Sust. Build. **6**, 6 (2023)

https://doi.org/10.1051/sbuild/2023007

Sustainable Buildings

Available online at:
www.sustainable-buildings-journal.org

Review Article

Open Access

Introducing luminescent solar waveguides for sustainable buildings for enhanced circadian rhythm regulation

Wai Qian Tham[1,*], Subhash Chandra[1], Brian Norton[2], and Sarah McCormack[1]

[1] Department of Civil, Structural and Environmental Engineering, School of Engineering. Museum Building, Trinity College Dublin, The University of Dublin, Dublin, Ireland
[2] Tyndall National Institute, Lee Maltings, Cork, Ireland

Received: 28 March 2023 / Accepted: 31 July 2023

Abstract. As the world strives towards a low-carbon future, nearly-zero energy buildings (NZEB) have been the goal to reduce carbon emissions. Artificial lighting is estimated to consume as high as 40% of the total energy consumption in a commercial building. By utilising daylighting, which is the practice of allowing natural light into a building, energy consumption by artificial lighting can be reduced. Luminescent solar concentrators (LSCs) can act as a collector and waveguide to transport outdoor light into the building through total internal reflection. Besides, LSCs absorb a part of the solar spectrum and shift them to different wavelengths through up-conversion or down-conversion. Thus, the output spectrum can be manipulated for the desired indoor applications. Circadian rhythm is the periodic variations in behaviour that follows a 24-hour cycle, which is mainly regulated by light response. A regulated circadian rhythm is important for a healthy life, whereas a disturbed circadian rhythm can lead to health issues such as insomnia and mood disorders. There has been a consensus that our circadian rhythm strongly responds to shorter wavelength light, corroborated in studies. Thus, manipulating the output light of LSCs to contain larger proportions of light with shorter wavelengths could enhance circadian regulation. LSC devices have the potential to transport sufficient daylight up to 5m deep into the building, achieving areas beyond the reach of windows. Thus, LSCs can serve as a tool for daylighting purposes, regulating circadian rhythm and providing sufficient light for comfortable indoor visibility.

Keywords: Circadian rhythm / luminescent solar concentrator / daylighting / light guide

1 Daylighting

Daylighting is the controlled use of daylight in and around buildings [1]. With the use of natural light, artificial lighting can be avoided, resulting in less energy consumption. Besides, prior to electrical lighting, our circadian response has been done through daylight. Using daylighting would allow natural light to maintain our circadian response even indoors. As the outdoor light would follow a typical 24-hour period, with bright sunlight during the daytime, and the absence of light after sundown, this can help with regulating our circadian health. Thus, daylighting can provide an internal space illuminated for a healthier lifestyle [1].

There is a need for sustainable buildings, to achieve nearly-zero energy buildings (NZEB) for a low-carbon future. Based on an Inernational Energy Agency (IEA) report, about 30% of the global energy sector emissions are directly or indirectly through building operations [2]. One main energy usage is for lighting. The total usage of electricity for artificial lighting relies on multiple variables, from the amount of daylighting used to the total daytime, and the efficiency of the lighting appliances.

It has been estimated that energy consumed by lighting is around 10–20% of total energy consumption [3,4], with office buildings consuming about 40% for lighting [5]. With the use of daylighting, energy consumption by lighting can be reduced by about 40% [6]. A simple way for allowing daylighting is through the installation of windows and sunroofs, as seen in Figure 1.

Many countries have set up daylight standards and experts providing recommendations for interior lighting [7,8]. One such regulation is by the European Committee for Standardisation (CEN) requiring a minimum of 300 lux covering a minimum of 50% of the building [7]. To achieve NZEB, this requirement has to be achieved by daylighting alone. One problem with windows is that they can only light up areas close to the exterior of the building, resulting

* e-mail: wtham@tcd.ie

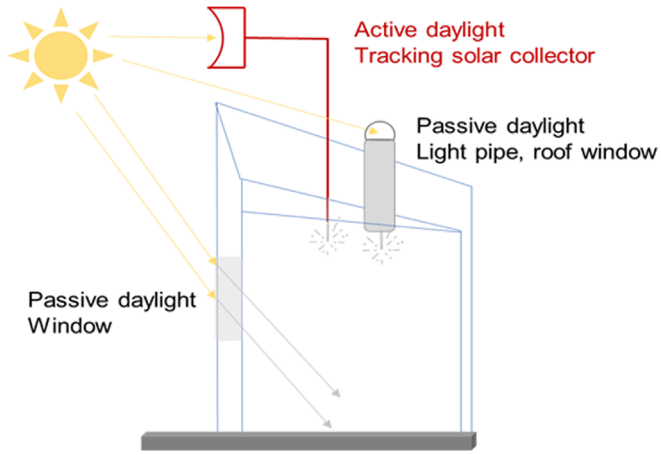


Fig. 1. An illustration of daylighting, where outdoor light can enter the building interior during the day. Passive daylighting systems have static collectors which allow light to enter the building interior, whereas an active daylighting system uses energy to power sensors and mechanical devices to allow solar tracking.

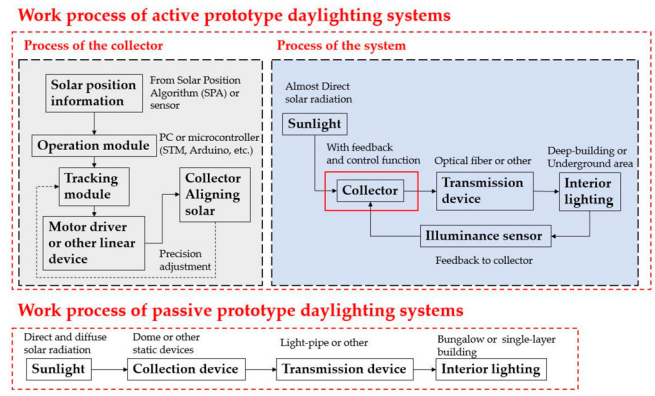


Fig. 2. The work process of active and passive daylighting systems. An active daylighting system has a sun-tracking mechanism to maximise sunlight collection, whereas a passive daylighting system is static thus not requiring any energy input [10].

in darker centres of the building. Thus, certain daylighting systems have been introduced to mitigate that issue. Such daylighting systems work by collecting natural light, transporting them through a transmission device, then diffusing the light indoors illuminating the interior space. Some active daylighting systems also include sensors for solar tracking and indoor illuminance tracking to increase daylight collected [9,10]. Such methods will allow the light to be transported deep into the room with minimal electrical input. A flow diagram of the work process of daylighting systems can be seen in Figure 2.

With the current trends, passive daylighting systems seem to be more popular, typically using tubular daylighting systems. Tubular light guides collect the light using a dome-shaped collector, to capture light throughout the day, which will then be transmitted deep into the building using a high-reflectance tubular light guide [9,10]. Active daylighting systems, however, require a precise solar-tracking mechanism to allow high efficiency of sunlight collection, thus increasing the complexity compared to passive daylighting systems. The most common is by using a Fresnel lens as the solar concentrator collector, which will be transported into the building using optical fibres [9,10].

2 Circadian rhythm

According to the National Institute of General Medical Sciences, USA [11], circadian rhythms are any physical, mental, and behavioural changes that follow a 24-hour cycle. Although these changes are affected by various kinds of environmental cues called zeitgebers, the primary source of synchronisation of circadian rhythm is through light responses [11]. The synchronisation of our internal clock to environmental cues is known as entrainment, and it affects most living beings.

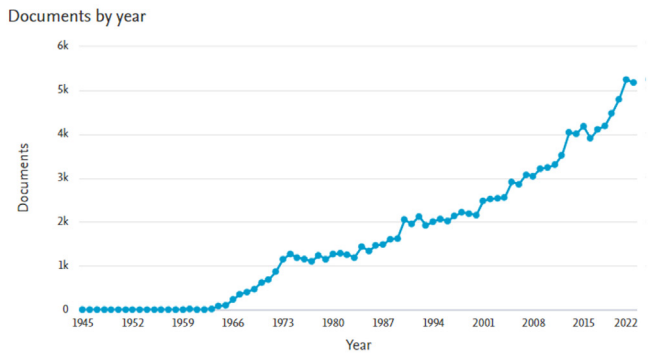
2.1 Research trend of circadian rhythm

The earliest research on the periodic variations in behaviour was found in 1934 [12]. As artificial lighting has become a common application in buildings, and electrical lighting has the ability to produce bright light output, there is a breakdown in the natural light-dark cycle as the night becomes brighter. This resulted in a growing interest in research on circadian rhythm in the 1960s [13–15]. At the same time, light entrainment has been hugely researched and deemed as one of the main processes [16–18].

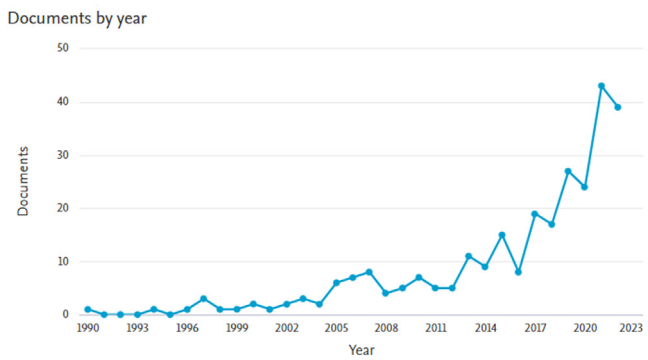
Research into circadian rhythm grew quickly since the start of the 21st century when a new type of photoreceptor was discovered. This photoreceptor was known as the intrinsically photosensitive retinal ganglion cell (ipRGC) was found as the receptor for light entrainment [19]. They found that the ipRGCs have a different sensitive range to rods and cones [20–22]. Thus, research into ipRGC and the impact of light towards our internal clock grew. The trend in research made can be seen in Figure 3a, showing the number of publications on the topic [23]. The publications are based on the Scopus database by Elsevier, with the keyword circadian rhythm. Figure 3b shows the refined search on the number of publications done when the wavelength or brightness of the light was manipulated.

2.2 The concept of circadian rhythm and photoentrainment

Typically, our internal clock does not match the 24-hour day, which can be seen through the sleep-wake rhythm of blind people as their circadian rhythm is 'free-running' [24,26]. To allow our internal clock to match 24 hours, it is theorised that living things use sunlight as the primary path for entrainment, thus the importance of light entrainment (photoentrainment) [21,27].



(a) Scopus database of documents with the keyword "circadian rhythm". The earliest document on Scopus is dated in 1945, and this graph shows the trend until 2022.



(b) Scopus database of documents on circadian rhythm, refined with the keywords "wavelength" and "illuminance". The earliest document is in 1990, and this graph shows the trend until 2022.

Fig. 3. Research trends on circadian rhythm. Data sourced from scopus.com. [23].

Biologically, the method of measuring circadian regulation is through melatonin suppression and alertness [21,24,28]. Hence, much research has shown that ipRGCs have a distinct sensitivity range to the visual photoreceptors (rods and cones) [22,29,30]. The two distinct light responses are summarised in Figure 4. Our visual sensitivity (photopic) peaks around the wavelength of 555nm while the entrainment sensitivity (melanopic) peaks around the wavelength of 480 nm, as seen in Figure 5. The figure also shows that the melanopic sensitivity spectrum shape matches the regular daylight (CIE D65) spectrum, which has a higher amount of short wavelength [21].

Recent research also shows that light entrainment has a non-linear response to brightness. Figure 6 shows that melatonin suppression has a strong pick-up around 100–300 lux, with the increase in response slowing down, especially near 10^4 lux [21,28]. This shows that high brightness (>250 lux) is best for maximising the effect of light entrainment, while low brightness (<10 lux) is preferable at night as it does not cause entrainment [21]. The intermediate region should work for entrainment but is considered sub-optimal [21].

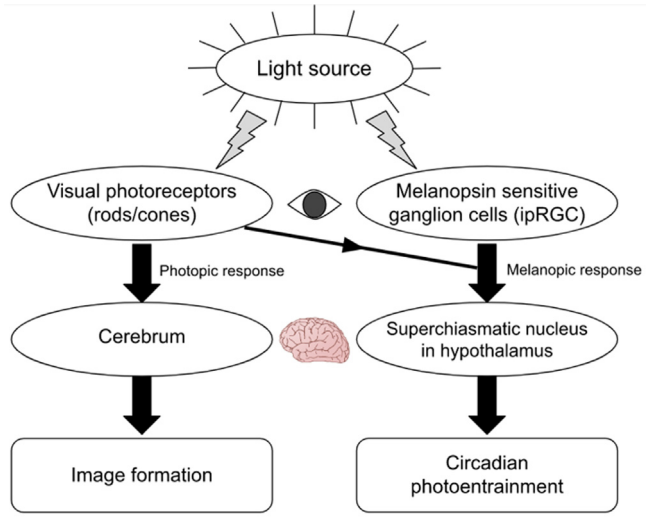


Fig. 4. The visual and non-visual response to light. The visual response is through rods and cones. Although rods and cones play a small role, the non-visual response is mainly through the retinal ganglion cells (ipRGCs) causing photoentrainment.

However, one factor to consider regarding circadian entrainment is the difference in light sensitivity between individuals. Studies have shown that there are differences in melatonin suppression sensitivities between individuals [31]. On a general trend, there are differences in circadian response across different age groups too, with younger people having stronger circadian response whereas older people having weaker response [21,32–34]. Thus, the required amount of light for entrainment might be higher for older people.

As daylight in the morning tends to have shorter wavelengths, daylight is recommended to cause melatonin suppression, resulting in a well-regulated circadian rhythm [21]. However, this might not be feasible for certain people, thus indoor lighting is required to achieve such goals. Daylighting has also the benefit of using daylight for suppressing melatonin during the day while the reduction in illuminance at night would reduce melatonin suppression in preparation for sleep. There are many different daylighting systems, and one of such system is luminescent solar concentrators.

3 Luminescent solar concentrators

Luminescence is the spontaneous emission of light. Photoluminescence occurs when a photon is absorbed by the luminescent centre (luminophore) based on its characteristic absorption spectrum, thus gaining energy. The energy will then be spontaneously emitted as photons following its emission spectrum [35]. Through this method, a luminescent material can shift the wavelengths of photons through down-conversion or up-conversion. Down-conversion is when high-energy photons are converted to lower-energy photons through Stokes shift, such as UV light is converted into visible light, whereas up-conversion converts low-energy photons into high-energy photons through anti-Stokes shift. This process can be seen

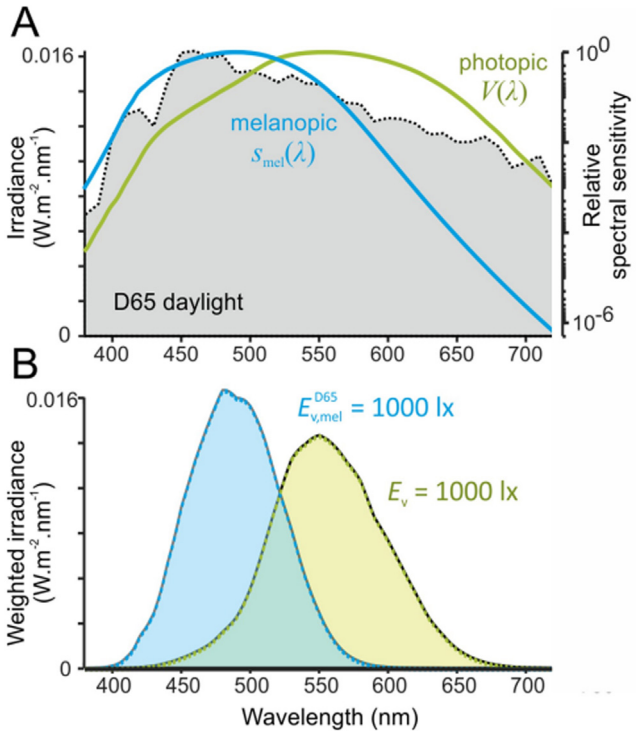


Fig. 5. A comparison in photopic and melanopic spectral sensitivity. The photopic response is our visual response to light (rods and cones) whereas the melanopic sensitivity is the non-visual response to light, resulting in light entrainment of our circadian rhythm. (A) shows the comparison of both spectral sensitivity to D65 daylight, a daylight standard set by the International Commission on Illumination (CIE). It shows that the melanopic spectral sensitivity has a closer match to daylight. (B) shows both spectra multiplied with similar irradiance of 1000 lux. Figure adapted from Brown T. M. et al. [21].

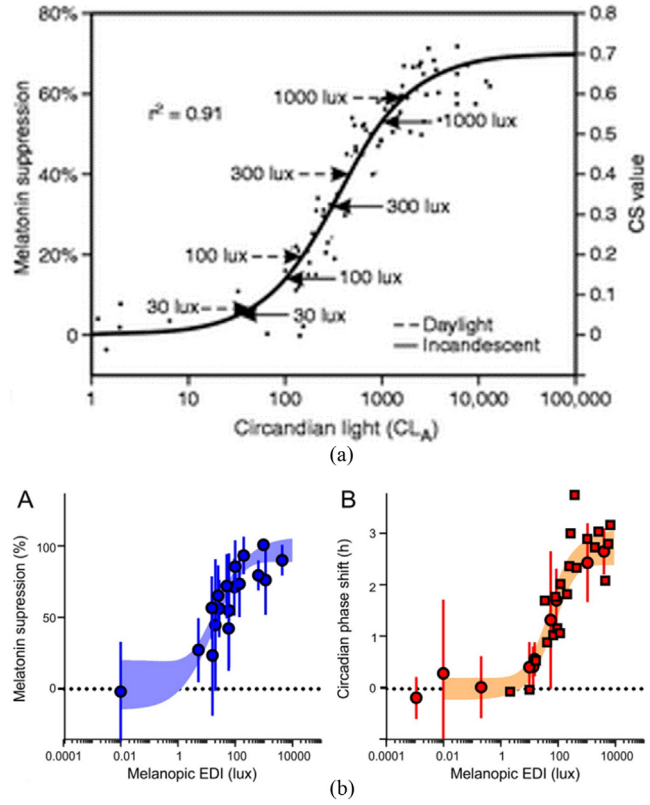


Fig. 6. The non-linear response of circadian entrainment to light brightness. (a) shows a non-linear light entrainment response, with a stronger pickup of melatonin suppression around 300 lux [28]. The two figures in (b) show similar non-linear responses, comparing data on melatonin suppression (A) and circadian phase shift (B). The shaded region is the 95% confidence limit. Similarly, the data shows a strong pickup in light entrainment response around 100 lux to 300 lux Figure adapted from Brown T. M. et al. [21].

in a simple energy level diagram in Figure 7. Such conversions will occur with an efficiency based on the luminescent quantum yield, η_{QY}:

$$\eta_{\mathrm{QY}} = \frac{N_{\gamma,\mathrm{em}}}{N_{\gamma,\,\mathrm{ab}}}, \tag{1}$$

where $N_{\gamma,\mathrm{em}}$ is the number of photons emitted, and $N_{\gamma,\mathrm{ab}}$ is the number of photons absorbed. The η_{QY} value depends on the luminescent material itself. Such luminescent materials can exist as organic dyes [36], quantum dots [37] or rare earth materials [38].

Luminescent solar concentrators (LSCs) are luminophores doped in a transparent polymer. As the emission is isotropic, the direction of the emitted photons is randomised, having the same radiation intensity in all directions. If the emitted light is larger than the critical angle, it will undergo total internal reflection (TIR). Thus, the host material itself could act as a waveguide for the emitted light. If the light has a smaller angle than the critical angle cone, it will refract out of the LSC, thus being in the LSC's escape cone.

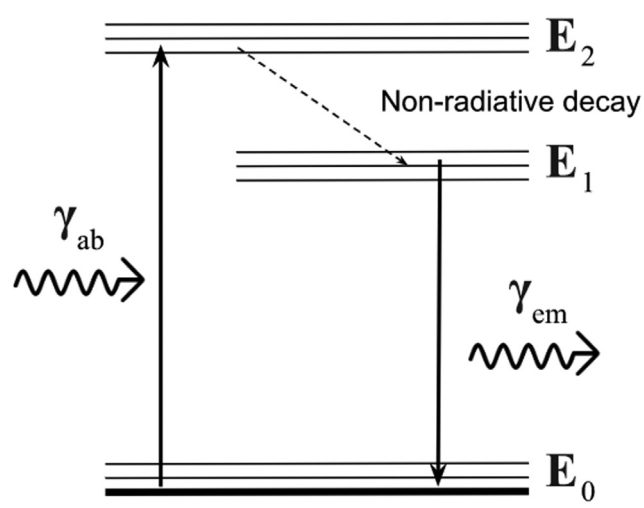


Fig. 7. The absorption and emission processes for a luminescent material. When the photon is absorbed, the luminophore will be excited, and its energy will then be released through an emitted photon through spontaneous emission.

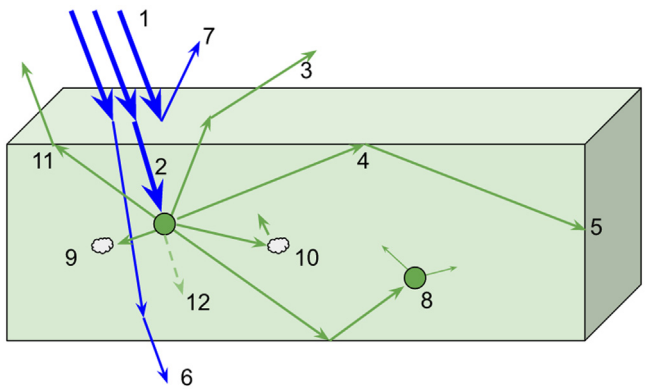


Fig. 8. The working mechanisms of a luminescent concentrator. (1) When a photon enters the luminescent material, (2) it will undergo absorption if it is within the absorption spectrum. When spontaneous emission occurs, the photon will be emitted isotropically, which means the radiation has the same intensity in all directions. (3) If the angle of incidence is smaller than the critical angle, the photon will refract out of the material through the escape cone as a loss. (4) Otherwise, the photon will undergo total internal reflection (TIR). (5) After a number of TIR, the photon will reach the output surface and be coupled out. Some of the loss mechanisms include (6) transmission through the LSC without absorption, (7) surface reflection, (8) self-absorption, (9) host matrix absorption, (10) host scattering, (11) surface scattering and (12) non-radiative decay due to $\eta_{QY} < 1$.

One of the properties of LSC is the geometric gain factor, G [39]:

$$G = \frac{A_{abs}}{A_{out}}, \tag{2}$$

where A_{abs} is the area of the absorption surface, while A_{out} is the area of the desired output surface of the LSC. Thus, by increasing A_{abs}, more luminescence can be produced, while a decrease in A_{out} will result in a higher photon concentration output. However, G represents the theoretical limit of the concentration factor, C, which can be defined as the ratio of the flux of output photons (N_{out}) to the number of incident photons (N_{in}) [39]:

$$C = \frac{N_{out}}{N_{in}}. \tag{3}$$

By comparing both (2) and (3), a linear relationship between C and G could be deduced, however, due to multiple loss factors, C has a sub-linear relationship with G and will reach an asymptotic limit based on the characteristics of the LSC losses. The working principles of an LSC [40,41] are illustrated in Figure 8, where certain LSC losses are also considered.

Depending on the LSC material used, from the luminophore to the host, there exist a few losses. Some of the incident light will undergo Fresnel reflection losses. Not all of the light in the solar spectrum will also be absorbed by the LSC too. As the light has to undergo TIR so that the host can work as a waveguide, any light emitted within the escape cone will be lost.

If there is an overlap between the absorption and emission spectra, the emitted light could then be re-absorbed by the LSC itself, known as self-absorption. Scattering and absorption could also happen through surface defects, the host matrix or the high doping concentration of the LSC, resulting in loss through absorption or scattering of waveguided light to undesired directions [39,42]. To minimise any waveguide losses, the LSC should be clean, smooth and flat [42].

Thus, we can summarise the optical efficiency of the LSC, η_{LSC}, as [41]:

$$\eta_{LSC} = (1 - R)\eta_{abs}\eta_{QY}\eta_{trap}\eta_{SA}\eta_{WG}, \tag{4}$$

where R is the amount of reflection from the LSC surface, η_{abs} is the fraction of light absorbed by the LSC, η_{QY} is the quantum yield efficiency, η_{trap} is the trapping efficiency, which is the probability that the light emitted will undergo TIR, and η_{SA} and η_{WG} takes into consideration the losses due to self-absorption and waveguide scattering and absorption.

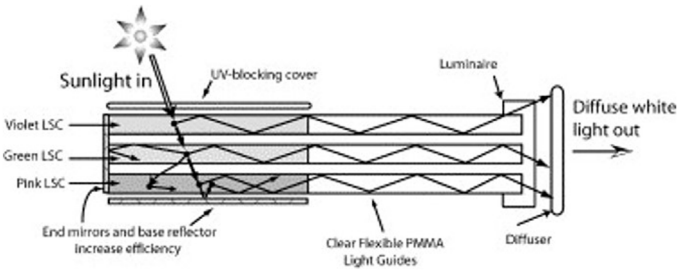
3.1 LSC for daylighting

One proposed method for using LSC for daylighting can be seen in the schematic in Figure 9a [11], with the emission spectrum shown in Figure 9b. The three LSCs used cover the full visible spectrum, which then can form white light through colour mixing.

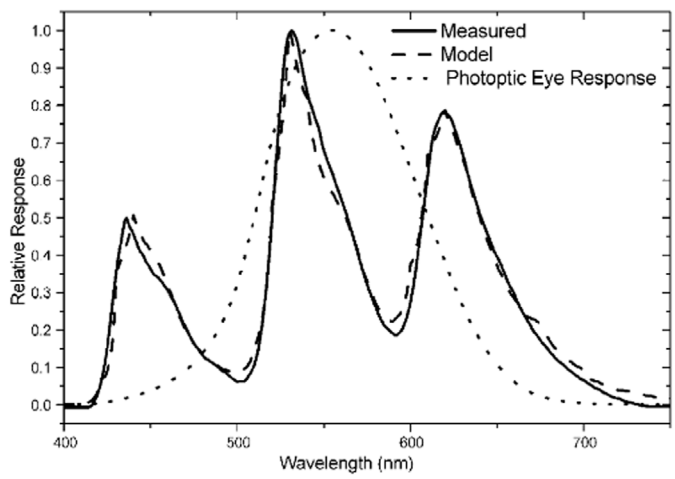
Given the multiple losses that are mentioned such as self-absorption and waveguide loss, the efficiency of waveguided emission decreases as the collector length increases, showing the sub-linear relationship between G and C mentioned in page 5. This is shown in Figure 10. Given that the increase in the LSC area would mean an increase in cost, there is less cost benefit to increasing the collector area, thus limiting the length of the LSC collector area [43]. Besides, due to the waveguide host contributing to scattering and absorption losses even without the luminophores, there is a limit to the depth that the light could travel for sufficient daylighting purpose [42]. An introduction of a UV-blocking cover seen in Figure 8 could increase the lifespan of the LSC as UV light could cause photodecomposition of the LSC, however, it would block out the UV light that could be absorbed by the LSC, reducing the light output [43]. Therefore, Earp A. A. et al. determined that the collector length beyond 1.2m contributed little extra value [42]. Despite that, under clear sky conditions, the system used in Figure 8 can produce a brightness of 1000 lumens at a distance of 5m deep into the building [43], which is sufficient for daylighting purposes.

3.2 Why LSC for daylighting?

Similar to other daylighting systems, daylighting could provide comfortable interior visibility for indoor activities during the day [9]. This reduces energy consumption for artificial lighting, thus contributing towards the NZEB goal. Having daylighting could also promote better health



(a) The triple LSC design done for daylighting. Violet, green and pink LSCs are used to cover the full visible spectrum. For any photons emitted larger than the critical angle, the light will undergo TIR through the PMMA host towards the diffuser in the building. The UV-blocking cover was installed to ensure a longer lifespan of the LSCs [43].



(b) The output spectrum of the triple LSC design. The design was done such that it has a higher green output for better visual response [43].

Fig. 9. Triple LSC design used for daylighting by Earp A. A. et al. [43].

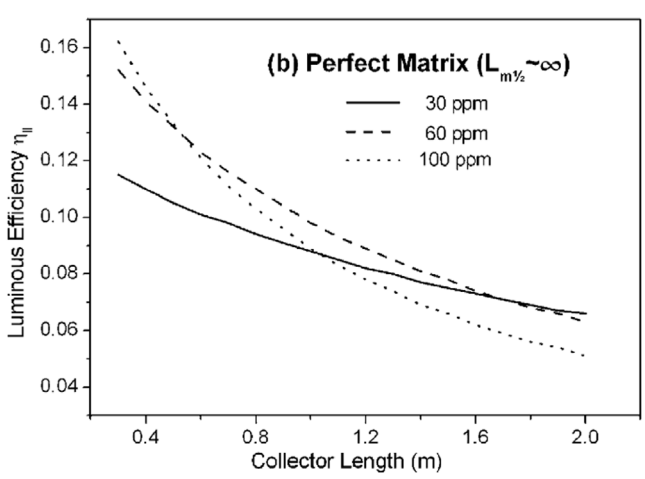


Fig. 10. The theoretical output efficiency for a green fluorescent dye LSC by Earp A. A. et al.. The luminous efficiency follows an exponential drop due to self-absorption [44].

and productivity [10]. With daylighting, melatonin suppression could occur in the daytime, while the reduction in illuminance at night would reduce melatonin suppression, resulting in better circadian regulation and better sleep [10,21]. Therefore, any artificial lighting installation could have lower illuminance (<10 lux) to prepare for sleep, while having sufficient light for night activities. These artificial lighting could also have warmer white light to reduce the blue wavelength which causes strong photoentrainment.

Furthermore, as the direction of absorbed light would not impact the isotropic nature of the light emission, LSCs are able to collect light from both direct and diffuse light [40], thus there is no need for a solar tracker. Unlike other passive daylighting systems that require a dome-shaped collector to increase collection efficiency throughout the day [44], LSCs only require a flat surface. This meant that the fabrication of LSCs can be simpler and more cost-effective, while the size of the collector can be easily customisable. Despite the potential size of the LSC collectors, LSCs having doped with luminophores could provide an aesthetic look to enhance visual comfort [40]. As the emitted light is isotropic, it could be installed on the side of the building too, while other passive daylighting systems require the installation of collectors on the rooftops. Therefore, LSC systems could be installed for lower floors of multiple-storey buildings, and not compete with other daylighting systems installed on rooftops.

As the LSC would cause a shift in wavelength, the output light of the device could be shifted for specific purposes. As seen that circadian regulation is stronger at wavelengths of 480nm, a stronger emission output could be made at that wavelength to enhance photoentrainment. This would be helpful for areas with shorter daytime during winter, to enhance photoentrainment with the limited time. Although having sunlight outdoors is always recommended, this could benefit indoor workers who have limited outdoor time in the daytime [45–47].

A few luminescent dopants could produce light in the wavelength region of 480nm. ZnCdSeS quantum dots can produce $\lambda_{max,em} = 480 \pm 5$nm under UV absorption with $\eta_{QY} \approx 90\%$, while ZnCdSe or ZnS quantum dots can achieve $\eta_{QY} \approx 70\%$ [48,49]. Lead halide perovskites such as $MePbX_3$ to have $\lambda_{max,em} = 480 \pm 15$nm, under UV absorption, with $\eta_{QY} \approx 90\%$, where X is a monovalent halide (Cl, Br, I). Lastly, certain materials using rare earth ions in the Lanthanides group (Ln^{3+}) such as Yb^{3+} and Er^{3+} could be used to allow up-conversion [35,50]. Although the absorption is in the near-infrared range, thus avoiding the harmful effects of UV, the absorption rate is low as it requires a combination of multiple photons.

4 Conclusion

LSCs have been demonstrated to provide a solution with sufficient brightness with the triple-LSC device [43]. Given that LSCs can be installed on the side of the building, this could allow solar panels or other daylighting systems to be installed on the rooftop to increase sustainability.

Our circadian rhythm is mainly regulated through light response. As sunlight in the morning tends to have shorter wavelength light, our circadian rhythm synchronisation has been adjusted so that it is more sensitive towards shorter wavelength light, thus developing the melanopic response, which has a different sensitivity to the photopic (visual) response. The peak melanopic wavelength sensitivity is around 480nm. Besides, a brightness of larger than 300 lux has been recommended to allow sufficient light for photoentrainment.

As the LSCs can shift the wavelength to the desired output, LSCs can be used as a daylighting tool to cause enhanced photoentrainment, by adjusting the LSC to produce a larger proportion of light with wavelengths of around 480nm. Thus, compared to other daylighting systems, LSCs have the potential and advantage to tackle issues such as seasonal affective disorder (SAD) which affects people in the winter season.

Funding

The authors would like to thank Velux Stiftung for providing the funding, and support funding from European Research Council (ERC) grant entitled PEDAL (Grant agreement 639760), H2020 grant entitled IDEAS (Grant agreement 815271), and Science Foundation of Ireland.

References

1. Velux, Daylighting. n.d. Available at: https://www.velux.com/what-we-do/research-and-knowledge/deic-basic-book/daylight/daylighting [Accessed 2 December 2022]
2. IEA, Technology and Innovation Pathways for Zero-carbon-ready Buildings by 2030. 2022. Available at: https://www.iea.org/reports/technology-and-innovation-pathways-for-zero-carbon-ready-buildings-by-2030 [Accessed 24 February 2023]. License: CC BY 4.0
3. J. Byun, T. Shin, Design and implementation of an energy-saving lighting control system considering user satisfaction, IEEE Trans. Consum. Electron. **64**, 61–68 (2018)
4. W.N.W. Muhamad, M.Y.M. Zain, N. Wahab, N.H.A. Aziz, R.A. Kadir, Energy efficient lighting system design for building, in: 2010 International Conference on Intelligent Systems, Modelling and Simulation, 2010, pp. 282–286
5. B. Obradovic, B.S. Matusiak, Daylight transport systems for buildings at high latitudes, J. Daylighting **6**, 60–79 (2019)
6. M. Bodart, A. De Herde, Global energy savings in offices buildings by the use of daylighting, Energy Build. **34**, 421–429 (2002)
7. Kingspan, What is EN 17037, The European Daylighting Standard? 2019 Available at: https://www.kingspan.com/ie/en/knowledge-articles/what-is-en-17037—-a-brief-introduction-to-the-european-dayligh/ [Accessed 18 January 2023]
8. Velux, Daylight requirements in building codes. n.d. Available at: https://www.velux.com/what-we-do/research-and-knowledge/deic-basic-book/daylight/daylight-requirements-in-building-codes [Accessed 18 January 2023]
9. N.O. Onubogu, K.-K. Chong, M.-H. Tan, Review of active and passive daylighting technologies for sustainable building, Int. J. Photoenergy **2021**, 8802691 (2021)
10. A.J.-W. Whang, T.-H. Yang, Z.-H. Deng, Y.-Y. Chen, W.-C. Tseng, C.-H. Chou, A review of daylighting system: For prototype systems performance and development, Energies **12**, 2863 (2019)
11. NIGMS, Circadian Rhythms. n.d. Available at: https://nigms.nih.gov/education/fact-sheets/Documents/fact-sheet-circadian-rhythms.pdf [Accessed 20 January 2023]
12. G.L. Freeman, C.I. Hovland, Diurnal variations in performance and related physiological processes, Psychol. Bull. **31**, 10 (1934)
13. A. Jürgen, Circadian rhythms in man, Sci. **148**, 1427–1432 (1965)
14. J.N. Mills, Human circadian rhythms, Physiol. Rev. **46**, 128–171 (1966)
15. C.S. Pittendrigh, The entrainment of circadian oscillations by skeleton photoperiods, Science **144**, (1964)
16. M.L.R. Goff, F.W. Finger, Activity rhythms and adiurnal light-dark control, Science **154**, 1346–1349 (1966)
17. R.K. Ringer, Effect of light and behavior on nutrition, J. Anim. Sci. **35**, 642–647 (1972)
18. F. Hollwich, The influence of light via the eyes on animals and man, Ann. N. Y. Acad. Sci. **117**, 105–128 (1964)
19. D.M. Berson, F.A. Dunn, M. Takao, Phototransduction by retinal ganglion cells that set the circadian clock, Sci. **295**, 1070–1073 (2002)
20. G.C. Brainard, J.R. Hanifin, J.M. Greeson, B. Byrne, G. Glickman, E. Gerner, M.D. Rollag, Action spectrum for melatonin regulation in humans: Evidence for a novel circadian photoreceptor, J. Neurosci. **21**, 6405–6412 (2001)
21. T.M. Brown, G.C. Brainard, C. Cajochen, C.A. Czeisler, J.P. Hanifin, S.W. Lockley, R.J. Lucas, M. Münch, J.B. O'Hagan, S. N. Peirson, L.L.A. Price, T. Roenneberg, L.J.M. Schlangen, D. J. Skene, M. Spitschan, C. Vetter, P.C. Zee, K.P. Wright, Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults, PLoS Biol. **20**, e3001571 (2022)
22. J.J. Gooley, S.M.W. Rajaratnam, G.C. Brainard, R.E. Kronauer, C.A. Czeisler, S.W. Lockley, Spectral responses of the human circadian system depend on the irradiance and duration of exposure to light, Sci. Transl. Med. **2**, 31ra33 (2010)
23. Scopus, Analyse search results: Circadian rhythm. Available at: scopus.com [Accessed 18 January 2022
24. S.W. Lockley, D.-J. Dijk, O. Kosti, D.J. Skene, J. Arendt, Alertness, mood and performance rhythm disturbances associated with circadian sleep disorders in the blind, J. Sleep Res. **17**, 207–216 (2008)
25. R.L. Sack, A.J. Lewy, M.L. Blood, J. Stevenson, L.D. Keith, Melatonin administration to blind people: Phase advances and entrainment, J. Biol. Rhythms **6**, 249–261 (1991)
26. M. Uchiyama, S.W. Lockley, Non-24-hour sleep-wake rhythm disorder in sighted and blind patients, Sleep Med. Clin. **10**, 495–516 (2015)
27. R.L. Sack, A.J. Lewy, Circadian rhythm sleep disorders: Lessons from the blind, Sleep Med. Rev. **5**, 189–206 (2001)
28. I. Acosta, R.P. Leslie, M.G. Figueiro, Analysis of circadian stimulus allowed by daylighting in hospital rooms, Light. Res. Technol. **49**, 49–61 (2017)
29. R.J. Lucas, S.N. Peirson, D.M. Berson, T.M. Brown, H.M. Cooper, C.A. Czeisler, M.G. Figueiro, P.D. Gamlin, S.W. Lockley, J.B. O'Hagan, L.L.A. Price, I. Provencio, D.J. Skene, G.C. Brainard, Measuring and using light in the melanopsin age, Trends Neurosci. **37**, 1–9 (2014)

30. C. Zhang, Z. Zhu, J. Zhao, Y. Li, Z. Zhang, Y. Zheng, Ubiquitous light-emitting diodes: Potential threats to retinal circadian rhythms and refractive development, Sci. Total Environ. **862**, (2023)
31. A.J.K. Phillips, P. Vidafar, A.C. Burns, E.M. McGlashan, C. Anderson, S.M.W. Rajaratnam, S.W. Lockley, S.W. Cain, High sensitivity and interindividual variability in the response of the human circadian system to evening light, PNAS **116**, 12019–12024 (2019)
32. V. Gabel, C.F. Reichert, M. Maire, C. Schmidt, L.J.M. Schlangen, V. Kolodyazhniy, C. Garbazza, C. Cajochen, A. U. Viola, Differential impact in young and older individuals of blue-enriched white light on circadian physiology and alertness during sustained wakefulness, Sci. Rep. **7**, 2017 (2017)
33. T.L. Sletten, V.L. Revell, B. Middleton, K.A. Lederle, D.J. Skene, Age-related changes in acute and phase-advancing responses to monochromatic light, J. Biol. Rhythms **24**, 73–84 (2009)
34. A. Steponenaite, S. M. Biello, G. S. Lall, Aging clocks: Disrupted circadian rhythms, Aging **10**, 3065–3066 (2018)
35. X. Huang, S. Han, W. Huang, X. Liu, Enhancing solar cell efficiency: The search for luminescent materials as spectral converters, Chem. Soc. Rev. **42**, 173–201 (2013)
36. A.P. Green, A.R. Buckley, Solid state concentration quenching of organic fluorophores in PMMA, Phys. Chem. Chem. Phys. **17**, 1435–1440 (2015)
37. D.J. Norris, M.G. Bawendi, Measurement and assignment of the size-dependent optical spectrum in CdSe quantum dots, Phys. Rev. B **53**, 16338–16346 (1996)
38. B.M. van der Ende, L. Aarts, A. Meijerink, Lanthanide ions as spectral converters for solar cells, Phys. Chem. Chem. Phys. **11**, 11081–11095 (2009)
39. J. Roncali, Luminescent solar collectors: Quo vadis? Adv. Energy Mater. **10**, 2020 (2020)
40. M. Rafiee, S. Chandra, H. Ahmed, S.J. McCormack, An overview of various configurations of Luminescent Solar Concentrators for photovoltaic applications, Opt. Mater. **91**, 212–227 (2019)
41. J. Sathian, J. D. Breeze, B. Richards, N.McN. Alford, M. Oxborrow, Solid-state source of intense yellow light based on a Ce:YAG luminescent concentrator, Opt. Express **25**, 13714 (2017)
42. A.A. Earp, G.B. Smith, P.D. Swift, J. Franklin, Maximising the light output of a Luminescent Solar Concentrator, Sol. Energy **76**, 655–667 (2004)
43. A.A. Earp, G.B. Smith, J. Franklin, P. Swift, Optimisation of a three-colour luminescent solar concentrator daylighting system, Sol. Energy Mater Sol. Cells. **84**, 411–426 (2004)
44. K. Sharma, V. Kumar, D.S. Bisht, H. Garg, Comparative study of acrylic flat plate and dome shaped collector for summer and winter solstice conditions, Mater. Today: Proc. **45**, 5489–5493 (2021)
45. A. Josephine, Biological rhythms during residence in polar regions, Chronobiol. Int. **29**, 379–394 (2012)
46. I.H. Hahn, M.B. Grynderup, S.B. Dalsgaard, J.F. Thomsen, A.M. Hansen, A. Kærgaard, L. Kærlev, O. Mors, R. Rugulies, S. Mikkelsen, J.P. Bonde, H.A. Kolstad, Does outdoor work during the winter season protect against depression and mood difficulties? Scand. J. Work Environ. Health **37**, 446–449 (2011)
47. A. Magnusson, An overview of epidemiological studies on seasonal affective disorder, Acta Psychiatr. Scand. **101**, 176–184 (2000)
48. CD Bioparticles, DiagNano^{TM} *TM* PEG-NH2 CdSe/ZnS quantum dots, Phys. Rev. n.d. Available at: https://www.cd-bioparticles.com/product/diagnano-peg-nh2-cdse-zns-quantum-dots-480-nm-item-dnp-x052-12995.html [Accessed 21 February 2023]
49. Y. Sun, F. Masia, W. Langbein, P. Borri, Fabrication and optical properties of thin silica-coated CdSe/ZnS quantum dots, Phys. Status Solidi (A) Appl. Mater. Sci. **206**, 2822–2825 (2009)
50. A. Ghazy, M. Safdar, M. Lastusaari, H. Savin, M. Karppinen, Advances in upconversion enhanced solar cell performance, Sol. Energy Mater Sol. Cells. **230**, 111234 (2021)

Cite this article as: W.Q. Tham, S. Chandra, B. Norton and S. McCormack: Introducing luminescent solar waveguides for sustainable buildings for enhanced circadian rhythm regulation. Sust. Build. **6**, 6 (2023).