Discover Energy

Perspective

From source to sink: the path to efficient energy harvesting with LEDs and displays

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Abstract

In the last three decades, light emitting diodes (LEDs) have represented a breakthrough innovation for optoelectronic applications. From optical communication to lighting and compact displays, LEDs are nowadays the device of choice in all those fields where high fluence, low power consumption and high pixel density are required. While LEDs are usually designed to maximize their performance in terms of light emission, they share the same materials and basic structure with solar cells. This similarity suggests to exploit LEDs in photovoltaic mode to be operated for harvesting energy from light in the environment. Despite the apparent simplicity of this approach, only a few examples to this extent are available in literature and several technical aspects of the corresponding implementation of LEDs as energy harvesters remain unexplored. Hereby, we report on recent progress in employing LEDs in the photovoltaic mode for energy harvesting and discuss future research directions, advocating increased efforts towards the exploitation of LEDs and LED-displays for the reduction of the energy footprint of portable appliances and electronic devices.

1 Introduction

Energy harvesting, also known as energy *scavenging*, involves capturing energy from the environment and converting it into usable electrical energy. This concept parallels large-scale approaches for renewable energy generation such as solar and wind power, albeit on a significantly smaller scale. While traditional renewable energy systems aim to generate megawatts of power, energy harvesting is primarily focused on converting small amounts that would otherwise be lost, addressing low-power electronic devices and autonomous systems that typically operate within the micro- to milli-Watt range.

Typical microsystems that would primarily benefit from energy harvesting are wireless sensors, which form the backbone of wireless sensor networks. Such networks often consist of several sensor nodes, each equipped with sensing, processing, storing and communication capabilities. Given their wireless nature, traditional power sources such as batteries pose significant limitations, including e.g. finite storage capacity, the need for periodic replacement or recharging, and environmental concerns associated with their disposal. The implementation of energy harvesting strategies in microsystems can effectively tackle these issues, increasing the time span between maintenance need by human operators, and reducing the footprint of batteries (or even eliminating them).

The applications of energy harvesting technologies are indeed vast, spanning across multiple domains besides sensing, with key applications in medical devices, consumer electronics, remote monitoring, wearable and portable elements.

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Energy harvesting technologies have attracted a lot of attention in the last two decades and are rapidly expanding, as demonstrated by the related market status and forecast (USD 1 billion in 2023 and expected to reach USD 3.0 billion by 2032, growing at a CAGR of 13% [1]) and by the large amount of scientific papers (more than 24,000 articles published in the last twenty years, with more than half of them published in the past five) [2]. An introduction to energy harvesting and related reviews are available in Refs. [3–5].

The most used environmental energy sources for harvesting are optical [6], mechanical [7], thermal [8] and electromagnetic [9]. The effectiveness of these approaches depends on the energy density at the source and the efficiency of the converting device. Reference values are shown in Fig. 1 for the most relevant [4, 10–12].

Kinetic energy can be converted into electric from various sources including pressure fluctuations, bending, folding, and stretching motions by relatively simple piezoelectric transducers. The mechanical power density available from humans' daily life, machineries and constructions ranges from 20μW/cm^2 to 1mW/cm^2, with the corresponding harvesting devices achieving conversion efficiencies between 1 and 10%. Thermal energy sources from unused, environmental, or human body heat can provide up to 1mW/cm^2, but only about 0.1–3% of this can be converted into electricity due to the limitations of the current technology. The environment is exposed to pervasive electromagnetic radiation including radio-frequency waves emitted by wireless communication devices (GHz) and broadcast waves (MHz). Electromagnetic energy sources exhibit lower power densities, between 2 and 50μW/cm^2, but suitable antennas can reach large conversion efficiencies, up to 50%. The most promising energy source for harvesting is optical energy. Optical radiation, while electromagnetic as well, is considered separately because of its distinct frequency range (400-700THz), encompassing visible to infrared radiation. Optical energy is abundant both outdoor and indoor with a significant power density ranging from 0.1 to 100mW/cm^2. In addition, photovoltaic devices, from low-cost amorphous Silicon cells to advanced multi-junction solar cells can convert between 5 and 30% of this energy into electric power. Such diverse efficiencies and densities highlight the potentials and challenges of various energy harvesting approaches, emphasizing the need for continued innovation and development to maximize their effectiveness and exploit their capabilities, including less studied sources such as infrared light [13] biochemical and biomechanical ones [14, 15].

Among the sources available in the environment, solar energy is the most interesting for an excellent combination of factors, such as wide availability, high power density, efficiency of converting devices, absence of moving parts and low cost. For these reasons, solar photovoltaics has become one of the most important renewable, clean, and sustainable energy sources at the residential, industrial, as well as utility scales. In this light-driven scenario, energy harvesting is attracting a lot of attention also at much smaller scales, for example in power sensors, wrist watches, calculators, portable power-banks, indicators, and in all applications where illumination is available and the power requirements can be met. Small scale energy harvesting from light has been discussed and reported in several scientific papers and review articles [16, 17], with attention to ultra-small scale monolithically integrating solar cells in electronic integrated circuits, as well [18, 19].

However, even a small solar module, despite the aforementioned advantages as a versatile and efficient harvester, is an added element in a self-powered microsystem and requires more space and a custom design, resulting in increased costs and complexity, thus reducing the economic sustainability of the overall system.

In this Perspective, we discuss the potentialities of a novel approach to harvest energy by using light emitting diodes (LED): devices designed and fabricated for a different application but which, when not in use as such, can be operated as solar cells and produce energy.

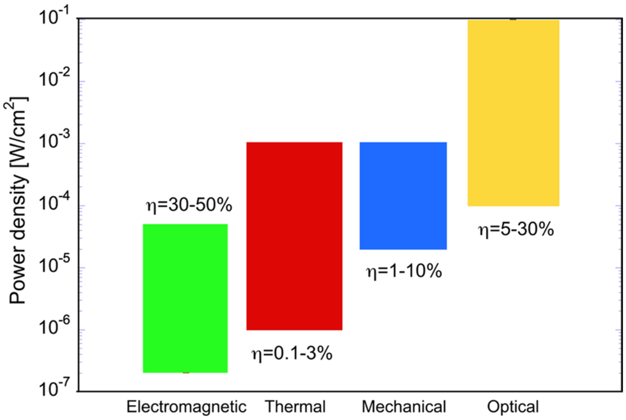

Fig. 1 Reference power density and conversion efficiency for the most relevant energy sources used in energy harvesting (data extracted from Refs. 10–13)

The idea is based on two facts: a) LEDs and solar cells are semiconductor devices with so many common features that LEDs can effectively function as photovoltaic devices; b) LEDs are quite widespread, including their use in large monitors, smartphone screens, laptops, television sets, and lighting appliances, thus they are easily available without requiring substantial changes in the architecture of electronic systems.

2 Solar cell—LED comparison

Solar cells and LEDs are very similar semiconductor devices since their operation is based on two reciprocal light-matter interactions. The solar cell operation is based on optical absorption and the subsequent carrier generation (electrons and holes), provided by incident photons with energy greater than the semiconductor band gap. LED operation is based on electron–hole radiative recombination that yields emission of photons at wavelength corresponding to the semiconductor band gap.

For solar cells and LEDs, a semiconductor *pn* junction is employed to obtain the photovoltaic effect and the electrically stimulated light emission, respectively.

In a solar cell, the *pn* junction allows the charge separation necessary to produce a voltage between the anode and the cathode and a flow of carriers (current) in an external circuit to generate electrical power. In a LED the *pn* junction, when forward biased, provides carrier injection from an external current source, in order to produce the excess electrons and holes to promote recombination and photon emission. The absorption and recombination processes, the junction band-diagrams and the device circuits are schematically displayed in Fig. 2 for both a solar cell (top) and a light-emitting-diode (bottom).

Despite their common basic structure, that is the *pn* junction, solar cells and LEDs may exhibit significant differences in term of size, doping profiles and optical design.

Silicon (Si) solar cells are typically n^+p junctions, featuring a highly doped, thin (a few hundred nanometers) n^+-type emitter and a thick (hundreds micrometers) *p*-type base, which acts as the active layer. The power conversion efficiency

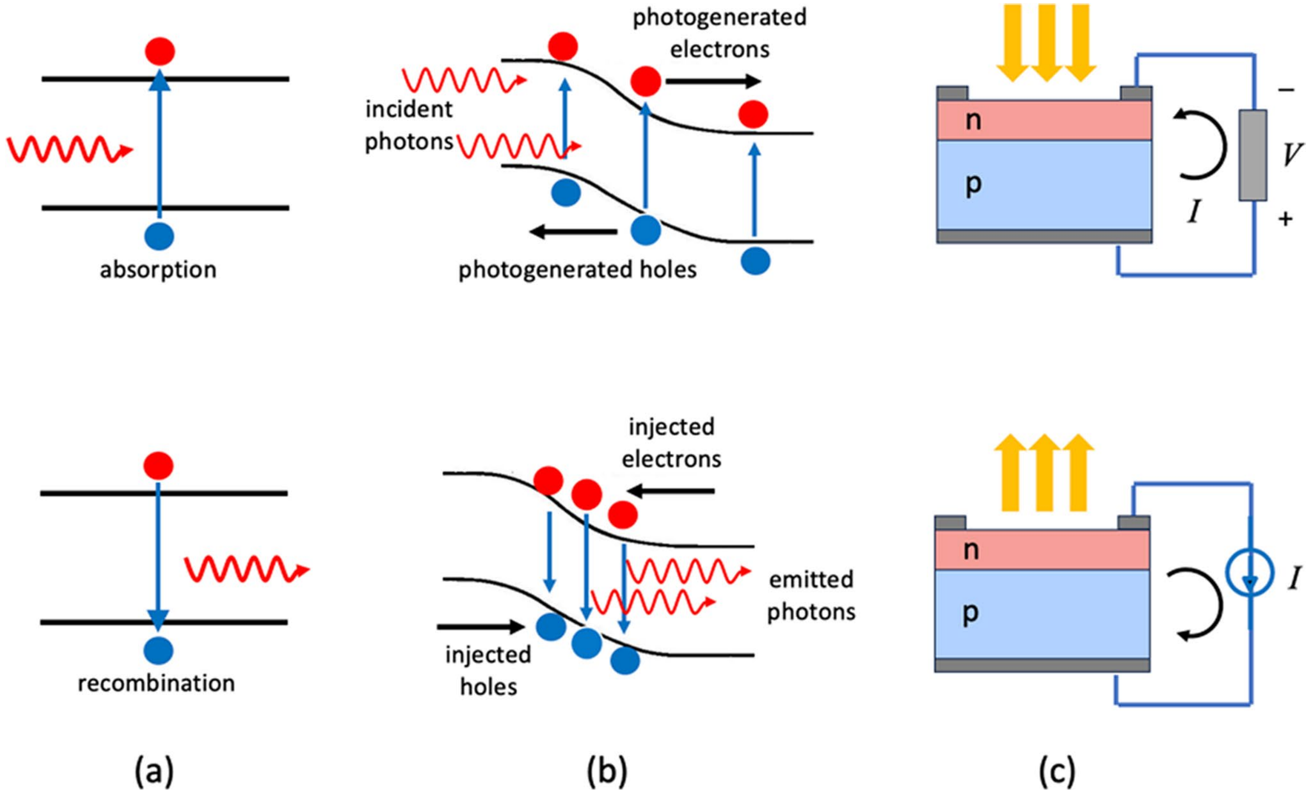

Fig. 2 Schematic drawings of the **a** optical absorption and recombination processes, **b** the *pn* junction band diagrams and **c** the device circuits in a solar cell (top) and a LED (bottom)

of these cells largely depends on the base thickness and low recombination rate. Achieving a low recombination rate requires an optimal doping density, usually around 10^{17} cm^{-3}, which balances the carrier diffusion length with the inverse saturation current. To enhance performance, the cell top surface is often coated with a wideband antireflection layer to reduce light reflection [20]. Monocrystalline Si solar cells on the market typically reach efficiencies of 20% to 25%, while thin-film technologies like CIGS (Copper Indium Gallium Selenide) and CdTe achieve maximum efficiencies between 12 and 18%. Such efficiency ratings are usually determined under standard AM1.5G solar illumination and may differ under other light sources.

An LED consists of a thin *pin* double heterojunction diode, just a few micrometer thick, with the emitting layer made of a semiconductor with a lower band gap. To enhance radiative recombination, the doping levels of the *pin* structure are usually high. This diode is deposited on a thick, heavily doped GaAs substrate and covered with a current-spreading layer. LEDs often feature antireflection coatings optimized for their emission wavelength.

Common materials for the active layer include AlGaAs, AlGaInP and InGaN, depending on the color range. AlGaAs is used for visible and near-infrared, AlGaInP for red, orange, and amber, and InGaN for green, blue, and UV LEDs. White light is typically produced by exciting one or more phosphors using blue or UV LEDs [21].

3 State of the art in energy harvesting with LEDs

Despite the above mentioned differences, several studies have demonstrated that LEDs can effectively operate as solar cells to power electronic circuits.

The first attempt to use already available *pn* junctions in a circuit for energy harvesting dates back to 2006. The junctions, operated as solar cells, were able to power an on-chip ring-oscillator. The prototype consisted of an integrated circuit with energy harvesting photodiodes, a storage capacitance, the ring oscillator and buffers to drive the signal off the chip [22].

An early attempt to use an LED for energy harvesting involved a proof-of-concept system which harvested energy and transmitted optical data at different wavelengths using the same LED. The system was exposed to a laser beam and included a DC-DC converter to charge a storage capacitor. The authors demonstrated the possibility of both receiving power and transmitting light pulses without any external supply [23]. Regrettably, the required laser intensity was much larger than typically available from the environment.

A few years later, the capability of charging a small capacitor by both visible and infrared LED arrays under fluorescent tube illumination was first investigated [24] and a harvester consisting of arrays of infrared LEDs, a commercial power management unit, and a supercapacitor for generating more than 400μW under tube and bulb lights was reported [25].

Horvat et al. developed an LED-powered identification tag made of an energy harvesting array of LEDs, a power management circuit with a storage capacitor, and a microcontroller unit. In order to feed the microcontroller for as long as possible and ensure data integrity of the identification process, optimization was implemented. Measurements on optimized tag showed that five series-connected LEDs could be exposed to a 10W LED-lamp to supply enough energy to the microcontroller and an output LED, along with the control of the power-on circuitry [26].

A rather interesting evaluation of the energy-harvesting capability of several LEDs exposed to sun light was performed, and electric power exceeding 100μW was obtained from a single 3mm x 3mm red LED. In addition, a bidirectional buck-boost DC-DC converter able to transfer energy to and from a LED array was built and tested, achieving up to 2.76 W harvested from a 96 × 216 LED display [27].

Meli et al. proposed a very low-cost battery-less sensor-node based on 4 LEDs, a DC-DC step-up converter, a microcontroller and a low-energy Bluetooth transceiver: they demonstrated that 4 LEDs operated at 250 lx can store enough energy to send proprietary messages every 76 s. At 1000 lx, the message frequency increased to 1 every 23 s [28], opening new perspectives to practical applications of energy harvesting with LEDs.

In a recent paper it was proposed that in visible light communication systems, the incorporated LED can be used to charge the receiver's battery or power a specific module. It was also proven that the quantity of collected energy depends on the power rating of the LED and that using the LED for harvesting energy confers to the mobile terminal a cost-effective advantage [29].

Other authors exploited the operation-duality of LEDs and performed three different functions, namely sensing, harvesting and emission of light. The LED-based system consisted of a 20 × 20 LED array, a switching network, voltage regulation circuitry, a transimpedance amplifier and a field-programmable gated-array (FPGA) for control and communication. The three different modes were demonstrated and a total 16mW power was harvested under 100mW/cm^2 solar irradiation [30].

The feasibility of employing LEDs in harvesting enough energy for practical applications is essentially related to the substantial optical absorption of the materials (typically III-V direct band-gap semiconductors), which allows for large photogeneration of carriers and their efficient collection even in thin layers. However, the high doping concentrations and the presence of several heterointerfaces increase charge recombination, limiting LEDs' photovoltaic efficiency to a narrow range of wavelengths where the collection is appreciable. This happens when electron–hole pairs are generated within the intrinsic layer or close to the diffusion length of the minority carriers.

The relationship between electroluminescence and conversion efficiency in a solar cell has been discussed and investigated by several authors, theoretically and experimentally demonstrating that an augmented emission of photons corresponds to a larger open-circuit voltage, contributing to an increased conversion [31, 32].

In an efficient solar cell, internally emitted photons are likely to be trapped, reabsorbed and re-emitted, enabling their recycling at open-circuit. This internal reabsorption can regenerate electron–hole pairs, extending the minority-carrier lifetime. Conversely, non-radiative recombination would reduce the efficiency. It should therefore come as no surprise that LEDs, designed to maximize radiative recombination, also perform well as solar cells.

It is also known that measuring the electroluminescence of forward-biased solar cells can be exploited as a contactless Voltmeter to evaluate quasi-Fermi level separation and is often used for quality control in solar cell manufacturing, practically demonstrating the close relationship between emission and collection efficiency.

Moreover, some LED coatings are bidirectional, reducing surface reflectance when exposed to light and enhancing energy harvesting near the emitted wavelength. Consequently, while LEDs can operate as solar cells, their photovoltaic capabilities are strongly related to material properties and the overall efficiency is mainly linked to the wavelength.

Despite the interest in LEDs as harvesters, little systematic research has been reported to date on their energy conversion dependence on typical characteristics (i.e., peak emission wavelength, power and spectral range) and on the spectrum of the illuminating light source. This is relevant towards their use in a new paradigm for sustainability; hence, we recently investigated the potentials of a large number of visible and near-infrared LEDs for energy harvesting, using various light sources from solar irradiation to fluorescent tubes, to LED and halogen lamps. In our study, we observed a correlation of the LED spectral characteristics and the available source with the overall quantum efficiency, thereby demonstrating that a careful selection of the harvesting LED can provide unexpectedly high power conversion efficiencies, as large as 39% and 30% under fluorescent and LED illumination, respectively [33].

Taking into account that indoor light power-density can easily reach 100μW/cm^2, the electrical power density produced by an LED can therefore be in the 30-40μW/cm^2 range.

Due to the wide spectrum of solar light, the maximum measured conversion efficiency of an LED under sun irradiation is significantly lower (about 8%). Corresponding power densities of 8μW/cm^2 and 8mW/cm^2 can be obtained indoor and outdoor, respectively.

Unfortunately, typical white LEDs for lighting exhibited rather low (about 2.5%) harvesting conversion due to the presence of phosphor, which is a good emitter but works as an absorbing filter when the device operated in solar-cell mode [33].

4 Discussion

Despite that a clear and decisive demonstration of the effectiveness of LEDs as energy harvesters has been obtained, several steps are still needed towards their full exploitation in practical/commercial applications. The optimization of LEDs for photovoltaic operation can be obtained leveraging different aspects, from the material stack composing the diode itself to the characteristics of the harvesting system, considering the whole energy chain from the converting element to short or long-term energy storage. Hereby we intend to highlight the perspectives for the implementation of LED-based energy harvesters, encouraging/triggering the research community to fill up the gaps towards a proper design and engineering of such systems.

4.1 LED device characteristics and optimization

As detailed in Sect. 2, solar cells and LEDs share a similar structure but with some important differences which may limit the efficiency of LEDs for harvesting. Radiative recombination in the intrinsic layer and non-radiative recombination in the doped layers typically hamper the photovoltaic efficiency, reducing the total power provided by LED-based harvesters. The role of radiative and non-radiative recombinations should be analyzed separately because radiative effects could even improve the overall efficiency, thanks to the increased carrier lifetime stemming from a cascaded three-step process, namely (1) recombination of photogenerated carriers, (2) emission of photons with energy close to the bandgap of the intrinsic material, and (3) reabsorption of those photons with the consequent generation of new electron–hole pairs. The nature of this mechanism, however, has yet to be fully comprehended and its impact on the efficiency of LED light converters are still debated [34]. A thorough analysis on the relationship between radiative recombination and the efficiency of LEDs in photovoltaic mode is still missing in the literature, despite being crucial for optimizing LED design for harvesting. Conversely, non-radiative recombination is clearly detrimental for both light emission and photovoltaic power generation, thus the path towards more efficient LEDs is expected to provide additional advantages for their use as harvesters.

Of importance for photovoltaic efficiency is the presence of anti-reflection (AR) coatings, typically deposited on LED emission facets. These films are usually designed to grant high transmissivity in a very narrow wavelength range, corresponding to the LED emission peak of the LED. The introduction of broadband AR films could dramatically enhance the efficiency of LED harvesters under solar irradiation. Several designs have been proposed for standard solar cells and could be easily transferred to LEDs. However, broadband AR typically trade off the wide spectral range with a lower peak transmissivity, not well suited for light emitters. A detailed analysis of optimized AR coatings for both photon emission and photovoltaic generation is still missing and could become a milestone towards the widespread implementation of LEDs for energy harvesting. Since ultra-bright white LEDs are nowadays widely available for illumination purposes, and many countries are entirely replacing old-type bulbs (e. g., incandescence and halogen lamps and fluorescent tubes) with them, a comment is in order on white LEDs for energy harvesting. Unfortunately, the phosphor layer typically employed to obtain a white spectrum acts as an absorbing filter, thus hindering the operation in photovoltaic mode. Systems intended to employ LEDs as both sources and harvesters should contain RGB LEDs rather than phosphor-based diode to increase the conversion efficiency while being good white light emitters. However, the advantages in terms of harvested energy will come at the cost of an increased complexity of the driving circuits and a reduced irradiance.

Even though we realize that the design space for LED optimization is quite limited and substantial improvements are unlikely, a class of forthcoming devices may be developed not aiming at the highest emission efficiency but rather at their dual use as both LEDs and solar cells, aiming at a reasonable and convenient tradeoff.

A final remark is in order with reference to organic LEDs (OLED). Despite their large use in several applications including displays, to our knowledge OLEDs have not been investigated as energy harvesters to date. Conversely, organic materials have been employed in high efficiency photovoltaic devices [35]. This hints to the possibility of exploiting available OLEDs as energy harvesters. This pinpoints a gap in the scientific literature and should trigger discussion and research in such direction.

4.2 LED matrices and displays for energy harvesting

LEDs are commercially available both as single devices and as two-dimensional matrices. Typically, the active surface of an LED ranges from 0.3mm^2 to 1mm^2, thus being only a small fraction of the standard area of a small solar cell (up to 0.5-1cm^2) and permitting the absorption of a limited amount of photons. Bigger LEDs are not available on the market, although several modern displays rely on LEDs for either backlighting (as in LCD displays) or direct image generation (as in μLED technology), being equipped with a large number of LEDs and reaching a wide equivalent area. Interestingly, LEDs in displays are typically turned off for a large amount of time if compared to the whole lifetime of the system they are embedded within. An apparent example is the screen of a mobile phone, which is typically off for more than 70% of the time in a typical day of operation. Exploiting the off-time of LEDs and displays to harvest light would greatly benefit mobile devices, allowing to increase their battery lifetime and reducing their energy footprint. To use the same LEDs for displaying information and for energy harvesting, specific electronic circuits are required.

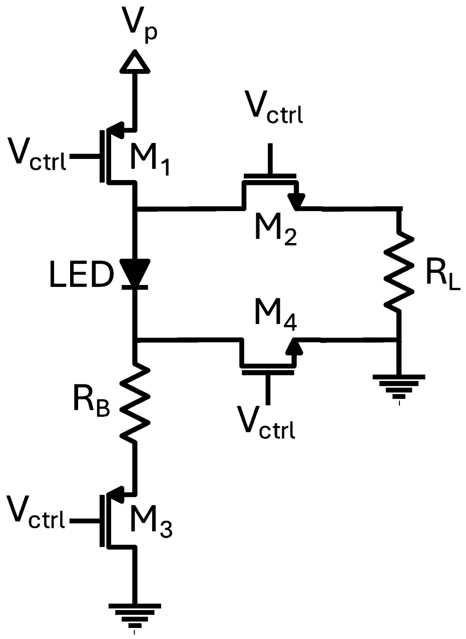

Fig. 3 A possible circuit for dynamic switching between lighting- and photovoltaic-mode

Single LED can be dynamically converted to harvesters via simple switching circuits and logic controls. An elementary electronic circuit for switching from lighting to harvesting mode is illustrated in Fig. 3. Four different complementary transistors (M_1-M_4) controlled by the same logic signal (V_{ctrl}) can connect an LED to either a power source (V_p) and a current-limiting resistor (R_B) for lighting or a load (R_L) for harvesting. This simple scheme could be reproduced for multiple LEDs but it is not suitable for large matrices and megapixel displays due to increased footprint and cost. As of today, the possibility of employing displays as energy generators has been just hinted to in the literature [30], due to the complexity of the switching circuits and the need for dedicated bidirectional DC-DC converters operating both as power sources for the LEDs and as boost converters for harvesting. Nevertheless, the very large integration density of modern electronics could facilitate novel harvesting strategies where, for instance, just a reduced amount of pixels in a high-definition display could be switched to photovoltaic mode when the display is off. This would enable energy generation with a modest increase in costs and complexity. Nevertheless, reaching this stage requires thorough investigations by the scientific community dealing with design and integration of mixed-signal electronics. Numerous topologies can be designed for controlling the operating mode of LEDs, and an accurate performance analysis is mandatory towards cost-effective harvesting systems directly integrated with display technology.

4.3 System-level optimization and performance evaluation

The successful functioning of a harvesting system depends on all its components. The typical block diagram of a photovoltaic harvester is presented in Fig. 4. The first block in the chain is the LED harvester. Just like standard solar cells, LEDs in the photovoltaic mode can grant top performance only when connected to a load allowing for the conditions (i. e., voltage drop and current absorption) yielding maximum power from the device itself. This issue has been dealt with in solar cells resorting to power management units (PMU) that implement a maximum power point tracking (MPPT) algorithm, dynamically adapting the operating point to illumination and load figures. The PMU can either provide power to

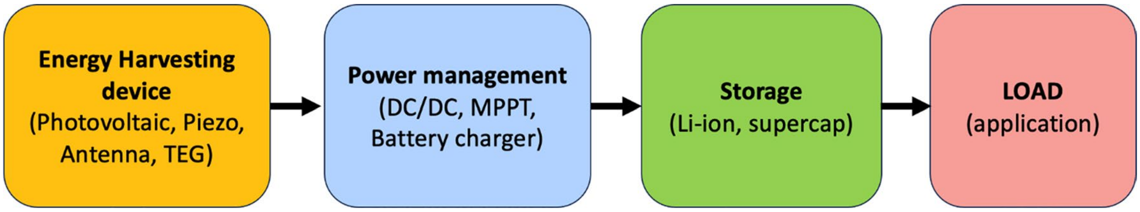

Fig. 4 Schematic block diagram of an energy harvesting system

the load directly, or accumulate charge in a storage system (e. g., a rechargeable battery). To function correctly, PMUs currently available require a minimum input voltage from the harvester, between 0.4V and almost 6.0V. These PMUs, specifically developed for energy harvesting, are optimized to work at very low power (< 1W) with high conversion efficiency (> 80%) [36, 37]. Another relevant aspect in energy harvesting is the quality (and efficiency) of storage systems. Such systems consist, most commonly, of rechargeable batteries (e. g., NiMH or Li-ion batteries) and, more recently, of solid-state electrolyte supercapacitors [38]. Due to the inherently intermittent nature of power from harvesters, long-lasting and efficient storage systems are of the uttermost importance to grant continuous operation of the load. Accumulating systems, mainly based on Li-ion batteries, are widespread and available in various capacities and footprints. They can grant extended lifetime to the load circuits, but at the cost of complex charge-control circuitry. Fortunately, such circuits are typically embedded in PMUs. Supercapacitors, on the other hand, are less demanding in terms of charge-current profiles, thus allowing for simpler and less expensive PMUs. Supercapacitors are affected by a reduced energy–density and cannot retain the charge for a long time due to self-discharge. The research community is actively trying to enhance both Li- batteries and supercapacitors, with significant progress reported in the last decade [39, 40] We expect storage system to become smaller and leaner, thanks to an increased energy density. Moreover, better performing supercapacitors should soon reach the market, allowing for longer charge retention and smaller footprint. Such increased storage capacity should be accompanied by larger input power in order to keep the charging time brief enough to be practical. Thanks to the flexibility of modern PMUs, even a single LED can produce enough voltage to power-up an energy harvesting system, but the total generated power remains very low, and the battery-charging can take a long time. Employing multiple LEDs in parallel can allow for higher input current for the PMU, thus reducing the charging time. In this context, the exploitation of LED matrices and display could enhance the performance in terms of battery charging time. The last block in the energy chain (Fig. 4) is the load, which is generically represented by as a resistor draining power from the storage and the PMU. Depending on the specific application, the power required by the load can span several orders of magnitude, as graphed in Fig. 5. Even assuming negligible losses in the PMU and in the storage, a harvesting system based on photovoltaic LEDs should be able to produce power from tens of μW to a few mW, making it best suited as a source for low-consumption devices such as sensor nodes and microcontrollers. It should also be noted that, in various applications, continuous operation is not required, and the load can be dynamically turned off or put in a ultra-low consumption state while the harvesting device is not operating at best (e. g., when the illumination is too low to provide enough power to feed the PMU). This is the case of self-powered sensor nodes, where the sampling frequency can be greatly lowered to save energy (i. e., when the system operates only on batteries) or dynamically increased (when the

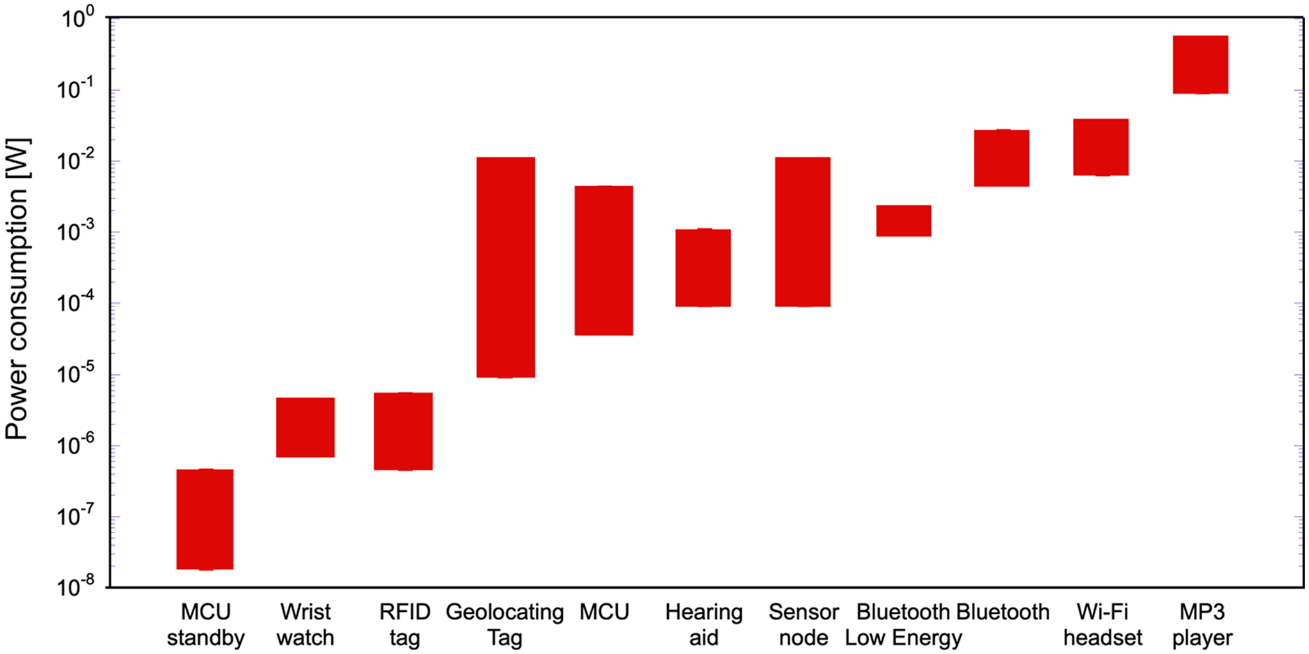

Fig. 5 Power requirements in various devices. Data from references [41–43] and manufacturers' datasheets. The large error-bars are due to differences in terms of product technology, performance and specific task, with significantly larger power consumptions when data transmission is involved

harvesting system is fully functioning). In general, load optimization is pivotal for granting long-lasting systems that are only powered by harvesting devices; effort has to be devoted to this aspect when designing a system.

5 Conclusions and perspectives

Semiconductor light emitting diodes appear quite promising for optical energy harvesting, both indoor and outdoor. With respect to other harvesting approaches, the benefits introduced by LEDs are manyfold; often they are already available in electronics systems and, aside from white LEDs, can reach rather high conversion efficiencies indoor and outside. The cost and footprint of LED is very low, and LED matrices or displays are in many cases part of electronic systems, used as active light emitters but only for a small time with respect to the whole operating lifetime of the apparatus. Despite such apparent advantages, even though the basic working principle has been thoroughly understood, numerous aspects still need research towards the design optimization and the commercial deployment of LED-based harvesters.

At the device level, further studies need to optimize the anti-reflection layers already present at the output facets of LEDs to make them suitable for efficient transmission in wider spectral ranges, thus allowing for better conversion efficiencies in outdoor operation. LEDs specifically designed for ambient illumination are normally equipped with luminescent phosphors to get extended emission in wavelength. These LEDs perform poorly as harvesters due to the filtering effect of the phosphor layer. At variance with the latter, RGB LEDs employed for white light generation can retain a high photovoltaic efficiency. A proper assessment of pros and cons of RGB LEDs as multifunctional devices for lighting and harvesting is still missing in literature: when available, it may pave the way to a new generation of ecofriendly sustainable lighting systems.

Besides the progress expected from in-depth activities aiming at the optimization of LED harvesters, scientific studies should also characterize and improve harvesting systems. More specifically, efficient bidirectional DC-DC converters and storage solutions, explicitly designed for energy harvesting, are still to be developed with performance above the state-of-the-art; commercially available systems are still limited in terms of conversion efficiency, power management, and storage.

Finally, the exploitation of LED matrices and displays as large-area energy harvesters is pivotal for the development of mobile devices with an ultra-low energy footprint. The most important limiting factor is the difficult integration of the necessary electronics with the matrix onto the same Silicon chip. Nevertheless, considering the very high integration densities ensured by modern CMOS-technology nodes, this issue could be easily solved by a thorough re-design of the control logic in displays. Despite the technical challenges and inherent interest, this pathway should be also investigated in terms of the economic perspectives to better assess advantages and disadvantages and so define its economic sustainability in the long term.

In this Perspective, we have described and discussed the exploitation of LEDs as energy harvesters, underlining the large amount of energy available in the natural environment and the high efficiency of LEDs as photovoltaic devices. Despite the numerous studies present in literature and dealing with this topic, we pinpointed several gaps in the current knowledge and awareness, trying to trigger the attention of the scientific/technological communities towards a thorough investigation of the yet-to-be analyzed aspects of this approach to energy harvesting. In a world dealing with an increasing demand for power and affected by climate changes, every progress towards greener electronic devices and systems is relevant; ignoring the potentials of LEDs as energy harvesters despite their extensive availability appears rather shortsighted: an issue that the community should address as soon as possible.

Author contributions The authors A. De Iacovo, G. Assanto and L. Colace have equally contributed to the paper.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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