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Review article

Nature-inspired interfacial engineering for energy harvesting

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Abstract

The ever-increasing demand for low-carbon energy underscores the urgency of harvesting renewable energy sources. Despite notable progress, current energy harvesting techniques are still limited by low efficacy and poor durability. Biological systems exhibit diverse principles of energy harvesting owing to their ability to interact with the environment. In this Review, we explore diverse energy harvesting processes in nature to establish a fundamental understanding of nature's strategies and provide a biomimicry design blueprint for high-efficiency energy harvesting systems. Next, we systematically discuss recent progress in nature-inspired surface/interface designs for efficient energy harvesting from water, sunlight and heat. We then highlight emerging hybrid approaches that can integrate multiple energy conversion processes within a single design through interface engineering to achieve mutual reinforcement. Finally, we deliberate on remaining fundamental and technical challenges to guide future research directions and potential applications of sustainable energy harvesting.

Sections

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Key points

- Exploring diverse energy harvesting processes in nature to establish a fundamental understanding of nature's strategies in energy manipulation.
- Probing nature-inspired surface regulation for efficiently transformating environmental energy source inputs to energy outputs.
- From the perspective of the phase state, summarizing interface engineering involved in water, sunlight and heat energy harvesting.
- Systematically discussing recent progress in nature-inspired interface designs for water, sunlight and heat energy harvesting.
- Highlighting emerging hybrid energy harvesting systems to achieve mutual reinforcement through interface engineering.
- Presenting perspectives on remaining challenges and future directions in nature-inspired interfacial engineering for energy harvesting.

Introduction

The use of fossil energy has been a major contributor to rising environmental pollution and energy crises[1,2]. Tapping into the vast renewable energy sources such as water, solar and heat, sustainable energy harvesting has emerged as a low-carbon energy solution. However, most existing energy harvesting technologies are associated with low efficacy, poor durability and limited scalability, which are often dictated by the surface and interfacial properties of materials[3–5]. Nature is an engineer proficient in energy manipulation. Biological systems have orchestrated diverse strategies to harvest energy based on surfaces with well-defined interfacial properties to interact with surrounding sources such as water, sunlight and heat, achieving the highest energy efficiency with minimal materials[6–11]. Based on physics-guided design, nature-inspired interfacial engineering, which regulates surface properties of materials to control interfacial behaviours at multiple spatial–temporal scales, has been developed to harvest energy from diverse environmental sources.

In this Review, we provide a holistic view on a nature-inspired framework to guide the design, selection, fabrication and tailoring of engineered materials and interfaces, with the ultimate goal to develop advanced highly efficient energy harvesting systems. We first present an overview of energy harvesting processes in nature to provide a biomimicry design blueprint for artificial energy systems. Next, we discuss recent progress in translating these principles into nature-inspired interface designs for developing efficient energy harvesting technologies targeted at different energy sources, including water, solar and heat. We then highlight emerging hybrid approaches that can integrate multiple energy conversion processes within a single design to achieve performance with mutual reinforcement by interface engineering. Finally, we present perspectives on remaining fundamental and technical challenges to guide future research directions and potential applications of sustainable energy harvesting.

Energy harvesting in nature

Nature relies on interfacial interactions with the surroundings to harvest energy with high efficiency and minimal materials. Natural organisms can harvest and manipulate energy to facilitate a wide range of biological activities through diverse energy transformation, storage and even direct electricity generation. There are many examples in nature when sophisticated surfaces are used for efficient energy harvesting and electricity generation, including water-enabled energy harvesting, sunlight energy harvesting and storage, diverse bioelectricity generation and energy extraction in electrogenic bacteria.

Water-enabled energy harvesting in nature

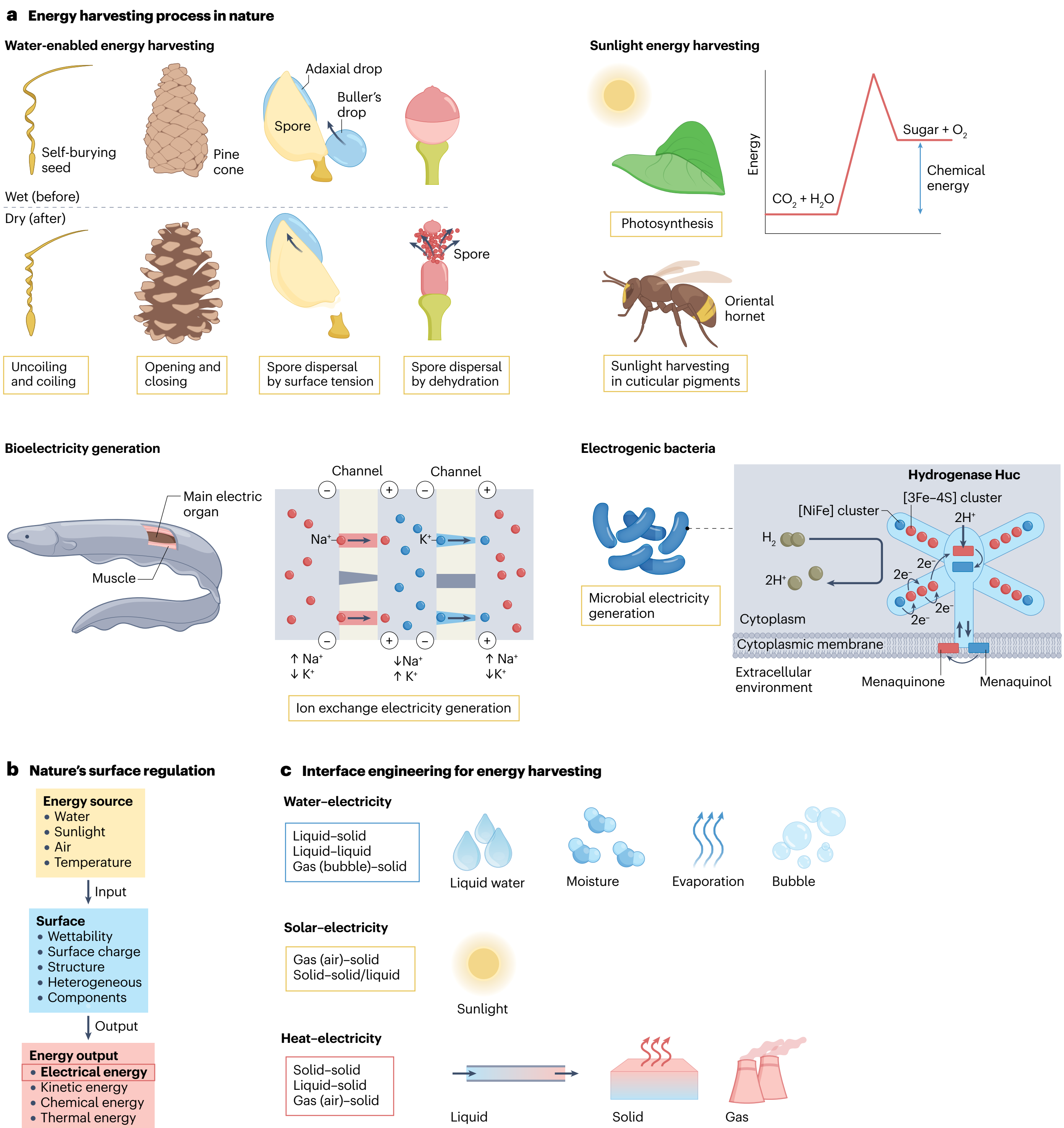
Confined in a place permanently without the presence of muscles or nerves, plants and fungi in nature leverage dynamic water–surface interactions to achieve energy harvesting through the uptake or loss of water in response to environmental conditions. In this process, water serves as the primary medium for energy transformation, driving reversible or irreversible mechanical activities. One notable example is the self-burial seed of *Erodium cicutarium*[12,13] (Fig. 1a). The self-burial is facilitated by the hygroscopic bilayer structure of awns in seeds, which enables spontaneous helical coiling and uncoiling in response to changes in dry and wet conditions, converting energy into mechanical motions that drill the seed into soil. A similar process has been found in other organisms such as pine cone and moss capsule peristomes that close and open in response to wet and dry conditions[14,15].

Water-enabled adaptive energy harvesting also facilitates a wide range of irreversible mechanical momenta, achieved through continuous water uptake or loss on plants' surfaces or hygroscopic structures. A typical example is Buller's drop for diaspore ejection found in most species of *Basidiomycota*[16,17]. Formed by continuous condensation and coalescence of water on the hydrophilic surface, Buller's drop can merge into the adaxial drop. The rapid flow of water induced by surface tension provides enough momentum to propel the spore off of the sterigma, converting the surface energy of condensed water into kinetic energy. Contrary to water condensation, water evaporation or dehydration in a dry environment could also generate efficient mechanical momenta, such as the explosive spore ejection of *Sphagnum* moss[18,19] and the cavitation catapult of fern sporangium[20]. Central to these water-enabled energy harvesting mechanisms is the natural surfaces and structures that feature heterogeneous wettability, stiffness and charge, enabling intricate interactions with water. These natural features serve as a valuable inspiration for the development of efficient water energy harvesting systems[21,22].

Fig. 1 | Energy harvesting in nature. a, Energy harvesting processes in nature can be divided into water-enabled energy harvesting and transformation (reversible mechanical movements in response to wet and dry conditions, such as helical coiling and uncoiling of the self-burying seed or closing and opening of a pine cone; and irreversible mechanical momentum, such as the surface tension catapult of Buller's drop or spore dispersal by dehydration); sunlight energy harvesting, in photosynthesis and the oriental hornet; bioelectricity generation in the electric eel based on ion-selective channels; and electrogenic bacteria that generate microbial electricity by extracting energy from the surroundings, such as atmospheric hydrogen. **b**, Surface regulation of transforming input environmental sources into energy outputs. **c**, Interface engineering for energy harvesting. Interfaces for water energy harvesting can be categorized into liquid–solid, liquid–liquid, gas–solid interfaces, depending on the phases of water sources and surfaces for electricity generation. Solar energy harvesting entails the combined gas–solid interfaces between the intangible sunlight and interfacial materials, as well as other internal solid–solid/liquid interfaces. Interfaces for heat energy harvesting can be classified into liquid–solid, solid–solid and gas–solid, based on the phase of heat sources and surface.

Sunlight energy harvesting in nature

Sunlight is the fundamental driver for energy flow, matter cycling and atmosphere regulation through photosynthesis, a process that converts sunlight into stored chemical energy that sustains most life[23,24]. Photosynthesis takes place in chloroplasts, where pigments absorb sunlight, triggering electronic excitation (Fig. 1a). Surface structures of photosynthetic organisms, especially in leaves and petals, present with complex textures such as subwavelength and hierarchical structures to promote sunlight harvesting by decreasing the loss of incident light and maximizing the absorbed light[25]. For example, petals of a rose leverage closely packed nanoscale papillae with broadband and omnidirectional anti-reflection as well as light-trapping capability[26]. Moreover,



although photosynthesis does not directly generate electricity, it has inspired the development of photovoltaics that can directly convert sunlight into electricity. The surface structures and components of plants have inspired the design principle for dye-sensitized solar cells and organic photovoltaics[27,28]. The capability of oriental hornets to harvest sunlight by distinct cuticular pigments in their stripes[29,30] offers valuable insights for the advancement of sunlight energy harvesting in photovoltaic technologies.

Bioelectricity generation in nature

Direct bioelectricity generation is a remarkable trait of electrogenic creatures, such as electric eels, electric rays and electric catfish, which can emit electric pulses with diverse frequencies, amplitudes and durations for predation, protection and detection. Typically, an electric eel can generate electric shocks of up to 600 V[31,32] (Fig. 1a). Such powerful electrical discharge is emitted by the membrane proteins that are decorated with voltage-gated Na^+/K^+ channels in its electric organ. The Na^+/K^+ channels enable ion selectivity through the regulation of interfacial properties such as the molecular component, spatial configuration and charge distribution. Regulated by ion-selection channels, chemical energy is efficiently converted into ion gradient energy under the control of neural signals. Another type of bioelectricity is bio-piezoelectricity, originating from the piezoelectric effect that converts external mechanical stimuli into internal bioelectrical signals. Upon mechanical stimulation, a wide range of interfacial polarized tissues, such as keratin, DNA, tendons and elastin, generate bio-piezoelectricity, which plays an active role in physiological phenomena[33,34].

In addition, as substantial microbial ecosystem engineers, electrogenic bacteria can generate electrical energy by extracting energy from the surroundings (Fig. 1a). Unique filamentous cable bacteria feature highly ordered fibre structures that can generate and mediate long-distance electrical currents across cell membranes, allowing for electron donor and acceptor harvesting in widely separated space[35,36]. In addition, some electrogenic bacteria manifest the ability to extract energy from the atmosphere, such as hydrogen[37]. Central to this diverse bioelectricity generation, ranging from selective ion channels to piezoelectric materials and electrogenic bacteria, is the sophisticated surface charge manipulation of biological systems. Taking inspiration from elegant surface charge regulations paves the way for sustainable electricity generation, including osmotic power generation, piezoelectric energy harvesting, moisture power generation and microbial fuel cells.

Surface and interface regulation in nature

Despite the diverse strategies used by biological organisms to harness energy from their environments, a common underlying feature is the evolution of surface properties enabling dynamic interaction with the surroundings to maximize energy efficiency. By regulating surface physico-chemical properties – wettability, surface charge, structure, heterogeneity and components – the input environmental sources, such as water, solar and heat, could be efficiently transformed into energy in the form of electricity, kinetic energy, chemical energy and thermal energy (Fig. 1b). Desert beetles, lotus leaves and water spiders manifest a wide range of surface wettability to regulate and rectify water surface energy, so that they can collect water from dry environments, repel water to self-clean and even gather air from underwater for survival[38,39]. Moreover, this ability can be further tailored and even amplified by surface topological structures, heterogeneity and components, giving rise to more versatile multiple spatial–temporal scales for preferential mass, momentum and energy exchange[40]. Surface charges, often neglected at the macroscopic scale, are another driving force for mediating liquid flow[41] and can be harvested by electric eels to emit electric energy with varying frequencies, amplitudes and durations for predation, protection and detection.

Understanding, controlling and mimicking nature's surface regulation and involved dynamic interfacial interactions also facilitates the efficient generation and transport of energy carriers (molecules, ions, charges and photons) at the microscale, which fundamentally shapes the macroscopic energy processes such as water fluidics, sunlight capture and heat transfer. The new insights learned from nature can prove instrumental for designing new energy harvesting systems[42,43].

Tailoring interfaces for energy harvesting

Despite advances in the design of engineered systems, it is unlikely for one specific surface to address all of the challenges across multiple spatial–temporal scales in the complex energy harvesting processes. In this section we discuss recent advancements in nature-inspired interfacial engineering for energy harvesting from water, sunlight and heat. Energy harvesting technologies from each source are categorized based on the triple-phase interfaces for electricity generation, formed by the energy source and the surface of an energy device (Fig. 1c).

Water energy harvesting

The water cycle stores about 60 trillion kilowatts of energy each year, three orders of magnitude higher than the annual global energy demand. Conventional techniques mainly rely on hydroelectric turbines to collect high-frequency and centralized energy sources, such as river potential and tidal energy. However, a significant reservoir of water energy stored in decentralized and low-frequency forms, such as evaporation, osmosis, moisture and raindrops, remains largely untapped. The past decade has witnessed a surge in exploiting various technologies for harvesting these underutilized water energy sources, including hydrovoltaic technology[4], reverse electrodialysis[44] and triboelectric nanogenerators[45] (Fig. 2a). All these approaches rely on the manipulation of interfacial electric charges through interaction between water and interfacial materials[46,47]. Despite progress, achieving water energy harvesting with high efficiency, scalability and high durability remains challenging, partially owing to the lack of rational design of the interface and material design. To tackle this challenge, natural living organisms – especially their intriguing surfaces – can serve as inspiration for material design.

Water energy harvesting via hydrophilic surfaces. Generating electricity from water energy sources through osmosis, evaporation and moisture requires a durable and intimate water–material interface to facilitate the continuous charge generation and ion redistribution. Such interaction has been found in various natural hydrophilic surfaces. As a result, many nature-inspired hydrophilic surfaces have been developed and applied in water energy harvesting technologies.

Water energy stored in the salinity difference between seawater and river water, referred to as blue or osmotic energy, has an estimated power density of 0.8 kWh m^{-3} at the sea–river interface[48]. Current osmotic energy harvesting mainly relies on two strategies: pressure retarded osmosis and reverse electrodialysis. Between the two, electrodialysis has received increasing attention owing to its lower operating pressure, broader applicability and greater stability[49,50]. Reverse electrodialysis generates electricity leveraging the ion diffusion process across a semi-permeable membrane between salinity-gradient water, which can result in charge separation and an electric potential difference. Conventionally, the ion-selective membrane serves as the core material for reverse electrodialysis owing to its abundance, large area and high ion selectivity[51,52]. However, such a design suffers from limited power density, mainly because the ion-selective membranes feature

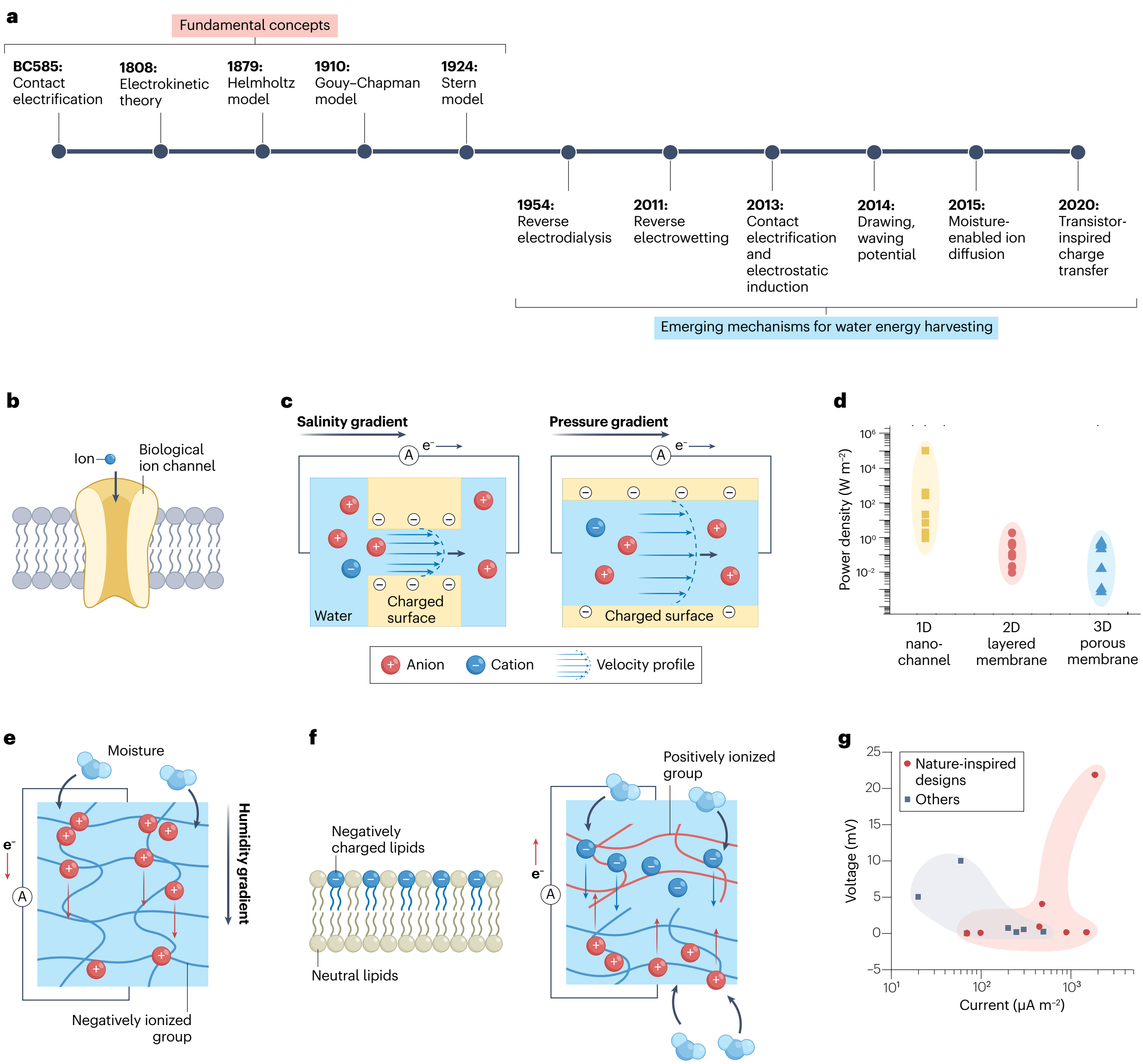


Fig. 2 | Nature-inspired engineering for hydrophilic surface-based water energy harvesting. a, Development of water energy harvesting based on the manipulation of interfacial electric charges, including common fundamentals (red) and emerging mechanisms for water energy harvesting (blue). **b**–**d**, Nature-inspired osmotic energy harvesting and evaporation-induced energy harvesting. Symmetrically structured ion channels embedded in lipid bilayers can regulate transmembrane ion flow with high efficiency (**b**). The mechanism for water/ion flow-induced water energy generators based on charged nano/microchannels that can regulate ion behaviour under either the salinity gradient (left) or evaporation-induced pressure (right), with the velocity profile inside the channel dragging the ions (**c**). Performance summary of osmotic energy harvesting with materials in various formats, including a one-dimensional (1D) nanochannel/nanopore, two-dimensional (2D) layered membrane and three-dimensional (3D) porous membrane (**d**). **e**–**g**, Nature-inspired moisture energy harvesting. Moisture energy harvesting based on materials with homogeneous structure (**e**). Asymmetrical lipid bilayer consisting of the neutral lipids on one side and negatively charged lipids on the other side (left), and moisture energy harvesting based on materials with heterogeneous structure (right) (**f**). Performance comparison of moisture energy harvesting with nature-inspired design and others (**g**).

sub-nanometre scale pores comparable with the size of ionic species and large thickness (several hundreds of micrometres). These features weaken the ion transport due to the high ion resistance and charge polarization occurring at the membrane–solution interface, and easily lead to fouling from environmental substances such as heavy metals, biological pollutants and large organic chemicals[53,54].

Inspired by the biologically structured ion channels that can transport ions at a large flux of 10^7 ions per second[55] (Fig. 2b), the strategies for osmotic energy harvesting have shifted towards designing various nanofluidic channels, which feature larger channel dimensions and highly charged surfaces. The nanofluidic channels give rise to the enhanced ion flux in diffusion-osmotic flow, low charge polarization and resistance to environmental fouling, thereby enhancing electricity generation[56,57] (Fig. 2c, left). By optimizing parameters such as geometry, surface functionalization and size, the nature-inspired nanofluidic membranes can selectively transport specific ions, which improves ion separation efficiency and, thereby, energy harvesting performance[58,59]. Theoretically, the nature-inspired nanofluidic membranes can improve the power density of the osmotic energy harvesting technology up to 10^6 W m^{-2}, much higher than the ion-exchange membrane-based design[32,56,60] (Fig. 2d). Moreover, the design of nanofluidic channel-based membranes offers better suitability for large-scale integration owing to the inherent flexibility and layered structures[61]. Currently, nanofluidic channel-based osmotic energy harvesting is still at the laboratory stage and has not been widely used in practical scenarios[52]. Presently, practical applications are limited by the trade-off between selectivity and flux, performance saturation when scaling up and the lack of simple fabrication methods.

Evaporation is a ubiquitous phenomenon that drives energy transfer in the Earth's climate. However, harvesting energy from evaporation remains challenging owing to the lack of explicit working principles and reliable devices. One possible strategy is to harness the energy stored in evaporation from water-responsive material deformation[62] or interfacial ion transport[63]. Leveraging the advances in nanomaterials, harvesting energy from the evaporation-induced interfacial water/ion flow has become a leading generic strategy with high adaptability to various environments[64,65] (Fig. 2c, right). Facilitating continuous water and ion transport with high flux and density requires a surface design characterized by high hydrophilicity, ionizability, durability and a large surface area[46,66]. However, meeting all these requirements is difficult for conventional nanomaterials, most of which focus one or two aspects of the requirements for surface design.

Addressing this challenge can be done by mimicking natural organisms' interfaces and materials. Materials with plant-inspired hydrophilic structures such as hierarchical and capillary channels feature a large specific surface area and high hydrophilicity, facilitating the water/ion transport flow for electricity generation[67]. Moreover, by taking inspiration from adaptive natural leaf structures such as stomata[68], surfaces capable of adapting to environmental change for efficient water/ion transport can be designed. Another approach for energy harvesting enhancement involves surface chemical modifications with active chemical groups to intensify the water–material reactions, which can increase ion density at the interface[69,70]. In addition to biomimetic materials, some biomaterials, such as cellulose and microbial film, with sufficient functional groups and porous structures, are suitable for evaporation-induced energy harvesting with environmental compatibility and renewability[71]. Although nature-inspired designs hold promise for enhancing evaporation energy harvesting, the interplay of various characteristics such as channel size, wettability and surface potential hinders identifying the specific sources of performance optimization. Therefore, it is critical to establish relationships between material properties and output power for guiding materials and interface design.

Ambient moisture is a tremendous natural energy source that can be harnessed through moisture-induced energy harvesting technologies. Techniques based on moisture-responsive materials can convert moisture into mechanical energy or chemical energy, and generate electricity by integrating with the piezoelectric effect[21], the electromagnetic effect[22] and redox reactions[72]. However, these approaches are limited by the extremely low energy density and complicated fabrication. The thermodynamic process of ambient moisture absorption by sorbents presents a controllable and sustainable method to harvest green energy from moisture[73]. This strategy relies on electricity generation by constructing asymmetric ion diffusion in the absorbent materials with a gradient or homogeneous structure[73,74] (Fig. 2e). These moisture energy generators still suffer from a low power density (0.1 W m^{-2}) and non-self-sustainable electricity generation owing to the low ion migration velocity and gradient invalidation.

Drawing inspiration from surface heterogeneity found in nature, designing materials with heterogeneous physico-chemical properties could be a promising solution. By imitating the heterogeneous lipid bilayer found in the cell (Fig. 2f), a moisture-based generator with a charge-heterogeneous structure can be constructed showing higher energy conversion efficiency and power density because of highly asymmetric ion movement[75,76] (Fig. 2f,g). For example, a bilayer membrane composed of negatively charged PSSA and positively charged PDDA can produce a power density of 0.5 W m^{-2} and a voltage of 1,000 V with integration design at 85% relative humidity, which is several orders of magnitude larger than the voltage from other designs[75]. Furthermore, introducing heterogeneous wettability into sorbents enables a balance between hydrophilic adsorption and hydrophobic desorption of moisture, thereby preventing the sorbents from total wetting and achieving self-sustainable electricity generation[77,78]. In addition to the heterogeneous material design, the direct usage of biomaterials, such as protein nanowires, spider silk and microbial film, allows for developing moisture energy harvesting, which is cheap, non-toxic and environmentally friendly[79–82]. Nevertheless, moisture energy is essentially a low-grade energy with a theoretical upper limit of 10% on its efficiency. Reaching or even breaking this limit calls for the disruptive design of materials and designs.

Hydrophobic surfaces for water energy harvesting. Hydrophobic surfaces have a low affinity for water, enabling transient contact and separation with water. This type of water–material interaction enables an interface transition and stronger charge redistribution than that on hydrophilic surfaces, making hydrophobic surfaces suitable for harvesting water from droplets and waves.

The triboelectric nanogenerator[83], reverse electrowetting[84] and drawing potential[85] are examples of hydrophobic surface-based water energy harvesting techniques. From the circuit architecture perspective, these generators can be treated as an open-circuit system, which brings about several drawbacks including the limited charge generation and the unwanted electrostatically screening effect imposed by the charges on the underlying electrode, which is a component for outputting electricity in typical triboelectric nanogenerators and reverse electrowetting.

One feasible strategy to overcome these limits is to use an architecture that can form a closed loop between the hydrophobic electret material, two electrodes located below and above the dielectric layer, and dynamically flowing water. The design is inspired by that of a field-effect transistor, which can dynamically gate the flow of carriers between its source and drain terminals[3,47] (Fig. 3a). The water energy generator with transistor-like architecture can fully harness the surface charge on the hydrophobic surfaces and generate electric outputs with an energy conversion efficiency three orders of magnitude larger than the conventional triboelectric nanogenerator and reverse electrowetting. The transistor-like design concept provides a possibility to generate electricity from a single droplet to droplet arrays[86,87], from natural rocks to artificial windows and solar panels[87,88], with continuous leaps in peak power density from 50 W m^{-2} to 10^5 W m^{-2} (refs. 89,90).

The performance of hydrophobic surface-based water energy harvesting is dictated by the interfacial properties of generator materials as well as their interaction with the liquid. Efficient and continuous electricity generation necessitates a high-density interfacial charge, a large liquid–solid contact area and rapid detachment of water from the generator. However, most hydrophobic surfaces feature a two-dimensional (2D) contact with water that leads to a low surface charge density and a low water–surface contact area. Moreover, the high-frequency contact of water on these surfaces may cause the formation of a continuous water film because of the long water–solid contact time, thereby disabling the continuous electricity generation.

One way of addressing these issues is to design a lotus-inspired superhydrophobic surface (SHS)-based water electricity generator[91–93] (Fig. 3b). The hierarchical structure of the SHS enables a three-dimensional (3D) contact with water, resulting in a large water–surface contact area and a high surface charge density. Moreover, the SHS can shed water within several milliseconds because of its water-repellent properties, thereby allowing high-frequency water energy harvesting. For example, the lotus-inspired water energy generator can generate three times higher average electrical energy from a 165 Hz droplet than that of a generator with a conventional hydrophobic surface[91]. Other superhydrophobic designs mimic the hierarchical nanoscale and microscale natural surfaces such as moth eyes and bamboo leaves, or natural surfaces such as leaves and stones[94,95].

Operating in various working conditions, solid hydrophobic surfaces are susceptible to external pollution and unwanted wetting transitions caused by hydrodynamic impact in extreme environments. More challenges emerge in the underwater condition. The hydrophobic surfaces face the high pressure and flow shearing from surrounding water, as well as the biofilm fouling. All these problems could result in the collapse of efficient contact and separation between water and the hydrophobic surface, impairing energy harvesting efficiency and durability.

Mimicking natural liquid surfaces that can repel immiscible liquids with high stability provides a feasible solution for designing hydrophobic generators with a liquid dielectric surface to enable liquid–liquid contact with water (Fig. 3b). Choosing dielectric liquid with proper viscosity and a dielectric constant, the liquid–liquid contact between

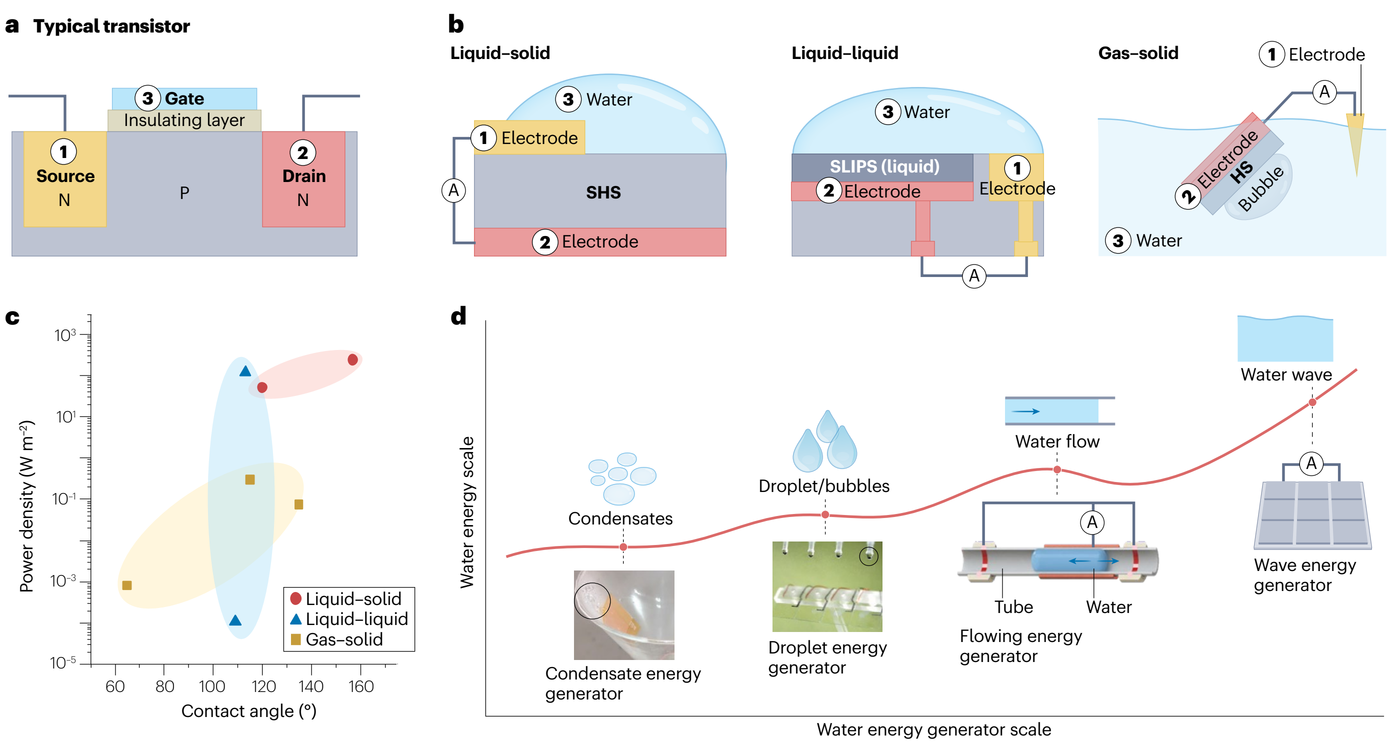


Fig. 3 | Nature-inspired engineering for hydrophobic surface-based water energy harvesting. a, A typical transistor with an NPN configuration, which can dynamically gate the flow of carriers between its source and drain terminals. The three terminals in the transistor labelled 1, 2 and 3 are analogous to the corresponding parts in the transistor-like water energy generators shown in **b**. **b**, Nature-inspired surfaces including a superhydrophobic surface (SHS), a slippery liquid infused surface (SLIPS) and a hydrophobic surface (HS) enable transistor-like water energy harvesting at the various interfaces, including liquid–solid, liquid–liquid and gas–solid interfaces. **c**, Performance summary of transistor-like water energy harvesting versus the surface wettability at various interfaces. **d**, Integration of transistor-like generators for harvesting water energy at various scales ranging from condensates to rain droplets, water flow and water waves. Panel **d** is reprinted with permission from: ref. 97, Elsevier; ref. 3, Springer Nature; ref. 86, Wiley-VCH; ref. 97, Elsevier.

water and the generator surface eliminates the unwanted wetting transition and increases the effective liquid–solid contact area, all of which are beneficial for water kinetic energy harvesting[96,97]. For example, inspired by the pitcher plant, slippery liquid infused surface (SLIPS)-based water energy generators show a stable electrical output in a wide spectrum of harsh environments, ranging from high salinity to caustic acid–base, in a wide humidity and temperature range[97–99] (Fig. 3c).

Although harvesting energy from water in the air provides an alternative energy harvesting strategy, this approach becomes ineffective in the offshore condition due to off-grid conditions and limitation of long-distance electricity transmission cables. One option is to harvest energy directly from bubbles in the underwater environment. However, the hydrophobic generator surfaces that function well in the air may break down when a continuous interfacial water film forms in the confined underwater environment, screening surface charges stored on the dielectric surface.

The design of surfaces for bubble energy harvesting draws inspiration from natural aquatic plants, such as water hyacinths or water lilies, that can store and transport gases in the water through their surface. Delicately tailored surface wettability endows dielectric surfaces with high-density surface charges which facilitate fast bubble spreading and subsequent departure in the process of liquid–solid interface transformation into a gas–solid interface. This interface transition allows for efficient charge transfer and electricity generation in a water environment[100,101] (Fig. 3b). In conjunction with the transistor-like design, a bubble energy generator with the optimal dielectric surface can yield an output at least one order of magnitude higher than the control studies without a surface control (Fig. 3c). However, the durability of a solid surface is susceptible to the harsh underwater environment that can lead to surface fouling and wetting transition. Potentially, the usage of a liquid dielectric surface with delicately controlled wettability could improve the stability and lifetime of the generator for applications in underwater and offshore operations where direct energy harvesting from small bubbles is otherwise impossible.

The fusion between the nature-inspired interface design and transistor-like architecture has formulated a genetic design concept that dramatically enhances electricity generation at various interfaces. (Fig. 3d).

Solar energy harvesting

Solar energy is the largest and inexhaustible natural energy source. Among myriads of solar energy harvesting processes, solar or photovoltaic cells are capable of directly converting sunlight into electricity via the photovoltaic effect. The operation of solar cells relies on sunlight harvesting and subsequent internal processes involving the generation, transport, separation and collection of charge. From the perspective of interface engineering, sunlight harvesting process at the gas (air)–solid interface involves intricate light–surface interactions between sunlight in the air and interfacial materials (Fig. 4a). Driven by advances in sunlight harvesting materials and fabrication, solar cells have undergone an impressive transition, from initially crystalline silicon solar cells to perovskite solar cells (PSCs), from single junctions to multi-junctions/tandems, making it possible to continuously break current efficiency limits[102,103].

Despite intense progress, existing solar cells still suffer from limited power conversion efficiency (PCE) and insufficient durability, especially when working in a harsh environment[5,104]. More challenges arise with the growing power demands of portable and wearable electronic devices, which necessitate more stable and optimized integration[105]. One possible solution to tackle these challenges lies in the design of nature-inspired surfaces that can regulate light–surface interactions to enhance sunlight harvesting, achieve optimal carrier dynamics and optimize device integration as well as improve long-term stability and durability. In this section, we focus on discussing recent advances in optimizing solar cell performance through interface engineering, from the aspects of nature-inspired structural design for sunlight harvesting capability and nature-inspired surface design for enhanced stability (Fig. 4b).

Nature-inspired structural design for sunlight harvesting. The efficiency of sunlight harvesting of solar cells is closely dependent on the structure. Conventional solar cells usually exhibit relatively smooth non-textured structures, which is partially due to the fabrication process and materials used. Despite facile manufacturing and low processing cost, these non-textured structures restrain efficient light–surface interactions, leading to high optical losses and low sunlight utilization. Ideal sunlight harvesting structures necessitate optimal light–surface interactions that contribute to broadband light absorption, minimized light reflection losses, enhanced light trapping and so on. Inspired by excellent light management in the surface structure of moth eyes, butterfly wings and petals of flowers[10,25,106,107], three types of biomimetic structures have been extensively utilized to maximize sunlight harvesting (Fig. 4b), including designing subwavelength structures to minimize surface reflection, hierarchical micro/nanoscale textures to enhance light trapping and other multiscale structures for enhanced sunlight absorption.

Highly ordered nanostructured pillar arrays are a representative subwavelength structure with characteristic sizes smaller than the incident light's wavelength, which can control light propagation to minimize reflection, creating anti-reflective surfaces that enhance light absorption in solar cells[106,108]. To enhance light trapping, hierarchical microscale/nanoscale textures have also been engineered, which is beneficial to increase the path length of light and facilitate multiple reflections and scattering of light within the active materials, contributing to efficient sunlight absorption[107,109]. As a step forward, distinct from the above structures, a more elegant approach is to leverage multiscale structure with diverse dimensions and textures. Despite their different functions, these structures interact and complement each other to optimize light propagation and interactions for maximum solar energy harvesting. For example, sunlight harvesting structures that mimic the surface structures of rose petals and viola flowers enhance the PCE of solar cells by 13.7% and 6.2%, respectively, compared with flat and untextured counterparts[26,110]. It is anticipated that nature-inspired structural design offers a new dimension in regulating light management for efficient solar energy harvesting, particularly with the rapid development of multi-junction or tandem solar cell devices involving multiple interfaces.

Nature-inspired surface design for enhanced stability. Achieving high efficiency and long-term durability of solar cells is crucial for their practical deployment. Operating outdoors, conventional solar cells are easily susceptible to the deposition and accumulation of dust, water and moisture on the surface, which significantly compromises the stable output power and requires frequent cleaning[111,112]. Further performance degradation can be accelerated by moisture-induced lead leakage in lead halide PSCs, ultimately causing device failure and even environmental pollution[113,114]. Moreover, the operational stability of solar cells is affected by the dynamic changes of natural light

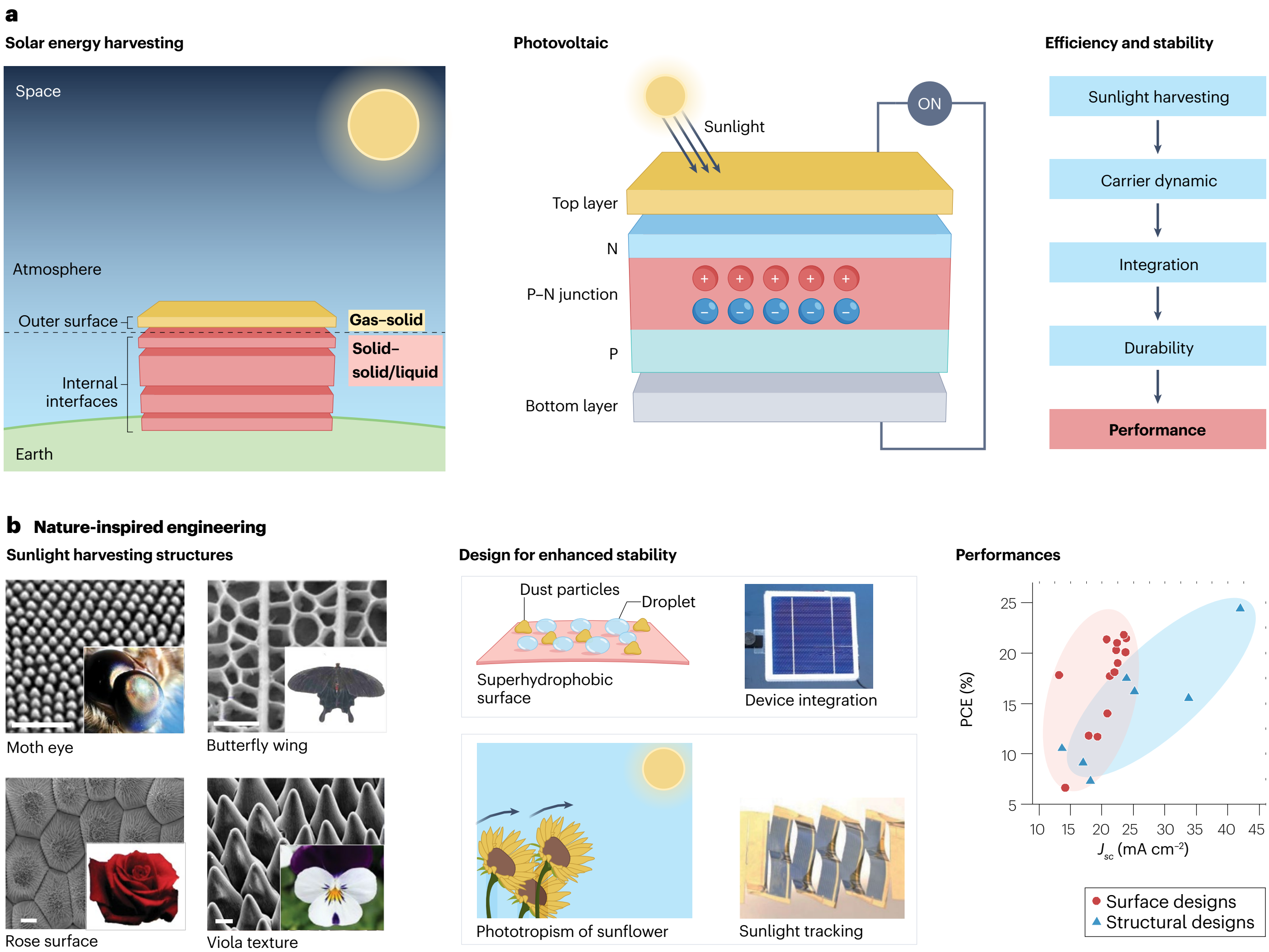


Fig. 4 | Nature-inspired engineering for solar energy harvesting at a gas (air)–solid interface. a, Design principles of solar energy harvesting in solar cells that directly convert sunlight to electricity (left to right): typical working interfaces, basic photovoltaic effect and main performance factors dictated by interface engineering in solar cells. **b**, Nature-inspired interfacial engineering for solar cells (left to right): nature-inspired structural design for sunlight harvesting, as exemplified by subwavelength structures in moth eyes, hierarchical textures in butterfly wings and multiscale structures in the petal surface of rose and viola; nature-inspired surface design for enhanced stability and durability, including a superhydrophobic surface (SHS) that enables self-cleaning and seamless device integration, as well as adaptive sunlight-tracking design that mimics phototropism of sunflower; and performance summary of solar cells by nature-inspired interfacial engineering in terms of power conversion efficiency (PCE) and short-circuit current density (J_{sc}). Panel **b** is reprinted with permission from: ref. 106, Springer Nature; ref. 107, AAAS Science; ref. 26, Wiley-VCH; ref. 110, American Chemical Society; ref. 118, Elsevier; ref. 123, Springer Nature.

throughout the day, which causes energy-density loss and fluctuation in output power. These issues can be mitigated by regulating surface wettability and adaptability of solar cells. Inspired by natural superwetting surfaces, a wide range of strategies have been developed to endow solar cells with self-cleaning capabilities to ensure high energy efficiency and long-term durability (Fig. 4b).

Inspired by high roughness and low surface adhesion of surfaces in lotus leaf, external surfaces of solar cells decorated with water-repellent coatings can effectively prevent surface pollution and, thereby, ensure stable operation[112,115]. The inherent water-repellent capability helps seamlessly integrate solar panels with water-based electricity generators, which requires timely shedding of liquids from the dielectric surface. Combining solar cells with water-based electricity generators enables energy harvesting in all-weather conditions[116–118]. Apart from the wettability regulation on the external surface of solar cells, it is equally important to tailor the wettability of internal interfaces for some PSCs. By controlling materials, structures and chemistry at the molecular level, the design of interface wettability can further reduce surface defects and establish interface shields that effectively mitigate environmental-induced degradation and failure, ensuring long-term stability and durability[119,120]. One remarkable example is superhydrophobic engineered PSCs, which retain 90% of their initial efficiency during photovoltaic operation for 1,000 h at 40% relative humidity, in striking contrast to the untreated samples that rapidly drop to 43% efficiency under the same conditions[121]. Mimicking nature's adaptivity, such as the phototropism of sunflowers that can self-orient towards the sun to maximize sunlight exposure, adaptive solar cells with sunlight-tracking have been developed[122,123]. Capable of dynamically sensing and responding to changes in natural light, adaptive solar cells achieve stable efficiency throughout the day, contributing to enhanced energy harvesting performance. Using these strategies, performances of the solar cells (Fig. 4b) can be improved through nature-inspired engineering.

Heat energy harvesting

Approximately 67% of energy is wasted as heat[124,125]. Tremendous efforts have been dedicated to developing thermal energy harvesting technologies to capture, store and utilize waste heat, including molten salt technology, thermal chemical storage and thermal power generation[126–128]. However, these technologies rely on bulk volume and only work with high-temperature thermal energy, leaving decentralized and low-grade (<100 °C) heat energy largely unexplored[129,130]. To this end, thermoelectric generators (TEGs) have emerged based on different mechanisms such as the Seebeck, Peltier and Thomson effects, by which thermal phonon motion from the external medium is converted into internal ion and charge movement for electricity generation[131–133] (Fig. 5a). These mechanisms have led to the raid development of TEGs with various modes, including the typical TEG (thermoelectric

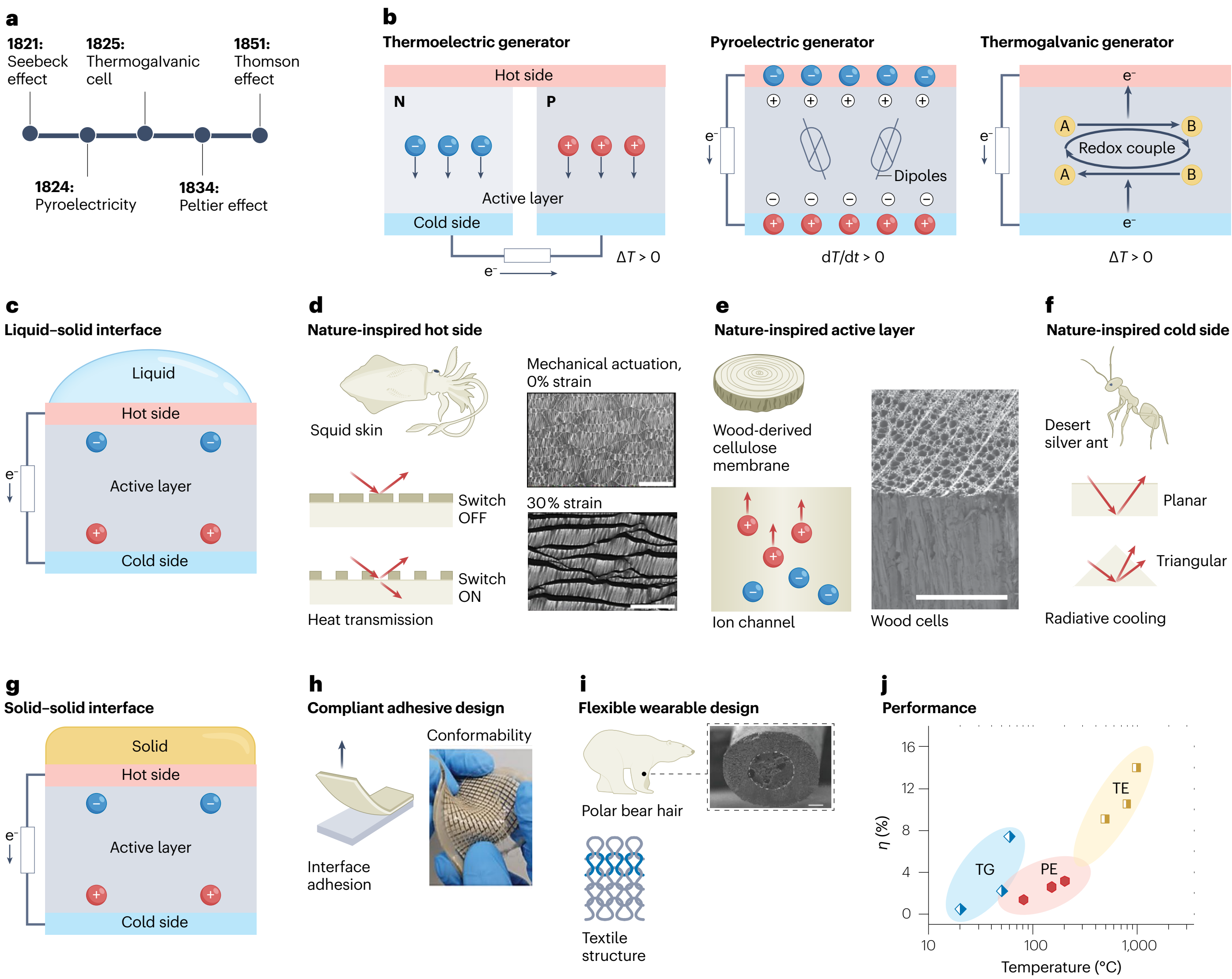


Fig. 5 | Nature-inspired engineering for heat energy harvesting. **a**, Evolvement and development of the thermal electricity generation. **b**, Three fundamental modes of the thermal electricity generations based on the thermoelectric effect, pyroelectric effect and thermogalvanic effect, respectively. **c**–**f**, Nature-inspired liquid–solid interfaces for thermal energy harvesting (**c**), involving hot side design using a functional coating inspired by squid skin (**d**), active layer design featuring porous ion channels utilizing wood-derived cellulose membrane (**e**) and cold side design leveraging desert silver ant-inspired radiative cooling (**f**). **g**–**i**, Nature-inspired solid–solid interfaces for thermal energy harvesting (**g**), including compliant adhesive design with conformal contact (**h**) and flexible wearable design with seamless integration (**i**). **j**, Performance summary of thermal energy harvesting, in terms of energy conversion efficiency (η) and temperature. Panel **d** is reprinted from ref. 146, Springer Nature. Panel **e** is reprinted from ref. 147, Springer Nature. Panel **h** is reprinted from ref. 151, Springer Nature. Panel **i** is reprinted with permission from ref. 156, AAAS Science.

effect)[134,135], the pyroelectric generator (pyroelectric effect)[136,137] and the thermogalvanic generator (thermogalvanic effect)[138] (Fig. 5b). Despite intensive progress, current TEGs still suffer from low energy efficiency, limited scalability and inadequate durability. Nature-inspired advanced interfacial designs may offer new possibilities to meet requirements for highly efficient heat energy harvesting[139–142]. In addition, waste heat is commonly stored in liquid and solid, underscoring the crucial role of the interface between the TEGs and the thermal medium in enhancing TEG performance.

Nature-inspired liquid–solid interface. Waste heat in the form of liquid is ubiquitous, ranging from the vapour exited from nuclear power plants to the cooling water used in steel mills. Unlike the intensive exploration of advanced materials for TEGs, less attention has been placed on the interfacial interaction between TEGs and hot liquid mediums (Fig. 5c). Interfacial interaction, however, is an important factor that directly affects heat transfer, ion separation and charge migration, influencing the performance of TEGs[130,140]. First, the high fluidity and deformability characteristics of liquids facilitate convective heat transfer and ensure stable voltage output. Liquids can seamlessly adapt to various heat transfer surfaces regardless of shape, composition and size with maximal contact area and minimal thermal resistance. Moreover, being excellent carriers of ions, liquids can decrease the ohmic resistance at the solid–liquid interface and generate electrical power through electrochemical redox reactions for harvesting low-grade heat[143].

Specifically, nature-inspired super-hydrophilic surfaces can significantly expand contact surfaces and reduce thermal resistance between liquid–solid interfaces, thereby promoting heat transfer[144,145]. Incorporating functional coatings, that is, dynamic thermoregulatory material inspired by squid skin[146], on the surface of TEGs can also facilitate heat conduction and prevent surface oxidation and corrosion, resulting in improved durability (Fig. 5d). Apart from surface modification, the internal structure manipulation of TEGs, such as the utilization of wood-derived porous cellulose membranes[147], endows the TEGs with larger accessible surface area, shorter heat transfer path and optimized integration to ensure high energy conversion efficiency (Fig. 5e). In addition, structural chemical components in TEGs further contribute to improving the heat harvesting capability as evidenced by the radiative cooling materials inspired by desert silver ants[148]. The triangular shape of the silver hairs can increase the reflection of near-infrared rays to dissipate heat in the dry and hot environment (Fig. 5f). Overall, these strategies, despite their different functions, interact and complement each other to optimize heat transfer and harvesting for maximum heat to electricity conversion.

Nature-inspired solid–solid interface. Effectively harvesting waste heat stored in solid mediums is critical for many industries such as electronics, automotive, aerospace, power generation and directed energy systems. Current solid-state TEGs are capable of harvesting waste heat for electrical generation; however, their practical application is hindered either by low conversion efficiency or complex design. From an interface perspective, these shortages arise from the mismatches of lattice and surface topology between TEG materials and hot mediums (Fig. 5g). First, the lattice mismatch between TEG materials and hot mediums may induce energy barriers and inhomogeneous thermal expansion, both of which hinder heat transfer. Furthermore, the utilization of high-temperature heat mediums (>1,000 °C) necessitates more stable TEG materials to prevent oxidation, deformation or even cracking and melting[149]. Second, the surface topology mismatch between TEGs and heat mediums introduces unwanted air gaps that hinder their conformable contact and degrade heat transfer and charge migration.

Mitigating the above mismatches necessities nature's strategies to efficiently regulate the microstructure and composition of TEG surfaces. One potential solution is choosing flexible TEG materials to construct compatible solid–solid interfaces, thereby reducing the heat transfer resistance. For example, the utilization of stretchable and adhesive hydrogels as conformable thermal interfaces presents a promising solution for effective heat transfer and enables compliant designing of TEGs in complex application scenarios[150,151] (Fig. 5h). Another feasible approach is to introduce functional coatings as intermediate layers between heat sources and TEG materials to reduce thermal radiation losses and improve thermal energy conversion efficiency. One typical example lies in hollow structured thermal insulating materials inspired by polar bear hairs[152]. Additionally, the excellent processability of solid materials allows for the microscale design of TEGs, making them suitable for emerging applications such as the Internet of Things, wireless sensor networks and microelectronics[153]. In particular, they can be seamlessly integrated into flexible wearable devices to power advanced low-energy electronic devices[154–156] (Fig. 5i). TEGs with distinct working mechanisms have their operation temperature ranges (Fig. 5j). Among them, the TEG demonstrates a relatively higher energy conversion efficiency (η) of around 13%, followed by the thermogalvanic generator (7.8%) and the pyroelectric generator (3.4%).

Hybrid energy harvesting

Nature-inspired interfacial design has reshaped the way of harvesting individual energy sources such as water, sunlight or heat. However, in most scenarios, these energy sources coexist and can be mutually converted. Harvesting these energy sources in a hybrid manner offers the potential to overcome the intermittency of individual energy harvesting (Fig. 6a). Current strategies mainly rely on the simple stacking of different individual energy harvesters, which may sacrifice the advantages of individual energy harvesting and even lead to lower overall efficiency. An ideal design of hybrid energy harvesting should achieve mutual reinforcement in individual performance, thereby leading to collective benefits, such as low cost, increased space utilization and energy conversion efficiency, as well as enhanced availability and stability.

One solution is to seamlessly integrate water–sunlight–heat energy generators through rational interface design and material optimization. To this end, the characteristics of each energy harvesting process should be carefully considered for optimized collective performance (Fig. 6b). For example, integrating a SHS-based water energy generator with a photovoltaic cell provides superior self-cleaning, anti-reflection and longer operation time[87,116,117]. A similar interface engineering principle enables hybrid water and heat energy harvesting, in which the kinetic energy and latent energy of water can be fully utilized[157–159]. Integrating a photovoltaic cell and a TEG with a common interface can simultaneously improve the temperature difference of the TEG and cooling efficiency of the photovoltaic cell, facilitating the mutual enhancement in energy harvesting efficiency[142,160,161]. By harvesting multiple energy sources in a parallel manner, these hybrid energy generators can also improve energy utilization efficiency, energy reliability and stability, and provide cost reduction.

In addition to parallel energy harvesting, optimizing the generator surfaces also enables hybrid energy harvesting leveraging the serial energy transduction (Fig. 6c). For example, designing interfaces

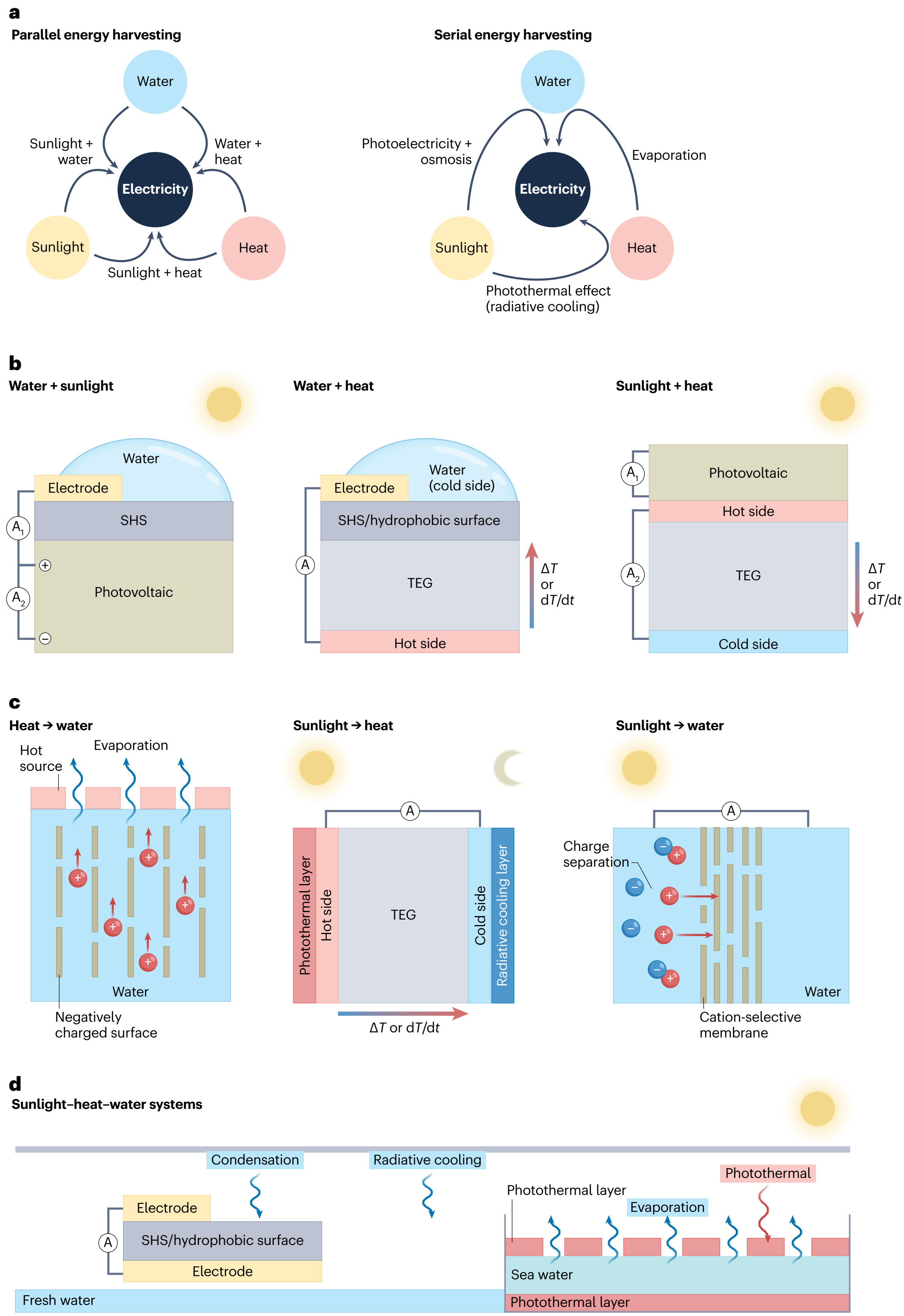

a
Parallel energy harvesting
Water
Sunlight + water
Water + heat
Electricity
Sunlight
Heat
Sunlight + heat
Serial energy harvesting
Water
Photoelectricity + osmosis
Evaporation
Electricity
Sunlight
Heat
Photothermal effect (radiative cooling)
b
Water + sunlight
Water
Electrode
SHS
A1
A2
Photovoltaic
Water + heat
Electrode
Water (cold side)
SHS/hydrophobic surface
A
TEG
Hot side
ΔT or dT/dt
Sunlight + heat
A1
Photovoltaic
Hot side
A2
TEG
Cold side
ΔT or dT/dt
c
Heat → water
Hot source
Evaporation
Water
Negatively charged surface
Sunlight → heat
A
Photothermal layer
Hot side
TEG
Cold side
Radiative cooling layer
ΔT or dT/dt
Sunlight → water
A
Charge separation
Water
Cation-selective membrane
d
Sunlight–heat–water systems
Condensation
Radiative cooling
Photothermal
Photothermal layer
Evaporation
Electrode
A
SHS/hydrophobic surface
Electrode
Sea water
Fresh water
Photothermal layer

Fig. 6 | Hybrid energy harvesting. a, Hybrid energy harvesting systems harness a sustainable water–sunlight–heat nexus, including parallel energy harvesting from multiple sources (parallel energy harvesting; left) and serial energy transduction between multiple sources for electricity generation (serial energy harvesting; right). **b**, Representative examples of parallel energy harvesting from multiple sources, including water–sunlight, water–heat and sunlight–thermal energy generators. **c**, Representative examples of serial hybrid energy harvesting systems involving energy transduction between multiple sources, such as heat to water (evaporation)-enabled electricity generation, photothermal effect–radiative cooling-induced thermoelectricity generation and photoelectric–osmotic electricity generation. **d**, A highly integrated mixed hybrid energy harvesting system harnessing sunlight, heat and water energy in one scenario. SHS, superhydrophobic surface; TEG, thermoelectric generator.

containing photothermal and radiative cooling materials can collectively generate thermal gradients or fluctuations for thermoelectricity generation, enabling all-day energy harvesting from both the sun and outer space[162–164]. In addition, the sunlight to water energy conversion can harvest energy through integration of photoelectric materials and the ion-selective membrane, synergistically converting the sunlight energy and salinity gradient into electricity[165,166]. Moreover, the coexistence of sunlight, heat and water sources in the natural environment can facilitate multiple energy transductions via a highly integrated hybrid system (Fig. 6d), allowing for weather-adaptive energy harvesting in one scenario.

Nature-inspired interfacial engineering in individual energy harvesting paves the way for the springing out of hybrid systems with mutual reinforcement. Promoting these hybrid designs in practical applications faces more challenges owing to mismatch in the forms and scales of electrical output produced by different energy generators. We envision that a combination of interdisciplinary technologies such as intelligent electronic control, energy storage and management can solve these problems, enabling maximum utilization of various energy sources.

Outlook

Learning from the ways energy is utilized in nature through the evolution of surface engineering has provided ample opportunities to achieve sustainable electricity generation with high efficiency (Table 1). However, more scientific effort is required to reveal underlying mechanisms in diverse energy processes.

Table 1 | Nature-inspired interfacial engineering for energy harvesting

Energy harvesting technique	Water energy		Solar energy	Heat energy
	Continuous water: osmotic, evaporation, moisture	Discrete water: droplets, waves and so on		
Interfacial design principle	High surface charge density High water affinity High specific surface area Approaching Deby length High mechanical durability	High surface charge density Low water affinity High specific surface area Low contact angle hysteresis High mechanical durability	High sunlight harvesting Low surface reflection Surface defect passivation Optimal carrier dynamics Tunable band gap Photochemical stability	Low heat resistance Fast ion/charge transfer High specific surface area Matched/compatible contact with heat source Thermal stability
Characteristics of natural counterparts	Abundant functional groups Hydrophilic High ion selectivity High porosity Heterogeneous property Topological structure	Hierarchical structure Hydrophobic High porosity Topological structure Slippery surface Heterogeneous property	Subwavelength structures Hierarchical textures Superhydrophobic Photosensitive Adaptive phototropism Photoelectrocatalytic	High porosity Fractal structure Good thermal insulating Flexible/conformable High reflection High infrared emissivity
Advantages of nature-inspired systems	Electrical output improvement High energy efficiency Mutual reinforcement of hybridization Seamless integration/scalability Enhanced durability	High flexibility/conformability High compatibility/adaptivity Diverse portability Favourable wearability High sustainability		
Challenges of nature-inspired systems	**Fundamentally** Limited energy conversion efficiency Inefficient charge manipulation Biological complexity imposed by the multiple spatial–temporal scales processes	**Technically** Inadequate precision of manufacturing Deficient materials Inadequate reproducibility Limited scalability Insufficient durability		
Potential applications	**Cross-scales power supplier** Wearable devices Portable electronics Industrial monitoring Environmental monitoring Smart building	**Self-powered sensors** **Other scenarios** Remote areas and offshore Deep space exploration Smart farming Internet of Things		

Translating nature's inspiration to practical applications calls for the innovative fusion of multidisciplinary fields. Firstly, despite extensive progress, the basic mechanisms underlying electricity generation from different resources remain to be fully clarified. For instance, the charging mechanism of triboelectric nanogenerators is still under debate regarding whether it involves electrons, ions or mass transfer[167]. The processes occurring at diverse interfaces and displaying distinct spatial–temporal scales are strongly related to the local physico-chemical properties of interfaces, such as wetting, structure, surface charges, heterogeneity and composition, which together dictate the global behaviour, the energy efficiency. Although energy efficiency is easy to measure and quantify, a holistic understanding is elusive owing to its complexity imposed by the multiscale processes. Therefore, a combination of advanced techniques in manufacturing, characterization, visualization and modelling as well as the latest toolkits in machine learning is needed to accelerate the in-depth fundamental exploration[168].

Translating our fundamental understandings into practical applications presents several challenges. Nature-inspired interfacial engineering has led to energy efficiency enhancement; however, the precision as well as functions of current engineered interfaces are not yet comparable with their biological counterparts. Further scaling up as well as the development of hybrid energy harvesting systems may compromise reproducibility, compatibility and reliability of engineered interfaces. Addressing these challenges necessitates innovations in material design, manufacturing and soft technologies, such as artificial intelligence, molecular dynamics and smart energy management algorithms. This approach will accelerate the miniaturization of energy harvesting systems, which can be seamlessly integrated into self-sustained electronic devices, including wireless sensors and wearable electronics for a wide range of fields such as environment monitoring, infrastructure health management or space exploration[169,170]. Moreover, these innovations can facilitate the scaling up of energy harvesting systems for utility-scale applications, especially in remote or offshore regions with abundant natural resources but limited access to electricity. In addition to enhancing their ability to effectively harness abundant natural sources such as water, solar and heat, it is possible to achieve mutual reinforcement of hybrid energy harvesting systems for sustainable electricity supply, particularly in emerging fields such as the Internet of Things and smart farming.

The advances in nature-inspired interfacial engineering have demonstrated immense potential in the design of new materials and devices to harvest multiple energy sources, paving the way for sustainable electricity generation at multiple spatial–temporal scales and scenarios. Projecting to the future, our continued venture into nature through the innovative convergence of multidisciplinary fields can, potentially, lead to transformative and highly efficient energy harvesting systems. These advancements would hold increasing promise in accelerating the upgrade and transition of a low-carbon energy portfolio. Finally, stimulating general interest among researchers from diverse disciplines and interactions within the scientific and industrial communities is required to drive the evolution of this exciting and dynamic field.

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