Windows as a low energy light source in residential buildings: Analysis of impact on electricity, cooling and heating demand

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SUMMARY

The energy performance of windows as light sources is investigated. Medical research indicates that humans need light levels that are higher than the levels needed for purely practical, visual purposes, in order to ensure long-term beneficial health effects. The light levels associated with long-term health effects are believed to be in the range of 500-2500 lux.

The hourly daylight levels received in a typical house in Berlin, Paris, Rome or Istanbul is determined, and it is found that the daylight levels exceed 500 lux during 1300-1600 occupied hours per year at each location.

The electricity consumption required to reach similar light levels with artificial lighting is determined, and it is found that the total primary energy demand of the house is increased by at least a factor of 5 from 88-138 kWh/m² to 617-747 kWh/m² if artificial lighting is used instead of windows. The study shows that windows are efficient low energy light sources.

INTRODUCTION

The electricity used for lighting is currently considered for only non-residential buildings in the European Energy Performance of Buildings Directive (EPBD) in EU. However, energy consumption for electric light represents 15-20% of the total electricity demand in residential buildings, emphasizing the importance of daylighting as a means to reduce electricity consumption.

Lighting design in residential buildings traditionally focuses on providing the light levels needed to solve practical tasks, i.e. visual needs. From lighting standards the necessary levels for solving e.g. tasks at a work desk can be found. Writing, reading and typing at a desk requires 500 lux [1]. No levels specifically for residential buildings exist, but actual average lux levels in residential buildings are much lower.

EN 15193 states that strongly daylit rooms require a daylight factor of 6% on the work plane for façade windows or 7% for roof windows. To achieve medium daylight penetration, a daylight factor of 4% on the work plane is required regardless of window location. A daylight factor of 2% is categorized as weak daylight penetration. Under standard overcast conditions, daylight factor levels of 2%, 4% and 7% correspond to 200 lux, 400 lux and 700 lux, respectively [2].

But requirements for human health may be much higher. Medical research indicates that humans need higher light levels for ensuring long-term beneficial health effects; levels that are usually not achieved with electric light designed for solving specific visual tasks. Veitch [3] concluded that the daily light dose received people in Western countries might be too low for the non-visual effects of light. Webb [4] concludes that daylighting design can be used to promote alertness. Mardaljavich [5], Bommel [6] and Begemann [7] found that exposure to light in the range of 500-2500 lux is believed to have beneficial health effects.

This paper investigates the available daylight levels in a typical house located in three different European climates: Berlin, Paris, Rome and Istanbul.

It is further investigated how much electricity would be required to provide the same light levels with electric light only, assuming that the windows were taken out of the house. The purpose of this investigation is to compare windows as light sources with electric light sources with regards to energy performance.

METHODS

House topology

A 1½-storey house with an 8x12 m footprint is used at all locations with the thermal properties of Table 1. The house is defined in [8]. See Figure 1 for a visual representation.

Table 1. Thermal properties of building envelope

	Berlin	Paris	Rome	Istanbul
U_{floor} [W/m²K]	0.2	0.8	0.2	0.2
U_{walls} [W/m²K]	0.3	1.0	1.2	1.2
U_{roof} [W/m²K]	0.2	0.5	0.8	0.8

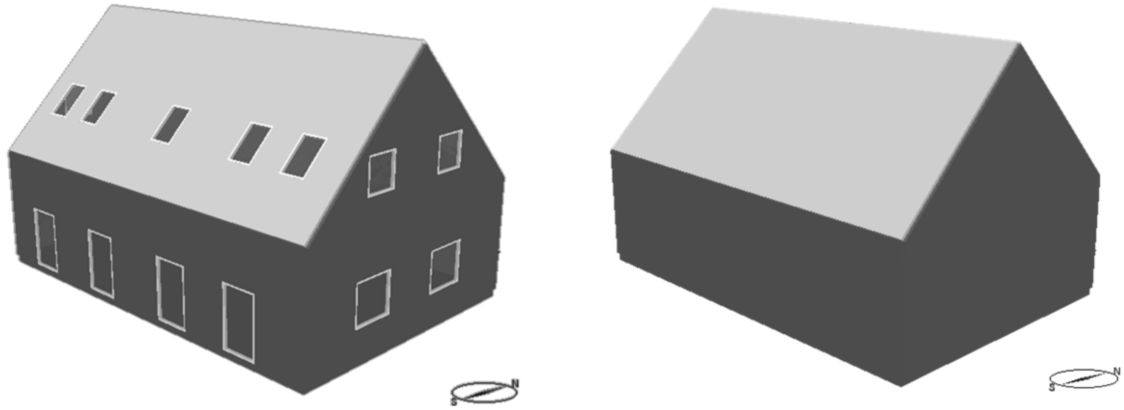

Figure 1. Visual representation of the house used in the study. House with windows on the left; house without windows on the right.

The total floor area is 163 m², and the window area corresponds to 20% of the floor area, i.e. 23 m² façade window and 4 m² roof window. The windows have a declared U-value of 1.4 W/m²K in vertical position, a g-value of 0.6 and a visual transmittance of 0.77.

Daylight levels

The average lux-level on a working plane for each hour of the year was determined with Daysim, which is a dedicated daylight tool with a radiance-based engine. Daysim is considered to provide more reliable daylight levels than most thermal simulation tools [9].

The house model was set up in Daysim model with a 0.25 m x 0.25 m sensor grid on a plane 0.85 m above floor level. The reflectance of walls is assumed to be 60%, the ceiling 90%, and the floor reflectance 30%.

Energy performance

House models for Berlin, Paris, Rome and Istanbul were set up in the thermal simulation tool Energy and Indoor Climate Visualizer (EIC Visualizer) [10]. EIC Visualizer uses the IDA ICE engine and is targeted at residential buildings [11]. A heating and cooling system was assigned, with set points at 21°C and 26°C, respectively. The ventilation rate during the heating season was 0.5 ACH, while it was increased during the cooling period by window airings. External solar shading was applied to the house in Rome and istanbul.

Four scenarios were set up:

1. Model with windows. The model has a heating and cooling demand, but no demand for electricity for lighting.

2. Models for the house without windows.
   a. Electric light levels identical to the daylight levels in the house with windows.
   b. Electric light levels identical to the daylight levels in the house with windows but with a maximum limit of 500 lux, corresponding to “medium” light level
   c. Electric light levels identical to the daylight levels in the house with windows but with a maximum limit of 200 lux, corresponding to “weak” light level

As it is not possible to input hour-by-hour electric light gains in EIC Visualizer, a simplified method was used. For each location the year was divided in a cooling and a heating season. For each season the average daylight lux level during occupied and non-sleep hours was determined (hours 6-8 and 14-23, 365 days per year). From the average lux level of each season, a corresponding electric light gain was determined, based on fixtures fitted with a mix of halogen and fluorescent light sources with a luminous efficacy of 14 lumen/W and 44 lumen/W, respectively. This light gain was applied in the EIC Visualizer model.

RESULTS

Daylight levels

For each hour, the mean daylight level at the working plane is determined for the four locations. Hourly values for Berlin and monthly mean values for each location when the occupants are at home and awake are presented in Figure 2. The house in Rome receives the most daylight during the year. The house in Berlin receives the least light, except in April and May, where the house in Paris receives the least.

The daylight levels which are considered to have positive health effects are in the range of 500 – 2500 lux, with the strongest effects in the high end of the range. In the house in Berlin, which receives the least light of the three, the peak daylight level exceeds 2500 on several days of each month of the year including the winter season.

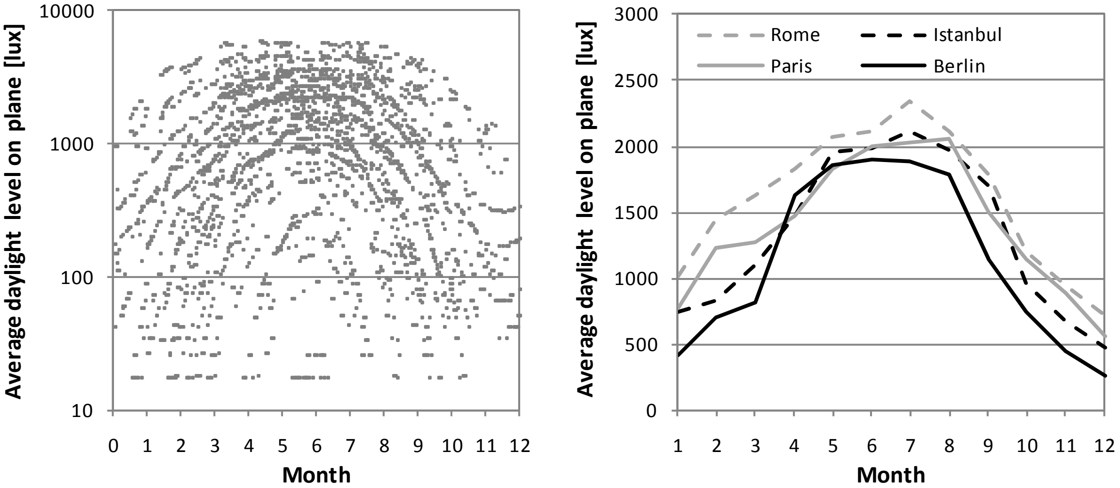

Figure 2. Hourly daylight levels for Berlin (left) and monthly mean daylight levels for all locations (right) during occupied, non-sleep hours. Data from Daysim simulations on a working plane 0.85 m above floor level.

Table 2 shows the number of hours for each location when the daylight level is above 500 and 2000 lux, and when the occupants are present and awake in the house.

Table 2. The number of occupied non-sleep hours when the daylight level is above 500 lux and 2000 lux, respectively. Data for the cooling and heating seasons, and annual total.

	>500 lux			>2000 lux		
	Cooling season	Heating season	Year	Cooling season	Heating season	Year
Berlin	909	388	1297	465	131	596
Paris	957	531	1488	506	209	715
Rome	1024	546	1570	572	249	821
Istanbul	996	463	1459	518	149	667

As input to the thermal simulations, the mean daylight level for the cooling and heating season is calculated for each location. The Daysim results have been processed in three scenarios (2.a – 2.c). Scenario 2.a represents the unmodified house with windows. In scenario 2.b a maximum value of 500 lux is applied, so that all values of 500 lux or higher have been replaced with 500 lux. 2.c is similar to 2.b, except a 200 lux limit is applied. Table 3 presents the results for each scenario.

Table 3. The average daylight level during occupied non-sleep hours (6-8 and 14-23) for scenarios 2.a – 2.c and for the heating and cooling season.

Daylight levels [lux]	Berlin		Paris		Rome		Istanbul	
	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating
2.a No lux limit	1221	329	1436	482	1290	618	1169	438
2.b 500 lux limit	301	120	320	150	278	166	272	151
2.c 200 lux limit	130	60	139	71	119	76	116	72

Energy performance

From the light levels of Table 3, corresponding electric light gains are determined based on a luminous efficacy of a mix of fluorescent and incandescent light sources. Light gains for each season and location is determined. The light gains are applied in EIC Visualizer as 24-hour mean electrical equipment loads for the heating and cooling season, respectively.

The demands for heating and cooling for each location and scenario are taken from the simulation results. The demands for heating and cooling are converted to primary energy by multiplying with a conversion factor, so that these loads can be compared to heating load. For Berlin and Paris the national conversion factors of 2.7 and 2.58 are used. No national conversion factors exist for Italy or Turkey, so a factor of 2.5 is assumed. Figure 3 shows the primary energy demands.

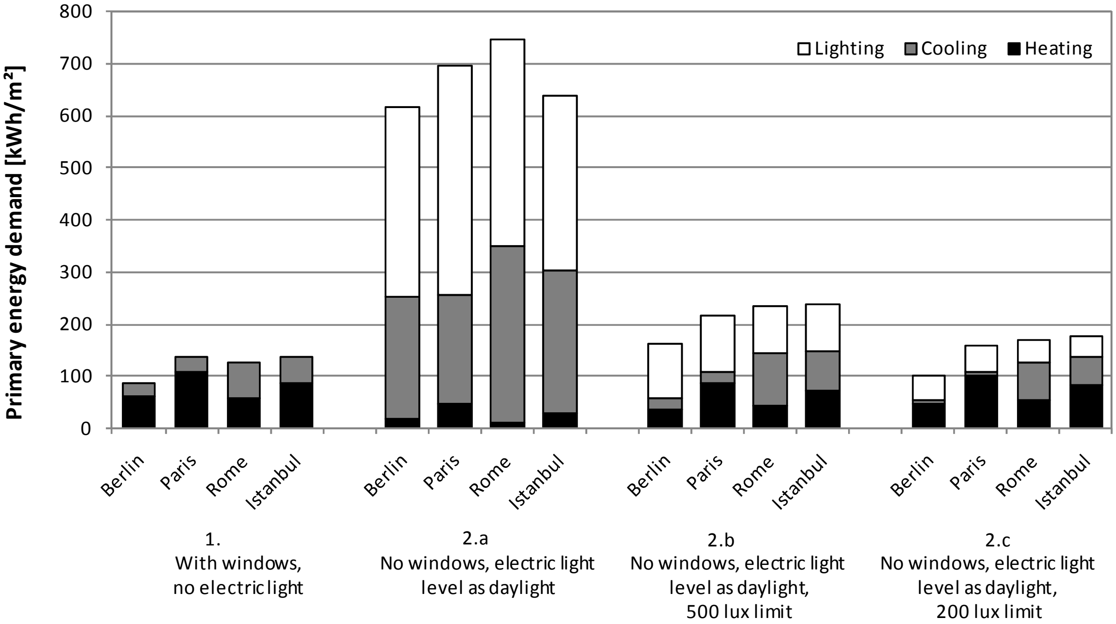

Figure 3. Primary energy demands for heating, cooling and lighting for each location and scenario.

The difference in primary energy demand of the three scenarios without windows is compared to the scenario with windows in Table 4.

Table 4. Increase in total primary energy demand for scenarios 2.a – 2.c compared to scenario 1. with windows.

	2.a Electric light level as daylight [kWh/m²]	2.b Electric light level as daylight, 500 lux limit [kWh/m²]	2.c Electric light level as daylight, 200 lux limit [kWh/m²]
Berlin	529	72	14
Paris	559	81	24
Rome	620	109	41
Istanbul	499	99	39

For each location the lowest total primary energy demand is achieved with scenario 1, which is the building with light provided by windows. Scenario 2.a provides the same light levels as scenario 1, but with electric light. The total demand of scenario 2.a is at least a factor of 5 higher than scenario 1 for each location. The electric light gains alone are in the range of 300 – 450 kWh/m² of primary energy in scenario 2.a.

Scenario 2.b and 2.c do not provide light levels above 500 or 200 lux, respectively, but the total energy demands of these scenarios is higher than scenario 1.

DISCUSSION

Medical research indicates that humans need light levels that are higher than the levels needed for purely practical purposes, in order to ensure long-term beneficial health effects. The light levels associated with long-term health effects are believed to be in the range of 500-2500 lux. The study shows that daylight levels above 500 lux are achieved between 1300 and 1600 hours during the occupied part of the year in a typical house located in Berlin, Paris or Rome.

The energy performance of the windows as light sources is investigated by using electrical light sources to supply the same light levels as the windows supply. This is done in a house without windows, and only with the purpose of investigating the energy performance. Clearly, the indoor environment in a room without windows and with electric light levels up to 7000 lux is completely unacceptable for human occupancy, as well as unrealistic.

In scenarios 2.b and 2.c an upper limit of 500 or 200 lux is applied to the electric light levels, but scenario 1 with windows and much higher light levels still has better energy performance than scenarios 2.b and 2.c without windows. Furthermore, the light levels of scenarios 2.b and 2.c meet the visual requirements of solving most practical tasks, but do not provide the light levels that are believed to have beneficial long-term health effects.

High light levels are provided in scenario 2.a with electric lighting. The primary energy demand in scenario 2.a is found to be at least 5 times higher than in scenario 1 where light is supplied by windows.

These findings underline that windows are low energy light sources. When light levels of 200 or 500 lux are considered, the energy performance of a house with windows is better than a house without window. But more importantly, when the light levels which can be achieved with windows are considered, the energy performance of a house with windows is substantially better than the house without windows.

Windows can be used in building design to reduce the electricity consumption for electric lighting. Further, windows shall be used to design building which are sensible to our biological needs and promote human health..

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