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**Abstract**. Daylight availability is an important aspect that can potentially improve both the quality and the energy performance of buildings. However, it is not always straightforward easy to assure that an increase in the daylight availability leads to a reduction of electric energy use for artificial lighting. In this study, experimental measurements and numerical simulations were conducted to analyse the relation between the uses of artificial light and the daylighting availability for different groups of users who lived for one month each in a Zero Emission Building single-family house located in Trondheim, Norway. The use of electric lighting and the outdoor environment conditions (irradiance and illuminance on the horizontal plan) were recorded through advanced daylighting simulations, carried out with *DIVA-for-Rhino*, the daylighting availability during the periods of occupancy was then reconstructed, using as input data the outdoor environmental variable recorded during the experimental analysis. The results show that the coefficient of correlation between daylight availability and the artificial light is in general low and the use of artificial lighting seems to be largely independent from the availability of natural light.

## 1. Introduction

A homogenous daylight distribution has relevant benefits on the building's energy saving, on the human health and on the occupants' well-being [1]. In order to maximize and optimize the quality of daylighting, the building surrounding and the climatic boundary conditions should be taken into account to while designing a building. Maximizing the sunlight penetrating in the interiors also allows a reduction of electric energy use for artificial lighting [2]. A relationship between increased daylighting and reduced use of electric lighting can be found for office buildings: a decrease in the electric lighting use occurs when a proper range of illuminances is provided on the horizontal work plane [3]. However, it can be more challenging to find such a relationship in the context of residential building, probably because of the different user behavior in domestic setting [4]. There, the users' habits and preferences can turn out to be highly unpredictable and cause relevant impact on the buildings' energy use. The study presented in this paper originates from this challenge and aims at investigating how the users interact with electric lighting in a domestic environment, and more precisely at analyzing if the availability of natural light is correlated with the use of artificial lighting by real users.

## 2. Method and materials

This work is the follow up of a previous study where the relationship between electric lighting and daylight availability in a residential context [5]. The previous study aimed to evaluate the correlation

between the electric energy use for lighting and the average indoor illuminance on the horizontal plane placed at 0.85 m from the floor level, equal to 100 $m^2$, in a residential building in Nordic climate. In the previous study, the correlation was assessed considering the whole floor area of the house without any distinction between the different rooms. The findings demonstrated that, in residential context, it is rather difficult to find a strong inverse correlation between the daylight availability and the use of artificial lighting. This means, in practice, that users generally do not switch off or dim the light when the internal illuminance owing to natural light increases. However, such a missing correlation might be linked to the very heterogeneous conditions in the different rooms of the building. In this study, the level of detail is then increased, and the relationship between daylighting and energy use for artificial lighting is broken down to the single rooms of the building.

### *2.1. The experimental facility*

The Zero Emission Building (ZEB) Living Laboratory a single-family house located in Trondheim (Norway, latitude 63°25' N and longitude 10°27' E) (Figure 1) has been used to collect data on user occupancy, daylighting, and artificial lighting use. The ZEB Living Laboratory was designed to be representative of the Norwegian residential building stock for detached house typology. This research facility was built to carry out experimental investigations at different levels [6]. It is equipped with sensors that measure the indoor environmental quantities, such as temperature, $CO_2$ concentration and relative humidity. The monitoring system keeps also track of the electric energy use in the building, with a degree of detail down to the individual power line, light source, and appliances. This information allows one to know the actual energy use of the house, when it is occupied. Outdoor sensors are also installed to measure the climatic boundary conditions of the system [7].

**Figure 1.** The ZEB Living Laboratory and its surrounding.

### *2.2. Structure of the methodology*

The methodology is structured in two parts (Figure 2). One part is related to the calculation, starting from experimental data, of the electric energy use for lighting in the building down to each individual room (Figure 2 on the left). The other part is related to the estimation of the daylighting availability (Figure 2 on the right) for the periods of occupancy. The data collection includes indoor data for electrical use and outdoor data for solar radiation and definition of indoor illuminance level respectively. To collect data of illuminance in the indoor environment, illuminance sensors, with an accuracy of ±10%, placed on the ceiling of all the living areas were used. Electric energy meter for lighting and dimmer status of each light source were used for the characterization of the lighting system in each room. Regarding the outdoor environment, a pyranometer with accuracy of ±3% was used to measure global solar irradiance on the horizontal plane, while the direct measurement of the different components of solar radiation (direct and global diffuse) was not implemented, but reconstructed from experimental data. Finally, the statistic tool of Pearson Correlation Coefficient (r) has been used to assess the correlation between the two variables: (i) the electric use for lighting, evaluated in a single room and (ii)

the average illuminance on the horizontal plane placed at 0.85 m from the floor level, in each analyzed room.

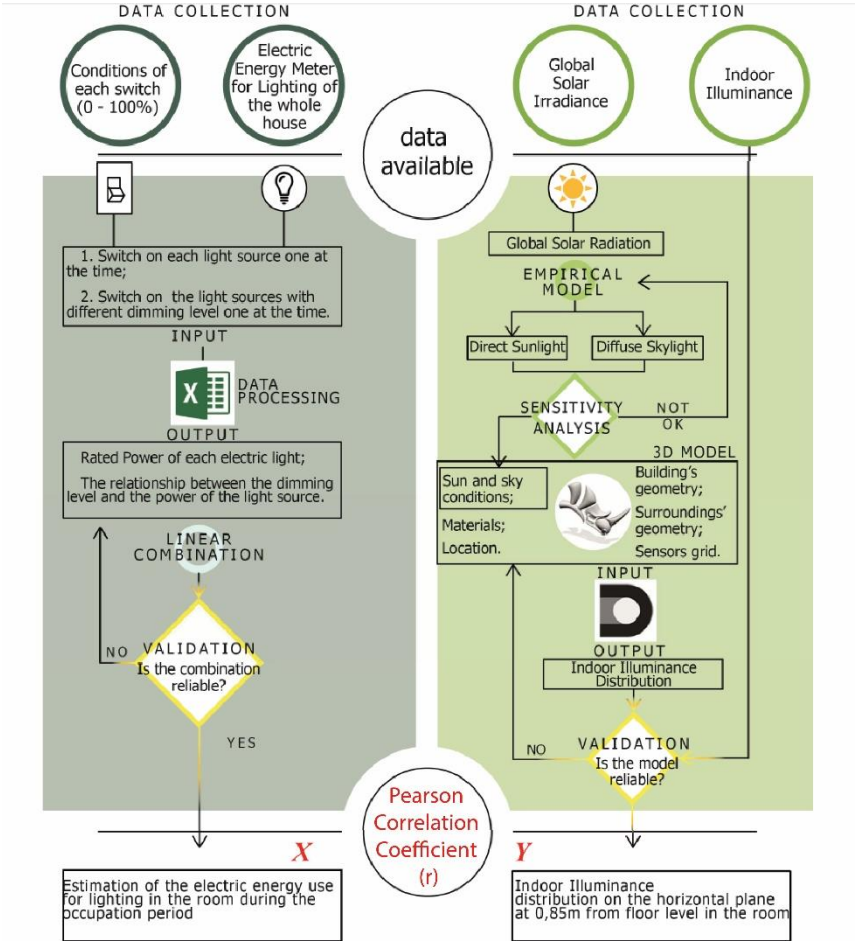


**Figure 2.** Flow chart of the methodology.

2.2.1. *Monitoring experiment at ZEB Living Laboratory*

This study is included in a wider qualitative and quantitative monitoring experiment which took place in the ZEB Living Laboratory between October 2015 and April 2016. During this period, six groups of users moved in the ZEB Living Laboratory and they used it as their own home for twenty-five days each. The groups, composed by two or four people, were chosen to be representative of the three main demographic categories, such as: young students, families with children, and elderly couples [8]. The users were invited to continue with their routines and habits by avoiding any unusual behavior. Furthermore, in order to observe the adaptation of the users to the house systems, very basic information was provided about the building operation. In order to give the users the time to get familiar with the system, only the data of the last week of the occupational period of each group was considered in this study. This strategy allowed one minimizing any uncertainty due to the unawareness of the users of the building operation system and interference. The experiment was conducted according to the best practice and Norwegian regulations and the consent to use personally non-identifiable data for research activities was released by the Norwegian centre for research data (NSD, Norges Samfunnsvitenskapelig Datatjeneste).

2.2.2. *Daylight simulations and model validation*

In order to reconstruct the inner spaces of the ZEB Living Laboratory (Figure 3a), a 3D model was built in *Rhinoceros* environment. The urban surrounding constitutes by the nearby buildings and terrain

profile were also modelled to reproduce the geometry of the urban surrounding. Indoor illuminance levels for the analyzed rooms (the bedrooms west and east, the kitchen and the living area (Figure 3b)) were recreated through climate-based simulations using *DIVA-for-Rhino*, a *Radiance*-based software by customizing Perez sky model as input date and time as well as measured irradiances data (section 2.3.3).

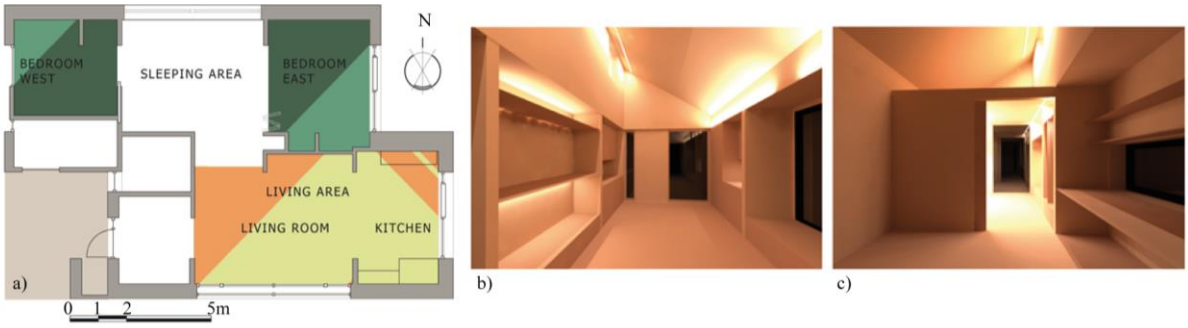


**Figure 3**. (a) Plan of the ZEB Living Lab: highlighted the analysed areas; (b) Rendering of the living room and (c) inside the bedroom east setting the Radiance's simulation parameters (Table 2).

By referring to a similar example in literature [9], *Radiance* simulation parameters (Table 1) and primitives (Table 2) were set to simulate the indoor materials of the ZEB Living Laboratory. The values of the natural illuminance on the horizontal plane positioned at 0.85 m above the floor level were extracted from the simulations.

**Table 1.** Radiance's simulation parameters**.**

| ambient bounces (ab) | ambient divisions (ad) | ambient supersamples (as) | ambient resolution (ar) | ambient accuracy (aa) |
|---|---|---|---|---|
| 5 | 1024 | 16 | 256 | 0.10 |

**Table 2.** Radiance's simulation parameters.

| Description | Material/Colors | Radiance material | RGB | Specularity | Roughness |
|---|---|---|---|---|---|
| Ceiling | Opaque | WoodenCeiling | 0.6/0.4/0.3 | 0 | 0 |
| Wall | Opaque | WoodenInteriorWall | 0.6/0.4/0.3 | 0 | 0 |
| Floor | Opaque | WoodenFloor | 0.5/0.3/0.2 | 0 | 0.02 |
| Furniture | Opaque | WoodenFurniture | 0.5/0.3/0.2 | 0 | 0 |
| Single Glazing | Translucent | Glazing_SinglePane_88 | 0.96/0.96/ 0.96 | | |
| Triple Glazing | Translucent | Glazing_TriplePane_Krypton | 0.51/0.51/0.51 | | |
| Mullions | Opaque/ dark grey | MullionsSheetMetalmatted | 0.1/0.1/0.1 | 0.8 | 0 |
| Outside Wood | Opaque | OutsideWood | 0.5/0.3/0.2 | 0 | 0 |

2.2.3. *Model validation and sensitivity analysis*

This *Radiance* engine allows one obtaining climate-based daylighting metrics [10] by using typical weather data for a specific geographical location. In this case, the International Weather for Energy Calculations (IWEC) converted in energy plus weather (.epw) data file of Trondheim was used [11]. The original file was updated in order to include the actual measured data values of the global solar radiation recorded by the pyranometer at the period of the experiments. In fact, climate-based simulations require data of the direct normal and diffuse horizontal radiation to recreate the luminous distribution of the sky vault. However, the pyranometers installed in the ZEB Living Laboratory senses only the global solar irradiance on the horizontal plane but does not provide information about the direct and diffuse radiation. Therefore, to obtain values of solar radiation in direct normal and diffuse horizontal components (as required by the .epw data file), the following empirical model was considered:

$$Global\ Radiation = Diffuse\ Radiation + Direct\ Radiation\ \left[\frac{Wh}{m^2}\right]$$

Where, the global solar radiation, measured by the pyranometer, was distributed in its two components according to the following criteria:

- When the measured global solar radiation was lower than 100 W/m$^2$, it was assumed to be only diffuse solar radiation component;
- When the measured global solar radiation was higher than 100 W/m$^2$, it was considered diffuse solar radiation until 100 W/m$^2$, and the excess part was equivalently divided in direct (50%) and diffuse (50%) solar radiation.

In order to assess the reliability of this simple empirical model, a sensitivity analysis was conducted through different sets of analysis by setting the following inputs:

- In the first set of simulations, the direct solar radiation component in the original .epw data file was increased by 20% and the diffuse solar radiation component was reduced accordingly to reach the total value of the global radiation measured by the pyranometers;
- In the second set of simulations, the direct solar radiation component in the .epw file was decreased by 20% and the diffuse solar radiation component was increased accordingly to reach the total value of the global radiation measured by the pyranometers.

The sensitivity analysis showed that the empirical model is not very sensitive to the differences between direct and diffuse solar radiation components replaced in the .epw data file at the same level of global solar radiation (Figure 4).

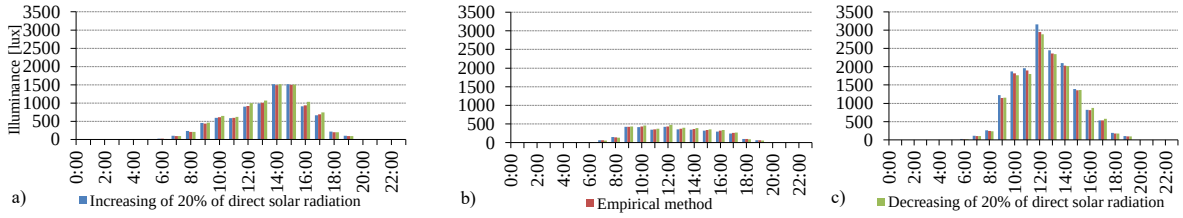


**Figure 4**. Sensitivity analysis: comparison between the illuminance values carried out from the analysis in *DIVA-for-Rhino* of daylight autonomy conducted in the (a) bedroom west, (b) bedroom east and (c) living area and the kitchen together on the 13$^{th}$ of April.

The proposed empirical model was used to split the global solar radiation measured by the pyranometers into direct and diffuse components and replace them as inputs data in the .epw data file. Daylight Autonomy simulations were run for the analyzed rooms and the outputs were compared with the collected data in order to assess the reliability of the empirical model. The data of indoor illuminance sensed by the indoor sensors facing downwards placed at the ceiling height of the analyzed rooms were compared against the simulated indoor illuminance values calculated at ceiling height. The data collection was carried out in three days of May (Figure 5), characterized by a) overcast (1$^{st}$ of May), b) intermediate (7$^{th}$ of May) and c) clear (9$^{th}$ of May) sky conditions. The analyses showed that the simulated values qualitatively and quantitatively approximate the real behavior of the natural light.

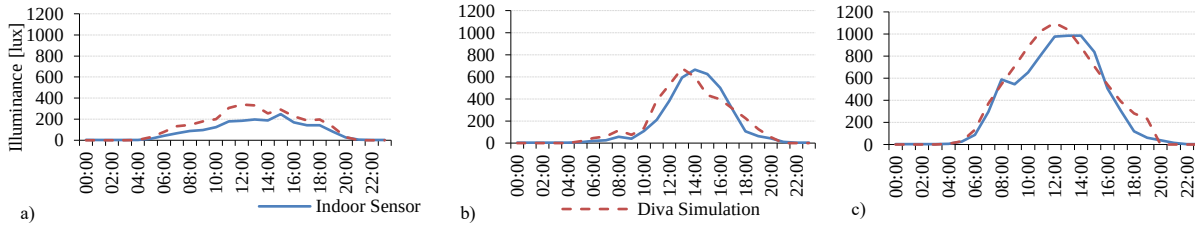


**Figure 5**. Comparison between the illuminance values carried out from the analysis of daylight autonomy and the values recorded by sensors installed on the ceiling of the living room in a) overcast (1$^{st}$ of May), b) intermediate (7$^{th}$ of May) and c) clear (9$^{th}$ of May) sky conditions.

### 2.2.4. *Characterization of the electric lighting*

The lighting fixtures of the ZEB Living Laboratory are LED strips that operate with a potential difference of 12V. A power transformer, always active for the conversion from 240V to 12 V, draws a

permanent base-load of 33W. This base-load must be subtracted to the overall electric energy use measured every hour in order to be able to assess the energy use down to each individual room and lighting fixture. The characterization of the lighting system was carried out during January and February 2018. In particular, the following features were analysed:

- Energy usage of each lighting at the highest of its power, which means with no dimming (this condition will be indicated as Dimmer status 100%);
- The relationship between the dimming level and the energy use of the single lighting source, analysed only for the most used lighting sources.

Experimental data were collected and elaborated to classify the components of the lighting system. In the first step of the electric lighting characterization, the light sources were switched on for a sufficient amount of time, and one at the time, to allow the acquisition data system to record the electric energy used only by the active light. Then, the electric energy use in that time interval was divided by the time interval to find the power of the involved electric light, and then the base-load was subtracted. Below, a calculation example is shown for one light source. This operation was repeated for all the lights.

$$BaseLoad = 33\ W$$

$$E_{analysed\ light} = 86\ Wh\ ; t = 0.52\ h; P_{analysed\ light} = \frac{86\ Wh}{0.52\ h} = 170\ W$$

$$Nominal\ Power_{analysed\ light} = 170W - 33\ W = 137\ W$$

The second step aimed at assessing whether or not a relationship between the light dimming and the power of the light source could be found. This procedure was necessary to estimate the contribution of each lighting fixture to the overall electric energy meter using the available data of the condition of each switch (percentage of dimming). This part was conducted for the light sources placed on the ceiling of each room. After this, it was possible to assess the electric use in every single room by linear superposition, knowing the condition of each physical switch recorded by the monitoring system during the occupation period and its nominal drawn power at different dimming states (Figure 6).

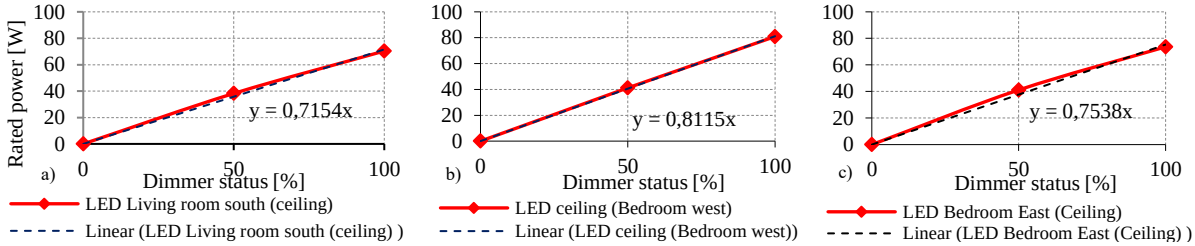


**Figure 6**. Plot of the Dimmer status-Rated power relationship for the LED installed on the ceiling of a) living room, b) bedroom west and c) bedroom east.

## 3. Results and discussion

In the Table 3 the results carried out from the calculation of the Pearson Correlation Coefficient (r) show the differences in the groups' behavior. Generally, the groups belonging to the same category tend to behave in the same way towards artificial lighting. A peculiar case is the group of students that is the only one using actively the sleeping area during the day. The Day 7 constitutes a particular case. In contrast with the other cases of non-applicable (N/A) results, in this case the electric consumption stays constant, despite the increasing or decreasing of the daylight availability. It means that the use of artificial lighting is totally independent of the daylight availability. This may also be due to the use of curtains, which is not recorded, or the need for a higher level of illuminance on a specific area of the room or simply that the user forgot to switch off the light when left the room. This day also shows the difficulty in defining preferences and assessing universally accepted level of indoor illuminance in a residential context. In this case, the different pattern and preferences are shown by the use of artificial light in the bedrooms. Even if in the bedroom facing west a level of illuminance higher than 100 lux is reached during the day (>), this is not related to a decreasing of the electric energy use for lighting

(Figure 7 a and b). On the other hand, a strong negative correlation was found for the bedroom facing east, despite the low level of illuminance (Figure 7 c and d).

**Table 3.** The results of the Pearson Correlation Coefficient (r) for the five groups of users monitored.

| Day | Year Period Users | Pearson Correlation Coefficient r | | | | Year Period Users | Pearson Correlation Coefficient r | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Liv. room | Bed. west | Bed. east | Prev. Study | | Liv. room | Bed. west | Bed. east | Prev. Study |
| Day 1 | | N/A* | N/A | N/A | 0,097 | | N/A | N/A | N/A | -0,367 |
| Day 2 | | 0,324 | **0,565** | -0,040 | 0,282 | | N/A | N/A | N/A | 0,331 |
| Day 3 | 2015 | 0,300 | 0,385 | **0,673** | 0,388 | 2016 18-24.01 | N/A | N/A | N/A | 0,008 |
| Day 4 | 27.11/04.12 | -0,392 | -0,431 | -0,420 | -0,398 | Family | N/A | N/A | N/A | 0,380 |
| Day 5 | Two students | -0,271 | -0,302 | -0,279 | -0,279 | with two | N/A | N/A | N/A | 0,290 |
| Day 6 | | **0,021** | -0,066 | -0,147 | 0,325 | children | **0,599** | N/A | N/A | **0,603** |
| Day 7 | | -0,473 | N/A | **-0,770** | -0,470 | | -0,485 | N/A | N/A | -0,490 |
| Day 1 | | **-0,574** | N/A | N/A | -0.531 | | -0,392 | -0,460 | N/A | 0,376 |
| Day 2 | | **-0,589** | N/A | **-0,573** | **-0.589** | 2016 | 0,192 | N/A | N/A | 0,172 |
| Day 3 | 2016 | **-0,575** | N/A | N/A | 0.013 | 12-18.03 | -0,435 | -0,473 | -0,348 | -0,474 |
| Day 4 | 09-15.02 | **-0,761** | N/A | N/A | **-0.786** | Family | -0,356 | -0,503 | N/A | 0,002 |
| Day 5 | Retired couple | **-0,771** | N/A | -0,588 | **-0.796** | with two | -0,473 | -0,477 | -0,429 | -0,490 |
| Day 6 | | **-0,732** | N/A | N/A | **-0.769** | children | -0,367 | -0,415 | -0,248 | -0,249 |
| Day 7 | | -0,380 | N/A | -0,274 | -0.476 | | 0,128 | -0,192 | 0,033 | 0,170 |
| Day 1 | | N/A | N/A | 0,455 | 0.079 | | | | | |
| Day 2 | | -0,329 | N/A | N/A | -0.085 | | | | | |
| Day 3 | 2016 | **-0,629** | N/A | N/A | -0.441 | | | | | |
| Day 4 | 11-17.04 | -0,467 | N/A | N/A | -0.650 | | | | | |
| Day 5 | Retired couple | -0,052 | N/A | N/A | -0.439 | | | | | |
| Day 6 | | -0,282 | **0,556** | N/A | -0.348 | | | | | |
| Day 7 | | N/A | N/A | 0,455 | **0.726** | | | | | |

In bold are highlighted all the strong correlations.

* N/A (not-applicable): represent the cases in which there is no electric energy use for lighting (lights switched off) in the room during the daylight hours of the day, therefore it is not possible to assess the correlation.

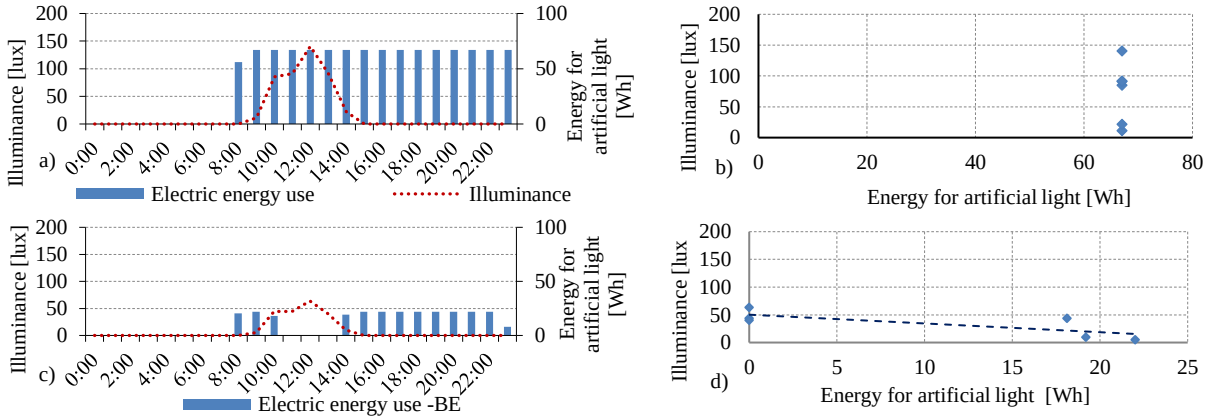


**Figure 7**. The hourly illuminance values and energy for artificial light and the correlation between illuminance level and energy for artificial light in bedroom facing west (a and b) and east (c and d).

The analysis related to the family with children that experienced the limited daylight hours in January, reveals that there was no the energy use for indoor lighting during the working hours. This underlines completely different habits from the group of students. Moreover, on day 6 a strong direct correlation in the living room demonstrates that even in this case the indoor illuminance level was, apparently, not enough for visual task. In fact, the positive value indicates that the energy use for electric lighting increases as the indoor daylight illuminance increases. For the second family with children, the Pearson's coefficient takes a medium value most of the days. The electric lights in the bedrooms are used only in the early morning and late afternoon. Even in this case, the use of electric lights is more dependent on the occupancy schedule than on the availability of daylight. Furthermore, the results show that the period 09-15 February 2016 (retired couple), counts more values in the range of strong correlation ($\pm 0.5 \leq r \leq 1.0$). In this period, there are also values close to -1 especially in the living room.

It means that the relationship between the daylight availability and the electric energy use for lighting is strong, which reflects that the electric lighting energy use decreases as the daylight availability increases (i.e. the users tended to switch off the lights in the room when the daylight provision of the space increased). Finally, not-applicable cases is the most common result in the bedroom (64% in the bedroom facing west and 58% in the bedroom facing east) while only 7% of the cases in the living room. This latter data might prove the user's carefulness in switching off the lights when leaving the room.

## 4. Conclusions

This study confirmed the main findings of the previous work [5]. Despite the level of detail for the calculation of daylight availability increased to the individual room. These are:

- It cannot be found a strong correlation between daylight availability and energy for lighting;
- It is difficult to obtain a robust correlation in the domestic context of residential buildings due to the fact that the users' behaviour is often unpredictable when they interact with artificial lighting system in their everyday life.
- The use of electric lights is more dependent on the occupancy schedule, the users' behaviours, the culture, the habits and the psychological aspects rather than on the availability of daylight.

## Acknowledgments

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