

Bioinspired Distributed Energy in Robotics and Enabling Technologies


Rudra Mukherjee, Priyanka Ganguly, and Ravinder Dahiya*

On-board sources of energy are critically needed for autonomous robots to work in unstructured environments for extended periods. Thus far, the power requirement of robots has been met through lead-acid and Li-ion batteries and energy harvesters. However, except for a few advances such as light weight, shape, and size, the batteries used in robotics have remained unchanged for several decades, even if the research advances in energy storage have led to devices with flexible form factors. Besides being slow at adopting new energy technologies, robotics also appears to have settled with the idea of centralized energy, as evident from the battery backpack designs of several humanoids. This is in contrast with the biological world, where energy sources are distributed all over the body. Although several attempts have been made to imitate the distributed tactile skin, the energy distribution has strangely not caught attention. With distributed energy, a robotic platform can benefit in terms of increased energy density, lesser design complexities, improved body dynamics, and operational reliability. By focusing on the distributed energy, this first comprehensive review presents the benefits of bioinspired distributed energy in robotics and various energy-storage and energy-harvesting technologies that are available or are tuned to attain the same.

1. Introduction

Robotics has advanced tremendously from performing simple pick-and-place tasks in structured environments to operating in a range of real-world environments and terrains full of uncertainties. Often these advances have been motivated by biological systems.^[1] As a result, the field has grown from simple robotic arms performing preprogrammed industrial tasks^[2] to human/animal-like robots or prosthetic devices that autonomously conduct wide-ranging tasks using various sensory modalities.^[3–5]

Dr. R. Mukherjee, Dr. P. Ganguly, Prof. R. Dahiya
Bendable Electronics and Sensing Technologies (BEST) Group
James Watt School of Engineering
University of Glasgow
G12 8QQ, Glasgow, UK
E-mail: Ravinder.Dahiya@glasgow.ac.uk

 The ORCID identification number(s) for the author(s) of this article can be found under <https://doi.org/10.1002/aisy.202100036>.

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The advances in robotics have closely followed the developments in the fields of functional materials, sensing, actuation, and communication technologies, as well as artificial intelligence, which altogether have enabled robots to mimic the morphology and functionalities of biological systems to a high degree.^[6] As an example, the implementation of large-area tactile skin or electronic skin (e-skin) has allowed robots to exploit tactile feedback from the whole body for working in unstructured or cluttered environments, just as animals do.^[5,7] Likewise, miniaturized and yet powerful actuators and electronic components have allowed the development of dexterous hands and agile robots.^[8] In recent years, 3D/4D printing has also opened the ways for the development of sensitized robots with complex shapes and soft structures.^[9,10] Thus, advances in robotics have closely followed the technological advances in other areas such as electronic hardware, advanced materials, and manufacturing.

However, there is one critical area where robotics appears to have largely missed to follow the technological trend, i.e., the energy needed to power the robots.

A reliable source of energy is critical for the smooth operation of autonomous robots, particularly in environments where mains power is not readily available. In fact, the majority of applications today require robots to be autonomous, and as such, they must rely wholly on batteries for their source of power. Analyzing the state of the art, we note that not much progress has been made in terms of adopting the advanced energy solutions in the robot, despite major advances in battery technology.^[11] Starting from the first autonomous wheel-based robot Shakey^[12] in 1966 to the state-of-the-art humanoid robots developed during the last 30 years and the quadrupedal MIT cheetah robot^[13] of 2018, the battery the autonomous robots use has improved only in terms of light weight and energy density (Figure 1).^[14–16] In contrast, the energy-storage technology itself has evolved from the bulky and leaky liquid electrolyte-based systems^[17,18] to printed batteries, flexible supercapacitors (SCs) with safe electrolytes, and elegant textile-based devices.^[19–22] The battery technology has improved in terms of a Watt-to-weight ratio, form factors, lifetime, ruggedness (thermal and chemical), etc., and nowadays, flexible, stretchable, and printed batteries are increasingly being explored.

The energy requirement of robots can also be met with the harvesting of renewable or ambient energy. In this regard,

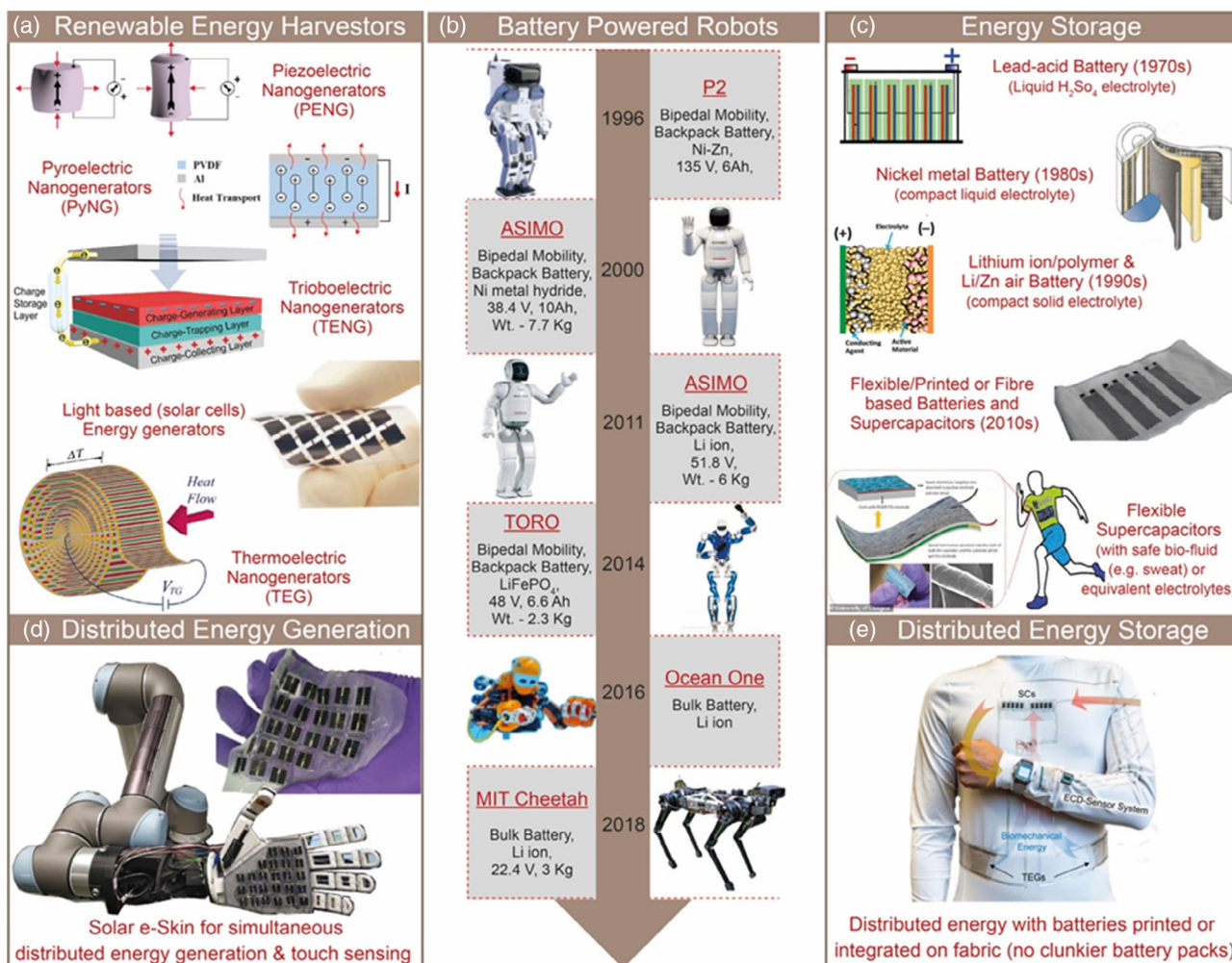


Figure 1. b) The evolution of battery-powered autonomous robots, starting with humanoids to recent lookalikes of other animals. Over the years robots have become lighter and so has been the battery they use; in fact, the latter majorly contributed to their lower weights. One thing that has remained unchanged is the centralized energy, i.e., battery at one location such as backpack. On the contrary biological systems have distributed energy. Significant advances in a) energy generation/harvesting and c) energy-storage technology in recent years raise the hope for another revolution in robotics—this time through bio-inspired distributed energy. A first example, in this regard is the d) solar e-skin, which generates energy as well as provides the sensation of touch (without additional touch sensors). e) Distribution energy is also being explored in wearables. a) TENG: Reproduced with permission.^[23] Copyright 2020, Nature Publishing Group. b) MIT Cheetah: Reproduced with permission.^[13] Copyright 2018, IEEE. P2, Asimo: Reproduced with permission.^[14] Copyright 2010, Wikimedia Commons. TORO: Reproduced with permission.^[15] Copyright 2014, IEEE. OceanOne: Reproduced with permission.^[16] Copyright 2016, IEEE. c) Nickel battery: Reproduced with permission.^[18] Copyright 2013, Elsevier. Flexible supercapacitor: Reproduced with permission.^[20] Copyright 2020, Wiley-VCH. d) Reproduced with permission.^[27] Copyright 2021, IEEE. e) Reproduced with permission.^[29] Copyright 2021, Nature Publishing Group.

various mechanisms such as thermoelectric, pyroelectric, piezoelectric, triboelectric energy harvesting, as well as photovoltaic cells have been explored (Figure 1).^[23–26] The amount of energy generated by these harvesters is generally insignificant in comparison with the power requirements of robots. Although recently the solar cells-based e-skin or solar skin has been reported to have modest energy (≈ 380 mW over adult palm size area^[27]), there is still a long way to go when it comes to full energy autonomy. Furthermore, as mentioned earlier, the current approach of using energy sources in robotics is very much centralized. For example, humanoids use backpack battery designs, which impose many design limitations such as structural imbalances, as discussed later in Section 2. In sharp contrast, the

biological systems harvest, store, and utilize the energy in a decentralized or distributed fashion, just as the sensory organs such as the skin.^[28] The energy generation and storage capacities and architectures greatly influence the size, weight, and autonomy of the robotic systems. In this regard, robotics could greatly benefit from energy technologies such as flexible and conformable energy devices that allow distributed architectures.

Although the applications such as wearable systems have benefited from distributed energy (Figure 1),^[29] the focus in robotics has been primarily on energy efficiency through strategies such as using low-power electronics, neuromorphic computing, event-driven approaches, power management strategies, etc.^[1,4,30] Various reviews to date on the topics related to robot

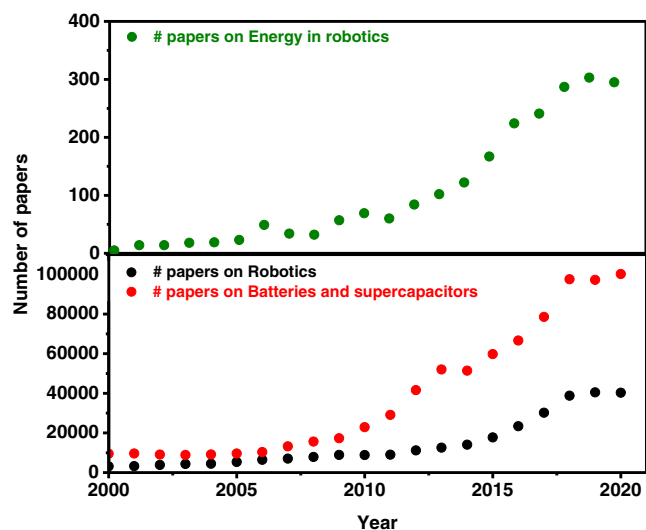


Figure 2. Number of papers on energy-related topics in robotics (top) with respect to overall number of papers on robotics and batteries and SCs (bottom). Source: Web of Science. Keywords: “robot,” “battery” or “supercapacitor,” and “energy and robot.” Despite being central to the operation of autonomous robots, the energy has attracted insufficient attention.

powering have mainly focused on the energy efficiency, flexible energy harvesters, and their integration.^[31] This observation also gets support from the plots in **Figure 2**, which show robotics and energy-storage devices (e.g., battery or SCs)-related publications in 2000–2020. Individually, these disciplines have witnessed a significant cumulative number of research articles during the last 20 years: “Robotics”-335,633 (keyword: robot) and “Batteries and Supercapacitors”-900,148 (keyword: battery or supercapacitor), the concept of energy in robots has not received much attention (e.g., just 2340 papers for keyword “energy” and “robot” and 20 papers for “distributed energy” and “robot”). The few articles that have discussed the energy in robots have dealt with topics such as efficient ways of replacing/charging the batteries,^[32] energy recycling,^[33] etc. Few reports also examine the efficient placement of biomorphic batteries on a robot,^[34] e.g., placing directly atop the moving parts (actuators) to enhance energy efficiency. However, none of the robotics papers have explored the usage of state-of-the-art flexible or stretchable, fiber-based, or bio-based batteries to obtain distributed energy architecture. Clearly, the adoption of new and advanced battery technologies in robotics has been slow. In this regard, the use of battery architectures allows distributed energy to appear far-fetched, if not impossible.

The discussion in this first Review on the distributed energy in robotics is aimed to bridge the technological gaps that exist today between advanced robotics and energy technologies. To this end, we present the latest energy-storage devices, energy harvesters, and energy-related technologies having features suitable for robotics, particularly to enable distributed energy architectures. We also discuss how robotics could benefit from the adoption of the latest energy-storage or energy-harvesting technology. Taking cues from the distributed energy in the biological world, the discussion in Section 2 focuses on the distributed energy architectures in robotics and the benefits in terms of enhanced energy

density, lesser design complexities, improved body dynamics, and operational reliability. This is followed by the discussion in Section 3 on latest trends in energy-storage devices such as batteries or SCs, supported by few examples that can help attain distributed energy architectures in robotics. The discussion of energy in robotics is incomplete without energy harvesters. This is covered in Section 4, with discussion on vibrational, optical, or biotic energy-harvesting solutions. This section briefly presents flexible piezoelectric and triboelectric nanogenerators (PENGs/TENGs), 3D-printed biofuel cells, followed by examples covering thin-film solar cells (perovskite cells, solar skin, etc.), which show great prospects for distributed energy harvesting. The distributed energy generation and storage has its own share of challenges, which have been discussed throughout the Review. A focused discussion on some of these challenges is presented in Section 5, along with potential solutions and the new opportunities for autonomous robotics in different areas. The summary of key outcomes from this Review is discussed in Section 6, whereby we emphasize the need for biology-like energy distribution, which is vital for the efficient and continuous operation of autonomous robotics. We envision that this Review will provide a complete picture of the opportunities that lie ahead for robotics with distributed energy and the usefulness of the approach for other areas such as wearable systems with soft artificial muscles for controlled stiffness to address the need of applications such as rehabilitation.

2. Distributed Energy and Bioinspiration

This section examines the merits of a distributed energy architecture over the centralized schemes such a battery backpack that are in use in robotics today. A bulky energy device at a centralized location places several constraints on the designing of a robot. As an example, the position of the centre of gravity (C_g) has a significant impact on the locomotion and stability of a robot.^[35] The battery is usually the heaviest component on the robot’s body, and mounting it at a particular location could shift the C_g unfavorably. This is shown in **Figure 3**, which shows the scheme of a drone with a battery placed at different locations. The placement of the battery toward the upper half imparts the system’s

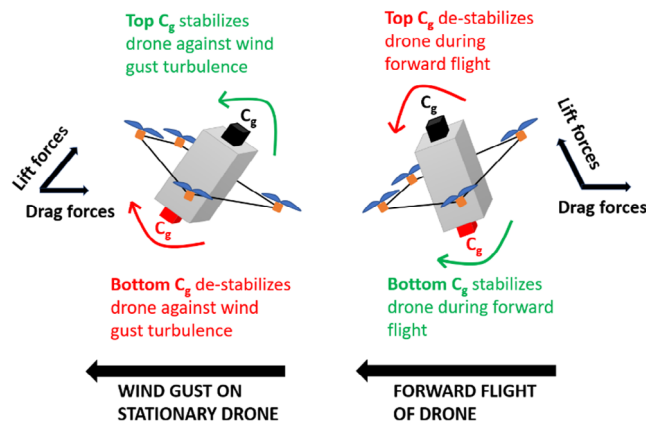


Figure 3. Schematic illustration of the effect of position of center of gravity in a quadcopter.

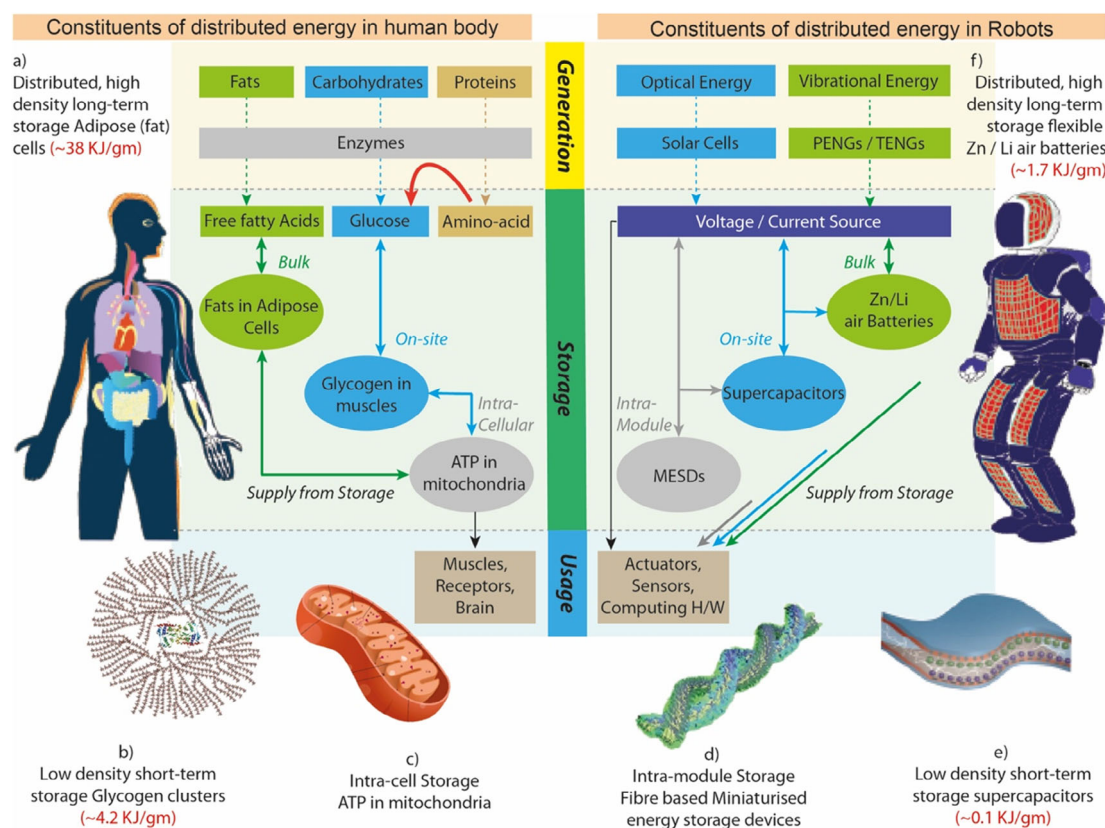


Figure 4. Distributed energy architecture in the human body (left) and an approximate analogous for humanoid robots (right). a) Reproduced with permission.^[43] Copyright 2021, LifeMap Sciences Inc. d) Reproduced with permission.^[140] Copyright 2019, Wiley-VCH. e) Reproduced with permission.^[20] Copyright 2020, Wiley-VCH.

positional stability but makes the drone unstable during forward flight. In contrast, a bottom-mounted battery stabilizes the forward flight at the cost of positional stability. Having a battery distributed uniformly over the entire drone body could ensure favorable C_g and provide the system with both positional and velocity stability. A distributed energy scheme, already present in the biological systems, makes them highly energy efficient and structurally stable.^[36] **Figure 4** shows the distributed energy harvesting, storage, and the distributed components consuming the energy in the human body as well as their realizable analogous counterparts in robotics. The raw fuel from carbohydrates, fats and proteins, and oxidizer (oxygen itself) is continuously circulated throughout the body by the blood vessels to support the working of the energy architecture. The fuel is converted into three different pools: 1) glucose pool, to meet the energy (muscles and brain) needs and fill up the glycogen stores, 2) free fatty acid pool, to augment and meet the extra energy needed when the glucose pool falls short of the requirement, and 3) amino acid pool, which is generally used for repairing functions of the body but can be converted into glucose when needed. Along with the chemical sensory backbone of the body, all these energy pools maintain an energy equilibrium in the body. The autonomous robotic systems, particularly the aquatic robots and hydraulic-powered robots, could possibly follow this type of intrabody arrangement to distribute power to its various modules.^[37]

Table 1. Energy density and location of energy storage in the human body.

Storage form	Energy density [kJ gm ⁻¹]	Location	Analogous energy-storage devices for robotics
Triacylglycerols in adipose cells ^[38]	38	Distributed all over the body	Distributed stretchable or fiber-based batteries
Glycogen clusters ^[39]	4.2	Around muscles	Ultracapacitors
ATP in mitochondria ^[40]	0.05	Intracell	MESD and bio-battery-powered nanobots

The energy storage in the human body can be divided in three levels according to the amount and duration of energy they provide: 1) high-density bulk storage in the form of triacylglycerols in adipose tissues,^[38] 2) onsite quick energy with glycogens (i.e., chemical energy) in liver and muscles,^[39] and 3) microscopic cell level energy in the form of adenosine triphosphate (ATP) molecules in mitochondria.^[40] These three routes are shown in **Table 1** and described along with analogous energy solutions for robotics.

2.1. High-Density Bulk Storage with Triacylglycerols:

The high-density bulk storage in the human body is attained through triacylglycerols, the highly energy-dense materials,

which can store up to 38 kJ gm^{-1} ,^[41] i.e., ≈ 50 times higher than the commercial lithium-ion batteries (energy density of $\approx 0.7 \text{ kJ gm}^{-1}$ ^[42]) available today. The globules of triacylglycerols stored in the adipose cells are strategically distributed all along with the muscular framework (voluntary and involuntary) of the body (Figure 1a).^[43] When required (e.g., when signaled by the muscles through secreting enzymes such as adipose triglyceride lipase [ATGL], etc.), the triacylglycerols are converted into glucose by lipolysis^[44] and subsequently used by mitochondria to generate energy (discussed in Section 2.3). In addition to energy storage, the adipose (fat) tissues also act as protective layers (shock absorbers) over the vital organs of the body. This type of distributed energy storage forms a strong motivation for the biomorphic, stretchable, or fiber-based batteries distributed over the entire body of a robot to provide distributed energy and bring about a paradigm shift in the way robots are designed. The mechanical, chemical, and thermal ruggedness are required for this type of battery architecture and ideally, the battery itself can form the casing or the mantle of a robot. Solid-state zinc–air and lithium–air batteries could be suitable for this type of design.

2.2. Onsite Quick Energy with Glycogen Stores

The quick onsite energy in the human body is provided by glycogens, which are formed by glucogenesis (polymerization) of glucose molecules and can support the human body for up to an average of 24 h. Glycogens are stored mostly in the liver and skeletal muscles, and they provide quick onsite energy but with lower energy density (4.2 kJ gm^{-1})^[45] than triacylglycerols. When the glucose level in the blood falls below the reference value, the glycogen breaks down into its monomers and releases an average of 120 000 glucose molecules into the bloodstream.^[46] It appears that this form of energy storage in the human body is designed to augment the energy requirement of the muscles for a short period of time, just like how the SCs or ultracapacitors are used in hybrid cars during acceleration. A similar strategy could be useful for robotics with onsite ultracapacitors modules

installed in various parts (e.g., joints) to meet or augment the local energy demand.

2.3. Miniaturized, Distributed storage with ATP in Mitochondria

The human body contains ≈ 30 trillion cells. Each of these cells has its own miniaturized storage unit called mitochondria, which, in addition to storing energy in the form of ATP, also possesses the mechanism of synthesizing the ATP from its immediate environment, i.e., cell cytoplasm. ATP is the final energy currency in the body. When needed, the phosphate bonds in ATP break to produce a tiny amount of energy (0.06 kJ gm^{-1}).^[47] Analogous to this, there are two rapidly growing technologies that have the potential to act as the robot counterpart of ATP in humans. These are miniaturized energy-storage devices (MESDs)^[48] and biobatteries.^[49] By following a design similar to mitochondria, the nanorobots (e.g., used for targeted drug delivery) could have active material coated on their bodies to continuously absorb and store ambient energy and lead to the complete energy-autonomous robots.

Unlike the biological systems, the robots have a centralized power structure (Figure 5) with a backpack-type energy storage using a bank of battery cells or SCs or fuel cells powering all devices on their body. The biological organism-type distributed energy architecture in the robot, as shown in Figure 5, will have several benefits and can bring a paradigm shift in the way robots are designed. Some of the advantages of decentralizing or distributed energy in robotics are 1) better operational reliability. In a centralized system, any damage to the only power source or the main transmission line can paralyze the whole system. In contrast, similar dysfunction in a distributed energy system would affect the operation of a few parts of the robot. 2) The energy efficiency of a distributed system is expected to be better as the ohmic losses during transmission of power will be lower. For example, the components to be powered could be placed directly on top of distributed energy modules, as shown in Figure 5. In addition, there is flexibility in terms of specifications

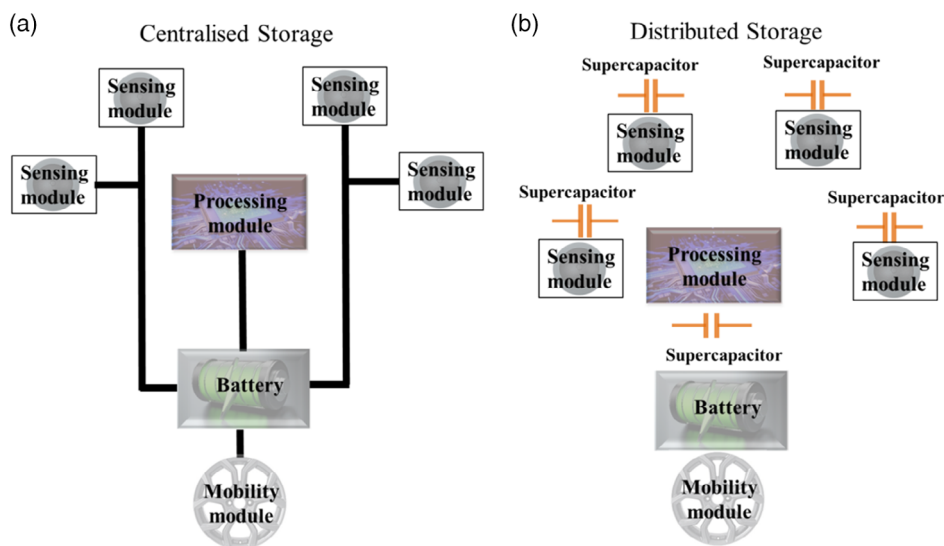


Figure 5. Centralized versus distributed power architecture.

of energy devices as they can be selected as per the local power requirements, thus removing the need for additional components such as convertors and transformers. 3) Similar to the adipose tissues in the human body, with suitable encasing, the flexible power modules can also absorb some external impact and protect the robot's body. 4) A power source placed at the outer periphery of the robot's body will be easier to replace and aid the systems' wireless charging ability. This said, the decentralized power distribution system may still fall short of the high-power requirements of some advanced robotic systems. In such cases, a hybrid system having both a smaller central battery and the distributed power modules can still be implemented as an alternative to the current central battery system. In such cases, the distributed modules can serve as the primary source of power, whereas the central battery can kick in when augmentation is needed. Such a hybrid mechanism would essentially mimic the release of glucose by the liver into the bloodstream when the sugar level of the body falls below a limit. A few examples of energy-storage and energy-harvesting devices that can potentially enable human-like distributed energy architectures in robotics are discussed in the following sections.

3. Energy-Storage Technologies:

A stable and highly efficient energy-storage solution is the key to long stretches of autonomy for robots, defining the limits of their size, weight, and working mechanism.^[24] As discussed earlier in Section 1, autonomous robots today rely on localized backpack batteries. The latest flexible and printable avatars of batteries and SCs have not been adopted so far in robotics. The present section entails the newer forms of battery and SC technologies that are available, which provide a promising outlook to be easily integrated into the robotic designs to achieve the notion of distributed energy architecture, as shown in Figure 4 and 5.

Figure 6a shows the spectrum of energy density and power density of various sources. At the higher corner of the specific energy are the fuel cells, with energy concentration as high as $1000 \text{ Watt h kg}^{-1}$ but also the low output power per kg ($<10 \text{ Watt kg}^{-1}$).^[50,51] At the lower side of the specific power

spectrum lie the SCs, which can release bursts of enormous amounts of energy ($\approx 1000 \text{ Watt kg}^{-1}$) in a short period of time but can only store $<10 \text{ Watt h kg}^{-1}$. Depending on the functionality of robots or their parts, a hybrid energy structure consisting of more than one of these technologies can prove to be optimum. As an example, normal powering of a robotic hand by batteries or fuel cells could be augmented with a burst of energy by SCs. An unmanned aerial vehicle (UAV) perhaps offers the best example of variable power requirements and hence the opportunity to integrate various energy-harvesting and storage technologies. A UAV requires a high amount of power during its take-off or steep maneuverings, whereas it requires less power during a stable flight. An ultracapacitor can satisfy its power surge, but as shown in Figure 6a, it cannot provide energy for a long duration. At the same time, a high-energy-dense battery can provide this long duration energy but falls short of the power requirement during the take-off. A combination of batteries and SCs can quench both the power and energy levels required by the system. The usual LiPo batteries can support flight time of about 90 min.^[52] Considering the much higher energy density of fuel cells, they can power longer flights without adding to the weight of the UAV, which can also benefit from quasi-instantaneous refueling. The integration of solar cells discussed in the next section with the batteries and SCs can further enhance the autonomy of the system.^[53]

Figure 6b shows the gravimetric energy density and the volumetric energy density values of the common types of batteries currently used in autonomous robotics.^[42] Table 2 shows the battery technologies used by the current state-of-the-art humanoids. For example, the humanoid robot TALOS has the ability to work in complicated industrial and research settings, using torque sensor feedbacks to grip materials. It uses a 1080 Wh lithium-ion battery, which is operational for 1.5 h of walking and 3 h of operation on standby.^[54]

Another remotely operated vehicle (ROV) for underwater exploration, OCEAN ONE, possessing intuitive haptic interactions in oceanic environments, contains eight bulk batteries placed around the tail end of the robot powering the thrusters.^[16] For applications requiring high energy capacity but low power dissipation, bulk lead-acid batteries are offering high energy density

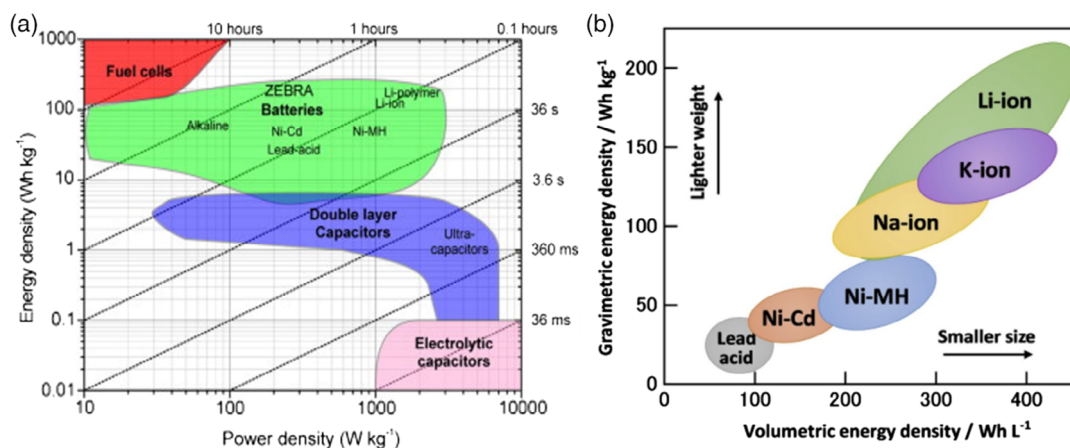


Figure 6. a) Comparative analysis of various power source technologies and b) gravimetric energy density and the volumetric energy density values in different battery types. a) Reproduced with permission.^[51] Copyright 2020, Elsevier. b) Reproduced with permission.^[42] Copyright 2020, Elsevier.

Table 2. Summarized details of different types of humanoids and the integrated power system.

Robot	Power Specs. and Operational time	Functionality	Ref.
TALOS	Single Li-ion battery, 1080 Wh, 1.5 h	Locomotion, gripping	[54]
OceanOne	Single battery in the tail section	Aquatic exploration	[16]
Pepper	Li-ion battery 30.0 Ah/795 Wh, 12 h	General purpose	[141]
Manav	Li polymer, 1 h	General purpose	[142]
Poppy	Li polymer, 11.1 V 1800 mAh	General purpose	[143]
TORO	LiFePO ₄ 48 V, 6.6 Ah	General purpose	[15]
NimbRo-OP	Li polymer, 14.8 V, 3.6 Ah	General purpose	[144]
COMAN	Li-ion battery, 2.5 h	General purpose	[145]
Asimo	Li ion, 51.8 V, 1.5 h	General purpose	[14]
REEM-C	Two Li-ion batteries 48 V, 3 h	General purpose	[146]

(40 Wh kg⁻¹), and voltage output (2 V)^[55] is a good choice. They exhibit a linear discharge pattern with a longer shelf life. Nickel cadmium (NiCd) batteries and nickel metal hydrides (NiMH) batteries are superior in terms of energy capacity, ≈130 and ≈150 Wh kg⁻¹, respectively, but are heavier and also display a higher rate of self-discharge. The lithium-ion, lithium-polymer, and cobalt-based batteries offer the better of both sides. They have an output voltage of 3.6 V and energy density value of up to 265 Wh kg⁻¹, along with a low rate of self-discharge. However, they are quite expensive in comparison with lead-acid batteries. Another crucial factor that is expected to attract major attention in the future is the impact of these energy sources on the safety, toxicity, and environment impact.^[50]

There is a natural limit up to which these bulk technologies can improve the robot's autonomy in terms of energy capacity and operational time. As this is also governed by the dynamics of the robotic body, the distributed energy storage over the whole body could be an attractive solution to such limitations. In this regard, it is imperative to adopt advanced energy-storage technologies such as batteries and SCs printed or fabricated on flexible substrates or fibers. A few examples of such energy-storage devices are shown in **Figure 7** and discussed in the following subsections.

3.1. Batteries

The evolution of various classes of batteries has been an exciting dimension in the technological advancement of the 21st century. For example, the primary/nonrechargeable batteries have been replaced by several secondary or rechargeable batteries for their low cost, ease of usage, lower energy-to-weight ratio, and increased lifetime. Likewise, the flexibility and stretchability of new battery technologies have been made possible by the ability of all its components (e.g., electrodes and electrolyte, etc.) to withstand tensile/compressive strain.^[56] Nanomaterials such as graphene, carbon nanotubes (CNT)-based composite materials, etc. have the potential to act as electrodes for lithium-ion batteries. Their tunability into flexible sheet-like structures and into woven fabrics makes them attractive for applications such as e-skin, smart textiles, and various autonomous systems.^[27,55,57] **Figure 7a–d** shows few examples of printable and stretchable

forms of batteries. 3D graphene foam (GF) has been used to realize a bendable, flexible, and binder free Li-ion battery structure. This includes a composite structure of LiFePO₄ (LFP)/GF and Li₄Ti₅O₁₂ (LTO)/GF electrodes, which demonstrates charge–discharge cycles up to 200 °C. Using LFP as the cathode and LTO as the anode, an ≈800 nm-thick battery displayed an efficiency of 143 mAh g⁻¹ at an operating voltage of 1.9 V. Repeated twisting to a radius of <5 mm did not show any kind of structural failure and change in performance.^[58] The addition of multiwalled CNT (MWCNT) composites with LTO and LiMn₂O₄ (LMO) is reported to form wire-shaped batteries (**Figure 7a**).^[59] These structured batteries display high power density and are beneficial in supporting smaller robotic platforms.

3D printing has been a promising route to develop thinner and more flexible patterns. In particular, fused deposition modeling (FDM) is a suitable alternative to conventional fabrication techniques. 3D-printed lithium-ion battery fabricated from filaments of lithium iron phosphate/poly(lactic acid) (LFP/PLA), graphite/PLA, and SiO₂/PLA filament for the positive electrode, negative electrode, and separator, respectively, was reported recently (**Figure 7b**). The printed battery displayed a specific capacity of 43 mAh g⁻¹.^[60] Stretchable conductors are essential components for wearable electronics displaying high electrical conductivity under high mechanical strain. Layer-by-layer assembling (LbL) technique can be utilized to design a gradient-assembled polyurethane (GAP)-based stretchable conductor with gold nanoparticles (Au NPs) as negatively charged and polyurethane (PU) as the positively charged material (**Figure 7c**). The battery device assembled using the GAP displays a charge–discharge rate of 100 mAh g⁻¹ at a current density of 0.5 A g⁻¹ and remarkable cyclic retention of 96% after 1000 cycles.^[61] Further rooted to the idea of all-flexible lithium-ion batteries is the idea of fiber-form battery structures utilizing the 3D printing technique. Polymer inks of high viscosity containing CNTs and either LFP or LTO can be used to print LFP fiber cathodes and LTO fiber anodes, respectively (**Figure 7d**). The all-printed fibers are assembled by twisting and held with gel polymer as the electrolyte. The device displayed a specific capacity of 110 mAh g⁻¹ at a current density of 50 mA g⁻¹.^[62] **Table 3** shows a summary of various new-generation battery technologies, which can aid in realizing the distributed energy architecture.

3.2. Supercapacitors

SCs or ultracapacitors are mainly used to provide a quick power surge, for e.g., during acceleration of a mobile robot or the beginning phase of weight lifted by a robot, when more energy is needed.^[20,63,64] As shown in **Figure 6a**, SCs/ultracapacitors have the highest specific power (Watt kg⁻¹ ratio)^[65] and can play a crucial role in enhancing the overall power efficiency. As the capacitance of a device is proportional to the plates' surface area and inversely proportional to the distance between the electrode and the separator, the newer technologies utilize novel nanomaterials such as graphene and other 2D nanostructured composites to build flexible and high-surface-area electrodes.^[20,21,66] Also, integrating these structures at the nanodimension reduces the distance between the separator and the electrode, resulting in the

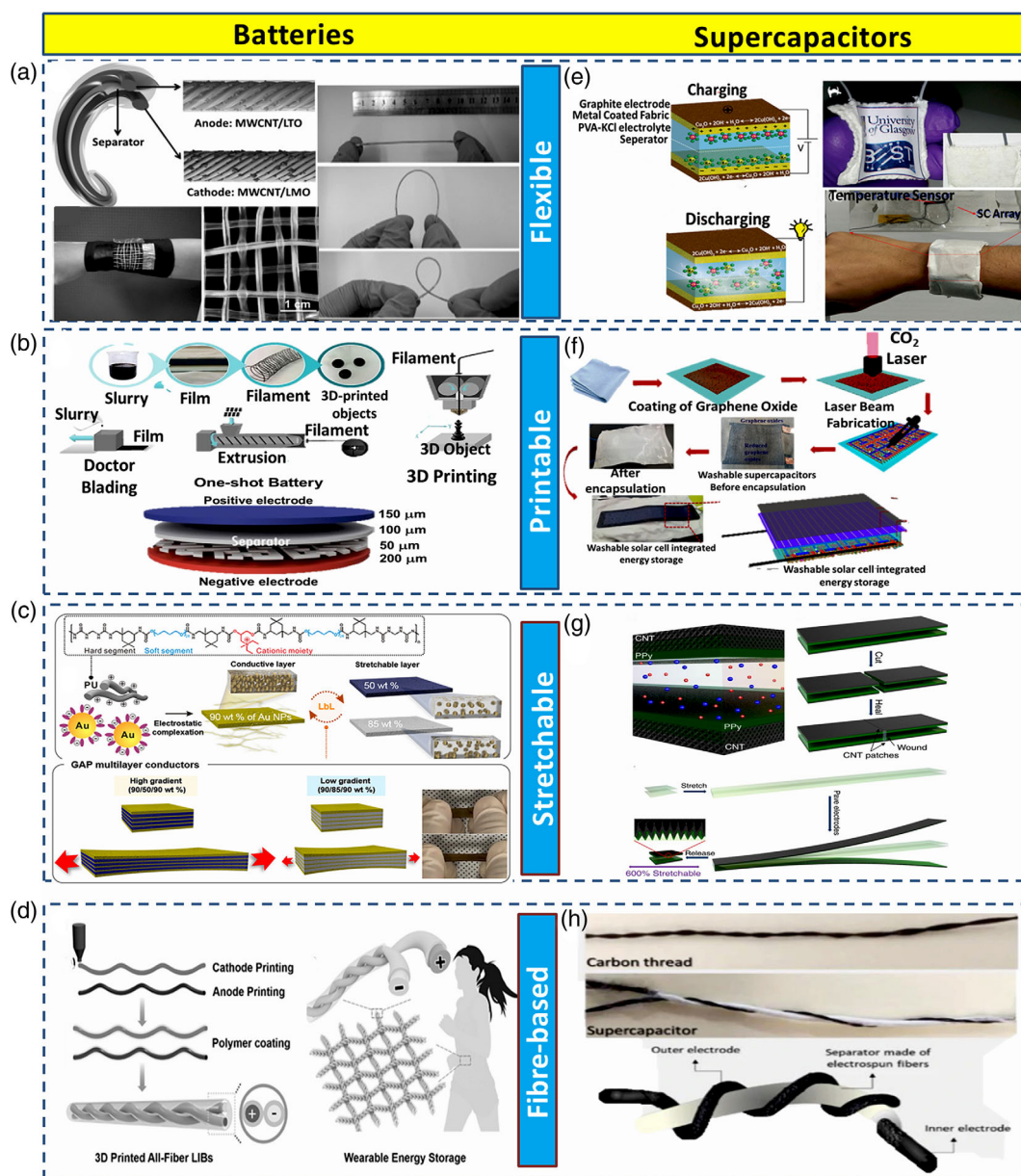


Figure 7. a–d) Examples of various forms of advanced batteries as potential solutions for distributed energy storage: a) wire-shaped battery with MWCNT/Li₄Ti₅O₁₂ (LTO) and MWCNT/LiMn₂O₄ (LMO) electrodes. b) 3D extrusion-based printed batteries where LFP and LTO were incorporated into the PVDF solution with CNT conductive additive to form electrodes. c) Stratified assembly of stretchable nanocomposites of GAP with different concentrations of Au NPs in the elastic layer. Image shows the GAP multilayer conductor under relaxed and strained conditions. d) Schematic of the design concept and fabrication process of 3D-printed all-fiber flexible LIBs and the potential application of fiber-shaped batteries for wearable applications. e–h) Examples of various forms of SCs. e) Metal-coated fabric-based SCs with PVA–KCl as electrolyte used to power up temperature sensors. f) Fabrication stages for the large-scale water-proof laser-printed graphene solar energy storage on textiles in 3 min. g) Schematic of the SCs comprising polyacrylic acid dual crosslinked by hydrogen bonding and vinyl hybrid silica NPs (VSNPs-PAA) polyelectrolyte and polypyrrole (PPy)-deposited CNT paper electrodes. Fabrication of the patch-assisted nonautonomous self-healable SC. Schematic of the fabrication of a super-stretchable SC. h) Twisted configuration of the carbon thread-based SC. a) Reproduced with permission.^[59] Copyright 2014, Wiley-VCH. b) Reproduced with permission.^[60] Copyright 2019, Springer. c) Reproduced with permission.^[61] Copyright 2019, American Association for the Advancement of Science. d) Reproduced with permission.^[62] Copyright 2017, Wiley-VCH. e) Reproduced with permission.^[21] Copyright 2020, Wiley-VCH. f) Reproduced with permission.^[70] Copyright 2019, Springer Nature. g) Reproduced with permission.^[74] Copyright 2015, Springer Nature. h) Reproduced with permission.^[77] Copyright 2020, Springer Nature.

enhanced capacitive output. Conductive fabric-based capacitive devices developed offer ready integration with various sensor modules of the robotic systems.^[20,66,67]

CNT and graphene-based ultrathin, flexible ultracapacitors have been able to power flexible electronics. In a recent study, a SC device was fabricated using a free-standing film of graphene

Table 3. Brief summary of various flexible battery technologies.

Electrode	Capacity [mAh g ⁻¹]	Efficiency and Bendability	Ref.
LiFePO ₄ (LFP)/GF and Li ₄ Ti ₅ O ₁₂ (LTO)/GF	143	Bendable and flexible at an operating voltage of 1.9 V, 30 bending cycles	[58]
MWCNT/Li ₄ Ti ₅ O ₁₂ (LTO) and MWCNT/LiMn ₂ O ₄ (LMO)	138	Wire-shaped battery, 200 bending cycles	[59]
Supramolecular lithium-ion conductor (SLIC) polymer as electrolyte, LiFePO ₄ (LFP)-SLIC/CB, and Li ₄ Ti ₅ O ₁₂ (LTO)-SLIC/CB	120	Flexible electrolyte with ionic conductivity provided by a low-T _g polyether and mechanical properties are provided by 2-ureido-4-pyrimidone (UP), 400 cycles	[147]
Electrodes of poly (3,4-ethylenedioxythiophen): poly (styrene sulfonate) (PEDOT: PSS) and polyethyleneimine (PEI)	5.5	Screen printing of ultrathin battery (440 μm)	[148]
Electrode materials of LFP and LTO were incorporated into the PVDF solution with CNT conductive additive	141.3	3D extrusion-based printing technology, 30 cycles	[149]
Polyethylene oxide (PEO) composite polymer electrolytes (CPE) embedded with silane-treated hexagonal boron nitride (S-hBN) and LFP as cathode	146.0	Direct ink writing (DIW) method, 100 cycles	[150]

nanoplates/carbon black (CB) (film thickness of 20 nm). The device integration shows the promising applications for wearable systems and robotics as the SCs connected in series display impressive results.^[68] Recently, we also presented the first demonstration of the SCs moving the motors of a 3D-printed hand to grasp a soft object (Figure 8d). In this case, the SCs were charged using the energy generated by solar cells on top.^[64] Likewise, we reported flexible SCs, including those based on fabric, for wearable systems, and demonstrated their use for the development of self-powered sensors.^[20,22,63,69] The example shown in Figure 7e uses in-house-made graphite paste printed on top of two variants of fabrics. The Armor FR (Ni/Cu-coated polyester fabric) (AFR-Gr) and Nora Dell (Ni/Cu/Ag-coated polyamide) (ND-Gr)-based SCs, with a gel (PVA–KCl) electrolyte, displayed the specific capacitances of 99.06 and 46.88 mF cm⁻², respectively, at scan rate of 5 mV s⁻¹. Further, the ND-Gr device displayed excellent cyclic stability (5000 cycles).^[21] In another work reported in the literature (Figure 7f), the printing technique has been used to fabricate large-scale graphene SCs using laser printing on textile material with excellent water stability. The SC up to a dimension of 100 cm² could be fabricated within 3 min and demonstrated an aerial capacitance of 49 mF cm⁻², energy density of 6.73 mWh cm⁻², power density of 2.5 mW cm⁻², and stretchability of up to 200%.^[70] Fabrication of energy devices by printing could open interesting new opportunities for several applications, for example, direct printing on the robot's curvy body. A wide range of printing technologies have been explored, and details can be found in other studies.^[9,71,72]

Stretchable SCs are the rising stars among new devices; however, the issues of breakage and rupture of electrodes and spillage of electrolyte are concerns that require equal attention when conceptualizing the idea of stretchable devices. In this regard, the notion of self-healable capacitive devices is quite interesting,^[73] which can be achieved using a suitable electrolyte. For example, polyacrylic acid (PAA) dual cross linked with vinyl hybrid silica NPs (VSNPs-PAA) via hydrogen bonding shows self-healability, tunable ionic conductivity, and high stretchability (Figure 7g). The polypyrrole (PPy)-deposited CNT paper electrodes with VSNPs-PAA polyelectrolyte display capacitance comparable with

the commonly used PVA/H₃PO₄ electrolyte. The electrolyte is self-healable at room temperature and repaired samples show efficiency similar to a new device. In addition, the stretchability of the device was observed up to 600% without any crack.^[74] Stretchability has been introduced in electronic devices in many ways, either using geometrical patterns (e.g., serpentine or honeycomb structures) or elastomers with suitable fillers.^[75] An omnihealable SC, demonstrated in another study,^[76] can naturally restore its electrolyte, electrodes, and interfaces. Even after mechanical failure, the repairing process occurs in normal condition for up to 15 breaking/healing cycles without any external stimuli. In this case, the electrodes were prepared by incorporating poly(vinyl alcohol) grafted with *N,N,N*-trimethyl-1-(oxiran-2-yl)methanaminium chloride (PVA-g-TMAC) networks cross linked by diol-borate ester bonding. Due to the presence of quaternary ammonium ions in TMACAs, the PVA coagulation remains incomplete and hence the hydrogel prepared turns out to be extremely malleable. The addition of KCl ions into the hydrogel results in the electrolyte and the addition of activated carbon (AC) and acetylene black (AB) into the PVA-g-TMAC networks results in the formation of the electrode. Such studies open the door for self-restorable energy-storage devices for robotics, wearable electronics, and smart textiles.

The advent of flexible and stretchable electronics has also led to fiber-based energy-storage devices. Figure 7h shows one such example, where a symmetrical capacitor device is developed with conductive polymer (polypyrrole) that is functionalized with carbon fibers and uses sweat as an electrolyte. Electrospun cellulose acetate fibers act as the separator for the device and further twist around the electrodes. The fabricated device displayed excellent cyclic performance and displayed a specific capacitance of 2.3 F g⁻¹, an energy of 386.5 mWh kg⁻¹, and a power density of 46.4 kW kg⁻¹.^[77] The flexible SCs based on other fibers, e.g., jute fiber^[22] and sweat or sweat-equivalent electrolytes,^[20] have also been reported recently. The fiber-based approach is interesting as the devices woven with fabrics require less surface area and facilitate easy integration.

A major advantage of SCs over batteries is that their charging time is comparatively much lower. For example, a SC takes only a

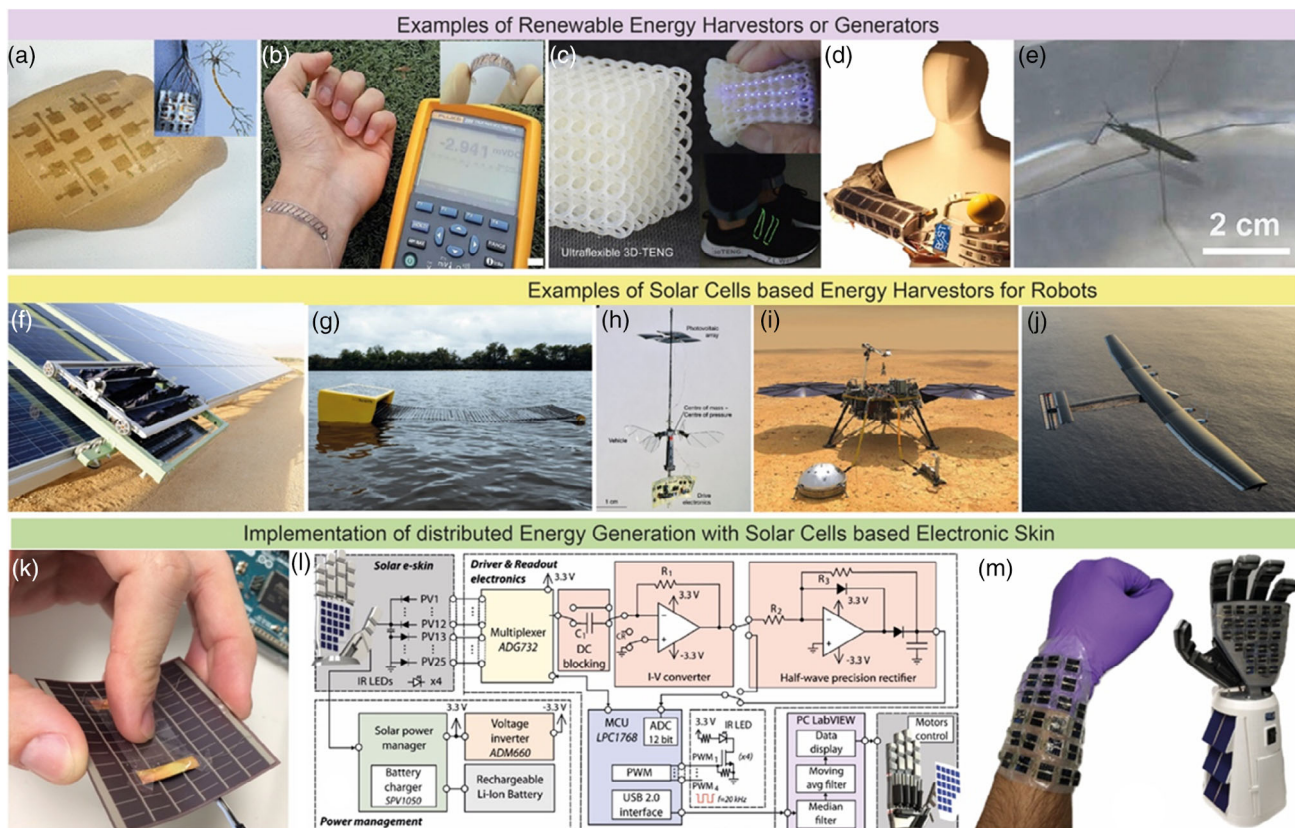


Figure 8. a–e) Examples of various renewable energy-harvesting methods: a) PENGs, b) flexible TEGs; c) 3D TENGs; and d) solar cells covering the arm of a dummy. Energy generated by solar cells is stored in the SCs underneath the solar cells. e) Floating robotic insects getting electric energy from the water surface. f–j) Examples of solar cells-based energy harvesting in robotics and aerial vehicles. f) Autonomous, self-rechargeable Ecoppia robot equipped to do waterless cleaning for the installed solar panels; g) sea-swarmed water robot with solar panel installed; h) untethered insect-sized microscale aerial vehicle powered by solar cells; i) Mars InSight lander with installed solar panels; j) solar-powered airplane “Solar Impulse 2.” k–m) Implementation of solar cells-based e-skins. k) Graphene-based transparent touch sensitive layer on flexible solar cell, leading to energy-autonomous e-skin. l) Schematic diagram showing the main blocks of the first energy-generating e-skin for simultaneous touch sensing and energy generation (without using touch sensors). Schematic shows the solar skin as a distributed array of solar cells; the driver and readout electronics; the power management subsystem; and the digital processing and communication interface. m) The solar e-skin prototypes placed on hand (showing flexibility) and on the 3D-printed robotic hand. a) Reproduced with permission.^[84] Copyright 2018, American Chemical Society. b) Reproduced with permission.^[85] Copyright 2018, Elsevier. c) Reproduced with permission.^[86] Copyright 2018, Elsevier. d) Reproduced with permission.^[64] Copyright 2019, Wiley-VCH. e) Reproduced with permission.^[87] Copyright 2019, Elsevier. f) Reproduced with permission.^[104] Copyright 2021, Eccopia. g) Reproduced with permission.^[106] Copyright 2010, MIT Senseable City Lab. h) Reproduced with permission.^[107] Copyright 2019, Springer Nature. i) Reproduced with permission.^[108] Copyright 2018, NASA/JPL-Caltech. j) Reproduced with permission.^[110] Copyright 2016, Solar Impulse Foundation. k–m) Reproduced with permission.^[27] Copyright 2021, IEEE.

few seconds to get completely charged as compared with hours taken by batteries.^[65] Another fundamental benefit of using SCs in the robotic system is their ability to be charged and discharged multiple times (90–95% or higher). In contrast, batteries offer limited cyclic events (<105 cycles). However, similar to batteries, self-discharging poses a major challenge in SCs too. Despite these differences, the hybrid distribution of the energy and the combination of the power sources are critical to complete the desired functionality.^[78]

Even though there has been a great deal of advancement in energy-storage technologies, various issues still remain to be addressed. For example, the self-discharge of batteries and SCs has always remained a concern. The leakage of energy in due course of time, just being kept on the shelf, is a constant

issue that even pertains to many new energy-storage devices. The internal resistance is not the fundamental cause in this case. In contrast, the parallel resistance built up in the electrochemical setup effectively contributes to the constant leakage and dissipation of energy. However, the combination of the internal resistance and the self-discharge is crucial to configure the battery's geometry. This case is relevant if only the energy source is left for standby usage or there pertains a long gap in the use between the charge and discharge cycle. The rates of discharge of the different classes of energy-storage devices are essential as well, as with higher charge been drawn out, lesser energy is available for the rest of the usage duration. In contrast, the lower rate of discharge is also crucial as the remnant charge can dissipate as heat energy, which can be utilized by thermoelectric nanogenerators

integrated with energy-storage devices such as batteries. This is further explained in Section 4.

3.3. Fuel Cells

Another attractive energy-storage option is the fuel cell, which offers about 240 times higher storage capacity (stores H₂ or methanol) than lithium-ion batteries.^[79] Using external feed of gases, hydrogen or methanol as the fuel and oxygen as the oxidant, these electrochemical cells display high volumetric power density. The fuel cells have been explored as a green alternative for the automotive industry along with battery-powered systems.^[80] The refueling of the hydrogen fuel cells is much faster as compared with charging a battery. A combination of H₂ fuel cells and electrical cells can provide a more robust system, where the electrical port would maintain continuous supply and the fuel cells will provide an extra thrust when required, for example, during the take-off of an electric airplane. Another advantage of fuel cells is their low noise levels as compared with combustion engines. The fuel cell technology comes with some challenges too. Storage of H₂ fuel in metal hydride or carbon fiber tanks or a liquefied source is challenging for various logistic usage ranges, especially for mobile units.^[80] Second, pressure matching may be needed between the fuel and oxygen lines, calling the need for adding compressors to the system. Finally, similar to the electric batteries, thermal management of the reaction chamber of the fuel cells is critical. Any additional cooling system needed will add to the system's weight and has the potential to nullify the gains possible by fuel cells for distributed energy, particularly for small-sized robots.

4. Energy-Harvesting Technologies

A wide range of ambient energy harvesters has been reported in the literature using mechanisms such as piezoelectricity, thermoelectricity, triboelectricity, solar cells, etc.^[24] (Figure 1). The devices such as PENGs, TENGs, thermoelectric generators (TEGs), etc. have been used extensively to either power few sensors or as self-powered sensors in wearable systems and robotics.^[26,81–83]

The piezoelectric harvesters made from materials such as piezoceramics and piezoelectric polymers (e.g., PVDF) can harness the energy from mechanical impacts between the robot and its environment with body movements. For example, single-electrode PENGs having been used in wearable electronics to sense steady-state pressure and temperature (Figure 8a).^[84] These PVDF nanofiber-based devices generate an open-circuit voltage of ≈ 4.5 mV when steady pressure is applied. Similarly,

the robots' thermal energy (e.g., heat generated by motors or body heat) can be harnessed by the TEGs, as shown in Figure 8b. The flexible screen-printed TEGs shown in Figure 8b are based on Bi₂Te₃ and Sb₂Te₃ pastes and can provide a peak output power of 3.8 mW cm^{-2} .^[85] Another way to harness mechanical energy is using TENGs. Ultraflexible 3D-printed TENGs (Figure 8c) have been fabricated using composite resin parts as the electrification layer and ionic hydrogel as the electrode, offering a peak power of 10.98 W m^{-3} .^[86] Other examples of energy-harvesting robots involve an aquatic bot having superhydrophobic wires as its artificial legs. This TiO₂-coated Cu and Mg superhydrophobic wire electrodes support the redox reactions to generate a voltage of 1.38 V and an output current of 25 mA (Figure 8e)^[87] that can power their locomotion, an light emitting diode (LED), and a temperature sensor.

These harvesters often lead to energy from the micro- to milli-Watt range,^[24] which is suitable for micro-/nanorobots, or to provide local power for few printed sensors, low-power electronics, the antennas for intermodule communications, etc. Among these nanogenerators, TENGs can offer a much higher power density (up to $\approx 500 \text{ W m}^{-2}$ ^[88]), and hence their potential goes well beyond just powering low-powered sensors. For example, TENGs have been proposed for wave energy harvesting, and by tapping this potential, it is possible to open new routes for energy-autonomous marine robots.^[81] A comparison of the aforementioned nanogenerators is shown in Table 4. The table shows the peak power produced by these nanogenerators.

These fast-evolving technologies have the potential to satisfy a major portion of the humanoid robot's energy requirements if their outer surface area ($\approx 2 \text{ m}^2$, roughly equal to that of an adult human being^[89]) is covered with these nanogenerators. Of course the power generated by these nanogenerators can be highly intermittent, but coupling them with high-efficiency SCs or batteries can accrue a significant amount of energy over time. Figure 8d shows one example where the solar cells' energy is used to charge the SCs underneath, and the stored energy has been used to move motors in hand to grasp soft objects.^[64]

Another holistic energy-harvesting technique relies on bio-fuel cells. Deployed on miniaturized robots, these biofuel cells can continuously derive energy from their organic environment by mimicking the digestive mechanism in biological systems. Living micro-organisms,^[90] mitochondria,^[91] and isolated enzymes are used as the harvesting units. These biobattery-powered bots, termed commonly as Gastrobots,^[92] use pyruvates, fatty acids, amino acids, etc. as their fuels, which are abundantly available in the human body.^[93]

Table 4. Power densities of the state-of-the-art nanogenerators.

Type	Materials	Specifications	Ref.
Piezoelectric	Vitamin B ₂ /PVDF	$465 \mu\text{W cm}^{-2}$, $V_{oc} = 61.5 \text{ V}$, $J_{sc} = 12.2 \text{ mA}$ (area = 1.6 cm^2)	[151]
Thermoelectric	Bi ₂ Te ₃ -based TEG leg/Ag nanowire electrodes	$0.262 \text{ mW cm}^{-2} \text{ K}^{-2}$, $V_{oc} = 2.116 \text{ V}$ (DT = 40 K and area = 16.77 cm^2)	[152]
Pyroelectric	PbZr _{0.53} Ti _{0.47} O ₃ /CoFe ₂ O ₄	$47\,372 \text{ kJ m}^{-2} \text{ cycle}^{-1}$ ($T_{high} = 300 \text{ K}$, $T_{low} = 100 \text{ K}$)	[153]
Triboelectric	R-cellulose	307 W m^{-2} , $V_{oc} = 300 \text{ V}$, and $J_{sc} = 2.6 \text{ mA}$	[154]

4.1. Triboelectric Nanogenerators

TENGs are newly emerging renewable energy harvesters that rely on the triboelectric effect to convert mechanical energy to electrical energy. The repeated contact of surfaces having different electron affinities results in repeated cycles of charge transfer and repeated generation of an electric field capable of driving an alternating current.^[81,94] Their combination of high efficiency at low frequency, light weight, portability, flexibility, and low cost also makes them unique among electricity generators. These attributes have made TENGs one of the most promising technologies for harnessing kinetic energy. Their output performance depends on a number of factors: materials, contact force, surface topography, frequency, and separation distance. Due to their versatility, TENGs have been used for harnessing energy from a wide variety of mechanical sources, including wave,^[95] wind,^[96] machine vibration,^[97] and human motion^[98] for applications such as energy-autonomous wearables^[1,24,99] and portable personal entertainment devices.^[100] Considering the high degree of physical interaction of mobile humanoids with their environments, TENGs have the potential to satisfy a major share of their energy requirements.

The technology supporting TENGs has evolved very quickly and has been coupled with various analogous technologies. For example, the triboelectrification effect and electrostatic breakdown have been coupled to generate a triboelectric charge density of $430 \mu\text{C m}^{-2}$, which is much higher compared with the conventional TENGs. Such TENG modules attached to the robot's moving parts may be able to withstand strains without any impact on their performance. Fiber-based flexible TENGs with high strain-bearing capability^[101] could be suitable for this purpose. Such solutions use silicone rubber as the core fiber, on which CNTs are used to form the polymer matrix and the conductive layer. The copper microwires-based electrodes are convoluted on this fiber structure. These devices display appreciable efficiencies that can be scaled up by increasing the number of coils of the fiber. In addition, the tensile strain improved TENG performance.

A magnetic resonance-based wireless triboelectric nanogenerator (MR-WTENG) is the wireless variant of TENG. The capacitive TENG is integrated with an inductor coil and incorporated with a synchronized microswitch. A sinusoidal voltage with a fixed resonant frequency is generated from the TENG's pulsed voltage, and the AC signals are wirelessly communicated via a primary inductor coil. They are received by a secondary inductor coil at a distance with high-energy transmission efficiency ($\approx 73\%$). A $40 \times 50 \text{ mm}^2$ MR-WTENG can wirelessly power 70 blue LEDs or can charge a $15 \mu\text{F}$ capacitor up to 12.5 V in $\approx 90 \text{ s}$.^[102] A few examples of hybrid TENGs combined with PENGs and/or electromagnetic PENGs have also been reported in the literature.^[103] These technologies open up new methods of wireless charge transmission, having potential applications, especially in the case of swarm robots.

4.2. Flexible Photovoltaic Cells

Due to higher power output, the most popular class of harvesters used in robotics is solar cells.^[24] Figure 8 shows a wide variety of

robotic applications, where solar modules (mainly rigid) have been used. For example, Figure 8d shows an array of silicon cells stacked on SCs for continuous operation of the motors in the robotic hand for controlled grasping.^[64] Another example of solar-powered robots is shown in Figure 8f, where robots are used for waterless cleaning of the surfaces of solar panels^[104] to mitigate issues related to the soiling of the solar panels, which can decrease the efficiency of panels by 4–5%.^[105] A swarm of aquatic robots (Seaswarm) powered by the on-board solar cells to allow cleaning the dissolved and floating contaminants in oceans is shown in Figure 8g.^[106] Solar cells-based energy harvesting has also been used in microrobots, as shown in Figure 8h.^[107] The power requirements (110–120 mW) of a flapping-wing aerial microrobot have been met with GaAs solar cells having specific power densities of 2.3 W g^{-1} . In unstructured environments such as remote planets and space station, solar cells have been traditionally used as the source of energy. NASA's InSight Lander, shown in Figure 8i, is one such example where the robot is powered by two 7.1 foot, 600 W triple-junction InGaP/InGaAs/Ge solar cells.^[108] However, other sources are also being explored nowadays for such rovers. For example, Perseverance, which landed on Mars in February 2021, carries a radioisotope power system (Multi-Mission Radioisotope TEG), which produces electrical energy using the heat of plutonium's radioactive decay and uses it to charge the two primary batteries of rover.^[109] Another interesting area is next-generation airplane flying, where renewable energy sources could help reduce the carbon footprint. One such example, shown in Figure 8j, is the all-electric airplane (Solar Impulse 2), which is fit with 17 428 thin-film silicon solar panels, generating a total energy of 340 kWh per day.^[110]

Initially, the integration of solar cells with robots was limited due to their rigid form factors and brittle nature of the early version of solar cells. The development of flexible solar modules with conventional homojunction semiconducting materials like silicon was hindered due to the high deposition temperature at $\approx 1000 \text{ }^\circ\text{C}$.^[111] The polymer-based flexible substrates could not withstand much higher temperatures. In contrast, the low-temperature-processed organic solar cells could not match the efficiencies of the silicon cells. In fact, such issues have been common to flexible electronics research, and several alternatives that have been explored to overcome such thermal budget issues, including contract and transfer printing approaches, are discussed in other studies.^[71,112] The recent development of low-temperature-processed active materials like methyl ammonium-based perovskites ($\approx 100\text{--}150 \text{ }^\circ\text{C}$) paved the way for high-efficiency flexible solar modules ($\approx 19.5\%$ power conversion efficiency [PCE]).^[113] The ease of conformal integration of these panels on robots of various shapes and sizes makes them an attractive choice for energy harvesting in autonomous systems.^[114] Silicon technology has also kept up with the challenge; epitaxially deposited Si on flexible substrates such as Ni film or bilayer porous silicon, followed by exfoliation of the bulk wafers, could achieve 14.9% efficiency. CdTe, Cu (In, Ga)Se₂, (CIGS) are other potential materials, but further optimizations are required to decrease their thermal budget to make them compatible with the low-temperature polymeric substrates.

Although the high energy density of solar modules has enabled several energy-autonomous systems, such as those

mentioned earlier, the cells' rigidity limits their deployment on robots such as humanoids, wherein conformability to the curved surfaces is needed. Although the flexible version of solar cells would be ideal for addressing the conformability requirements, placing miniaturized rigid solar cells on a flexible substrate is also an attractive route, considering that rigid solar cells still have higher efficiency. The latter is akin to large-area tactile skin based on rigid off-the-shelf electronic components integrated on flexible printed circuit boards.^[5,115,116] Following a similar approach, we recently reported the first example of energy-producing solar e-skin, as shown in Figure 8l–m.^[27] The e-skin comprises an array of miniaturized solar cells and infrared LEDs (for operation in dark areas). The solar cells generate energy when not touched, but the light intensity would vary when an object approaches them, or they are touched, and as a result, the energy output will vary. The intelligent interpretation of this variation in the energy output of solar cells (coupled with the infrared LEDs) has been used in this work to estimate the contact with objects, their distance during the approach, orientation, and identification. Interestingly, the solar e-skin does not have any touch sensors, and yet it is able to detect the touch. This means that this solar e-skin is the net generator of energy. Figure 8m shows the solar e-skin covering the palm area of a 3D-printed robotic hand,^[9] and the generated energy can be used to operate motors of the hand. The power management (Figure 8l) of the system involves an ultralow power energy harvester with an embedded MPPT algorithm (ISV019V1). Coupled with a 3.7 V LiPo battery, the system can satisfy the 155 mW power requirement of the readout electronics.^[27] With an energy surplus of 383.6 mW from the palm area alone, the e-skin can generate more than 100 W if present over the whole body (area: $\approx 1.5 \text{ m}^2$). Solar e-skin is an excellent example of distributed energy in robotics. These types of multifunctional systems can improve the overall energy density and the design of the robotic systems, as discussed in Section 5.

One challenge with monocrystalline solar cells used in this work is that they may break easily during the interaction of objects (particularly when the impact force is high) due to their

brittle nature. With suitable packaging such as 3D printing or a similar approach,^[117] it is possible to overcome such challenges. The solar e-skin discussed earlier does not use any touch sensor to detect touch sensing. There are some difficulties with this approach when it comes to measuring the amount of applied pressures. Where needed, such challenges can be overcome using transparent touch sensors on top of solar e-skin, as shown in Figure 8k. The figure shows a touch-sensitive layer developed from single-layer graphene (on polyvinyl chloride substrates) with coplanar interdigitated capacitive touch sensors with 0.01 kPa^{-1} sensitivity.^[25,118] The graphene-based touch sensor requires only 20 nW cm^{-2} for its operation. Further, being highly transparent, graphene allows most of the light to pass through and hence solar cells would still generate almost the same level or energy as without touch sensing later on top.

The distributed energy generation as in solar e-skin can be advanced further by selecting suitable solar cell technology based on flexible form factors (e.g., flexible), power conversion efficiency, and the specific power (i.e., the power output per kg of solar cells). The latter is important for robotics as solar cells will add to the robot's dynamic weight, which may impact the overall design and control strategy. Figure 9a shows the output power and weight (per m^2) of various flexible solar cell technologies. The state-of-the-art multijunction cells like InGaP can provide very high efficiencies upto 28%, equivalent to 280 W m^{-2} of power under 1 sun illumination, but are quite heavy ($\approx 500 \text{ gm m}^{-2}$). These cells are suitable for applications where the weight of the module is less important, for, e.g., in robots used in space applications, electric cars, etc. In contrast, the amorphous Si and CZTS technologies have relatively lower weight ($< 150 \text{ gm m}^{-2}$), but they are also less efficient ($\approx 10\%$ PCE). Considering the trade-off between weight and power output, the flexible hybrid organic/inorganic perovskite cells and single-molecule/polymer-based organic cells are optimum with efficiencies ($\approx 15\%$) and weight ($< 10 \text{ gm m}^{-2}$). Considering $\approx 2 \text{ m}^2$ available area on robots' outer surface, the InGaP cells can provide peak powers up to 560 W but will add $\approx 1 \text{ kg}$ weight to the robot. In contrast, the flexible or printable perovskite or organic solar cells can provide $\approx 300 \text{ W}$ to the robot while adding just $\approx 15 \text{ g}$ to its weight. Hence, integration of these solar cells on the robot's body would not require considerable redesigning of moving parts. The hybrid organic–inorganic perovskite tandem cells also have the lowest cost, $\approx 0.15 \text{ € W}^{-1}$, as compared with other technologies.

Similar to TENGs, the output of the solar cells could be intermittent due to the variable optical power available to the robot from its environment. Seamless integration of the flexible storage devices (Section 3) with these energy harvesters is the key to deploy them for continuous energy supply in robotics. A hybrid approach combining TENGs and solar cells could also be explored as an alternative. Another approach toward an energy-efficient system is to reuse the energy lost during the de-acceleration of the moving parts of the robot. Depending on the system, different kinds of kinetic energy-recovery systems (KERS), namely, mechanical KERS, electric KERS, hydraulic KERS, and hydroelectric KERS,^[119] can be deployed.

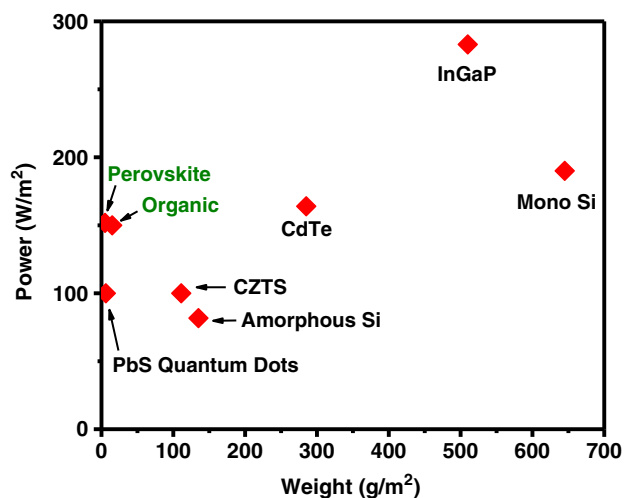


Figure 9. Output power and weight per m^2 of various flexible solar cell technologies.

5. Challenges and Opportunities

5.1. Integration-Related Challenges and Potential Solutions

Various technologies discussed in previous sections can enhance the power performance of robots, but there are still several design challenges that have to be met before these technologies can be deployed for distributed energy. As an example, for better reliability, the storage and harvesting over large areas should have a modular design. However, such designs also come with the potential of increasing the wiring complexity, which has been a longstanding issue in robotics, particularly in context with large-area tactile skin.^[116] Some of these complexities can be avoided by estimating the power requirements of various sensors/actuators and connecting only the required number of energy modules in their immediate vicinity, as shown in Figure 5, instead of connecting all the individual energy modules in series. Further the inter-module integration can be simplified by adapting the advanced metallization patterns used in 3D-stacked electronic devices^[120] and using printing technologies on the soft skin substrates. Likewise, a multisource distributed energy system requires intelligent power management strategies. For example, a sensor must be able to draw power from nearby sources when its local SC runs out of energy. These power management systems must not add a huge overhead to the computational load. In this regard, the technological solutions that allow distributed computing (e.g., e-skins^[28]) can be helpful.

Integrating the distributed energy architecture with low-power neuromorphic systems^[121] can allow these decisions being taken locally instead of relying on the central processor of the robot. The self-discharge of the batteries is another concern. The internal resistance is not the fundamental issue in this case, but the parallel resistance built up in the electrochemical setup can facilitate constant leakage and dissipation of energy. To prevent such leakages, the effect of the battery's geometry on the rate of discharge must be evaluated.

Another challenge with distributed harvesting and storage devices over a robot's body is related to the added weight. One way to address such challenges is to use multifunctional energy-harvesting/energy-storing devices. For example, a battery, SC, or solar cell can also act as a tactile, strain, or temperature sensor.^[122] In doing so, we eliminate the need for additional sensors and reduce the weight and the overall complexity with simpler readout circuitry, etc. The response of many of the energy devices depends on the ambient conditions, and intelligent use of the temporal variation of their output can allow the measurement of ambient conditions. The solar e-skin discussed in Section 4 is one such example. **Figure 10** shows a few more examples, including energy devices, where the multifunctional operation has been demonstrated. The stretchable SC, shown in Figure 10a, exhibits variable output with tensile strain, and hence the device can be used both for energy storage and strain sensing.^[123] In fact, this device's strain-sensing operation has been shown to measure the volumetric expansion of the

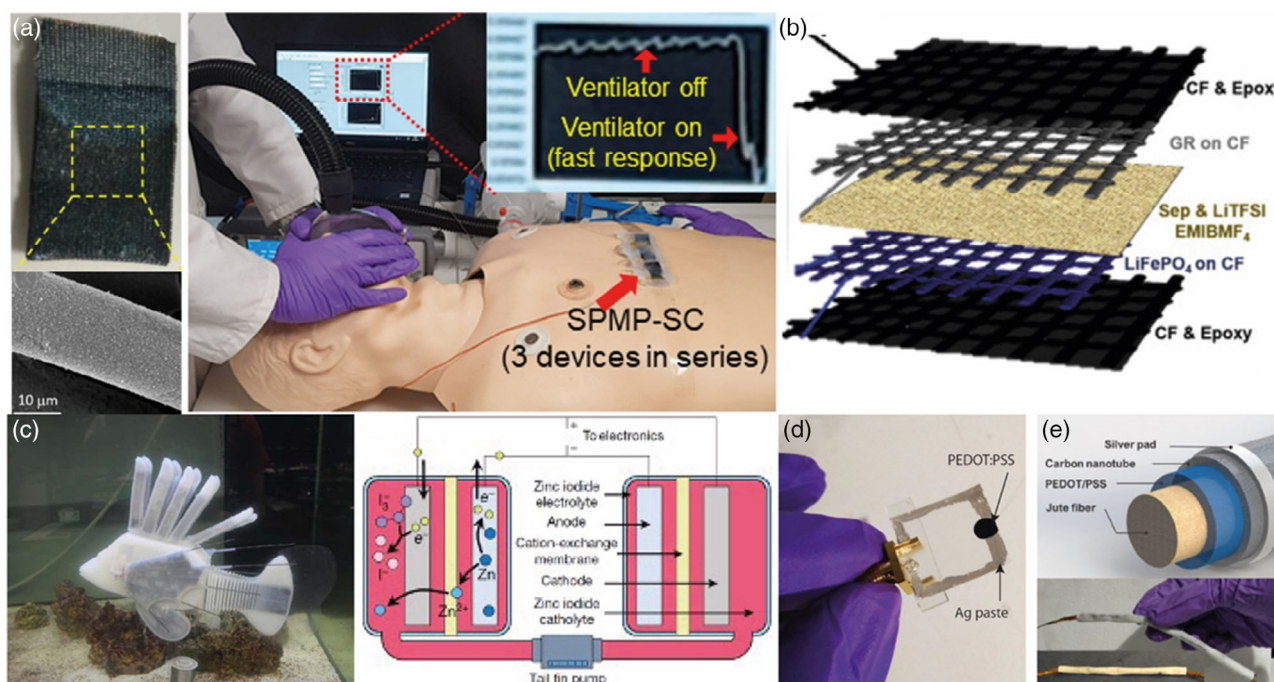


Figure 10. Examples of multifunctional devices. a) Multifunctional stretchable SC with intrinsic strain sensing. The multifunctionality of this stretchable SC has been demonstrated for volumetric expansion of the chest of a manikin during ventilator operation and the joint angle of a robotic hand during grasping. b) Structural battery with load-bearing capability. c) Hydraulic-powered aquatic robot with hydraulic fluid also acting as electrolyte of integrated redox-flow battery. d) Multifunctional temperature-sensing antenna. Antenna in different configurations can also be used for wireless powering. e) Jute fiber/PEDOT: PSS/single-wall carbon nanotubes-based SC and jute/PEDOT: PSS-based temperature and humidity sensor. a) Reproduced with permission.^[124] Copyright 2020, Wiley-VCH. b) Reproduced with permission.^[126] Copyright 2020, Elsevier. c) Reproduced with permission.^[37] Copyright 2019, Springer Nature. d) Reproduced with permission.^[122] Copyright 2021, IEEE. e) Reproduced with permission.^[22] Copyright 2021, Wiley-VCH.

manikin's chest connected to do it yourself ventilator.^[124] The sensor data from such multifunctional devices can be transferred wirelessly to mobile phones^[125] or to the on-board computers on a robot. Another weight-efficient way is to use the battery itself to build the mechanical structure of the robot, as shown in Figure 10b.^[126] Up to 23% weight reduction can be achieved by integrating battery housing and the thermal management system.^[127] Yet another example shown in Figure 10c is the aquatic robot, which can transport power via the hydraulic fluid (zinc–iodide)-based electrolyte for the redox-flow battery.^[37] Wireless power transfer is an efficient way to energize micro-robots, and this has been explored for UAVs too.^[128] In this regard, printed antennas can offer a low-weight solution. Figure 10d shows a multifunctional-printed antenna that resonates at 1.2 GHz and 5.8 GHz frequencies. As the system's temperature changes, the resistance and hence the induced current vary, resulting in a sensitivity of $\approx 1.2\% \text{ } ^\circ\text{C}^{-1}$.^[122]

5.2. New Opportunities Enabled by Distributed Energy

The advent of smart electric vehicles (EVs) and connected objects via the Internet of Things (IoT) concept has brought forward interesting applications for autonomous navigation in land, air, or water. The discussion on distributed energy also applies to these vehicles as the energy devices distributed over the whole body of the vehicle can help improve interiors and user comfort (e.g., more leg space in EVs), in addition to the stable movements, as discussed in Section 2. The charging time of the best-in-class batteries of EVs can be between 30 and 90 min.^[129] This is time inefficient as compared with combustion-powered vehicles. Affixing a carpet-type battery along with distributing solar cells could be a way of resolving this issue. Wireless charging^[130] can be an alternative to solar cells. As the rate of charge

transfer depends on the active surface area, the carpet-type battery can also be charged at a faster rate.

As discussed in Section 5.1 (Figure 10b), the structural battery could be a potent solution for all-electric futuristic airplanes or drones. In the case of aerial vehicles, the Watt-to-weight ratio is one of the most important factors that determines the fuel efficiency. The high energy density of combustible fuels ($\approx 44 \text{ kJ g}^{-1}$) is ideal for the generation of a large amount of thrust needed during take-off and steep maneuverings. With the best inline batteries providing $\approx 2 \text{ kJ gm}^{-1}$, the overall weight of the plane has to be significantly reduced. The extra thrust needed for take-off can be powered by multipurpose SCs. The distributed energy-harvesting unit can also increase the flight time of aerial vehicles. For example, the Solar impulse aircraft (Figure 8j) uses more than 17 000 silicon solar modules with the capacity of collecting $\approx 340 \text{ KWh}$ of energy per day,^[131] allowing it to complete a 26 h long flight. A downside of handling such an enormous amount of electrical energy is the overheating of batteries.^[132] As the heat dissipation of batteries depends on its exposed surface area, the distributed energy can also be the savior for aerial vehicles too. Another area that can benefit from distributed energy is swarm robotics. Swarm robots derive their motivation from animal swarms, where a collection of individual units work in tandem to complete a specific task. More than one independent functional unit can assemble/disassemble as per the task. In a majority of applications of these types of robots, the continuity of operation is not of vital importance. However, by depending on the power distributed among each other in the swarm, the robots can have the opportunity to work together. To enhance the reliability of the swarm, a dedicated number of them can act as recharging units for the application-critical units. Similar to swarm robots, the micro-/nanorobots can work in tandem for biomedical applications such as precision drug delivery,^[133] to rupture tumor/cancer cells^[134] or detect

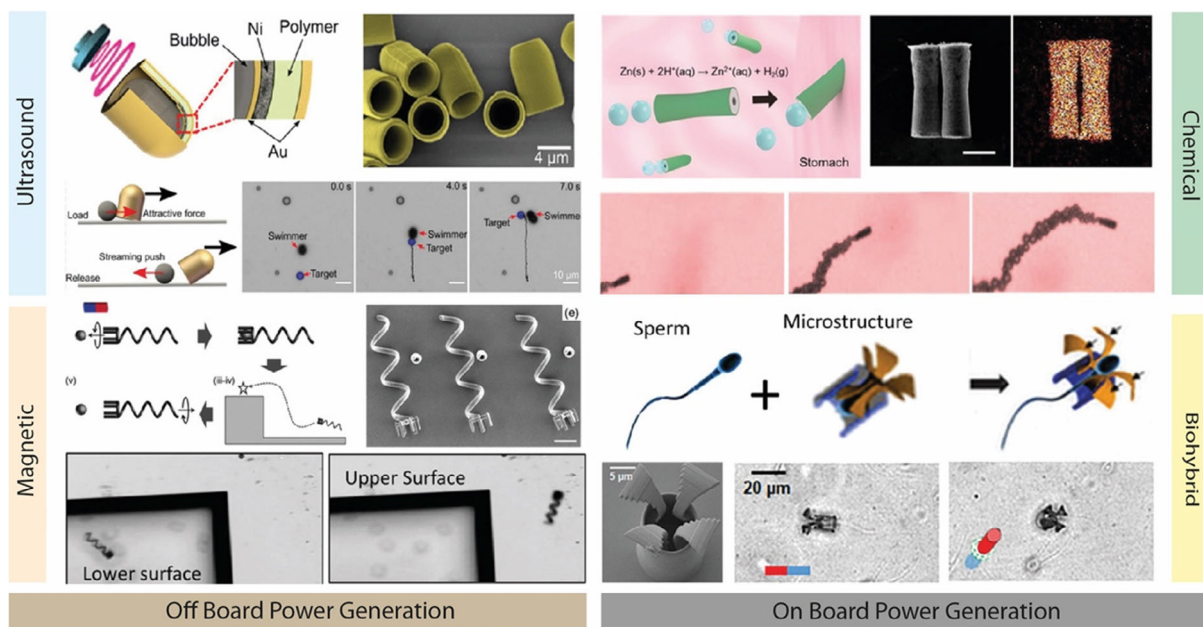


Figure 11. Nanorobots with off-board and on-board power generation modules. Reproduced with permission.^[135] Copyright 2020, Wiley-VCH.

and repair damages in internal organs, etc.^[133] Most of the current nanorobots are external, i.e., wirelessly energized by magnetic or ultrasound sources (Figure 11).^[135] They have limited energy density to efficiently conduct the detection and repairing tasks and must have an onboard/local power unit instead of the wireless form of power transmission.^[136] These needs can be met with submicron-scale energy devices such as biofuel cells^[137] and MESDs.^[48] Other approaches involve robots harnessing chemical energy from their environment by redox-based reactions and integration with biohybrid structures (Figure 11).

5.3. Challenges Related to Recyclability and Biodegradability of Batteries/SCs

While distributed energy architectures make a compelling case for meeting the energy requirements of future autonomous robots, the increasing use of batteries in the ever-increasing number of robots also raises concerns related to environmental sustainability. This is because of the lack of sufficient methods for disposing the toxic chemicals in most of the high-energy density devices. Considering this, sustainability must be a criterion at all stages of design, and development and biocompatible and biodegradable materials could be used for energy storage and harvesting.^[22,82,93,138] An example is shown in Figure 10g, where a natural jute fiber SC is presented along with jute fiber-based temperature and humidity sensors.^[22] The SC is based on (PEDOT:PSS)/single-walled CNT electrodes, a cellulose-based separator, and a hydroxyethyl cellulose–potassium chloride-based gel electrolyte giving out energy and power densities of $0.712 \mu\text{Wh cm}^{-1}$ and $3.85 \mu\text{W cm}^{-1}$, respectively. This SC can power the jute fiber-based humidity and temperature sensors. A complete switch to an ecofriendly energy device is not an overnight task. It will take a long time and will require community participation, which often comes at a slow pace. Considering this, alternative approaches such as the reusing of batteries must be explored. For example, old batteries from high-performance EV systems can be reused as storage units for small wind turbines or solar cells.^[139] Similarly, several hybrid systems of fuel cells with batteries/ultracapacitors are available for standard application, especially in the automobile industry.

6. Conclusion

The autonomy of robots is tightly coupled to the availability of energy. In this regard, we have attempted to closely investigate the progress in the field of energy for robotics, particularly with the goal of establishing biological systems like distributing energy. Recent reports show that the energy requirements of advanced humanoids can be in the order of 50–100 Wh. These requirements generally align with the batteries and SCs and energy harvesters such as solar cells. With whole-body-distributed energy harvesting using solar cells, energy generation in the order of 100 W is possible. The matching performance metrics are very encouraging and offer tremendous opportunities for the development of self-sustainable robotic platforms for applications where extended operational time is needed with no or negligible access to the mains supply. Meanwhile, energy storage and harvesting are yet to be enhanced to power

high-demand components such as joint actuators. There are several critical points that have to be considered for the development of an effective platform. These include the distributed storage and generation of sufficient power coupled with good power management. While addressing these scientific and engineering challenges, we may be faced with opportunities. For example, pursuits to find ways to distribute the energy could also lead to the simple designs of the robot's body and use the same to develop a virtual platform, which could be subsequently used to simulate performance prior to the development of an actual system. This can provide a means to develop application-centric solutions. In addition, distributed energy in general can benefit those pursuing even wearable systems and the swarm of micro/nanorobots for precision medicine. We believe that the distributed energy systems, leveraging their attractive features such as high flexibility, availability, and ecofriendliness, are an inseparable integral in the next-generation robotic systems that are truly safe, have high efficiency, and self-sustainable.

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Conflict of Interest

The authors declare no conflict of interest.

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biomimetics, distributed energy, flexible electronics, robotics

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Rudra Mukherjee is a Marie Curie early-stage researcher in Bendable Electronics and Sensing Technologies (BEST) group, University of Glasgow. He completed his Ph.D. in Nanotechnology from CeNSE, Indian Institute of Science, Bangalore, India. He received DEITY (Visvesvaraya) Fellowship in 2017. His research interests include integrated-sensing energy-harvesting systems, semiconductor device physics, and defect spectroscopy.



Priyanka Ganguly received her Ph.D. in Nanotechnology from the Institute of Technology Sligo, Ireland, in 2020. She is currently a Marie Curie early-stage researcher in the Bendable Electronics and Sensing Technologies (BEST) group at the University of Glasgow. Her research interests include the synthesis and characterization of 2D nanomaterials, ternary chalcogenides, and several metal oxides for various energy and environmental applications. She has authored/coauthored more than 20 research articles and presented in several international and national conferences. She also received the Institute of Chemistry of Ireland Postgraduate Award in 2020.



Ravinder Dahiya is Professor of Electronics and Nanoengineering in the University of Glasgow, U.K. He is the leader of Bendable Electronics and Sensing Technologies (BEST) research group, which conducts multidisciplinary research in flexible and printed electronics, electronic skin, robotics, and wearable systems. He has authored about 400 articles and has led several international projects. He is President-Elect (2020–2021) of IEEE Sensors Council and has chaired several conferences including IEEE FLEPS, which he founded. He has received several awards, including 9 best paper awards as author/coauthor in International Conferences and Journals. He is Fellow of IEEE.