Comparison of simulated energy consumption by smart and conventional lighting systems in a residential setting

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Abstract. This paper investigated and compared how the energy consumption of a conventional and Smart Lighting System (SLS) in a simulated residential setting is affected by different households’ arrangements and occupancy pattern. An agent-based simulation model of a one-bedroom apartment in Sweden was chosen for comparison with different scenarios. The result shows that the number of residents within an apartment does not necessarily lead to higher energy consumption. Further findings indicate that, even though it has standby energy consumption, SLS is more energy efficient compared to the conventional lighting system. Additionally, energy consumption during weekends was considerably higher than during weekdays.

Keywords: Intelligent Lighting, residential environment, efficient lighting

1. Introduction
In recent years, there has been a growing concern about energy consumption within the residential buildings. Globally, the energy use in residential buildings has increased from 1990 to 2009 by 32% (IEA, 2012), where a significant part is consumed by electric lighting. The great contribution is mainly due to the shorter lifespan of lighting installations compared to buildings and by using inefficient energy systems (Boyce, 2014). Currently, two main strategies are available for reducing energy consumption by lighting, according to Martirano (2011): either increasing efficiency or effectiveness. The efficiency improves by applying more efficient light sources while effectiveness means the implementation of automated control systems including, for instance, daylight harvesting or occupancy sensors. For home environments, the energy efficient light sources currently available on the market are Compact Fluorescent Lights (CFLs), Light Emitting Diodes (LEDs) and Smart LEDs. Despite differences in light quality, user acceptability and price, compared to CFLs, LEDs are much more energy efficient. Smart lighting system (SLS), requiring Smart LEDs, supposed to be even more efficient than conventional lighting systems (using CFL or LED) by using protocols or preset modes while connected and adjusted via wireless networks for user needs and requirements. Earlier studies on lighting optimisation in non-residential buildings indicated energy saving potentials between 40-80 % (Dubois and Blomsterberg, 2011, Williams et al., 2012, Bonomolo et al., 2017, Chew et al., 2016, Tzempelikos and Athienitis, 2007, Jennings et al., 2000).

However, the Electric Lighting Energy Consumption (ELEC) in a residential environment is not only affected by the type of light source or lighting system, but also by user behaviour and activity (e.g., Gerhardsson et al., 2018). A field study of energy-related behaviour in 57 Swedish homes concluded that more time is spent on energy-consuming activities during the weekends as compared to weekdays (Hiller, 2015). Additionally, a simulation study by Kwon et al. (2014), including a laboratory experiment indicated more ELEC for activities which require task lighting (i.e., cooking or reading a book).
Hence, the objective of this study was to simulate and compare the impact of two household organisations, including different occupancy patterns supported by different light settings on the ELEC in a residential environment.

2. Material and methods

In a light and energy simulation study, the ELEC for two different household scenarios were investigated in a one-bedroom apartment (Figure 1). The ELEC was calculated and compared in a MS Excel spreadsheet for the kitchen, living room, and bedroom only. A separation was made between General Lighting (GL) and Task Lighting (TL) and each investigated room were equipped with both types. The GL was set up to provide a minimum amount of light required for performance and visual comfort, and the TL provided mainly the required light level for specific tasks.

2.1. Household scenario and occupancy pattern

Two types of households, a single member, and a two-member were defined to demonstrate the impact of different occupancy patterns on energy consumption. The single-member household imitated the daily life of a university professor who works part-time in a distant city. (leaving the apartment unoccupied for a few days. For this household, 11 different activities were defined and distributed over the week to create a 24-hour occupancy pattern plan (see Table 1). Additionally, as the single household apartment is assumed to be unoccupied for certain days per week, Monthly Scenarios (MS) were created to investigate the influence of the duration of unoccupied (travelling) time due to standby energy consumption. Travelling scenarios including were MS1: not travelling, MS2: travelling on weekends (4 days per months), MS3: travelling all weekends and 4 weekdays (12 days) and MS 4: travelling 4 weekend days and 11 weekdays (15 days).

Table 1. Occupational patterns adapted from De Lauretis et al. (2017).

| Activity     | Time-use categories                                           |
|--------------|--------------------------------------------------------------|
| Morning ritual| Exercise, taking a shower, make-up                           |
| Breakfast    | Preparation, cooking, eating and cleaning                    |
| Care         | Caring for another family member                             |
| Lunch        | Preparation, cooking, eating and cleaning                    |
| Nap          | Rest                                                         |
| Leisure time | Reading, conversations, crafts, playing music, practising sports at home |
| Housework    | House cleaning, doing laundry, cloth care                    |
| Dinner       | Preparation, cooking, eating and cleaning                    |
| Gathering    | Spending time with family, friends                           |
| Outside      | Working, travelling                                         |
The two-member household includes a couple with the daily job. For this household, 10 different activities were defined, and it does not have travelling schedules. The specified occupancy patterns for both households for one entire week is presented in Table 1. The occupancy patterns are adapted from De Lauretis et al. (2017).

2.2. Lighting (control) design
In this study, two lighting systems, a conventional and an SLS are introduced. The conventional system includes CFL and LED, while the SLS involves smart LEDs and sensors. The conventional lighting system is controlled manually and the SLS is programmed according to the household type’s occupancy pattern including required dimming levels. Furthermore, standby energy consumption is considered when the SLS is turned off, yet plugged in. The standby energy use is calculated for each smart LED (Philips Hue, 0.4 Wh) and a bridge (Philips, 1.5 Wh) according to Swedish Energy Agency (2016)

2.3. Measures and procedures
Measured parameters for the simulation study consist of illuminance (in lux) and electric lighting energy consumption measured in kWh for the kitchen, living room and bedroom area. Standby energy consumption for SLS is measured in Wh and kWh. The amount of general lighting is based on the recommendations of the Energy Saving Trust (2016) for the living room (150 lx at floor level), bedroom (100 lx), and kitchen (180 lx). Task lighting for this study was set for the household members at 400 lx for cooking, watching television, and reading a book. The total ELEC is calculated without the presence of daylight.

First, the energy consumption of each light source is put in Excel and multiplied by its operational time to show ELEC for each activity per hour. Secondly, the ELEC was calculated separately for week and weekend days. Thirdly, the ELEC per week, month and year are calculated in order to compare overall energy performance for different lighting systems and household scenarios. Additionally, the ELEC for three different travelling scenarios (MS2, MS3, and MS4) is simulated for one month (February).

3. Results
An overview of the results per household is shown Table 2. 2019 was taken as the reference year, and in this year, there are 253 workdays and 112 weekend days (including holidays).

3.1. Occupancy pattern and energy consumption
Based on the simulation, results for both the single and the multi-user household showed more energy consumption during the weekends. For the multi-user household, the maximum ELEC occurred in the kitchen area, while for the single household this was in the living room. For the single household, the highest energy consumed activity (666 W) was ‘Care’ by using conventional CFL lighting system during the weekend/holidays, whereas the least energy consumed activity was ‘Dinner’ during the weekdays (9 W) using SLS in the kitchen.

For the multi-user household, the maximum energy consuming activity occurred during the weekend/holidays (603 W) in the kitchen, living room, and the bedroom equipped with conventional CFL. Conversely, the least energy consuming activity (9 W) was ‘Breakfast’ using SLS.
Table 2. Occupancy pattern (activity, location and duration) for both household scenarios and their energy consumption over a week and weekend together with standby ELEC for SLS

| Activity                  | Location         | Weekdays Duration (Mins) | EC for CFL (W) | EC for LED (W) | EC for SLS without standby (W) | Weekends Duration (Mins) | EC for CFL (W) | EC for LED (W) | EC for SLS without standby (W) | Stand-by ELEC (W) |
|---------------------------|------------------|--------------------------|---------------|---------------|-------------------------------|--------------------------|---------------|---------------|-------------------------------|--------------------|
| Morning ritual            | Living Room      | 30.0                     | 46.5          | 33.0          | 16.5                          | 30.0                     | 46.5          | 33.0          | 16.5                          | 276.4              |
| Breakfast                 | Kitchen          | 60.0                     | 69.0          | 38.0          | 18.0                          | 60.0                     | 69.0          | 38.0          | 18.0                          | 1103.4             |
| Outside                   | -                | 165.0                    | 0.0           | 0.0           | 0.0                           | 0.0                      | 0.0           | 0.0           | 0.0                           | 262.9              |
| Care                      | Kitchen, Living Room | 0.0                   | 0.0           | 0.0           | 0.0                           | 270.0                    | 666.0         | 423.0         | 247.5                         | 467.5              |
| Lunch                     | Kitchen          | 135.0                    | 195.5         | 83.5          | 47.3                          | 60.0                     | 69.0          | 38.0          | 18.0                          | 195.0              |
| Eating Lunch              | Kitchen          | 0.0                      | 0.0           | 0.0           | 0.0                           | 0.0                      | 0.0           | 0.0           | 0.0                           | 262.2              |
| Nap                       | Bedroom          | 30.0                     | 0.0           | 0.0           | 0.0                           | 30.0                     | 0.0           | 0.0           | 0.0                           | 210.4              |
| Leisure time              | Living Room      | 45.0                     | 69.8          | 24.5          | 24.8                          | 45.0                     | 69.8          | 24.5          | 24.8                          | 271.4              |
| Housework                 | Living Room      | 180.0                    | 360.0         | 240.0         | 114.6                         | 0.0                      | 0.0           | 0.0           | 0.0                           | 257.0              |
| Diner                     | Kitchen          | 30.0                     | 34.5          | 19.0          | 9.0                           | 30.0                     | 34.5          | 19.0          | 9.0                           | 207.3              |
| Family gathering          | Living Room      | 0.0                      | 0.0           | 0.0           | 0.0                           | 270.0                    | 198.0         | 132.6         | 19.1                          | 272.2              |
| Leisure time              | Bedroom          | 90.0                     | 61.5          | 36.0          | 18.0                          | 75.0                     | 31.3          | 30.0          | 12.0                          | 199.1              |

| Total (kW) | - | 0.77 | 0.50 | 0.25 | - | 1.3 | 0.8 | 0.5 | 0.8 | 3.4 | 44 |

| Activity                  | Location         | Weekly Duration (Mins) | EC for CFL (W) | EC for LED (W) | EC for SLS without standby (W) | Monthly Duration (Mins) | EC for CFL (W) | EC for LED (W) | EC for SLS without standby (W) | Yearly Duration (Mins) | EC for CFL (W) | EC for LED (W) | EC for SLS without standby (W) | Stand-by ELEC (W) |
|---------------------------|------------------|-------------------|---------------|---------------|-------------------------------|------------------------|---------------|---------------|-------------------------------|------------------------|---------------|---------------|-------------------------------|--------------------|
| Morning ritual            | Living Room      | 30.0              | 46.5          | 33.0          | 16.5                          | 30.0                   | 46.5          | 33.0          | 16.5                          | 276.4                 | 1103.4         | 13265         | 10.0                          | 1103.4              |
| Breakfast                 | Kitchen          | 60.0              | 69.0          | 38.0          | 18.0                          | 60.0                   | 69.0          | 38.0          | 18.0                          | 262.9                 | 811.4          | 9737          | 20.0                          | 811.4               |
| Outside                   | -                | 165.0             | 0.0           | 0.0           | 0.0                           | 0.0                    | 0.0           | 0.0           | 0.0                           | 267.9                 | 2591.4         | 31007         | 40.0                          | 2591.4              |
| Care                      | Kitchen, Living Room | 0.0            | 0.0           | 0.0           | 0.0                           | 270.0                  | 666.0         | 423.0         | 247.5                         | 467.5                 | 1869.8         | 22438         | 50.0                          | 1869.8              |
| Lunch                     | Kitchen          | 135.0             | 195.5         | 83.5          | 47.3                          | 60.0                   | 69.0          | 38.0          | 18.0                          | 195.0                 | 779.9          | 9359          | 60.0                          | 779.9               |
| Eating Lunch              | Kitchen          | 0.0                | 0.0           | 0.0           | 0.0                           | 0.0                    | 0.0           | 0.0           | 0.0                           | 262.2                 | 1129.0         | 13548         | 80.0                          | 1129.0              |
| Nap                       | Bedroom          | 30.0              | 0.0           | 0.0           | 0.0                           | 30.0                   | 0.0           | 0.0           | 0.0                           | 210.4                 | 841.7          | 10100         | 120.0                         | 841.7               |
| Leisure time              | Living Room      | 45.0              | 69.8          | 24.5          | 24.8                          | 45.0                   | 69.8          | 24.5          | 24.8                          | 271.4                 | 1001.7         | 13124         | 165.0                         | 1001.7              |
| Housework                 | Living Room      | 180.0             | 360.0         | 240.0         | 114.6                         | 0.0                    | 0.0           | 0.0           | 0.0                           | 257.0                 | 1028.2         | 12338         | 210.0                         | 1028.2              |
| Diner                     | Kitchen          | 30.0              | 34.5          | 19.0          | 9.0                           | 30.0                   | 34.5          | 19.0          | 9.0                           | 207.3                 | 829.1          | 9640          | 255.0                         | 829.1               |
| Family gathering          | Living Room      | 0.0                | 0.0           | 0.0           | 0.0                           | 270.0                  | 198.0         | 132.6         | 19.1                          | 272.2                 | 1088.6         | 13664         | 345.0                         | 1088.6              |
| Leisure time              | Bedroom          | 90.0              | 61.5          | 36.0          | 18.0                          | 75.0                   | 31.3          | 30.0          | 12.0                          | 199.1                 | 796.3          | 9556          | 216.0                         | 796.3               |

| Total (kW) | - | 0.77 | 0.50 | 0.25 | - | 1.3 | 0.8 | 0.5 | 0.8 | 3.4 | 44 |

The results for the monthly travelling scenarios (MS2, MS3, MS4) for SLS indicated less potential for energy saving compared to the not travelling scenario (MS1). Comparing three monthly travelling scenarios (MS2, MS3 and MS4) for the single household demonstrated no substantial difference in ELEC between the LED system and SLS, see Figure 2. However, the ELEC for the CFL lighting system remains higher than the other two lighting systems due to the standby energy consumption of Smart LED and the bridge.

**Figure 2.** Monthly energy consumption for travelling scenarios for single-member household.
3.2. ELEC for different lighting systems

The annual ELEC per light system and household are presented in Figure 3. This result shows that the replacement of CFL by LED light sources reduces the annual energy consumption by 36% for both household types. When introducing an SLS to replace the conventional lighting, it further reduces the consumption by 27% for the single-member household and by 34% for the two-member household. Changing all the light sources in the apartment from CFL to Smart-LED, including implementation of occupancy sensors results in significant savings. Thus, the ELEC for the single member household is decreased by 53% and for the multi-member household with 58%.

![Annual energy consumption for electric lighting per light source type](image)

**Figure 3.** Annual ELEC for different lighting system and different households

4. Discussion

This study aimed to compare simulated ELEC for two different types of lighting systems (CFL, LED and SLS) in a one-bedroom apartment considering two different households. The findings show that SLS consumes the least ELEC and has a higher energy saving potential compared to CFL and LED. This can be explained by the placement of sensors, Smart LEDs, and pre-defined settings based on occupancy pattern. For example, the GL level in SLS is automatically dimmed in rooms while in the other lighting system (using CFL or LED) keeps the lights on. Furthermore, by using SLS and occupancy sensors, lights can automatically be turned off when the room is not occupied. Results indicate a reasonable amount of energy saving, 36%, by only replacing the CFL lighting system to LED.

The simulated findings confirmed that activities which require task lighting were consuming more energy. For example, comparing ‘Cooking’ and ‘Eating’ activities during the weekends for the two-member household shows that ‘Cooking’ consumes more ELEC. Besides, comparing the ‘Breakfast’ as the same activity for both households affirms that two-member household consumed less energy than single-member household both using the same lighting system. This is due to the assumption that this activity for the single-member household takes an hour, as compared to the two-member household (30 min.). Furthermore, in this study, the ELEC for ‘Breakfast’ (for the two-member household) using a conventional lighting system with LEDs consumed 19 W (TL=400 lx and GL=180 lx) while in a similar study by Kwon et al. (2014) it resulted in 35.5 W (GL=400 lx). The differences are accounted for the decrease of illuminance levels when TL was not needed anymore.

In this simulation study, based on the occupancy pattern in both households, there was a higher energy consumption found during a weekend day, compared to a weekday. It is consistent with the study of Hiller (2015), which found higher energy use in residences during the weekend. Comparing different
travelling scenarios with not travelling revealed that the energy saving potential was reduced by 11% for SLS, and this can be explained by the standby energy consumed by the Smart LEDs and bridge. For example, considering ‘Nap’ shows no energy consumption by lighting, but it exhibits 210W of energy consumption by using SLS over a week.

5. Conclusions
The main conclusions from the paper indicate that replacing CFL light sources with LEDs or Smart LEDs improves energy saving. This can be even further increased by implementing SLS which can adapt to the occupancy pattern using various sensors. Secondly, for the types of households investigated in this study, the number of residents in an apartment does not necessarily lead to higher energy consumption for lighting. Energy consumption is affected by the type of light source, lighting system used, occupancy pattern, and duration of activities. Finally, the energy saving potential of SLS may be decreased due to active standby energy consumption as compared to conventional lighting systems.

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