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Bridging solar harvesting technologies using hydrogels towards sustainability

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The utilization of solar energy has been integral to biological evolution, industrial revolution, and humanity's journey across the past, present, and future, shaping both natural ecosystems and technological advancements. Effectively harnessing this sustainable energy is crucial for addressing the escalating and coupled global energy–water–environment crises. This tutorial review advances an integration paradigm in which hydrogels serve as adaptable and scalable matrices enabling cost-effective solar harvesting that aligns with sustainability and economic feasibility. We first summarize the challenges inherent in existing solar technologies and extrinsic factors beyond material design that influence their sustainable development. Next, we highlight the transformative potential of integrating hydrogels into advanced solar systems through hierarchical energy utilization, multifunctional coordination, and enhanced environmental adaptability and stability. Finally, we assess the broader technological and societal implications of integrated solar harvesting systems by considering regional economic disparities, local resource availability, societal needs, and environmental impacts. By offering a pragmatic perspective on hybrid solar technologies, this tutorial review bridges academic innovation and practical application, charting pathways toward high-efficiency, cost-effective solar energy utilization, with hydrogels serving as a versatile integration platform. These advancements not only foster sustainable development but also contribute to aquatic and terrestrial ecosystem resilience while driving progress toward more resilient, eco-friendly societies.

Key learning points

(1) Pros and cons of conventional solar technologies.
(2) Hydrogels serve as adaptable and scalable matrices enabling cost-effective solar harvesting that aligns with sustainability and economic feasibility.
(3) How hydrogels can bridge different solar energy harvesting techniques.
(4) How to meet the practical requirements of integrated solar technologies.
(5) Assessment of integrated solar energy harvesting within the circular economy.

1. Introduction

The substantial consumption of fossil fuels and chemical products has resulted in severe environmental challenges such as water eutrophication, microplastic and heavy metal contamination, PM2.5 pollution, and increased occurrences of floods and droughts, often linked to phenomena such as the El Niño phenomenon.[1–6] This continued reliance underscores the urgency of addressing the intensifying energy and environmental crises by developing high-efficiency solar energy solutions, alongside advanced pollution remediation and/or upcycling technologies towards a sustainable society.[7–11] Solar technologies have been widely deployed across academia and industry and play a central role in renewable and sustainable energy.

Conventional solar technologies, including solar cells, solar water systems, solar catalysis, and other solar electronics (hydrovoltaic (HV) cells, thermoelectric (TE) cells, thermogalvanic (TG) cells, solar cells, moisture energy generators (MEGs), *etc.*)

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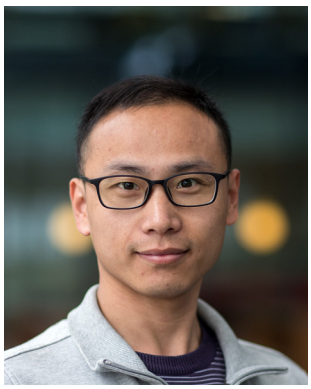
(Fig. 1 and 2), collectively contribute more than 50% of clean energy production.[12–18] For best performance and maximum cost-efficiency, specific solar technologies are strategically deployed according to geographic contexts, for example thermo-solar plants and solar panels are installed in regions with prolonged daylight and minimal cloud cover.[19–21] However, with the exception of solar cells, most of these solar technologies exhibit low energy conversion efficiencies (Table 1), typically below 20% at the laboratory scale,[4,18–24] with substantial energy lost as waste heat. Specifically, the energy conversion efficiency (η) of photocatalytic systems is generally below 10%, in which η values are approximately $<5\%$ for hydrogen generation,[25,26] below 2% for water splitting,[26] and usually below 5% for photodegradation.[27] Furthermore, the η value of solar electronics is generally below 20% (except solar cells $>30\%$[23,28]), where the η value is below 0.1% for TG cells (Carnot-relative efficiency $\sim$ 1%); when utilizing low-grade heat energy,[29,30] the η value can reach 10–20% under higher temperature differences for TE cells,[31–33] and the η value is usually below 1% (electrokinetic conversion efficiency $<$ 3%[34]) for HV cells and MEGs.[17] Such inefficiencies not only restrict the effectiveness of clean energy harvesting but could also cause localized issues such as heat accumulation, disrupted mass (ions, charges) migration, instability of output and efficiency, *etc.*[17,26,27,29–31]

In recent years, a plethora of hybrid solar technologies have been explored to address the abovementioned challenges.[35–75] Although such solar technologies can achieve multifunctionality by allocating input solar energy in either graded (equal distribution) or hierarchical (cascaded distribution) systems, their performance often remains limited because modules are simply stacked with weak or disjointed integration (Fig. 1a). For instance, a solar catalytic system can be combined with hydrovoltaic and/or thermoelectric cells to simultaneously utilize sunlight for photocatalysis and electricity generation separately. However, performance trade-offs and competition for input energy and wasted energy frequently occur in these combined systems due to rigid integration,[76,77] resulting in low energy conversion efficiency.



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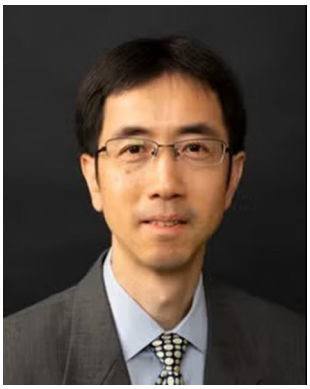

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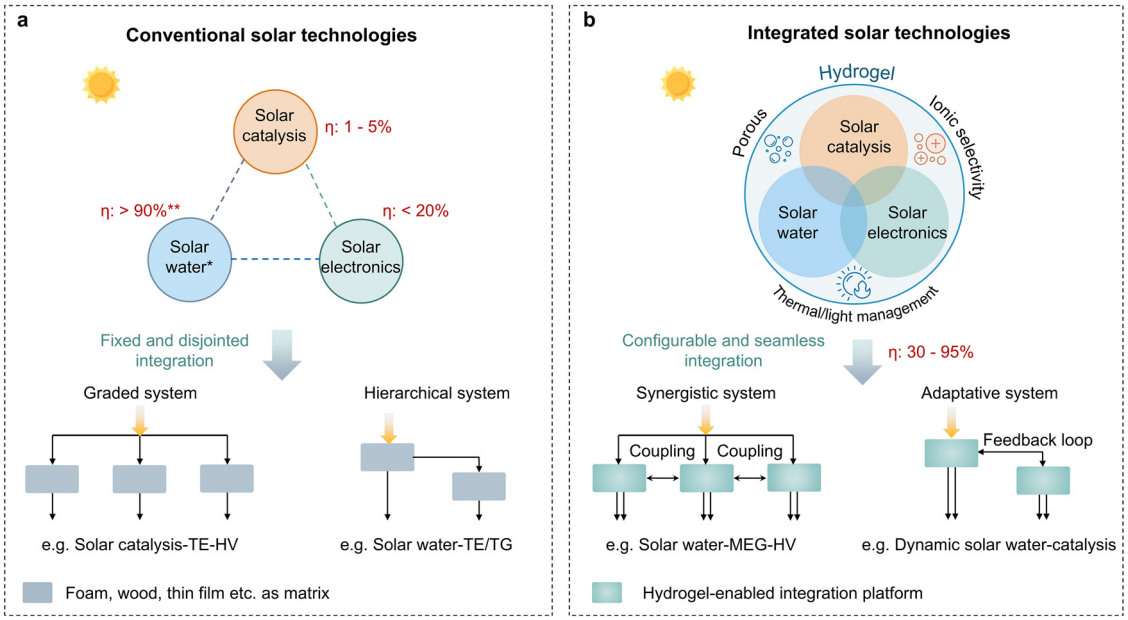

Fig. 1 Comparison between conventional and integrated solar technologies. (a) Conventional solar technologies include solar water (absorption/desorption and evaporation), solar catalysis, and solar electronics. Here, the advances of solar cells will not be discussed in detail since they have already been extensively reviewed in previous studies. Fixed and disjointed integrated systems typically include graded systems where the solar energy input is distributed equally among modules, while the solar energy is mainly utilized by the main modules in a hierarchical system and subsequently cascaded down to the sub-modules. (b) Integrated solar systems consist of solar technologies bridged by hydrogels, in which the configurable, coherent, and seamless systems can be divided into synergistic and adaptable systems. There are coupling effects between modules in synergistic systems, while adaptable systems involve feedback effects that dynamically regulate performance. *Solar water mainly refers to two representative solar–thermal water harvesting technologies, namely solar water evaporation and solar-driven water absorption/desorption. **The energy efficiency of solar water systems is calculated solely based on the photothermal conversion efficiency during the water evaporation process and does not include the efficiency of condensation.

Owing to their high compatibility, hydrophilicity, and unique spatial architectures that enable tunable ionic selectivity as well as thermal and light management, hydrogels offer a promising platform to bridge these challenges by integrating multiple solar technologies into coherent, configurable, and seamless systems.[78] These hydrogel-based platforms are capable of achieving high energy utilization efficiency (>30%), while concurrently producing clean fuels such as hydrogen, methanol, *etc.*[79–84] Furthermore, hydrogels possess tunable thermodynamic stability across diverse working conditions,

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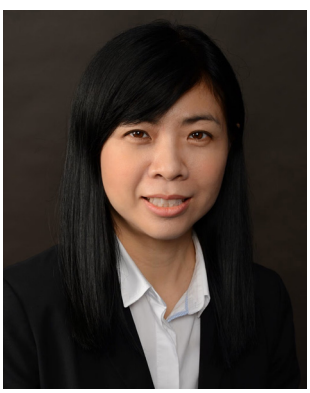

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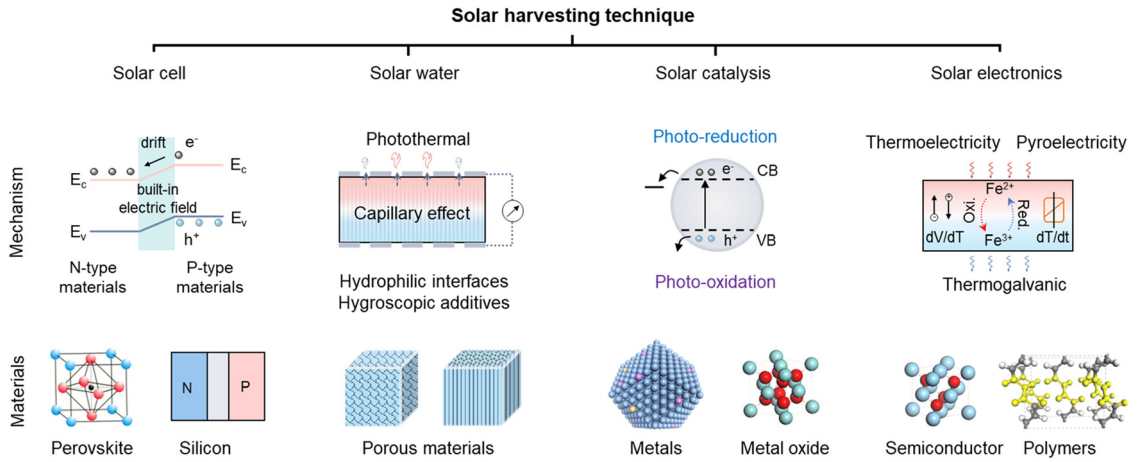

Fig. 2 Categories of clean solar harvesting techniques and corresponding mechanisms and materials.

enhancing the adaptability and synergistic performance of these systems (Fig. 1b). For example, in a hydrogel-based adaptable system that combines photocatalysis and solar evaporation, the photocatalysis system can be the main functional module that utilizes sunlight for chemical reactions (η below 5%), while residual heat drives a solar evaporation sub-module. This not only produces freshwater but also helps regulate the working temperature at an optimal level to maintain maximum photocatalysis efficiency.[79,85] Realizing such adaptable systems with other matrices remains highly challenging, whereas hydrogels offer a particularly promising platform by uniquely combining desirable features such as hydrophilicity, tunable spatial architecture, and broad compatibility with diverse systems. Similarly, when solar evaporation is combined with MEGs and HV systems, hydrogels enable concurrent extraction of freshwater or minerals and electricity generation. In this configuration, solar energy powers the photothermal module for evaporation to achieve freshwater and/or minerals (salts or lithium, *etc.*) and at the same time, water flow within the hydrogel matrix, driven by solar evaporation, generates electricity through the HV system, while vapor flow across the surface is harnessed by the MEG module to generate electricity *via* the large evaporation surface.[86] Furthermore, the high rate of dark evaporation sustains the continuous operation of the MEG and HV modules, while these hydrogel-based modules respond to solar evaporation and mediate ion transport, selectivity and thermal management. Therefore, hydrogels offer a unique and ideal platform to customize and transform solar technologies from loosely combined modules into integrated, programmable, synergistic, and adaptable systems, thereby maximizing η and functional versatility.

Although individual solar technologies have been widely reviewed, the integration across different solar technologies, especially symmetric and adaptable hydrogel-based systems aimed at high energy utilization and effective designs that consider extrinsic factors towards practical applications, has not been summarized and analysed. To address this gap, in this tutorial review, we highlight current solar energy technologies, outline their challenges, and propose potential solutions to bridge academic research and practical applications. Specifically, we present an overview of current solar technologies and the integration of solar harvesting systems enabled by hydrogels. A detailed evaluation of solar harvesting techniques will be provided, emphasizing cost-effectiveness, sustainability, and efficiency across material design and energy efficiency. Furthermore, we analyse the technological outlook and performance of these sustainable, high-efficiency solutions in relation to extrinsic factors, including geographical and economic factors. By offering a forward-looking and balanced assessment of existing and integrated solar technologies, this tutorial review aims to guide future developments toward low-cost, sustainable innovations in clean energy.

2. Material morphology and attributes in hydrogels

Hydrogels are three-dimensional networks of cross-linked hydrophilic polymeric chains, possessing high water retainability, soft and flexible in nature, and exhibit extensive tunability in structures and properties (Fig. 3).[78] They are distinguished by their high-water content and low solid fraction, which result in an exceptionally high specific solid surface area in their liquid region, maintaining a solid or quasi-solid form without any water leakage.[87] This unique structure provides abundant sites for reactions and absorption in the hydrogel framework, making them highly versatile for diverse solar applications.[78,88–91] Notably, the mechanical properties of hydrogels can be readily adjusted by varying factors such as solid fractions, crosslinking agents, and intrinsic molecular characteristics, including molecular weight, functional groups, and intra-/inter-molecular interactions (Fig. 3a).[78] These tunable properties allow hydrogels to be shaped into diverse architectures and endowed with multifunctional capabilities, making them ideal candidates as matrices or supporting components for solar systems across various applications.[92–94]

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Table 1 Governing mechanisms and factors of solar technologies

	Governing equations	Challenges	Energy system	Characteristics of hydrogels	Benefits of integration	Figure of merit (FOM)
Solar water	• $\Delta P = -\gamma(1/r_1 - 1/r_2)$ • $h = 2\gamma\cos\theta/rg\rho$ • $\eta_{SV} = h_E J/P_{sun}$	• Simple attribute (water collection) • Latent heat waste • Lack of scale-up • Poor wicking efficiency • Fouling, accumulation of salt and lack of self-cleaning surfaces		• Hydrophilic • Porous • Thermal insulation • Tunable microstructure • Aqueous condition • Tunable mass transport channels	• Endowed with diverse attributes • Hierarchical energy utilization • Regulable systems • Sustainability and cost-effectiveness • Regulable architectures	• Higher energy conversion • Diverse attributes, water collection, anti-salt, and oil resistant • Mineral/microplastic collection
Solar catalysis	• Solar adsorption: $g = \alpha(\lambda)I_0 e^{-\alpha(\lambda)x}$ • Carrier dynamics: $\partial n/\partial t = D\nabla^2 n - (n - n_0)/\tau + G$ • Surface reaction: $r_r = kG/(1 + KC)$	• $\eta < 10\%$, (H_2: 1–5%, water splitting: ~2%, degradation: ~5%) • Heat waste (>50%) • Lack of high surface area • Bubbles will affect/block light absorption • Difficult to recycle and handle photocatalysts	• Hierarchical • Graded • Synergistic	• No (obvious) light absorption • Porous/hydrophilic • 3D framework • Mass transport channels • Thermal management • Aqueous conditions	• Higher energy conversion • Automatic dynamic reaction condition more reaction sites • Regulable reaction temperature • Regulable architectures	• >20% Energy conversion • >1600 ml g^{-1} h^{-1} H_2 production • Pollution degradation (>95%) and removal (>90%)
Solar electronics	• $\Delta P = -\gamma(1/r_1 - 1/r_2)$ • TE: $V = \int S\mathrm{d}T$ $ZT = kS^2\sigma T$ • TG: $S = -ZF\Delta S$ $E = E_0 + RT/ZF\ln([Ox]/[Red])$ • Hydrovoltaic: $V = \zeta\Delta P\varepsilon/(\eta\sigma)$ $\eta = \eta_e\eta_t < 10^{-3}\%$	• $\eta < 20\%$, (TG: 0.1%, TE: 10–20%, hydrovoltaic: <1%, MEG: <1%) • Low output (TG: μW; TE: μW; HV: nW; MEG: μW) • Heat waste (>50%) • TG: need high ionic mobility, redox activity, stable ΔT, and stable aqueous conditions • MEG: need strong hygroscopicity and architecture design for ion diffusion	• Adaptable	• Aqueous conditions • Thermal insulation • Porous • Tunable mass transport channels • Ionic selectivity • Hydrophilic	• Higher energy conversion, • Higher output benefit (corresponding to low output) • Regulatable architectures with diverse micro-structures and attributes	• >20% Energy conversion • Diverse output: electricity, water, and minerals • Asymmetric pores, directional pores with differentiated ion diffusion, and thermal transport

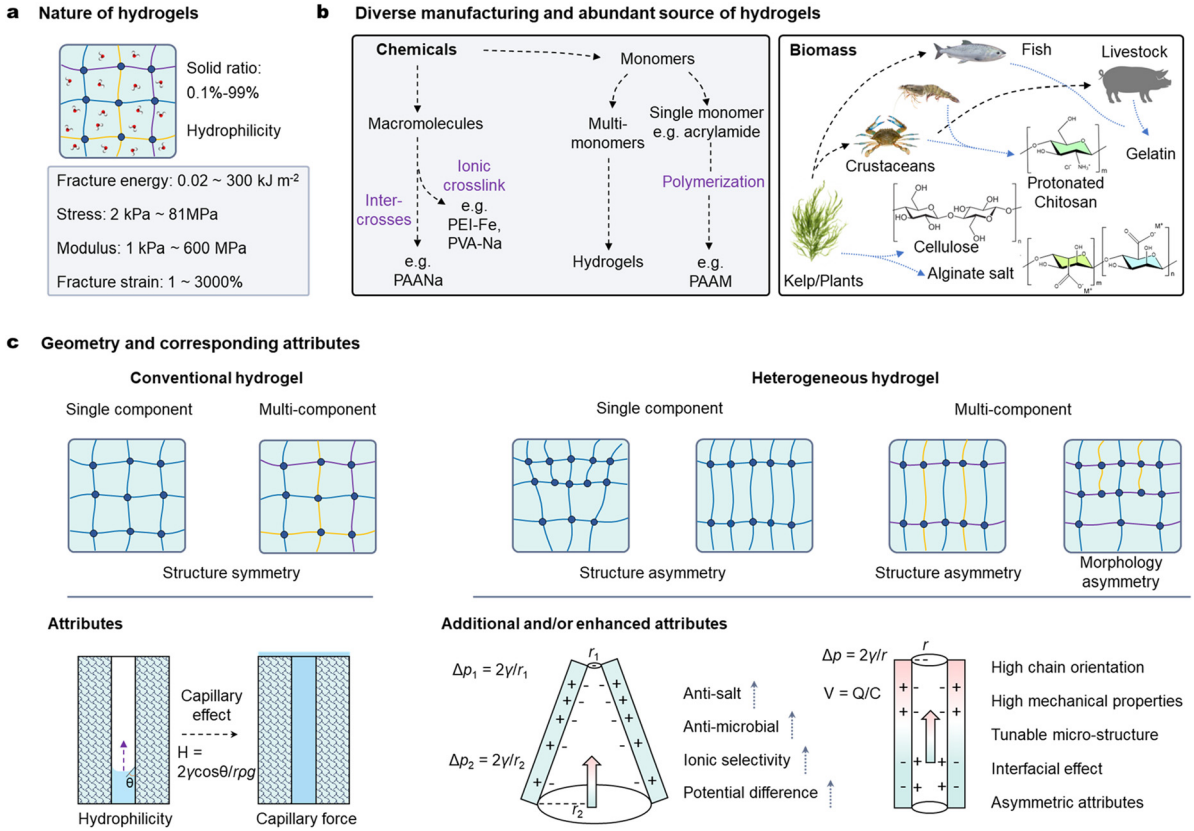

Fig. 3 Manufacturing processes and attributes of hydrogels. (a) Mechanical properties of hydrogels. (b) Diverse manufacturing and abundant sources of materials for hydrogel production. Here, PAANa, PVA-NA, PEI-Fe, and PAAM are sodium polyacrylate, polyvinyl alcohol crosslinked using sodium ions, polyethyleneimine crosslinked using iron ions, and polyacrylamide. (c) Comparison of geometries and attributes between conventional and heterogeneous hydrogels.

Furthermore, the sources for hydrogel production, namely industrial chemicals and natural biomass,[14,91,95–101] are in abundance. Industrial chemical sources, including monomers and macromolecules, differ significantly in their fabrication processes and applications (Fig. 3b). For instance, polyvinyl alcohol (PVA) is a promising candidate for hydrogels through various chemical or physical methods, like freeze-thawing, ionic crosslinking, *etc.*,[88,89] and polyacrylic acid (PAA) can be regarded as an inter-crosslinked macromolecule.[102] On the other hand, monomer-based polymerization can be further divided into single- and multi-monomer systems based on their precursors, enabling greater structural and performance tunability.[103] Some hydrogel raw materials are derived from natural waste or by-products; examples include sodium alginate extracted from algae, chitosan sourced from crustacean shells, gelatin sourced from fish and livestock, and cellulose from plants.[91,95–100,104–109] The diversity of sources underscores the low cost and minimal geographical constraints associated with hydrogel production, making them highly accessible for solar and other applications.

Box 1 Chemophysical perspectives of hydrogels

The mechanical properties of hydrogels can be readily adjusted by varying factors such as solid fraction, crosslinking agents, and intrinsic molecular characteristics, including molecular weight, functional groups, and intra-/inter-molecular interactions (Fig. 3a).[78] These tunable properties allow hydrogels to be shaped into diverse architectures and endowed with multifunctional capabilities, making them ideal candidates as matrices or supporting components for solar systems across various applications.[92–94] For instance, the regulated solid fraction corresponding to diverse pore sizes and water fractions can adapt to the diverse usage conditions with different evaporation rates and water mobility inside, further regulating the system temperature and media rejection efficiency in water evaporation systems and integrated solar water systems. The tunable mechanical properties indicate the adaptability to other solar systems at the interfaces, avoiding the hard contact, as well as serious interfacial thermal gaps and transport barriers.

Polyvinyl alcohol (PVA), as a biocompatible and hydrophilic candidate for hydrogels, can be dissolved in water at different temperatures, depending on their molecular weight (MW) and degree of hydrolysis. To ensure the long-term stability of hydrogels, PVA with high MW and hydrolysis degree will be suggested and their other properties, including functional groups, hydrophilicity, and polarity, are barely affected by MW. Meanwhile, the microgeometry of PVA hydrogels like pore orientation and pore size can be regulated during the fabrication *via* the pristine concentration of PVA solution, freezing direction, and the concentrations and types of salts used for crosslinking.[88,89] Typically, the pore size and orientation directly affect the evaporation rate and mass transport of PVA hydrogels (Fig. 3c). Similarly, polyacrylic acid (PAA) hydrogels are prepared using the monomer acrylic acid and the pore density and mechanical properties of PAA hydrogels depend on the concentration of acrylic acid and crosslinkers.

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In the case of hydrogels using chemical polymers (non-biomass), macromolecules form the hydrogel network mainly using the inter-/intra-molecular interactions in the long macromolecular chains, chain assembly (crystals), entanglements, and crosslinking *via* crosslinkers or ions (alkalis, alkaline-earth metals, and transition metals). For instance, PAA and PVA hydrogels can be prepared with or without crosslinkers or ions. In the case of hydrogels using biomass, there are many oxygen functional groups in most biomass, which can coordinate with metal ions to form a stable network. For instance, sodium alginate solution can be transformed into a hydrogel using calcium salts and cellulose can be coordinated using iron, sodium, potassium ions, *etc.*[213–215]

The attributes of hydrogels also depend on their components and microarchitectures, besides crosslinking, water content, *etc.*[78] Conventional hydrogels typically consist of single or multiple components with symmetrical structures, characterized by uniform hydrophilicity and capillarity. While these features lead to simple and symmetric performance, they limit the range of potential integrated applications. In contrast, heterogeneous hydrogels, designed with asymmetric architectures,[88] offer unique properties and diverse geometry that broaden their utility across various solar technologies (Fig. 3c). Their asymmetric pore sizes and ordered structures facilitate anti-salt accumulation and ionic selectivity in water evaporation systems, while their inherent hydrophilicity maximizes the driving force for water transport. When these hydrogels are engineered with high polymer chain alignment, enhanced mechanical properties, and directional channels, water transport is optimized along defined pathways, realizing the applications in solar systems.[110] Thus, the nature of hydrogels, including their aqueous environment, flexible geometry, and abundant source, as well as compatibility with the basic attributes of each solar system, meets the diverse and critical requirements in integrated solar systems (Table 2).

3. Bridging solar harvesting techniques using hydrogels

Solar technologies can be broadly classified into three categories, namely (1) solar water for clean water and/or mineral collection, (2) solar catalysis for green energies and pollution degradation, and (3) solar electronics towards energy harvesting and conversion.[111] These systems can exist independently, or they can also be coupled together, with solar water being the fundamental system upon which the others are built synergistically. In this section, we will discuss each of them in detail, followed by the integration of synergistic and adaptable systems realised through hydrogels to achieve cost-efficiency and multi-functionality.

3.1. Solar water employing hydrogels

Solar water systems are designed to address water scarcity and contamination issues by exploiting the thermodynamics of water phase changes. To be specific, traditional solar water systems, including absorption–desorption and evaporation technologies, are primarily used for freshwater production

Table 2 Shortcomings and corresponding solutions of hydrogels

	Properties	Inherent	Optima	Methodology	Applications	Suggestions
Hydrogels	Optical	Coloured	Transparency and high-absorption	Adding similar refractive index additives and high-absorption materials	Solar catalysis	(1) Integrated systems from the structure and properties, rather than a simplified combination (2) No or less inter-interfaces in integrated systems (3) Proper design based on the corresponding requirements
		Opaque			Solar thermal	
	Thermal	Thermal insulation	Low-conduction	Avoid conductive materials	Solar thermal	
			High-conduction	High-conductive materials	Solar electronics and solar catalysis	
	Electrical	Electrical insulation	Low-conduction	Avoid conductive materials	Solar catalysis	
		Electrical conduction	High-conduction	High-conductive materials	Solar electronics	
	Mechanical	Wide-range	Softness	Less crosslinking (physical/chemical)	Solar electronics	
			Robustness	High crosslinking (physical/chemical)	Solar catalysis	
	Stability	Low thermal stability	High stability	Crosslink/affinity	Solar systems	
		Low chemical stability	Biodegradability	Biomass		
	Compatibility	Low at interfaces High at inner surfaces	High compatibility	Proper integration	Solar systems	

through solar-driven water evaporation.[84,106,112–120] Typically, in adsorption–desorption systems, porous matrices that possess a large specific surface area and high adsorption–desorption rates are used.[121] They are usually made of hydrophilic materials, for instance, hydrogels, foams, phase-transition materials, and other porous polymers. Hygroscopic additives such as metal organic frameworks (MOFs),[122–125] covalent organic frameworks (COFs),[126–129] ionic liquid,[130,131] and hygroscopic salts[107,109,121] (*e.g.*, lithium chloride (LiCl), calcium chloride ($CaCl_2$), *etc.*) are often incorporated into the porous matrices to enhance the adsorption–desorption performance. During operation, water vapor from the ambient environment is absorbed by these hygroscopic additives and subsequently desorbed with solar heat to realize a sustainable water collection cycle.

In evaporation systems, hygroscopic additives are not needed due to their aquatic working conditions. Instead, the porous matrix provides fast water transport channels for evaporation from water bodies such as seawater. Specifically, high water evaporation rates can be achieved with oriented channels and asymmetric structures to improve mass transfer and maximize energy efficiency. The solar-to-vapor efficiency (η_{sv}) in pristine solar water systems, calculated as a ratio of the enthalpy of vaporization of water to the absorbed solar energy, can reach an extremely high efficiency in the solar thermal convention.[113,114] However, this efficiency tends to be overestimated as the calculation often neglects factors such as dark evaporation, thermal dissipation, water clustering, and latent heat effects.[107,109] To genuinely improve energy efficiency, especially in solar evaporation systems, it is crucial to reduce heat loss to the surrounding air and water, exploiting the temperature difference between upper and lower layers, and reclaiming latent heat from vapor condensation.[113,114,132] For instance, thermal insulators such as polyurethane and polystyrene foam can be placed around the evaporation layers to reduce heat dissipation.[113] Other approaches involve separating evaporated water from mass-transfer water and capturing low-grade energy sources, such as latent heat from vapor and thermal gradients.[87,113]

However, most pollutants in water, including heavy metals (*e.g.*, mercury and cadmium), microplastics, and organic compounds (*e.g.*, petroleum derivatives, dyes, organophosphates, and organonitrogen compounds) are readily transported *via* the tri-phase transitions (liquid–gas–solid) of water (Fig. 4).[133] As a fundamental thermodynamic system without any chemical reactions, pristine solar water technology shows limited purification capacity in practice (Fig. 5a).[111,134] Consequently, pollutants can disperse far beyond their original sources,[56–84] spreading and accumulating in downstream water collection processes. This indicates that the pristine solar water system alone is unable to satisfy the requirements of practical applications. Thus, integration with complementary solar systems such as solar catalysis is beneficial to achieve multifunctionality, including freshwater collection, pollution removal and others, with high cost-effectiveness and practical values.

Given the flexibility and compatibility of hydrogels, advanced solar technologies, including solar electronics and solar catalysis, can be seamlessly integrated with basic solar water systems using hydrogels to achieve multifunctionality with enhanced energy and cost efficiency (Fig. 5bii–iv).[135–162] For instance, hydrovoltaic systems can be incorporated into solar water systems to generate voltage by harnessing water flow (Fig. 5bii),[34,163] which will be discussed in Section 3.3. In addition, thermoelectric and thermogalvanic cells can exploit the thermal gradient between the top and bottom layers of solar water systems,[164,165] further enhancing their functionality and efficiency (Fig. 5biii), which will also be discussed in Section 3.3. By enabling efficient mass transfer, architectural optimization and cost-effectiveness, hydrogels could bridge the gap between academic design and practical engineering.

Furthermore, although solar water evaporation systems with specialized geometries offer enhanced performance, including improved η_{sv} and water transport rates, significant challenges persist, including salt accumulation, fouling, and thermal dissipation, among others. To overcome these issues, further optimization of solar water systems requires advancements not only in architectural design but also in material selection and functional integration. Hydrogels are ideal materials for this purpose since they feature characteristics like directional pores or channels, superhydrophilicity, and flexibility. Heterogeneous

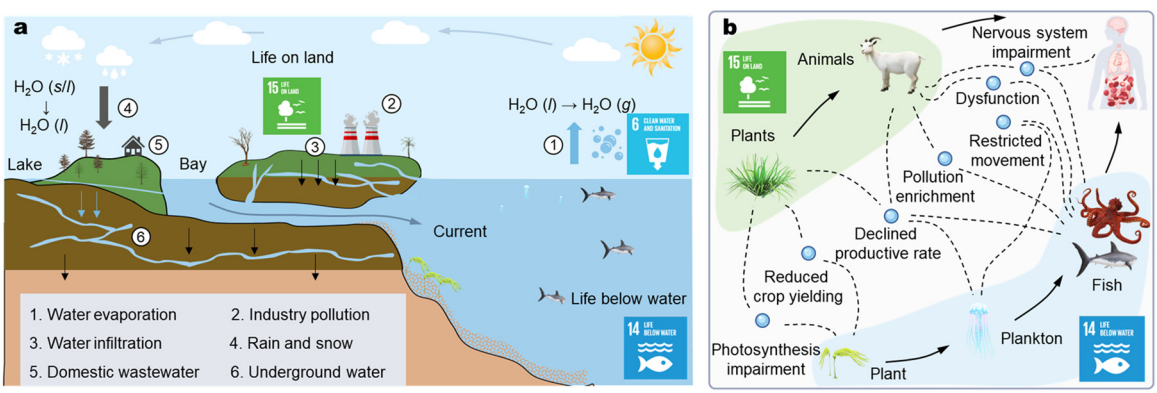

Fig. 4 (a) Water circulation in the ecosphere, illustrating the migration of pollutants through water flow and biological chains. (b) Detrimental impacts on biological chains, affecting both aquatic and terrestrial life.

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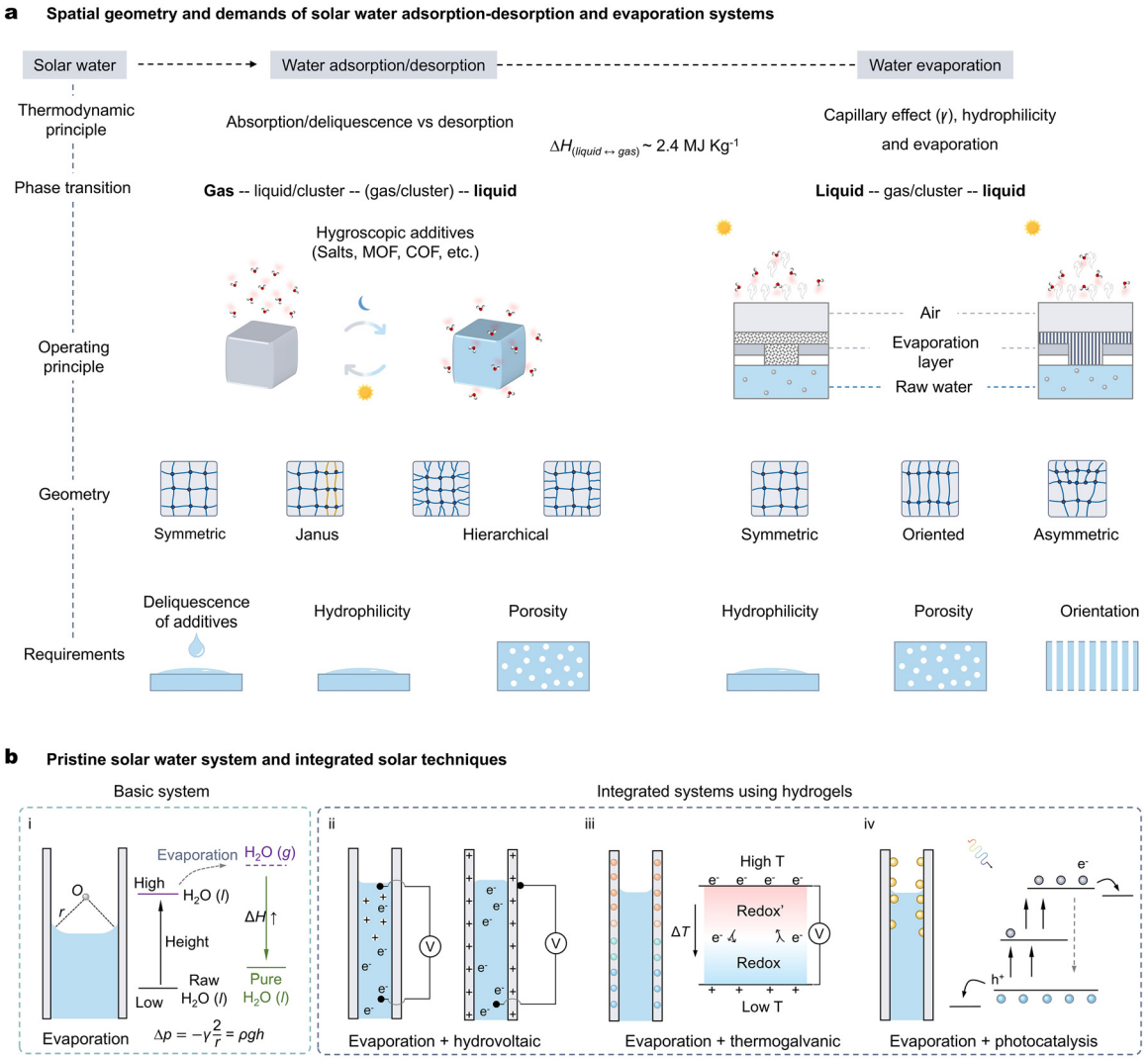

Fig. 5 Clean energy harvesting in solar water. (a) Spatial geometry and demands of solar water adsorption–desorption and evaporation systems. (b) Hydrogel-integrated solar water evaporation systems, featuring diverse functional attributes, where the solar water system is the basic system to integrate with other systems.

hydrogels, in particular, can be engineered with oriented pores through methods like ice templating and salt-crosslinking, such as PVA,[88,89] sodium alginate,[166] and chitosan hydrogels.[167] These structures offer excellent structural compatibility with other additives to facilitate the development of integrated solar water systems (Fig. 5b).[79,163,166,168–171] In addition, these features position heterogeneous hydrogels as robust and versatile materials, and their long-term physicochemical stability can be further bolstered through chemical cross-linking and strong inter- and intra-molecular interactions.[78]

3.2. Solar catalysis employing hydrogels

Solar catalysis has been extensively investigated for pollutant degradation and fuel generation. Different photocatalysts, depending on their energy band structure, can absorb solar light across various wavelengths (Fig. 8a).[13,18,22,115,132,172–176] For instance, traditional catalysts like titanium oxide (P25) are activated exclusively by ultraviolet (UV) light due to their wide-band gaps. Although these catalysts effectively lower activation energy barriers and enhance reaction coordination, their limited absorption across the full solar spectrum restricts their efficiency.[77,85,174] To address this challenge, hybrid catalysts have been developed to create staggered energy band structures with smaller band gaps, enabling electron excitation under visible light. Furthermore, near-infrared (NIR) light can be harnessed through the photothermal effect, where the generated heat further boosts photocatalytic performance by either lowering activation energy barriers or energizing electrons to higher energy states.[177] Despite these advances, challenges in photocatalysis still remain, including limited reaction sites, slow reactant transfer rates, and constraints on catalyst loading capacity and stability, all of which continue to hinder the broader application of photocatalysts.[77,79,174] As a result, the solar catalysis efficiency (η_{sc}) remains below the levels

Box 2 Interaction between hydrogels and water molecules

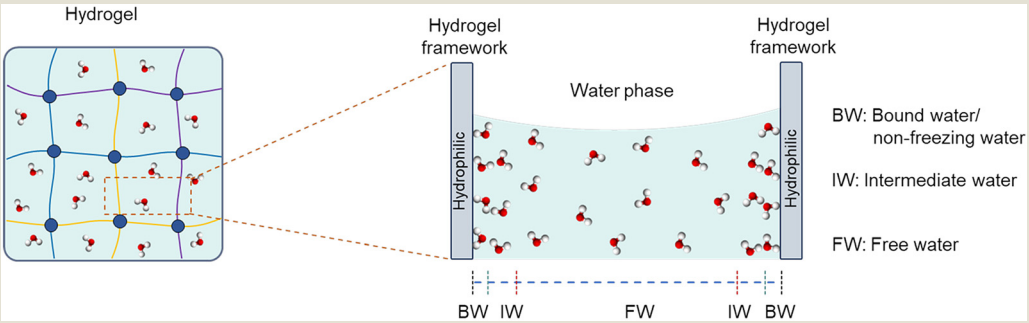

Fig. 6 Schematic illustration of hydrogels and different states of water, including free water, intermediate water, and bound water.

Although slight differences exist in the definitions of free water, intermediate water, and bound water among different publications,[216–218] these studies generally adopt a similar classification framework (Fig. 6). Bound water refers to water molecules that strongly interact with surfaces or polymer matrices through hydrogen bonding, electrostatic interactions, or other intermolecular forces, resulting in highly restricted molecular mobility. Such bound water is typically associated with the hydration shells of molecules or polymer chains within the surface or the matrix and contributes minimally to evaporation and latent heat transfer. Water molecules that interact with bound water and functional groups through hydrogen bonding and van der Waals interactions are generally classified as intermediate water, which also exhibits restricted mobility. Intermediate water is considered responsible for the reduced latent heat of evaporation. In contrast, the remaining water molecules in the aqueous system are categorized as free water, which possesses relatively high molecular mobility.[39,71,91,218] Therefore, the porous and hydrophilic hydrogel can promote higher water evaporation rates compared to the bulk water systems.

of industrial technologies such as thermocatalysis (η_{tc}: 40–96%)[178–181] and electrocatalysis (η_{ec}: 60–99%).[182–184]

To overcome these limitations, an ideal framework for photocatalysts must offer hydrophilicity to facilitate reactant transport, high porosity, and compatibility with other components (Fig. 8b–d). Given the porous geometry and mechanical flexibility, heterogeneous hydrogels effectively satisfy these stringent criteria by providing abundant reaction sites and efficient transport pathways due to their low solid content and three-dimensional spatial framework.[79] Photocatalysts anchored within the hydrogel framework maintain close contact with reactants, which are efficiently directed along the hydrogel's channels.[79] Furthermore, hydrogels can enhance multifunctional capabilities of photocatalysis in aqueous environments, which include degradation of chemical pollutants and microplastics, ion reduction/oxidation, and water disinfection.[110] Despite potential degradation of hydrogels under solar irradiation and light shielding/adsorption effects, their long-term stability can be enhanced through effective physical or chemical crosslinking.[78] In addition, light shielding can be mitigated by incorporating additives like glycerol, which has a refractive index similar to the hydrogel matrix, minimizing light loss and maximizing efficiency. To broaden functionality, solar catalysis can be coupled with other forms of catalysis using hydrogels. For example, photo-electrocatalysis is a combination of photocatalysis and electrocatalysis, while photothermal catalysis integrates photocatalysis and thermal catalysis.[185,186] These integrated catalytic systems generally achieve higher energy conversion and cost-effectiveness than single photocatalytic systems.[177,185,187] Besides, hydrogels enable the integration of solar catalysis with solar electronics using hydrogels, where evaporation-driven water flow supports both mass and charge (information) transport, for instance, delivering reactants and reagents, as well as carrying charge and current for energy harvesting or system monitoring.[80,93] Such coupling optimizes reaction kinetics and enhances overall catalytic performance in these synergistic and adaptative solar systems.

The spatial enhancements and unique attributes of hydrogels in solar catalysis reflect the synergistic integration of solar systems, resulting in a flexible and resilient substrate with increased contact and reaction sites, and a dynamic Gibbs-free-energy-driven reaction environment.[18,115,175,187] In these integrated systems, pollutants and chemicals in water can be decomposed efficiently, simultaneously yielding clean water and fuels. Compared to the low energy conversion efficiency of pristine photocatalysis (typically under 10%),[186,188] hydrogel-enhanced photocatalysis achieves higher efficiency (15%–60%),[79,85] while also contributing to cost-effectiveness. This improvement arises not only from the extended reaction interfaces and efficient charge transfer facilitated by the hydrogel matrix, but also from improved light harvesting, reactant accessibility, and thermal management. Thus, considering the above factors, the integrated solar catalysis system bridged by hydrogels presents high cost-effectiveness, stability, and energy efficiency towards a circular community and sustainable society.

3.3. Solar electronics employing hydrogels

Solar electronics have emerged as promising clean energy technologies in recent decades, encompassing widely used solar cells, hydrovoltaic cells, moisture energy generators, and thermoelectric and thermogalvanic cells (Fig. 9a).[17,34,84,92,94,189–192] Solar cells have evolved through multiple generations to achieve

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Box 3 Water current and charge distribution in hydrogel channels during evaporation

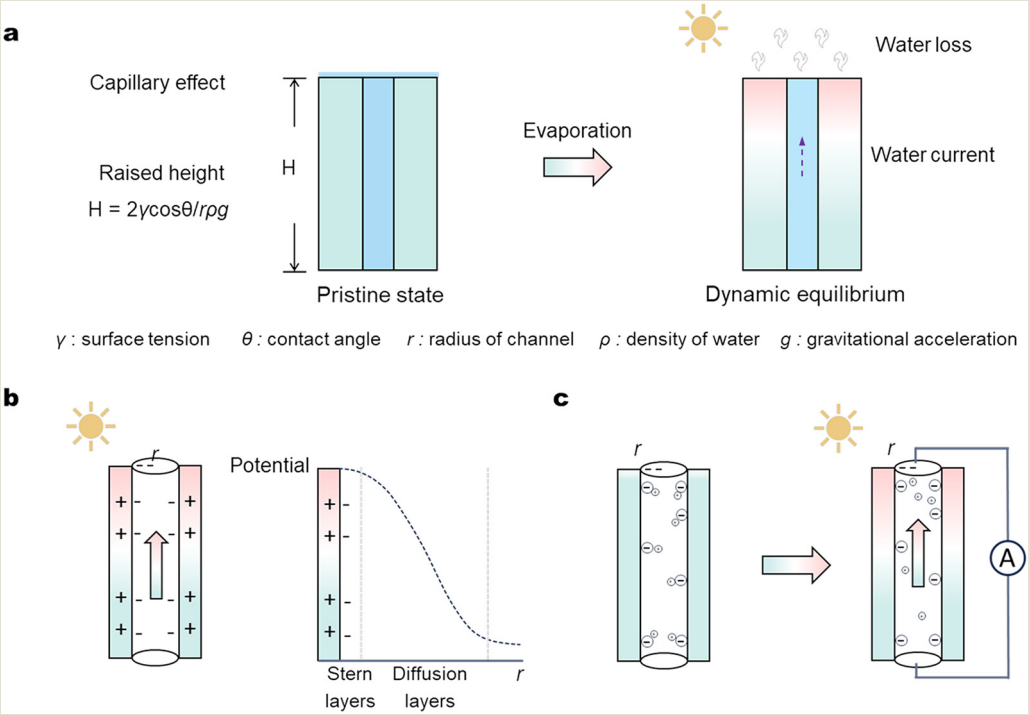

Fig. 7 (a) Dynamic equilibrium of water evaporation process in hydrogels, in which water loss induced by evaporation leads to continuous water current driven by the capillary effect. (b) Charge generation in hydrovoltaic (HV) systems arising from electrical double layers (EDL) formed at solid–liquid interfaces under evaporation-driven water flow. (c) Charge generation in moisture-enabled electricity generation (MEG) systems induced by water diffusion and the hydrolysis effect.

In hydrovoltaic systems, where solar irradiation and high vapor pressure liquid facilitate solar evaporation, the evaporation-induced water currents created within the channels generate a charge differential between the dry upper region and the wet lower region.[87,111,117,171] In such systems, the charges originate from mobile counter-ions within the channels, which possess opposite polarity to the fixed surface charges and form electrical double layers on the inner channel surfaces (Fig. 7). In the MEG systems, the charges are primarily attributed to the water diffusion and hydrolysis of the functional groups, *e.g.* $-SO_3H$, –COOH, and –OH.

higher efficiencies, with the highest recorded efficiency of approximately 47.1% achieved using high-cost single-crystal films in III–V multijunction cells under 143 Suns.[24] Widely used silicon solar cells and hybrid perovskite–silicon tandem cells have reached maximum efficiencies of approximately 26.8% and 32.5%,[23,28] respectively. However, unutilized energy absorbed by these systems is typically dissipated as heat that affects the lifespan and reduces the energy efficiency of solar cells.[193] To address this limitation, efficiency-boosting strategies have focused on multijunction cells and tandem structures, with an emphasis on material composition and manufacturing approaches.[28] Another solution is to regulate the localized heat using external systems such as air/water cooling systems, and hydrogel-based coolers. Since the advances of solar cells have been extensively reviewed in previous studies, they will not be discussed in detail here.

Instead, this section focuses on other emerging solar electronics realised by hydrogels that employ diverse mechanisms to utilize hierarchical energy and enhance performance since the solar-to-electricity efficiency (η_{se}) in standalone solar electronics is generally below 5%.[194] For instance, in hydrovoltaic systems where solar irradiation and high vapor pressure liquid facilitate solar evaporation, the evaporation-induced water currents created within the channels generate a charge differential between the dry upper region and the wet lower region.[87,111,117,171] Similarly, moisture energy generators rely on water dynamics, where the absorption and desorption of water molecules from a matrix generate a chemical potential difference between active adsorption/desorption regions due to hydrolytic charges or ions.[17] In both cases, the thermodynamics of water molecules govern charge generation, indicating that system performance can be tuned by thermodynamic factors including temperature, saturated vapor pressure, and solar absorption. However, the thermodynamic-to-electricity efficiency is rather low, resulting in poor overall η_{se} in these systems. Nevertheless, external factors such as structural

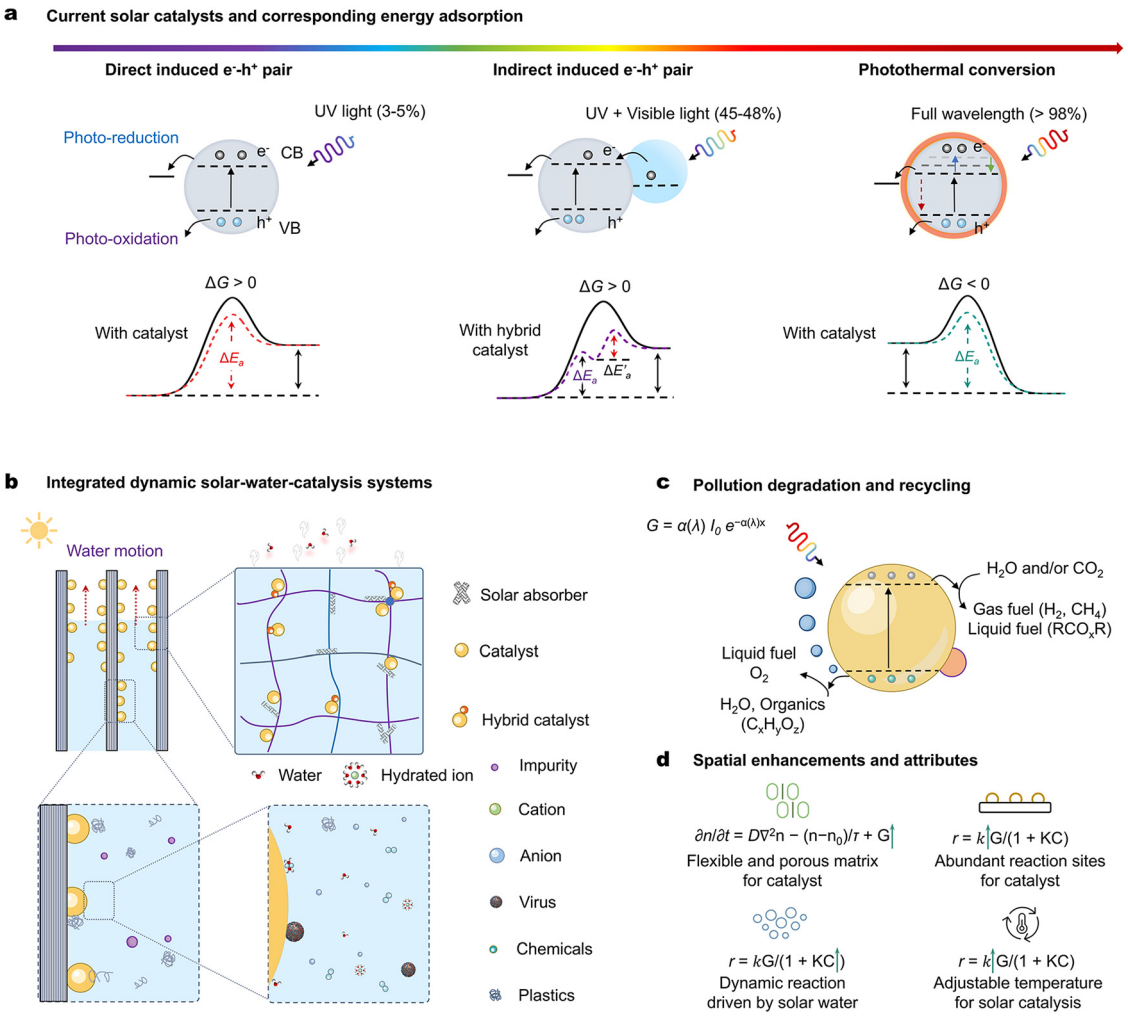

Fig. 8 Clean energy harvesting technology in solar catalysis. (a) Three types of catalysts activated by absorption of solar light at different wavelength ranges. (b) Schematic of integrated dynamic solar–water–catalysis systems, where hydrogels serve as porous matrices to provide a mass of photocatalysis reaction sites and dynamic reaction conditions. (c) Pollution degradation and recycling in dynamic solar–water–catalysis systems. (d) Spatial enhancements and attributes of integrated dynamic solar–water–catalysis systems. Here, r, n, t, D, G, C, K and κ represent the reaction rate (mol m^{-3} s^{-1}), charge carrier density, time, effective diffusion coefficient, absorbed photon flux, concentration of reactant, adsorption equilibrium constant (L mol^{-1}) and surface reaction rate constant in photocatalysis, respectively.

geometry, wettability, and directional channels can also be tuned to influence system performance. Another example of solar electronics is thermoelectric and thermogalvanic cells, which can leverage thermal gradients in the systems induced by solar irradiation.[164,165,168] In thermogalvanic cells, this thermal gradient drives redox reactions, while in thermoelectric cells, it induces electrons/holes migration. Therefore, effective localized heat management is a critical factor in these standalone thermal cells, whilst optimizing the migration rate and quantity of charge carriers constitutes internal factors that require appropriate system architecture and material selection.

Hydrogels, especially heterogeneous hydrogels, with their high-water content, hydrophilicity, and porous structure, ensure a continuous supply of water and efficient migration of charge carriers,[81,85,87,93,165,166,168,170,195] making them well-suited for advanced solar electronic systems. For instance, in hydrovoltaic cells, they provide directional water channels to enhance performance, while in moisture energy generators, they improve adsorption and desorption efficiency.[34,80,94,163,196] In thermogalvanic cells, hydrogels act as effective thermal insulators and are able to hold a high concentration of charge carriers, optimizing redox reactions.[164,165,169] In addition, the integration of water evaporation with TE cells using hydrogels can boost the thermopower of TE cells and/or the evaporation rate of hydrogel-based water evaporation according to the requirements of the system.[130,131]

The intrinsic properties and excellent compatibility of hydrogels also facilitate seamless integration across solar electronics systems to optimize energy efficiency and functionality (Fig. 9b). For example, combining hydrovoltaic cells with moisture energy generators leverages solar evaporation-induced water flow to create a charge gradient, while water molecule adsorption and desorption under dark conditions generate a proton gradient.[34,80,94,163,196] This integrated system supports

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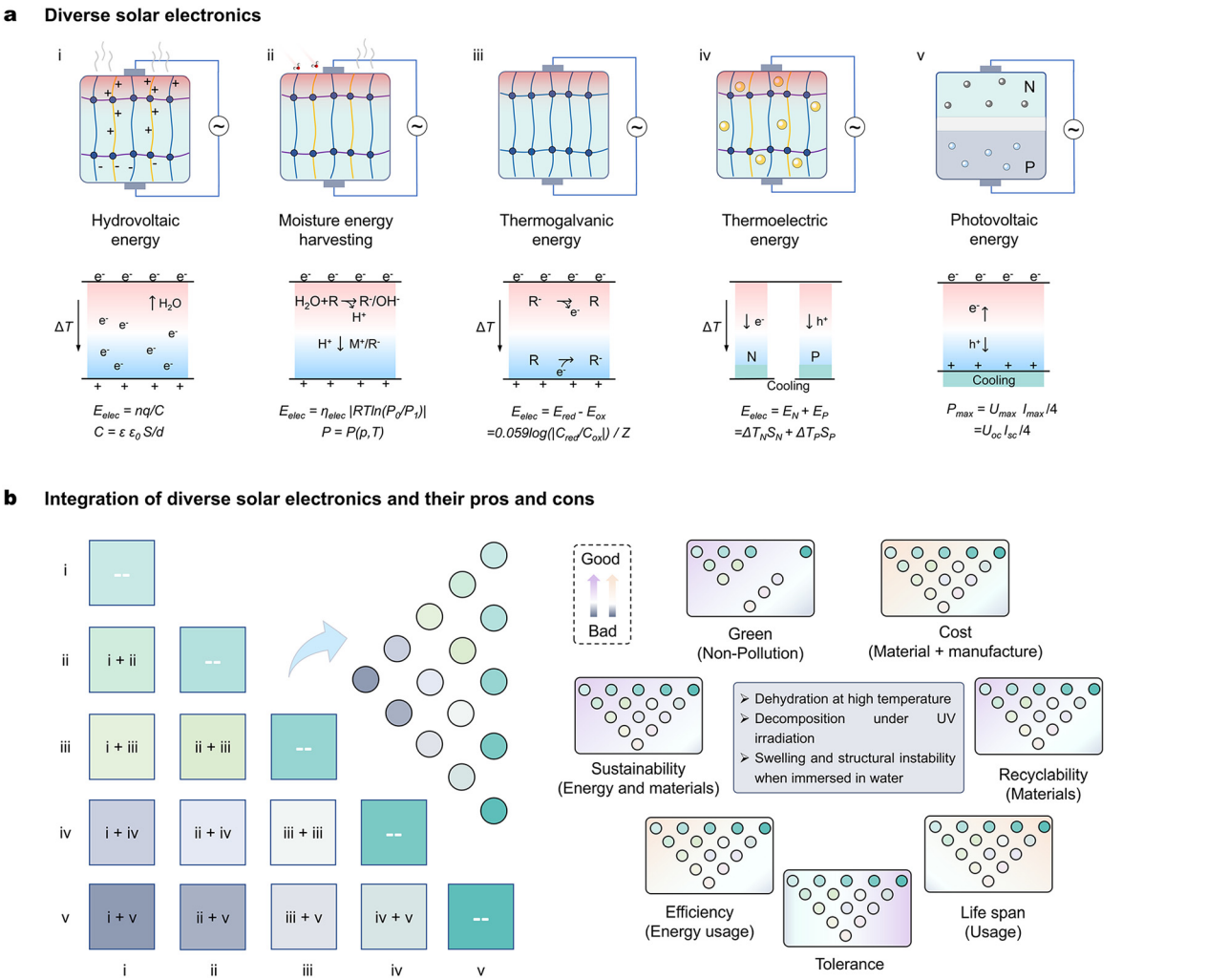

Fig. 9 Clean energy harvesting technologies in solar electronics. (a) Overview of diverse solar electronics and their operating principles. Here, the solar electronics includes solar-driven HV cells, MEGs, and TG, TE, and PV cells. (b) Cross-integration of diverse solar electronics leveraging hydrogels and analysis of their pollution impact, cost, sustainability, recyclability, efficiency, tolerance and lifespan. Here, the dot triangle is the mapping from a combination of i–iv systems (solar-driven HV cells, MEGs, and TG, TE, and PV cells).

all-weather solar energy harvesting and ambient energy collection. Such complementary mechanisms ensure adaptability under varying conditions; for instance, moisture energy generators remain effective in high-humidity environments, such as rainy days, when water evaporation is limited. Similarly, these solar electronics systems can also integrate with solar catalysis. For instance, when thermoelectric and thermogalvanic cells incorporate solar catalysis through heterogeneous hydrogels, solar catalysts utilize sunlight to generate electrons while dissipated heat is captured and repurposed by the thermal cells.[197] Concurrently, the electrons generated by the thermal cells boost the reaction efficiency of solar catalysis.[197] This synergistic integration supports efficient energy circulation during low-grade heat conversion. In addition, by bridging through hydrogels, system integration can be extended to more than two technologies, with multiple solar technologies being combined in customized configurations to maximize energy utilization while minimizing pollution and cost.

Generally, solar electronics exhibit lower output voltage and power density compared with conventional photovoltaic solar cells. As a result, they are primarily utilized for harvesting low-grade energy, as well as for monitoring and regulation functions within integrated solar systems. For example, in solar water–electronic systems, solar electronic modules can be employed for low-power energy generation, such as hydrovoltaic (HV) and moisture-enabled electricity generation (MEG) devices. Meanwhile, the output voltage or current generated by these solar electronic components can serve as an indicator of the operational state of the integrated system.[80,168,198,199] Similarly, in integrated solar electronic platforms, such as thermoelectric (TE) systems and solar cells, thermoelectric modules can generate a voltage signal corresponding to the back-surface temperature of solar panels. In addition, these thermoelectric modules can function as passive cooling units, thereby reducing the temperature of solar panels and maintaining stable operation.[42,54,64,68]

The feasibility of using hydrogels for industrial applications is evaluated based on several factors, including the environmental impact (green and non-polluting characteristics), cost (total capital and operational expenses), sustainability (efficient energy and material utilization), recyclability (material recovery), efficiency (energy usage), lifespan, and tolerance (Fig. 9b).[4,98,121,162,163,171,174,200] From the discussion above, it is evident that hydrogels can fulfil all these criteria, albeit with some limitations. Possible challenges include hydrogel dehydration at elevated temperatures, polymer chain degradation under UV irradiation, and swelling or instability of hydrogels in aqueous environments.[78] However, these issues can be mitigated through specialized polymer formulations and high degrees of crosslinking.[78] Further analysis also shows that integrated solar technologies can effectively address the urgent demand for clean, sustainable energy while enhancing energy conversion efficiency. By balancing their advantages and limitations, these systems will pave the way for transformative advances in solar energy utilization.

4. Summary and perspectives

In this tutorial review, we highlight the current challenges of solar technologies on the path to a sustainable society and how hydrogels can play a bridging role across these different solar technologies to address them. Beyond the intrinsic factors of materials science, we provide an overview of solar technologies combined with hydrogels and pioneer the evaluation of integration between multi-solar systems and hydrogels from the perspective of hierarchical energy use, synergistic performance and energy efficiency. Finally, we offer perspectives on the potential applications of clean energy technologies across global regions with consideration of regional environments and needs and illustrate how hydrogel-bridged solar integration can align with the principles of the circular economy.

4.1. Perspectives on the natural environment and potential applications of clean energy technologies across global regions

Naturally occurring factors such as geography and climate play vital roles in determining the cost-efficiency, feasibility and overall effectiveness of solar technologies in different regions. However, these factors have often been overlooked in previous studies. Considering the advantages and limitations of various solar technologies, the best way to maximise their performance is to strategically deploy according to the environmental conditions in the specific region, such as rainfall, water availability, evaporation rates, and solar irradiation (Fig. 10a). For instance, equatorial regions in Asia experience high solar irradiation and significant water evaporation rates, offering favourable conditions for solar water, solar catalysis, solar electronics, and their integrated applications. In contrast, inland deserts and plateaus may possess high water evaporation rates but experience low rainfall and limited water resources, limiting the feasibility of solar water technologies. However, the abundant solar irradiation and extended sunshine duration in these regions present significant opportunities for solar catalysis, solar electronics and integrated systems. Meanwhile, coastal and riverine regions with ample water resources, but facing significant challenges in water purification and pollution removal, can leverage solar water and related integrated solar technologies for effective water remediation and sustainable energy generation.

Beyond geographic considerations, economic conditions and regional needs are pivotal in shaping the development and adoption of clean technologies (Fig. 10b and c).[201–205] We present predictions of suitable solar-technology deployments by location based on climate conditions (Fig. 10c). These predictions are derived by analysing the data of climate conditions of various countries from NASA Earth Observations and the economic factors from the World Development Indicators (WDI) by the World Bank. In Africa, for instance, northern regions are dominated by desert landscapes, characterized by long coastlines, strong solar irradiation and limited freshwater resources. Here, integrated solar water and catalysis technologies can be utilised for seawater desalination to meet drinking and other domestic needs.

Meanwhile, low-cost solar electronics would also be essential in these regions to provide reliable electricity for daily use in economically constrained communities.[204] In the Middle East and Arab regions, where water resources are scarce but oil extraction and processing industries are prominent, solar catalysis, solar water and related technologies are critical for pollution control and water resource management.[203–205] In Australia, many seawater desalination plants rely on reverse osmosis technology, a process associated with high capital and operating costs and the discharge of brine or hypersaline effluents that threaten coastal ecological balance. Given the country's abundant solar radiation and water resource, solar water and related clean technologies present a low-cost and zero-net emission strategy to meet the Australian Drinking Water Guidelines. In the U.S., uneven distribution of natural water resources causes the shortage of freshwater for industries and habitats in some locations, where cost-effective water collection and treatment methods are in need based on the suggestions from the U.S. Department of Energy (DOE). Pristine solar water and solar water integrated with solar catalysis systems can produce fresh water to address the above issues without geographical and economic limitations.[206] In Europe, efforts to address freshwater scarcity and excessive CO_2 emission include coupling solar water systems with concentrating solar power, as reported by CORDIS of European Commission. In water-stressed Mediterranean regions, current solar water systems can produce up to 5000 L of fresh water daily from seawater using only solar energy. However, projections indicate that 60% of European coastal regions will still face severe water stress by 2040. Cost-effective integrated solar systems with additional anti-salt and sterilization functions are required to address the above issues, for instance, using solar water systems with optimized heat management and integrated solar water systems with solar catalysis. Thus, by aligning solar technologies with regional environmental and economic

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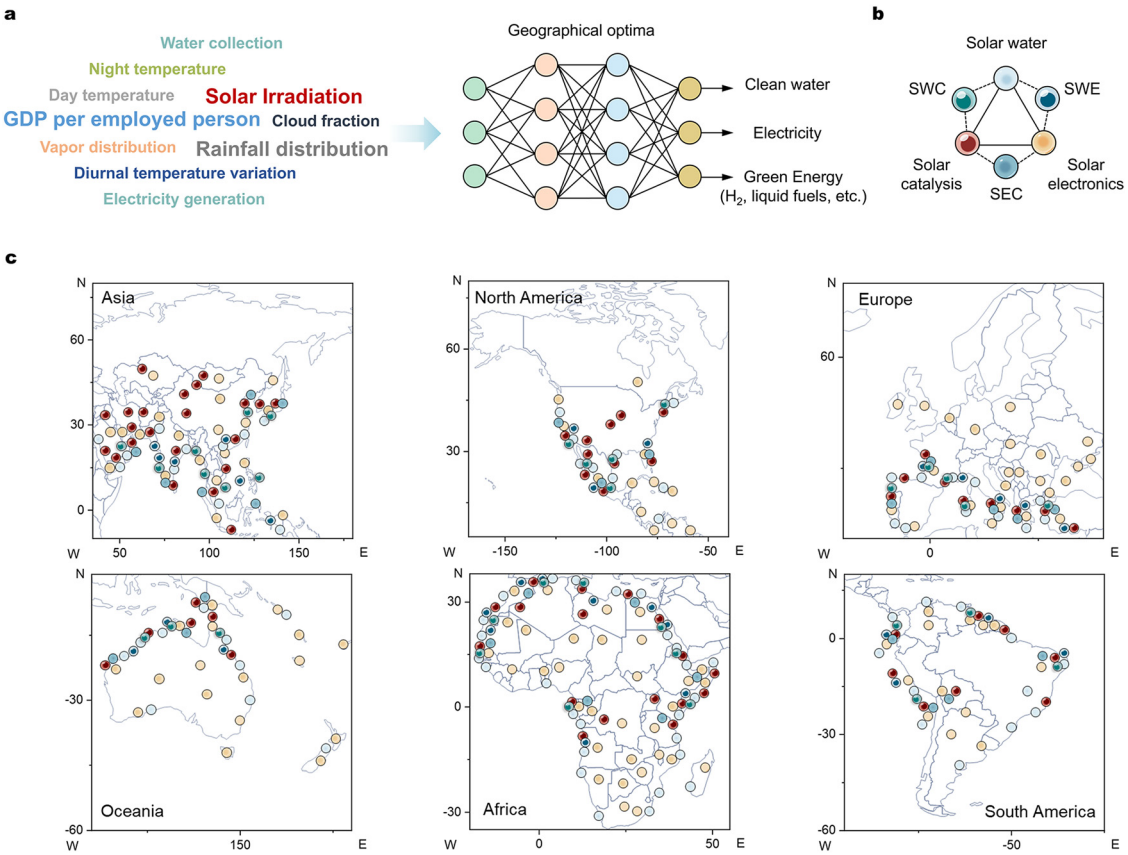

Fig. 10 Economic and environmental factors. (a) Influence of environmental factors on solar systems and corresponding energy and resources. (b) and (c) Prediction of potential solar technology deployment across global regions based on natural environment and resource availability. Here, the SWC, SWE, and SEC represent the solar water catalysis, solar water electronics, and solar electronics–catalysis systems, respectively.

conditions, clean energy solutions can be effectively deployed to address diverse global challenges, ensuring sustainability, affordability, and resilience (Fig. 11).

4.2. Assessment of integrated solar harvesting for the circular economy

To bridge the gap between laboratory design and cost-effective practical applications, an all-encompassing circular economy assessment of hydrogel-integrated solar harvesting systems has been conducted (Fig. 11).[207–209] In natural ecosystems, CO_2 is sequestered biologically through plant photosynthesis. Natural biomass and biowaste can then be extracted from plants and crustaceans for hydrogel production. These materials can be integrated into various solar technologies with negligible topographical or environmental constraints, in line with the United Nations' Sustainable Development Goals (SDGs). While small amounts of CO_2 emissions are produced during the manufacturing process, a portion of CO_2 can be captured using industrial technologies such as lye absorption or membrane separation. This captured CO_2 can subsequently be converted into useful chemicals *via* solar catalysis. Optimized hydrogel-based solar water and catalysis technologies contribute to clean water production, improved sanitation, and pollution mitigation, benefiting both aquatic and terrestrial ecosystems. These advancements drive progress toward creating sustainable societies and communities.

In addition, the long-term stability and degradation of hydrogels in integrated solar systems could be considered further corresponding to certain systems, although the regulation of properties in hydrogels has been discussed in Section 2. To adapt to complex operational conditions, hydrogels are required to maintain high thermal stability under elevated temperatures in integrated solar-thermal systems. In this context, hydrogels with a high degree of crosslinking and high molecular weight (MW) are generally preferred. Meanwhile, in solar–water–catalysis systems, additional chemical stability must be taken into account to prevent hydrogel degradation during photocatalytic and catalytic processes. Furthermore, biofouling presents important and often unavoidable challenges in hydrogel-based systems, particularly in biomass-derived hydrogels such as alginate, chitosan, and cellulose. To mitigate these issues, self-cleaning and/or antibacterial functionalities can be integrated into solar-driven systems. In many solar-thermal systems, natural solar irradiation combined with elevated operating temperatures (>60 °C) can effectively inactivate most microorganisms, thereby reducing biological contamination and material degradation. In solar–catalysis integrated systems, organic pollutants can be further degraded under thermally enhanced reaction

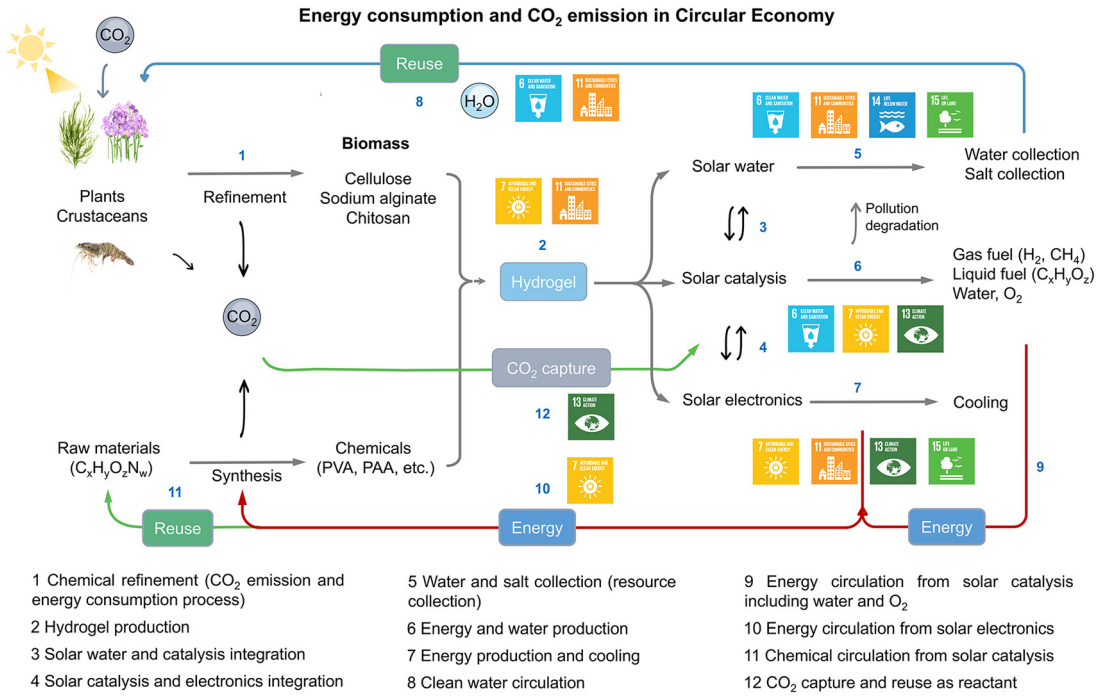

Fig. 11 Energy consumption and CO_2 emissions of clean energy harvesting technologies using hydrogels within the circular economy framework.

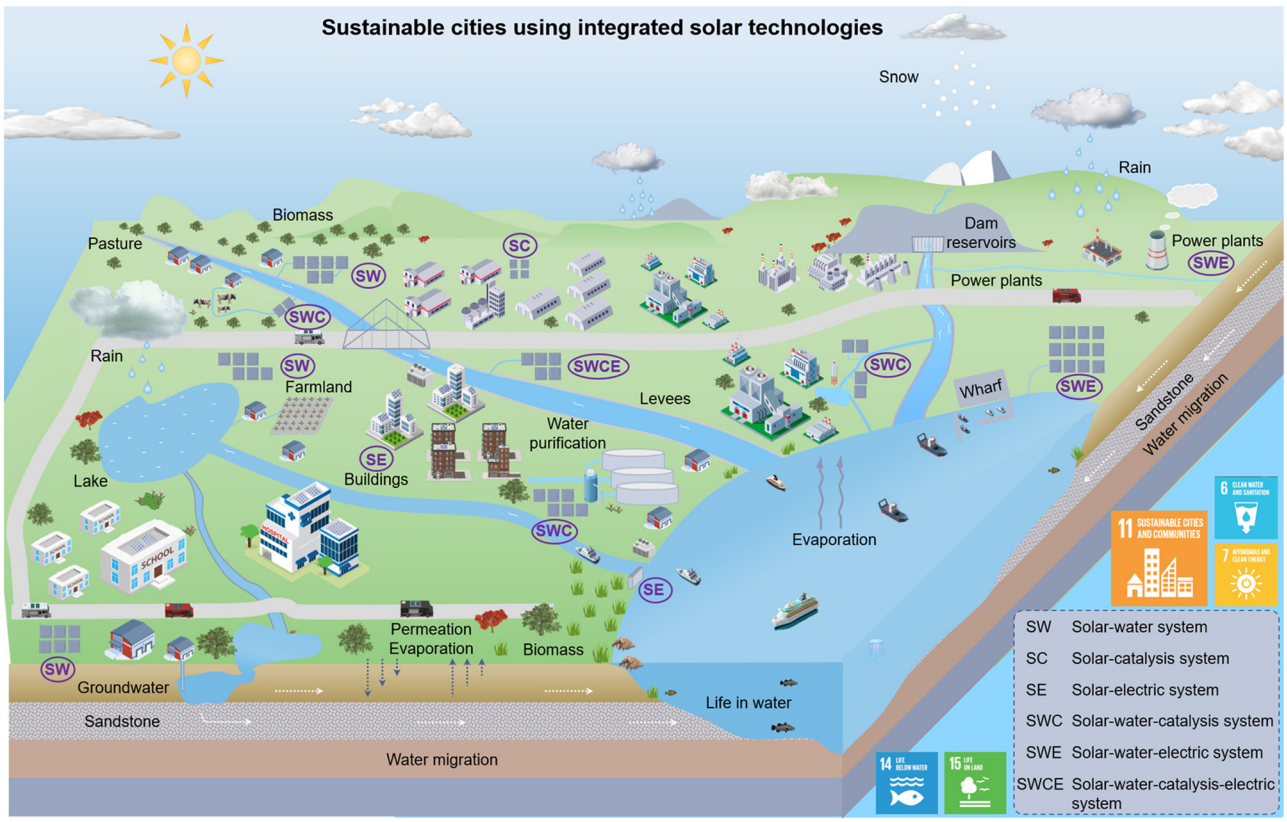

Fig. 12 Smart clean cities and communities using integrated solar technologies. Abundant solar and water resources enable the implementation of integrated clean technologies, driving progress toward achieving the sustainable development goals (SDGs). These resources support sustainable energy solutions and foster resilient, eco-friendly cities and communities, paving the way for a cleaner and more equitable future.

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conditions. Similarly, structure design of channels in hydrogels can effectively avoid salt accumulation, even though there is a trade-off between salt rejection and evaporation efficiency. For instance, the vertical radiant structure or the interconnected hierarchical porous structure can be obtained using freeze-casting.[210–212]

Hydrogel-enhanced solar catalysis also demonstrates effective degradation of solid and gaseous pollutants, microplastics collection and decomposition, and the conversion of waste and by-products into clean water and fuels. These advancements align with critical SDGs including clean water and sanitation, affordable and clean energy, and climate action, addressing the urgent need to combat climate change and its impacts. The pure water generated through these solar technologies can be applied across various sectors, including agriculture, fisheries and animal husbandry, daily life and industry. Furthermore, hydrogel-enhanced solar electronics not only generate electricity through water dynamics and heat gradients, but also provide interfacial cooling and system monitoring, extending device lifespan and maintaining efficient performance. The generated electricity can further be used to manufacture raw materials and process hydrogels using industrial chemicals in a certain content, fostering a sustainable, net-zero-emission framework for a circular economy (Fig. 11).[2,6,14,18,101,135,137,139,160,175,187]

The schematic of sustainable cities and communities is conceptualized through the implementation of integrated solar technologies (Fig. 12). In this framework, solar–water–catalysis (SWC) systems are utilized to mitigate organic pollutants in wastewater, such as soluble chemicals and insoluble microplastics. In addition, SWC systems upcycle plastics into valuable fuels such as hydrogen, methanol, and alkanes. Solar–electric (SE) and solar–water–electric (SWE) systems play a pivotal role in regulating the temperature of solar panels and managing graded thermal energy in industrial devices, addressing heat dissipation challenges and mitigating localized heat effects that adversely impact efficiency and lifespan. Solar–water (SW) systems contribute to freshwater production for drinking and husbandry, while concurrently refining salts to be used as industrial raw materials. Furthermore, abundant biomass resources, such as crustacean carapaces and cellulose, serve as essential feedstocks for hydrogel production. Collectively, these factors enable a reduction in CO_2 emissions and pollution in sustainable cities and communities by approximately 20–50% through the graded energy utilization and clean energy harvesting when 20–30% of total consumed energies, such as illumination, cooling, and heating, as well as water purification, are supplied by clean technologies. Given their high feasibility and cost-effectiveness, these integrated solar technologies, particularly those enhanced with hydrogels, are expected to provide a sustainable pathway toward achieving a clean and resilient future.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software or code have been included, and no new data were generated or analysed as part of this review.

Acknowledgements

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