Energy Balance of a Continuous Structural Health Monitoring System based on Energy Harvesting

Carmine Stefano Clemente¹, Daniele Davino² and Vincenzo Paolo Loschiavo²

¹ Department of Energy, Systems, Territory and Constructions Engineering, University of Pisa, 56122 Pisa, Italy
² Department of Engineering, University of Sannio, 82100 Benevento, Italy
E-mail: carmine.clemente@ing.unipi.it; davino@unisannio.it; loschiavo@unisannio.it

Abstract. The Structural Health Monitoring (SHM) may be a relevant technique to monitor historical buildings, masonry, bridges, etc. It becomes even more important if it can be applied in a continuous way, once incorporated in a Wireless Sensor Network (WSN), being able to provide data in an automatic and endless mode without any human intervention. Of course, WSN needs a power source, a role prevalently held by batteries. However, this solution has several issues: it is not eco-friendly and needs a periodic replacement hence increasing costs and reducing the SHM spread. The Energy Harvesting (EH) is a very promising technique to supply WSN. It converts the environmental energy into electrical energy allowing its local accumulation, within the sensor node, in supercapacitor or rechargeable batteries. Anthropic environments are plenty of energy (photovoltaic, kinetic, etc) but this is a non-continuous source and then an energy balance could highlight the suitability of an EH solution. This work is aimed to present a clear picture of EH for SHM by considering all the previous elements in the context of cultural heritage. The result is the definition of specific applications in which those WSNs, based on EH, could be competitive with respect to more traditional technologies.

1. Introduction

Nowadays, the monitoring and control of civil structures or infrastructures is persecuted through the Structural Health Monitoring (SHM) which is a methodology of in-service health assessment for a structure within an autonomous monitoring system [1, 2, 3]. Health monitoring is necessary, especially for historical and cultural buildings, since they may exhibit premature deterioration, structural damage and performance problems, or they may even have aged beyond their expected design life. The sensitive data are obtained by periodically measuring the structural response or the operational environment conditions by means of suitable sensors and devices interconnected in a Wireless Sensor Network (WSN), as sketched in Figure 1. The most widely used power supply consists in batteries. They have indeed a great energy density and, with their reduced dimensions, contribute to the compactness of the single sensor node. Furthermore, their long lifetime guarantees a sensor’s autonomy of years, by depending on the power consumption of the on-board electronics. Nevertheless, batteries have to be substituted or recharged resulting in several issues, such as disposal and periodical maintenance operated by a specialized worker. [5]. These factors could penalize the use of WSNs for SHM in civil structures, especially for cultural heritage, and then reduce the spread of such kind of applications.
In this paper, we provide an overview on the main Energy Harvesting (EH) techniques since they could represent in the near future a valid alternative to the batteries, overcoming the problems outlined above. In particular, our aim is to underline through few test cases what is the state-of-the-art of the EH technology stressing how far we are from its real application to the SHM within the cultural-heritage context. EH applications scavenge small quantities of
energy in the surrounding environment [6]. These quantities are converted into electrical energy in order to supply low-power consumption electronics, such as single sensor node. Ambient energy is present substantially everywhere in the form of vibrations, thermal gradient, pressure gradient, electromagnetic radiations, etc, and it represents energy which, if not captured, would otherwise be wasted [7]. As a consequence, ambient energy represents the best “candidate” to be used in EH techniques. The key advantages of EH are mainly related to the possibility to minimize the maintenance frequency of batteries (charging or replacing them) or even to eliminate the maintenance for the whole device’s lifetime [8, 9]. It is important to highlight that nowadays batteries still have more practical advantages, such as energy capacity, reliability and costs, compared to the EH techniques. However, as a matter of fact, WSNs powered by batteries are not widespread since sensor node dimensions and consumptions are progressively reducing. This circumstance opens scenes of interest for the EH.

In the context of cultural heritage, environments are plenty of energy (photovoltaic, kinetic, radio waves, etc) due to the anthropic actions. However, the effective harvested energy could be non-continuous in time, for example due to the periodicity of natural or artificial illumination or the availability of vibrations. Moreover, the wireless sensor node is characterized by a certain energy consumption that depends on multiple factors, such as: the typology of sensors, the type of measurement (temperature, humidity, accelerations, displacements, pollutants, etc), the measurements frequency, the data sending frequency, etc.

In the following, a single wireless sensor node is considered and the total required energy per year is computed. Different scenarios regarding the SHM in cultural heritage have been considered, by taking into account, for each one, different EH typology application, as conceptualized in Figure 2. The harvested energy is compared with the required one, with the aim of present a clear picture of the potentiality of EH devices for SHM in the specific context of cultural heritage.

2. Considered Sensor Node

The wireless sensor node considered in this manuscript is composed of four parts: the μ-processor Texas Instruments (TI) MSP430, the trans-receiver module ESP32 WiFi/bluetooth, the tri-axial accelerometer ADXL 362 and, finally, the embedded temperature and humidity sensor HTU21D(F). Table 1 shows some technical information about the sensor node. With these data the yearly total energy required by the sensor node (\(E_{ns}\)) has been computed. In particular, it consists in the sum of the energy required in standby-mode and active mode, by considering a measuring time (\(t_1\)) of 60 s, a transmission data time (\(t_2\)) of 30 s and a processing CPU time (\(t_3\)) of 10 s. Moreover, \(E_{ns}\) is function of the the number of measurement (\(N_m\)) and transmissions (\(N_t\)) per year, considered both as one per week, one every two days, one per day, two per day and, finally, three per day. In Figure 3 it is shown the surface representing \(E_{ns}\) with respect to \(N_m\) and \(N_t\). It is worth noting that the matrix \(E_{ns}\) is triangular, because is meaningless to have a number of transmissions greater than the number of measurements. For the sake of simplicity, in this paper \(t_2\) is considered constant but, in general, it could depend on the data

Table 1: Power supply data of each component of the considered sensor node [10, 11, 12, 13].

| Electronic Component | Input Voltage | Input current in stand-by mode | Input current in active mode |
|----------------------|---------------|-------------------------------|-------------------------------|
| TI MSP430            | 3.3 V         | 0.7 μA                        | 270 μA                       |
| ESP32 WiFi/bluetooth | 3.3 V         | 20 μA                         | 100 mA                       |
| ADXL 362             | 3.3 V         | 10 nA                         | 3 μA                         |
| HTU21D(F)             | 3.3 V         | 20 nA                         | 450 μA                       |
quantity measured between two subsequently transmissions. Finally, Figure 3 shows a maximum required energy of the sensor node equal to 13.1 kJ/year when the $N_m$ and $N_t$ are three per day, while it presents a minimum value of 2677 J/year when one measurement and transmission per week occurs.

### 3. Radio frequency/Wi-Fi Energy Harvesting

Nowadays, in almost all the surrounding environment, wireless signals and their associated radiant energy are available. Radiant energy comes, in principle, from ambient electromagnetic waves such as visible light and ultraviolet rays [14]. Wireless signal can carry information as well as energy [15, 16], and thus it can be further exploited for wireless energy harvesting (WEH).

There are mainly three methods to achieve wireless EH [17], i.e., near-field methods including resonant inductive coupling [18, 19], magnetic resonance coupling [20, 21], and far-field method using radio-frequency (RF) energy harvesting [22, 23, 24]. These methods have all been studied extensively (e.g. [22, 25, 26]). Among them, we mainly focus on RF energy harvesting since the RF energy is a resource widely present both indoors (e.g., Wi-Fi signal from wireless router) and outdoors (e.g., cellular and DTV signal), representing a valid alternative solution to the energy harvesting issue within the context of cultural heritage. Many techniques have been developed, during the last years, to harvest the RF energy and still a lot of studies are ongoing in order to optimize the harvested energy amount [27, 28].

The green, small-size, and sustainable features make the RF-EH technique suitable for a wide range of applications, such as the Internet of Things (IoT), body area networks (BANs), and smart infrastructures [29]. Those applications, in fact, usually need the assistance of numerous wireless sensor nodes. However, it is worth to underline that the aim of this paper is not to provide a detailed overview on the state of the art related to the WEH. Instead, our aim is to provide a rough quantitative estimation of the energy that could be harvested via the main energy harvesting techniques. Therefore, let us focus for a while, just to stress the potentiality of the RF energy harvesting, on the daily typical visitors flow in a museum. The Wi-Fi is a typical indoor service offered by museums that is not constantly fully exploited, in terms of energy, by the users during the day. This allows the energy harvester to recover the unexploited part of energy (delivered anyway) to feed, for example, a sensor node. On the other hand, considering an outdoor application of the RF energy harvesting for monuments, e.g. for the Leaning Tower of Pisa, it is sufficient to imagine how they are continuously covered with cellular (e.g. GSM-900, GSM-1800 and UMTS-2100) or DTV signals.

First, we investigate an indoor application, as the one depicted in Figure 2a. In a RF energy harvesting system, the key component is the rectenna, which harvests the RF energy and then converts it into DC power. For our considerations on the possible harvested energy, let us consider a rectenna using beamwidth-enhanced antenna array for RF power harvesting applications, developed in [30]. The rectenna taken into account is designed to harvest the RF power from the 5.8 GHz Wi-Fi band. It is composed by a 1 x 4 antenna array, having total external dimensions of 129 mm x 30 mm. The results proposed in [18] show that the maximum power conversion efficiency (PCE) of 70.1% can be achieved when the input power density is $1276 \mu W/cm^2$. Furthermore, the PCE is more than 50% when the wave incident angle is between -38° and 35° at the H-plane under this power density. Therefore, considering an input power density of $1276 \mu W/cm^2$ with a non-optimal incident angle of around 22°, the output DC power is around 10 mW. At this point two different scenario have been considered: the first where the source of WiFi is constantly active and the RF harvester works during the night, i.e. 10 hour per day, while the second where WiFi is active only during the day and the RF harvester works when few people are in the museum, then 30 minutes per day. In the first case the RF harvested energy is about $E_{RF,in,n} = 130$ kJ/year, while in the second it is $E_{RF,in,d} = 6570$ J/year. Finally, as outdoor application, we consider a dual-band rectenna that can harvest ambient RF power.
of both GSM-1800 and UMTS-2100 bands [31]. The rectenna is based on a broadband 1x4 quasi-Yagi antenna array with an area of 190 mm x 100 mm, bandwidth from 1.8 to 2.2 GHz and high gains of 10.9 and 13.3 dBi at 1.85 and 2.15 GHz, respectively. Measurement results show that a PCE of 40% and an output DC voltage of 224 mV have been achieved over a 5 kΩ resistor when the dual-tone input power density is 455 µW/m², with a consequently output power of 3.45 µW and an outdoor RF harvested energy of about $E_{RF,out} = 110$ J/year.

In the RF outdoor applications (see Figure 2b), the harvested energy ($E_{RF,in,n}$) is not sufficient to supply the considered sensor node or, however, the antenna’s area should be in the order of tenths of m². Conversely, RF indoor harvesting could be a viable solution to feed sensor node. In particular, the RF energy harvested during the night (10 hours) is ten times greater than the max value of $E_{ns}$, then this solution is able to feed even a network of wireless sensor node (WSN). In Figure 4 are reported the matrix $E_{ns}$ (orange surface) and the RF energy harvested during 30 minutes per day $E_{RF,in,d}$, which is represented by the green plane. The orange surface below the green plane corresponds to a sensor node required energy which is less than the potential available harvested energy. Consequently, in this case, the harvester could feed the sensor node only for a number of transmissions per year less or equal to one per day ($N_t \leq 365$).

4. Indoor and Outdoor Photovoltaic Energy Harvesting

In this section, EH from solar cells has been considered as power source for the wireless sensor node taken into account. The working principle of this harvester is based on the photovoltaic (PV) effect, which consists in a detectable voltage through the terminals of a certain semiconductor junction material when it is exposed to light radiations (natural or artificial). Often, the output power of harvesters based on PV cells can range from µW to mW depending on the cell’s area, the typology of semiconductors and the amount of illumination [9].

The sensor node powered by PV cell could be installed outside the wall of an ancient building or tower in order to monitor tilt angles or vibrations, while it could be installed in closed spaces as like as museum to monitor and control sensitive parameters, such as temperature or humidity [32]. Indeed, in the latter scenario, artificial lighting radiation is considerably spreaded with the aim to better appreciate color tunes and shapes of paintings, frescoes, statues, sculptures or
historical objects [33, 34]. In general, the harvested power could depend significantly on various factors, among which light source type, radiation incident angle and PV cell material. Then, in both cases of outdoor or indoor applications, it is extremely important to have information on the incident radiation (spectral composition, global intensity, etc.) in order to properly estimate the harvested output power under given ambient light conditions, as reported in [33, 35].

Generally speaking, in indoor light applications the energy source density is about tenths of mW/cm² with a potential harvested energy density from tens up to hundreds of µW/cm² [36, 37, 38]. In case of indoor location, for example a museum as conceptualized in Figure 2c, both natural and artificial light radiation can be present. Very often, during the operating public time, the artificial lighting is regulated by museum staff, based on their personal judgment, when natural illumination is lower than 300 lux. Moreover, because there is no variable shading system, the control of daylighting is static and a high illumination, especially on a summer day, could occur [39]. This time cumulative illumination exposure could be dangerous for the preservation of artistic elements as well as economically expensive and non eco-friendly. To this aim, some research works studied the optimal intensity radiation in locations such as museum, by taking into account the quality of visitor experience, the energy saving and the environmental sustainability [33, 40].

By basing on recent works, it has been possible to estimate the intensity radiation present in a museum in a range from 150 to 500 lux, by depending on the typology of lamps (CFL or LED sources), historical elements, context and location [42, 43, 44]. Then, in this paper, a PV panel (50 mm x 20 mm) with an efficiency of around 10%, under an illumination condition of 500 lux has been considered, with an output power of about 450 µW [32, 45]. By considering a museum opening time of 10 hour per day, it has been possible to estimate an yearly harvested power $E_{PV,in} = 5913$ J/year. In Figure 5 are shown the matrix $E_{ns}$ (orange surface) and the indoor photovoltaic energy harvested in this scenario $E_{PV,in}$, which is represented by the blue plane. The orange surface below the blue plane represent the different working conditions of the considered sensor node supplied by the PV indoor sensor. It is worth to note that, in this case, the number of transmissions per year do not have to be greater then one per day ($N_t <= 365$).

In outdoor light applications the energy source density is about hundreds of mW/cm² with
a possible harvested energy density of tens of $\mu$W/cm$^2$ [9, 38]. In case of outdoor PV cell, it has been considered as hypothetical scenario an application of the wireless sensor node placed on top of the Leaning Tower of Pisa ($43^\circ43'22.5''$N $10^\circ23'47.9''$E), as shown in Figure 2d. In this case, it is feasible to proceed as normally done in the design studio of a traditional home PV implant. In particular, the monthly average daily global solar radiation on tilted surface (tilt angle: $45^\circ$, azimuth angle: $0^\circ$) with a ground reflection coefficient of 0.1 is represented in Figure 6 and, then, the global yearly radiation is estimated in about $R_g = 565.7$ kJ/cm$^2$ [41]. In such conditions, a 50 mm x 20 mm PV cell with an efficiency of $\eta = 5\%$ is capable to harvest an energy equal to $E_{PV,\text{out}} = 282.85$ kJ/year. This harvested energy is widely capable to supply not only the considered sensor node, but even different WSN.

5. Piezoelectric Kinetic Energy Harvesting
One of the most promising and studied EH techniques concerns the use of Piezoelectric materials (PZT) [4]. These belong to a subset of smart materials and, in particular, by compressing the opposite edges of piezoelectric materials, opposing charges start to move on that edges, behaving like a charged capacitor, producing an electric potential difference across it (direct piezoelectric effect). Then, by connecting the two ends of the material on a load an electric current flows. As consequence, a time-varying mechanical stress could be converted in electrical energy (Kinetic Energy Harvesting, KEH [46, 47]). Harvesters based on piezoelectric materials show high converted energy density and, because of the relatively cheapness of the active material, they are becoming widely adopted in technical and industrial application. Furthermore, several PZT harvesters are modeled and designed in literature [48, 49, 50].

A possible application of a piezoelectric KEH is to locate the harvester below the pavement or walkway placed in historical locations such as catacombs or archaeological sites, in order to supply one or more sensor nodes for SHM. In this scenario, a suitably modified piezoelectric KEH proposed in [51] is able to recover 1.3 mW continuous power from the ongoing walking of visitors (about 1 Hz). A schematic example of the possible application is shown in Figure 7, where the red arrow represents the compression stress transferred on the harvester by the walking people. Let us consider a number of visitors per day equal to 6000, the potential harvested energy is

Figure 7: 2-D scheme of the suitable modified piezoelectric KEH [51] implantable over the pavement, recovering energy from the foot-step of visitors.

Figure 8: Comparison between the energy required by the sensor node $E_{ns}$ (orange surface) and the PZT harvested energy $E_{KEH,\text{pzt}}$ (red plane).
\( E_{KEH,pzt} = 2847 \) J/year. Figure 8 shows the matrix \( E_{ns} \) (orange surface) and the PZT harvested energy \( E_{KEH,pzt} \), which is represented by the red plane. In the considered scenario, the sensor node could be supplied only in case of one transmission event per week. Finally, it is worth to note that even if this solution seems less promising with respect to other harvesting techniques, it could be a valid alternative where, for artistic and historical motivations, the PV and RF harvesting device are not installable.

6. Conclusions

The possibility to feed WSN for SHM through the energy harvested from the surrounding environment and human activity is investigated in this paper in the context of cultural heritage. In particular, the energy balance of a continuously supplied wireless sensor node is considered under the following EH techniques: radio frequency/Wi-Fi, photovoltaic and piezoelectric. The results show that the energy required by the sensor node strongly depends, among different parameters, by the number of measurements and transmissions of the sensitive data.

Between the EH techniques analyzed, the most powerful is the PV outdoor harvesting because of the great available quantities of yearly solar radiation. Indeed, it would be able to supply an entire WSN, while the RF outdoor harvesting is still not sufficient. However, in indoor applications, such as museum or archaeological center, RF and PV harvesting (indoor) are capable to feed a sensor node, which should work with one (or less) transmission event per day. Finally, in historical sites, when PV cell or RF antenna cannot be installed for aesthetic reasons, a KEH device based on piezoelectrics placed under the visitor’s walkway can be the main energy source. In this case, the sensor node could work with only one transmission per week, by depending on the visitors number.

Acknowledgments

Vincenzo Paolo Loschiavo’s work has been supported by PON Ricerca e Innovazione 2014-2020 - A.I.M. - Attrazione e Mobilità Internazionale, linea 1 (grant AIM 1823125 - 3).

References

[1] Balageas D, Fritzen C P and Güemes A (eds) 2010 Structural Health Monitoring (Wiley-ISTE)
[2] Chang P, Flatau A and Liu S 2003 Structural Health Monitoring: An International Journal 2 257–267
[3] Chang F K, Markmüller J F C, Yang J and Kim Y 2011 Structural health monitoring System Health Management: With Aerospace Applications (John Wiley & Sons, Ltd) pp 419–428
[4] Maiwa H 2016 Piezoelectric energy harvesting Piezoelectric Materials ed Ogawa T (Rijeka: IntechOpen) chap 06
[5] Najafi K, Galchev T, Aktakka E, Peterson R and McCullagh J 2011 Microsystems for energy harvesting 2011 16th International Solid-State Sensors, Actuators and Microsystems Conference (IEEE) pp 1845–1850
[6] Kaźmierski T J and Beebly S (eds) 2011 Energy Harvesting Systems (New York: Springer)
[7] Clemente C S, Davino D and Visone C 2017 IEEE Transactions on Magnetics 53 1–4
[8] Davino D, Pecce M, Visone C, Clemente C and Ielardi A 2015 Dynamic monitoring of guardrails: Approach to a low-cost system 2015 IEEE Workshop on Environmental, Energy, and Structural Monitoring Systems (EESMS) Proceedings (IEEE)
[9] Shaikh F K and Zeadal S 2016 Renewable and Sustainable Energy Reviews 55 1041–1054
[10] Texas Instruments MSP430 datasheet [Online]. Available from: https://www.ti.com [Accessed 26th November 2019]
[11] Espressif ESP32 datasheet [Online]. Available from: https://www.espressif.com [Accessed 26th November 2019]
[12] Analog Devices ADXL362 datasheet [Online]. Available from: https://www.analog.com [Accessed 26th November 2019]
[13] TE connectivity HTU21D(F) datasheet [Online]. Available from: https://www.te.com [Accessed 26th November 2019]
[14] Panatik K Z, Kamardin K, Shariff S A, Yuhani S S, Ahmad N A, Yusop O M and Ismail S 2016 Energy harvesting in wireless sensor networks: A survey 2016 IEEE 3rd International Symposium on Telecommunication Technologies (ISTT) (IEEE)
[15] Varshney L R 2008 Transporting information and energy simultaneously 2008 IEEE International Symposium on Information Theory (IEEE)
[16] Grover P and Sahai A 2010 Shannon meets tesla: Wireless information and power transfer 2010 IEEE International Symposium on Information Theory (IEEE)
[17] Zhao N, Zhang S, Yu F R, Chen Y, Nallanathan A and Leung V C M 2017 IEEE Access 5 10403–10421
[18] Valtchev S, Borges B, Brandisly B and Klassens J 2005 Efficient resonant inductive coupling energy transfer using new magnetic and design criteria 2005 IEEE 36th Power Electronics Specialists Conference (IEEE)
[19] Liu H 2011 Maximizing efficiency of wireless power transfer with resonant inductive coupling Kurs A, Karalis A, Moffatt R, Joannopoulos J D, Fisher P and Soljačić M 2007 science 317 83–86
[20] Kurs A, Karalis A, Moffatt R, Joannopoulos J D, Fisher P and Soljačić M 2007 science 317 83–86
[21] Jonah O and Georgakopoulos P 2010 Shannon meets tesla: Wireless information and power transfer 2010 IEEE International Symposium on Information Theory (IEEE)
[22] Zhao N, Zhang S, Yu F R, Chen Y, Nallanathan A and Leung V C M 2017 IEEE Access 5 10403–10421
[23] Visser H J and Vuillers R J M 2013 Proceedings of the IEEE 101 1410–1423
[24] Kim S, Vyas R, Bito J, Niotaki K, Collado A, Georgiadis A and Tentzeris M M 2014 Proceedings of the IEEE 102 1649–1666
[25] Sudevalayam S and Kulkarni P 2011 IEEE Communications Surveys & Tutorials 13 443–461
[26] Lu X, Wang P, Niyato D, Kim D I and Han Z 2016 IEEE Communications Surveys & Tutorials 18 1413–1452
[27] Bito J, Hester J G and Tentzeris M M 2015 Ambient energy harvesting from a two-way talk radio for flexible wearable devices utilizing inkjet printing masking 2015 IEEE MTT-S International Microwave Symposium (IEEE)
[28] Luo Y, Pu L, Wang G and Zhao Y 2019 Sensors 19 3010
[29] Kamalinejad P, Mahapatra C, Sheng Z, Mirabbaasi S, Leung V C and Guan Y L 2015 IEEE Communications Magazine 53 102–108
[30] Sun H and Geyi W 2017 IEEE Antennas and Wireless Propagation Letters 16 1451–1454
[31] Yue X, Kauer M, Bellanger M, Beard O, Brownlow M, Gibson D, Clark C, MacGregor C and Song S 2017 IEEE Internet of Things Journal 4 2092–2103
[32] Bito J, Hester J G and Tentzeris M M 2015 Ambient energy harvesting from a two-way talk radio for flexible wearable devices utilizing inkjet printing masking 2015 IEEE MTT-S International Microwave Symposium (IEEE)
[33] Balocco C and Volante G 2018 Sustainability 10 1671
[34] Balocco C, Farini A, Baldanzi E and Volante G 2018 IOP Conference Series: Materials Science and Engineering 364 012007
[35] Ma X, Bader S and Oelmann B 2017 IEEE Sensors Journal 17 3884–3891
[36] Tan Y K and Panda S K 2017 IEEE Transactions on Industrial Electronics 58 4424–4435
[37] Qiu Y, Liempd C V, het Veld B O, Blanken P G and Hoof C V 2011 5µw-to-10mw input power range inductive boost converter for indoor photovoltaic energy harvesting with integrated maximum power point tracking 2011 IEEE International Solid-State Circuits Conference (IEEE) pp 118–120
[38] Othman A and Maga D 2018 Indoor photovoltaic energy harvester with rechargeable battery for wireless sensor node 2018 18th International Conference on Mechatronics - Mechatronika (ME) (IEEE) pp 1–6
[39] Graaf T D, Dessouky M and Müller H P 2014 Renewable Energy 67 30–34
[40] Viani F, Polo A, Garofalo P, Anselmi N, Salucci M and Giarola E 2017 IEEE Sensors Journal 17 1213–1214
[41] ENEA-SOLTERM Atlante italiano della radiazione solare [Online]. Available from: http://www.solaritaly.enea.it/ [Accessed 26th November 2019]
[42] Scuello M, Abramov I, Gordon J and Weintraub S 2004 Color Research & Application 29 121–127
[43] Schanda J, Cseri P and Szabó F 2014 LEUKOS 12 71–77
[44] Zhai Q, Luo M and Liu X 2014 Lighting Research & Technology 47 795–809
[45] Mathews I, King P J, Stafford F and Frizzell R 2016 IEEE Journal of Photovoltaics 6 230–235
[46] Zhai Q, Luo M and Liu X 2014 Lighting Research & Technology 47 795–809
[47] Clemente C S and Davino D 2019 Materials 12 3199
[48] Zhao H, Ling J and Yu J 2012 Journal of the Ceramic Society of Japan 120 317–323
[49] Leinonen M, Palossaari J, Juuti J and Jantunen H 2013 Journal of Intelligent Material Systems and Structures 25 391–400
[50] Li X and Strezov V 2014 Energy Conversion and Management 85 435–442
[51] Shenck N and Paradiso J 2001 IEEE Micro 21 30–42