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Advances in Photovoltaic Technologies for Portable Devices: Materials, Integration and Emerging Applications

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Abstract: Energy autonomy is a major challenge for portable devices such as smart watches, biometric sensors, and connected textiles. The integration of photovoltaic cells appears to be a promising solution to overcome the limitations of rechargeable batteries. This article provides a critical analysis of the main photovoltaic technologies used in wearable systems, including silicon cells, perovskites, DSSCs, and organic-inorganic hybrid cells. Each technology has distinct advantages: durability and reliability for silicon, low-light performance for DSSCs, and high efficiency combined with flexibility for perovskites and hybrid cells. Practical applications in consumer wearable electronics, medical devices, IoT, and smart textiles illustrate the potential of PVs to provide autonomous power. However, material stability, architecture optimization, and durability in real-world conditions remain critical challenges. The choice of a suitable photovoltaic technology is therefore based on a multi-criteria assessment, incorporating energy performance, conditions of use, and integration constraints.

Keywords: *Portable Devices, Energy Autonomy, Self-Powered IoT, Smart Wearables, Flexible Cells.*

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I. INTRODUCTION

Wearable devices are smart devices that are typically worn as watches, bracelets, clothing, or even skin implants. They have become popular in recent years [1], [2]. The number of features available on wearable devices continues to grow. The integration of new features leads to increased energy consumption and more frequent battery recharging [3]. The power consumption of commonly used wearable devices varies between 3 μW and 500 mW [4]. Most portable devices are powered by rechargeable batteries [5]. However, batteries have a limited lifespan [6], [7]. Energy harvesting techniques have been used to extend the battery life of sensor systems [8], [9], [10], [11] [12]. Energy harvesting methods involve capturing and exploiting energy from the environment, such as solar energy [3], [13], heat [14], vibrations [15], kinetic energy [16], [17], and radio frequency (RF) energy [18], in order to supply energy to portable devices. In addition, efficient energy management systems maximize the use of available energy and ensure increased battery life [19]. Solar energy is the most commonly used energy source in energy harvesting systems, as it is possible to obtain 10-100mW of power with relatively small solar cells [3], [20].

Solar energy collectors are therefore the most relevant for improving the energy sources that can be used for portable devices. The central question that arises is: what criteria should be used to choose one photovoltaic cell over another, and what scientific and technical basis should this choice be based on? In order to answer these questions, this manuscript is organized as follows. In the first part, we will examine the different manufacturing technologies. In the second part, we will highlight the benefits of integrating photovoltaic cells into various devices and fields of application. Finally, our conclusion will be based on a critical interpretation of the results obtained and reported by researchers in the course of their research.

II. METHODOLOGIE

A. Solar Technologies Used in Portable Devices

➢ *Perovskites*

Perovskites have a crystal structure similar to calcium titanate ($CaTiO3$), which has shown potential for the development of high-performance solar cells with low production costs [21]. Indeed, they have excellent optoelectronic properties (broad absorption, adjustable bandgap) [22]. Recently developed solid-state solar cells based on light-absorbing inorganic halide perovskites have shown great promise for portable devices [23]. This is due to the economic and practical feasibility of their manufacturing processes, which involve low temperatures and roll-to-roll

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technology. The band gap of perovskites can be modified by changing the chemical composition, resulting in a broader photon absorption efficiency [24]. Bandgap tunability is one of the essential requirements for selecting photovoltaic energy sources for portable sensor modules, as PVs must be able to absorb light from different light sources, even indoors. These photovoltaic cells have a power conversion efficiency (PCE) of over 16% and fill factors (FF) of up to 84.3%, highlighting their potential as leading candidates in the portable technology sector [25]. In the laboratory, their PCE can reach 25% [26]. Nevertheless, these technologies still present major challenges, including their instability and environmental issues related to the presence of lead [22].

➢ *Dye-Sensitized Solar Cells (DSSC)*

Dye-sensitized solar cells (DSSCs) have attracted considerable interest from academia and industry due to their cost-effective production, compact structural design, and ability to efficiently convert energy at different light intensities. DSSCs use organic dyes as photosensitizers and semiconductors to convert light into electrical energy. In addition, these solar cells are comparatively more flexible and lighter, depending on the substrate used. Due to these distinctive characteristics, dye-sensitized solar cells (DSCs) are well suited as an energy source for portable sensor modules and other applications such as building-integrated photovoltaic systems, automotive-integrated photovoltaic systems, and portable and indoor power generators [27]. In addition to the ruthenium dye complex, porphyrin and organic dyes have shown energy conversion efficiencies (PCE) of 13% and 14.7%, respectively [28].

➢ *Silicon Solar Cells*

Silicon solar cells are widely used. During the manufacturing process of a photovoltaic cell, it is necessary to add doping to one or more layers of silicon. This involves adding impurities to generate n-type or p-type semiconductor layers. The majority carriers in p-type layers are holes, and those in n-type layers are electrons. Photovoltaic cells are prepared by placing a p-type doped layer next to an n-type layer. Electrons and holes move within the layers, creating an internal electric field. Electrons and holes move within the layers, creating an internal electric field. When light interacts with a photovoltaic cell, the incident light energy is absorbed, causing electrons to be excited and electron-hole pairs to be generated. The excited electrons in the conduction band move to the n-type layer and the corresponding holes move to the p-type layer, producing the current in the photovoltaic cells. The typical efficiency of these solar cells is around 20%, but it is strongly influenced by the duration and intensity of light exposure [29], [30]. Although reliable and durable, its rigidity and weight limit its integration into portable systems [31].

➢ *Organic-Inorganic Hybrid Solar Cells*

These solar cells incorporate organic and inorganic materials in order to exploit the respective advantages of each component. Organic components offer the advantage of flexibility and cost-effective processing [32]. Conversely, inorganic materials have desirable characteristics such as stability, rapid charge mobility, and a wider variety of absorption capabilities. The interface between organic and inorganic materials enables efficient charge transfer and separation, thereby improving device performance. Studies have revealed energy conversion efficiencies greater than 15% in organic-inorganic hybrid solar cells, demonstrating their potential in the field of photovoltaic cells [33], [34].

➢ *Comparative Analysis*

Photovoltaic technologies have varying characteristics in terms of efficiency, flexibility, and applications. Perovskite cells offer high efficiency (between 16 and 25%) and great flexibility depending on the substrate.

Table 1 Comparative Analysis of the Main Photovoltaic Technologies for Wearables

Technology	Structure / Materials	Power Conversion efficiency	Flexibility / Weight	Advantages	Limitations / Challenges
Pérovskites	Inorganic halides, $CaTiO_3$-type crystal structure	16 % à 25 %	Flexible depending on substrate	Wide absorption, adjustable band, low-temperature manufacturing, reduced cost	Instability, presence of lead, long-term durability
DSSC (Dye-Sensitized Solar Cells)	Semiconductor + organic dyes (ruthenium, porphyrin, others)	13 % à 14,7 %	Lightweight, flexible	Effective in low light, compact design, low production cost	Lower efficiency than perovskites and silicon, sensitivity to the environment
Silicium	n-type and p-type doped silicon layers	≈20 %	Rigid, heavy	Reliable, durable, mature technology	Limited integration into portable devices, not very flexible
Organic-inorganic hybrids	Organic + Inorganic Materials	>15 %	Flexible	Flexibility/stability compromise, effective load separation	Lower efficiency than perovskites, long-term stability needs improvement

DSSCs are lightweight, flexible, and efficient in low light, but their efficiency (13 to 14.7%) remains lower than that of perovskites and silicon. Silicon cells are reliable and durable (around 20%), but rigid, which limits their use in

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portable devices. Finally, organic-inorganic hybrid cells combine flexibility and stability, with an efficiency greater than 15%, making them a good compromise between performance and adaptability. The choice of technology therefore depends on the specific constraints of portable applications and autonomous systems. Table 1 presents a summary of the comparative analysis of the photovoltaic technologies mentioned.

B. Application in Portable Devices

➢ *Consumer Portable Electronics*

Solar backpacks, photovoltaic chargers, and other outdoor devices use conventional or thin-film PV modules [42]. In particular, the studies reported in [43] and [44] illustrate the effective integration of photovoltaic modules into portable devices designed to ensure sustainable energy autonomy. The flexible smart bracelet presented in [43] uses thin solar panels deposited on a plastic substrate, with an optimized conversion architecture achieving 90% efficiency. The wearable is illustrated in Fig 1.a. This configuration allows energy collection of up to 16 mW outdoors and 0.21 mW indoors, sufficient for near-continuous monitoring of blood oxygenation and data transmission via Bluetooth, thus confirming the feasibility of self-powered biometric sensors. In addition, the prototype solar backpack for camping applications described in [44] incorporates two 12 W photovoltaic panels mounted on a modular rail, as illustrated in Fig 1.b, combined with a 12 V, 7 Ah lead-acid battery. The unit, equipped with USB outputs and a modified sine wave inverter, allows mobile devices to be recharged while maintaining an optimized center of gravity for carrying comfort. The study by Ding et al. presents a portable physiological monitoring device powered by flexible organic photovoltaic cells, providing sufficient power to operate a biometric sensor module. The device is capable of measuring and transmitting five physiological signals (ECG, heart rate, SpO_2, body temperature, and movement) at a supply voltage of 3.3V. Experimental results have confirmed the reliability and extended autonomy of this device for long-term portable health monitoring [45]. These examples demonstrate that portable photovoltaic solutions can combine energy autonomy, ergonomics, and functionality in biometric applications as well as in leisure and outdoor devices.

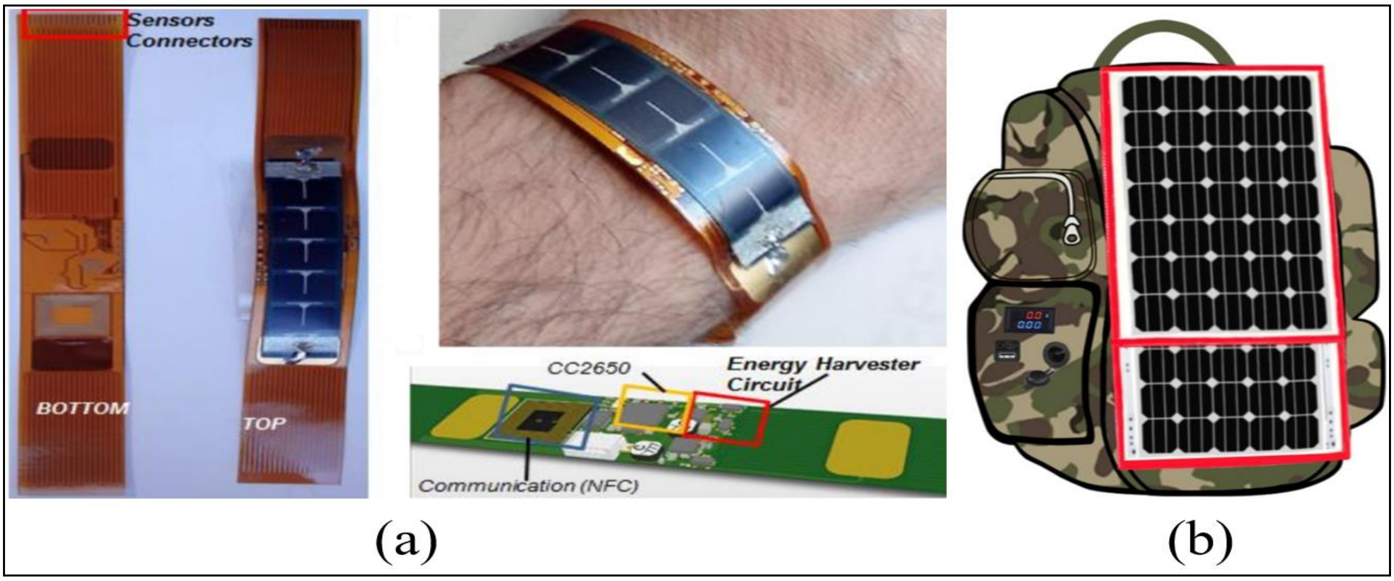

Fig 1 a) Flexi Bracelet b) Solar Powered Backpack

➢ *Medical and Health Devices*

Smartwatches, bracelets, and skin patches already use flexible solar cells to extend their battery life. These systems enable continuous monitoring of physiological parameters without frequent recharging [38]. Recent work shows that integrating flexible photovoltaic cells and adaptive energy management systems can overcome these limitations. For example, C. Park et al. have developed a portable platform powered by ambient light, integrating flexible photovoltaic cells, photoluminescent materials, and an adaptive energy management algorithm, reducing energy consumption by 86.22% while measuring heart rate, SpO_2, body temperature, movement, and biomarkers in sweat [39]. Similarly, Páez-Montoro et al. experimented with a solar energy recovery system based on the SM141K04LV module to power a smart medical device. The device consists of an electrodermal activity sensor, temperature sensor, heart rate sensor, accelerometer, and Bluetooth communication module, with an average power dissipation of 18.5 mW [3]. The device illustrated in Fig 2.a. In [40], Mohsen et al. raised the issue of battery life limitations. They hypothesized that the use of a hybrid photovoltaic-thermoelectric energy harvester could power a portable medical sensor system consisting of a MAX30205 temperature sensor, an ADXL335 accelerometer, a MAX30100 pulse oximeter, and a low-power HM-10 Bluetooth module, as illustrated in Fig 2.b. The photovoltaic module used in this research is the MPT 4.8–75 from PowerFilm Inc. Finally, N. T. Bui et al. developed a prototype of a portable, autonomous electrocardiogram, electronically composed of the PIC16LF19168 microcontroller, the ADS1293 sensor system, and an RN4020 BLE transmitter. The system is powered by a 2.4V, 0.25mW photovoltaic module [41]. These studies demonstrate that flexible photovoltaic technologies offer a viable solution for portable medical devices to operate autonomously over long periods of time.

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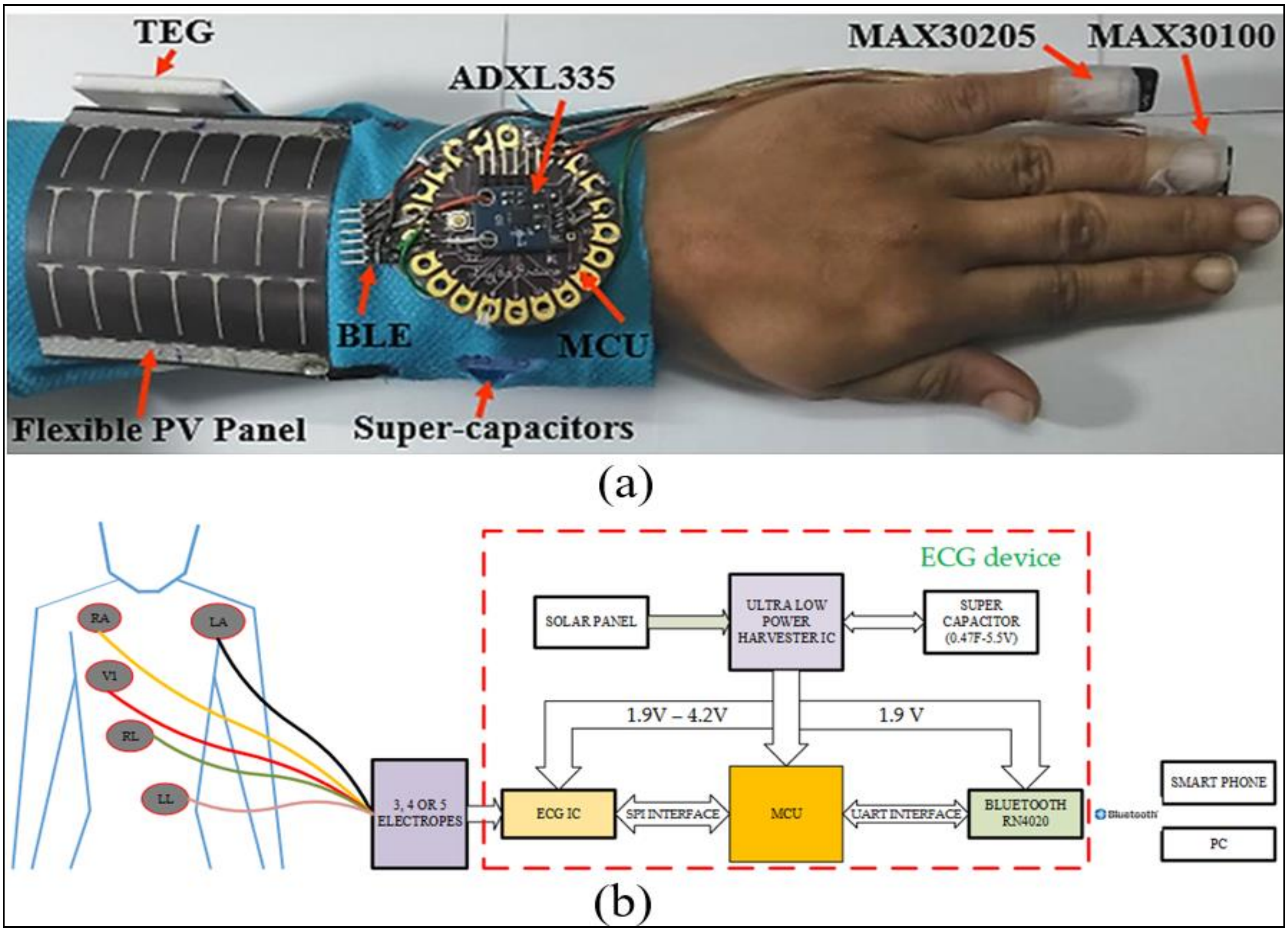

Fig 2 a) Wearable Medical Sensor System Prototype b) Electrocardiogram Monitoring System Design

➢ *IoT and Autonomous Sensors*

In the field of IoT, microsensors incorporating PV cells enable maintenance-free energy autonomy. This is particularly promising for connected healthcare networks and home automation [46]. Recent research highlights innovative electronic solutions for the energy autonomy of portable devices and IoT sensors. Min et al. [47] present a portable sweat sensor powered by a flexible quasi-2D perovskite photovoltaic module, offering a conversion efficiency of 31.1% under indoor lighting. This module provides sufficient power to ensure the continuous operation of multimodal measurement circuits (glucose, pH, sodium, temperature, sweat flow) and wireless transmission, while guaranteeing autonomy of more than 12 hours without a secondary battery. The illustration is shown in Figure 3.b. Zhang et al. [48] propose a textile architecture integrating conductive polymer fibers and photo-rechargeable storage modules, combining photovoltaic conversion and electrochemical storage directly in the fabric. This integration enables stable operation of body sensor networks (BASN), while resolving mechanical and ergonomic constraints through a flexible and industrializable structure. It is illustrated in Fig 3.a. Finally, Mishu et al. [20] develop a hybrid thermoelectric-photovoltaic (TE-PV HEHS) system based on the combination of a PV module (under 50–200 lux illumination) and a TE module (ΔT of 5–13 °C), capable of generating between 0.14 W and 2.13 W together. The energy is stored in a 0.47 F/5.5 V supercapacitor, charged to 4.12 V in just 17 s, ensuring a temporary autonomy of 92 s in the absence of energy sources. This system also incorporates an ESP32 with transmission via MQTT protocol, confirming the feasibility of self-powered IoT networks even in environments with fluctuating energy resources. This work demonstrates that the joint optimization of photovoltaic architecture, integrated storage, and hybrid systems is a major lever for autonomous, reliable biometric and IoT sensors that are adapted to real-world uses.

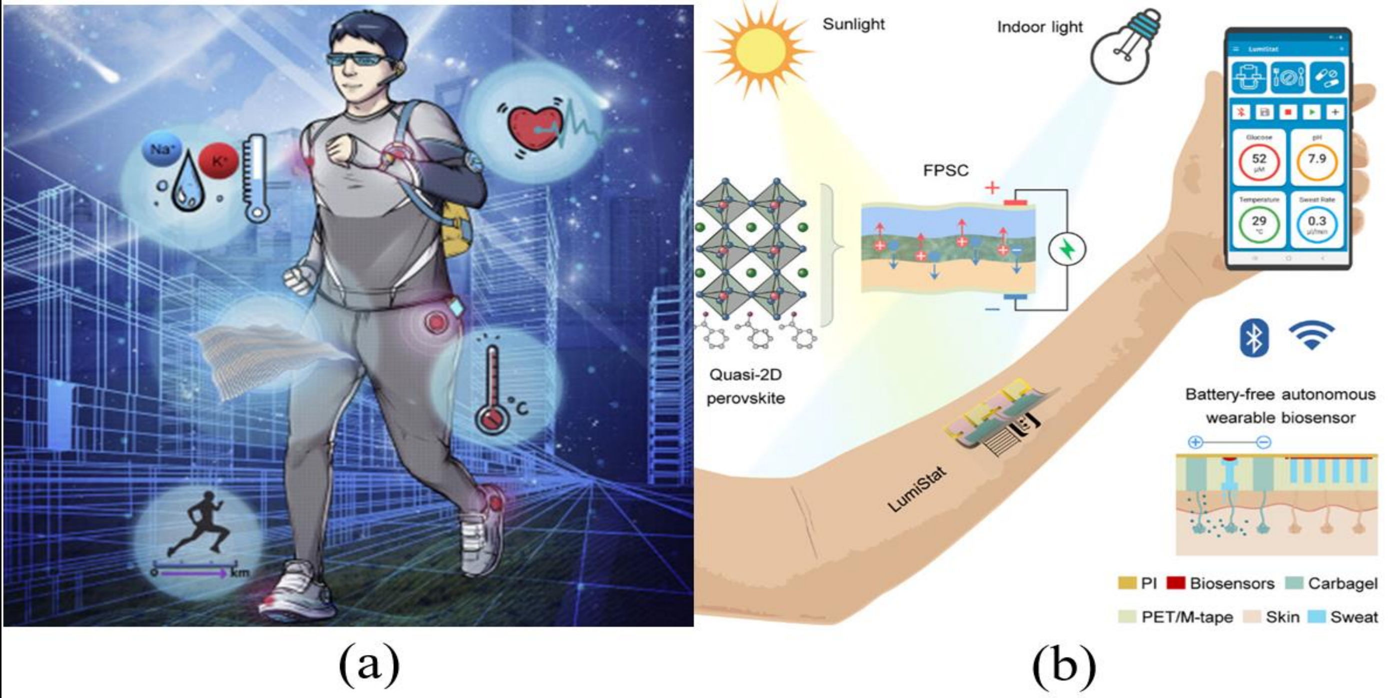

Fig 3 a) Illustration of an Autonomous Body Area Sensor Network b) Illustration of the Energy Autonomous Wearable Device that is Powered from Both Outdoor and Indoor Illumination Viaa Quasi-2D Flexible Perovskite Solar Cell (FPSC) and Perform Multiplexed Wireless Biomolecular Analysis Across a Wide Range of Activities. Carbagel, Carbachol Hydrogel; M-Tape, Medical Tape; PET, polyethylene terephthalate; PI, polyimide

➢ *Smart Textiles*

Photovoltaic textiles, incorporating flexible solar fibers or films, pave the way for clothing that can power biometric sensors and communication systems. Their main challenge remains durability [35]. Nevertheless, the study conducted by Ilén et al. presents the development of textiles incorporating washable solar cells, designed to autonomously power portable biometric sensors [36]. Their main objective is to reconcile renewable energy production with user comfort, ensuring that the solar cells remain functional even after multiple domestic or industrial washing cycles. To achieve this, they encapsulated thin photovoltaic cells directly into the textile fibers using a lamination process compatible with industrial production. Experimental tests show that these textiles retain usable power after several wash cycles, thus ensuring sufficient autonomy to power small integrated biometric sensors and communication modules. This approach paves the way for autonomous, durable smart clothing suitable for everyday use, while highlighting remaining challenges, including optimizing energy efficiency in low-light conditions and long-term mechanical durability. The study thus confirms that the integration of washable solar cells into textiles is a significant advance in the design of self-powered wearables. In [37], A. S. Khan et al. proposed an integrated vital sign monitoring system powered by a jacket equipped with ten flexible solar cells, it is illustrated in Fig. 4.

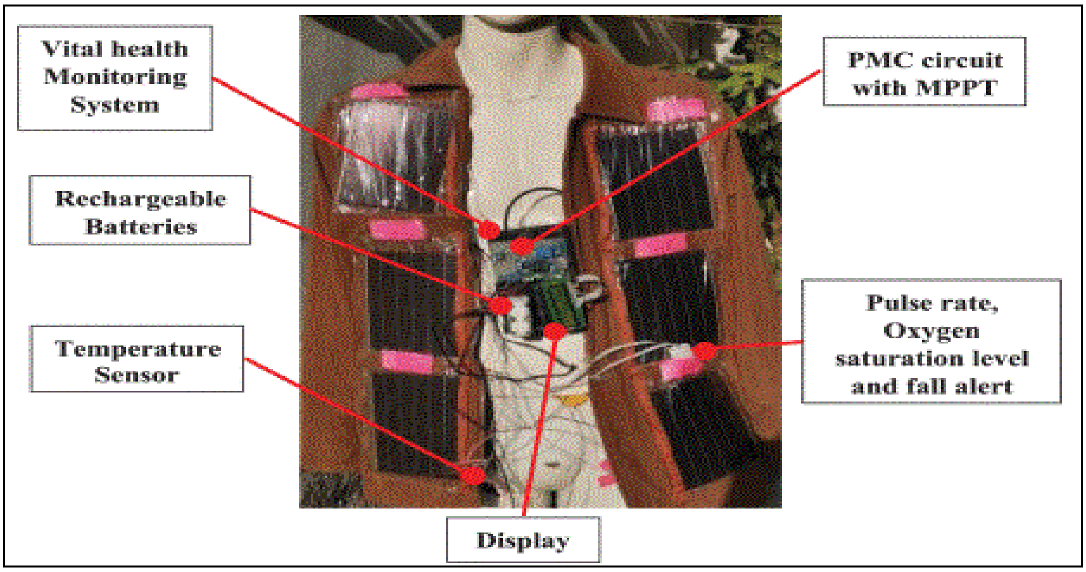

Fig 4 Vital Health Monitoring System Based Self-Powered Wearable Jacket

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The originality of this work lies in the implementation of a maximum power point tracking (MPPT) algorithm, which optimizes energy recovery even in low light conditions (minimum measured power: 7.95×10^{-5} mW at 10 kΩ). Laboratory and field experiments show that at 41,000 lux and 780 W/m², the jacket generates a voltage of 45V and a maximum power of 1282.57 mW. Thus, washable photovoltaic textiles enable smart clothing to autonomously power biometric sensors while remaining durable after washing. In addition, flexible multi-cell systems with MPPT prove that these wearables can generate significant energy even in low light conditions, confirming their potential for reliable portable applications.

➢ *Comparative Analysis*

Portable photovoltaic devices cover consumer electronics, medical applications, the Internet of Things (IoT), and smart textiles. They offer sustainable energy autonomy and can power sensors or portable devices thanks to flexible and sometimes hybrid modules, whose power is adapted to each use. However, the main limitations concern dependence on light, limited power for certain devices, and long-term mechanical durability. Overall, these technologies offer significant potential for combining functionality, ergonomics, and autonomy in a variety of portable applications. Table 1 summarizes a comparative analysis of use cases.

Table 2 Summary of the Main Areas of Application for Portable Photovoltaic Devices

Domain/Device type	Example / Materials	Power / Efficiency	Advantages	Limitations / Disadvantages	Main applications
Consumer portable electronics	Flexible smart bracelets, solar backpacks, thin PV panels on plastic	Bracelet: 16 mW external, 0.21 mW internal, conversion efficiency 90%; Backpack: 2×12 W	- Energy harvesting for portable devices - Sustainable energy autonomy - Optimized ergonomics and comfort	- Dependence on ambient light - Limited power for more energy-intensive devices	Biometric tracking, mobile device charging, camping, leisure activities
Medical and healthcare devices	Smartwatches, skin patches, flexible biometric sensors, PV MPT 4.8–75 modules	Example: 0.25 mW for portable ECG; 86.22% reduction in energy consumption with adaptive management	- Continuous monitoring without frequent recharging - Extended battery life - Integration of adaptive energy management systems	- Battery limitations - Limited power depending on device	Continuous health monitoring, portable ECG, physiological sensors (heart rate, SpO_2, temperature, movement)
IoT and autonomous sensors	Sweat sensors, textiles incorporating PV modules, TE-PV hybrid systems	Flexible perovskite PV sensor: 31.1% indoors; hybrid system : 0.14–2.13 W	- Maintenance-free autonomy - Stable operation for IoT networks and body sensors - PV + electrochemical storage combination	- Complexity of hybrid architectures - Dependence on light or ΔT for TE-PV	IoT sensors, home automation, connected health, body sensor networks
Smart textiles	Flexible solar fibers and films, jackets with washable PV cells	Maximum power: 1282.57 mW; minimum measured power: 7.95×10^{-5} mW	- Self-powered, sustainable clothing - Integrated biometric sensors - Continues to function even after washing	-Optimized efficiency in low light conditions - Long-term mechanical durability	Smart wearables, vital sign monitoring, wearable sensors integrated into clothing

III. RESULTS

Recent advances in photovoltaic (PV) cells for portable devices show a diversification of technologies and continuous improvement in performance. Perovskites stand out for their optoelectronic properties and conversion efficiencies of 16 to 25% [21]–[26], despite issues with stability and toxicity. Flexible DSSCs, suitable for low light intensities, achieve up to 14.7% PCE [27], [28], while reliable silicon cells (≈20% PCE) remain limited by their rigidity [31]–[31]. Organic-inorganic hybrid cells offer a compromise between flexibility, stability, and efficiency (>15%) [32]–[36].

In application, smart textiles incorporate washable PVs capable of sustainably powering biometric sensors [37], [38], and jackets equipped with flexible cells with MPPT can generate >1.2 W, confirming the feasibility of autonomous power supply [40]. In the medical sector, flexible and hybrid PV modules (PV-TE) power oximeters, ECGs, and smart patches, reducing dependence on batteries [3],[41]–[43].

For consumer wearable electronics, such as connected bracelets and solar backpacks, thin PVs offer power outputs ranging from 0.21 mW indoors to over 16 mW outdoors for sensors [44], and integrated charging systems reach 12 W with onboard storage [45]. In the IoT, solutions combining flexible perovskite modules, photovoltaic fibers, and PV-TE hybrid systems provide a stable power supply of 0.14 W to 2.13 W, sufficient to maintain connectivity and data processing via ESP32 and MQTT [20], [48].

Thus, the integration of photovoltaic technologies into portable devices promises sustainable energy autonomy, although material stability, architecture optimization, and durability in real-world conditions remain major challenges.

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IV. CONCLUSION

Analysis of the various photovoltaic technologies and their applications in portable devices shows that the choice of a photovoltaic cell cannot be reduced to a simple criterion of energy efficiency. It is based on a set of scientific and technical parameters that take into account the intrinsic properties of the materials (conversion efficiency, stability, flexibility, manufacturing cost), the expected lighting conditions (direct sunlight, ambient or indoor light), and the specific nature and constraints of the portable device in question.

Silicon cells, although reliable and durable, have limitations due to their rigidity and weight, which are not very compatible with the ergonomics of wearables. Conversely, emerging technologies such as perovskite and organic-inorganic hybrid cells offer competitive efficiency and flexibility suitable for portable applications, but still raise issues of stability and environmental impact. DSSCs, on the other hand, are distinguished by their efficiency in low light and their light weight, making them particularly suitable for indoor environments or low-power sensors.

Therefore, the selection of a suitable photovoltaic cell for a portable device must be based on a multi-criteria analysis that takes into account the actual energy requirements of the system, the conditions of use, the expected performance, and the sustainability of the solution. This systemic approach provides the scientific and technical basis for guiding future choices and highlights the need for further research into material optimization, architectural integration, and reliability under real-world conditions.

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