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Perspective

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Sustainable moisture energy

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Abstract

Harvesting energy from the ambient is a promising approach to fulfil decentralized energy demands and facilitate the transition to low-carbon economy. Moisture-sorption-based energy harvesting (MSEH) is a promising strategy for obtaining heat, cold and electricity from ubiquitous moisture anywhere and anytime. Advances in water-sorption materials have promoted the development of sustainable moisture energy. However, MSEH technology faces the challenges of low-energy productivity and limited recognition of its working mechanisms and thermodynamic analysis. We centre this Perspective article around an in-depth understanding of the underlying mechanisms and thermodynamic limitations of sustainable moisture energy. We first introduce the working principles of MSEH for heat, cold and electricity generation, and summarize recent progress in water sorbents. We then discuss thermodynamic limitations and evaluate global potential for sustainable moisture energy. We outline future challenges of water-sorption kinetics and propose technical directions for accelerating water sorption-desorption with ordered cross-scale energy transfer and mass transport. Finally, we offer an overview of future research areas for water sorbents with higher water uptake, tunable water affinity and faster water sorption for next-generation high-performance MSEH.

Sections

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Introduction

Energy harvesting from the ambient provides access to green energy, capable of powering various grid-independent applications, such as personal thermal management and self-powered electronics[1]. Ubiquitous moisture in the ambient air offers a natural energy reservoir, attracting broad interest in developing moisture-induced energy harvesting technologies[2,3]. Evaporation-induced electricity generation is an emerging way to harvest energy through natural processes rather than mechanical work[4,5]. However, the natural evaporation of water is limited by the reliance on liquid water sources for long-term operation and is subject to climate conditions[6]. Alternatively, artificially modulating ambient water between gaseous and adsorbed states by water vapour sorbents presents a controllable and sustainable method to harvest green energy from the ambient. The reversible phase-change transition of water enabled by sorbents, known as water sorption and desorption, spontaneously converts gaseous water to adsorbed water from unsaturated moisture with relative humidity (RH) below 100%[7,8]. The diversity of sorbents with different water affinities gives them high climate adaptability, making sorbent-based water phase change theoretically accessible anywhere and anytime[9].

Because conventional sorption chillers or dehumidifiers rely on additional heat sources to drive sorbent regeneration[10,11], the classical viewpoint considers water-sorption technologies as air processes or energy storage technologies rather than energy harvesting technologies. Exciting progress in sorption-induced electricity generation and desorption cooling has demonstrated that moisture-sorption-based energy harvesting (MSEH) can maintain a long operation time and can be driven by the ambient energy of a humidity gradient or circadian humidity fluctuation without extra energy consumption[12–14], enriching the contents and functions of water-sorption technologies. Unlike traditional closed water-sorption-based heating and cooling systems that need vacuum maintenance and expensive valves and pumps, the MSEH system directly exchanges water with ambient moisture, making the technology passive and flexible[15]. As the types and functionalities of MSEH technology have rapidly grown, an understanding has become gradually accepted that ambient moisture is not only a working medium for energy conversion and storage, but also a widely accessible green energy source in some cases[16]. According to the reports from the International Energy Agency, nearly half of the global energy demand is devoted to heating and cooling[17], denoting the vast potential for energy saving in thermal energy harvesting, conversion, storage and utilization processes.

Although the feasibility of MSEH has been confirmed by a few reported sorbent materials and devices[18–20], their low energy density, low power density and inconvenient operation limit their commercialization applications[21]. Tackling these challenges urgently requires an in-depth understanding of the underlying working principles and energy conversion mechanisms. Here, we introduce recent breakthroughs in water sorbents for MSEH. We then reveal the fundamentals of MSEH from the viewpoints of thermodynamics and kinetics, highlighting its working potential for producing heat, cold and electricity from moisture. Accordingly, we provide guidelines on the design of next-generation water sorbents to achieve high-energy and high-power-density MSEH. We further point out the current challenges and future focuses related to sustainable energy supply and applications for the human body and buildings, encouraging continued interdisciplinary research and development in MSEH technologies. The thermodynamic and kinetic analyses related to sorption in this Perspective article are also useful for analysing other sorbent-based technologies including atmospheric water harvesting, carbon capture, energy storage and gas separation.

Working principles of MSEH

Moisture-sorption and moisture-desorption processes are accompanied by energy generation, conversion and transfer. The generated energy comes from the phase conversion of water between the high-enthalpy and high-entropy gaseous state and the low-enthalpy and low-entropy adsorbed state (enthalpy varies ~2,500 kJ $\mathrm{kg_{water}}^{-1}$ and entropy varies ~8 kJ $\mathrm{kg_{water}}^{-1}\,\mathrm{K}^{-1}$, generally)[22], which can be converted to heat, cold and electricity.

Sorption heating

Sorption heating can be easily understood as the water-sorption process accompanied by the forming of bonds or van der Waals forces between sorbents and water molecules (Fig. 1a), involving a large amount of heat release[23,24]. The exothermic effects are always found during the water-sorption process, whose intensity depends on the water-sorption enthalpy and water uptake capacity of the sorbents. Different sorption mechanisms generally present different sorption enthalpies[25]; thus, testing the sorption enthalpy value is an efficient method to distinguish different water-sorption mechanisms, such as chemical and physical sorption, in which the latter typically has a relatively lower value[26,27].

Desorption cooling

Similarly, the water desorption process shows a considerable endothermic effect caused by breaking of bonds or van der Waals forces (Fig. 1b), but traditional sorbents were used only for sorption heating and rarely reported for desorption cooling in the past few decades. This is because traditional solid sorbents with high water affinity require high regeneration temperature, such as the regeneration temperature of zeolites above 200 °C (refs. 28,29). Various new sorbents can release water vapour into the air and absorb heat from the ambient spontaneously owing to their mild or weak water affinity, leading to the development of passive desorption cooling technologies[30,31]. The weak water affinity of these sorbents allows the absorbed water to be released into the air at moderate temperatures; at the same time, the sorbents can self-recover by spontaneously capturing water from moisture or energy-efficient humidification, making this technology more reliable and water-saving than conventional direct evaporation cooling[32].

Electricity generation

Fairly different from sorption heating and desorption cooling, moisture-sorption-induced electricity generation, as a nascent field, has now been found in some nanomaterials with plentiful hydrophilic functional groups, such as carbon nanoparticles, polymers and biofibres[20]. One possible working mechanism can be explained as analogous to photovoltaic electricity generation, in which – similar to how the photons excite the electrons in semiconductors – the water molecules interact with the hydrophilic functional groups on the sorbents, initiating the dissociation and migration of charged ions from the sorption interface to the interior and thus generating voltage and current effects[13] (Fig. 1c). The enthalpy changes between gaseous water and adsorbed water provide the energy output of MSEH; however, the enthalpy changes cannot completely convert to electricity as a result of the limits by the second law of thermodynamics.

In addition to directly generating energy, moisture sorption can also indirectly generate electricity through several strategies[21,33].

For example, the captured water from air can indirectly drive electricity generation based on streaming potential[34], reversible deformation[35–37] and redox reactions[38–42]. For these methods, the generated energy may not, or may not only, come from the moisture-sorption process itself; instead, moisture sorption works as a water supplier to trigger the energy-generating process. In this article, we focus on direct electricity generation during the moisture-sorption process.

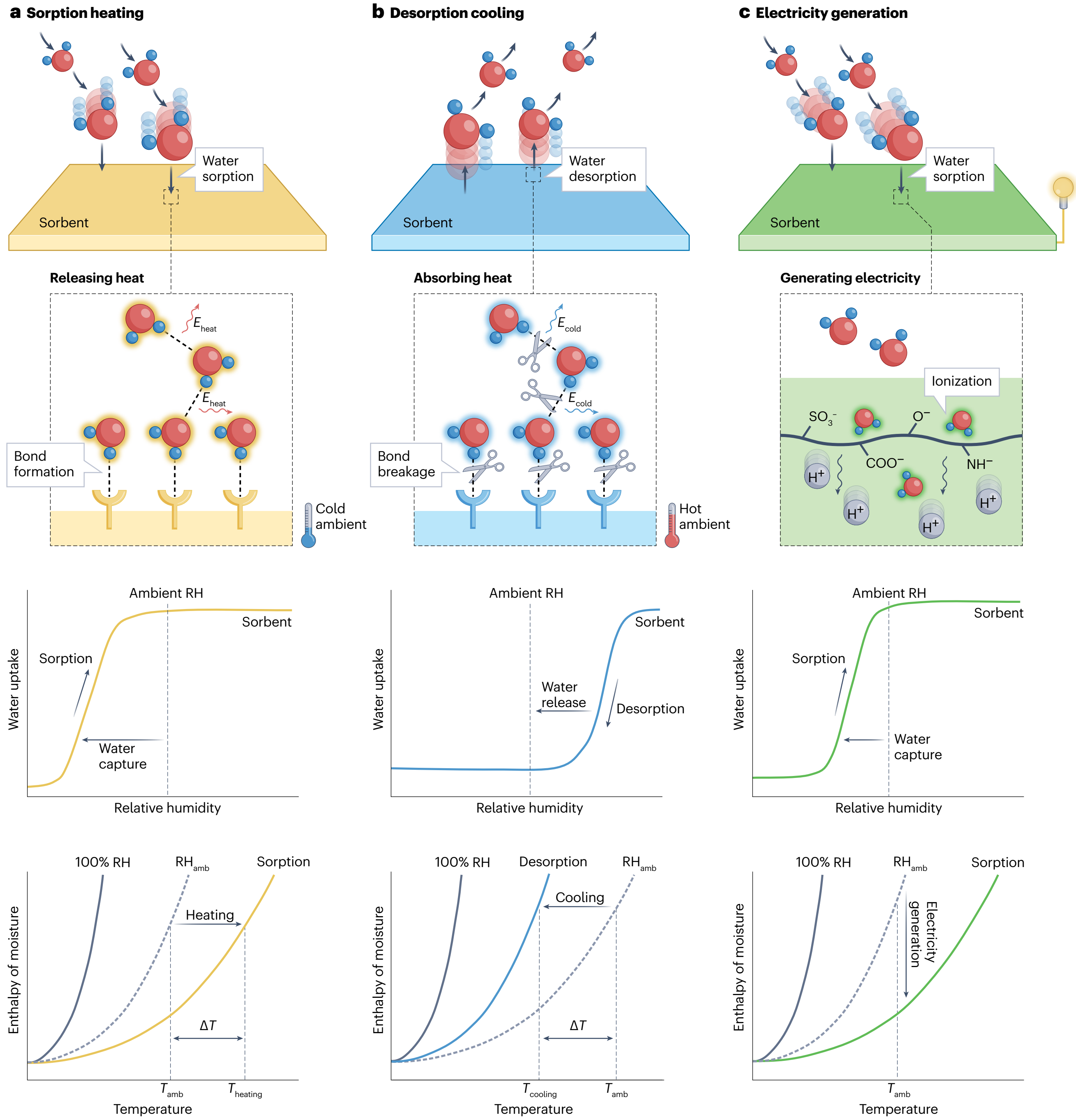


Fig. 1 | Schematics and operating principles of moisture-sorption-based energy harvesting for heating, cooling and electricity generation. **a**, Sorbents capture water from the ambient air with bond formation (exothermic effect), inducing heat release and temperature rise. **b**, Water escapes from sorbents to the ambient air with bond breakage (endothermic effect), inducing heat absorption and cooling effects. **c**, Ambient moisture contacts the functional groups of sorbents, inducing charged ions dissociation, directional diffusion and electricity generation. RH, relative humidity.

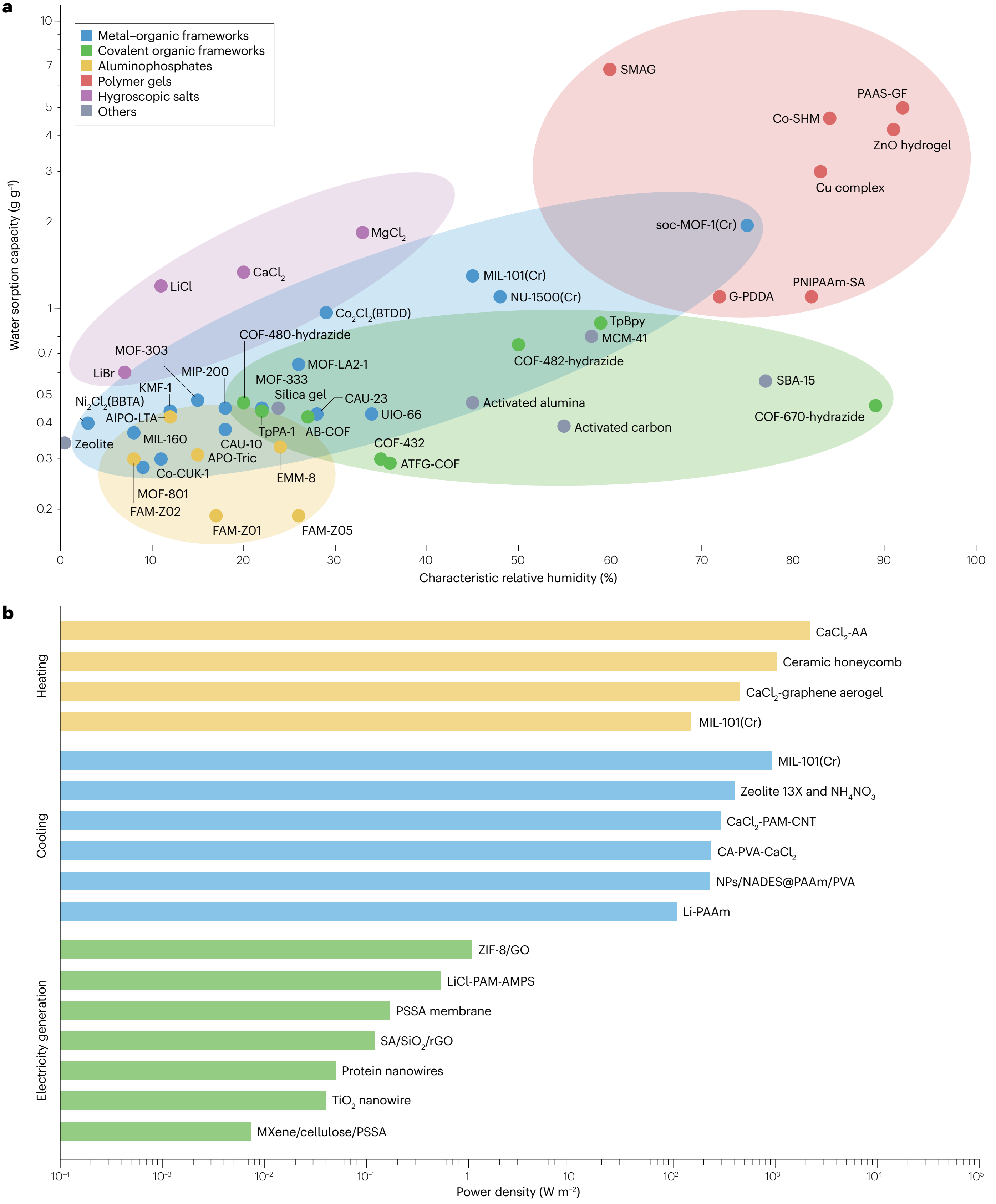

a
Metal–organic frameworks
Covalent organic frameworks
Aluminophosphates
Polymer gels
Hygroscopic salts
Others
Water sorption capacity (g g⁻¹)
10
7
5
4
3
2
1
0.7
0.5
0.4
0.3
0.2
SMAG
PAAS-GF
Co-SHM
ZnO hydrogel
Cu complex
soc-MOF-1(Cr)
MgCl₂
CaCl₂
LiCl
MIL-101(Cr)
NU-1500(Cr)
G-PDDA
PNIPAAm-SA
Co₂Cl₂(BTDD)
TpBpy
MCM-41
COF-480-hydrazide
COF-482-hydrazide
MOF-303
LiBr
MIP-200
MOF-LA2-1
MOF-333
SBA-15
KMF-1
Silica gel
CAU-23
Ni₂Cl₂(BBTA)
Activated alumina
COF-670-hydrazide
AlPO-LTA
UIO-66
Activated carbon
TpPA-1
AB-COF
Zeolite
MIL-160
CAU-10
COF-432
APO-Tric
ATFG-COF
Co-CUK-1
EMM-8
MOF-801
FAM-Z02
FAM-Z01
FAM-Z05
0
10
20
30
40
50
60
70
80
90
100
Characteristic relative humidity (%)
b
Heating
CaCl₂-AA
Ceramic honeycomb
CaCl₂-graphene aerogel
MIL-101(Cr)
Cooling
MIL-101(Cr)
Zeolite 13X and NH₄NO₃
CaCl₂-PAM-CNT
CA-PVA-CaCl₂
NPs/NADES@PAAm/PVA
Li-PAAm
Electricity generation
ZIF-8/GO
LiCl-PAM-AMPS
PSSA membrane
SA/SiO₂/rGO
Protein nanowires
TiO₂ nanowire
MXene/cellulose/PSSA
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
10
10²
10³
10⁴
10⁵
Power density (W m⁻²)

Fig. 2 | Water-sorption capacity of sorbents and power density of moisture-sorption-based energy harvesting. a, Gravimetric water uptake of typical moisture sorbents versus the characteristic relative humidity (RH) at which half of the total uptake is reached. For hygroscopic salt, the characteristic RH represents the deliquescence RH. Typical water vapour sorbents are divided into five types, including metal–organic frameworks (MOFs)[63,116–130], covalent organic frameworks (COFs)[46,131–134], aluminophosphates[47–49,135], polymer gels[64,74,136–141], hygroscopic-salt-based materials and others[142–146]. **b**, Power densities of typical sorbents for heating[60,72,73,147], cooling[30,31,148–151] and electricity generation[13,59,152–156], respectively. The majority of the data directly come from the literature, and part of the heating and cooling power data is calculated according to the reported gravimetric or volumetric power densities and the surface area of sorbents or devices in the literature. AA, anodic alumina; AB-COF, azine-benzene-COF; ATFG-COF, azine-triformylphloroglucinol-COF; AMPS, 2-acrylamide-2-methyl propane sulfonic acid; AlPO and APO, aluminophosphates; CA, cellulose acetate; FAM, ferroaluminophosphate; GF, graphene framework; GO, graphene oxide; NADES, natural deep eutectic solvent; NPs, nanoparticles; PAAm, polyacrylamide; PAAS, sodium polyacrylate; PAM, acrylamide; PNIPAAM, poly(*N*-isopropylacrylamide); PSSA, poly(4-styrensulfonic acid); PVA, poly(vinyl alcohol); rGO, reduced graphene oxide; SA, sodium alginate; SHM, super-hygroscopic material; SMAG, super moisture-sorbent gel; soc, square-octahedron; ZIF, zeolitic imidazolate framework.

Water sorbents of MSEH

A myriad of sorbents have been developed with high performance. Considering that the foundation of MSEH lies in the transformation of different states of water molecules, water-sorption capacity is one of the most important parameters for these sorbents. It not only determines the total amount of energy generation per unit of sorbent but also is relevant to the operation duration of the energy release process. In the past decade, water uptake has been improved by one order of magnitude at high RH. Figure 2a summarizes the water-sorption capacities of five representative types of sorbents, including metal–organic frameworks (MOFs)[43,44], covalent organic frameworks (COFs)[45,46], aluminophosphates[47–49], polymer gels[50] and hygroscopic-salt-based sorbents[51,52]. As the water uptake of hygroscopic-salt-based sorbents is contributed mostly by the salt, we refer to their sorption capacities by the water uptake of pure hygroscopic inorganic salts at the deliquescence RH. Numerous MOFs and COFs exhibit highly competitive water-sorption capacities at low and middle RH, whereas polymer gels demonstrate substantial advantages in high RH conditions[52–57].

There are several major conceptual challenges left to solve with respect to water-sorption capacity. The water-sorption capacity of sorbent is still below the levels needed for high-energy-productivity MSEH, especially when it works at low humidity. We anticipate that high-porosity materials with extraordinary pore volumes and plenty sorption sites are required to address this challenge. Currently, hygroscopic-salt-based materials have the highest water uptakes at low RH, but they generally face challenges of agglomeration, corrosion and solution leakage. These drawbacks have been partially overcome by confining hygroscopic salts inside a highly porous matrix to encapsulate them securely[52–54] or by using a swellable matrix[55–57]. However, their long-term stability and reliability in practical applications are still questionable. Another challenge is the unregulatable characteristic RH of major water sorbents, which results in limited accessible RH ranges and poor climate adaptability of MSEH. Efficiently and smartly tuning the water affinity (sorption transition RH) of sorbents for versatile applications is one of the most promising research directions for next-generation water sorbents.

Over the course of the development of MSEH materials and devices, the power density of MSEH technology has improved substantially, by at least two orders of magnitude (Fig. 2b). The power density of electricity generation has improved from 0.001 W m^{-2} to over 1 W m^{-2} (refs. 58,59), and the sorption heating and desorption cooling have improved to the level of 1,000 W m^{-2} (ref. 60), comparable to other green energy technologies such as radiative cooling and solar heating. However, the complicated transfer processes of water and energy, which are key to the moisture-sorption and moisture-desorption kinetics, are still poorly understood. Different designs for sorption materials, components and devices substantially influence the final demonstrated power densities, wherein the kinetics of sorption materials are one of the core factors. Therefore, a cross-scale consideration and design for enhancing water-sorption kinetics is required for future high-power-density MSEH. Furthermore, systematically revealing the fundamentals of the performance–structure relationship could provide insights into bridging the gap between sorbents and applications.

In summary, the water-sorption performance of sorbents has a crucial role in the working performance of MSEH, where sorption capacity determines the energy density, and sorption kinetics of sorbents controls the power density. Rapid advances in new sorption materials have led to performance improvement of MSEH; however, the technology still faces major challenges in achieving high-energy productivity. Further breakthroughs in energy productivity require an in-depth understanding of the thermodynamics and kinetics of water sorption, guiding the design and development of next-generation water sorbents.

Thermodynamics analysis of MSEH

Ambient air has a maximum water vapour storage ability, known as the saturated state at 100% RH. Supersaturated water vapour is rarely reached except in foggy weather; thus, there exists a limit to generate energy from moisture. The thermodynamics of water sorption and desorption determine the amount of energy that can be harvested from moisture. In particular, the first law of thermodynamics points out the total energy generation of water sorption and desorption processes, and the second law of thermodynamics limits how much exergy (usable power) can be extracted[61].

Thermodynamics fundamentals

The maximum extractable amount of energy during water sorption or desorption process is the enthalpy difference between the gaseous water in the air and the adsorbed state in sorbents (ΔH_{sorp}), wherein part of the energy (E_{output}) converts into thermal energy (E_{therm}) or electrical energy (E_{elec}) and the rest is not utilized (E_{loss}). The first-law energy conversion efficiency can be described by the following equation:

$$\eta_{\mathrm{en}} = \frac{E_{\mathrm{output}}}{\Delta H_{\mathrm{sorp}}}. \tag{1}$$

Similar to solar energy utilization, most of the moisture energy can be easily converted into thermal energy with a high-energy conversion efficiency; however, fairly less energy is reported to be transferred into electricity at this stage[62]. Therefore, further fundamental research should focus on the energy conversion mechanisms of moisture-sorption-induced electricity generation, finding effective pathways to exploit maximum electricity generation potential by suppressing unnecessary heat dissipation.

As discussed earlier, one primary direction for improving energy generation is to improve the water-sorption capacity of the sorbents. For example, extending the length of the linkers to increase pore volume is an efficient way for MOFs[63] and exposing more sorption sites to moisture is effective for polymer gels[64]. Post-synthetic modification by oxidation, reduction, linker substitution or ion exchange is also a promising strategy[65,66]. However, there remains no standardized approach to control the sorption capacity of different sorbents at this stage. Controlling and enhancing the moisture-sorption-induced release and migration of charged ions still needs an in-depth understanding of the working mechanisms with molecular-level calculation and measurement.

A desirable MSEH system should be both energy-efficient and exergy-efficient, generating a substantial amount of energy with a high grade. We here use the Gibbs free energy changes (ΔG) to describe the usable power (the exergy) of moisture energy quantitatively, and the partial molar Gibbs free energy is expressed as chemical potential. The chemical potential of water (μ_{water}) can be described by the following equation at the assumption of single-component ideal gas[61,67,68]:

$$\mu_{\mathrm{water}} = \mu^{\theta}_{\mathrm{water}} + RT\,\ln\left(\frac{P_{\mathrm{vapour}}}{P_{\mathrm{atm}}}\right), \tag{2}$$

in which $\mu^{\theta}_{\mathrm{water}}$ is the chemical potential of water in its standard state (−228.6 kJ mol^{-1} for water vapour). R, T, P_{vapour} and P_{atm} are the ideal gas constant, temperature, partial pressure of water vapour and standard atmospheric pressure, respectively. Notably, this equation is not applicable for calculating chemical potential at extremely low vapour pressure but is acceptable for evaluating MSEH under normal climate conditions. For a given ambient temperature, the saturated moisture has the highest vapour pressure (RH = 100%), corresponding to the highest chemical potential. Because unsaturated moisture (RH < 100%) has the potential to obtain water molecules from liquid water by evaporation, we here define the evaporation potential ($\Delta\mu_{\mathrm{evap}}$) of unsaturated moisture as the difference between the chemical potential of unsaturated moisture and that of the saturated moisture, equalling to $-RT\ln(P_{\mathrm{vapour}}/P_{\mathrm{sat}})$.

Unsaturated sorbents are inclined to obtain water molecules from ambient water vapour. The difference between the chemical potential of saturated moisture and dry sorbents can be described by the Dubinin–Polanyi sorption potential ($\Delta\mu_{\mathrm{sorp}}$) and is equal to $-RT\ln(P_{\mathrm{sorp}}/P_{\mathrm{sat}})$[22]. The P_{sorp} is the water sorption transition pressure of sorbents, and the ratio of P_{sorp} and P_{sat} generally represents the water affinity of a chosen sorbent. The description of the chemical potential here is under the assumption of pure water, whereas the practical chemical potential of water in sorbents is more complicated, involving other matters and more processes such as dissolution and swelling[69,70]. Considering the competitive relationship between dry sorbents and unsaturated air to obtain water, the potential difference between unsaturated moisture and unsaturated sorbents determines the direction of moisture sorption, which is judged by the following equation:

$$\Delta\mu_{\mathrm{evap}} - \Delta\mu_{\mathrm{sorp}} < 0. \tag{3}$$

When the evaporation potential is above the sorption potential, the moisture can trigger the water desorption of sorbents, whereas the water sorption of sorbents can be induced at the contrary condition (Fig. 3a). In other words, it is possible for sorbents to both sorb water from moisture and release water to moisture if the evaporation potential of moisture fluctuates above and below the sorption potential. For example, sorbents with mild water affinity, such as the MOF of MIL-101(Cr) with a relatively low sorption potential of 2.2 kJ mol^{-1} (ref. 71), are able to produce both sorption heating and desorption cooling effects if the evaporation potential of moisture varies around this value[72]. More data on enthalpy, entropy and chemical potential for water evaporation and water sorption are given in Supplementary Table 1 and Supplementary Table 2. The difference value between the evaporation potential of unsaturated moisture and the sorption potential of a sorbent denotes the maximum extractable Gibbs free energy changes of moisture energy. The larger the value of $|\Delta\mu_{\mathrm{evap}} - \Delta\mu_{\mathrm{sorp}}|$, the higher the sorption heating temperature, the lower the desorption cooling temperature and the greater the electricity generation capacity. Weak-water-affinity sorbents, such as hydrogels with hydrogen-bonded intermediate water or free water[25], easily release the captured water into the air and have considerable promise for desorption cooling. By contrast, strong-water-affinity sorbents, such as salt hydrates with chemical-bonded water molecules, are more desirable for sorption heating[73].

It is worth noting that over-strong water affinity will result in a very high desorption temperature, whereas over-weak water affinity will cause the failure of water sorption from the ambient air. Therefore, the trade-off between performance and climate adaptability of sorbents cannot be ignored. Combining several sorbents with different water affinities is a possible route to mitigate this challenge.

Alongside this point, one of the critical design goals for next-generation sorbents is to be able to tune their sorption potentials for specific applications. Stimulation-responsive or humidity-responsive characteristics, in particular, are highly desirable for smart, controllable high-grade energy generation. For example, a sorbent can be designed to have a temperature-dependent water affinity by integrating it with a thermo-responsive polymer such as poly(*N*-isopropyl acrylamide), which has a desirable critical transition temperature of ~32 °C. Such a sorbent is able to adsorb more water below the transition temperature and easily releases water when the temperature exceeds the phase transition temperature[74,75]. The so-called breathing materials — materials with flexible pore structures that respond to vapour pressure, such as MIL-51 and Co(bdp)[76,77] — can change their water affinity based on humidity. Thus, they may be useful for developing sorbents with RH-dependent water affinities. These breathing materials need to be explored further to match their characteristic transition pressures to the operation conditions of MSEH. In addition, modifying water sorbents with light-responsive and/or electric-responsive materials might make their water affinities similarly responsive, enabling smart sorbents that adjust to their environment or are able to regenerate under various conditions, according to the requirements of users. Therefore, there exist huge research opportunities for next-generation smart MSEH.

To fully exploit energy from the moisture, an optimized thermodynamic working process of MSEH with fewer energy losses and exergy losses is also necessary. The exergy efficiency of MSEH for thermal energy can be described by the equation:

$$\eta_{\mathrm{ex,therm}} = \frac{E_{\mathrm{therm}}\left(1 - \frac{T_0}{T_{\mathrm{real}}}\right)}{\Delta H_{\mathrm{sorp}}\left(1 - \frac{T_0}{T_1}\right)}, \tag{4}$$

in which the T_0, T_1 and T_{real} are the ambient temperature, maximum temperature change under an adiabatic condition and the real temperature

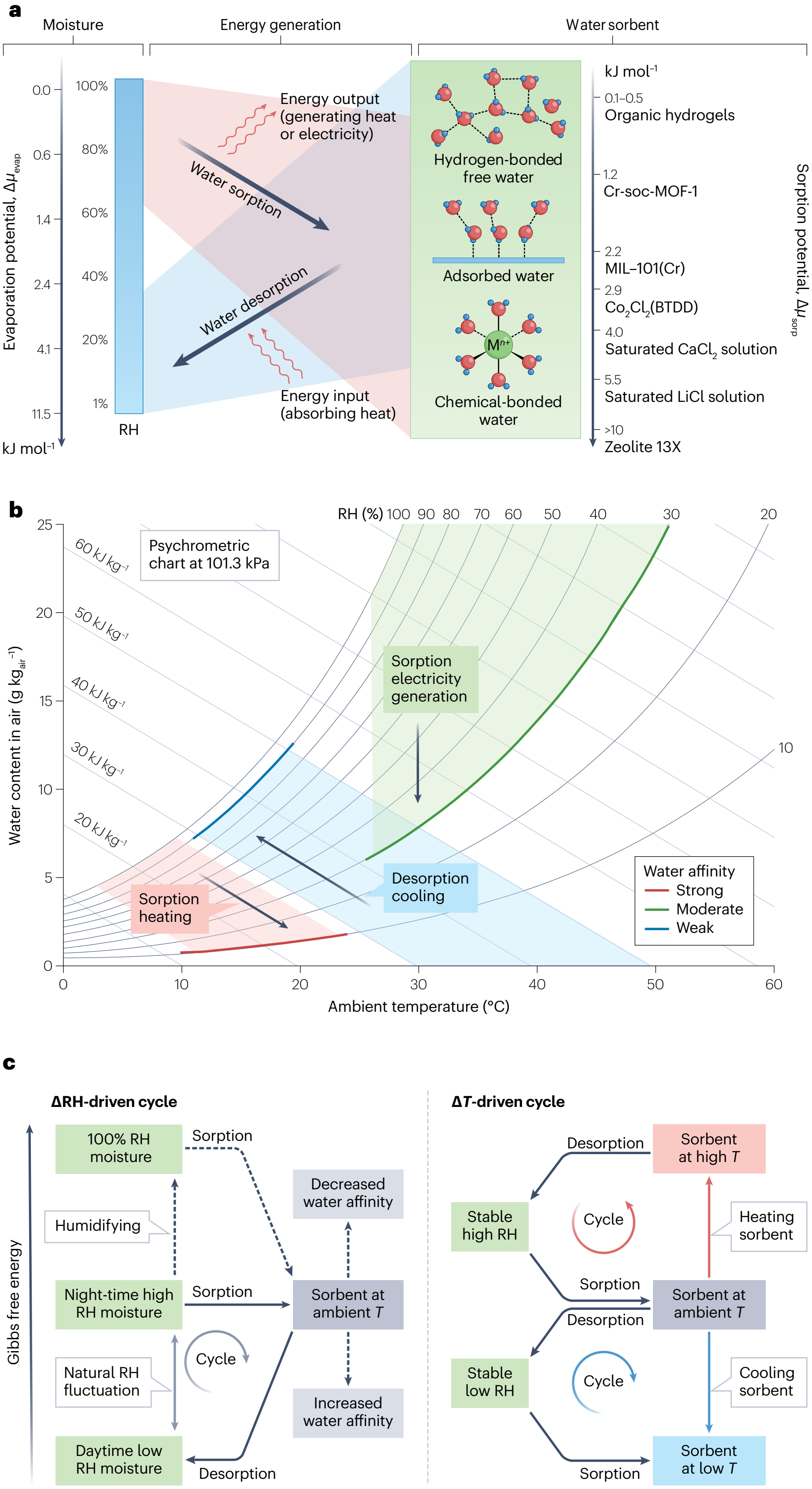


Fig. 3 | Thermodynamics and energy potential of moisture-sorption-based energy harvesting. **a**, Schematics showing the difference between the evaporation potential of moisture and the sorption potential of sorbent determines the direction of water sorption or water desorption. **b**, Psychrometric chart showing the ideal thermodynamic process of moisture-sorption-based energy harvesting with suitable water-affinity sorbents: adiabatic sorption heating by strong water-affinity sorbents, adiabatic cooling by weak water-affinity sorbents and isothermal electricity generation by moderate water-affinity sorbents without exothermic effects. The diagonal lines represent the isenthalpic lines of moisture with specific temperatures and water contents. **c**, Gibbs free energy changes during the two typical continuous cycles of moisture-sorption-based energy harvesting driven by the natural relative humidity (RH) fluctuation of moisture and external heat and cold sources.

changes for practical MSEH devices, respectively. A desirable sorption heating process should be adiabatic and use high water-affinity sorbents working in a high RH climate (Fig. 3b). Similarly, desirable desorption cooling applications are suggested to use low water-affinity sorbents and work in dry climates for efficient cold production. For the sorption-based electricity generation process, a sorbent with moderate water affinity is preferred to allow both water sorption from moisture and self-release of the water molecules driven by low-energy consumption or the ambient RH fluctuation, and working in the climate with high RH. The construction and maintenance of ion concentration gradient are also critical factors for electricity generation. A desirable electricity generation process is isothermal without temperature increase, in which the low sorption temperature at ambient temperature endows maximum electricity output corresponding to the maximized chemical potential difference of $|\Delta\mu_{\mathrm{evap}} - \Delta\mu_{\mathrm{sorp}}|$[62], whose exergy efficiency can be described by the following equation:

$$\eta_{\mathrm{ex,elec}} = \frac{E_{\mathrm{elec}}}{|RT_0 \ln(\frac{P_0}{P_1})|} \tag{5}$$

in which P_0 and P_1 represent the vapour pressure of the ambient moisture and the equilibrium pressure of water sorption, respectively. Owing to the limitations of the second law of thermodynamics, the enthalpy change in the sorption process cannot fully convert into electrical energy and has a low conversion efficiency, indicating that the moisture energy is a low-grade energy. However, there is a great opportunity to approach the theoretical efficiency of beyond 10% by rationally modulating the moisture, materials and devices, together with converting the generated thermal energy to electricity. More details about energy efficiency are described in Supplementary Note 1 and Supplementary Figs. 1 and 2. Accordingly, efficient ways to increase the energy generation during the sorption process are to increase the evaporation potential of moisture by lowering temperature through radiative cooling and to increase humidity through humidification. More importantly, increasing enthalpy and reducing the entropy of sorbents by introducing stronger sorption sites are major research targets to improve the sorption potential (details illustrated in Supplementary Fig. 7).

Cycles and global potential

Continuous energy generation requires timely regeneration of the sorbent once it reaches sorption equilibrium or desorption equilibrium states. Figure 3c shows two typical sorption–desorption cycles, driven by either natural RH fluctuations or external heat and cold sources, from the perspective of Gibbs free energy. The commonality of the ΔRH-driven and ΔT-driven cycles is that tuning the Gibbs free energy of moisture to above or below that of sorbent drives its regeneration process. For the ΔRH-driven cycle, all of the energy comes from the ambient without extra energy consumption. For the ΔT-driven cycle, the extra energy consumption of heating or cooling should be taken into account for fairly evaluating the overall cyclic energy efficiency (more details about the MSEH cycling are described in Supplementary Note 2 and Supplementary Figs. 3–6). To replenish water promptly after desorption cooling, humidification and sky radiative cooling can be introduced to increase RH of the ambient air. To make regeneration after sorption heating or electricity generation more energy-efficient, sustainable heat sources can be integrated into the MSEH system to drive desorption, such as solar thermal, industrial waste heat and dissipated heat from photovoltaic panels, electronics or human skins. In addition, the sustainability and adaptability of MSEH can be further improved by coupling the ΔRH-driven cycle strategy with the ΔT-driven cycle strategy under varying climate conditions.

Figure 3c also indicates the cycles that are possible by tuning the Gibbs free energy of sorbents via changing their water affinity. For example, a recent work proposed a self-sustained energy generation strategy[78], in which moisture is spontaneously absorbed through the hygroscopic layer and the absorbed water is transported to the hydrophobic evaporative layer for vaporization simultaneously. This new working mode constructs a persistent running water cycle in the device to avoid the presence of an adsorption equilibrium state, realizing continuous and enhanced electricity generation. We expect more efforts to be devoted to such asymmetric-hydrophilic and self-regulating hydrophilic sorbents, not only for self-sustained energy generation but also for inspiring self-sustained dehumidification, water harvesting and other related applications based on such continuous sorption–desorption processes.

To realize an ideal thermodynamic process of MSEH, sorbents should be designed to avoid unnecessary energy dissipation, such as by reducing the internal thermal and/or electricity transfer resistance. In addition, design of MSEH devices should also be optimized to improve the energy conversion efficiency, such as adopting heat recovery[79], mass recovery and cascade energy production; however, these methods have rarely been studied for MSEH yet.

With further advances in materials, and once optimized operating processes eventually approach the thermodynamic limit, we anticipate that massive energy can be harvested from ambient moisture for sustainable heating, cooling and electricity generation globally (Box 1). It is worth noting that the theoretical global potential of MSEH is obtained on the basis of the assumption of an ideal thermodynamic process of energy production, regardless of the exergy losses during irreversible processes of heat, mass and ion transfer at the device level. To show the working potential of the cycling process, we further demonstrate the theoretically maximized energy generation of the emerging continuous energy generation driven by natural RH fluctuations, given in Supplementary Note 2 and Supplementary Fig. 5.

Kinetics analysis of MSEH

The kinetics of sorption and desorption determines the power density of MSEH, which is the rate of extracting energy from air. A typical moisture-sorption process involves tandem transport-sorption steps: water transport and energy transfer outside the sorbent, among the sorbent particles, inside the micropores and/or mesopores, and sorption or reaction at the sorption sites (Fig. 4a). Therefore, a high-power-density MSEH requires a cross-scale analysis, design and enhancement of water-sorption kinetics.

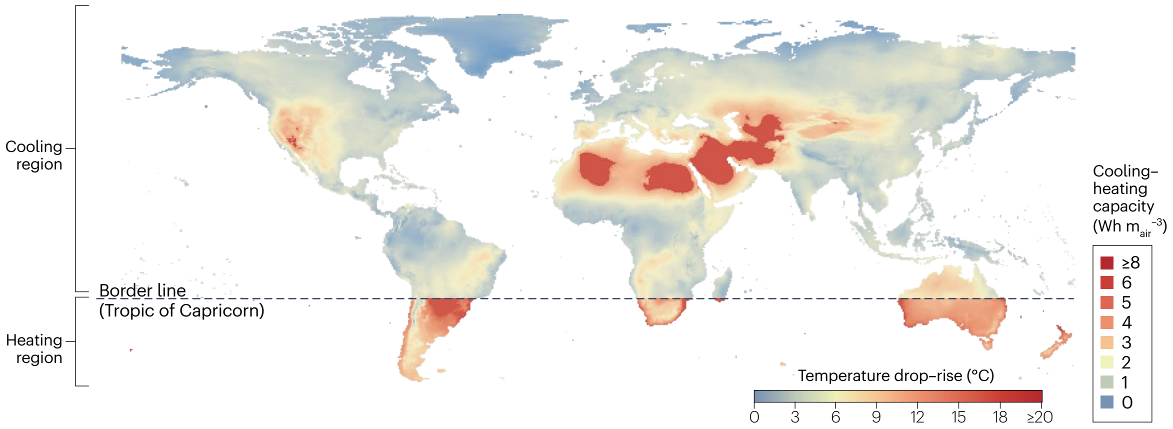
Challenges of slow kinetics

According to the porous transfer theory[80], the water diffusion kinetics are regulated by the transfer coefficient (D), the porosity (ε), the tortuosity factor (τ) and the thickness (δ) at each level. One crucial reason for slow sorption kinetics comes from the large diffusion resistance resulting in an apparent pressure drop from the ambient water vapour pressure (P_{air}) to that near the sorption sites (P_{mic}) (Fig. 4b). Another reason is the poor heat transfer performance of porous materials, resulting in a fast temperature rise and shifting the thermodynamic equilibrium of sorption or reaction to a required high sorption pressure (P_{sorp}); however, it has not been investigated enough in MSEH. The classical Arrhenius kinetics equation indicates that the slow sorption

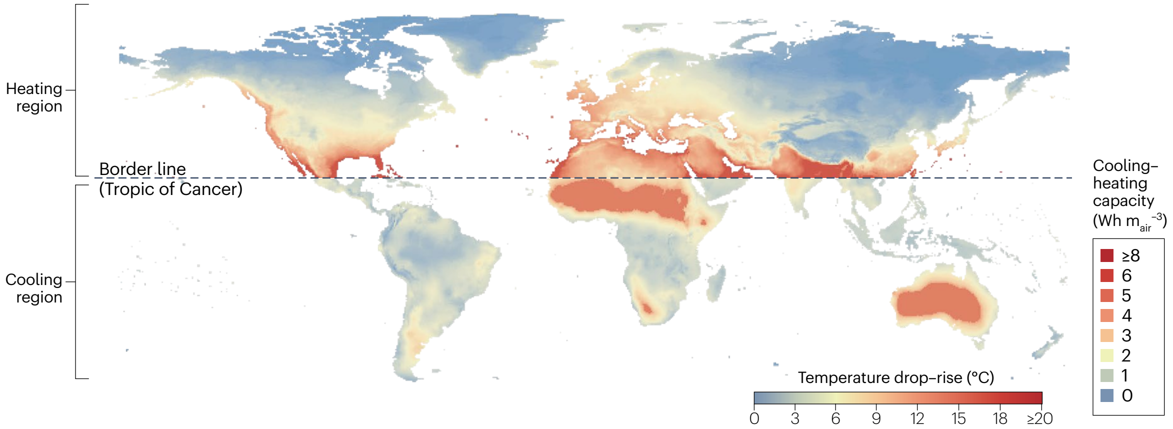
Box 1

Global energy generation potential of moisture-sorption-based energy harvesting

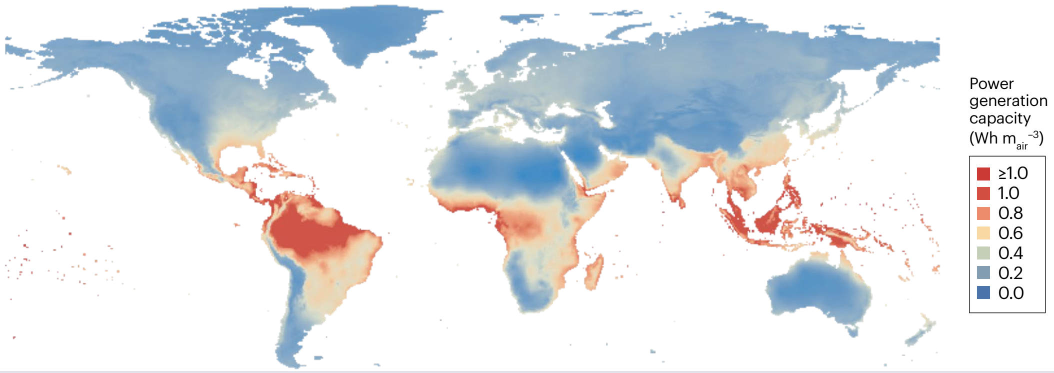
a Global potential of heating–cooling in July



b Global potential of heating–cooling in January



c Global potential of annual mean electricity generation



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According to the thermodynamic analysis, the global potentials of heating, cooling and electricity generation by moisture-sorption-based energy harvesting (MSEH) are evaluated on the basis of the climate data and the ideal thermodynamic processes of adiabatic heating, adiabatic cooling and isothermal electricity generation. The theoretically maximum specific energy generation capacities of heating (q_{heating}), cooling (q_{cooling}) and electricity generation (q_{elec}) during the sorption or desorption process are calculated by the following equations:

$$q_{\mathrm{heating}} = \Delta H_{\mathrm{sorp}}(Y_{\mathrm{air}} - Y_{\mathrm{sorp}}),$$

$$q_{\mathrm{cooling}} = \Delta H_{\mathrm{desorp}}(Y_{\mathrm{desorp}} - Y_{\mathrm{air}}),$$

$$q_{\mathrm{elec}} = |\Delta\mu_{\mathrm{evap}} - \Delta\mu_{\mathrm{sorp}}|(Y_{\mathrm{air}} - Y_{\mathrm{sorp}}),$$

in which the ΔH_{sorp} and $\Delta H_{\mathrm{desorp}}$ represent the sorption enthalpy and desorption enthalpy, and Y_{air}, Y_{sorp} and Y_{desorp} represent the water content in the ambient air and the water content in the air after reaching sorption equilibrium and desorption equilibrium, respectively. To calculate the maximum value of the energy generation capacity, the Y_{sorp} and Y_{desorp} are set as zero and saturated values for sorption heating and desorption cooling, whereas Y_{sorp} for electricity generation is set as the water content of moisture at 30% RH. If all the generated thermal energy is transferred into the sensible heat of air for space heating or cooling, the temperature lift of heating ($\Delta T_{\mathrm{heating}}$) and the temperature drop of cooling ($\Delta T_{\mathrm{cooling}}$) can be obtained by the following equations under the assumption of ignoring the sensible heat of sorbents:

$$\Delta T_{\mathrm{heating}} = \frac{q_{\mathrm{heating}}}{C_{\mathrm{p\ air}}},$$

$$\Delta T_{\mathrm{cooling}} = \frac{q_{\mathrm{cooling}}}{C_{\mathrm{p\ air}}}.$$

We analyse the global energy generation capacity of MSEH based on the temperatures and humidity in 2021 and using version 4.06 of the Climatic Research Unit Time Series (CRU TS) data set[157]. Considering the seasonal differences between the northern and southern hemispheres for heating and cooling, we separately show the heating and cooling potential in July (see the figure, part **a**) and in January (see the figure, part **b**). The tropic of Capricorn or Cancer is selected as the borderline of heating and cooling, considering the all-year-round cooling requirements in equatorial regions.

The hot and dry regions have substantial desorption cooling potential, whereas the warm and humid regions have considerable sorption heating potential, and the maximum temperature regulation capacity of MSEH can reach above 20 °C for heating or cooling. Remarkably, several reported sorption-heating and desorption-cooling devices deliver excellent temperature lift or drop up to approximately 10 °C (refs. 30,73), which can be further enlarged by materials development and engineering innovation to step closer to the theoretical limits. The generated heat or cold can be used to cool photovoltaic panels, cool electronics and save energy for buildings. Although the electricity generation potential of moisture is relatively low, it is enough to drive w-scale electronics such as sensors (see the figure, part **c**). It is worth noting that the heating and electricity generation potential in cold regions is very limited, ascribing to the low water content in the cold air (less than $5\,\mathrm{g\,m_{air}^{-3}}$ if the temperature is below 5 °C); thus, an accelerated fresh air process speed is necessary to ensure a continuous supply of water vapour.

kinetics is also influenced by the high activation energy (E_a) and a small pre-exponential factor (A) if the sorption process involves reaction[81]. In the view of thermodynamics, the slow kinetics caused by large mass transport resistance or energy transfer resistance will bring unacceptable exergy losses. These challenges related to slow kinetics will be substantially magnified if MSEH technologies go up in scale from laboratory to market and accordingly have much longer mass transport and energy transfer distances.

Opportunities and strategies

The above kinetics mechanisms reveal research directions to improve the power density of MSEH. As illustrated in Fig. 4c, the pathways for improving sorption kinetics should not be limited to a single-scale step, but should comprehensively consider cross-scale energy transfer, mass transport and sorption or reaction. High resistance in any step will lead to poor kinetics performance owing to the essence of tandem transfer-sorption process. Therefore, a synergetic enhancement of mass transport and energy transfer at different scales is vital for improving the power density of MSEH.

At the scale of devices, the key research issues are to design highly efficient heat exchangers, air ducts, electrodes and interfaces between the sorbents and ambient, with the aim of accelerating water transport inside sorbents and energy transfer from sorbents to the users[82]. Replacing natural air flow with forced air flow is a common and effective way to realize faster water transfer on the air side[83]. By actively controlling the airflow speed, a stable and enhanced power density can be achieved[29]. Modifying the interfacial properties of sorbents by fabricating functional sorbent surfaces and reducing interfacial transport resistance are important research directions to improve the transfer efficiency and kinetics[84,85]. In addition, advanced fabrication methods such as 3D printing will help to precisely engineer highly efficient devices and suitably match the shapes, sizes and functions of water sorbents. To improve the diffusion kinetics on the scale of the macroporous pores, one of the most emphasized directions is to construct hierarchical-porous structures of sorbents with ordered mass transport and energy transfer channels[51,86,87]. Many existing methods used to create macroporous structures in other types of materials can be introduced to water sorbents for MSEH, such as in situ self-growth, templating methods and 3D printing[88,89]. Two-dimensional materials such as graphene and MXene provide new choices of precursor materials to construct functional, ordered and robust structures[90].

For nanoscale mass transport and energy transfer, it becomes challenging to regulate the micropore properties markedly. Designing new materials from scratch or adjusting the compositions or properties of the precursor materials is typically more effective at realizing kinetics breakthroughs than trying to modify the pores after the sorbent is synthesized. When the scale goes down to the molecular level, a more in-depth understanding of the interrelationship between chemical properties and sorption kinetics is required to optimize the density and activity of sorption sites[91]. Tools such as in situ characterization and first-principles calculations prove to be promising for molecular-scale understanding and design[92].

Outlook

High-energy productivity

Advances in water vapour sorbents have sparked new research into the ability of MSEH technology to produce heat, cold and electricity without temporal and spatial restrictions. Although the proof of concept of MSEH has been well demonstrated and proven, developing high-performance MSEH is the prerequisite for its deployment in wider applications with various energy demands[93]. In particular, to pursue MSEH devices that have high-energy output and light weight, small volume and tiny projected area, it is valuable to use the perspectives of thermodynamics and kinetics to increase their energy density, power density and energy grade (Fig. 5a).

A sustained focus of this field is how to realize a high sorption capacity in sorbents, especially those that operate at low RH. Conventional strategies are to develop sorbents with specific pore structures, higher specific pore volumes and more sorption sites, but the synthesis of entirely new materials is still quite challenging and unsystematic. Machine-learning and big-data techniques hold promise for accelerating sorbent design, optimization and high-throughput

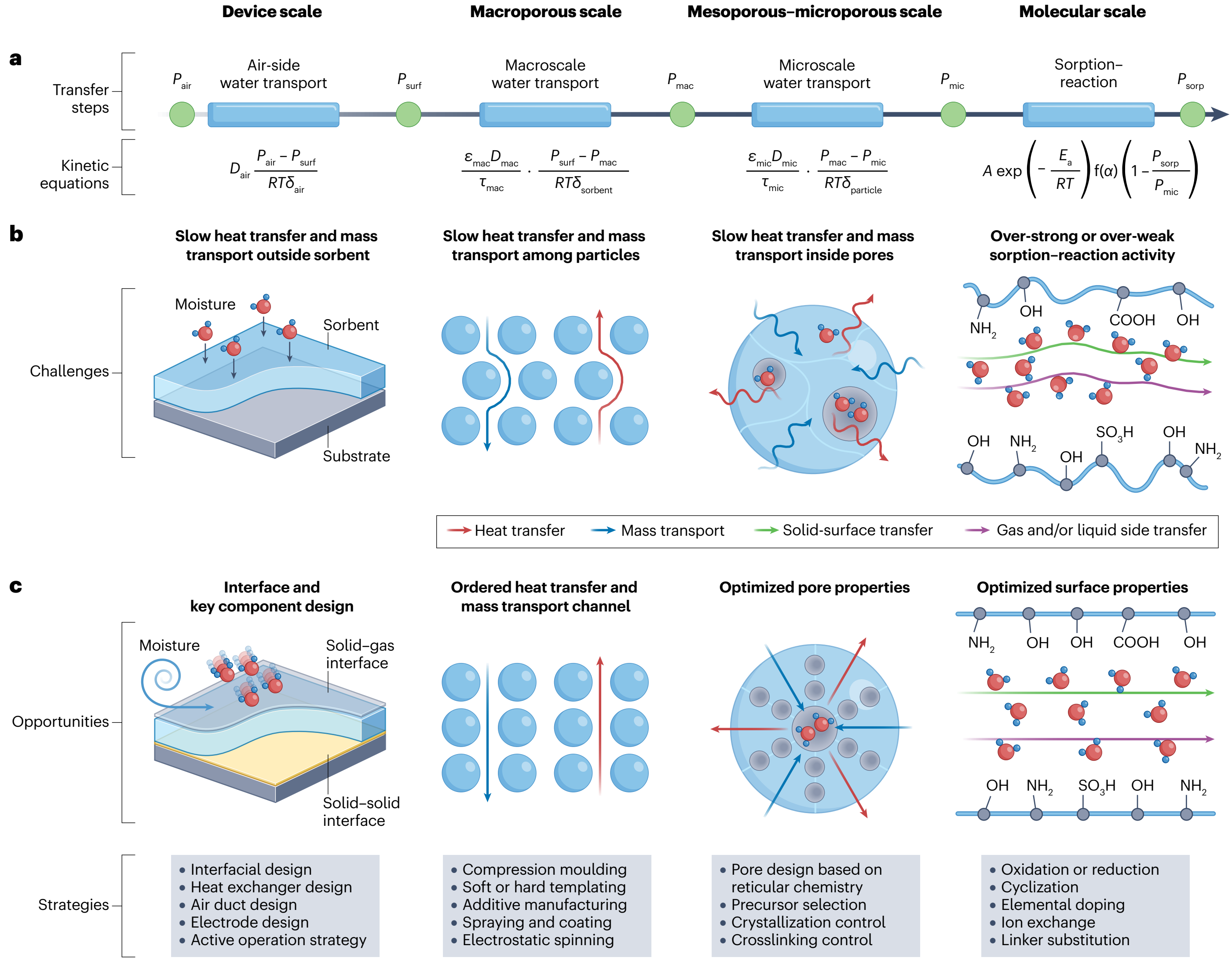

Fig. 4 | Challenges and opportunities of sorption kinetics. a, Multistep sorption processes for moisture-sorption-based energy harvesting, whose kinetics are controlled by cross-scale energy transfer, mass transport and sorption or reaction resistance. **b**, Challenges of slow water sorption–desorption kinetics caused by slow energy transfer and mass transport, together with over-weak or over-strong sorption or reaction activity. **c**, Opportunities and strategies for improving water sorption–desorption kinetics by designing ordered cross-scale energy transfer and mass transport. α, sorption conversion ratio; δ, thickness; ε, porosity; τ, tortuosity factor; A, pre-exponential factor; D, mass transfer coefficient; E_a, sorption or reaction activity energy; P_{air}, water vapour partial pressure at the ambient air; P_{mac}, water vapour partial pressure at macroporous pores; P_{mic}, water vapour partial pressure at mesoporous and/or microporous pores; P_{sorp}, equilibrium pressure of water sorption; P_{surf}, water vapour partial pressure at the external surface of sorbent.

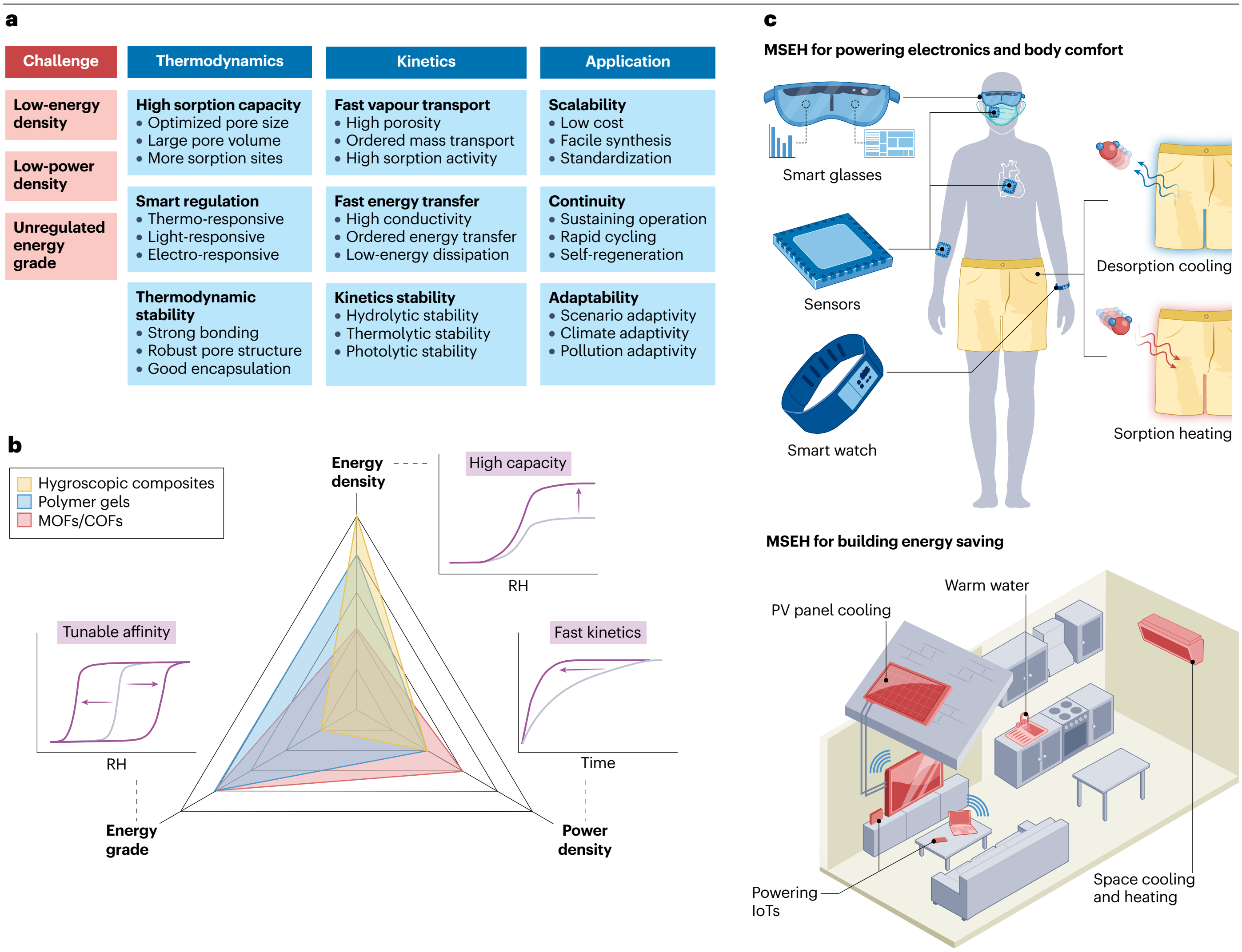

Fig. 5 | Perspectives on designing next-generation sorbents and future practical applications. a, Outlook of research outlines and methods of future water vapour sorption materials for high-performance moisture-sorption-based energy harvesting (MSEH). **b**, Three major evaluation dimensions of sorption capacity, water affinity and sorption kinetics for sorbents. Balancing these three properties and developing sorbents without apparent shortcomings is a crucial direction for future research. **c**, Two typical applications scenarios of MSEH for personal and buildings energy management. COF, covalent organic framework; IoT, Internet of Things; MOF, metal–organic framework; PV, photovoltaic; RH, relative humidity.

screening[94,95]. In addition, many porous and gel materials in other research fields also have the potential for water sorption, which is waiting to be explored; we expect diverse kinds of new materials, including new MOFs, COFs and MXenes, to be applied in MSEH, especially for electricity generation.

Another key research direction is to improve energy conversion efficiency with maximum Gibbs free energy output. We discuss the difference between water sorption potential and evaporation potential of moisture as the key parameters for high-grade energy harvesting. Developing sorption materials with suitable sorption potential or adjustable water affinity for different application scenarios is of great value. For example, the polymorphisms in MOFs can be utilized to tune their water affinity[44,96,97]. In particular, artificially adjusting the water affinity of sorbents by external stimulation of heat, light, force or magnetism will shift MSEH technology from passive operation to active smart regulation, substantially improving the regeneration versatility, energy productivity and climate adaptability of MSEH[74,75,77,98,99]. We hopefully anticipate a considerable amount of global energy potential to be exploited if the thermodynamic potential is fully released. For moisture-enabled electricity generation, whose working mechanism is still not clear enough, the theories and tools of electrochemistry are suggested to be introduced to more deeply understand its thermodynamic characteristics.

This Perspective article also demonstrates the irreplaceable role of kinetics enhancement for high-power-density energy generation. It is necessary to understand the essence of the structure–performance relationship, optimizing dynamic performance by considering an overall structure design from the material level to the device level.

Moreover, as the complicated kinetics process of MSEH involves water molecule transport, heat transfer and ion diffusion, we underline the importance of synergetic and systematic enhancement of both mass transport and energy transfer at different scales – including the external active flow of moisture, interfacial design and internal pore design – on geometry, tortuosity and surface effects. Constructing high-performance sorbents with cross-scale and hierarchically ordered mass transport as well as energy transfer paths is a feasible scheme to greatly enhance the power density of energy generation.

It is worth noting that the enhancement of kinetics performance is often at the expense of weakened thermodynamic performance. Perfect sorbents that achieve high-energy density, high-grade energy and high-power-density operation simultaneously are still lacking. Therefore, figuring out how to balance kinetics performance and thermodynamics performance deserves special attention in future research (Fig. 5b). The trade-offs between high-energy density and high-power density should be considered according to the specific application requirements. For application scenarios that require high-power density, the focus should be on improving sorption kinetics and effectively controlling the dynamic output power at a both high and stable value. By contrast, for application scenarios that require high-energy density for a long-term operation, the focus should move to improving the sorption capacity with weakened sorption kinetics.

Although finding the right balance is important in the short term, it is highly valuable to aim for perfect sorbents without shortcomings; thus, different sorption materials should have their own distinct research focuses and breakthrough goals. For example, MOFs and COFs have superior tunable water affinities compared with other sorbent materials, but they display relatively low capacities at low RH and slow kinetics if these particles or powders are randomly stacked in large-scale utilization. This is mainly caused by a serious deterioration in transport resistance with longer diffusion path. For salt-based hygroscopic sorbents, more attention should be paid to improving kinetics while maintaining performance; they also face substantial challenges (as well as opportunities) in altering their water affinities, owing to their simple chemical structures, which generally do not interact with other substances. Using porous matrices with certain chemical, thermal or mechanical characteristics or nano-confinement effects may unlock new pathways for regulating the sorption properties of hygroscopic salts[70,100]. To facilitate the advancement of MSEH technology, we appeal to the research community to establish comprehensive evaluation indexes on energy production capacities from the perspectives of weight, volume, occupied area and cycling efficiency, measured by standardized methods under identical external climate conditions of temperature, RH, airspeed, atmospheric pressure and so on.

Practicality and application

The convenience and reliability of MSEH should be improved towards practical applications. Currently, new water sorbents and devices generally remain at laboratory scale; their costs and stabilities should be carefully evaluated for large-scale applications. It is exciting to see that various new sorbents have been shown to be produced at scale[101,102]. Economic evaluation methods, such as payback period calculation, market demand survey and life cycle assessment, are required for MSEH technology to go deep into the broad consumer market.

Achieving continuous operation is another aim: the need for water sorbent to re-establish itself once it reaches sorption or desorption equilibrium interrupts and complicates the operation process. To overcome this obstacle, the traditional approach is to construct a dual-bed or multi-bed sorption system, in which one bed works at the desorption stage and the other works at the sorption state[51]. One emerging strategy is to develop high water content sorbents or reduce the water sorption rate to prolong the working duration of MSEH[13,40,103], but these sorbents will suffer from capacity degradation after a long running time. Harnessing the natural fluctuations in RH is an efficient way to drive the regeneration of sorbents without extra consumption, but requires certain climate conditions and sorbent properties[12]. An interesting artificial-hydrological-cycle (AHC) strategy for self-continuous operation was reported in recent studies[104,105]. In analogy with the natural hydrological cycle of precipitation, water run-off and evaporation, the core of AHC is to establish a persistent water cycle between the sorbent and ambient moisture, continuously capturing water from the moisture at one side of the sorbent and simultaneously releasing water to the air at the other side. The key to construct such an AHC is to design the sorbent with a heterogeneous distribution of water affinity, where part of sorbent sorbs water and the rest desorbs water simultaneously[78,106]. Loading hygroscopic salt on part of the sorbent is an efficient way to regulate its water affinity[104,105]. Another feasible strategy is to design multilayer structures with gradient hydrophilicity by combining materials with different water affinities[78,107]. Importantly, the kinetics of water sorption–desorption needs to be enhanced and sufficiently matched with the internal water flow rates within a long-term operation. This AHC strategy can be extended to other water sorption applications, such as atmospheric water harvesting and dehumidification, to achieve self-continuous operation[108].

Furthermore, combining MSEH systems with other energy resources and technologies will broaden the prospective working scenarios. For example, solar thermal energy can be introduced to accelerate water desorption if cold is not demanded, and a thermoelectric device can be used to produce extra electricity (driven by the temperature difference between water sorption and water desorption) if electricity generation is required exclusively[109]. With the increasing demand for a comfortable living environment of suitable temperature, humidity and high air quality, various gas sorbents can be functionalized for different domains, including dehumidification[110], water harvesting[53,111] and fuel production[112]. Rapid progress in sorbents will accelerate the development of hybrid energy systems such as those that co-generate thermal energy and electricity, co-generate energy and water[113], and couple co-generation of energy and water with carbon capture[114]. For dual-functional or multi-functional moisture-sorption systems, realizing synergistic reinforcement, efficient coupling and smart control will be the future focuses and major challenges. In this case, it is favourable to endow sorbents with additional properties beyond high water sorption–desorption performance, such as high solar absorptivity, high emissivity at atmospheric windows and sorption capacity for carbon dioxide or volatile organic compounds.

With the energy–water–air nexus and emerging green-economy era, MSEH, as a passive sustainable energy harvesting technology, will blossom in the near future as multidisciplinary efforts converge. We envision some possible scenarios of MSEH devices in personal and building energy management (Fig. 5c). For instance, some wearable sensors can be powered by moisture-sorption-induced electricity[115], and sorption heating and desorption cooling can be used for personal thermal management integrated with clothes and masks. Correspondingly, certain properties, such as biocompatibility, flexibility and self-continuity, are highly desired for these MSEH sorbents. In buildings, MSEH is expected to considerably reduce the energy consumption for space heating and cooling by reducing the energy consumption of conventional air conditioning. The produced electricity can participate in the construction of a self-powered Internet of Things, contributing to net-zero-energy buildings.

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Author contributions

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