Another possibility is the case of interior space illuminated exclusively by an electric light. In this case electric lighting is used throughout the whole time interval $\langle t_1, t_2 \rangle$.

Note. In general we can use the results of this analysis for every electrical appliance working daily for an equal time interval throughout the whole year – to evaluate the efficiency of replacing one electric appliance by another with a lower consumption. For example TV set. The case of a refrigerator is more complicated – consumption of a refrigerator increases substantially with an increase in temperature of its surroundings, thus it has higher daily consumption in summer than in winter.

6.2. Base of computing of duration of lighting

It is necessary to determine the duration of electric lighting during a year and split this time into neutral, heating and air conditioned periods.

For every single day of the year it is necessary to determine a pair of times $t_{1\psi}, t_{2\psi}$ (morning time and evening time), when the elevation angle of the sun ψ acquires limit value ψ_m. To calculate these times $t_{1\psi}, t_{2\psi}$, the author has used his own algorithm. Using times $t_{1\psi}, t_{2\psi}$ and the time interval of demanded lighting of interior $\langle t_1, t_2 \rangle$, we can calculate the duration of electric lighting Δt for this day.

The annual duration of electric lighting then equals the sum of daily durations of electric lighting throughout the whole year $t = \Sigma \Delta t$. If the given day coincides with a heating period (air conditioning period), then the duration of the electric lighting for that day is included into the annual duration of lighting in heating period t_h (annual duration of lighting in air conditioning period t_c).

6.3. Determination of heating period and air conditioning period

These periods can be given as fixed days in a year.

The second possible approach is to use annual behaviour of average outside temperature t_{OUT} – heating period lasts when t_{OUT} is lower than given limit temperature for heating (e.g. 12°C), air conditioning period lasts when t_{OUT} is higher than given limit temperature for air conditioning (e.g. 20°C).

In some places t_{OUT} for the whole year is lower than limit temperature for heating i.e. heating period lasts the whole year.

7. Results

7.1. Energy consumption of electric lighting during a year

Table 2: Table of energy consumption during a year for lighting
of the same intensity as lighting by (set of) bulb of input 1 kW

Conditions:

O Lighting is demanded over the time interval 6 – 22 h, limit elevation angle of sun $\psi_m = 0°$.
O Limits of the outside average temperatures – for heating 12°C, for air conditioning 20°C.
O Annual behaviour of average outside temperature – from [2].
O Heating system - efficiency of utilization of energy $\eta = 100\,\%$.
O Air conditioning - ratio between heat taken out and consumed electric energy $l = 3$.
O Ratio of light efficiency fluorescent lamp versus bulb $s = 5$.
O Daylight saving time (excl. locations *) is used. Beginning and end of DST for year 2011.

Locality			Climate			Duration of el. lighting a year			Direct energy consumption of el. lighting a year			Effective energy consumption of el. lighting a year			
Region	Location, state	Longitude	Average temperature	Heating	Air conditioning	Total	Heating period	Air cond.	Bulb	Fluorescent lamp	Saving	Bulb	Fluorescent lamp	Saving	Relative effective saving
		°	°C	day/year	day/year	hour/year	%	%	kWh	kWh	kWh	kWh	kWh	kWh	1
Nordic	Svalbard, Norway	78.3	-6.4	365	0	2413	100	0	2413	483	1930	0	0	0	0.000
	Stockholm,Swed.	59.4	5.8	262	0	1581	94.5	0	1581	316	1265	87	17	70	0.044
Moderate	Berlin, Germany	52.5	8.9	221	0	1473	86.1	0	1473	295	1178	204	41	163	0.111
	Paris, France	48.7	11.2	196	0	1393	79.4	0	1393	279	1114	287	57	230	0.165
	Vienna, Austria	48.3	9.4	211	0	1474	80.3	0	1474	295	1179	290	58	232	0.157
S. Europe	Rome, Italy	41.8	15.0	138	103	1421	55.4	14.4	1421	284	1137	702	140	562	0.395
Subtropic	Cairo, Egypt *	30.1	21.0	0	210	1548	0	49.5	1548	310	1238	1804	361	1443	0.932
Tropical	Singapore, Sing. *	1.4	26.9	0	365	1430	0	100	1430	286	1144	1906	381	1525	1.067

As the meaning of relative effective saving could be not sufficiently clear, all “primary” quantities - direct consumption of bulb, fluorescent lamp and saving, effective consumption of bulb, fluorescent lamp and saving are also listed.

Evaluation

Selected locations represent various cases of duration of heating period, air conditioning period and lighting.

Duration of electric lighting for all locations with the exception of the far north remains near 1 500 hours a year. Relative duration of electric lighting in heating period for a moderate region is about 80 % (and for Nordic locations even more) – that means that for about 80 % of the time lighting heat lowers the energy needed for heating. This is a high value! Then it is not surprising that the relative effective saving of energy is only about 0.15 – that means that replacing bulbs with fluorescent lamps decreases energy consumption by approximately only 15 %.

As we move towards the south the relative duration of electric lighting in heating period significantly decreases – a large part of lighting takes place at a time when heat from lighting has no usefulness. The relative effective saving of energy increases – its value is 0.4 or more.

In tropical locations relative effective saving of energy can acquire values even higher than 1. This is really true – using a more effective type of electric lighting can save more energy than the direct consumption of the previous non effective lighting. It is thus because we save not only on input of electric lighting but even on the input of air conditioning.

Table 3: Monitoring of influence of various parameters

Basic values of parameters are listed above Table 2.

Location: Vienna, Austria longitude 48,3°		Climate			Duration of el. lighting a year			Direct energy consumption of el.lighting a year			Effective energy consumption of el. lighting a year			
Changed parameter	Value of parameter	Average temperature	Heating	Air condition	Total	Heating period	Air condition	Bulb	Fluorescent lamp	Saving	Bulb	Fluorescent lamp	Saving	Relative effective saving
		°C	day/ year	day/ year	hour/ year	%	%	kWh	kWh	kWh	kWh	kWh	kWh	1
Lighting - time interval	6 – 22 h	9.4	211	0	1474	80.3	0	1474	295	1179	290	58	232	0.157
	7 – 23 h	9.4	211	0	1659	74.4	0	1659	332	1327	424	85	339	0.205
	8 – 24 h	9.4	211	0	1967	70.6	0	1967	393	1574	578	116	462	0.235
Lighting - limit elevation angle of sun	$\psi_m = 0°$	9.4	211	0	1474	80.3	0	1474	295	1179	290	58	232	0.157
	$\psi_m = 5°$	9.4	211	0	1853	77.7	0	1853	371	1482	414	83	331	0.179
	only el.	9.4	211	0	5840	57.8	0	5840	1168	4672	2464	493	1971	0.338
Heating limit temperature	t<12°C	9.4	211	0	1474	80.3	0	1474	295	1179	290	58	232	0.157
	t<15°C	9.4	249	0	1474	87.2	0	1474	295	1179	188	38	150	0.102
Light efficiency coeff.	$s = 5$	9.4	211	0	1474	80.3	0	1474	295	1179	290	58	232	0.157
	$s = 3$	9.4	211	0	1474	80.3	0	1474	491	983	290	97	193	0.131

Evaluation

Results depend not only on the given natural conditions – longitude, climate; they are also strongly influenced by human habits such as time of getting up and going to bed, temperatures at which heating or air conditioning are turned on.

If the light is on long into the night, the total time of lighting increases, relative duration of electric lighting in the heating period decreases and the relative effective saving of energy increases.

7.2. Price of energy consumption of electric lighting during a year

Table 4: Price of energy consumption during a year for lighting
of the same intensity as lighting by (set of) bulb of input 1 kW

Basic values of parameters are listed above Table 2.

Location			Unit price of energy *		Price of direct energy consumption of el. lighting a year			Price of effective energy consumption of el. lighting a year			
Region	Location, state	Longitude	El. energy - lighting, air cond.	Natural gas - heating	Bulb	Fuorescent lamp	Saving	Bulb	Fluorescent lamp	Saving	Relative effective saving
		°	€ cent /kWh	€ cent /kWh	€	€	€	€	€	€	1
Nordic	Stockholm, Swed.	59.4	15.80	16.91	250	50	200	-3	-1	-2	-0.009
Moderate	Berlin, Germany	52.5	22.78	6.38	336	67	269	255	51	204	0.607
	Paris, France	48.7	13.19	5.38	184	37	147	124	25	99	0.541
	Vienna, Austria	48.3	19.41	6.54	286	57	229	209	42	167	0.583
S. Europe	Rome, Italy	41.8	16.29	6.35	231	46	185	193	39	154	0.666

* Household prices including energy, distribution and taxes in February 2010 [3]

Evaluation

While relative effective savings of energy for locations in moderate climatic region is little (Table 2), the relative effective savings in the price of energy is much higher – around 0.6. If the price of energy for heating is much lower than the price of electric energy used for lighting (and it is true in a considerable majority of European countries), then relative effective savings in the price of energy for lighting is noticeable.

An exception is Stockholm; the price of energy from natural gas is higher than the price of electrical energy. In Stockholm, if we use natural gas for heating and replace bulbs with fluorescent lamps, the relative effective saving in the price of energy will be negative.

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