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ACCURACY OF THE LIGHTING ENERGY CALCULATION METHOD

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Abstract

Electric lighting is widely used all over the world and lighting energy use has become one of the major uses of energy in many countries. The application of energy-efficiency measures can reduce energy consumption of this kind. The European Commission's directive for energy performance of buildings aims to promote the improvement of the energy efficiency of buildings by imposing new energy-performance requirements. These requirements include a calculation procedure and performance limits. This paper presents the calculation of lighting energy use in a building, «Valotalo», at Helsinki University of Technology, together with the measurements of electricity use for lighting. The purpose is to check the reliability and accuracy of the calculation method by comparing it with measured data and to discuss the different parameters used for the calculation.

Introduction

The European Union (EU) is the world's second largest energy consumer; the demand for energy in the EU is increasing year by year. The building sector accounts for about 40% of total energy consumption of the European Union, and has the largest energy saving potential, 22%, in the short term (up to 2010) [1]. Under the Kyoto protocol, the EU is committed to reducing emissions of greenhouse gases by 8% of the 1990 level by 2012; buildings have a major role to play in achieving this goal. The EU directive 2002/91/EC for energy performance of buildings adopted in 2002 is an attempt to reduce energy consumption by improving energy efficiency in buildings. According to the directive, every building in the EU has to be tested for its energy efficiency when it is constructed, sold or rented out. The directive also requires every government to apply a methodology that calculates the energy performance of buildings. For lighting, the methodology should include the built-in lighting installation and the positive influence of natural lighting should also be taken into consideration [2].

Energy-efficiency improvements mean a reduction in the energy used for a given energy service while keeping the service the same or making it even better. This reduction of energy use can be achieved by the use of more efficient components and technologies, as well as by more efficient ways of using the energy. The new building of the Department of Electrical and Communications Engineering of Helsinki University of Technology is equipped with energy-efficient components and efficient lighting technique that includes the application of daylight. The lighting energy use in the building is calculated and the calculation is verified by measurement. The results of the calculation and measurement are presented in this paper, together with the findings.

Energy in Buildings

The building sector is responsible for the consumption of a large share of energy, while energy demand in general is rapidly increasing. In the EU, the building sector represents more than 40%

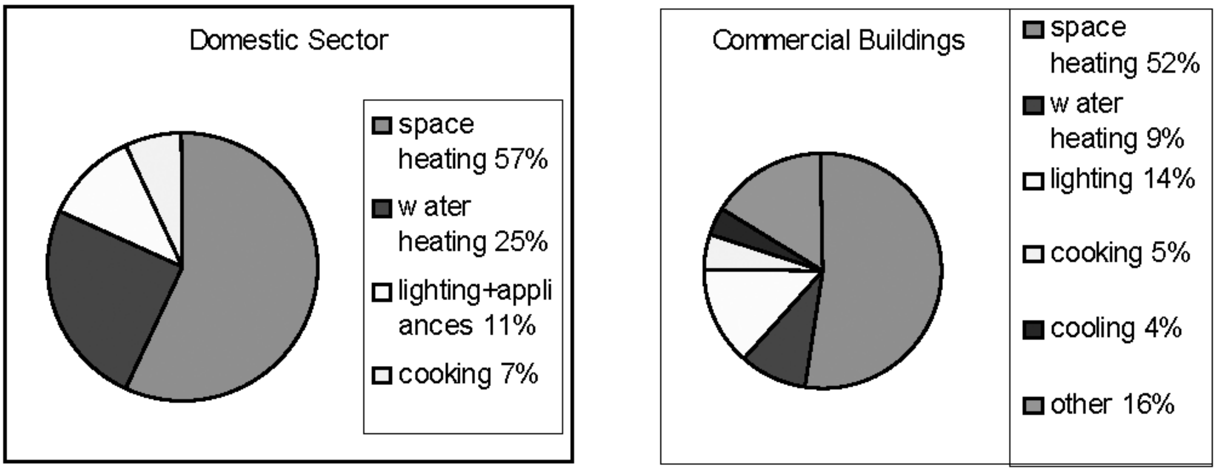


Fig. 1. Energy consumption by end use in the EU domestic and commercial building sectors

of total energy demand [1]. Space heating is the leading energy consumer in both domestic and commercial building sectors, followed by water heating in the domestic sector and lighting in the commercial sector.

The share of heating-energy use over total energy is very high in residential buildings. EU residential buildings use about 82% of their total energy for heating (space heating 57%, water heating 25%) [1]. In commercial buildings, this share is reduced a little by the heavy energy use of lighting and the energy used by cooling and air conditioning systems, and electrical appliances. Cooling and air conditioning systems in Europe are mainly used in commercial buildings, of which about 6% of existing offices and commercial and industrial buildings are cooled, while less than 1% of residential buildings have cooling systems.

Lighting is one of the major energy consumers in many buildings. Lighting accounts for 23% of all electricity consumed in the United States. Of United States national lighting energy use, residential lighting is estimated to constitute about 20%, commercial lighting 60%, industrial 16% and street lighting and other uses 4% [3].

In the European Union, electricity used for lighting accounts for nearly 90 TWh/year (17% of all residential electricity use) in the residential sector and for more than 160 TWh/year in the tertiary and industrial sectors [4]. In many buildings, lighting is a substantial energy consumer and a major component of service costs. Table 1 shows the percentage of electricity used for lighting in European buildings.

TABLE 1

Percentage of total electricity used for lighting in European buildings

Building types	%
Offices	50
Hospitals	20–30
Factories	15
Schools	10–15
Private Buildings	10

Description of the Building

The building selected for the purpose of calculation and measurement is an extension of the Department of Electrical and Communication Engineering, Helsinki University of Technology. This four-storey building was built as a demonstration

Fig. 2. The south façade of the test building «Valotalo»

building for lighting research. The latest technologies for the integration of artificial and natural lighting are applied in the building.

The calculation and measurement of lighting energy use is performed in ten rooms used by the Lighting Laboratory (G435 to G442, G432 and G434) situated on the 3rd floor of the building. Rooms G435-G441 are used as office rooms. Room G442 is a common area where there is a coffee table, printers, fax and the small library for the laboratory. Room G432 is a toilet and G434 is the small kitchen of the office. All the office rooms are occupied only during working days, usually between 8:00 am and 4:00 pm. The lamps used in the test rooms are T5 fluorescent and compact fluorescent. Information about the test rooms is given in Table 2.

Three rooms, G437, G438 and G442, have south-facing windows with laser-cut panels in the upper half of their frame. These panels eliminate the direct glare from windows and redirect sunlight to the back end of the rooms. They also have Venetian blinds in the lower half of the window frame. Rooms G435 and G436 have west-facing windows, whereas rooms G439, G440 and G441 have east-facing windows. Different kinds of lighting control systems are installed in the test rooms. Room G435 has a pure LON-control system, rooms G436 and G437 have a Mimo LON system and rooms G438-G442 have a Digidim light-controlling system. Rooms G432 and G434 do not have any control system. The pure LON system has only manual up/down light control. The Mimo LON system has a constant light control

TABLE 2

Information about lighting systems and windows of the test rooms

Room	Size m^2	Personnel	Luminaries	Control	Window and size	Shading
G435	26.30	3	4 luminaries with 3 (T5 28W) lamps in each	manual up/down light control	West 5.76 m^2	shades
G436	14.50	1	2 luminaries with 3 (T5 35W) lamps in each	presence, daylight, manual dimming and switch	West 3.76 m^2	shades
G437	22.40	2	4 luminaries with 3 (T5 28W) lamps in each	presence, daylight, manual dimming and switch	South 7.63 m^2	laser-cut panels*, shades
G438	22.90	1	4 luminaries with 3 (T5 28W) lamps in each	presence, daylight, manual dimming and switch	South 7.7 m^2 East 1.88 m^2	laser-cut panels, shades
G439	14.30	1	2 luminaries with 3 (T5 35W) lamps in each	presence, daylight, manual dimming and switch	East 3.73 m^2	shades
G440	14.20	1	1 luminaire with 3 (T5 35W) lamps & 1 with 2 (T5 35W) lamps	presence, daylight, manual dimming and switch	East 3.69 m^2	shades
G441	19.00	3	2 luminaries with 3 (T5 28W) lamps each & 2 luminaries with 2 (T5 35W) lamps each	presence, daylight, manual dimming and switch	East 2.64 m^2	shades
G442	45.10		11 Compact fluorescent (18 W) lamps, 1 luminary with 3 (T5 35W) lamps	manual up/down light control	South 3.36 m^2	laser-cut panels, shades
G432	3.10		2 Compact fluorescent (18 W) lamps, one fluorescent lamp (18 W)	—	—	—
G434	3.90		One compact fluorescent (18 W) lamp	—	—	—

* laser-cut panels on the upper half of the window, slides on the lower part.

with a photosensor, rotary control switch and occupancy sensor. Digidim is a digital light controlling system based on the DALI protocol. The DALI systems consist of a wall-mounted panel with four pre-programmed lighting scenes, occupancy and constant light control with multi-sensor and IR-remote control.

Lighting Energy Calculation

Calculation Methods

The purpose of developing an energy calculation method for lighting in the buildings of a country is to calculate the energy consumption in relation to energy requirements of the National Building Regulations of that country. These building regulations should have a calculation procedure and target performance limits. This enables energy-efficient lighting to be used to help meet an overall building energy standard. Most of the countries in the European Union did not have measures to encourage efficient lighting in their building energy regulations in 2003 [5]. Only four countries — Greece, France, Netherlands and the Flemish region of Belgium — had a detailed calculation procedure for lighting in their building energy regulations [5]. In these countries, energy consumed by lighting in a building can be estimated and included in the overall building energy consumption estimation profile. Each of the calculation procedures estimates an overall average energy or power consumption for the lighting in the building.

The Netherlands developed the calculation procedure for lighting first; this was broadly replicated then copied with some modifications by Flanders-Belgium and France [5]. These calculation procedures have a number of similarities. All the procedures carry out the calculation by dividing the building into daylight and artificial light zones and taking into account the different reduction factors for the controls. The calculation in each zone is performed by multiplying the installed load by area of zone, the burning hours and the different factors dependent on the control system. But there are also some differences between the methods. The Belgian method includes the consumption of sensors used for lighting control, which other methods do not include in their calculation methods. Another important difference is in the way in which daylight is taken into account in the calculation procedure. Although all four methods include daylight, the Dutch method includes only a crude 'daylight zone' allowance. The French calculation is similar but includes an extra factor, 'climate zone'. The Belgian method is more detailed as it includes a 'daylight zone' procedure and also an option of a detailed daylight calculation. The Greek procedure is the most detailed of all, with a full calculation of the daylight factor.

Calculation for 'Valotalo'

Calculation and measurement of the energy used by lighting is performed for the Laboratory rooms on the third floor of the building. The calculation is made by dividing the areas into 'daylight' and 'artificial light' areas. All the calculations were performed on the basis of the Belgian calculation method [6]. The annual electricity consumption for lighting (W_{lgt_r}) presented in Table 3 is calculated by summing up the total electricity consumption for the daylight area, artificial light area and the possible electricity consumption of all the control equipment. The annual electricity consumption of the daylight area of a room is calculated as:

$$W_{\_dl} = P_{\lg t\_r}\,\frac{A_{f,r\_d\lg t}}{A_{f,r}}\,f_{sw}\,(f_{m\_dl}T_d + f_{m\_ar}T_n),$$

where, $W_{\_dl}$ annual electricity consumption in the daylight area of room r, in kWh; $P_{\lg t\_r}$ calculation value for power for lighting in the entire room in kW; $A_{f,r\_d\lg t}$ floor area of the daylight sector in room r in m^2; $A_{f,r}$ floor area of room r in m^2; f_{sw} factor for the switching control system; f_{m_dl} factor for the modulation control system in the daylight area; f_{m_ar} factor for the modulation control system in the artificial light area; T_d number of daytime operating hours per year; T_n number of night time operating hours per year.

Similarly, the annual electricity consumption of the artificial light area of a room is calculated as:

$$W_{\_ar} = P_{\lg t\_r}\,\frac{A_{f,r\_art}}{A_{f,r}}\,f_{sw}f_{m\_ar}(T_d + T_n),$$

where, $W_{\_ar}$ annual electricity consumption in the artificial light area of room r, in kWh; A_{f,r_art} floor area of the artificial light area in room r in m^2.

And the annual electricity consumption for the control equipment in each room is calculated as:

$$W_{\_ctr} = [(P_{ctr\_on} f_{sw}(T_d + T_n)) + $$
$$+ P_{ctr\_out}(8760 - f_{sw}(T_d + T_n))],$$

where, $W_{\_ctr}$ annual electricity consumption of the control and sensors that is not yet included in the consumption, in kWh; P_{ctr_on} power of control equipment during the operating hours, default value for any control, ballast, sensor, etc.: 5 W; P_{ctr_out} power of control equipment outside the operating hours, default value for any control, ballast, sensor, etc.: 5 W.

The floor area of the daylight sector is calculated by summing up the surface contribution of the vertical projection of daylight opening with the floor area of the contribution of the (equivalent) vertical openings. Since none of the rooms [of] in our test have any horizontal or inwardly inclined daylight openings (windows), the calculation of daylight area involves only the calculation of the contribution of vertical daylight openings. The contribution of a vertical opening is the sum of the surface areas obtained by multiplication of the length and the depth of the daylight opening.

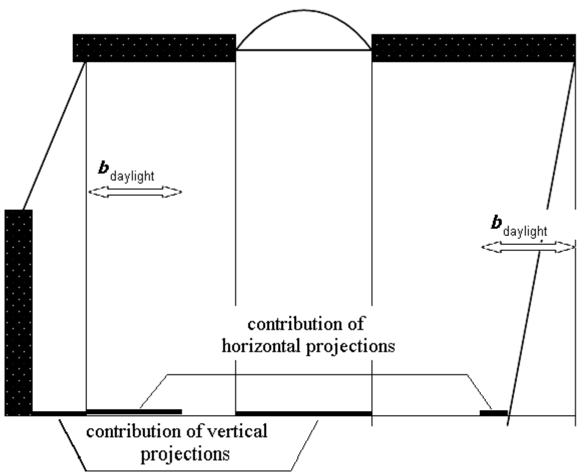


Fig. 3. Daylight area due to contribution of horizontal and vertical projection

The floor area of the artificial light area is the remaining surface of the room, which can be calculated by subtracting the floor area of the daylight sector from the total area of the room.

P_{nom} is the nominal power of all lamps in the room, which is calculated by summing up the power of all the light fittings. In the rooms where the lighting intensity of the light source is adjustable, the calculation value for the power for lighting ($P_{\lg t\_r}$) is calculated by taking into consideration the nominal power, variables for the lighting level of the room and the reduction factor. If the lighting intensity is not adjustable, then $P_{\lg t\_r}$ is just the nominal power. The burning hours T_d and T_n are taken according to the use of the rooms. The total of burning hours for office rooms is taken to be 9 hours a day, 5 days a week, 50 weeks a year. The factor for switching the control system is taken from the Belgian regulations. Its value is 1 for those rooms where there are manual switches and no occupancy sensing system. It is taken to be 0.8 for those rooms that have occupancy sensors as well as automatic switches. Factors for modulating control systems are taken to be 1 for the areas where there is no dimming. For the areas where dimming is possible, the factors are calculated as:

f_{m_dl} = max [0.6; min (1.0; 0.6 +0.4* (A_m −8)/22)]

f_{m_ar} = max [0.8; min (1.0; 0.8 +0.2* (A_m −8)/22)],

where A_m is the largest controlled surface area that is dimmed by one sensor in the room, in m^2.

The annual lighting energy consumption per square metre of a room ($W_{\lg t-r/m^2}$) is calculated by dividing the annual energy consumption of the room by the area of the room. By dividing the nominal power of all lamps in the room by its area, we get the installed power per square meter of room (W/m_2). Table 3 shows the results of the calculations.

Measurements

Measuring Instruments

Power & Current Transducer «SINEAX M 563» was used for the measurement of the electricity consumption by lighting in the test rooms. This transducer is programmable and can measure any three variables (voltage, current and power) of an electrical power system simultaneously generating three analogue output signals. Each pair of rooms, G438 & G439, G440 & G441 and G432 & G434, has common supply conductors at the point of measurement. Hence, only seven power supply channels had to be measured for the measurement of power in all ten rooms. As each transducer can

TABLE 3

Calculated value of Energy consumption by lighting in Laboratory rooms of Valotalo

Rooms	$A_{f,r}$, m²	A_{f,r_dlgt}, m²	A_{f,r_art}, m²	P_{nom}, kW	P_{lgt_r}, kW	T_{d+n}, hour	Factors			$W_{\_ar}$, kWh	$W_{\_dl}$, kWh	$W_{\_ctr}$, kWh	W_{lgt_r}, kWh	W / m_2, W/m²	$W_{lgt\_r/m2}$, kWh/m²
							f_{sw}	f_{m_dl}	f_{m_ar}						
G435	26.30		26.30	0.372	0.372	2250	1.00	1.00	1.00	837			837	14.1	32
G436	14.50	3.76	10.74	0.234	0.176	2250	0.80	0.72	0.86	201	58	44	303	16.1	21
G437	22.40	7.63	14.77	0.379	0.284	2250	0.80	0.86	0.93	314	147	44	505	16.9	23
G438	22.90	9.58	13.32	0.372	0.279	2250	0.80	0.87	0.94	273	180	169	622	16.2	27
G439	14.30	3.73	10.57	0.234	0.176	2250	0.80	0.71	0.86	200	58	109	367	16.4	26
G440	14.20	3.69	10.51	0.195	0.146	2250	0.80	0.71	0.86	167	48	109	324	13.7	23
G441	19.00	4.00	15.00	0.342	0.257	2250	0.80	0.80	0.90	328	77	109	514	18.0	27
G442	45.10		45.10	0.343	0.343	2250	0.80	1.00	1.00	617		44	661	7.6	15
G432	3.10		3.10	0.058	0.058	750	1.00	1.00	1.00	44			44	18.7	14
G434	3.90		3.90	0.019	0.019	750	1.00	1.00	1.00	14			14	4.9	4
Total	186			2.548	2.017								4191	Average 14	Average 23

P_{nom} nominal power of all lamps in room r in kW;
W_{lgt_r} annual electricity consumption for lighting of room r, in kWh;
W/m_2 installed power for lighting per square meter of room r, in kW/m²;
$W_{lgt\text{-}r/m2}$ annual lighting energy consumption per square meter of room r, in kWh/m².

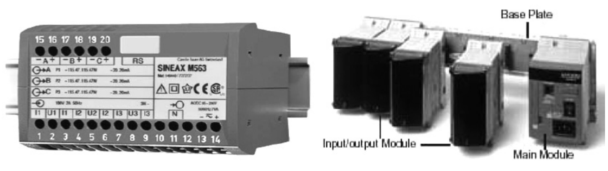
measure three channels, three transducers were used for measurement. Table 4 shows the arrangement of power measurement for different rooms with different transducers.

TABLE 4

Arrangement of measurement for different rooms

	Channel 1	Channel 2	Channel 3
Transducer 1	G432&G434	G435	G436
Transducer 2	G437	G438&G439	G440&G441
Transducer 3	G442	—	—

Data Acquisition Unit (MX 100) from Yokogawa was used to convert the output signals from the transducer to digital form for reading by the computer. The acquisition unit was connected to a PC via a hub and a straight Ethernet cable. The MX 100 standard software was used to capture and read the power data by computer. The acquisition unit read the power data from the transducers and recorded them in the computer every second.



(A) *(B)*

Fig. 4 (*A*) Power and current transducer and (*B*) Data Acquisition Unit

Data Analysis

The measurement was performed for seven consecutive days from 9th October to 15th October. The measurement days were taken as five working days and two non-working days. During the measurement period, there was very little sunlight as the sky was cloudy every day. The annual energy consumption was calculated from the power recorded for those seven days. The result of the measurement and the calculation for the annual energy consumption according to the seven-day measurement period is presented in Table 5.

An example of the power consumption curve of different rooms recorded during office hours is shown in Fig. 5. There are different control sys-

TABLE 5

Measured values of energy consumed by different rooms

Rooms	A m^2	P-day W	P-offday W	W-day Wh	W-offday Wh	W-total kWh/a	W/A kWh/m^2
G438&439	37.2	101	46	2431	1106	867	23
G440&441	33.2	153	28	3680	669	1298	39
G442	45.1	130	16	3115	395	1096	24
G432&434	7.0	7	1	168	15	59	8
G435	26,3	112	0	2686	0	940	36
G436	14.5	51	4	1229	94	432	30
G437	22.4	66	4	1597	106	560	25
Total	**186**	**621**	**99**	**14906**	**2387**	**5252**	Average **28**

A area of the room in m^2;
P-day average power on working days in W;
P-offday average power on holidays (Saturday, Sunday and holidays) in W;
W-day energy consumption per working day in Wh;
W-offday energy consumption per non-working day\ weekend, in Wh;
W-total annual energy consumption in kWh calculated from the seven days measurement period;
W/A energy consumption per square meter of the room in kWh/m^2.

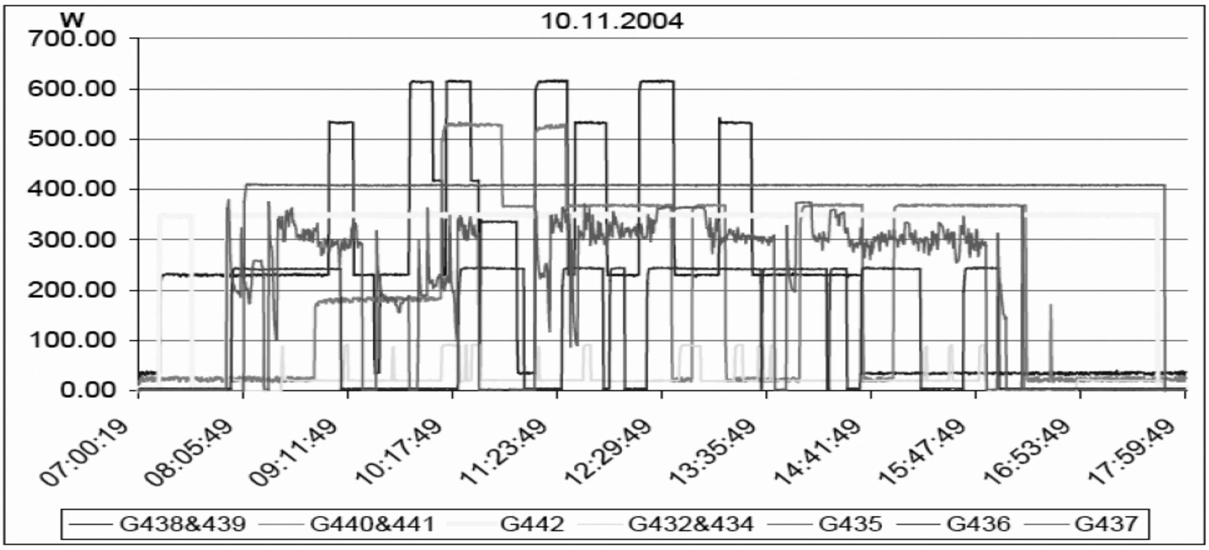


Fig. 5. Electric power consumption by different rooms of the building throughout a day

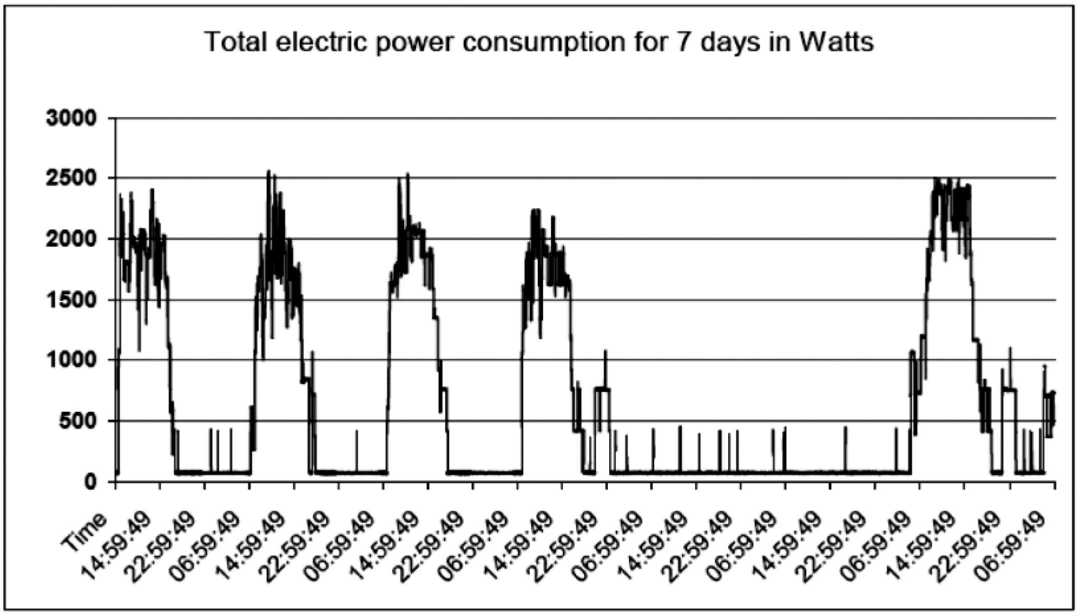


Fig. 6. Electricity consumption of all the rooms on the floor during the 7 measurement days

tems in different rooms, so the nature of the curves looks different for different rooms. For example, the curve of room G435 looks completely flat because this room has a pure LON system that offers only manual up/down light control. On the other hand, the power curve of room G437 changes over short intervals. The small variation in the curve is due to the daylight availability and dimming of the lamps, where as the large variations are due to the response of occupancy sensors when nobody is in the room. Fig. 6 shows the power curve of the total electricity consumption in all the rooms during the seven days measurement.

Comparing the measured data with the calculated values, it was found that the measured values are higher than those of calculated values. This difference is quite high in some rooms. The reason is that the measurement was made for a very short period of time; calculating the annual energy use by reference to the data from seven days did not seem practicable. Another reason is that there was a very small amount of daylight available during the measurement period, allowing all the lamps to operate in full-power mode most of the time. Similarly, in the season of the year when the measurements were taken, the days are shorter and nights longer in Finland. This is also one of the reasons for the difference in values between the calculation and measurements. To overcome these difficulties and to obtain reliable data, the measurement will be continued for a longer period. Also the measurement will be done for all seasons of the year and it will be verified with the calculated data.

Although we cannot draw any conclusions yet on the accuracy of the lighting energy calculation method based on the one-week measurement period, the values we got so far from both measurement and calculation are smaller compared to the annual electricity use for similar types of buildings in practice. The average calculated value of annual energy use for the rooms of «Valotalo» is 23 kWh/m^2 and the calculated value from the measurement is 28 kWh/m^2. These values are well below the average annual energy use for lighting in Finnish offices, which is 31 kWh/m^2 [7].

Conclusion

The calculation method used here takes into consideration the consumption of energy by the lighting equipment, and by the sensors and the control equipment. The default value of the power of a sensor is 5 W. It also takes into consideration the savings due to the dimming of lighting and the occupancy sensing systems. Lighting can be dimmed by daylight or by other control equipment, thus the calculation method takes into account savings through both.

The calculated and measured values are well below the average energy used by similar kinds of buildings. This is due to the application of modern lighting control systems integrated with occupancy sensing systems. The effect of daylighting on the electricity consumption could not be taken into account during the measurement period due to the small amount of daylight available. A seven-day measurement period is not long enough to judge the accuracy of the calculation method. Measurements will be continued for longer periods and for all seasons of the year to make a realistic evaluation of the calculation method. At the same time, the availability of daylight will also be measured.

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