Optimization of photoluminescent materials for lighting energy saving in the built environment

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Abstract. In the last decades, fossil fuels have become the primary resource for electricity generation, contributing to the aggravation of problems like global warming and ozone depletion. For this reason, innovative solutions are being continuously developed in order to improve energy efficiency in the construction sector. Beyond heating and cooling, urban lighting plays a significant role on the final energy consumption of a city, including both indoors and outdoors. In this work, photoluminescent materials are investigated as possible light sources to be implemented in urban lighting systems, focusing on the free-cost and renewable luminous gain they provide after being exposed to a proper radiation. In particular, commercially available photoluminescent powders are evaluated by means of spectroradiometric techniques and using a specifically designed experimental setup. Measurements are repeated for different intensities and wavebands of irradiation to identify the most promising “pigment-lamp” combination in terms of (i) luminous intensity and (ii) photoluminescence duration. Results show that the shorter the distance between the emission spectra of the exciting source and the photoluminescent powder, the better the performance of the latter. Therefore, the choice of both afterglow and exciting source cannot be independent from the final system’s application and the required end-use lighting level.

1. Introduction
The evolution of the urbanization process that has been affecting cities all over the world for years has led to environmental consequences that are no longer negligible. The unruly expansion and exploitation of rural land has increased the energy and environmental impacts of urban areas, contributing to exacerbate cities-related greenhouse gases (GHGs) emissions and resources consumption [1]. Among the driving factors influencing the energy demand of a city, public lighting accounts for up to 60% of the total electricity costs [2]. For this reason, municipalities are increasingly looking for innovative and more efficient solutions that may reduce the costs linked to the provision of public services for citizens [3, 4]. The same motivation has paved the way for the replacement of the most inadequate technologies with more energy efficient alternatives, leading to the adoption and the diffusion of solid state lighting technology, based on light-emitting diodes (LEDs), that helps in saving up to 70% of electricity [5, 6]. LEDs have also proven to be an effective solution towards more sustainable lighting systems, thanks to their lower impact in terms of GHG footprint with respect to that of the widely used high-pressure sodium lights [7]. Moreover, the optimization of LED lighting systems can be further
improved with the implementation of dimming and controlling options that can be set according to parameters like people presence, daylight availability and so on. On the other hand, in highly populated urban areas, people have started to spend more time outside for both leisure and work activities, so that public spaces often become real “outdoor living rooms” [8]. Therefore, beyond the main task of providing a proper and safe detection of objects and vehicles, the inevitable role of lighting in citizens’ social well-being must be taken into account [9].

In this context, the present work tackles the idea of exploiting peculiar materials with photoluminescent properties for lighting purposes, combining them with the artificial irradiation that best matches their re-emission features. In fact, photoluminescence consists in the emission of light by a material in the dark, after the energy absorption from an ultraviolet (UV) or visible (VIS) radiation exposure. If the luminous emission lasts for an appreciable time from the end of the excitation, the phenomenon is called “phosphorescence”, otherwise “fluorescence” [10, 11]. During the last decades, photoluminescent compounds have been widely investigated from a physical-chemical point of view, thanks to the promising performances demonstrated in terms of both luminous intensity and afterglow duration [12, 13]. However, their actual implementation in more complex materials for civil applications is still at the very beginning [14, 15, 16]: as a matter of fact, commercially available photoluminescent materials are currently used only for decorative and ornamental goals. Given the optimistic results obtained by recent studies on luminescent compounds [17, 18, 19], instead, the aim of this work is to carry out a preliminary investigation about the photoluminescence response to an artificial light excitation, thinking about the possible future combination between its renewable and free-cost luminous gain and existing or specifically designed urban lighting systems.

2. Materials and methods

2.1. Materials and samples preparation

The materials investigated in this work are photoluminescent powders with peculiar afterglow colors, determined by their specific chemical composition. Usually, they are dispersed into different solutions to make more complex materials glow in the dark (e.g. glasses, ceramics, coatings). Seven re-emission colors have been selected in order to cover almost all the VIS spectrum: purple (P), blue sky (BS), blue (B), yellow (Y), orange (O), red (R) and white (W). For the experimental investigation purposes, quartz cuvettes ($1 \times 1 \times 4.5 \text{ cm}^3$) have been filled with the selected photoluminescent pigments and hermetically sealed, so that identical samples could be tested. Since the photoluminescent emission is highly influenced by the type of radiation it is exposed to, different tunable and dimmable lighting sources have been selected for the complete characterization of the powders.

2.2. Test equipment and procedure

Photoluminescent powders are investigated through an in-lab experimental campaign, aimed at detecting the luminous behavior of the samples according to different excitation sources. The procedure is carried out by means of a spectrophotometer (Varian Cary 4000, equipped with an integrating sphere) to obtain the reflectance spectra of the powders, and a spectroradiometer (JETI Specbos 1211UV), for both the photometric characterization of the exciting lamps and the monitoring of the photoluminescence evolution during its charging and extinguishing phase.

A dedicated experimental setup has been specifically realized for the spectroradiometric analysis. A wooden box with a removable lid, internally coated with a black matt paint, has been equipped with a mobile internal shelf for housing the cuvette containing the powder. The lid of the box allows the installation of 4 light bulbs near the corners, each controlled by a switch that comes out of the box itself. A hole has been drilled on the cover of the box, corresponding to the position of the sample on the internal shelf and with the same size as the detector of the spectroradiometer. Two different configurations of the experimental setup are used. For
the lighting sources characterization, the spectroradiometer is placed inside the box, with the
detector pointed towards the bulbs, at the same height as the shelf on which the sample is then
housed. During the monitoring of the photoluminescence evolution, instead, the sample is on
the shelf inside the box, while the instrument is outside, with the detector inserted in the hole
of the box lid, pointing the cuvette.

The overall methodology can be summarized in three main steps: (1) measurement of the
diffuse reflectance spectra of the pigments, in order to make considerations about the absorbing
capacity of each sample; (2) characterization of the selected exciting lamps in terms of spectral
irradiance provided at the sample’s position in the box; (3) evaluation of each “pigment-lamp”
combination in terms of: spectral radiance and luminance emitted by the sample, exposure
time required for the stabilization of the photoluminescent phenomenon and decay time of
the photoluminescence itself. More specifically, the afterglow decay time is calculated up to a
luminance value of 0.3 mcd/m², considered as the threshold of the human photopic vision. The
procedure follows the standard DIN 67510-1 [20] and requires the experimental monitoring of
the luminance provided by the photoluminescent sample from the end of the solicitation onward.
Plotting the logarithmic values of luminance against time, a polynomial curve is fitted to the
data in the range from 20 minutes of decay to the last recorded value. The photoluminescence
decay time is then derived from the equation of the fitting curve.

3. Results

3.1. Samples’ reflectance and exciting irradiation profiles
As previously introduced, investigations about the reflectance spectra of the photoluminescent
samples are carried out with the aim of identifying the criteria for the selection of the proper
lighting system responsible for the best luminescent performance of each afterglow color. To
this aim, Figure 1a shows the comparison between the reflectance profiles of the samples
(continuous lines) and the spectral irradiance profiles of the lighting sources used to activate
their photoluminescence (dot lines). The latter are detected by means of a spectroradiometer,
at the same height of the sample in the box. Figure 1b represents the irradiation intensities
that each lamp can provide at the sample’s height, exploiting the dimmable option of the bulbs:
blue, green and red lights have only a fixed irradiating power (I), while white and UV may
be improved up to three (I, II, III) and four (I, II, III, IV) levels of irradiation, respectively.
Focusing on Figure 1a, it can be seen how the photoluminescent powders reflect most of the
VIS wavelengths, i.e. they absorb in the UV and blue spectral range. Only R’s absorption is
centered around 500 nm. Such preliminary results suggest that UV, blue and white lights may
be the most suitable sources to optimize the samples’ absorption of energy, since their emission
involves part of the wavelength range that best excites the pigments.

3.2. Photoluminescence evolution through increasing exposure time
The last assumption is confirmed by the following steps of measurement, in which samples are
exposed to every type of light until their luminous response becomes stable. Figure 2 and
3 show the “pigment-lamp” combinations that manage to provide for the photoluminescence
activation. In particular, Figure 2 reports luminance trends through increasing exposure periods,
highlighting the time after which the luminous behavior of the sample becomes constant. In
Figure 3, instead, the photoluminescent spectral radiance at the charging time needed for a
stable emission (continuous line) is compared to the irradiance profile of the light that activates
it (dot line). As expected, green and red light does not activate photoluminescence in any
of the investigated pigments, while blue light (I) can be combined only with Y and B samples.
Accordingly with the absorption capacity, Y reaches higher luminance values than B in a shorter
time of exposure. The same relation occurs using the other sources, at the same irradiation level
(I): in particular, white light helps in reaching higher luminances, while UV light guarantees a
faster activation of the photoluminescent phenomenon. All the other samples are activated by white and/or UV light, according to increasing intensities of irradiation. In particular, BS and W get excited by the same irradiation level of white and UV light (II and III, respectively), while R and O emissions require different intensities of the two sources. P photoluminescence, instead, can be charged only by UV (III) light. Beyond the identification of the optimal “pigment-lamp” combinations, it can be noticed how the behavior of O, P and R pigments differs from that of the other samples: even if an asymptotic trend is recognizable among all the luminance evolutions through time, such samples reach a peak value after a few minutes of exposure that subsequently decreases up to a constant, but lower, emission level.

3.3. Photoluminescence decay time
Following the procedure introduced in Section 2.2, Table 1 summarizes the photoluminescence decay time related to each “pigment-lamp” couple. In particular, two luminance reference
Figure 3. Spectral radiance profiles (continuous lines) of the photoluminescent samples after being excited for the time necessary to the emission stabilization, grouped by the same type of irradiation (dot lines).

values are considered as thresholds for the luminous emission of the material, 0.03 cd/m² and 0.3 mcd/m². While the first is linked to the spectroradiometer range of measurement, the second is standardized as the low limit of human photopic visual. It can be noticed how B and Y samples guarantee good afterglow duration in combination with all the investigated lighting sources, requiring also a modest intensity of irradiation (I). Indeed, their luminous contribution keeps luminance values 100 times higher than the visible threshold (0.3 mcd/m²) up to more than 2 and 5 hours, respectively. Samples like BS and W, instead, decay in a significantly faster way, even if their luminance takes more than 30 hours to reach 0.3 mcd/m². Finally, O, P and R pigments provide for the worst performances in terms of photoluminescence persistence: not only they need high irradiation levels to be activated, but their luminous gain lasts only for few minutes or even seconds from the end of the excitation.

4. Conclusions

In this work, seven commercially available photoluminescent pigments are experimentally studied with the aim of evaluating their potential for lighting energy saving in the built environment. In fact, their implementation in more complex construction materials can be combined with existing urban lighting systems, with a view to reducing their operating time (and energy consumption) by exploiting the renewable light emission of photoluminescence. For this reason, different “pigment-lamp” combinations are investigated during both the charging and the extinguishing phase of photoluminescence, in order to identify the best type of irradiation for each sample and, subsequently, the most suitable re-emission colors for lighting purposes. Related to this, the selection of a yellow or blue afterglow color results in being the most promising solution, thanks to higher luminance values, longer decay times and also lower required levels of irradiation. More in general, for a given intensity, UV light guarantees a faster activation of photoluminescence, while the use of a white irradiation, more commonly applied in lighting systems, involves longer decay times of the phenomenon itself. These preliminary assumptions pave the way for future studies that may deeper explore the optimization of photoluminescence-based lighting systems, considering also the architectural and the visual/safety lighting requirements to be met in the built environment.
Table 1. Photoluminescence decay time of the investigated pigments (y=log(L) and x=log(t)).

| Light   | Sample | L<sub>max</sub> (cd/m<sup>2</sup>) | Decay time to: | Data fitting curve | Adj.R<sup>2</sup> |
|---------|--------|-------------------------------|----------------|-------------------|------------------|
|         |        |                               | 0.03 (cd/m<sup>2</sup>) | 0.3 mcd/m<sup>2</sup> |                  |
| Blue(I) | Y      | 1.91                          | 5.08 h         | 100.88 h          | y=−0.32+0.68x−0.23x<sup>2</sup> | 0.999 |
|         | B      | 0.50                          | 2.09 h         | 50.51 h           | y=−1.33+0.98x−0.27x<sup>2</sup> | 0.994 |
| White(I) | Y     | 2.61                          | 4.58 h         | 86.30 h           | y=−0.29−0.69x−0.23x<sup>2</sup> | 0.998 |
|         | B      | 0.64                          | 1.93 h         | 53.89 h           | y=−0.82−0.69x−0.23x<sup>2</sup> | 0.993 |
| White(II) | BS   | 0.21                          | 0.36 h         | 30.16 h           | y=−1.09−0.42x−0.18x<sup>2</sup> | 0.979 |
| White(III) | W     | 0.90                          | 0.39 h         | 140.16 h          | y=2.24−1.43x+0.07x<sup>2</sup> | 0.982 |
|         | O      | 0.41                          | 0.08 h         | 3.64 h            | y=0.08−0.31x−0.14x<sup>2</sup> | 0.890 |
|         | R      | 1.21                          | 0.01 h         | -                 | y=1.97−2.83x+0.42x<sup>2</sup> | 0.363 |
| UV(I)   | Y      | 1.18                          | 2.07 h         | 74.12 h           | y=−0.02−0.25x−0.17x<sup>2</sup> | 0.996 |
|         | B      | 0.56                          | 1.17 h         | 29.41 h           | y=−0.71+0.65x−0.24x<sup>2</sup> | 0.990 |
| UV(II)  | BS     | 0.28                          | 50.04 h        | 118.10 h          | y=0.09−0.35x−0.07x<sup>2</sup> | 0.941 |
|         | O      | 0.56                          | 0.08 h         | 0.62 h            | y=−7.85+6.10x−1.44x<sup>2</sup> | 0.999 |
| UV(III) | W      | 1.20                          | 0.39 h         | 38.74 h           | y=1.02−0.69x−0.04x<sup>2</sup> | 0.969 |
|         | P      | 0.13                          | 0.02 h         | 5.37 h            | y=−2.16−0.84x−0.27x<sup>2</sup> | 0.916 |
| UV(IV)  | R      | 0.01                          | 0.03 h         | -                 | y=7.08−6.06x+0.91x<sup>2</sup> | 0.230 |

5. Acknowledgments

Acknowledgments are due to the European Union’s Horizon 2020 program under grant agreement n. 764025 (SWS-HEATING).

References

[1] Angel S, Parent J, Civco D L, Blei A and Potere D 2011 *Progress in Planning* **75** 53–107 ISSN 0305-9006

[2] European Commission 2013 *Digital Agenda for Europe* [URL] https://ec.europa.eu/digital-single-market/en/news/new-commission-report-lighting-cities-accelerating-deployment-innovative-lighting-european

[3] Traverso M, Donatello S, Moons H, Rodriguez Quintero R, Gama Caldas M, Wolf O, Van Tichelen P, Van Hoof V and Geerken T 2017 *Publications Office of the European Union, Luxembourg* 8–9

[4] Mockey Coureaux I and Manzano E 2013 *Energy for Sustainable Development* **17** 357–362 ISSN 0973-0826

[5] Yoomak S, Jettanasen C, Ngaopitakkul A, Bunjongjit S and Leelajindakrairerk M 2018 *Energy and Buildings* **159** 542–557 ISSN 0378-7788

[6] Khan N and Abas N 2011 *Renewable and Sustainable Energy Reviews* **15** 296–309 ISSN 1364-0321

[7] Takhkhem L and Halonen I 2015 *Journal of Cleaner Production* **93** 234–242 ISSN 0959-6526

[8] Pan W and Du J 2021 *Building and Environment* **192** 107587 ISSN 0360-1323

[9] Boyce P R 2019 *Building and Environment* **151** 356–367 ISSN 0360-1323

[10] Capelletti R 2017 *Luminescence Reference Module in Materials Science and Materials Engineering* (Elsevier) ISBN 978-0-12-803581-8

[11] Jain A, Kumar A, Dholke S and Peshwe D 2016 *Renewable and Sustainable Energy Reviews* **65** 135–153

[12] Rondá C 2017 *Rare-earth phosphors: Fundamentals and applications Reference Module in Materials Science and Materials Engineering* (Elsevier)

[13] Chiatti C, Fabiani C and Pisello A L 2021 *Annual Review of Materials Research* **51**

[14] Chiatti C, Fabiani C, Cotana F and Pisello A L 2021 *Energy* (in press)

[15] Fabiani C, Chiatti C and Pisello A L 2021 *Renewable Energy* **172** 1–15 ISSN 0960-1481

[16] Gao Y, He B, Xiao M, Fang Z and Dai K 2018 *Construction and Building Materials* **165** 548–559

[17] Taikar D 2020 *Journal of Alloys and Compounds* **828** 154405

[18] Rojas-Hernandez R E, Rubio-Marcos F, Angel Rodriguez M and Fernandez J F 2018 *Renewable and Sustainable Energy Reviews* **81** 2759–2770 ISSN 1364-0321

[19] Kang C, Liu C, Chang J and Lee B 2003 *Chemistry of Materials* **15** 3966–3968

[20] DIN 67510-1 2020 Phosphorescent pigments and products - part 1: Measurement and marking at the producer