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Review

Progress and Expectation of Atmospheric Water Harvesting

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Even if people live in an arid desert, they know that plenty of water exists in the air they breathe. However, the reality tells us the atmospheric water cannot help to slake the world's thirst. Thus an important question occurs: what are the fundamental limits of atmospheric water harvesting that can be achieved in typical arid and semi-arid areas? Here, through a thorough review on the present advances of atmospheric water-harvesting technologies, we identify the achievements that have been acquired and evaluate the challenges and barriers that retard their applications. Lastly, we clarify our perspectives on how to search for a simple, scalable, yet cost-effective way to produce atmospheric water for the community and forecast the application of atmospheric water harvesting in evaporative cooling, such as electronic cooling, power plant cooling, and passive building cooling.

Introduction

Just as Leonardo da Vinci said, "water is the driving force of all nature." Freshwater scarcity is increasingly perceived as a globally systemic risk. Taking into account the seasonal fluctuations in water consumption and availability, recent research[1] found that two-thirds of the global population (4.0 billion people) live under conditions of modest water scarcity for at least one month in a year. Even worse, a half billion people on Earth face severe water scarcity all year round. However, the atmospheric water, which is considered a huge renewable reservoir of water and enough to meet the needs of every person on the planet, is unfortunately ignored.[2] Atmospheric water usually exists in three basic types:[3] clouds floating in the sky, fog close to the land, and water vapor in the air. Cloud and fog are all made up of tiny drops of water (typically with a diameter from 1 to 40 μm, compared with the size of rain droplets varying from 0.5 to 5 mm), but the concentration of water droplets in fog is usually larger. When water is taken out of the air, different from desalination, little influence may occur to disrupt the hydrological cycle or steal water away from important critical sources nearby.[4] In addition, since the source of the atmospheric water is normally clean, the water quality is good enough for drinking and for other domestic and agricultural purposes.[5]

Thus, today water harvesting from air shows a great promise in supplying water for community use in arid areas,[6] portable water production by decentralized systems,[7,8] and emergency water supply in post-disaster times.[9] The millennium development goals[10] set by the United Nations highlight the critical needs of self-sustenance in potable water supply through small-scale decentralized water production in impoverished and developing regions of the world. On one hand, 1.7 million deaths per year are caused by poor water quality, sanitation, and hygiene.[11] On the other hand, fresh water availability is essential for the economic development in small communities in remote areas, where annual rainfall is negligible and traditional water sources such as rivers, lakes, wells, and springs are also not

Context & Scale

Airborne moisture is a potential source of a plentiful amount of freshwater that is accessible everywhere and can be easily co-operated with a renewable energy source (solar energy). This paper presents a comprehensive and critical review of state-of-the-art research on atmospheric water harvesting. From the viewpoint of applications, we are concerned most about whether an atmospheric water harvester can produce sufficient freshwater under a wide range of weather conditions in an energy-efficient way. Therefore, a variety of harvesting methods, including radiative cooling, solar distilling, and sorption-based water collecting, are reviewed and discussed based on their capture materials, system designs, and thermodynamic cycles. The study also presents a systematic performance comparison of recently proposed atmospheric water harvesters. Furthermore, we discuss four key problems that limit the cost-effectiveness and provide some solutions as perspectives.

Atmospheric water-harvesting technology has experienced significant progress in the past 20 years. However, little research on atmospheric water harvesters is conducted with broad horizons, and system integrations have viable.[12–15] Moreover, in recent years the frequency and intensity of natural disasters induced by climate change have been dramatically increasing.[16] One of the first priorities after a disaster is to provide safe drinking water.[9] In the past bottled water and/or water tankers were delivered to the affected population. However, limited water capacity and relatively expensive continuous delivery are the major drawbacks. Thus, sustainable onsite water supply technology is more practical and promising. Two techniques are usually applied to overcome such obstacles: desalination of saline water (ground or underground) and extraction of water from the air. The source of the water is usually chosen based on availability and cost. Current water desalination methods include distillation, dew vaporation, reverse osmosis, electrodialysis, and electrosorption.[17,18] However, for small-scale applications these techniques both require accessible brackish water sources and expert labor for operation and maintenance, which narrows the application conditions.[18–20] Instead, atmospheric water harvesting is accessible everywhere and can be easily co-operated with a renewable energy source (e.g., solar energy) for local needs.[21]

been poorly examined. More research is expected to deal with these issues to facilitate the efforts of turning decades of research on atmospheric water harvesting into tangible benefits in our daily life.

Despite the significant value of the potentially extractable fresh water in the world,[22–24] few atmospheric water-harvesting systems are commercially operating currently, leaving distribution of such systems a huge challenge. In general, any viable atmospheric water-harvesting technology must satisfy five primary criteria: It should be efficient, cheap, scalable, wide-band, and stable enough to operate for a whole year or at last a monsoon season. Currently none of the existing commercial atmospheric water generators (AWGs) meets all these five criteria. From the point of view of thermodynamics, this is mainly due to the energy inefficiency of the process.

As a first step for understanding different AWGs, we should comprehend the thermodynamic fundamentals and examine the performance indexes involved in the atmospheric water-harvesting technology (here we take the sorption-based AWG[25] as an example). The workflow of one AWG is usually described as follows: capture the moisture from thin air, then condense the captured moisture into liquid water. The separation process and the condensation process may consume energy, where renewable energy, such as solar or wind energy, is a top priority. Just as with desalination,[19,20] three indexes are usually employed to evaluate the performance of AWG, including the specific water production per day per unit collector area (SWP), the specific energy consumption per unit mass water production (SEC), and the recovery ratio of the feed air (RR). The SWP is usually used for evaluating the water productivity of the passive AWG (without the need of energy input), while SWP and RR are more often used to assess the energy efficiency and the water vapor condensing effectiveness of the active AWGs. For water collection by direct cooling, the value of SEC and RR can be defined as follows:

$$SEC = \frac{Q_{cond}}{m_{H_2O}} \approx C_p \left(\frac{\varepsilon_T}{\varepsilon_d}\right)\left(\frac{T_i - T_{cond}}{d_i - d_{cond}}\right) + h_{fg}, \quad \text{(Equation 1)}$$

$$RR = \varepsilon_d \left(1 - \frac{d_{cond}}{d_i}\right), \quad \text{(Equation 2)}$$

where T_i and d_i are the temperature and humidity ratio of the inlet air of the condenser, respectively. T_{cond} represents the condensation temperature. m_{H_2O} is the water production per unit mass dry air (kg/kg). ε_T and ε_d are the heat-exchange effectiveness and mass exchange effectiveness of the condenser, respectively. The total cooling load of the moist air, Q_{cond}, is the sum of the sensible heat load, associated with the temperature change of the moist air, and the latent heat load, associated with the enthalpy of condensation, h_{fg}. Obviously, a smaller sensible heat

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load may result in a smaller *SEC*, which means a higher relative humidity of the inlet air is expected. A similar index (Moisture Harvesting Index [MHI]) was defined by Gido et al.[24] and a simple relationship between *SEC* and MHI can be obtained: SEC × MHI = h_{fg}. The definitions of SEC and RR indicate that a low T_{cond} and an inlet air state with low T_i and high d_i are optimal.

Here, we first review the historical developments of the atmospheric water-harvesting technologies in brief. We then categorize different kinds of AWGs according to their moisture-capturing methods and comment on their strengths and weaknesses. Based on this, we deduce that the sorption-based AWGs have the greatest potential to be the cost-effective and scalable AWG technology. Thus in the following section, we discuss the progress of the materials, devices, and system structures used in sorption-based AWGs in detail. Lastly, we propose our perspectives on the future trends on how to achieve a scalable sorption-based AWG.

Methods

Natural Harvesting

Nature has adapted different methods for surviving dry, arid, xeric conditions. One of the first known studies of plants absorbing airborne moisture is carried out by Hales in 1727.[26] In 1957, a literature review was carried out by Stone[27] concentrating on dew and the absorption of water in plants. In 2014, a thorough review of the literature was carried out by Malik et al.[26] which updated and extended the work, focusing on direct dew, fog, and moisture harvesting in plants and animals, such as beetles, frogs, lizards, spiders, *Opuntia microdasys*, *Stipagrostis sabulicola*, and *Trianthema hereroensis*.

Early AWGs

The idea of collecting water from fog can be traced back to centuries ago. Several accounts or even legends concern dew "springs" and "ponds,"[3] which essentially come from the artificially harvested dew by using large stones or trees. Therefore, it seems that mankind considered dew as a source of fresh water since time immemorial. Unfortunately, it was not until the 20th century that such condensers that only appear in old-time accounts or tales came true. Historically it is argued in science that the Early Greeks who founded Theodosia as early as the 6th century BC used dew condensers to fulfill their water demands. This opinion first comes from a Russian forester, F.I. Zibold, who built an experimental stone condenser in the shape of a bowl during 1905 and 1912,[4,21] following what he considered to be an Early Greek condenser. However, some researchers challenged Zibold's experimental results and few positive responses were given. Therefore, until nowadays the Early Greek dew condenser still remains a tale rather than a scientific story.[3,28]

During the first half of the 20th century, Zibold's attempt inspired extensive experiments with this type of water condenser in the South of France by L. Chaptal, M. Goddard, and A. Knapen.[3] These installations called "aerial wells" or (vapor) "captors" were analogous to the Crimean prototypes. Some of the constructions successfully produced condensed water, but the amount was less than expected. These massive aerial condensers are designed to take advantage of the temperature variation during day and night. At night, the stone heap is cooled down by the chilled air. During daytime, the warm air that comes from the ocean and thus is more or less saturated with water vapor reaches this chilled surface and is consequently condensed. However, due to the low thermal conductivity, the effective working layer of the stone is believed to be very thin. Furthermore, the low heat capacity of this thin active layer crucially limits the water condensation amount.

After the rosy hopes for massive aerial condensers failed, the publication by Monteith[29] in 1957 can be considered as a marker in dew research, shifting the focus from observation and dew measurement attempts to understanding the energy and heat balance mechanisms of dew formation and dew evaporation. Since then, research on modern atmospheric water-harvesting technologies has continued,[30] and a number of atmospheric water-collection methods,[4,5,31] which were mainly applied in arid and semi-arid areas, have been studied.

Modern AWGs

According to the forms of airborne water, the atmospheric water-harvesting technologies can be divided into three different categories: artificial rain collection,[32–34] fog water collection,[6,31] and dew water collection.[35] Weather modification (also known as cloud seeding or "artificial rain") may produce substantial precipitation but only in the troposphere where water-abundant clouds gather. No evidence shows that the same process can be achieved at ground level in a routine, controllable fashion.[32,33] Fog collection, unlike weather modification, is a proven technology for a substantial supply of potable water in certain arid regions.[6,31] Dew collection can be achieved by passing the humid ambient air over a cooled surface, and condensed liquid water is obtained if the surface temperature is lower than the dewpoint temperature of air.[5]

Fog Water Collection. Fog harvest is feasible and technologically accessible to slake the lack of fresh water, typically in arid coastal areas. The usual method to collect fog water is placing a rectangular mesh perpendicular to the wind, which traps fog droplets. When exposed to a foggy environment, water droplets carried by the wind are pushed against the mesh and become trapped. After successive impacts, the droplets grow by coalescence until they are large enough to fall by gravity, and a gutter transports the water to a tank. In 1956, the Catholic University of the North in Antofagasta in northern Chile conducted the first conclusive experiments with nets.[36] Since 1987, several experiments following such ideas but on larger scales were conducted by Schemenauer and colleagues[31] in many arid parts of the world, for instance, the coastal deserts of West Africa (Namibia), South America (Chile and Peru), and the Middle East (Saudi Arabia and Oman, monsoon season). The successful results inspired similar fog-collection projects nowadays that have been initiated and implemented in many parts of the world.[37] Typical conditions are liquid water content around 0.1–0.5 g/m^3, 40% fog immersion time, and 50% collection efficiency with 3 m/s wind speed.[38] Most of the advanced systems using high-elevation fog have the water production ability of 3–7 $kg/day/m^2$,[31,38] and the literature review results are listed in Table S1. In most of the above projects, the fog collectors were not assembled close to the residents. The installation of a pipeline was needed to deliver the water to the users in the mountains. The pipe costs from collectors to users were one of the major infrastructure costs that made the system uneconomic and hydraulically difficult. Therefore, Abdul-Wahab et al.[39] examined the potential of residential-type fog collectors built in the vicinity of the houses. As Schemenauer and Cereceda[40] stated, a viable and efficient fog-extraction project should meet the following criteria: (1) fog must occur frequently throughout the year and should persist for a relatively long time; (2) high-elevation fogs, with relatively high liquid water content, are of primary interest for fog water-collection projects in arid lands; (3) fog collection must be accompanied by wind to achieve a higher efficiency.

Today, the biggest challenge for fog collection is the low efficiency that is defined as the ratio between the water reaching the collector's gutter and the liquid water

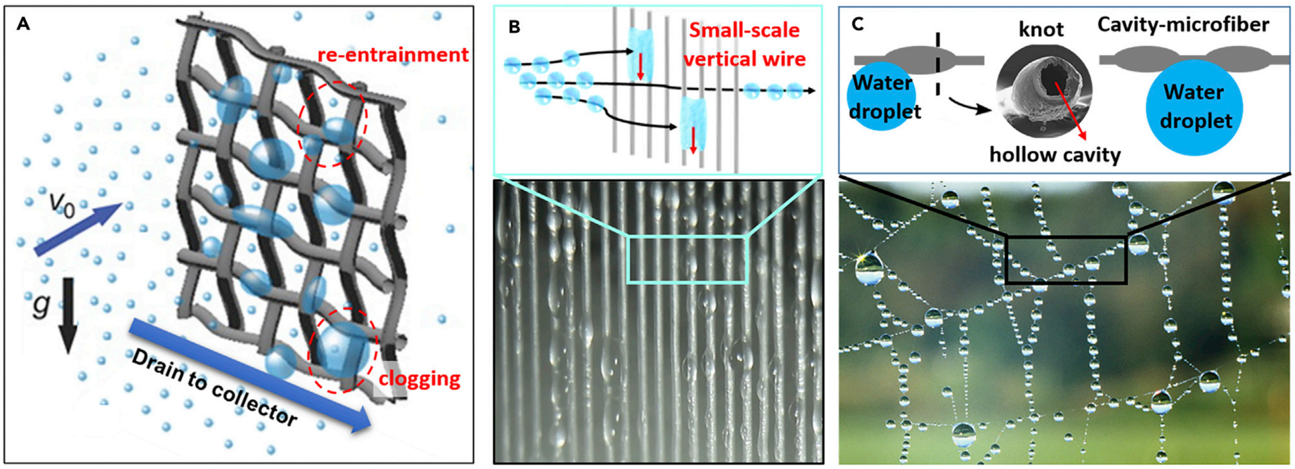

Figure 1. Fog Collectors

(A) Traditional fine meshes, having problems of re-entrainment and clogging. As the small deposited water droplets coalesce, the growing droplets are influenced by the competition between aerodynamic drag forces and surface adhesion forces. When the drag force overwhelms the adhesion force, the droplets are re-entrained in the fog flow. In the clogging region, the hysteretic wetting force pinning a droplet in the interstices of the mesh exceeds the gravitational draining force when the deposited water droplet size is less than a critical volume. Reproduced from Park et al.[41] with permission.

(B) Fog harps, utilizing ultrafine-scale and untreated metal wires to both capture and drain fog efficiently and durably. The vertical wires running parallel to the drainage pathway serve to reduce the pinning force of captured droplets, which enables the efficient drainage of small water droplets even for micrometric wire sizes. Reproduced from Shi et al.[42] with permission.

(C) Spider-web-like cavity-microfiber topological networks, where the cavity-microfiber is fabricated via the one-step microfluidic method. If a water droplet is located on a knot near the intersection, it moves directionally toward the intersection and coalesce with the droplet at the intersection. Reproduced from Tian et al.[43] with permission.

flux normal to the collector's mesh.[38] Collection efficiency is adversely affected by two issues that depend on the surface wettability: re-entrainment of deposited droplets and clogging of the mesh with pinned droplets (Figure 1A). The wire meshes currently utilized for fog harvesting suffer from dual constraints: coarse meshes cannot efficiently capture microscopic fog droplets, whereas fine meshes suffer from clogging issues. While superhydrophobic surface treatments can prevent clogging, they are often not durable enough for long-term use. Shi et al.[42] have presented an approach to avoid these problems (Figure 1B); they used small-scale, vertically arranged wires ("fog harps") to replace the traditional cross-like mesh. Another study demonstrated the high efficiency of spider-web-like meshes (Figure 1C) assembled by low-cost cavity-microfibers in directional water transportation.[43] Frankly, these methods show great potential for collection efficiency improvement, but these studies were only conducted under controlled laboratory conditions and still need more field tests to verify their true performance.

Dew Water Collection. Among alternative approaches, dew water collection[5,44–47] has been widely recognized as the ideal candidate because it is minimally affected by climatic and geographical constraints compared with fog water collection. It is also more cost-effective than the cloud seeding in less cloudy areas. Initially research mainly focused on passive radiative condensers,[4,5,48,49] which do not need extra energy input. Such condensers normally work during the night since the solar radiation in the daytime usually results in a higher surface temperature than the ambient temperature. Researchers in Sweden and France[3,4] developed a correct theoretical basis to build efficient radiative condensers. The International Organization for Dew Utilization has standardized the characterizations of dew collection in terms of methodology, instrumentation, and data obtained from field experimental tests. This organization recommends the use of a standard material made of a special white low-density polyethylene (PE) foil. This material provides hydrophilic properties that lower the nucleation barrier at the onset of the condensation process together with a high emissivity in the near infrared (wavelength range of 7–14 μm). These two features are important in favoring dew formation. According to the radiative cooling ability available for condensation, the upper limit of dew yield is 0.8 kg/day/m^2.[5] However, the maximum recorded yields of dew water in arid and semi-arid climates typically fall within a range of 0.3–0.6 kg/day/m^2 of surface area[5] (for the literature review results see Table S2). In general, the process is limited by the rate of radiative heat exchange, the weather conditions, and the surface properties. In particular, weather conditions dictate the ratio of latent to sensible heat exchange between the surface and the air.

With the advance of chillers, active condensers[24,44,45] were designed as an alternative method for dew collection that produces more water by using additional energy inputs. Early active dew condensers were developed in the 1930s, but rapid and wide innovations did not occur until the commercialization of mechanical refrigeration after the 1980s. Active condensers are now considered as an innovative option for locally managed water supply systems in areas with water quality and/or quantity problems. Active condensers work in a manner similar to that of a dehumidifier, which extracts water from the air. It is reported that the unsatisfied high energy consumption was due to the inefficient heat-exchange process and the low amount of water obtained by small units.[50] Several designs of active condensers have been patented, of which the yields can reach 20 L/day by portable devices and up to 200,000 L/day by larger agricultural water devices.[5,51] The energy consumption mainly depends on the system design. To date, most of the commercially available AWGs are using conventional air-conditioning technology to generate water, and the tested efficiency rates are within 650–850 Wh (electricity)/kg and among which the best efficiency is ca. 250 Wh (electricity)/kg.[52] The literature review results are listed in Table S3. Note that lowering the temperature of the moist air can be achieved by a much simpler solution that directly expands the air in an expander. Following this idea, the feasibility of the expander-based AWG has been explored in theory by Subiantoro[53] and Shelton and Christiansen.[54] Despite its advantages of compactness and simplicity, few experimental prototypes have been reported.

To reduce the fossil fuel energy cost, researchers began to use solar energy to drive the AWGs.[55,56] Two methods have been reported and concluded by various investigators: one is the sorption-regeneration-condensation method,[57] and the other is dew water harvesting by a solar-powered sorption chiller.[58]

The sorption-regeneration-condensation method is an old wisdom that uses desiccants to capture the moisture from the air in the shade and then desorb the water out of the desiccant under the sun. The generated water vapor will be liquefied and removed while the reactivated desiccant will be cooled down in the shade again for further water-capture cycles. The liquid desiccant was preferred because of its system continuity. However, an additional large cooling surface is necessary to cool the reactivated solution. So a modified version[25,59] is proposed and applied to simplify the system. The desiccant materials extract moisture from the humid air during nighttime and the regeneration process occurs during daytime utilizing solar heat. In this case, the desiccant in the sorption phase can be cooled by the feed air itself during the night. There are three kinds of basic configurations of the sorption-regeneration-condensation systems, as shown in Figure 2. Figures 2A and 2B show a kind of glass-covered greenhouse (also called solar still).[60–65] At night, the window or

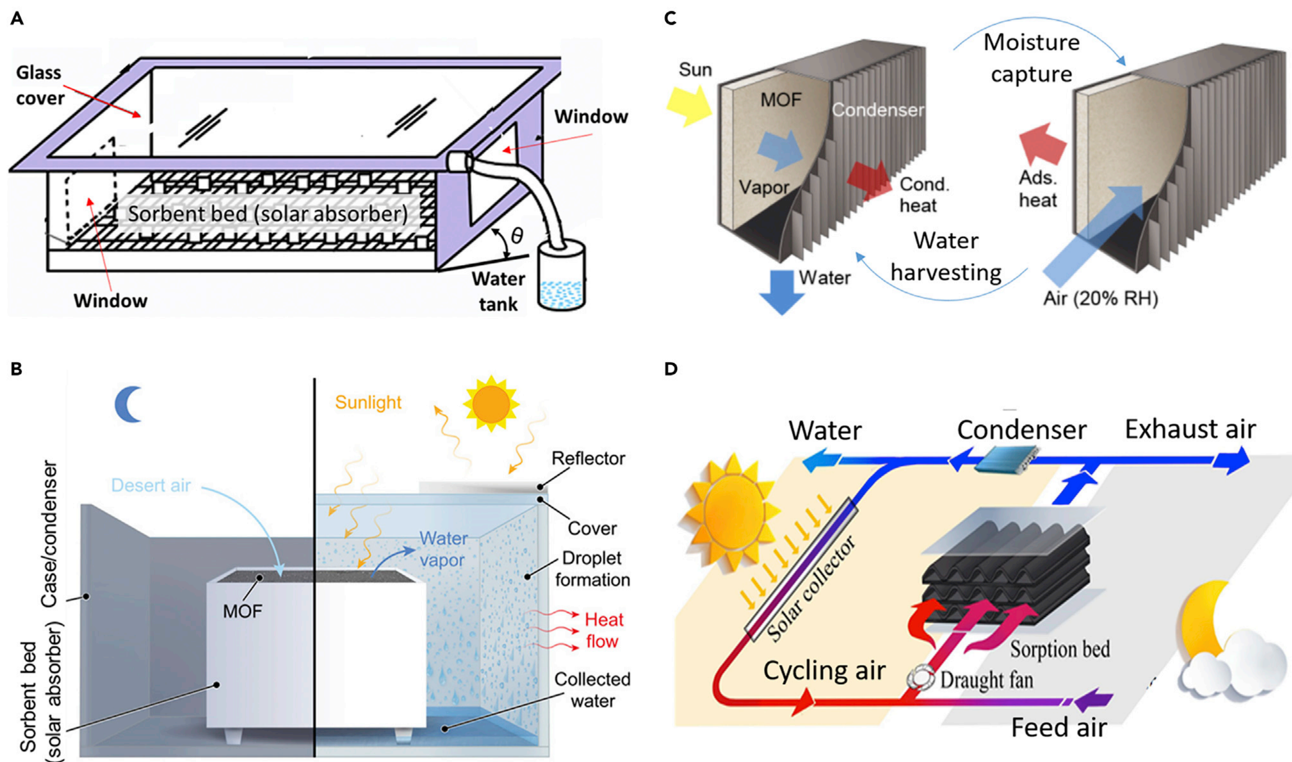

Figure 2. Sorption-Based AWGs

(A and B) Glass-covered greenhouse sorber. Reproduced from Kumar et al.[63] and Fathieh et al.[64] with permission.

(C) Sandwich plate sorber. Reproduced from Kim et al.[67] with permission.

(D) Packed columns sorber. Reproduced from Wang et al.[70] with permission.

Their SWPs depend on the temperature difference between the desiccant and the condenser surface, thus the optimal designs need to maximize the solar radiation heat received by the desiccant and keep the condenser surface cool enough. In general, (A) has a smallest average temperature difference during daytime due to the high-temperature glass surface; (D) has the largest average temperature difference owing to water cooling. The aims of (B) and (C) are to improve the desiccant temperature and to reduce the condensing temperature, respectively.

the glass cover is opened and the desiccants capture the moisture in the feed air by natural or forced convection. During daytime, the sorber absorbs the incident solar radiation and thus the desiccant temperature increases. At this time, the released water vapor is condensed underneath the glass cover (Figure 2A) or in an additional condenser only powered by ambient cooling (Figure 2B). Figure 2C is a sandwich plate,[66,67] which integrates the solar absorber and desiccant layer on two sides of a metal plate, while another plate on the opposite side acts as the condenser. Figure 2D shows a packed columns sorber and a separated condenser.[68,69] The previous three (Figures 2A–2C) are passive AWGs, which have been studied extensively due to their simple construction. The water productivity is in the range of 1.0–2.5 kg/day/m^2 of collector area, and the literature review results are listed in Tables S4 and S5. The last AWG (Figure 2D) is an active sorber, more compact but inevitably with more complex structure. This configuration needs an independent solar heat collector and an additional condenser. The reported lowest SEC is ca. 2.0 kWh (heat)/kg.[70]

Dew water harvesting by sorption chillers can work continuously in daylight and at night if integrated with heat storage. This technology is one kind of dew water collector driven by direct cooling. Some researchers[58] claimed that this method was too complicated and expensive to be applied in water production. However, the related research is insufficient because only the simplest adsorption chillers were applied in experiments.

Solar photovoltaic (PV)-powered thermoelectric condensers[47,71–74] are usually chosen among portable AWGs to meet the needs of low water production in some special applications due to their small volume and low cost. For instance, Muñoz-García et al.[47] built a mini AWG based on the thermoelectric effect to provide the minimum amount of soil moisture needed by young trees for successful rooting when they are transplanted from the nursery into open fields, especially in dry-climate areas. Joshi et al.[75] developed and experimentally investigated a thermoelectric fresh water generator for individual person usage.

An interesting application concerns the HVAC (heating, ventilation, and air-conditioning) systems. Cooling the air below its dew point (mostly in summer times) is a dehumidification process, which produces a lot of condensed water that usually is thrown away. Such condensed water from air-conditioner cooling coils usually ends up in municipal sewerage systems and wasted. Therefore, an integration of an air-conditioning system and a water-harvesting system could be a potential solution to achieve optimized energy consumption and sustainable use of resources. In this perspective, the water production can be considered almost as a free benefit, or in other words is obtained as the "by-product" of a smart HVAC system design. Obviously, two fundamental conditions need to be fulfilled in order to obtain good performance by applying such integrated system: firstly, a real indoor air-conditioning process rather than on-purpose water harvest is necessary; secondly, compatible external hygrometric conditions are required. Recently, an excellent literature review conducted by Salem et al.[76] has summed up the HVAC condensate recovery technologies and their applications.

In brief, the technologies of AWGs summarized in Table 1 can be divided into three main categories: direct harvesting by condensation, vapor concentration by membrane or desiccant, and by-product collection from an integrated system, as shown in Figure 3. Meanwhile, according to the dependence on external energy input, both the vapor concentration process and the water vapor condensation can be categorized as the passive one without extra energy input and the active one powered by an external energy source. Selection of methods is an engineering decision depending on both local climatic conditions and economic factors such as capital, operation, and energy costs.

In the last 20 years, several modifications and improvements have been proposed in the literature to improve the performance (e.g., water productivity or efficiency) of the water-harvesting system, regarding different weather conditions, materials, or collector design. However, until now the traditional AWGs have been restricted only to small-scale portable water production and emergency water supply after a disaster. It is still far away from people's expectation of scalable water production in an energy-efficient way. The fog water collection is efficient but limited to specific locations;[37] the passive radiative collector has a low SWP due to the low radiative cooling capacity;[5] the passive sorption-based AWG also has a low SWP due to its low RR;[77] and the chiller-based dehumidifier has an unexpected SEC associated with the low COP of the chillers.[23,24] In this case, the solar-powered sorption-based AWGs with active condenser reveal a great potential for compact systems, efficient operation, and wide adaptability. However, for reduction of the SEC according to Equation 1, several remaining hurdles must be surmounted prior to the practical application of sorption-based AWGs with active condenser for scalable atmospheric

Table 1. A Brief Summary of the Methods, Problems, and Perspectives of AWGs

Methods	Features	Capacity	Problems	Alternatives	Challenges	Applications
Cloud seeding	hygroscopic seeding	NA	considerable skepticism	sky river proposed by Wang	hard to predict cloud migration	weather modification
Fog seeding	hygroscopic salt particles	NA	hard to predict fog occurrence	dew collection by using PCM	PCM: sorption solidification	microclimate management
Fog mesh	easy to construct	1.5–12 kg/day/m^2	limited to locations	nano-engineering mesh surface	low collection efficiency	mount by the sea
Massive dew collector	passive way	very little output	thin valid layer	PCM dew collector	lack of high e^* materials	water-saving agriculture
Radiative dew collector	passive way	0.3–0.6 kg/day/m^2	large heat loss	high-performance emitter	metamaterials	low-T water production
Electric chiller Sorption chiller	high output compact	0.25 Wh/g (electricity)	great latent load	DEHP	durability and reliability	portable water production
Sorption-based AWG (solar distiller)	ambient cooling	1.0–2.5 kg/day/m^2	high T_{cond}	water-cooling condenser	Heat transfer enhancement	scalable water supply
Sorption-based AWG (solar air heating)	active condenser	2.0 kWh/kg (heat)	large heat loss	solar water-heating sorber	pump	scalable water supply
Sorption-based AWG (sandwich plate)	air cooling	1.2 kg/day/m^2	thickness of desiccant layer	high k desiccant	desiccant	electronic cooling
TEC dew collector (solar PV driven)	small &compact	COP < 0.1	low energy efficiency	desiccant-enhanced heat sink	proper application	meet minimum water load
Integrated system	by-product	depends on the latent load	cooling dependence	NA	NA	offsetting water use of A/C

AWG, atmospheric water generator; COP, coefficient of performance; DEHP, desiccant-enhanced heat pump; DRH, deliquescence relative humidity; MHI, Moisture Harvesting Index; RH, relative humidity; RR, recovery ratio of the feed air; SEC, specific energy consumption; SWP, specific water productivity; PCM, phase change material.

water production: (1) the lack of cost-effective heat sinks to maximize the SWP; (2) the energy-inefficient ways applied to desorb the desiccants; (3) the unreasonable design that fails to reduce heat loss or to achieve heat recovery before and after the condensing process; and (4) the ignorance of the kinetics in terms of material selection and sorber design. For sorption-based AWGs, besides the challenges for thermodynamic performance mentioned above, some current highly utilized desiccants, such as MOF-801,[78] are still unstable and unhealthy, which may result in severe safety issues. In addition, the methodologies on how to evaluate the feasibility and energy requirement of atmospheric water harvesting are also very important factors for location-specific and climate-specific design, but these still do not attract sufficient attention from researchers.

Progress

Progress in Lowering the Condensing Temperature

About 50% of the energy consumed in harvesting portable water by cooling down humid ambient air is wasted by producing unexpected cold air rather than water.[24] Hence, lowering the condensing temperature can improve the RR and eventually reduce the SEC. This can be achieved in two aspects: a cost-effective heat sink and a high effective condenser.

Cost-Effective Heat Sinks. Obviously, the cold dark Universe is an ideal low-temperature heat source. Radiative cooling technology utilizes the atmospheric transparency window (wavelength range of 8–13 μm) to passively dissipate heat from Earth into outer space (3 K).[79,80] The technology utilized in radiative dew water collector is relatively simple as it relies on exploiting the physical processes of dew

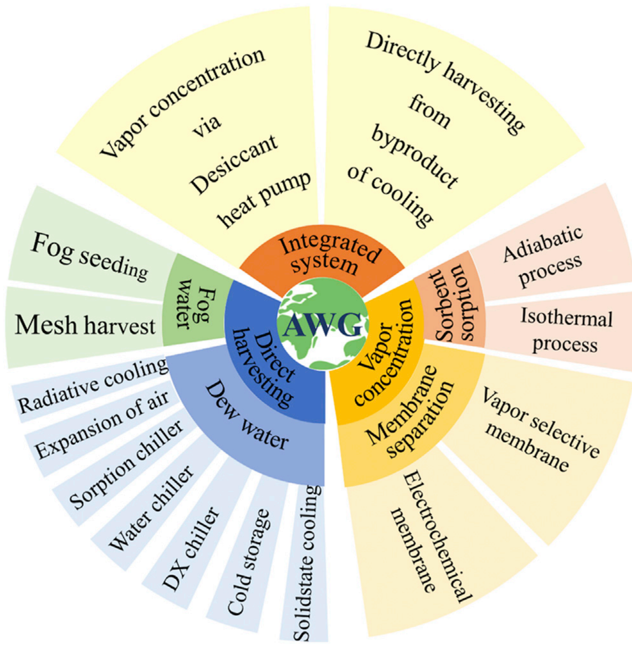

Figure 3. Technical Classification of AWGs

formation, without additional energy input. A well-performing radiative collector requires not only high radiative cooling power but also a slippery surface that allows the quick removal of condensate.[5] However, the radiative cooling power of passive dew collectors is a function of surface pattern (higher emissivity in infrared spectrum, small thermal mass, high wetting properties, and good thermal insulation) and the weather conditions (ambient temperature, relative humidity, wind speed, and cloud cover), which affect the yield in a relatively complex way. A traditional radiative cooler is designed for surface cooling at night whiling preventing warming up of the condenser during the daytime. For cooling at night, the demonstrated temperature reduction from ambient air is in the range of 15°C–20°C[15] in typical populous areas.

The influence of solar absorption during the day that causes radiative cooling spread to a subambient surface seemed an insurmountable barrier until 2014.[48,80] A thin polyethylene cover used to suppress convective exchange is transparent to infrared radiation. Below this cover, a stack of two thin oxides is deposited over a 200-nm-thick of silver layer on the silicon substrate, as shown in Figure 4A. The polymer acts as an all-dielectric mirror and its performance of reflecting blue wavelengths is even better than metal, leading to a very high solar reflectance. As a result, only 30 W/m^2 out of 1,000 W/m^2 incident solar energy is absorbed. The maximum temperature reduction in the absence of a convective barrier is 3°C at midday and 7°C at night in summer. About 2 years later,[81] another kind of radiative cooling device was reported as shown in Figures 4B–4D, which demonstrated a temperature reduction record. In a 24-hr day-night cycle in winter, the cooler is maintained at a temperature that is at least 33°C below ambient air temperature of 5°C–15°C, and a maximal temperature reduction of 42°C is observed. This maximum value occurs when the apparatus enclosing the cooler is exposed to the peak solar irradiance. In recent years,[49] with the emergence of new classes of selective infrared emitters, the radiative cooler can provide a cooling power that exceeds 100 W/m^2 at reasonable temperatures.

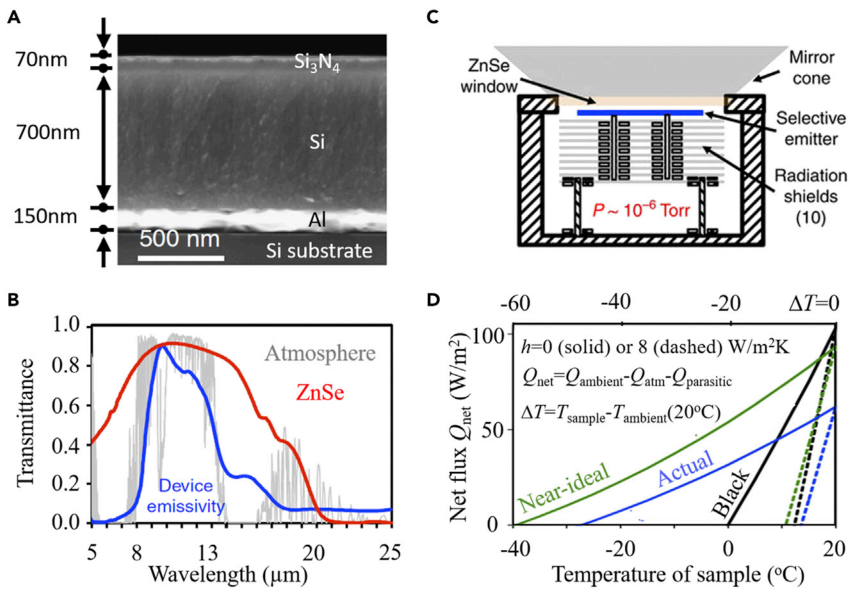

Figure 4. Radiative Coolers

(A) The first selective IR emitters that can achieve daytime radiative cooling. Reproduced from Raman et al.[48] with permission.

(B) The transmittance of the ZnSe emitter used in (C).

(C) The structure of the irradiative cooler achieving the record largest temperature reduction.

(D) The cooling performance of the cooler in (C).

(B)–(D) are reproduced from Chen et al.[81] with permission.

Of course, the Earth is also a good heat sink in summer considering the moderate temperatures deep in the ground to boost condensing efficiency. Depending on latitude, the temperature 6 m beneath the Earth's surface maintains a nearly constant value between 10°C and 16°C. Ground-coupled heat exchangers[82] have been widely used to warm or cool air or water and applied for residential, agricultural, or industrial uses. However, few researchers have investigated the ground heat exchanger to condense the water vapor for AWGs.

Besides radiative cooling, a noteworthy technique is cold storage at night and heat absorption during the daytime. The obvious variation of temperature between day and night in arid regions is very common,[25] thus a cold storage tank that can be charged during the night can work as a low-temperature heat source in the daytime. With the rapid development of heat storage, quantities of novel materials with ultrahigh thermal diffusivity have been produced,[83–85] which show a bright future for atmospheric water harvesting by using resonant ambient heat.

Condensation Enhancement. Dew formation on the condenser is influenced by the properties (e.g., surface roughness and chemical heterogeneities) of the material used as the surface cover. Properties such as initial nucleation of droplets, coalescence, and fast removal are expected.[86] Obviously, a traditional hydrophilic or hydrophobic surface cannot satisfy these requirements at the same time. For the hydrophilic surface, a lower energy barrier may assist the initial nucleation of droplets, making easier the coalescence of the droplet. However, large pinned droplets with further droplet growth and coalescence will form an insulating liquid film that may isolate the bulk air and the surface, alleviating or even stopping the condensation process. Instead, dropwise condensation on a hydrophobic surface allows the condensed droplets to roll off by gravity on a length scale comparable with the capillary length of water. The surfaces may then refresh for renucleation and growth of next-generation droplets, resulting in 5- to 7-fold higher heat transfer performance. However, a large number of micro-defects inevitably exist on the current hydrophobic surface, resulting in the formation of large pinned droplets that may eventually impede the condensation. In the hope of solving this problem, a very tempting solution obtaining spontaneous droplet jumping on nanostructured surfaces has been attracting increasing attention. For example, Zhai et al.[49] presented an approach to eliminate the micro-defects by using three-dimensional (3D) copper nanowire networks and successfully demonstrated stable and efficient jumping droplet condensation on a superhydrophobic surface. Similar studies bioinspired from natural plants or animals offer several new routes. Two typical approaches are: (1) 1D hydrophilic slippery rough surface to accelerate the droplet removal by gravity before flooding occurrence;[35] and (2) 2D hybrid surfaces with mixed wettability to delay uncontrolled flooding.[87]

For acceleration of droplet removal, a novel concept[87] of integrating the growth and transport of water droplets is derived from a combination of the strategies used by three distinct biological examples—Namib desert beetles, cacti, and Nepenthes pitcher plants—as summarized in Figures S1A–S1C. First, synthetic bumpy surfaces inspired by beetles are designed to optimize fast and localized droplet growth by focusing vapor diffusion flux at the apexes. The formed droplets then rapidly roll off the asymmetric slope in a direction-guided structure, which is similar to cactus spines, to guide capillary-driven transport of harvested water drops. Lastly, the molecularly smooth lubricant is coated on the bumps to dramatically diminish the friction. Experimental results confirmed that bumps that were rationally designed by integrating these mechanisms are able to grow and transport large droplets even against gravity and overcome the effect of an unfavorable temperature gradient.

Another interesting bioinspired design[35] is a hydrophilic directional slippery rough surface that is favorable for both droplet nucleation and removal, as shown in Figures S1D–S1F. The slippery rough surfaces combine the unique surface functions of pitcher plants (slippery interface) and rice leaves (micro-grooves parallel to the sliding direction of the droplet and the nanotextured surface on microscale bumps), which can repel liquids regardless of the wetness of surfaces. Molecular dynamics simulations showed that the physical origin of this efficient droplet nucleation was attributed to the hydrophilic surface functional groups, whereas the rapid droplet removal was due to the significantly reduced droplet pinning of the directional surface structures and slippery interface. Experimental results further demonstrated that the slippery rough surfaces, owing to their larger surface area, more hydrophilic slippery interface, and better directional liquid repellency, outperform conventional liquid-repellent surfaces in water-harvesting applications.

The strategy of enhancing the condensation process by accelerating droplet removal has wide applications in almost all atmospheric water-harvesting technologies. However, considering that the condensation heat eventually needs to be released through the surface layer into the cooling media, the thickness and the thermal conductivity of the surface material are also of great significance. Nevertheless, this information is still mostly missing in current research. Besides, the effects related to the accumulation of dust or other small solid particles on the duration and stability of these nanotextured surfaces have not been carefully investigated. Therefore, investigations on scalable nanostructured surfaces made from metals or plastics are still eagerly awaited to improve condensation heat transfer in realistic industrial applications. Despite the incompleteness, this research is still valuable because a bright future lies before us.

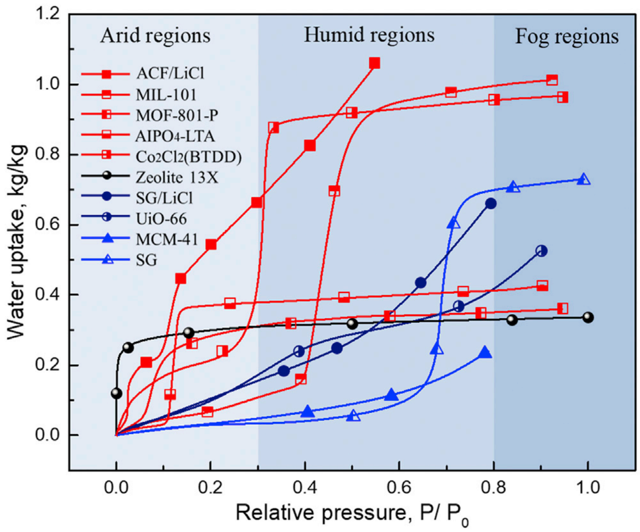

Figure 5. Promising Desiccants for Sorption-Based AWGs

The moisture capture performance mainly depends on the ambient relative humidity (RH). The region where the AWGs may be competitive can be divided into three categories according to the ambient RH. In general, the RH in arid regions is usually less than 30%. When the ambient RH is larger than 80%, the fog occurs relatively easily, particularly on a sunny morning. In the humid regions, the RH is in the range of 30%–80%, but the precipitation is rare.

Progress in Vapor Concentration

Since AWG by direct cooling wastes a large portion of the energy on cooling the air, vapor separation methods, only cooling the water vapor, may provide a technological alternative to reduce the operational costs of AWGs. A way to reduce this sensible heat load is to concentrate the water vapor.[88] Vapor concentration can be achieved by using desiccants that adsorb the vapor from the air, which can later be recovered in a thermal-driven step.[77]

Desiccant materials can be either solid or liquid. Traditionally, it is believed that solid desiccant systems can produce potable water but require large volumes of desiccant. Significant operating costs are also expected for the blowers to circulate both the fresh air for adsorption and the hot air for desorption. Furthermore, the efficiency of the desiccant bed will suffer a long-term reduction due to dust or other impurities deposited into the pores. Although this problem can be solved by adding air filters, this will lead to additional air pressure drop throughout the system. These drawbacks make the solid desiccant system less attractive. However, novel desiccants, such as nanoporous inorganic materials,[89] metal-organic frameworks (MOFs),[90–92] and composite materials[93,94] presented in Figure 5, show a much greater potential for water-harvesting systems than before. Composite desiccant materials are most frequently utilized in sorption systems, which are formed by impregnating hygroscopic salts into the porous desiccants. Since the hygroscopic salts play a major role in water absorption, water uptake of composite desiccants, such as ACF/LiCl[94] (Figure 5) and SG/LiCl[95] (Figure 5), increase with the partial pressure of water vapor.[94,96] For polymeric materials, such as $AlPO_4$-LTA[97] (Figure 6A), Co_2Cl_2(BTDD)[90] (Figure 6B), MIL-101,[98,99] MOF-801[66,67] (Figure 6C), MOF-303[64,100](Figure 6C), PIZOF-2,[91] nanoporous material zeolites 13X,[94] and mesoporous molecular sieves MCM-41,[94] their water absorption performance can be stepped within a very narrow relative humidity (RH) range due to their high degree of consistency of microstructures. Other

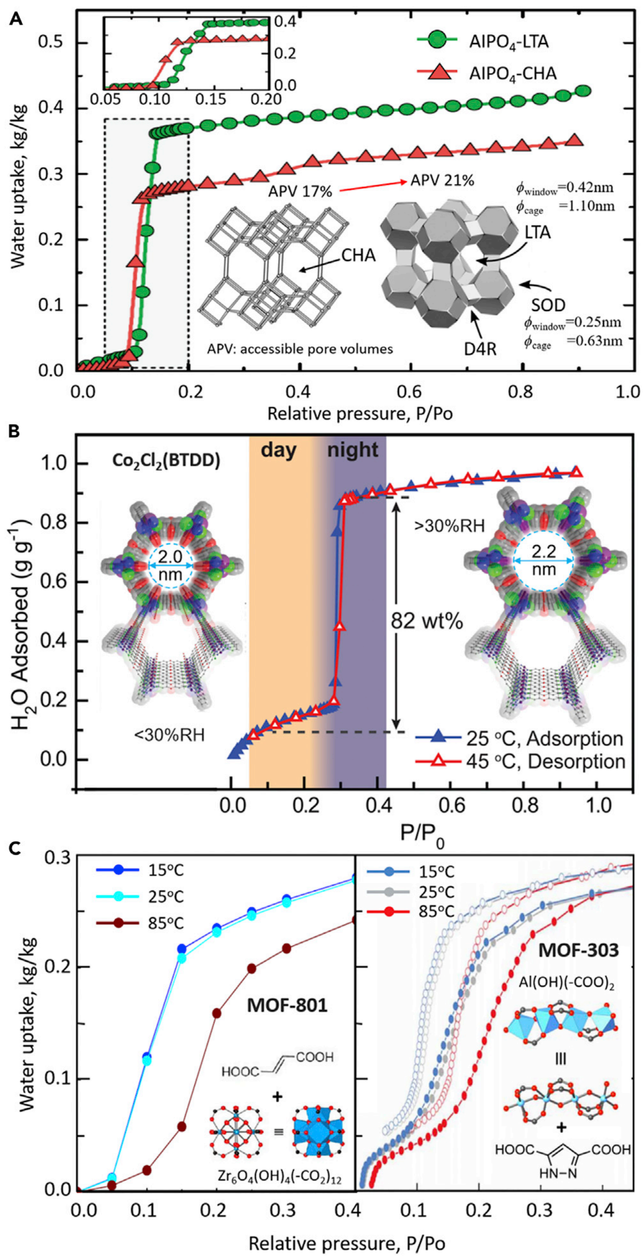

Figure 6. Strategies for Designing Superior Sorbents

(A) AlPO4-LTA. Microporous $AlPO_4$-34 is a very promising zeolite-like desiccant with highly hydrothermal stability, large sorption capacity, and narrow RH interval. According to the database of zeolite structure types, the accessible pore volumes for the LTA cages are expected to be somewhat larger than that of $AlPO_4$-34 with CHA topology. This inspires an idea that a microporous $AlPO_4$-n analogous to LTA-type Zeolite might have the even higher capacity and equally sudden water uptake as $AlPO_4$-34. This suggests that perhaps an even more capable material than $AlPO_4$-LTA can be found among the microporous $AlPO_4$-n with even larger pores. Reproduced from Andraz et al.[89] with permission.

(B) Co_2Cl_2(BTDD). Co_2Cl_2(BTDD) illustrates a general strategy for designing superior sorbents. Through open adsorbing metal sites binding water prior to pore filling, the pore diameter can be effectively reduced to the critical diameter. Reproduced from Rieth et al.[90] with permission.

(C) MOF-303 and MOF-801. MOF-303 has the same water-uptake capacity as MOF-801, but uses low-cost aluminum instead of toxic and expensive zirconium as the metal and uses water instead of

Figure 6. *Continued*
organic solvents (DMF) to wash the initial precipitates. It provides a novel approach to make MOFs with enhanced water sorption properties potentially meeting the specification of industrial large-scale production. Reproduced from Fathieh et al.[64] with permission.

candidates such as SG[94] and UiO-66[91] have increased water-uptake performances with a higher RH.

Through comparing the isotherms (at 25°C) (Figure 5) of some very promising desiccants reported recently, it is easy to see that excluding the zeolites 13X,[94] the ACF/LiCl composites[94] have the highest water uptake in the arid regions (RH < 30%) under the same RH. In other words, the ACF/LiCl composite[94] can take place of those expensive polymeric materials (labeled in red lines in Figure 5), including $AlPO_4$-LTA,[97] Co_2Cl_2BTDD,[90] MIL-101,[98,99] and MOF-801,[66,67] particularly considering that these materials usually have a relative small hysteresis. The same trend for silica gel/LiCl composite is witnessed in the humid regions, whose water-uptake capacity is much better than the UiO-66, MCM-41 and silica gel. However, a risk for these two composites should be noted: the leakage of the salt solution perhaps occurs because of overloading when the RH is larger than their deliquescence relative humidity (DRH).[101] This is why the scientists and engineers are still exploring other high-performance physical sorbents.

For screening of the optimal physical sorbents, the material properties of stability, hydrophilicity, and pore diameter are of critical importance. MOFs offer the flexibility required to optimize all these parameters at once.[90] To facilitate the application of the desiccants in AWGs, the pore hydrophilicity will usually be sufficient enough to allow the water nucleation and the pore-filling below an approximately 30% RH condition. Meanwhile, to avoid undesirable hysteresis upon water desorption, the pore size must be smaller than the critical diameter $Dc = 4\sigma T_C/(T_C - T)$[102] of the adsorbates. This implies that an adsorbent with a pore diameter of approximately Dc will maximize the internal volume available for filling with water while avoiding irreversible capillary condensation. The corresponding material design strategies are shown in Figure 6. Otherwise, it is noteworthy that the material densities are of great importance when comparing the different materials' adsorption capacity, because the adsorption capacity per unit volume is more important in practical application.

Of course, the vapor concentration can also be achieved by using polymeric electrolyte membranes (Figures 7A and 7B) or water vapor selective membranes (Figures 7C–7E) that allow the separation of water vapor from other molecules in air prior to the cooling process. Theoretically, the use of water vapor selective membranes can reduce the energy requirement for extracting water out of the humid air by more than 50%,[88,103] but until now related experimental investigation has not yet been conducted. Instead, current experimental results show that only 30% of the total power input was effectively used by the polymeric electrolyte membrane to pump humidity,[104] while the rest was wasted, leading to a relatively low COP. Thus, with regard to the limitation of the technology itself, the membrane separation is less competitive for vapor concentration in the foreseeable future.

Progress in Heat Recovery

In fact, one of the factors that lead to the high energy requirement of the water vapor condensers is the large temperature difference of heat transfer. A large portion of the cooling capacity of the cold fluid is wasted on producing cold air. Recently,

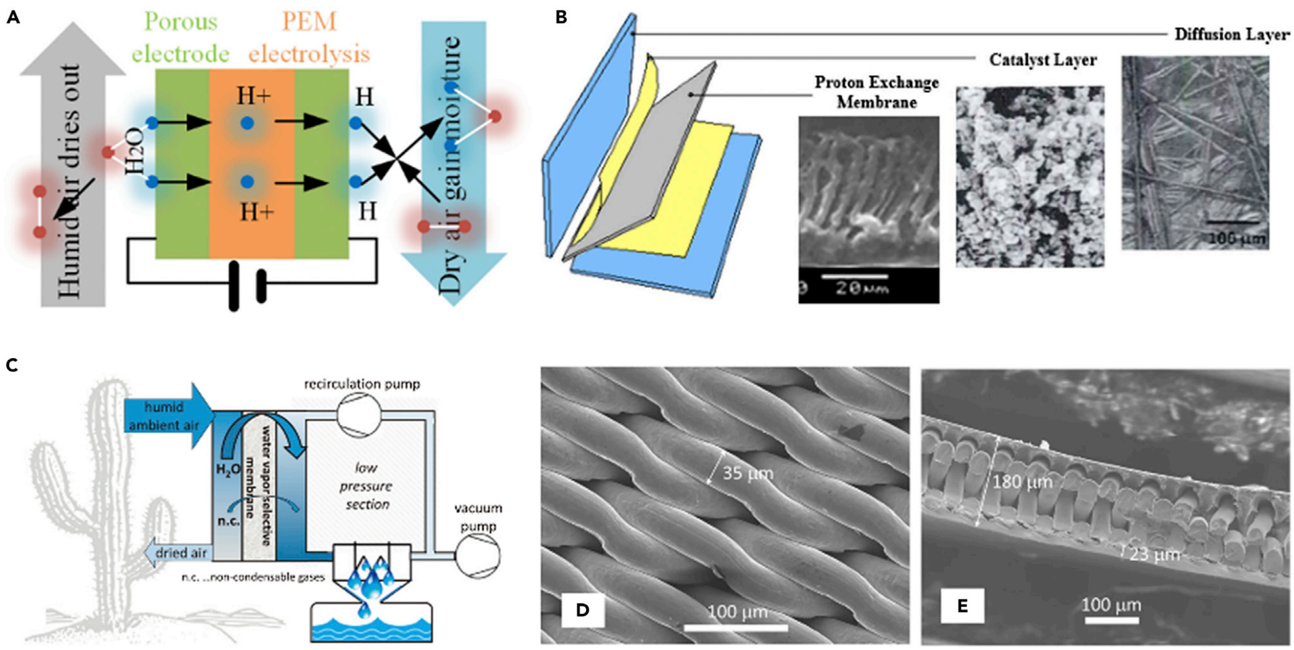

Figure 7. Membrane Facilitated AWGs

(A and B) Principle (A) and structure (B) of the polymeric electrolyte membrane. Reproduced from Qi et al.[104] with permission.

(C–E) System illustration (C) of the AWG based on water vapor selective membrane, with microstructure photos (D and E). Reproduced from Bergmair et al.[88] with permission.

two kinds of precooling design with heat recovery have been patented. The first one[105] achieves precooling of the inlet moist air of the evaporator by recovering the cooling capacity of the exhaust air of the same evaporator. The second one[106] designs a novel refrigerant path to obtain a large subcooling and a minimum heat transfer difference. These were very illuminating for several further investigations.

Progress in Location-Specific and Climate-Specific Design

Naturally, different locations experience distinct microclimate due to their specific altitudes, latitudes, distances to the coastline, surface albedo, vegetation cover, and other land cover attributes. Meanwhile, the weather conditions in a fixed location may also vary in a wide range in one day or as long as one year. Recently, Gido et al.[24] conducted a climate-specific analysis to assess the feasibility and energy requirements of atmospheric water harvesting by direct cooling in global range. They analyzed the fraction of the time suitable for AWGs by direct cooling in a total of 30 cities of 14 countries. Although this work is inspiring, it is used only to make decisions when choosing the chiller-based AWGs at a certain location. No information about alternatives is provided. Therefore, much more work on location-specific and climate-specific design is expected in the future.

Perspectives

System Design Principle: Match Desorption Operation with Moisture Condensation

During the desorption-condensation process, the inlet air of the condenser is at the state of the outlet air of the desorber. For the condenser, an inlet air condition of low temperature and high humidity is expected to achieve a low SEC, but an outlet air condition of high temperature and low RH indicates that the desorber can release

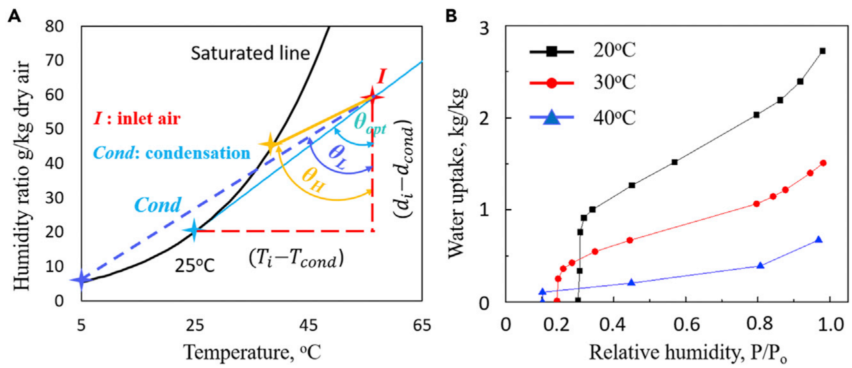

Figure 8. System Design Principle

(A and B) The optimal condensing temperature (A) and the isotherms of an ideal desiccant (B). Reproduced from Alayli et al.[25] with permission.

as much water vapor as possible to obtain a high SWP. For a given outlet air state of the desorber, a lower condensing temperature can result in a higher SWP But also causes a higher SEC. In this case, the desorption temperature and the condensation temperature should be carefully preferred to balance the SEC and SWP. However, it is still an open question as to how to determine the proper desorption temperature and the condensing temperature. Through thorough psychrometric analysis, we find a powerful tool to solve this problem. The inlet air state of the condenser is labeled as point *I* (T_i, d_i), and the condensation states of the moist air are labeled by colorful stars located on the saturated line in the psychrometric chart (Figure 8A), so that the tangent of angle θ can be expressed as follows:

$$\tan\theta = \frac{T_i - T_{cond}}{d_i - d_{cond}}. \qquad \text{(Equation 3)}$$

Thus, $SEC = C_p(\varepsilon_T/\varepsilon_d) \times \tan\theta + h_{fg}$. For a given condenser, if the condensation temperature is the only variable, the *SEC* is almost a linear function of the tangent of angle θ. Note that the tangent of angle θ ($\theta_H \rightarrow \theta_{opt} \rightarrow \theta_L$) will decrease first and then increase with the reduction in condensation temperature. Therefore, there exists an optimal condensation temperature that achieves the lowest tangent of the angle θ_{opt} and eventually the smallest SEC. It is easy to understand when the line through the point *I* (T_i, d_i) is tangent to the saturated line: the angle θ is the smallest. Therefore, the optimal condensing temperature $T_{cond,opt}$ for a minimum SEC at given inlet conditions *I* (T_i, d_i) can be obtained at the tangent point as shown in Figure 8A. Furthermore, we can find many iso-SEC or iso-$T_{cond,opt}$ lines. Instead, for a designed condensing temperature, appropriate condenser inlet air conditions can be found along with the iso-SEC lines and then the optimal desorption operating conditions can be obtained. For example, an appropriate heat source temperature and airflow rate can be selected by using this tool to obtain the expected outlet air conditions of the desorber.

Ideal Sorbents: Temperature-Sensitive Materials

Every specific application requires an ideal sorbent. For example, the optimal desiccants for an adsorptive chiller or heat pump are ones with S-type isotherms. Their sudden uptakes mean that the desiccant can be regenerated by lower temperature heat sources. Meanwhile, their narrow RH interval is well in accordance with the fixed working conditions of the adsorptive chiller or heat pump. However, an open system, such as AWGs, usually experiences a very wide range of weather conditions during one day or throughout a whole year. Thus to maximize the capacity of the

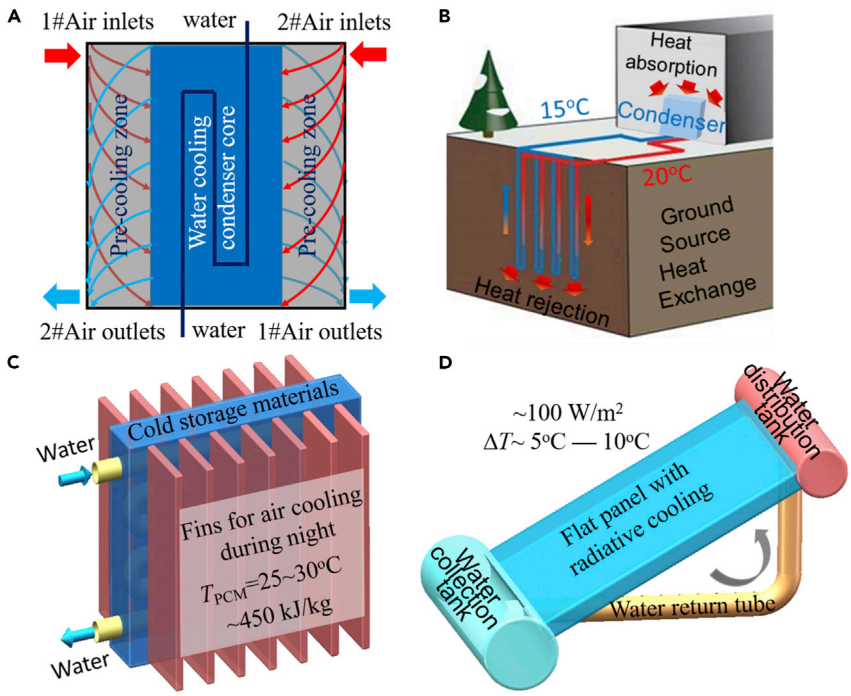

Figure 9. Efficient Condenser Design

(A–D) Water cooling condenser assembly with heat recovery (A) and alternative cost-effective cold water produced by ground source heat exchanger (B); cold storage tank (C); flat panel with radiative cooling (D). Reproduced from Zhao et al.[108] with permission.

AWG, a linear isotherm is expected for dehumidification, whose uptake will increase along with the rising RH.

Similarly, according to the above analysis, the ideal sorbents for air-water harvesting should have features as follows: (1) in the adsorption process (<25°C), their water sorption capacity should increase linearly with RH; (2) in the desorption process (>35°C), their water sorption capacity should drop steeply with increased temperature, shown as S-type isotherms. Although it is difficult to fully satisfy these features with the current commercial or laboratory desiccants, which are either temperature-insensitive or RH-sensitive, Alayli et al.[25] had reported a composite materials, a mixture of a natural wool and polyester doped with $CaCl_2$, which had typical linear isotherms at low temperatures and S-shaped isotherms at high temperatures, as shown in Figure 9B. Obviously this is an ideal desiccant, but unfortunately little attention has been attracted and scarce research regarding the material performance can be found in the past 30 years. Recently, Kallenberger and Fröba[107] reported another composite material that incorporated calcium chloride into an alginate-derived matrix. The water sorption isotherms of the fully dehydrated material at 28°C, 65°C, and 85°C show that its water uptake almost linearly increases with RH from 0% to 79% at 28°C. However, when the adsorption temperature rises to 65°C, the water uptake is very little, meaning the desiccant can be regenerated at a temperature as low as 65°C. This work thus provides a useful approach to design high-performance temperature-sensitive desiccants for AWGs. Of course, if the harvested water by AWGs is used for electronic cooling, an S-type isotherm is necessary and a lower RH at the onset of the isotherm is better because the ability to collect sufficient water under any climate condition is of primary importance.

Efficient Condenser Design

Given that water-cooling condensation has a much higher heat-exchange effectiveness than air cooling, a water-cooling condenser with heat recovery (Figure 9A, the same as the evaporator used in the direct expansion chiller[105]) may have a higher condensing efficiency. This is particularly helpful to the sorption-based AWGs where the regenerated moist air has a very high temperature. Meanwhile, three facts are worthy of note: (1) the earth collectors have been successfully proven, but no research has investigated the potential of dew water harvesting using the cold water from ground heat exchangers (Figure 9B); (2) the massive dew collectors have been proven ineffective due to the low specific heat capacity and the low thermal conductivity of the stone, although high-performance phase change materials (PCMs) recently have been able to solve these two problems[83] (Figure 9C); (3) with the rapid development of radiative cooling technology,[108] the radiative cooling panel not only can be directly used to condense the dew, but also can work as a cost-effective heat sink to improve the performance of the sorption-based AWGs (Figure 9D).

Efficient Sorber and System Designs

Sorption-based atmospheric water harvesting is a vital technology for cost-effective portable water production in arid areas. However, a key obstacle to its deployment on a large scale remains its cost, both capital and operating. In this context, the development of high-performance desiccants is a key research priority. Consequently, a great effort has been made to develop new materials for this purpose, with thousands of new materials having been proposed in the literature. One common feature of these studies is that they mainly focus on the equilibrium water-uptake capacity of the desiccants and frequently ignore other key factors such as kinetic properties.[109] To date, the majority of this effort has consumed plentiful time and resources and has almost exclusively focused on developing desiccants with increased water-uptake capacity and reduced heat of regeneration. This would appear rational given that desiccant regeneration largely affects operational cost. The transport and kinetic properties of the desiccants directly determine the size of the sorption-based AWGs and, thus, their capital costs. Therefore, in order to develop AWGs that will result in an obvious cost reduction, it is essential to move beyond the equilibrium-based metrics of the desiccants.

In the following section, we propose two new system designs for mass transfer enhancement to improve energy efficiency and reduce the system size. Our approaches use a kind of water-sorbing, desiccant-coated heat exchanger, the detailed parameters of which are referred to in several previous papers.[110–112] The water-sorbing heat exchanger can independently handle the sensible and latent loads at the same time. The desiccants coated absorb moisture almost isothermally because the heat of adsorption is directly taken away by the thermal fluid flowing through the heat exchanger. Meanwhile, due to a thin desiccant layer (less than 1 mm), the adsorptive and desorption kinetics are very fast and the desiccant also can be regenerated by low-temperature source. Therefore, the water-sorbing heat exchanger has great potential to efficiently concentrate the water vapor.

Solar Water Heating + Cost-Effective Water-Cooling Condensation. Through the comparison among the aforementioned different sorber configurations, it is clear that both the traditional greenhouse-type sorber and the solar air heating sorber suffer from a slow adsorption, thus taking a long time to become saturated. This is because the adsorption processes are adiabatic: the adsorption heat can only be taken away by the feed air. The temperatures of the desiccant and feed air rise quickly and remain at a high level for a long time, which eventually retards the

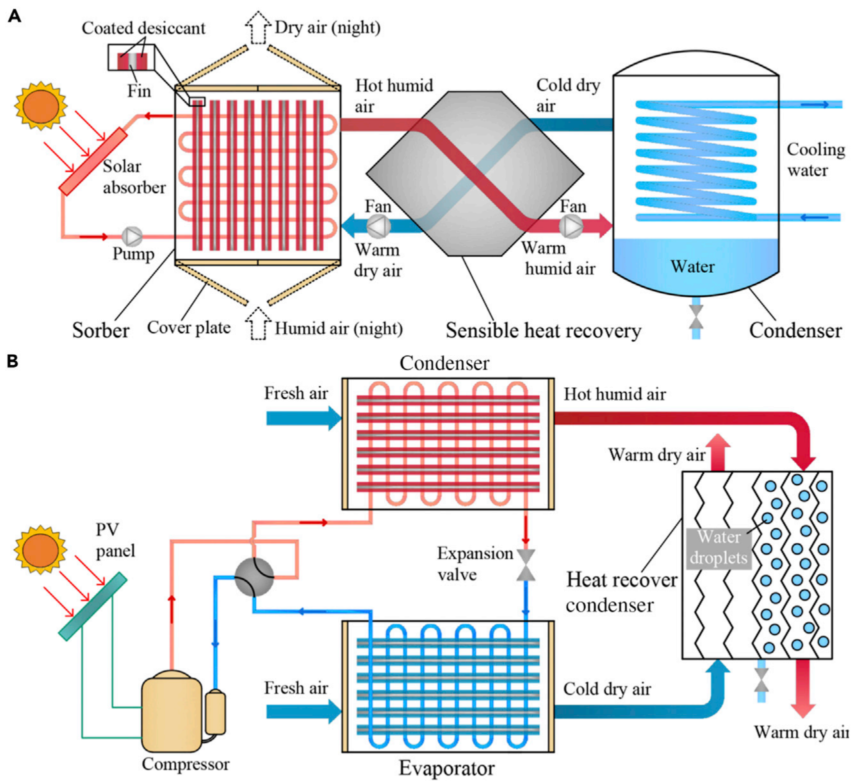

Figure 10. Efficient Sorber and System Designs

(A) Concept of the solar water-heating-powered AWG with heat recovery.

(B) Concept of the solar PV-driven AWG based on the desiccant-enhanced heat pump.

sorption process. Therefore, a new system configuration based on water-heating desiccant-coated heat exchangers,[110,111] as shown in Figure 10A, may be attractive, with the following features:

(1) Water-cooling adsorption is applied to maximize the RR. The adsorptive process will be almost isothermal, which is beneficial in enlarging the water uptake.
(2) Water-cooling condensation is adopted to reduce the SEC. The cold water comes from ground-source heat exchangers, radiative coolers, or cold storage tank (night storage and day discharge).
(3) The sorber made by a water-sorbing heat exchanger is introduced to internally cool or heat the desiccants, which further decrease the required temperature of the heat source and the outlet air temperature of the desorber.
(4) Heat recovery is involved between the outlet air of desorber and the outlet air of condenser to reduce the SEC.

Apparently, it is optimal for locations where the RH differs largely between day and night.

Solar PV-Driven Desiccant-Enhanced Heat Pump with Passive Heat-Recovery Condenser. Another very promising technology is desiccant-enhanced heat pump integrated with a passive heat-recovery condenser as shown in Figure 10B. The fresh air flowing through the system will be divided into two parts; one part is cooled and dehumidified and the other is heated and humidified. The dehumidification effectiveness and energy efficiency of the solar PV-driven desiccant-enhanced heat pump have been also investigated and proved in previous papers.[110,112] When the two air flows come into the heat-recovery condenser, the moisture in the humid and hot air will be condensed. Principally it is optimal for locations where continuous water production is needed or a constant high RH in a whole year or at least a monsoon season.

A New Vision of Water-Energy-Food Nexus

Water is precious. The water-food-energy nexus is central to sustainable development. Agriculture is the largest consumer of the world's freshwater resources. Cooling in air-conditioning systems, power plants, refining petroleum, producing fuel, and extracting energy resources from the earth make up a significant fraction of water use. Thus, the solar-powered scalable atmospheric water-harvesting technologies can inspire us to create new possibilities of energy-efficient water, water-efficient energy, and water-saving agriculture. For example, it is a promising opportunity to bloom in the desert by integrating the solar-powered atmospheric water-harvesting technologies with water-saving agriculture. Besides, utilizing the accessible water produced by such technologies can promote the application of evaporative cooling in overheating protection of outdoor electronic devices, wet cooling of the power plants in arid areas, and passive cooling in buildings, which may obviously lower the energy consumption. In this case, the atmospheric water-harvesting technologies will be adapted to the whole world in the future, far beyond the arid and semi-arid areas as summarized in Table 1.

SUPPLEMENTAL INFORMATION

Supplemental Information includes one figure and five tables and can be found with this article online at https://doi.org/10.1016/j.joule.2018.07.015.

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AUTHOR CONTRIBUTIONS

Proposal, R.W.; Conceptualization, Y.T., R.W., and J.W.; Original Draft, Y.T., Y.Z., and J.W.; Review & Editing, Y.T., Y.Z., and R.W.

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