JOURNAL OF ASIAN ARCHITECTURE AND BUILDING ENGINEERING
2023, VOL. 22, NO. 5, 2851–2866
https://doi.org/10.1080/13467581.2022.2161308

Taylor & Francis
Taylor & Francis Group

BUILDING STRUCTURES AND MATERIALS

OPEN ACCESS Check for updates

A proposal on residential lighting design considering visual requirements, circadian factors and energy performance of lighting

Egemen Kaymaz [a] and Banu Manav [b]

[a]Department of Architecture, Bursa Uludag University, Bursa, Turkey; [b]Department of Interior Architecture and Environmental Design, Kadir Has University, İstanbul, Turkey

ABSTRACT

This study assesses residential areas which have been converted into workplaces and are still used after the Covid-19 in terms of visual, non-visual, and energy performance requirements of lighting. We proposed a lighting design using LED systems with dimmable and tuneable features. Circadian factors in WELL Building Standard are analyzed for compatibility with the current visual requirements. The impact of various design parameters on lighting energy consumption, including daylight availability, lighting schedules, lighting control strategies, and light reflectance value of walls is evaluated through a case study in Turkey. Although the annual lighting energy consumption is higher than it was before the pandemic, building energy simulation results show that the application of LED systems with lighting energy measures can improve lighting energy performance by up to 38%. From the non-visual dimension of light, our data indicate that higher melanopic illuminance and/or colour temperature of light sources are necessary to entrain and sustain the circadian rhythm under overcast sky conditions in winter months. On the other hand, an increase in luminous intensity can lead to glare and higher energy consumption while a higher colour temperature may affect the physiology and psychology of occupants negatively.

ARTICLE HISTORY
Received 19 September 2022
Accepted 19 December 2022

KEYWORDS
Residential lighting; visual requirements; energy performance; circadian lighting design

1. Introduction

The COVID-19 pandemic has led many of us to a retreat at home, performing a great deal of daily routines indoors. Meanwhile, the modes of working, teaching, and learning have been widely rethought, hybrid modes of working emerging as a common solution in many workplaces. As residential spaces have emerged to take on working and learning functions with the pandemic, improving indoor environmental quality and energy conservation have become imperative, while ensuring comfort-related design needs. In this context, the design of interior lighting will also be considered in line with these issues.

It is well known that the light does more than just enabling vision. Besides supporting visual perception, the lighting design influences human physiology and psychology through its impacts on our mood, cognition, and the circadian system (Brown et al. 2022; Dai et al. 2017). Besides visual and non-visual aspects of lighting design, energy performance requirements need to be satisfied. Well-being is upheld by proper lighting design that satisfies visual and psychological comfort (So and Leung 1998; IWBI 2022; CIE S 026/E 2018). Therefore, recent studies have focused on the emerging lighting technologies that present opportunities for different lighting scenarios while promoting psychological well-being, improving user performance, and saving energy (Brown et al., 2022; Awada et al. 2021).

As shown by Viola et al. (2008), Arendt (2010), Do and Yau (2010), Jarboe, Snyder, and Figueiro (2020), light is effective in generating a non-image-forming, biological response affecting the human circadian clock. The human circadian system is impacted by not only the illuminance at human cornea but also the spectral power distribution, time, duration, and the spatial distribution of light. Figueiro et al. (2016) state that a lighting system delivering a circadian stimulus (CS) equal to or greater than 0.3 can reduce sleepiness and increase vitality and alertness in office workers. High levels of light reaching the cornea during the daytime will align circadian rhythms with a day-active and night-inactive (sleeping) pattern, hence increasing alertness during working hours (Figueiro et al. 2016; CIE S 026/E 2018; Blume, Garbazza, and Spitschan 2019). Similarly, Sahin and Figueiro (2021) analyzed the stimulating effects of bright white light (>1000 lx at the cornea) and compared with lower levels (30 lx) of short wavelength (blue light), showing that the long wavelength (red light) promoted alertness without suppressing melatonin levels and disturbing the circadian system. Another international

CONTACT Egemen Kaymaz ekaymaz@uludag.edu.tr Bursa Uludag University, Faculty of Architecture, Department of Architecture, Gorukle Campus, 16059 Nilufer, Bursa, Turkey

© 2022 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group on behalf of the Architectural Institute of Japan, Architectural Institute of Korea and Architectural Society of China.
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

building standard of the International WELL Building Institute (IWBI) focuses on the stimulation from light to support circadian entrainment indoors. Yet, no maximum threshold is stated in WELL Building Standard v2 Q4 (2022) which is defined as a system for "measuring, certifying and monitoring the performance of building features that impact health and well-being" (IWBI 2022).

In this study, we aim to assess residential spaces that have been converted into offices and/or study areas during and after the Covid-19 pandemic in terms of their visual, non-visual, and energy performance requirements of lighting. In this regard, we propose a lighting design with LED technology which is compatible with lighting control strategies and the human-centric lighting concept. The impacts on the annual lighting energy consumption of four factors i) the building orientation, ii) the occupancy-related lighting schedules, iii) manual and daylight-linked lighting control strategies, and iv) light reflectance value (LRV) of the walls is analyzed for the selected residential units.

1.1. Residential lighting and the Covid-19 pandemic

The Covid-19 pandemic has changed our living, working, and education conditions and habits. Since residences have been used as offices and/or study areas since the start of the pandemic, the prominence of residential lighting in the annual total energy consumption has increased with the elevated occupancy rate. According to the Turkish Energy Market Regulatory Authority's statistics (EPDK 2022), household electricity consumption in the study area increased by 8.2% in the period from the beginning of the pandemic to the controlled relaxation of the Covid-19 containment measures in Turkey, when compared to the same period of the previous year. In the same period, the annual household electricity subscription for households has shown a linear increase of ~0.2% (EPDK 2022). Demand for lighting as well as other appliances plug load is effective in the rise of this electricity load. The impact of "stay home living patterns" on energy consumption in residential buildings including lighting is also reported by Farrow (2020), Hinson (2020), IEA (2020), Krarti and Aldubyan (2021), Wang, Li, and Jiang (2021), Rouleau and Gosselin (2021), Abdeen et al. (2021), and Surahman et al. (2022).

Previous studies have also emphasized that residential lighting becomes the second-largest electricity consumer in buildings with about 20%, accounts for about 10% of the household electricity consumptions in the European area and a significant contributor to energy costs in most industrialized countries (Makaremi et al. 2017; EEA 2014; Baloch et al. 2018). Although there are numerous studies evaluating the visual requirements for user comfort and lighting energy consumption in households, there were no direct measurements of the impact of occupancy patterns during and after the pandemic and working from home on lighting energy. Furthermore, studies that focus on the non-visual effects of lighting in developing countries such as Turkey are limited. Therefore, we aimed to look at residential lighting design in a holistic way.

1.2. Residential Lighting Design Criteria

As recommended in EN12464 (2011), CIBSE (2012), IESNA (2011), the interior lighting design criteria focus on enabling its users to perform visual tasks. Illuminance, luminance direction and distribution, glare, colour rendering and colour appearance of the light are the main determinants of visual comfort and performance. On the other hand, the non-visual effects of light, which is related to the vertical (corneal) illuminance at the eye level, have recently been added to the standards and guidelines and started to be discussed in the lighting design practices. Although studies in the non-visual dimension of light remain limited seminal contributions have been made by Al Enezi et al. (2011), Lucas et al. (2014), Dai et al. (2018a); (2018b), Jarboe, Snyder, and Figueiro (2020) addressing the circadian lighting design principles. The research by Duff, Kelly, and Cuttle (2015) and Aguilar-Carrasco et al. (2021) highlights the importance of sufficient melatonin suppression to promote daily circadian entrainment with an exposure of daylight at least one hour. The literature review by Alkhatatbeh and Asadi (2021) indicates that a light source must be considered together with the circadian effect which is dependent on the melanopic illuminance, spectral power distribution (SPD), and the direction of the distribution of light.

Energy efficiency is another important criterion in lighting design. Mardaljevic, Heschong, and Lee (2009), Dubois and Blomsterberg (2011), Boubekri (2014), and Frascarolo, Martorelli, and Vital (2014) suggest that the first principle is to maximize the benefit from daylight. Singh and Garg (2010), and Yu and Su (2015) argued that the function of a space and its daylight availability determine daytime electric lighting load and energy savings. In this regard, Das and Saikat (2015) analyzed outdoor illuminance and the artificial lighting requirements in residential buildings, analyzing the impact of the location and the orientation of the building including the interior design based on several plan typologies, and occupancy patterns. Zhen et al. (2019) calculated the energy consumption of indoor lighting by optimizing natural lighting in residential buildings in Xi'an, China.

Some authors in the extant literature argued that not only daylight availability and technology but also humans' energy-related behaviour in buildings will be

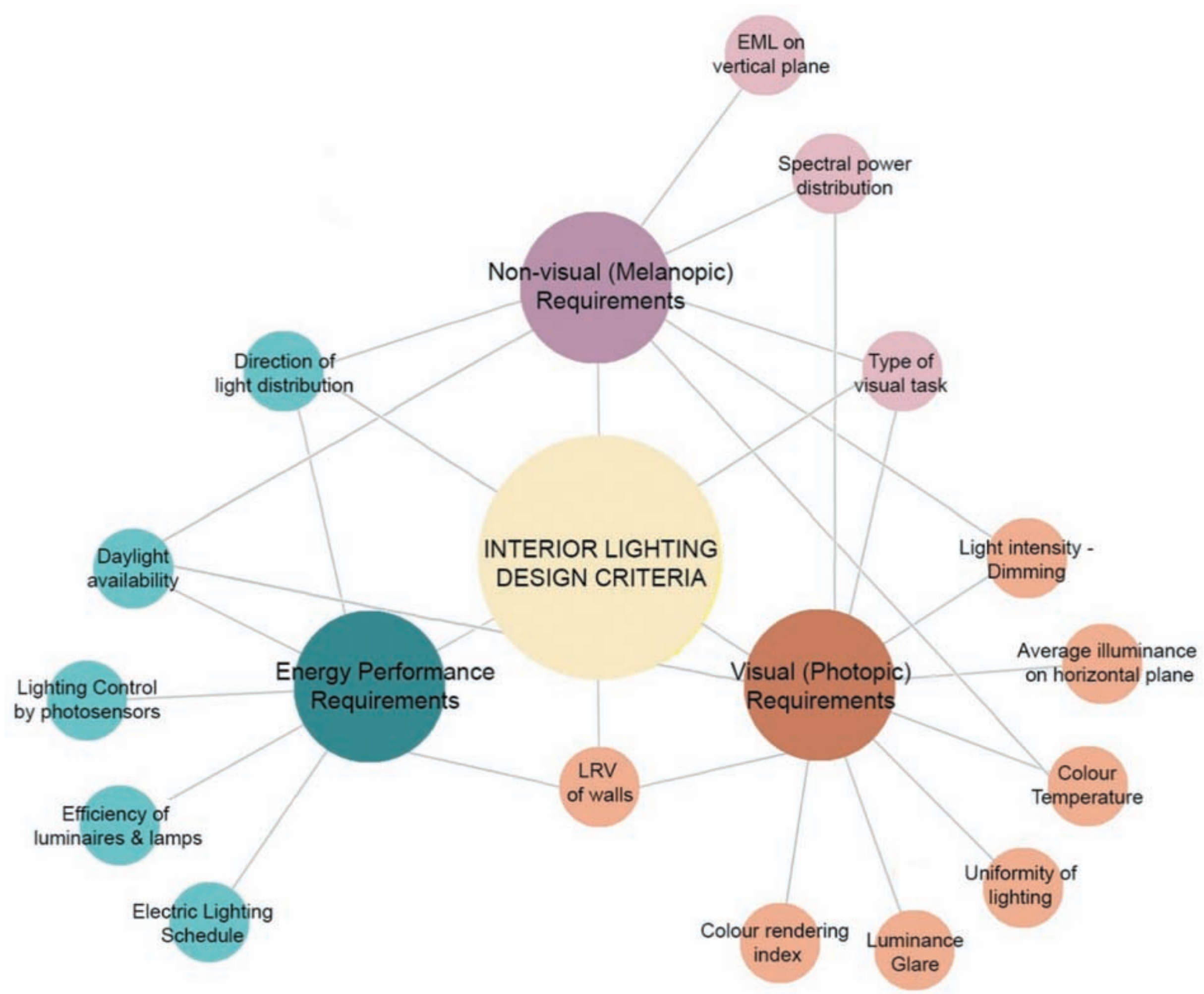


Figure 1. Residential lighting design criteria according to the visual, non-visual and energy performance requirements.

included in energy performance studies to assess whether building energy conservation goals can be achieved (Zhang et al. 2018). Bourgeois, Reinhart, and Macdonald (2006) studied behavioural models and investigated the impact of occupancy-based manual and automated lighting control on the total energy in buildings. The results show that the occupants prefer daylighting rather than artificial lighting can reduce the primary energy consumption by 40%, when compared to the users relying on constant electric lighting. In a recent study by Gerhardsson, Laike, and Johansson (2021), occupants' experiences with their residential lighting in Sweden are explored by a survey. The authors provide information on the background of wasted lighting energy linked to behavioural goals, such as safety, or psychological wellbeing or social needs.

The choice of light source and luminaire as well as the use of lighting control strategies has also a decisive impact on the lighting energy efficiency of buildings over the electricity consumption (Aman et al. 2013; Attia, Hamdy, and Ezzeldin 2017). There have been numerous studies to investigate lighting energy savings by controlling the regulation of lighting power gradually (dimming) or completely (on/off). For example, the literature review by Dubois and Blomsterberg (2011) provides evidence for energy conservation in office buildings by the improvements in electric lighting installation and daylight harvesting strategies. The findings of Frascarolo, Martorelli, and Vital (2014), Makaremi et al. (2019), Van Thillo, and Verbeke and Audenaert (2022) document the benefits of using LED technology with lighting control automation in energy savings.

The light reflectance value (LRV) of surfaces is another design variable that affects lighting energy consumption. Stephen and Coley (2011), Mohelnikova and Hirs (2016), Mangkuto, Rohmah, and Asri (2016), and Singh and Rawal (2011) suggest that the reflective property of interior materials can contribute to achieving the required illuminance, reducing the operating hours of artificial lighting, hence lowering the overall energy consumption.

The lighting design criteria outlined above and discussed in the scope of the study are illustrated in Figure 1.

1.3. Description of the study area

The research investigated the residential lighting design criteria depicted in Figure 1 through a case study of

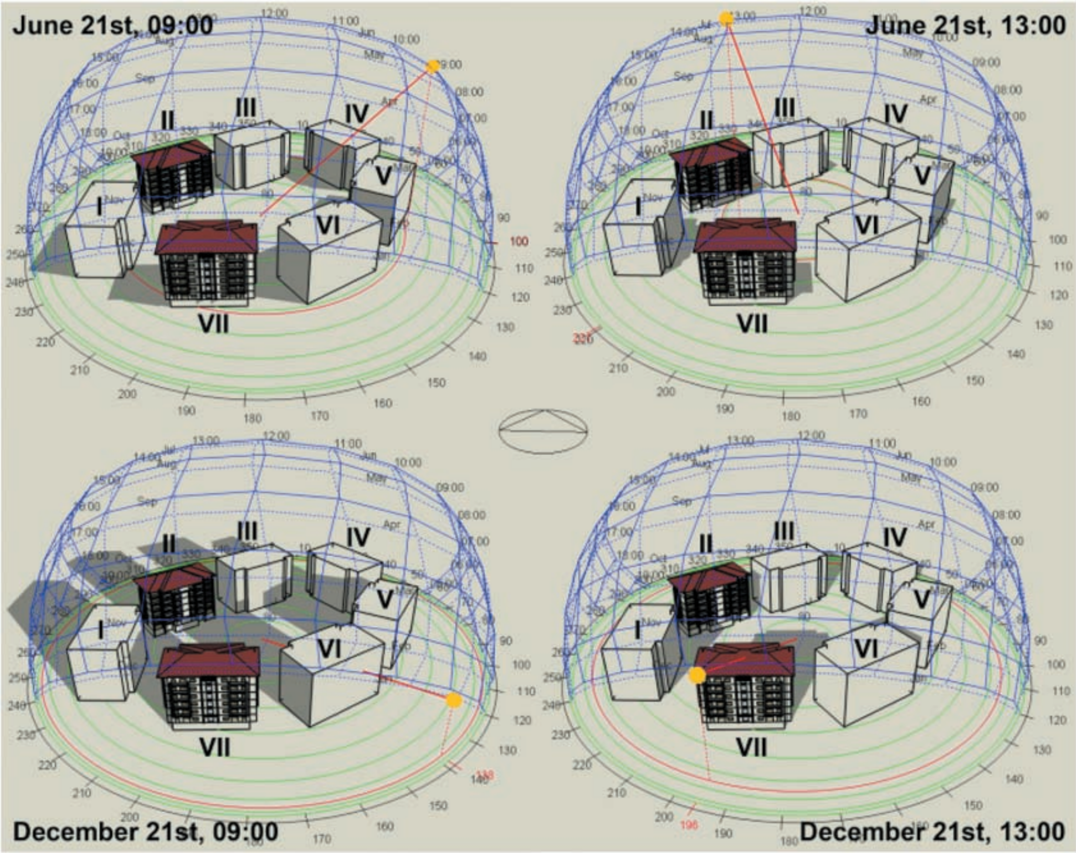


Figure 2. Shadow analysis of reference buildings at 09:00 and 13:00 on summer and winter solstice.

multi-storey apartment blocks in Bursa, Turkey. The housing complex meets the minimum energy performance standards in Turkey (BEP 2008) and holds an energy performance certification (EPC) according to Building Energy Performance National Calculation Methodology (BEP-TR 2010). The complex comprises six-storey residential buildings that were constructed on an area of 21,500 sq. m, with two flats on each storey.

The shadow analysis of the apartment blocks for the morning and noon hours on solstices is shown in Figure 2. Block VII is the least favourable building in terms of annual lighting energy; whereas Block II is the best. Considering the contrasting positions of these two blocks, lighting and building energy simulations were run and the results of improvement measures were evaluated for these two buildings. The sample residential units are located on the first floors of these two reference buildings with different obstruction angles and facade orientations. The flats have otherwise equivalent architectural and interior design features.

2. Material and Method

In this work, we propose a lighting model that considers the combination of visual and non-visual aspects of light together with the energy performance for exemplar residential units. The lighting design criteria in Figure 1 are investigated by computer-based building performance simulations for the reference buildings. Photopic and melanopic illuminance levels were calculated by DIALux Evo, a widely used parametric tool for lighting design and luminotechnical calculation. Annual lighting energy consumption was calculated by DesignBuilder software which is the graphical interface of the EnergyPlus simulation engine developed by the US Department of Energy.

2.1. *Residential Lighting Design Analysis*

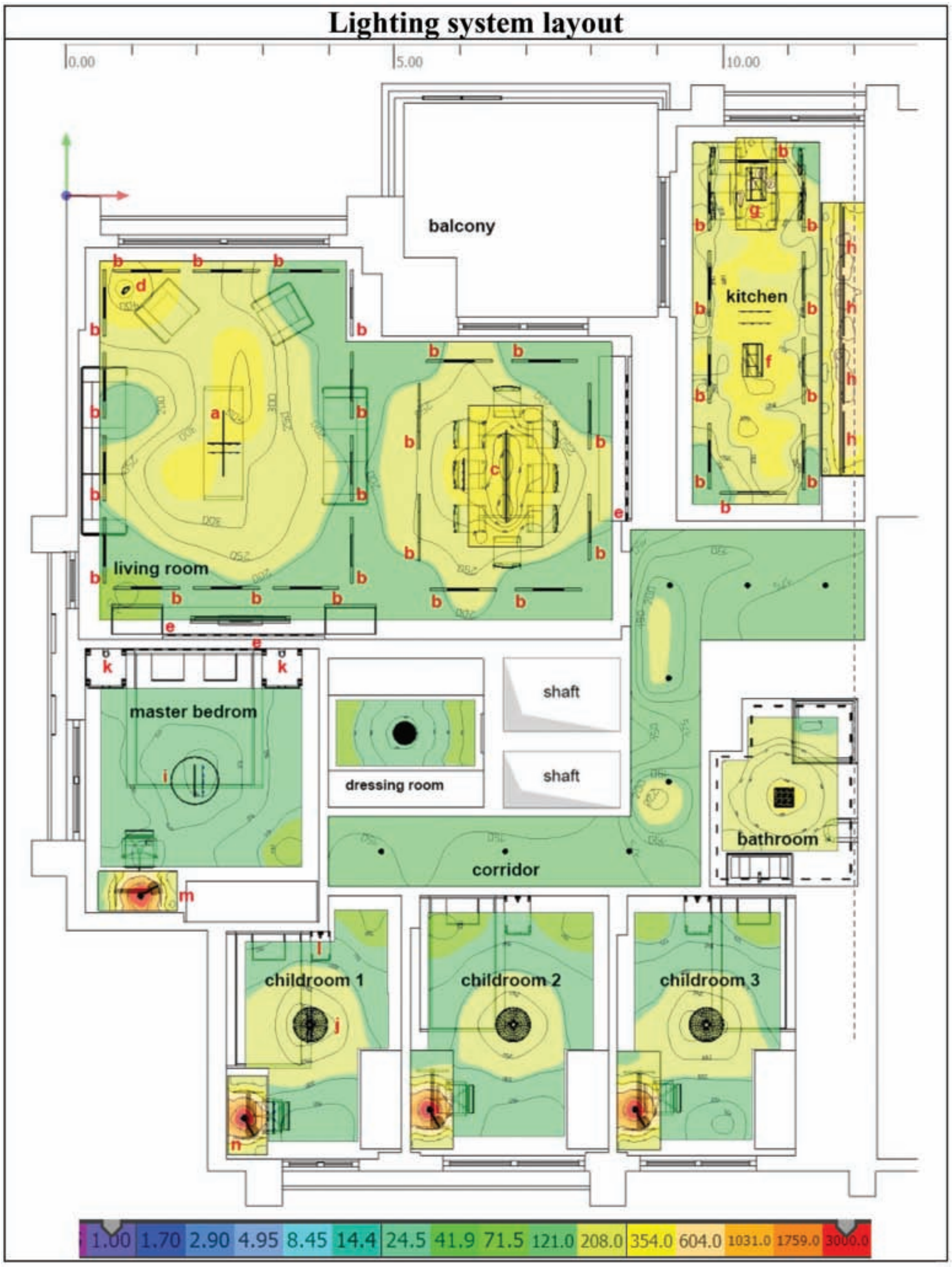
In previous research, Manav and Kaymaz (2021) analyzed occupants' preferences for lighting fixtures, lamp type, and colour temperature based on a questionnaire. In the present study, we use data from this survey based on which we model the reference building's lighting design in the DIALux Evo software. The lighting scenario considers dimmable LED lighting fixtures with a minimum of 50 lm/W efficacy, 80 CRI, and tunable white technology. The indoor environments are assessed according to the visual requirements recommended by EN 12464–1 standard (2011), IESNA Illuminating Engineering Society of North America (2011) and Guide F (2012) lighting guides together with the threshold levels for circadian entrainment in the toolbox of IWBI (2019) and WELL standard v2, Q4 (IWBI 2022).

In relation to the indoor visual requirements, the static lighting simulations are performed for the horizontal working planes (calculation grid is located 0.80

m above the ground and 0.5 m away from the room perimeter). All the luminaires in the residential unit are set to maximum (100%) and 60% intensity, respectively. Average illuminance level (E_{av}), uniformity of lighting (U_o: E_{min}/E_{av}) and unified glare ratio (UGR) are recorded for the visual tasks with respect to general and task lighting. The light reflectance values for floor, wall, ceiling and furniture are as follows; ρ_{floor} = 0.4, ρ_{wall} = 0.5, $\rho_{ceiling}$ = 0.8 and $\rho_{furniture}$ = 0.6. Table 1 shows the lighting system layout with isolines at the workplane level in a false colour rendering at 100% intensity and also the luminaire specifications. Further technical data about the selected products can be reached at the website of DIALux library (Lumsearch 2022). The following lighting design principles are considered in this study.

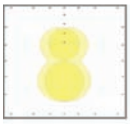
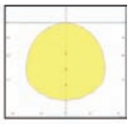
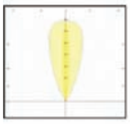
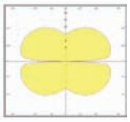
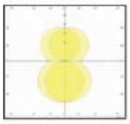
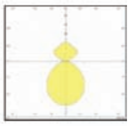
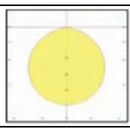
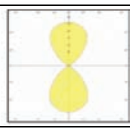
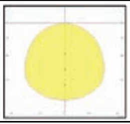
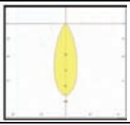
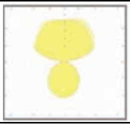
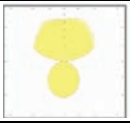
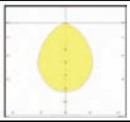
The living room is equipped with a dimmable and tunable luminaire above the seating area together with indirect strip lights that are installed as cove lighting. The dining area is also lit by a pendant luminaire with direct-indirect light distribution. One portable floor lamp and LED light strips are located in the living room. Pendant lighting fixtures are utilized for the general lighting of the kitchen and also above the dining table for task lighting. Linear light fixtures are placed under the kitchen cabinet to highlight the countertop. Master bedroom and child rooms are illuminated by

Table 1. Lighting system layout with LED luminaire specifications.



(*Continued*)

Table 1. (Continued).

Light distribution and specifications of LED luminaires used					
a. Pendant		φ: 1258 lm P: 24 W Tc: 2687 K CRI: 92	h. Furniture mounted		Φ: 743 lm P: 12.6 W Tc: 3000 K CRI: 80
b. Ceiling mounted		φ: 1287 lm P: 15.1 W Tc: 3000 K CRI: 80	i. Pendant		Φ: 3059 lm P: 34 W Tc: 2700 K CRI: 90
c. Pendant		φ: 2075 lm P: 36.6 W Tc: 3058 K CRI: 92	j. Pendant		Φ: 2916 lm P: 36 W Tc: 3000 K CRI: 90
d. Portable floor lamp		φ: 800 lm P: 10 W Tc: 2700 K CRI: 90	k. Wall-mounted		Φ: 958 lm P: 15 W Tc: 3000 K CRI: 90
e. Strip light		φ: 85 lm P: 1.7 W Tc: 3000 K CRI: 80	l Wall-mounted		Φ: 434 lm P: 6 W Tc: 3000 K CRI: 83
f. Pendant		φ: 1520 lm P: 19 W Tc: 2700 K CRI: 85	m. Table lamp		Φ: 835 lm P: 9 W Tc: 3000 K CRI: 90
g. Pendant		φ: 2880 lm P: 42 W Tc: 2700 K CRI: 85	n. Table lamp		Φ: 1210 lm P: 12 W Tc: 4000 K CRI: 90

pendant sources with semi-direct light emission. Above each bedside table, wall-mounted luminaires with direct and indirect light distribution are used alongside table lamps on desks.

2.2. Circadian Lighting Design Analysis

Several metrics for quantifying the non-visual effects of light have been proposed in the literature. Rea et al. (2012) proposed a model that introduces the parameters "circadian stimulus" (CS) and "circadian lighting" (CLA) to characterize light as a stimulus to the biological clock. The circadian stimulus model is based on data that depends on studies about the impact of light on melatonin suppression. This is a scale from 0.1 to 0.7 CS which is recommended by Figueiro, Gonzales, and Pedler (2016), and Rea and Figueiro (2018). They indicate that an exposure of 0.3 or higher CS at the eye for at least one hour in early hours of the day is effective in stimulating the circadian system. Lucas et al. (2014) proposed a metric to quantify the effective irradiance for each of the five photoreceptive inputs which includes two separate measures of the light's effect on the circadian rhythm: i) WELL Building Standard unit Equivalent Melanopic Lux (EML), and ii) the melanopic Equivalent Daylight Illuminance (mEDI) proposed by The International Commission on Illumination (CIE S 026/E 2018).

The entrainment of the circadian rhythm is evaluated in accordance with the recommendations from WELL Building Standard v2 Q4 (2022). WELL recommends the following values and settings for the living environment, work and learning areas:

- The measurements will be conducted for the vertical plane in the center of the room at the eye level (h:1.2 m) facing forward to stimulate and sustain the circadian rhythm of users.
- During the daytime, 200 or more EML is required in the living environment.
- During the nighttime, 50 or less EML will be provided on the vertical plane (h: 0.76) in the living environment.
- At 75% or more of workstations, a minimum of 200 EML will be provided during 9:00–13:00 for every day of the year, which may incorporate daylight.

3. EML or above will be provided at all workstations by electrical lights

- At 75% or more of study desks, a minimum of 125 EML will be provided at least for 4 hours every day of the year, which may incorporate daylight.

In order to assess whether the requirements in the WELL Standard for the specified time intervals in the

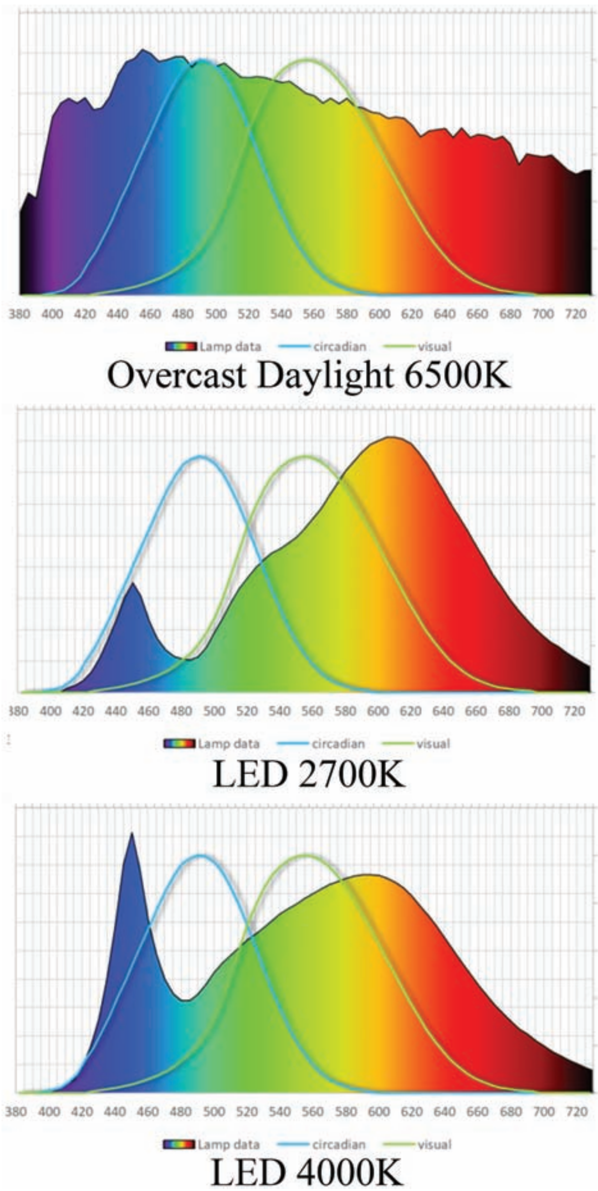


Figure 3. The relative spectral power distribution of sample sources including circadian and visual-eye response (Image source: IWBI, 2019).

day are met, lighting simulations are performed incorporating electric lighting and daylight for the morning (09:00) and the noon (13:00) hours on the the solstice days, i.e. 21st of June (CIE clear sky) and 21st of December (CIE overcast sky). EML is calculated for the rooms on the exemplar first floor with daylight access (living room, kitchen, child room, and master bedroom) according to the formula (IWBI 2022):

$$EML = LxR \tag{1}$$

where L is the simulated illuminance on the working plane and R is the melanopic ratio of the light source. This efficacy (R) is also referred to as "Melanopic to Photopic ratio" (M/P Ratio) in the WELL Building Standard. Figure 3 shows the relative spectral power distribution (SPD), the circadian stimulus, and the visual stimulus of the light sources in the toolbox of IWBI (2019). For the EML calculations, the simulated average illuminance (E_{av}) is multiplied by the M/P ratios for the 2700 K and 4000 K LED sources and daylight at 6500 K (D65) which are assumed to be 0.45, 0.76, and 1.1, respectively in line with IWBI (2019).

3.1. Annual Lighting Energy Performance Analysis

The reference building energy model was generated in the Designbuilder software and the annual energy performance simulations were run in the EnergyPlus engine in accordance with the architectural project and Building Energy Performance National Calculation Methodology (BEP-TR) results. The window-to-wall (WWR) ratio of the building is 27%. The total solar heat gain coefficient (SHGC) is 0.75 and the visible light transmittance of windows

(T_{vis}) is 0.80. The reference building's occupancy data is based on a previous survey (Manav and Kaymaz 2021) and the lighting power densities are specified according to the selected luminaires in the lighting scenario, as defined in Section 2.1. In the lighting energy analysis, occupancy-based lighting schedules, daylight-linked lighting control and the light reflectance value (LRV) of walls are evaluated. The average lighting energy use per square meter is compared with the reference buildings for the following scenarios.

3.1.1. Occupancy-based Lighting Schedule Scenarios

Lighting schedules were defined for general lighting operating hours, from 07:00 to 24:00, including weekdays and weekends. We specify these scenarios consistently with the occupancy patterns during and after the pandemic as identified in the research by IEA (2020), Krarti and Aldubyan (2021), Wang, Li, and Jiang (2021), Rouleau and Gosselin (2021), Abdeen et al. (2021), and Surahman et al. (2022) which also enables analyzing their electricity consumption implications.

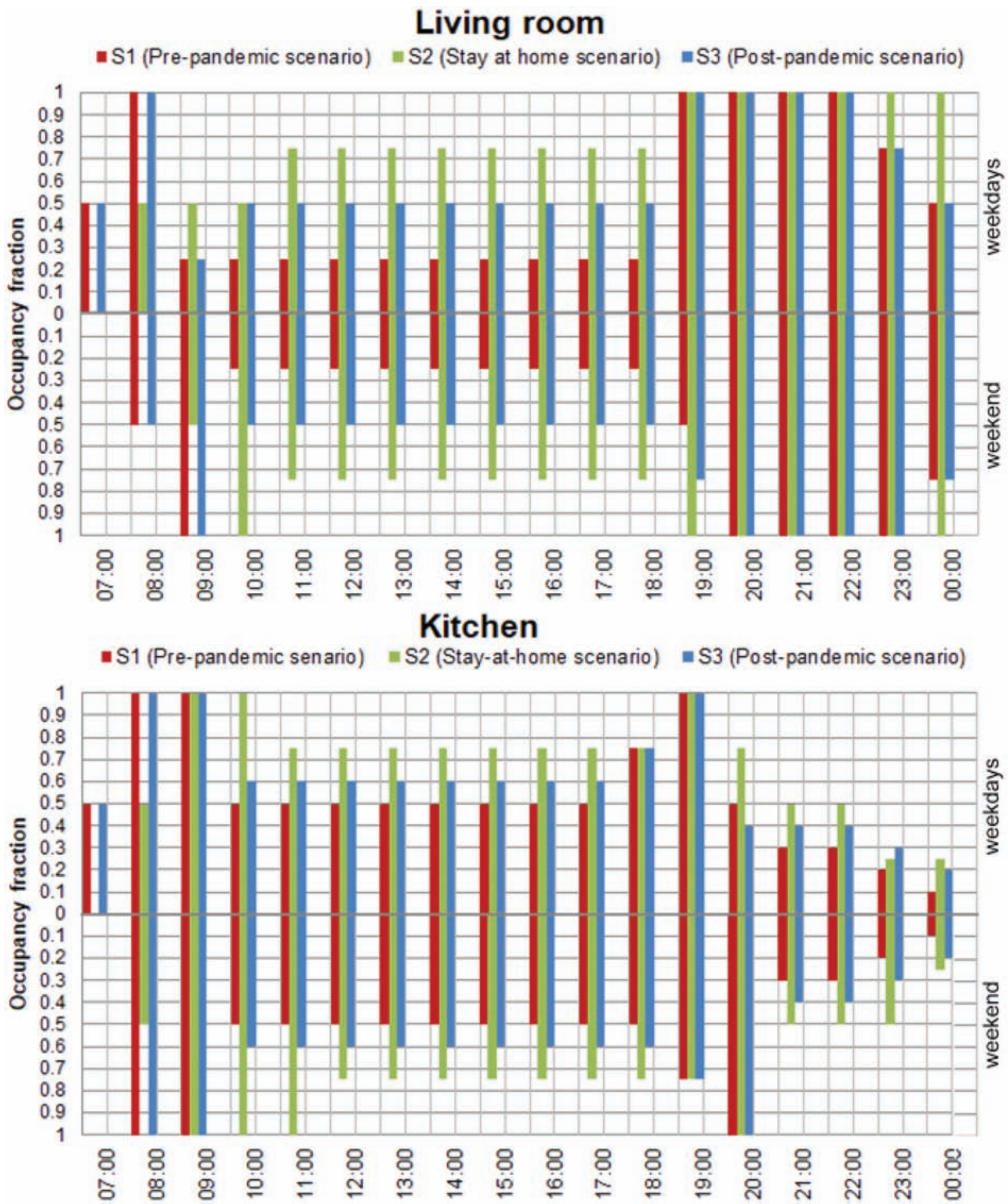


Figure 4. Lighting schedules regarding the occupancy rates before, during, and after the Covid-19 pandemic.

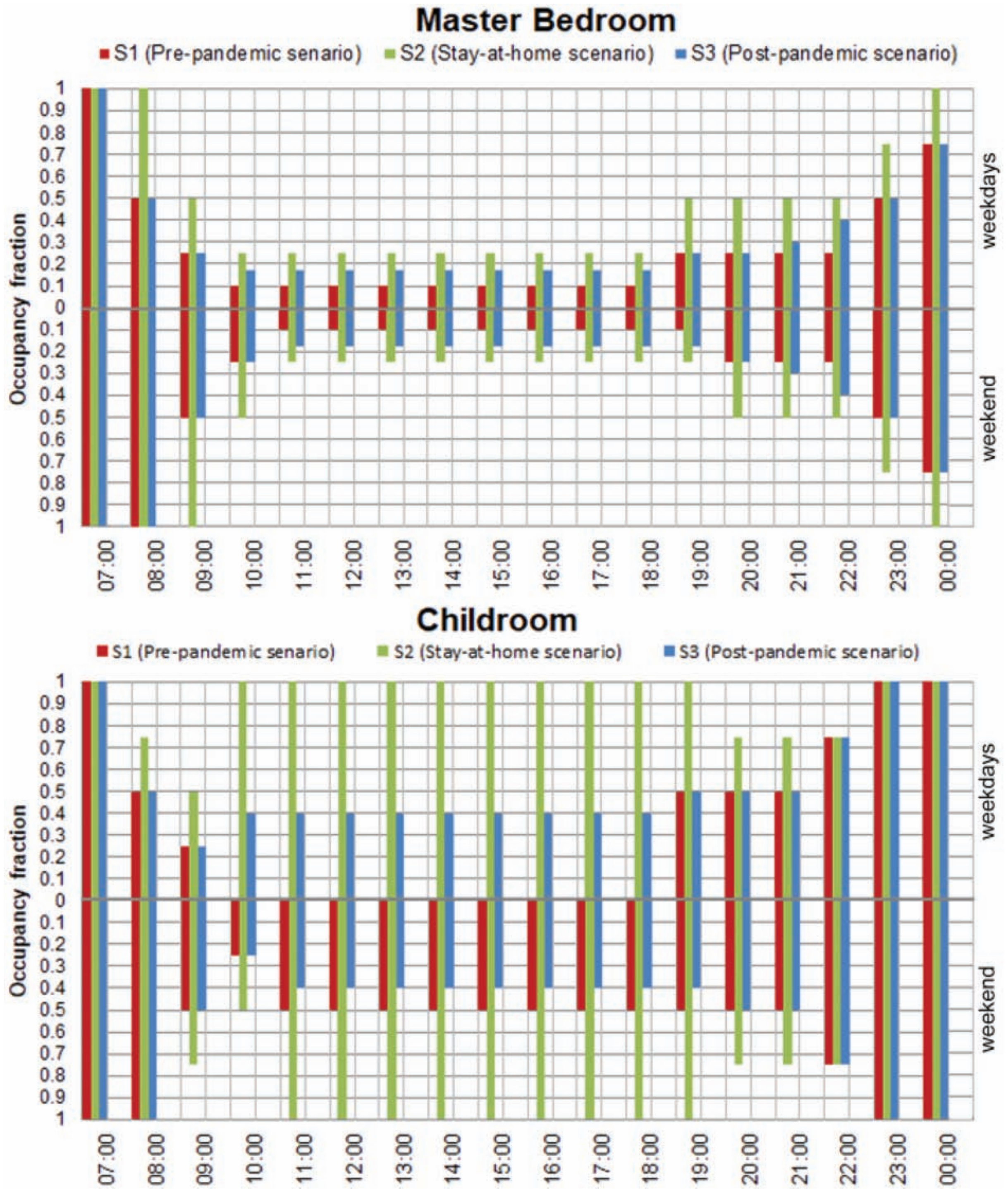


Figure 4. (Continued).

The considered lighting schedule scenarios are as follows:

- S_1 – pre-pandemic scenario: Lighting system operates mostly in the morning and during the night in line with previous survey results (Manav and Kaymaz 2021). It is assumed that each residence has at least one working member between 08:00 and 18:00.
- S_2 – stay-at-home scenario: The scenario reflects the increased use of residential space during the governmental restrictions and Covid-19 lockdown.
- S_3 – post-pandemic scenario: This scenario captures today's hybrid working conditions.

The occupancy-based lighting schedules are visualized in Figure 4, where the occupancy fraction is between 0 and 1 with zero indicating that the lights are off and one indicating they are fully on for the specified room and hour. Lighting schedules regarding the occupancy

Table 2. Daylighting simulation and EML calculation results for two reference flats located on the first floor of Block II and Block VII in DIALux Evo.

Block	Residential Space (Orientation)	Method	Working Plane	December 21st (Overcast sky)				June 21st (Clear sky)			
		Visual	Electric lights	09:00		13:00		09:00		13:00	
		EML	intensity (%)	60	100	60	100	60	100	60	100
Block II	Living room (SE)	E_{av} (lx)	General lighting	177	279	270	372	829	930	479	581
			Task lighting	293	551	353	571	464	682	416	634
		M/P:1.1 6500K	Living env.	162	268	275	364	1084	1176	733	840
			Work area	229	380	241	392	307	458	278	430
	Kitchen (SE)	E_{av} (lx)	General lighting	231	364	341	475	676	809	588	722
			Task lighting	407	608	793	994	1427	1628	1544	1745
		M/P:1.1 6500K	Living env.	161	249	264	352	1041	1129	650	738
			Work area	309	479	507	677	1529	1700	1063	1233
	Master bedroom (NE)	E_{av} (lx)	General lighting	118	185	179	246	346	413	213	281
			Task lighting	744	1230	800	1286	1119	1605	867	1353
		M/P:1.1 6500K	Living env.	69	111	101	142	184	226	132	173
			Learning area	216	323	237	344	357	464	268	375
	Child room (NW)	E_{av} (lx)	General lighting	147	228	245	325	276	356	304	384
			Task lighting	502	821	582	902	620	939	650	969
		M/P:1.1 6500K	Living env.	68	109	95	136	128	168	132	173
			Learning area	212	314	241	344	273	376	280	382
Block VII	Living room (N)	E_{av} (lx)	General lighting	179	282	272	374	330	432	321	424
			Task lighting	339	561	359	582	390	633	385	607
		M/P:1.1 6500K	Living env.	160	264	182	286	215	319	224	351
			Work area	233	384	257	407	312	462	310	460
	Kitchen (N)	E_{av} (lx)	General lighting	225	355	331	462	414	544	378	509
			Task lighting	407	608	791	992	1002	1204	879	1081
		M/P:1.1 6500K	Living env.	149	248	161	268	173	271	177	284
			Work area	266	434	299	547	365	534	342	511
	Master bedroom (W)	E_{av} (lx)	General lighting	135	202	259	326	292	360	370	437
			Task lighting	740	1226	779	1265	787	1273	803	1289
		M/P:1.1 6500K	Living env.	58	90	88	121	127	161	139	173
			Learning area	225	333	286	392	294	401	326	422
	Child room (S)	E_{av} (lx)	General lighting	148	228	245	326	319	399	533	614
			Task lighting	501	821	582	901	790	1110	831	1150
		M/P:1.1 6500K	Living env.	63	103	77	118	99	139	156	196
			Learning area	224	327	300	403	519	621	686	789

rates before, during, and after the Covid-19 pandemic. (Continued).

3.1.2. Daylight-linked Lighting Control Scenarios

Daylight availability and lighting control strategy are other major factors that affect lighting energy consumption in buildings. In the study, we consider four lighting control strategies to test the extent and efficacy of lighting energy savings.

C_1 scenario: Lights are fully-on due to user presence in a zone.

C_2 scenario: Lighting system is controlled by manual switching through according to the lighting schedule. Lamps are switched off when the target general lighting level, i.e., 150 lx in the living room, 300 lx in the kitchen, 100 lx in the bedrooms is achieved on the horizontal working plane by daylight only.

C_3 scenario: In the stepped lighting control strategy, the general lighting level can be dimmed by four steps, and finally switched on/off in response to daylight availability by a photo-sensor installed in the center of the room.

C_4 scenario: In the linear lighting control strategy, the light level can be dimmed continuously and linearly from maximum electric power to minimum light output as daylight penetration increases. The LEDs are switched off completely when the necessary set point is guaranteed by daylight.

4. Results and Discussion

4.1. Interior Lighting Simulation and EML Calculation Results

The lighting scenarios with two different dimming levels (electric light intensity: 100% and 60%) and three colour temperature values (CCT: 2700 K, 4000 K, 6500 K) are evaluated with respect to the recommended indoor visual and non-visual lighting requirements. The simulation results for the photopic and melanopic light intensity levels in the living, work, and learning areas are presented in Table 2 under different daylight scenarios (09:00 and 13:00 on the two solstice days at 6500 K). Due to the extended and shifting working hours with the Covid-19 pandemic, simulations were iterated including the night-time scenario. The simulation results for the indoor visual and circadian lighting requirements at night

Table 3. Electric lighting simulation and EML calculation results for the reference flat.

Dim Scenario	Residential Space	Indoor Visual Requirements (DIALux Simulation Results)				Circadian Lighting Requirements (EML Calculation Results)			
		Horizontal Plane	E_{av} (lx)	U_o	UGR	Vertical Plane	2700 K M/P:0.45	4000 K M/P:0.76	6500 K M/P:1.1
Electric lights intensity 100%	Living room	General lighting	253	0.40	23.2	Living env.	83	140	203
		Task lighting	545	0.71	19.2	Work area	154	261	377
	Kitchen	General lighting	334	0.47	11.2	Living env.	78	131	190
		Task lighting	503	0.61	<10	Work area	174	293	425
	Master Bedroom	General lighting	169	0.65	22.9	Living env.	32	54	78
		Task lighting	1215	0.21	24	Learning a.	139	235	340
	Child room	General lighting	201	0.49	22.8	Living env.	37	63	91
		Task lighting	799	0.24	22.6	Learning a.	125	211	306
Electric lights intensity 60%	Living room	General lighting	152	0.41	21.4	Living env.	49	84	120
		Task lighting	327	0.72	17.4	Work area	93	157	227
	Kitchen	General lighting	200	0.48	<10	Living env.	47	79	114
		Task lighting	302	0.61	<10	Work area	104	176	255
	Master Bedroom	General lighting	101	0.65	21.2	Living env.	19	33	47
		Task lighting	729	0.21	22.9	Learning a.	77	130	188
	Child room	General lighting	121	0.49	21	Living env.	23	38	55
		Task lighting	480	0.24	20.8	Learning a.	83	140	203

are given in Table 3. The electric lighting system is assumed to be the same for the two reference residential units with equivalent interior and architectural features.

The static simulation results in DIALux Evo are demonstrated by colour-coding where yellow indicates that the results meet the minimum threshold values, while red/green cells represent the values below/above the threshold. For UGR results, the inverse of the colour scale is applied.

Considering the recommended light level on the task area (EN 12464–1, 2011; IESNA, 2011; CIBSE, 2012), the required minimum average illuminance (E_{av}) of 150 lx is maintained for the living room (152 lx under 60%); 100 lx is satisfied for the master bedroom (101 lx under 60%) and child room (121 lx under 60%), and 300 lx is achieved for the possible workstations such as the dining table (327 lx under 60%) in the kitchen and the living room (302 lx under 60%), and study desk in the child room (480 lx under 60%) for both electric lights intensity scenarios (Table 3). When the luminaries in the kitchen are dimmed by 60% intensity, 300 lx general lighting on the horizontal working plane is not met by electric lighting (200 lx under 60%). However, the horizontal illuminance requirement is met with the influence of daylight except at 09:00 on the winter solstice (231 lx for SE and 225 lx for N under 60% in Table 2).

The illuminance uniformity (U_o) shall be greater than 0.40 for general lighting and 0.60 for task lighting for working areas (European Standard EN 12464–1 2011). According to the electric lighting simulation results in Table 3, 0.40 is satisfied in all zones; however, 0.60 is not achieved on the task plane of the bedrooms. The results for electric lights at 100% intensity also show that the viewing positions from the bedrooms exceed the UGR limit and causes uncomfortable glare, which should also be considered for the calculation points in the living room. On the other hand, the calculations of UGR measured at 60% intensity indicate that most working planes are below the recommended maximum 19 UGR for general lighting and 22 UGR for task lighting.

The EML calculations in Table 3 demonstrate how the residential lighting system would perform if all LED lighting fixtures were installed with flexibility where CCT can be adjusted between 2700 K and 6500 K together by dimming up and down the electric light intensity. When melanopic light intensity in the living environment of each zone is evaluated, the results in Table 3 show that the minimum requirement of 200 EML on the vertical plane at the eye level of the occupant can rarely be achieved by only electric lights (203 EML in the living room and 190 EML in the kitchen at 6500 K under 100%). Similarly, the same non-visual requirement cannot be satisfied in any of the calculation areas on December 21st at 09:00 due to the lack of sunlight penetration in Table 2. Despite the influence of diffused daylight on winter solstice and direct daylight on summer solstice, the vertical illuminance is not sufficient for any of the bedrooms in. On the other hand, 200 EML is exceeded in some of the living environments on December 21st when luminaires are tuned to 6500 K CCT at 100% intensity (268 EML and 249 EML for the SE facing rooms in Block II; 264 EML and 248 EML for the N facing rooms in Block VII in Table 3).

During the nighttime, the melanopic light intensity is above the maximum threshold of 50 EML in most of the residential areas at 100% intensity; yet, this target can be achieved by setting luminaires to lower CCT and/or dimming the light sources after 20:00 (2700 K and 60% intensity scenario in Table 3), as suggested in WELL Building standard (IWBI 2022).

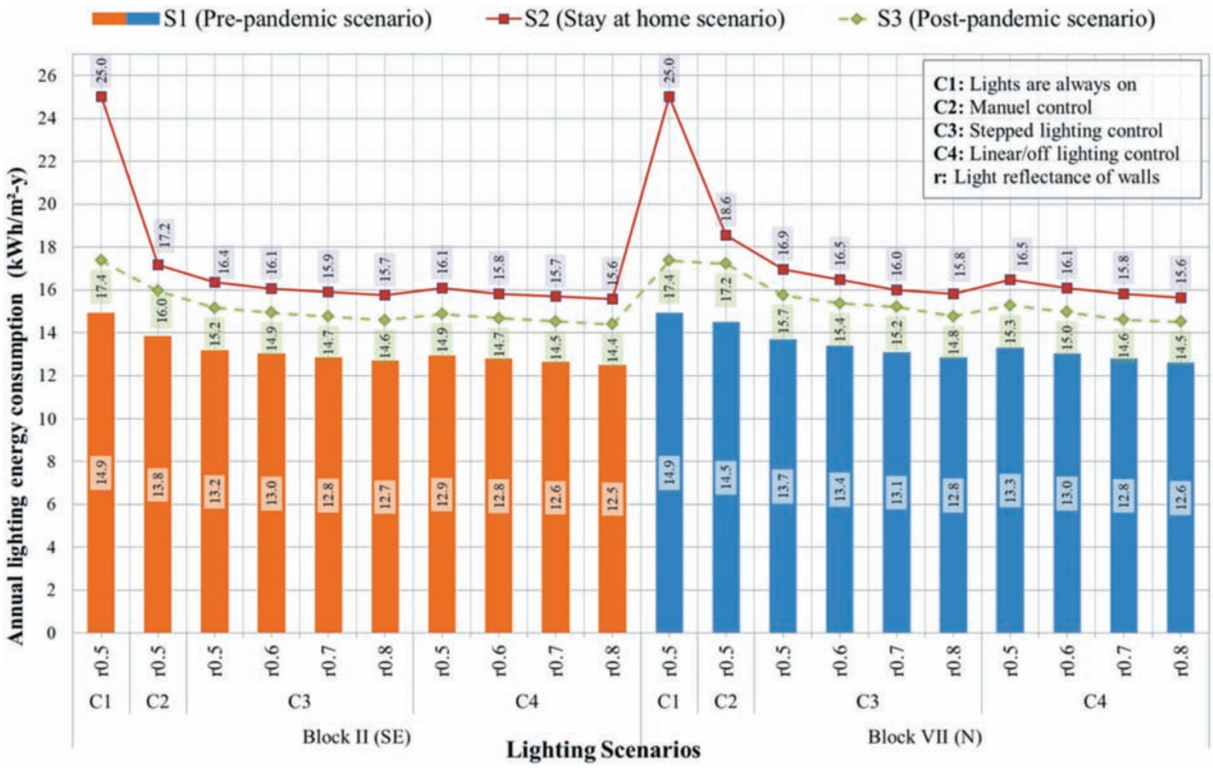


Figure 5. Annual lighting energy consumption of Block II and Block VII for the proposed scenarios.

Finally, in the context of home-office hybrid working, eye-level vertical illuminance is evaluated as the critical parameter in stimulating the circadian system. The minimum circadian lighting design target of 200 EML is achieved for all the work areas either by incorporating daylight (Table 2) or by changing the M/P ratio from 0.45 to 1.1 at 100% electric light intensity (Table 3). Table 2 represents that a minimum of 125 EML is achieved for at least 4 hours per day (between 9:00 and 13:00) on solstice days for the designated learning areas. However, as seen in Table 3, these task areas do not meet the minimum melanopic requirements on the vertical plane at 60% electric light intensity with luminaires of 2700 K CCT.

Since there is no direct correspondence between horizontal illuminance and vertical illuminance, the light level on the horizontal plane has to be increased significantly to also achieve sufficient EML that complies with the minimum melanopic requirements. Dubois et al. (2015) also pointed out the potential impact of vertical illumination suggesting that lower horizontal lighting levels can be more easily tolerated when vertical surfaces are well-lit. On the other hand, increasing the luminous flux should not cause overly high light levels, glare formation and excessive energy consumption, as discussed in the findings of the review by Alkhatatbeh and Asadi (2021). Since it is a complex task, an integrated approach (both daylight and artificial light with dynamic and tunable features) should be followed to satisfy the visual and non-visual requirements in residential spaces.

4.2. Annual Lighting Energy Simulation Results

The proposed residential lighting design is assessed for three different lighting schedules, four different control strategies, and four wall LRV options as defined in Section 2.3. The lighting energy results under the different scenarios are presented for Block II and Block VII in Figure 5.

Due to the increase in the occupancy rate, hence in the daily use of light sources during the Covid-19 pandemic, the annual lighting energy consumption in the stay-at-home scenario (S_2) is the highest in all cases. The pre-pandemic (S_1) to stay-at-home (S_2) percentage increase in lighting energy consumption varies between 24.1% and 67.5% across different cases, depending on building orientation, user behaviour, and lighting control preferences. The increase in lighting energy consumption is in accordance with the findings of Krarti and Aldubyan (2021) and Surahman et al. (2022) that increased electricity demand occurred in domestic households during lockdowns.

The use of electric lighting control systems is effective for energy efficiency through reducing the operating time of the lighting system. When general lighting level is modulated by photo-sensors, a percentage improvement of 4.7–5 and 5.6–8.7 is achieved by stepped-dimming control strategy (C_3), when compared to manual control (C_2) for Block II and Block VII, respectively. Likewise, linear off dimming control (C_4) decreases lighting energy consumption by 6.3–6.8% for Block II and by 8.4–11.3% for Block VII in comparison to the C_2 (manual on/off) scenario. Depending on the lighting schedule, the annual lighting energy consumption in Block VII (N facing living space) is 4.8–8.1% higher than in Block II (SE facing living space). This building orientation-based lighting energy difference decreases with the use of lighting control.

As Frascarolo, Martorelli, and Vital (2014) pointed out in their work, it is important to consider the need for manual control by integrating customizable lighting solutions for user-managed workstations. On the other hand, constant use of artificial lighting may result in higher energy consumption through the over-use of electric lighting and also in discomfort glare during the day. The simulation outcomes reveal substantial differences in energy loads between scenarios where the lights are controlled by photo-sensors and no user is involved (C3, C4) and the scenario where the lights are manually controlled in the fully-on mode (C1). For instance, linear off dimming control in the stay-at-home scenario (C_3-S_2) leads to electric savings up to 35.7% compared to the C_1-S_2 scenario. A similar conclusion was reached in the literature review by Dubois and Blomsterberg (2011) and Chew et al. (2017) that more than 40% energy savings can be achieved by using daylight-linked control systems depending on building orientation, window characteristics, reflectance of interior surfaces and shading factor.

Our findings also support the earlier results by Singh and Rawal (2011), Mohelnikova and Hirs (2016), Mangkuto, Rohmah, and Asri (2016) that changing the LRV of surface colours influences the lighting energy consumption without altering the number of light sources. Depending on the occupancy scenario, the annual lighting energy is decreased by 3.3–3.8% in Block II and 5.1–6.8% in Block VII via changing the LRV from ρ_{wall} = 0.5 to ρ_{wall} = 0.8.

5. Conclusion

The study proposes a residential lighting design that focuses on indoor visual requirements and lighting energy performance, while stressing the significance of lighting on circadian system. The impacts of several lighting design parameters are assessed through a simulation case study. The interior lighting simulations show that a relatively high melanopic illuminance and/or M/P ratio of sources are necessary to achieve the EML targets without daylight or under overcast sky conditions in winter months, which is key to stimulating and sustaining the circadian rhythm of occupants working and studying in residential spaces. However, increasing the vertical light intensity also increases the illuminance distribution on the horizontal plane, which causes glare and should be avoided according to European Standard EN 12464–1 (2011). Additionally, changing the M/P ratio with a higher (or lower) CCT influences the space perception, which is effective on the physiology and psychology of occupants. The horizontal illuminance needs to exceed 500 lx in order to reach the recommended targets of 150 EML and 125 EML for work and learning areas, respectively by electric light. However, this requires greater lighting power installation and energy consumption. On the other hand, the values recommended in the WELL building standard can be met across all cases when the daylight is included. Thus, interior lighting design should support the flexibility for the task planes with dimmable and tunable lighting features and a balance of melanopic and photopic illuminance should be achieved for workplaces by incorporating daylight in the lighting design.

Although the annual lighting energy consumptions are higher than the levels before the pandemic, the building energy simulations show that integrating dynamic LED systems with daylight-linked lighting control strategies and walls with higher LRV can improve lighting energy performance by up to 38%. Therefore, we propose lighting solutions that are robust against the changes in living, working, and learning habits expected to be sustained even after the pandemic.

The presented work is part of an ongoing research project investigating user comfort and residential lighting design requirements considering today's living and working conditions underlying the significance of occupancy patterns. From this standpoint, we believe that circadian lighting is a key component of the holistic lighting design approach. Future studies could further explore this scientific field by comparing the results based on computer simulations with on-site measurements. We want to apply our lighting setup in practice with dynamic LED lighting systems. To determine optimal lighting design solutions for user requirements, further post-occupancy investigations are also needed. Since energy efficiency in lighting is the main focus parameter, the association between circadian lighting design and daylight availability will also be addressed by annual climate-based daylight metrics in future research.

Disclosure statement

No potential conflict of interest was reported by the author (s).

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Notes on contributors

Egemen Kaymaz completed her B.Arch in 2009 and received M.Sc. Degree in Environmental Control and Building Technology in 2012 at Istanbul Technical University. As a Ph.D. candidate in Bursa Uludag University, her research

explores design support models, visual comfort, lighting energy performance, and optimization of buildings.

Banu Manav is an Interior Architect, with a Ph.D. in architecture/building science. Prof. Dr. Manav is currently the Dean of the Faculty of Art and Design, Kadir Has University, Turkey. She is the delegate of Turkey for (CIE) Division 6 (Photobiology and Photochemistry), a member of AIC Study Group on Environmental Colour Design, and the General Secretary of Turkish National Committee on Illumination. Her research areas include artificial lighting system design, space perception- color-light, light-health, lighting quality, and user comfort-design parameters.

ORCID

Egemen Kaymaz http://orcid.org/0000-0002-9435-8411
Banu Manav http://orcid.org/0000-0002-0709-5570

Author contributions

Conceptualization and methodology B. M.; investigation and computer simulations E.K.; writing and editing E.K. & B.M.

References

Abdeen, A., F. Kharvari, W. O'Brien, and B. Gunay. 2021. "The Impact of the COVID-19 on Households' Hourly Electricity Consumption in Canada." *Energy and Buildings* 250: 111280. doi:10.1016/j.enbuild.2021.111280.

Aguilar-Carrasco, M. T., S. Domínguez-Amarillo, I. Acosta, and J. J. Sendra. 2021. "Indoor Lighting Design for Healthier Workplaces: Natural and Electric Light Assessment for Suitable Circadian Stimulus." *Optics Express* 29 (19): 29899–29917. doi:10.1364/OE.430747.

Al Enezi, J., V. Revell, T. Brown, J. Wynne, L. Schlangen, and R. Lucas. 2011. "A "Melanopic" Spectral Efficiency Function Predicts the Sensitivity of Melanopsin Photoreceptors to Polychromatic Lights." *Journal of Biological Rhythms* 26 (4): 314–323. doi:10.1177/0748730411409719.

Alkhatatbeh, B. J., and S. Asadi. 2021. "Role of Architectural Design in Creating Circadian Effective Interior Settings." *Energies* 14 (20): 6731. doi:10.3390/en14206731.

Aman, M. M., G. B. Jasmon, H. Mokhlis, and A. H. A. Bakar. 2013. "Analysis of the Performance of Domestic Lighting Lamps." *Energy Policy* 52: 482–500. doi:10.1016/j.enpol.2012.09.068.

Arendt, J. 2010. "Shift Work: Coping with the Biological Clock." *Occupational Medicine* 60 (1): 10–20. doi:10.1093/occmed/kqp162.

Attia, S., M. Hamdy, and S. Ezzeldin. 2017. "Twenty-year Tracking of Lighting Savings and Power Density in the Residential Sector." *Energy and Buildings* 154: 113–126. doi:10.1016/j.enbuild.2017.08.041.

Awada, M., B. Becerik-Gerber, S. Hoque, Z. O'neill, G. Pedrielli, J. Wen, and T. Wu. 2021. "Ten Questions Concerning Occupant Health in Buildings during Normal Operations and Extreme Events Including the COVID-19 Pandemic." *Building and Environment* 188: 1–11. doi:10.1016/j.buildenv.2020.107480.

Baloch, A. A., P. H. Shaikh, F. Shaikh, Z. H. Leghari, N. H. Mirjat, and M. A. Uqaili. 2018. "Simulation Tools Application for Artificial Lighting in Buildings." *Renewable and Sustainable Energy Reviews* 82 (3): 3007–3026. doi:10.1016/j.rser.2017.10.035.

BEP. 2008. "*Building Energy Performance Regulation*. Ankara: Turkish Republic Ministry of Public Works and Settlements." *Turkish Official Gazette* 27075. https://www.resmigazete.gov.tr/eskiler/2008/12/20081205-9.htm

BEP-TR. 2010. "*Building Energy Performance National Calculation Method*. Ankara: Turkish Republic Ministry of Public Works and Settlements." *Turkish Official Gazette* 27778. https://beptr.csb.gov.tr/

Blume, C., C. Garbazza, and M. Spitschan. 2019. "Effects of Light on Human Circadian Rhythms, Sleep and Mood." *Somnologie* 23 (3): 147–156. doi:10.1007/s11818-019-00215-x.

Boubekri, M. 2014. *Daylighting Design: Planning Strategies and Best Practice Solutions*. Basel: Birkhäuser.

Bourgeois, D., C. Reinhart, and I. Macdonald. 2006. "Adding Advanced Behavioural Models in Whole Building Energy Simulation: A Study on the Total Energy Impact of Manual and Automated Lighting Control." *Energy and Buildings* 38 (7): 814–823. doi:10.1016/j.enbuild.2006.03.002.

Brown, T. M., G. C. Brainard, C. Cajochen, C. A. Czeisler, J. P. Hanifin, S. W. Lockley, R. J. Lucas, et al. 2022. "Recommendations for Daytime, Evening, and Nighttime Indoor Light Exposure to Best Support Physiology, Sleep, and Wakefulness in Healthy Adults." *PLoS Biology* 20 (3): e3001571. DOI:10.1371/journal.pbio.3001571.

Chew, I., D. Karunatilaka, C. P. Tan, and V. Kalavally. 2017. "Smart Lighting: The Way Forward? Reviewing the past to Shape the Future." *Energy and Buildings* 149: 180–191. doi:10.1016/j.enbuild.2017.04.083.

CIE S 026/E. 2018. *CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light Commission*. Vienna, Austria: CIE (Commission Internationale de l'Eclairage). doi:10.25039/S026.2018.

Dai, Q., W. Cai, L. Hao, W. Shi, and Z. Wang. 2018b. "Spectral Optimization and a Novel Lighting design Space Based on Circadian Stimulus." *Lighting Research & Technology* 50 (8): 1198–1211. doi:10.1177/1477153517733504.

Dai, Q., W. Cai, W. Shi, L. Hao, and M. Wei. 2017. "A Proposed lighting-design Space: Circadian Effect versus Visual Illuminance." *Building and Environment* 122: 287–293. doi:10.1016/j.buildenv.2017.06.025.

Dai, Q., Y. Huang, L. Hao, Y. Lin, and K. Chen. 2018a. "Spatial and Spectral Illumination Design for energy-efficient Circadian Lighting." *Building and Environment* 146: 216–225. doi:10.1016/j.buildenv.2018.10.004.

Das, A., and S. K. Paul. 2015. "Artificial Illumination during Daytime in Residential Buildings: Factors, Energy Implications and Future Predictions." *Applied Energy* 158: 65–85. doi:10.1016/j.apenergy.2015.08.006.

Do, M. T. H., and K.-W. Yau. 2010. "Intrinsically Photosensitive Retinal Ganglion Cells." *Physiological Reviews* 90 (4): 1547–1581. doi:10.1152/physrev.00013.2010.

Dubois, M. -C., F. Bisegna, N. Gentile, M. Knoop, B. Matusiak, W. Osterhaus, and E. Tetri. 2015. "Retrofitting the Electric Lighting and Daylighting Systems to Reduce Energy Use in Buildings: A Literature Review." *Energy Research Journal* 6 (1): 25–41.

Dubois, M.-C., and Å. Blomsterberg. 2011. "Energy Saving Potential and Strategies for Electric Lighting in Future North European, Low Energy Office Buildings: A Literature Review." *Energy and Buildings* 43 (10): 2572–2582. doi:10.1016/j.enbuild.2011.07.001.

Duff, J., K. Kelly, and C. Cuttle. 2015. "Perceived Adequacy of Illumination, Spatial Brightness, Horizontal Illuminance and Mean Room Surface Exitance in a Small Office." *Lighting Research Technology* 49 (2): 1–14. https://doi.org/10.1177/147715351559918

EEA European Environmental Agency. 2014. "Final Household Electricity Consumption by Use". Accessed 12 September 2022 http://www.eea.europa.eu/data-and-maps/daviz/final-household-electricity-consumption-by-use#tab-used-indicators

EPDK 2022. "*Electricity Market Sector Report 2022*." Ankara: Republic of Turkey Energy Market Regulatory Authority, Strategy Development Department. Accessed 21 April 2022. https://www.epdk.gov.tr/Detay/Icerik/1-1271/electricityreports

European Standard EN 12464-1. 2011. "Lighting of Work Places - Part 1: Indoor Work Places." European Committee for Standardization.

Farrow, H. 2020. "Commercial down Vs Residential Up: COVID-19's Electricity Impact." *Energy Insider* 1–23. 18 April 2022. https://www.energynetworks.com.au/news/energy-insider/2020-energy-insider/commercial-down-v-residential-up-covid-19s-electricity-impact/

Figueiro, M. G., K. Gonzales, and D. Pedler. 2016. "Designing with Circadian Stimulus: The Lighting Research Center Proposes a Metric for Applying Circadian Light in the Built Environment." *Lighting Research Center*. Accessed 6 February 2022 http://www.lrc.rpi.edu/resources/CircadianStimulusCalculator_30Apr2016.xlsx

Figueiro, M. G., L. Sahin, B. Wood, and B. Plitnick. 2016. "Light at Night and Measures of Alertness and Performance: Implications for Shift Workers." *Biological Research for Nursing* 18 (1): 90–100. doi:10.1177/1099800415572873.

Frascarolo, M., S. Martorelli, and V. Vital. 2014. "An Innovative Lighting System for Residential Application that Optimizes Visual Comfort and Conserves Energy for Different User Needs." *Energy and Buildings* 83: 217–224. doi:10.1016/j.enbuild.2014.03.072.

Gerhardsson, K. M., T. Laike, and M. Johansson. 2021. "Leaving Lights on – A Conscious Choice or Wasted Light? Use of Indoor Lighting in Swedish Homes." *Indoor and Built Environment* 30 (6): 745–762. doi:10.1177/1420326X20908644.

Guide F, C. I. B. S. E. 2012. *Energy Efficiency in Buildings*. 3rd ed. London: Chartered Institution of Building Services Engineers.

Hinson, S. 2020. "COVID-19 Is Changing Residential Electricity Demand." *Renewable Energy World* 1–15. 18 April 2022. https://www.renewableenergyworld.com/storage/covid-19-is-changing-residential-electricity-demand/

IEA International Energy Agency. 2020. "COVID-19 Impact on Electricity." Accessed 10 September 2022 https://www.iea.org/reports/covid-19-impact-on-electricity

IESNA Illuminating Engineering Society of North America. 2008. *Light + Design: A Guide to Designing Quality Lighting for People and Buildings*, IES-DG-18-08. New York: Illuminating Engineering 0879952318.

IESNA Illuminating Engineering Society of North America. 2011. "The Lighting Handbook Reference and Application." 10thed. edited by D. L. DiLaura, K. W. Houser, R. G. Mistrick, and G. R. Steffy. New York: Illuminating Engineering 0879952415.

IWBI International Well Building Institute. 2019. "EML Toolbox." Accessed 3 December 2021. https://standard.wellcertified.com/tables#melanopicRatio

IWBI International Well Building Institute. 2022. "WELL Building Standard v2 Q4 2022 Version. Section L03: Circadian Lighting Design." Accessed 2 January 2022. https://v2.wellcertified.com/v/en/light/feature/3

Jarboe, C., J. Snyder, and M. G. Figueiro. 2020. "The Effectiveness of light-emitting Diode Lighting for Providing Circadian Stimulus in Office Spaces while Minimizing Energy Use." *Lighting Research and Technology* 52 (2): 167–188. doi:10.1177/1477153519834604.

Krarti, M., and M. Aldubyan. 2021. "Review Analysis of COVID-19 Impact on Electricity Demand for Residential Buildings." *Renewable and Sustainable Energy Reviews* 143: 110888. doi:10.1016/j.rser.2021.110888.

Lucas, R., S. Peirson, D. Berson, T. Brown, H. Cooper, C. Czeisler, M. Figueiro, et al. 2014. "Measuring and Using Light in the Melanopsin Age." *Trends in Neurosciences* 37 (1): 1–9. doi:10.1016/j.tins.2013.10.004.

Lumsearch 2022. "DIAL GmbH Lighting Products Database." Accessed 8 February 2022. https://lumsearch.com/en#0

Makaremi, N., S. Schiavoni, A. L. Piselloa, F. Asdrubalic, and F. Cotana. 2017. "Quantifying the Effects of Interior Surface Reflectance on Indoor Lighting." *Energy Procedia* 134: 306–316. doi:10.1016/j.egypro.2017.09.531.

Makaremi, N., S. Schiavoni, A. L. Pisello, and F. Cotana. 2019. "Effects of Surface Reflectance and Lighting Design Strategies on Energy Consumption and Visual Comfort." *Indoor and Built Environment* 28 (4): 552–563. doi:10.1177/1420326X18793170.

Manav, B., and E. Kaymaz. 2021. "Analyses on Occupant Patterns and Energy Consumption in Residential Buildings Including the Covid-19 Pandemic." *Proceedings of the Conference CIE 2021* 27–29 September 2021. CIE. Kuala Lumpur, Malaysia, 2021. doi:10.25039/x48.2021.

Mangkuto, R. A., M. Rohmah, and A. D. Asri. 2016. "Design Optimisation for Window Size, Orientation, and Wall Reflectance with Regard to Various Daylight Metrics and Lighting Energy Demand: A Case Study of Buildings in the Tropics." *Applied Energy* 164: 211–219. doi:10.1016/j.apenergy.2015.11.046.

Mardaljevic, J., L. L. Heschong, and E. S. Lee. 2009. "Daylight Metrics and Energy Savings." *Lighting Research and Technology* 41 (3): 261–283. doi:10.1177/1477153509339703.

Mohelnikova, J., and J. Hirs. 2016. "Effect of Externally and Internally Reflective Components on Interior Daylighting." *Journal of Building Engineering* 7: 31–37. doi:10.1016/j.jobe.2016.04.009.

Rea, M., and M. Figueiro. 2018. "Light as a Circadian Stimulus for Architectural Lighting." *Lighting Research & Technology* 50 (4): 497–510. doi:10.1177/1477153516682368.

Rea, M., M. Figueiro, A. Bierman, and R. Hamner. 2012. "Modelling the Spectral Sensitivity of the Human Circadian System." *Lighting Research & Technology* 44 (4): 86–396. doi:10.1177/1477153511430474.

Rouleau, J., and L. Gosselin. 2021. "Impacts of the COVID-19 Lockdown on Energy Consumption in a Canadian Social Housing Building." *Appl. Energy* 287: 116565. doi:10.1016/j.apenergy.2021.116565.

Sahin, L., and M. G. Figueiro. 2021. "A 24-hour Lighting Scheme to Promote Alertness and Circadian Entrainment in Railroad Dispatchers on Rotating Shifts: A Field Study." *Lighting Research & Technology* 54 (5): 441–457. doi:10.1177/14771535211040985.

Singh, M. C., and S. N. Garg. 2010. "Illuminance Estimation and Daylighting Energy Savings for Indian Regions." *Renewable Energy* 35 (3): 703–711. doi:10.1016/j.renene.2009.08.023.

Singh, R., and R. Rawal. 2011. "Effect of Surface Reflectance on Lighting Efficiency in Interiors." *12th Conference of International Building Performance Simulation Association*, 2301–2308. Sydney, Australia.

So, A. T. P., and L. M. Leung. 1998. "Indoor Lighting Design Incorporating Human Psychology." *Architectural Science*

Review 41 (3): 113–124. doi:10.1080/00038628.1998.9697420.

Stephen, S., and D. Coley. 2011. "The Relationship between Wall Reflectance and Daylight Factor in Real Rooms." *Architectural Science Review* 54 (4): 329–334. doi:10.1080/00038628.2011.613642.

Surahman, U., D. Hartono, E. Setyowati, and A. Jurizat. 2022. "Investigation on Household Energy Consumption of Urban Residential Buildings in Major Cities of Indonesia during COVID-19 Pandemic." *Energy and Buildings* 261: 111956. doi:10.1016/j.enbuild.2022.111956.

Van Thillo, L., S. Verbeke, and A. Audenaert. 2022. "The Potential of Building Automation and Control Systems to Lower the Energy Demand in Residential Buildings: A Review of Their Performance and Influencing Parameters." *Renewable and Sustainable Energy Reviews* 158: 112099. doi:10.1016/j.rser.2022.112099.

Viola, A. U., L. M. James, L. J. M. Schlangen, and D. J. Dijk. 2008. "Blue-enriched White Light in the Workplace Improves self-reported Alertness, Performance and Sleep Quality." *Scandinavian Journal of Work, Environment and Health* 34 (4): 297–306. doi:10.5271/sjweh.1268.

Wang, Q., S. Li, and F. Jiang. 2021. "Uncovering the Impact of the COVID-19 Pandemic on Energy Consumption: New Insight from Difference between pandemic-free Scenario and Actual Electricity Consumption in China." *Journal of Cleaner Production* 313: 127897. doi:10.1016/j.jclepro.2021.127897.

Yu, X., and Y. Su. 2015. "Daylight Availability Assessment and Its Potential Energy Saving estimation–A Literature Review." *Renewable and Sustainable Energy Reviews* 52: 494–503. doi:10.1016/j.rser.2015.07.142.

Zhang, Y., X. Bai, F. P. Mills, and J. C. V. Pezzey. 2018. "Rethinking the Role of Occupant Behaviour in Building Energy Performance: A Review." *Energy and Buildings* 172: 279–294. doi:10.1016/j.enbuild.2018.05.017.

Zhen, M., Y. Du, F. Hong, and G. Bian. 2019. "Simulation Analysis of Natural Lighting of Residential Buildings in Xi'an, China." *Science of the Total Environment* 690: 197–208. doi:10.1016/j.scitotenv.2019.06.353.