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Potential Analysis of Atmospheric Water Harvesting Technologies from the Perspective of "Trading-in Energy for Water"

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Abstract: An applicable, high-volume, and sustainable water uptake technology can alleviate freshwater shortages, improve the energy utilization rate and promote the development of energy technology. Traditional seawater desalination, fog water, and dew collection are limited by the geographical environment, and the water resource transportation cost is high, or the water uptake volume is limited, so they cannot be used on a large scale. There are potential safety problems with wastewater reuse and recycled water. Atmospheric water harvesting technology uses energy for direct condensation or uses adsorbent to absorb water, which is characterized by strong sustainability, high applicability, decentralization, and stable water uptake. This study summarizes the working principle of mainstream atmospheric water harvesting technologies, mainly including condensation, absorption, and desorption water harvesting, and some active dew and fog collection technologies. It also theoretically analyzes the energy consumption of condensation and adsorption and desorption water harvesting technologies. Aiming at the problems of difficult condensing for direct condensation and long adsorption/desorption cycle of adsorption and desorption water harvesting, it summarizes the countermeasures of multi-stage condensation and multi-cycle adsorption and desorption. The development prospect of atmospheric water harvesting technologies is also discussed

Keywords: energy for water; atmospheric water harvesting; multi-stage condensation; multi-cycle adsorption and desorption; energy consumption

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1. Introduction

There are four billion people in the world facing water shortages, of which 500 million people are facing serious water shortages throughout the year, and the number is still rising [1]. Water shortages can be solved in two aspects: broadening sources and reducing expenditure. Limiting the water consumption of the basin, improving the water utilization rate, and better allocating water resources can alleviate water shortage from the perspective of "reducing expenditure" [2]. However, it does not increase the total amount of water resources. Meanwhile, the availability of surface water and groundwater is limited by their geographical position and intra-annual variability.

From the perspective of "broadening sources," many researchers devote themselves to finding a globally applicable and sustainable, high-volume water source. Seawater desalination is a relatively developed technology. However, the production cost of seawater desalination is about 1.28 times that of tap water and 1.20 times that of reclaimed water in China [3]. Moreover, water transmission incurs costs, and desalination plants also produce toxic byproducts in the process of reverse osmosis and multi-stage flash distillation [4]. For arid and semi-arid areas such as the United Arab Emirates, artificial precipitation enhancement technology may become more feasible and economical than seawater desalination [5]. Rainwater collection is widely used for water supply, which is limited by climate factors. The randomness and uneven seasonal distribution of natural precipitation is the biggest risk in the implementation of rainwater harvesting projects [6]. Besides, the water quality deteriorates in the process of collection, storage and household use, and the economic recovery period of rainwater collection systems is also long [7]. Reclaimed water, the treated domestic wastewater, or rainwater are mostly used for agricultural irrigation, groundwater recharging, toilet flushing or industrial water use due to water quality issues [8]. The quality of reclaimed water is distinct from that of drinking water; it is likely to deteriorate, even after advanced treatment, during distribution and transport [9]. Brackish water resources tend to occur in the upland areas of sedimentary basins close to recharge areas. On average, brackish water resources occupy about 11% of aquifer volume [10]. The exploitation and utilization of brackish water [11] and mine water [12,13] also significantly relieves the water supply pressure from local agriculture and industry and improves the problem of land salinization.

In recent years, technical methods of harvesting water from the air have been developed. Annually, the oceans transport 45,500 km^3 of net water vapor to the continents, and the total land evaporation is 65,500 km^3. With atmospheric circulation and water vapor diffusion, water vapor is widely distributed in the air, with a total number of 3000 km^3 over land [14]. The global average residence time of atmospheric water vapor is about nine days [15], and the water vapor can be rapidly updated. Thus atmospheric water is a potential renewable water source with huge reserves [14].

In addition to rainfall and snowfall with extremely uneven spatial and temporal distribution, fog and dew are important components of atmospheric water [16]. Fog is small water droplets suspending at or near the Earth's surface, reducing horizontal visibility to less than 1 km [17], and mainly occurs in coastal areas. Dew refers to water droplets formed on the base surface with a temperature lower than the dew point temperature and higher than the freezing point, which is more widely distributed.

Both fog and dew can be collected passively as water sources. The efficiency is determined by the air moisture, which is mainly affected by air temperature, air pressure, and relative humidity [18]. The basic idea of artificially collecting water vapor in the air is to extract water by condensing the vapor [19]. By increasing the dew point of compressed air condensation consumes too much energy and is not conducive to popularization [20]. There are roughly two technical paths for atmospheric water harvesting: (1) According to the thermodynamic principle, reducing the air temperature by using external energy can increase the relative humidity and make the water vapor reach the dew point temperature to produce dew, which can then be collected. (2) The adsorbent of water vapor can also be used to capture water vapor in the air, which is then heated for desorption to extract water. Generally, the atmospheric water harvesting technology using the adsorbent has lower requirements for air humidity, and water can be taken at lower air humidity [21].

There are several potential advantages of harvesting water from the air: (1) The atmospheric water has a large quantity with rapid renewal [15]. (2) It is relatively stable and can be used sustainably [22]. (3) The water quality is high [23], as the water harvesting device and the production process are physically isolated from the polluted underground and surface water. Meanwhile, onsite water harvesting also controls pollution during transfer and storage. (4) A decentralized device can make water available locally, saving the cost of laying pipelines or transportation. The cost of water extraction may be lower than that of drilling groundwater or pipeline water transmission [23].

This paper introduces the working principle and performance-influencing factors of two mainstream atmospheric water harvesting technologies, i.e., the direct condensation of air and adsorption and desorption water harvesting. Some active fog and dew water collection technologies are also introduced. Through theoretical calculation, it quantifies the energy consumption per unit of water uptake, the proportion of useless power, and the appropriate environmental range of different water uptake modes for direct condensation. The influence of different factors on the water harvesting performance of adsorption and desorption water harvesting is quantitatively analyzed. The ideas for the improvement of different water harvesting technologies are put forward. That is the summary of multi-stage condensation for the difficulty of water harvesting under low humidity conditions of direct condensation. Besides, the working mode of multi-cycle adsorption and desorption is summarized to solve the problem of long adsorption/desorption cycle of adsorption and desorption water harvesting. This paper also summarizes the technical development and application prospects of atmospheric water harvesting technology and provides a reference for the design and application of atmospheric water harvesting systems.

2. Atmospheric Water Harvesting by Condensation

2.1. Fundamentals of Technology & Equipment

Figure 1 shows the schematic diagram of atmospheric water harvesting systems based on condensation. After being fed into the system by the fan, the air is cooled by the condensing plate, and the water drops are collected after being condensed when the temperature is lower than the dew point temperature.

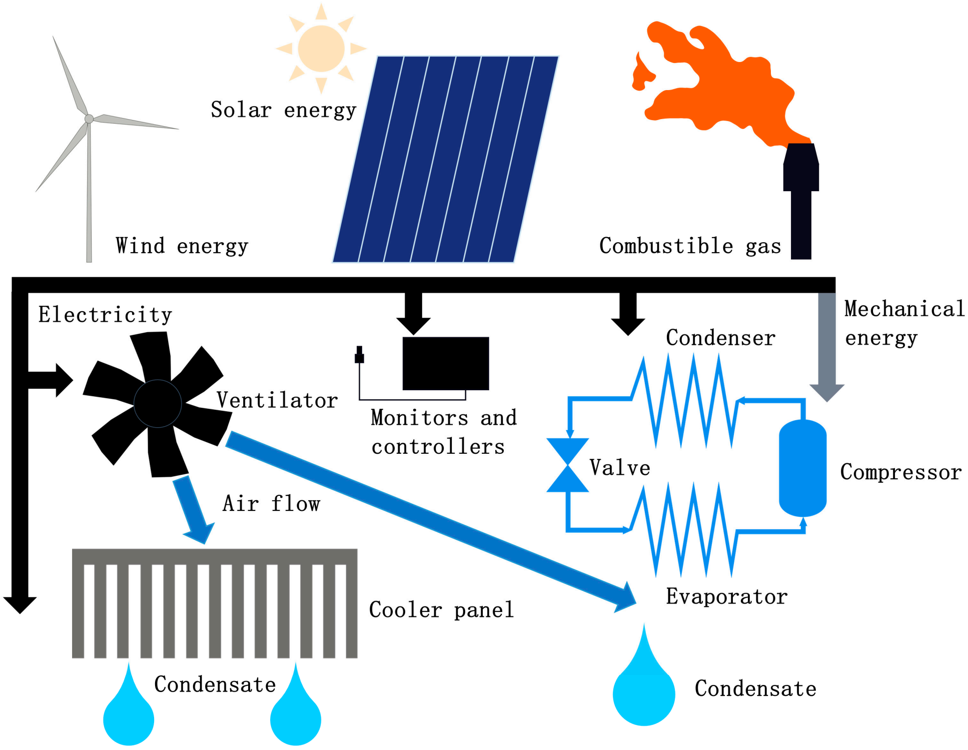

Figure 1. Schematic diagram of atmospheric water harvesting systems based on condensation.

The energy obtained from sustainable energies such as solar, wind, and thermal energy is mainly used in three ways: (1) refrigerating to reduce the temperature of the condensing surface and then the air temperature to obtain water; (2) transporting fresh air into the system to drive air circulation; (3) monitoring and controlling the system to adapt to the environment and reduce energy consumption.

The energy is mainly consumed in the refrigeration stage, either compressor refrigeration or semiconductor refrigeration. The compressor has higher refrigeration efficiency with large volume and potential environmental pollution risk, while the semiconductor is easy to miniaturize with lower refrigeration efficiency. Semiconductor refrigeration is a pair of thermocouples composed of two different metals using the Peltier effect. When direct current is applied to the thermocouple, heat absorption and heat release occur at the node of the thermocouple, forming a cold end and a hot end. The compressor refrigeration includes four stages: (1) The low-temperature and low-pressure refrigerant is compressed into a high-temperature and high-pressure state by the compressor. (2) It enters the condenser for heat dissipation and becomes a normal temperature and high-pressure liquid state.

(3) It changes into a low-pressure and low-temperature liquid through the throttle valve. (4) It is transported to the evaporator for evaporation and becomes a low-temperature and low-pressure gas state. This process absorbs the external heat for refrigeration.

2.2. Theoretical Energy Consumption

The following analyzes three aspects: (1) The energy consumption per unit of water uptake. (2) The proportion of energy consumption to the total energy consumption of water uptake in the process of improving air humidity. (3) The energy consumption difference of the same water uptake volume with multi-stage water uptake and single-stage water uptake.

2.2.1. Total Energy Consumption Per Unit Water Uptake

Rao et al. [24] regard reaching saturated humidity from a state point as the minimum energy requirement. However, in the actual water uptake process, the condensing temperature is set to zero to improve the water uptake rate. The temperature of the condensing plate shall not be lower than 0 °C to prevent frost formation. When the temperature is lower than 0 °C, the air moisture content is low, which is considered not feasible for water harvesting through condensing [24]. Then H_c is used to represent the ratio of energy consumption to water uptake from a certain state to 0 °C and relative humidity (RH) = 100 % [25].

$$H_c = \frac{h_{t,\phi} - h_{0,100}}{\omega_{t,\phi} - \omega_{0,100}} \quad (1)$$

where $h_{t,\phi}$ is the enthalpy of humid air at t °C and RH = ϕ, kJ/kg; $h_{0,100}$ is the enthalpy of humid air at 0 °C and RH = 100%, kJ/kg, $\omega_{t,\phi}$ is the air moisture content at t °C, and RH = ϕ, kg/kg; $\omega_{0,100}$ is the air moisture content at 0 °C and RH = 100%, kg/kg.

The enthalpy of humid air h is calculated by Equation (2) [18]:

$$h = (2491.3 + 1.90t)\omega + 1.0t \quad (2)$$

where ω is the air moisture content, kg/kg; t is the ambient temperature, °C.

The air moisture content ω is calculated by Equation (3) [18]:

$$\omega = 0.622\frac{E\phi}{P - E\phi} \quad (3)$$

where P is taken as standard atmospheric pressure, P = 101325 Pa; φ is the relative humidity, %; E is the saturated water vapor pressure at t °C, Pa.

The saturated water vapor pressure E at temperature t can be calculated using the Magnus formula shown in Equation (4) [26]:

$$E = E_0 \times 10^{\frac{7.45t}{235+t}} \quad (4)$$

where E_0 is the saturated water vapor pressure of the water surface at 0 °C, Pa.

However, H_c only represents the energy consumption of humid air between different states; actual energy consumption can be represented by H_{cr}:

$$H_{cr} = \frac{H_c}{EER} + \frac{v + s}{m} \quad (5)$$

where v is the ventilator power, W; s is the supplementary monitor and controller power, W; m is the water uptake, kg; EER is the refrigeration efficiency, dimensionless.

Gido et al. [25] used Moisture Harvesting Index (MHI) to represent the ratio of latent heat of water vaporization to energy consumption per unit of water uptake to determine the working environment. In practice, energy consumption per unit of water uptake can also be used to determine the working environment. As shown in Figure 2, at the same temperature, with the increase of relative humidity, the ambient temperature is closer to the dew point. Therefore, the environment is more conducive to water uptake, and the energy consumption per unit of water uptake is reduced. With the same air moisture content, the higher the temperature, the lower the relative humidity, and the farther the ambient temperature is from the dew point, the more unfavorable the environment is for water uptake. The energy consumption per unit of water uptake also increases. The slope of the 100% relative humidity line is steeper at higher temperatures, indicating that more water can be obtained by lowering the same temperature in the region than in the region with a lower temperature. The energy consumption per unit of water uptake is small only when the relative humidity is above 30%, and the higher the relative humidity is, the better. Besides, the white area outside the 100% relative humidity line represents the oversaturated area. Meanwhile, the black area represents the inaccessible area, i.e., the moisture content area corresponding to 100% relative humidity and 0 °C when the moisture content is lower. Such representations are also applicable in Figures 3 and 4.

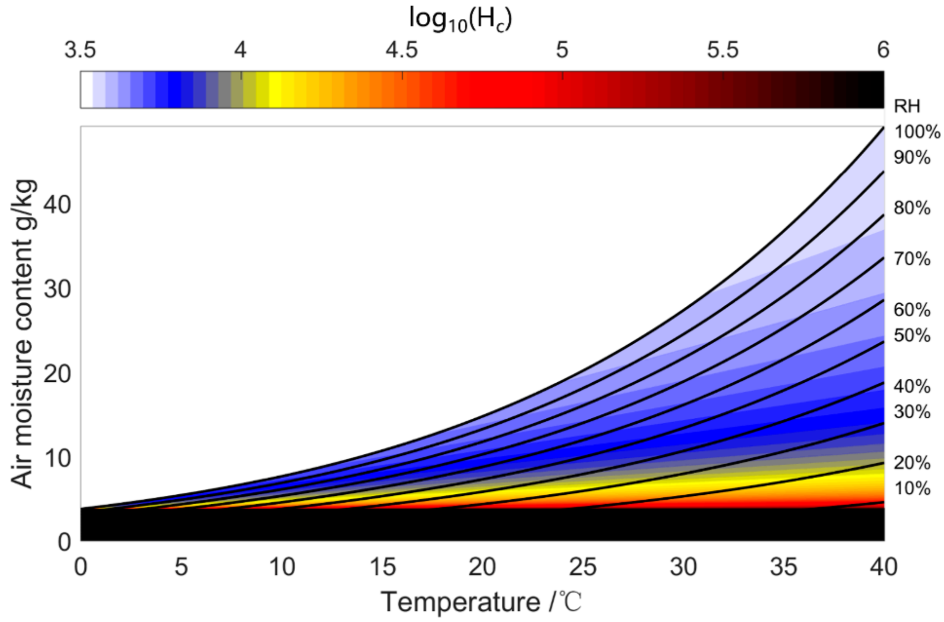

Figure 2. H_c, the ratio of energy consumption to water mass harvested by the condensation method.

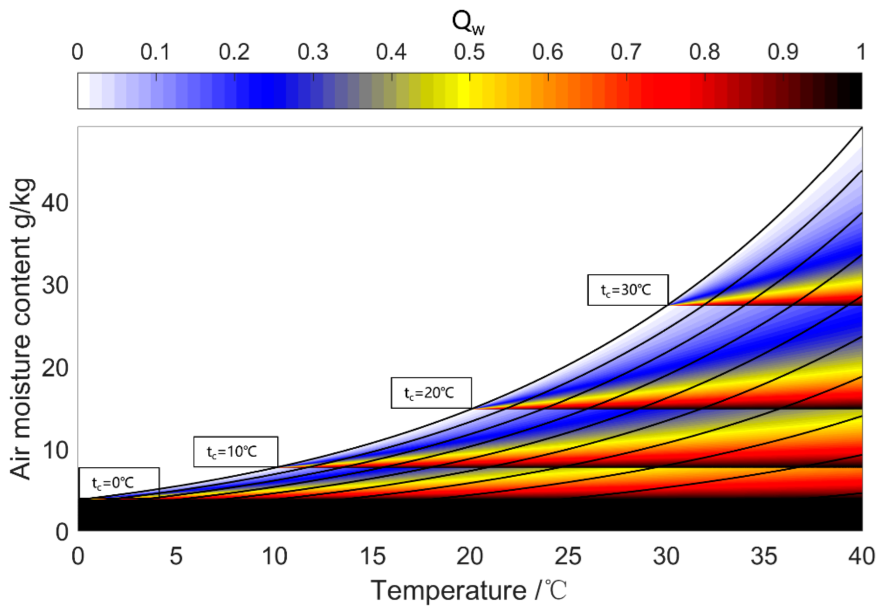

Figure 3. Q_W, the ratio of energy consumption to reach saturation to total energy consumption.

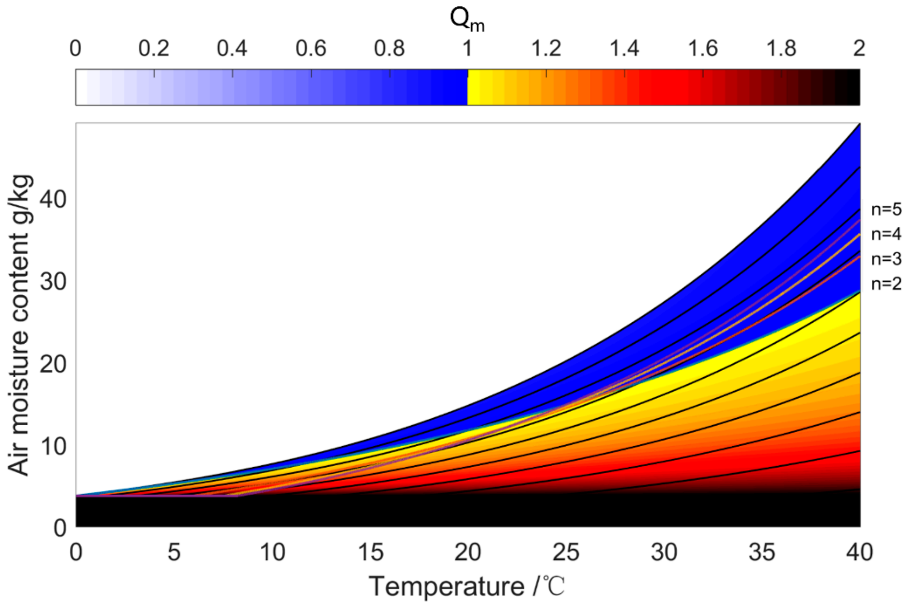

Figure 4. Q_m, the ratio of energy consumption by single-stage to energy consumption by multi-stage.

2.2.2. Proportion of Energy Consumption in Improving Humidity

From a certain state point to the saturated state of air, the external energy is only used to reduce the temperature of humid air and increase the RH. There is no water uptake, and this part of the work is useless. So Q_w is used to represent this part of work to the total work to the state at t_c °C and RH = 100%.

$$Q_w = \frac{(1.90\omega_{t,\phi} + 1.0)\left(t - t_{d_{t,\phi}}\right)}{\left(h_{t,\phi} - h_{t_{c,100}} - c_w t_c\left(\omega_{t,\phi} - \omega_{t_{c,100}}\right)\right)} \quad (6)$$

where $t_{d_{t,\phi}}$ is the dew point at t °C and RH = ϕ; t_c is the temperature of humid air out the system, °C; $h_{t_{c,100}}$ is the enthalpy of humid air at t_c °C and RH = 100%; c_W is the heat capacity of liquid water, 4.2 kJ/(kg*°C); $w_{t_{c,100}}$ is the air moisture content at t_c °C and RH = 100%.

The approximate value of dew point t_d is obtained by Magnus-Tetens Approximation shown in Equations (7) and (8) [27].

$$t_d = \frac{b\gamma(t,\phi)}{a - \gamma(t,\phi)} \quad (7)$$

$$\gamma(t,\phi) = \frac{at}{b+t} + \ln(\phi) \quad (8)$$

The constants a and b are a = 17.27 °C, b = 237.7 °C.

In Figure 3, the part above the moisture corresponding to t_c = 30 °C is the Q_w value under this working condition. The part between the moisture corresponding to t_c = 20 °C and t_c = 30 °C is the Q_w value under the working condition of t_c = 20 °C, and so on. The upper part of the boundary at each working condition is dislocated from the lower part to the left. This is because the corresponding state point at the upper part of the boundary is far from the dew point temperature and has less difference with the moisture at the boundary. The sensible heat and latent heat of water vapor are less, so the Q_w value becomes larger. At the same temperature, the higher the relative humidity, the smaller the proportion of useless work. Under the same moisture, the higher the temperature is, the greater the proportion of idle work is, which is consistent with the expression in Figure 2. With the increase of t_c, the dividing line of reactive power in each working condition becomes steeper, which indicates that the proportion of energy consumed to saturate from a state point decreases.

2.2.3. Energy Consumption of Single-Stage and Multi-Stage Condensation

Some researchers attempt to increase the amount of water in a water uptake process by increasing the number of water uptake stages. In order to compare the energy consumption of different water uptake stages from different state points, Q_m is used to represent the ratio of energy consumption of the same water uptake volume between single-stage water uptake mode and multi-stage water uptake mode.

$$Q_m = \frac{n\left(h_{t,\phi} - h_{t_{n,100}} - c_W t_n\left(\omega_{t,\phi} - \omega_{t_{n,100}}\right)\right)}{h_{t,\phi} - h_{0,100}} \tag{9}$$

where n is the number of water uptakes, $h_{t_{n,100}}$ is the enthalpy of humid air at t_n °C, and RH = 100%; t_n is the temperature corresponding to the air moisture content after one water uptake cycle when the number of times of water uptake is n; $\phi_{t_{c,100}}$ is the air moisture content at t_n °C and RH = 100%. Note: n represents the number of times of water uptake, which refers to the single-stage water uptake mode. Only n times of single-stage water uptake cycles can produce the same amount of water as one n-stage water uptake mode.

In Figure 4, n = 2 means that only 1/2 of the water is produced at this state point at one time. The same water volume as the two-stage water uptake mode is produced through two water uptake processes. In the area above the line Q_m = 1, the energy consumption by single-stage water uptake is lower for the same water volume, and the below means that the energy consumption by multi-stage water uptake is lower. With the increase in the number of stages, the areas with better single-stage water uptake are reduced in the upper part of the figure and increased in the lower part. As single-stage water uptake needs to overcome more times of useless work, it is only applicable in areas where the useless work was multiplied to account for less total work.

2.3. Energy Consumption of Existing Technologies

2.3.1. Single-Stage Condensation

Most water harvesting systems by condensing are single-stage, and the water uptake rate is not high due to the limitation of water uptake stages. The condensing plate is the key link from the cooling capacity of the condenser to the formation of water droplets when the air temperature drops. Many studies have made improvements based on this to improve the water uptake rate. Jin et al. [28] injected salt solution between the two films, incorporated the condensed water vapor with the salt solution, and regenerated the diluted salt solution through solar water uptake regeneration, realizing continuous water uptake at low temperatures without frost. The research results of the wetting characteristics of the substrate surface by dew and fog water collection can also be used for reference to improve the condensing water uptake surface [29,30]. The super hydrophobic condensation surface has faster water drop removal and higher heat transfer efficiency [30]. However, bead condensation on superhydrophobic surfaces is not conducive to the formation and merger of droplets. Besides, the non-directional ejection of droplets from the condensation surface is not conducive to the collection of water [31]. In the study of Zamuruyev et al. [32], the area with a contact angle of 126° has the largest droplet volume-to-area ratio. The angle at which the condensation plate is installed also affects the formation and removal of droplets. Hand et al. [33] studied the influence of heatsink orientation on condensate efficiency and obtained the highest water uptake rate when rotating and tilting at 60° and 75°, respectively. At the same time, when the heatsink is completely filled with water, the water uptake rate decreases by an order of magnitude. The water uptake rate of the surface cleaned per hour increases by 18%. The energy in the condensed dry cold air can also be used. Adding a heat exchanger to the system can enhance the heat dissipation of the hot end of the heatsink by using the sensible heat of the condensed dry cold air to reduce energy consumption [30].

2.3.2. Multi-Stage Condensation

In the daytime, the temperature is high, and the relative humidity is low. Meanwhile, the temperature is low at night, and the relative humidity is high, which is more conducive to the condensation of water vapor. Water uptake by condensation has poor water uptake performance due to low humidity during daytime operation. The system performance can be improved by multi-stage treatment of treated air, humidifying or concentrating the air, and then condensing at the next stage so as to enhance the adaptability of water uptake systems by condensation to the environment and water uptake rate. Tsutomu et al. [34] have made a multi-stage water uptake device using thermoelectric modules. The air enters the secondary water uptake unit for water uptake after passing through the primary water uptake unit. Under the conditions of constant air-specific humidity and different temperatures and relative humidity, the more stages of the water uptake device, the higher the water uptake, and the higher the water uptake under the same energy consumption. Tu et al. [35] proposed the use of a multi-stage dehumidification wheel to humidify the air with adsorption materials and then dehumidify the water through the evaporator. This method can improve the evaporation temperature and water uptake rate. Regenerative air from each stage of the dehumidification wheel absorbs heat from the heater and then releases heat from the humidification side of the dehumidification wheel. The adsorbed water vaporizes when the adsorption material heats up, and the humidity of the regenerative air increases. In comparison, the two modes of multi-stage dehumidification of air on the dehumidification side and air discharge after dehumidification at each stage on the dehumidification side, the latter is more efficient. Zhao et al. [36] used membranes with high permeability to water vapor and low permeability to nitrogen, oxygen, or carbon dioxide to pretreat air to concentrate water vapor, reducing energy consumption by 38.9%. However, the airflow of this method is small, which limits its water uptake rate.

Table 1 summarizes the features and parameters of selected atmospheric water harvesting systems based on condensation. Device performance is measured under different working conditions. In general, the multi-stage water uptake mode has higher water uptake performance than the single-stage water uptake mode. The numerical simulation study has a higher water uptake performance than the experimental study.

Table 1. Features and parameters of selected atmospheric water harvesting systems based on condensation.

Water Uptake Mode	Features	Working Condition	Performance	Research Type
Single-stage	Varied working conditions [30]	RH = 60–90%, ambient temperature at 24 °C, airflow= 30–70 m^3/h	0.14–0.41 L/kWh	Experiment
	Thermoelectric cooler array, air channel [37]	Ambient temperature at 318 K, RH = 75%	1.3 L/kWh	Simulation
Multi-stage	Multi-stage water harvesting unit [34]	Ambient temperature at 20 °C, air moisture content = 8.7 g/kg	0.16 L/kWh	Experiment
	Multi-stage dehumidification wheel, air humidification [35]	Ambient temperature at 10 °C, air moisture content = 5 g/kg or Ambient temperature at 20 °C, air moisture content = 6 g/kg	10.3–27.3 L/kWh	Simulation
	Enhanced membrane system [36]	Vacuum pressure = 0.17 bar, inlet air moisture content= 24.3 g/m^3, outlet air moisture content= 15.5 g/m^3	5.24 L/kWh	Simulation

2.4. Potential Analysis of Water Uptake by Condensation

2.4.1. Influence Factors on the Harvesting Efficiency of Condensation

The performance of the water uptake system by condensation is affected by many factors, which may be the reason for the low water uptake rate in actual use. The main influencing factors are weather and climate, ventilation, condensation surface temperature, cold end structure, and materials [25,29,30,37–40]. The weather and climate have a great impact on the energy consumption per unit water uptake of water uptake by condensation. The low temperature and low humidity environment sharply increase the energy demand [39]. Changes in the weather, climate, and diurnal fluctuation affect the water uptake performance of the system by affecting the ambient temperature and humidity. The air with high temperature and humidity has higher water content, which is conducive to water uptake. Selecting the operation at night and in the month with high humidity can significantly reduce energy consumption [25,34]. The wet air is sent into the system via a ventilator. Large air volume and fast air velocity can improve the heat transfer coefficient of the condensation surface. At the same time, the disturbance of the air accelerates the formed droplets to remove faster, which is conducive to heat transfer. However, when the refrigerating capacity of the evaporator is constant, excessive wind speed leads to insufficient heat exchange between the air and the condensation surface, and the water uptake decreases. The droplets can also be removed automatically after being generated on the hydrophobic surface, ensuring the heat transfer efficiency of the condensation surface. However, when the temperature of the condensation surface is too low, frost forms on the refrigeration fin, which blocks the refrigeration channel and reduces the water uptake [34]. In practical applications, the ambient temperature and humidity always change. Different ambient temperatures, humidity, and air volume correspond to different optimal outputs of the system. Therefore, the water uptake system that can monitor the environment and adjust the air volume and refrigeration temperature can be applied to more scenarios and can save energy consumption [38,40]. The experimental test shows that it takes more than 1 h from the start of the device to stable water production [30,37].

2.4.2. Application Prospect

The energy consumption of direct condensation is 1–4 L/kWh [39]. As shown in Figure 2, the boundary line of water uptake energy consumption is relatively close to the relative humidity line. Considering part of the energy consumption of the ventilator, monitor, and controller, the coefficient of performance can reach 3.8. To meet the water uptake performance of 1 L/kWh, $\log_{10}(H_c)$ should be less than 4. The corresponding air moisture content should be more than 5 g/kg, and the relative humidity should be more than 30%. Renewable energy can be used to supply energy for atmospheric water harvesting technology to reduce energy costs. Solar energy, wind energy, and combustible gas can be converted into different forms of energy, such as the electric energy of a condenser, the mechanical energy of a compressor, and the heat energy for desorption [41–45]. Take China as an example, given a household consumes 25 L of drinking water per day. Taking a water uptake performance of 1 L/kWh and an energy utilization rate of 50%, the electricity quantity of discarded wind and solar [46] can provide drinking water for more than 1.5 million households for one year. In addition, the problem of gas discarding also exists in the exploitation of combustible gas from natural gas, waste gas from landfills, and biomass gasification. The water consumption from natural gas exploitation is large. Atmospheric water harvesting technology can be used to improve energy utilization and provide water for natural gas exploitation [44]. The atmospheric water harvesting system based on biomass gasification and combustible gas energy supply is expected to solve the energy, environment, and water problems at the same time [41]. Water vapor can circulate rapidly, and the water uptake is mainly subject to the utilization of renewable energy and the performance of the condenser. With the improvement in condenser performance, the proportion of monitor and controller energy consumption decreases, and the proportion of ventilator energy consumption increases. In the process of converting the refrigerating capacity to a lower air temperature for water uptake, air volume, the temperature of the condensation surface, the thermal conductivity of condensation surface material, the wetting characteristics of the condensation surface, and the installation of condensation surface jointly affect the heat transfer efficiency. How to achieve the overall optimization is worth considering. For the problem that environmental conditions have a great impact on water uptake energy consumption, as shown in Table 1, the enhanced membrane system improves water uptake performance by reducing the proportion of useless work, which has a high water uptake potential. The dehumidification wheel also improves water uptake performance by humidifying the air, which is more adaptable to the environment and has greater potential than single-stage water uptake systems. Figure 4 also shows that the multi-stage water uptake mode has less energy consumption than the single-stage water uptake mode at lower relative humidity, but there is a significant difference between the performance of experimental research and theoretical research. Patel et al. [47] explored the performance of a water uptake system using a compressor under different climatic conditions. Under warm and humid conditions, the minimum water uptake energy consumption is 0.75 L/kWh, and the experimental value of energy consumption is about 2.75 times the theoretical value. In addition, the adaptability of the water uptake systems by condensation can be improved through the intelligent control of air volume and refrigeration temperature according to the environment, the development of the low-temperature frost free water uptake methods, the addition of the regenerator and the optimization of the system structure, so as to improve its practicability in the real scene.

3. Atmospheric Water Harvesting by Adsorption and Desorption

3.1. Fundamentals of Technology & Equipment

As shown in Figure 5, the main difference between the adsorption method and the condensation method lies in the use of the adsorbent. The adsorbent can adsorb water vapor at a lower air humidity and then use solar energy or other heat sources to heat the adsorbent for desorption. The water vapor is then passively or actively condensed to collect water, so it is more widely applicable than the condensation method. Generally, there is a positive correlation between the specific surface area of the adsorbent and the water absorption capacity. From the traditional silica gel, a molecular sieve, activated carbon, and hygroscopic salt form the composite adsorbent, Metal Organic Framework (MOF) material, a thermosensitive polymer, and nanoporous material; the water absorption capacity of the adsorbent has been improved step by step, providing a material basis for using the adsorbent to uptake water. The adsorbent is placed in the heat collecting bed, which is the key link from the heat source to water vapor conversion, and affects the transfer of material and heat. It should have good heat transfer performance and ensure gas flow so that the adsorbent can quickly absorb and desorb. The concentrator can direct sunlight to the heat-collecting bed to speed up the desorption process. The air can flow passively in the heat-collecting bed or be driven by a ventilator so as to speed up the adsorption process. The high humidity airflow generated by desorption can be passively condensed through the condensation plate, and the use of the condenser can improve the condensation efficiency.

3.2. Theoretical Energy Consumption

It is a spontaneous process for the adsorbent to adsorb water from the air, which does not require additional energy input [48]. The external energy is only used in the desorption stage. The high temperature and humid air after desorption can be collected through natural cooling and condensation. Peeters et al. [39] ignored the heat used to heat the adsorbent when calculating the energy consumption of the adsorption/desorption air-water harvesting process. Siegel et al. [49] considered the specific heat capacity of water and adsorbent as a whole. Now, water and adsorbent are considered separately. It is assumed that water is stored in the adsorbent as a liquid after being adsorbed. Both the adsorbent and the liquid water in it are at ambient temperature. Desorption starts when the water is heated to the desorption temperature. The energy consumption per unit water uptake H_s is expressed as:

$$H_s = \frac{h_d - h_a}{w_a - w_d} = \frac{(c_a + c_w w_a)(t_r - t_a)}{w_a - w_d} + h_{ad} - 1.9t_r \quad (10)$$

where h_a is the enthalpy of the system before desorption, kJ/kg; h_d is the enthalpy of the system after desorption, kJ/kg; w_a is the water absorption rate of the adsorbent before desorption, kg/kg; w_d is the water absorption rate of adsorbent after desorption, kg/kg; c_a is the specific heat capacity of adsorbent, kJ/(kg*°C); t_a is the temperature of the system before desorption °C; t_r is the temperature of the system after desorption, °C; h_{ad} is the adsorption heat, kJ/kg. It can be seen from the above formula that when the specific heat capacity of the adsorbent is smaller, the temperature after desorption is lower, the temperature before desorption is higher, the water absorption rate before desorption is larger, the water absorption rate after desorption is lower, and the adsorption heat is lower, the energy consumption per unit water uptake is smaller. where h_a is the enthalpy of the system before desorption, kJ/kg; h_d is the enthalpy of the system after desorption, kJ/kg; w_a is the water absorption rate of the adsorbent before desorption, kg/kg; w_d is the water absorption rate of adsorbent after desorption, kg/kg; c_a is the specific heat capacity of adsorbent, kJ/(kg* °C); t_a is the temperature of the system before desorption °C; t_r is the temperature of the system after desorption, °C; h_{ad} is the adsorption heat, kJ/kg. It can be seen from the above formula that when the specific heat capacity of the adsorbent is smaller, the temperature after desorption is lower, the temperature before desorption is higher, the water absorption rate before desorption is larger, the water absorption rate after desorption is lower, and the adsorption heat is lower, the energy consumption per unit water uptake is smaller.

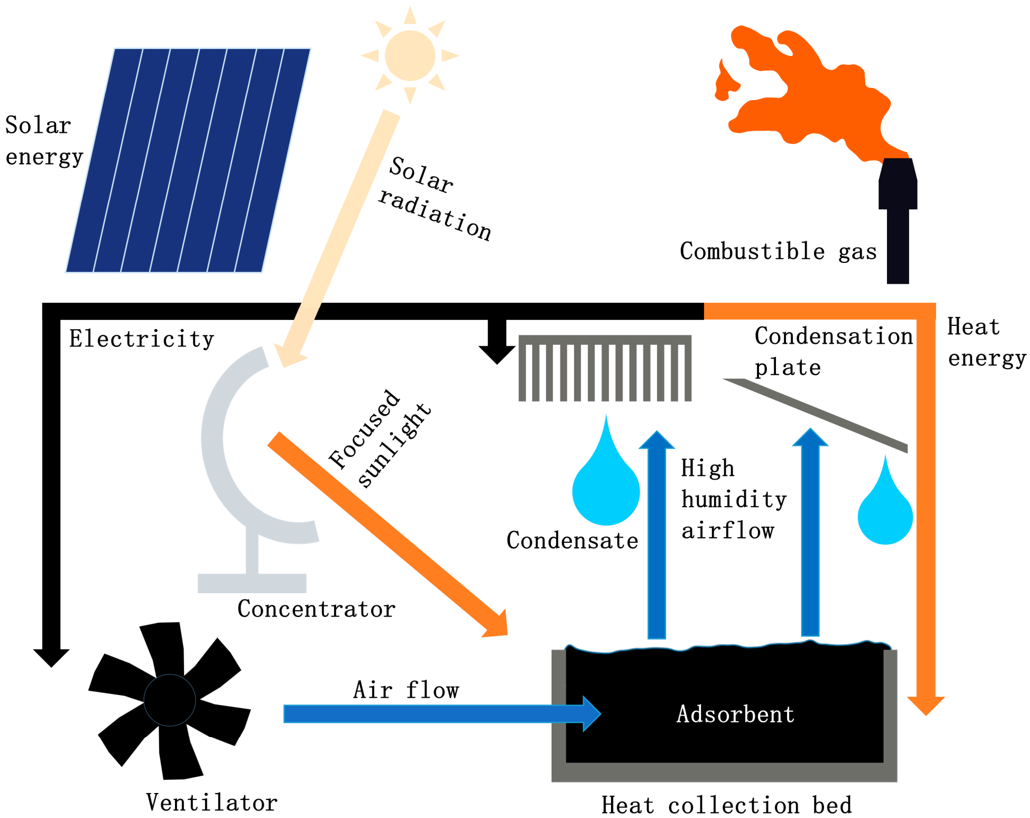

Figure 5. Schematic diagram of atmospheric water harvesting systems based on adsorption/desorption cycles.

The enthalpy of the system before desorption h_a can be calculated by Equation (11):

$$h_a = (c_a + c_w w_a)t_a \tag{11}$$

The enthalpy of the system after desorption h_d can be calculated by Equation (12):

$$h_d = (c_a + c_w w_a)t_r + (w_a - w_d)(h_{ad} - 1.9t_r) \tag{12}$$

The actual unit energy consumption H_{sr} also takes into account the thermal efficiency of the heat source and water vapor condensation rate, expressed as:

$$H_{sr} = \frac{H_s}{\eta_t \eta_c} + \frac{v + s + c}{m} \tag{13}$$

where η_t is the thermal efficiency, dimensionless; η_c is the conversion rate of released water vapor and obtained water, dimensionless; c is the power of the condenser, W.

In Figure 6, the horizontal axis shows that the respective variables change uniformly from the initial value to the final value. The specific heat capacity of the adsorbent changes from 0.76 kJ/kg/k to 0 kJ/kg/k, the water absorption rate before desorption changes from 0.8 to 4.8, the temperature after desorption changes from 85 °C to 42.5 °C, the temperature before desorption changes from 10 °C to 40 °C, the water absorption rate after desorption changes from 0.2 to 0, and the adsorption heat changes from 2645 kJ/kg to 2260 kJ/kg. When the water absorption rate before desorption increases, the reduction of energy consumption per unit water uptake is fast at first and slow then. When the above optimization is carried out for one variable and other independent variables are constant, the decreasing effect on energy consumption per unit water uptake is ranked from strong to weak as adsorption heat > temperature after desorption > temperature before desorption > water absorption rate after desorption > specific heat capacity of the adsorbent.

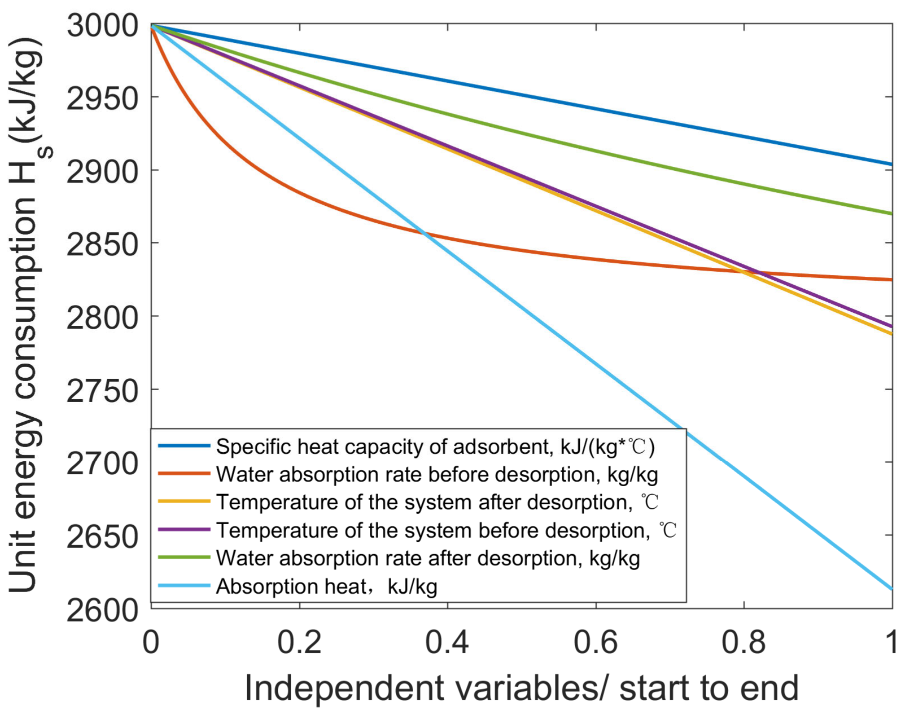

Figure 6. Relationship between energy consumption per unit water and independent variables of adsorption and desorption water harvesting.

3.3. Energy Consumption of Existing Technologies

The traditional adsorption and desorption water uptake system mostly adopts the day and night water uptake mode of absorbing water at night and desorbing during the day. Its water uptake is limited by the amount of water absorbed at night and requires a large number of adsorbents. In order to break through the limit of the adsorption and desorption rate of adsorbent on the number of water uptake cycles in a day, the system structure, the modification of adsorption materials, and the water uptake mode should be improved. In the early days, the adsorption and desorption rate of the adsorbent was limited, which could only be improved from the system structure, resulting in such modes as multiple sets of adsorbents, flippable adsorption stage, rotating adsorption table, etc. Liu et al. [50] used two sets of adsorbers, which can desorb when one adsorber adsorbs so as to achieve circulating water uptake. The time of one adsorption and desorption cycle is reduced, and the water uptake rate is improved. Wu et al. [51] assembled cylindrical adsorbent on both sides of the flippable adsorption stage. When one side desorbs, the other side absorbs. After one side is desorbed, the stage flips over to achieve continuous adsorption and desorption. This is due to the high heat transfer performance of the vertically aligned porous networks of cylindrical monoliths. Xu et al. [52] used lithium chloride, reduced graphene oxide, and sodium alginate matrix to manufacture nanocomposite adsorbent with vertical and layered pores. Four groups of adsorbents are used to adsorb and desorb alternately, and the ventilator is introduced to force air convection to achieve continuous water uptake. The improvement of adsorbent material can fundamentally solve the restriction of adsorption and desorption rates on multiple water uptakes in a day. It can mainly be improved by using liquid adsorbent, developing efficient photothermal adsorbent, and fluidizing adsorbent. Qi et al. [53] used liquid adsorbent to realize simultaneous adsorption and desorption, which improved the water uptake rate. The adsorbent is divided into the adsorption part and desorption part, which are connected with each other. The adsorption part absorbs water from the air, and the water diffuses from the adsorption part to the desorption part for desorption. Li et al. [54] designed and manufactured a nanoscale photothermal adsorbent, which can adsorb water vapor of the same weight as the adsorbent in 3 h at 60% relative humidity and desorbs in only 0.5 h under 1 kW/m^2 solar radiation. The outer layer of adsorbent particles is a hollow carbon ball and acts as a photothermal component at the same time. The inner layer is filled with hygroscopic salt LiCL, and the space between stacks ensures the transport of water vapor. The continuous air-water device based on adsorbent is manufactured. The adsorbent is installed on a rotating horizontal cylinder. The upper part of the cylinder is exposed to the sun for desorption, and the lower part absorbs water from the air, which may provide a solution for large-scale, automated, and factory deployment. Mulchandani et al. [55] adopted the same idea, using photothermal materials to improve the desorption speed and desorption water volume of the adsorbent so as to achieve multiple water uptake cycles within a day. Terzis et al. [56] used the fluidized MOF to realize the high-frequency adsorption-desorption cycle of water vapor. The continuous cycle can exert the water absorption capacity of MOF-801 by more than 75%, and the water uptake can reach 10 L per kilogram of MOF-801 per day. The suspended particles are composed of fine adsorbent powder, and their aggregates have a high specific surface area, which can realize rapid diffusion of mass and heat, so the adsorption-desorption cycle is fast. The water uptake mode can also be changed to achieve multiple water uptakes in a day. Park et al. [57] used solar energy to trigger multiple adsorption and desorption processes in a day according to the performance of the adsorbent. The absorbent absorbs for a period of time and desorbs for a period of time repeatedly, making full use of energy and increasing the water uptake rate by 80%.

Table 2 shows the features and parameters of selected atmospheric water harvesting systems with the multi-adsorption-desorption cycles mentioned above. The research mentioned is all experimental research. The performance of the device is measured under different working conditions, and the performance indicators are inconsistent. In general, the water uptake performance of the device is 0.42–2.81 L/kg/day or 0.039–0.52 L/kg/hour.

Table 2. Features and parameters of selected atmospheric water harvesting systems with multi-adsorption-desorption cycles.

Water Uptake Mode	Features	Working Condition	Performance
Multi adsorption/desorption cycle	Two adsorbers, alternating adsorption and desorption [50]	Temperature at 22.2 °C and RH = 44%; temperature at 10.4 °C and RH = 77%	0.0485–0.089 L/kg/hour, 4 h for one cycle
	Liquid sorbent, moisture diffusion [53]	RH = 80%	0.5 L/m^2/h, 2.8 L/m^2/day
	Flippable adsorbent stage [51]	RH = 20%, ambient temperature at 298 K	0.058 L/kg/h, one hour for one cycle
	Vertically aligned and hierarchical pores [52]	Ambient temperature at 30 °C	2.12 L/kg/day, eight cycles per day
	Rapid adsorption and subsequent desorption steps [57]	Ambient temperature at 23 °C, RH = 69%, solar radiation = 1 kW/m^2	0.2545 L/kg/h, one cycle for 46 min
	Nano vapor sorbent [54]	RH = 60%, solar radiation = 1 kW/m^2	1.6 L/kg/day, 3 cycles a day
	Nano-enabled photothermal desiccants [55]	RH = 40%	0.039 L/kg/h, 10 cycles per day
	Fluidized metal-organic frameworks [56]	RH = 18–39%	0.33–0.52 L/kg/h, 40–55 cycles per day
	MOF-303 [58]	RH = 10–32%, ambient temperature at 27 °C	0.7–1.3 L/kg/day
	Moisture-indicated Cellulose Aerogels [59]	RH = 25–85%	2.81 L/kg/day, 3 cycles per day
	Scaled-up device [60]	RH = 20–90%	0.42 L/kg/day, 2 cycles per day

3.4. Potential Analysis of Atmospheric Water Harvesting by Adsorption and Desorption

3.4.1. Influence Factors on the Harvesting Efficiency of Condensation

The adsorption material is the core of the adsorption and desorption water uptake system, which needs to have many characteristics. At the same time, the system structure affects whether the performance of the adsorption material can be exerted [61–65]. A good water uptake system based on adsorption and desorption should meet the requirements that the adsorbent has good water stability, high water absorption rate, fast adsorption and desorption, low desorption heat, low desorption temperature, small specific heat capacity, good regeneration stability, low cost, good heat transfer performance of the heat collection bed, and coordinated desorption and condensation. Good water stability is an inevitable requirement for adsorbent, and the non-deliquescence of adsorbent is beneficial to system structure design. Most improvements based on adsorption materials only focus on improving the water absorption rate, but the heat and mass transfer performance of the adsorbent are equally important. They affect the speed of adsorption and desorption and thus affect the performance of the system [61,62,64,65]. The fast adsorption and desorption mean that the water uptake system can complete more adsorption and desorption cycles in a day to achieve higher water uptake. Low desorption temperature, low specific heat capacity, and low desorption heat mean that the system requires lower energy for operation and can achieve higher water uptake per unit of energy. The energy of adsorption and desorption water uptake is mainly consumed in the heating and desorption stage of the adsorbent, part of which is used to heat water and adsorbent and part of which is used to make the adsorbed water vaporize. The addition of heat storage in the system can store excess heat, respond to solar radiation changes, and extend the desorption time [66]. Good regeneration stability of adsorbent is also the premise of the application of adsorption and desorption atmospheric water harvesting technology [61,65]. The adsorption and desorption of water harvesting require a large number of adsorbents, and the low-cost adsorbent is the guarantee for the economy of the technology in practical application. The excellent heat transfer performance of the heat collection bed can reduce energy loss. Meanwhile, the introduction of the condenser can strengthen condensation and improve water uptake [63]. The optimization of adsorbent bed structure and condensation can fully exert the water absorption capacity of adsorbent but fundamentally improve the water uptake.

3.4.2. Application Prospect

The adsorption and desorption water uptake system has lower requirements on the environmental temperature and humidity than the condensation water uptake system and is suitable for use in arid areas. The energy consumption is usually 0.1–1 L/kWh [39]. In the study of Lord et al. [67], the north of South America, the east of Africa, and Southeast Asia have a large potential for atmospheric water harvesting, and these regions are regions lacking in drinking water. The use of adsorption and desorption water harvesting technology is expected to achieve the goal of providing drinking water for 1 billion people. The key is to achieve continuous water uptake to improve the water uptake performance of the system. Increasing the adsorption and desorption speed can double the water uptake rate and reduce the amount of the adsorbent, which is conducive to the miniaturization of the device and reduce the manufacturing cost. The continuous water uptake can adsorb in the daytime, which is conducive to exerting the maximum adsorption capacity of the adsorbent and improving the energy utilization rate [68]. It is also a good option to use the photothermal adsorbent to integrate the adsorbent and the heat collection bed to improve the heat transfer efficiency of the adsorbent, which can enable the system to work at a lower ambient temperature [69]. In the study of Peeters et al. [39], the theoretical energy consumption of the adsorption and desorption method is no big different from the actual energy consumption. However, the adsorption and desorption water uptake system used in a low-humidity environment leads to low water uptake performance.

4. Active Collection of Fog and Dew

The traditional collection of fog and dew is passive. Improving the substrate surface materials and collector structure through bionics can improve the water collection capacity. However, due to the temperature and humidity factors generating fog and dew, the water collection capacity cannot be fundamentally improved. The application scope of fog and dew collection is also smaller than the condensation and adsorption and desorption atmospheric water harvesting technologies. Introducing energy into dew and fog water collection systems can improve water uptake and overcome the influence of unfavorable temperature and humidity conditions. Guan et al. [70] enhanced dew formation through artificial refrigeration, improving the water collection efficiency of the Teflon water collection panel by 45% and the aluminum water collection panel by 150%. Peng et al. [71] combined the cactus thorn structure with a magnetically induced flexible conical array, which can automatically and continuously capture fog water under the action of an external magnetic field under windless conditions. The water can be transported from the tip of the thorn to the bottom under the action of Laplace pressure, overcoming the difficulty of collecting water in static fog. Damak et al. [72] used electric field force to overcome aerodynamic resistance, introduced space charge into the fog through an ion emitter, made the fog droplets carry a net charge, and attracted them into the collector with an external electric field.

Table 3 summarizes the features and parameters of the selected active fog-dew water harvesting systems mentioned above. The mentioned researches are all experimental research. The performance of the device is measured under different working conditions. In general, the water collection performance of the device is 0.7–24 L/m^2/h.

The performance influencing factors and ways of influencing each atmospheric water harvesting technology are summarized in Table 4. There are many factors affecting the water uptake by condensation and the adsorption and desorption water uptake. (1) The environmental temperature and humidity and how to reduce the temperature of the condensation surface have a great impact on the efficiency of the water uptake by condensation. (2) The major influence on adsorption and desorption water uptake is how to achieve multiple adsorption/desorption cycles in a day. (3) The research focus of active dew and fog water collection is to achieve fog water collection in calm conditions and introduce external energy to improve dew collection.

Table 3. Features and parameters of selected active fog-dew water harvesting systems.

Water Uptake Mode	Features	Working Condition	Performance
Active dew collection	Enhanced by artificial cooling [70]	Ambient temperature at 5.7–11.9 °C, RH at 70.1–95.1%	Enhancement of 45% and 150% for Teflon and aluminum collectors, respectively
Active fog collection	Magnetically responsive flexible conical arrays [71]	Ambient temperature at 27 °C, RH = 80%	2 L/m^2/h
	Electrostatically driven [72]	Voltage = 10 kV, RH = 100%	24 L/m^2/h, 40 W/m^2
	Radial electric field [73]	Voltage = 40 kV, air velocity = 2 m/s	1.367 L/m^2/h
	Combining wires with electric field [74]	Voltage = 25 kV, RH = 100%	0.7–2.7 L/m^2/h, 60 W/m^2

Table 4. Performance influencing factors and influencing results of various atmospheric vapor harvesting technologies.

Type of Atmospheric Water Harvesting	Performance Influencing Factors	Ways of Influence	Lifting Rate of Water Uptake Rate
Direct condensation	Ambient temperature	High temperature is favorable for water harvesting	It determines whether there is condensate [39]
	Relative humidity	High relative humidity is favorable for water harvesting	It determines whether there is condensate
	Airflow	Affecting heat transfer and droplet removal, limited by cooling capacity	28% [30], 50% [37]
	Temperature of condensation surface	Low temperature is better, limited by frost	It determines whether there is condensate [37]
	Thermal conductivity of condensation surface material	High thermal conductivity is better, limited by frost	-
	Wetting characteristics of condensation surface	Affecting heat transfer and the generation and removal of droplets, limited by other factors	110% [31]
	Installation angle of condensation surface	Affecting droplet removal and system structure, limited by other factors	680% [33]
	Regenerator	Reducing energy consumption	-
	Intelligent monitoring and control	Improving the environmental adaptability of the device and reducing energy consumption	-
Adsorption and desorption	Water absorption rate	Affecting water release at desorption stage	4–6%
	Adsorption/desorption speed	Affecting the time of adsorption/desorption cycles	Multiplied by the times of absorption/desorption cycles
	Desorption temperature	Low temperature, low energy consumption	7–8%
	Specific heat capacity of adsorption material	Low specific heat capacity, low energy consumption	3%
	Desorption heat	Low desorption heat, low energy consumption	15%
	Regeneration stability of adsorbent	Affecting long-term water harvesting	-
	Adsorption material cost	Low cost, good practicability	-
	Heat transfer performance of adsorption bed	Affecting heat transfer efficiency	-
	Enhanced condensation	Improving water vapor condensation rate	-
	Heat storage	Respond to changes in energy supply and extend desorption time	-

Table 4. *Cont.*

Type of Atmospheric Water Harvesting	Performance Influencing Factors	Ways of Influence	Lifting Rate of Water Uptake Rate
Active collection of fog and dew	Enhanced by artificial-cooling	Improving water collection rate	45–150% [70]
	Magnetically responsive flexible conical arrays	Fog harvesting under windless conditions	It determines whether there is water collected [71]
	Electrostatically driven	Fog harvesting under windless conditions	It determines whether there is water collected [72]

There are more than ten manufacturers providing atmospheric water uptake devices in the market, such as Watergen [75], FND [76], SOURCE [77], Atlantis Solar [78], Drinkableair Technologies [79], etc. SuntoWater [80], an adsorption-based atmospheric water uptake device, uses solar energy, forced convection of a ventilator, and condensation after adsorbent heating and desorption. It can work under the condition that the ambient humidity is only 10%, producing 30 L of water a day, and the energy consumption for water uptake is 1.25 L/kWh. Another water uptake device named WEDEW [81] is powered by biomass, with a power of 25 kWh and a water uptake energy consumption of 3.33 L/kWh. Rainmaker [82] uses wind energy to make water. One water uptake unit can make 5000, 10,000, or 20,000 L of water a day, with power ranging from 25 kW to 100 kW. Some products also use power grids, solar energy, and generators to supply energy. However, there is still a long way to go from commercial publicity to actual household use. Bagheri [83] tested three types of household atmospheric water uptake devices with a nominal capacity of 30 L/day and a power of 1500 W. Results show that the actual energy consumption of the device was 1.02 kWh/L and 6.23 kWh/L respectively in warm humid and low-temperature humid environments, which is different from the performance advertised by the manufacturer. At present, the atmospheric water uptake device has not been widely seen by the public. It is still necessary to improve the actual performance of the device, reduce its water uptake energy consumption, and make it a more economical drinking water source than the traditional water source.

5. Conclusions

Atmospheric water is a potential renewable water source with huge reserves. This study analyzed the energy consumption of two major atmospheric water harvesting technologies, condensation and adsorption, as well as the application prospect of "Trading-in Energy for Water."

As for water harvesting by condensation, its water uptake performance and application scenarios are expected to be further expanded with an in-depth understanding of the factors affecting its performance [30,40]. The optimization of the system structure [23,37,84] and the development of new air humidification [35] and air concentration [36] technologies. For adsorption and desorption water harvesting technology, more research shifts the focus from improving the water absorption performance of the adsorbent to the heat transfer and system design. For example, the photothermal adsorbent improves the heat transfer performance of the adsorbent [54,55], the reflector improves the use of solar energy [85,86], and the condensation is enhanced to improve the water vapor condensation rate. It is expected to achieve efficient and continuous water uptake and improve energy utilization.

The atmospheric water harvesting technology has significant advantages in the open-source of water resources due to its wide applicability, guaranteed water volume, and sustainability. Atmospheric water harvesting technology can also improve the utilization rate of renewable energy and promote the development of energy technology. There is a lot of renewable energy, and there are a lot of water shortage areas in the world. Atmospheric water harvesting technology is expected to alleviate energy waste and water shortage, promote economic development, and conform to the concept of sustainable development. The limited refrigeration technology, air humidification technology, as well as the absence of highly efficient adsorbents are the main bottlenecks that are factors limiting the generation of presented technologies. The solution to these problems will help atmospheric water harvesting to become an economical daily drinking water source.

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