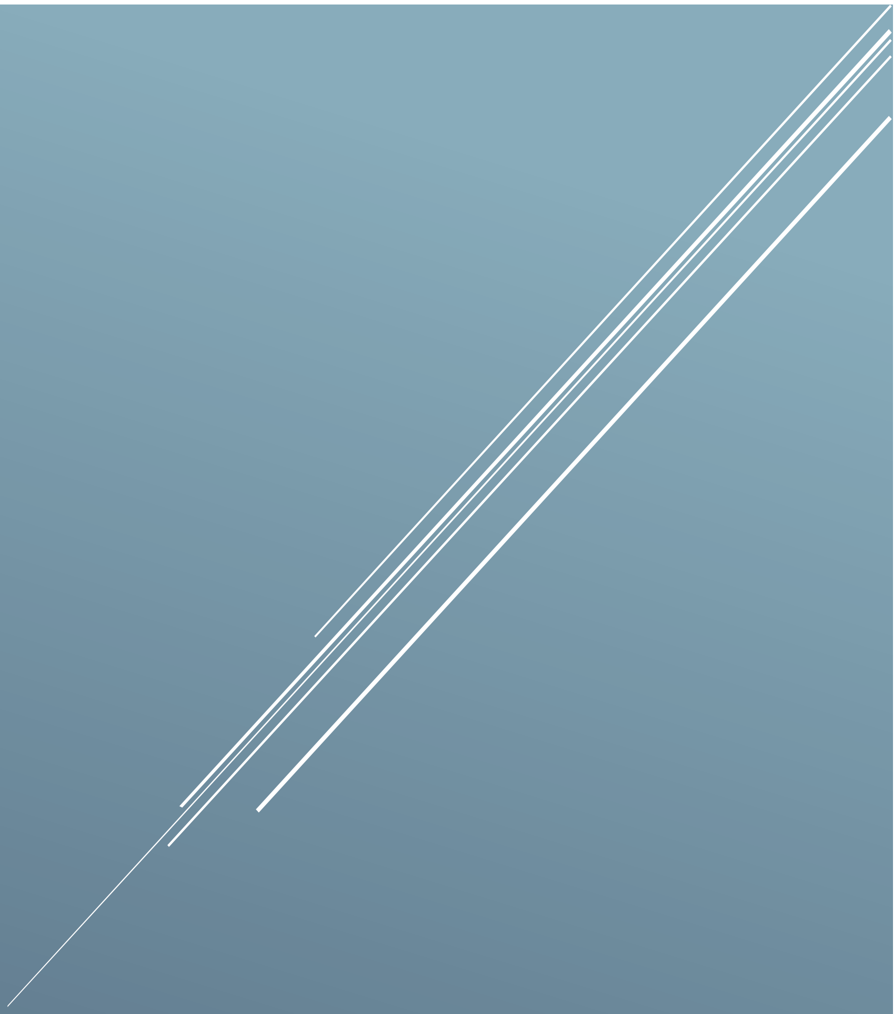

QUICK HANDBOOK ON DEW FORMATION AND PASSIVE RADIATIVE COOLING

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1. Introduction

Welcome to the Handbook of Dew Harvesting! In this comprehensive guide, we will delve into the fascinating world of dew and explore its potential as a valuable water resource. Dew harvesting, a method of collecting water from the atmosphere through condensation, has gained significant attention in recent years due to its simplicity, effectiveness, and sustainability.

This handbook aims to provide you with a solid foundation in the principles of dew harvesting, starting from the basics of condensation and the dew point. We will unravel the mysteries behind dew formation, exploring the intricate interplay between temperature, humidity, and other meteorological factors that contribute to the creation of dew.

By understanding the physics of passive radiative cooling, you will gain insights into how dew harvesting systems leverage natural processes to collect and condense water vapor. We will examine different techniques and designs employed in applied dew harvesting, from simple and low-cost solutions suitable for individuals and communities to more advanced systems utilized in agricultural and industrial applications.

But dew harvesting goes beyond science and technology. It has significant societal implications, particularly in regions facing water scarcity or lacking access to clean water sources. We will delve into the social, economic, and environmental aspects of dew harvesting, exploring its potential to empower communities, improve livelihoods, and contribute to sustainable water management.

Throughout this handbook, you will find illustrative pictures that bring the concepts and techniques to life, enhancing your understanding of dew harvesting principles and applications. We aim to provide you with a comprehensive and accessible resource that equips you with the knowledge and tools to explore and implement dew harvesting in various contexts.

Whether you are a scientist, engineer, student, or enthusiast passionate about water conservation and sustainable solutions, this handbook will serve as your guide to unlocking the potential of dew as a valuable source of water.

Join us on this captivating journey as we uncover the science, technology, and societal impact of dew harvesting. Together, let's embrace the power of dew to address water challenges and build a more sustainable future.

2. Principles of condensation, dew point and enthalpy

In gases it is understood that each molecule maintains a form of fast movement also called thermal motion. In the humid air the water molecules possess a high thermal energy by moving fast around within the gas mixture that is called air. Thus we need to understand the event of condensation as a highly dynamic event on a molecular scale. The moment a volatile H2O bonds onto a liquid state molecule this motion energy is dissipated. Now the water molecule has a very low motion or thermal energy and is in the liquid state. If a continuous withdrawal of this energy is applied, more gaseous water molecules will bond with their liquid partners. We then call this condensation and it is the same process that makes rain droplets grow. Usually droplets like to start to grow on a small particle or a surface.

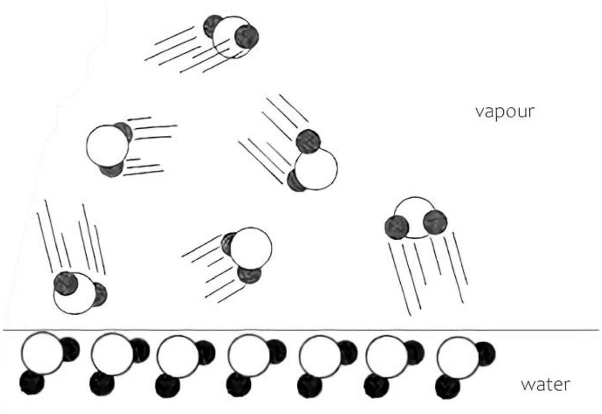

Figure 1 – molecular model of the boundary layer of vapour in air and liquid water

The closer to a condensing film of water one gets, the denser the arrangement of the water molecules becomes. One way to describe this saturation in humid air is the partial pressure e_{vapour}. Air can hold only a certain amount of water depending on temperature and barometric pressure. These factors also determine the maximum amount of water vapour air can hold also described through the saturation pressure e_{sat}. The partial pressure and the saturation pressure are expressed through the popular term of relative humidity.

$$RH = \frac{e_{vapour}}{e_{sat}} \qquad [RH] = \% \qquad 2\text{—}1$$

Since e_{sat} increases with increasing temperature the relative humidity sinks although the mass of water in the air doesn't change. Thus, the RH is good for human sensitivity but has no unit to be compared within common physical parameters.

A more comparable parameter than the relative humidity is its counterpart the dew point. The point on the temperature scale easily describes at what air temperature vapour starts to leave the air body and become liquid. For dew formation a surface temperature below the dew point is desired to ensure constant condensation.

$$\gamma_m(T, RH) = \ln\left(RH * e^{\left(b-\frac{T}{d}\right)\left(\frac{T}{c+T}\right)}\right) \qquad [\gamma_m] = 1 \qquad 2\text{—}2$$

$$T_{dp} = \frac{c * \gamma_m(T, RH)}{b - \gamma_m(T, RH)} \qquad [T_{dp}] = °C \qquad 2\text{—}3$$

with b = 17,368 ; c = 238,88°C ; d = 234,5°C ;

So motion energy is quantified for a majority of substances and called enthalpy of condensation. The reversed energy is the enthalpy of vaporization and is the same in quantity but in the opposite direction. The vaporization of water needs energy while the condensation of water releases energy called latent heat. The important effect here for dew formation is that latent heat is emitted when the volatile H2O molecules bond into liquid water. Thermodynamically speaking, vapour is of a higher state of energy than liquid water, so the process is exotherm. The amount of energy released equals the enthalpy of condensation and limits the condensable amount of water in practical terms. The specific enthalpy can be assumed as constant of L=2453 kJ/kg for temperatures and pressures perceived as normal in the lower atmosphere. In words, this means that for every kg of condensed water an enormous amount of 2,5 MJ is emitted at the spot.

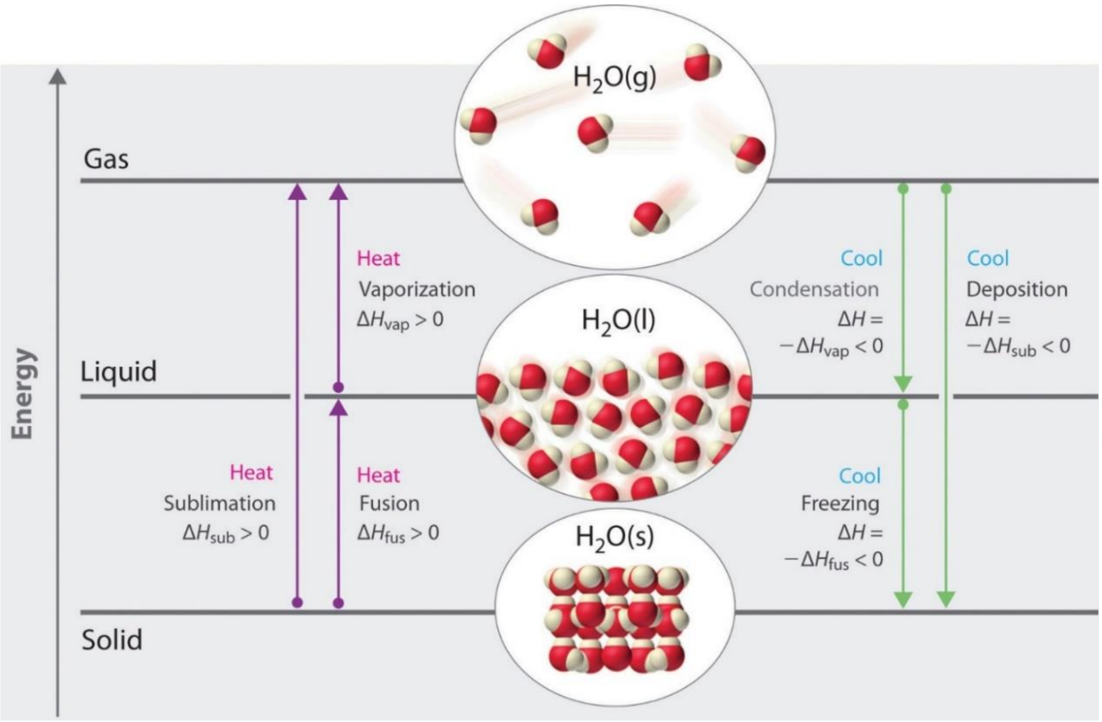

Figure 2 – changes of state visualisation. Note that condensation requires a negative enthalpy (—ΔH_{vap}) equaling the energy needed to withdraw

3. Principles of dew formation

Naturally dew can be observed in the early morning hours after a clear night sky with humid air and moderate wind. With a constellation like this, very radiant materials can achieve temperatures well below the dew point and collect fair amounts of water. Investigations on atmospheric vapour condensation are approached experimentally with different materials and designs in addition to simulations and theoretical calculus. There are no standards, but previous studies have shown data to form a set of techniques and environmental factors for efficiency and outcome. The harsh environmental conditions such as UV-radiation, strong winds and dust can affect the water quantity and quality to a high level. The set of factors for a full coverage of dew factors involving are of different nature but can be categorized in the ones affecting the quantity or quality.

The first studies date back to the early 60s where physics seemed to explain biological and agricultural issues with promising results. Monteith for example (Monteith 1965, 205) assessed dew within a complete water and energy balance for agricultural and natural fields. The energy balance involves fluxes from passive radiation by surfaces, sensible heat by air and the latent heat due to condensation. The physical basis relies in energy balances because all bodies with a temperature above 0°K emit infrared (invisible) electromagnetic waves.

The composition of the earth's atmosphere characterizes the thermal properties and respectively the transmittance or opacity of electromagnetic waves. The amount of energy emitted by a surface that can pass the atmosphere without being either blocked, absorbed or reflected determines whether the Besides the transparency in the wavelengths of visible light there is a so-called atmospheric window for wavelengths of about 8 – 12µm (infrared) where radiation can leave the earth without being absorbed or reflected by a compound in the atmosphere. Most of the radiative power is transmitted inside of the atmospheric window. The figure below generally describes the atmospheric opacity on a logarithmic scale by wavelength. However, the opacity in the infrared area is predominantly governed by the presence of clouds because of the high absorbency of water molecules. Thus, the atmospheric window "shuts" with high cloud coverage and outward radiation sinks to a minimum impeding a thermal loss of surfaces facing the night sky.

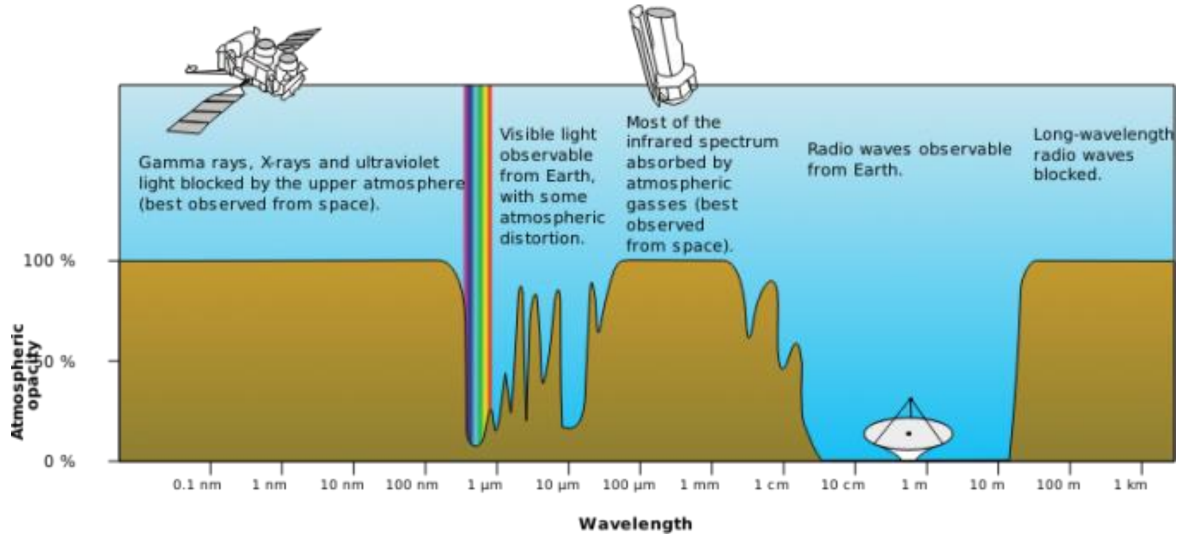

Figure 3 – Spectrum of which the earth's atmosphere blocks or is penetrated by incoming and outgoing electromagnetic waves

In order to experience a large thermal power loss leading to a low temperature at the surface, a dew collector material should have a high emittance (or equivalently, a high absorption) in the infrared wavelength range. A cooling effect is observable if the net radiation Rn is of negative nature, meaning the outgoing radiation exceeds the incoming and surface temperature starts to drop. The net radiation is an energy balance where La represents downward longwave radiation and Lf upward longwave radiation.

$$Rn = La - Lf \qquad [Rn] = \frac{W}{m^2} \qquad (3—1)$$

From the perspective of a condensing surface, all incoming radiation is positive whereas outgoing radiation is negative. During night-time, the incoming downward radiation La is smaller than the upward radiation Lf and the net radiation becomes negative leading to a refrigerated surface. Figure 4 is a simplified radiation-only approach where the radiation from the ground is neglected for the interest of upward net radiation.

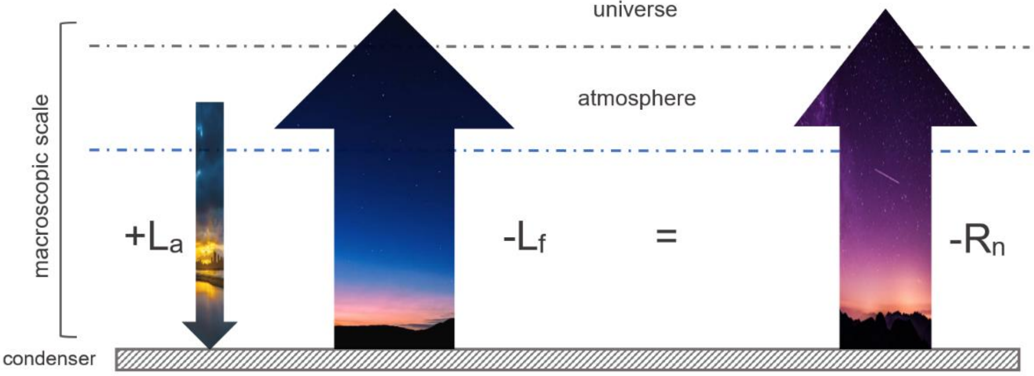

Figure 4 – negative net radiation on a self-cooling surface at night-time

This process is fundamental for radiative cooling applications. The magnitudes of incoming and outgoing fluxes depend on the weather conditions and surface quality for $+L_a$ and $-L_f$ respectively. For applied dew harvesting this real environment applications

For the model of passive radiative dew harvesting a graybody (emissivity $\varepsilon<1$) surface is considered to be insulated at the back and to lose net thermal radiation power causing it to drop below the ambient temperature. Once the net radiation (Rn) provides the cooling power necessary to overcome the sensible heat from above (Q_a) and from below (Q_i) the surface temperature begins to drop. Dew occurs when the condenser temperature falls below the dew point temperature, because an air layer adjacent to the condensing surface gets supersaturated. At this point the latent heat of condensation (*L*) act as an incoming energy flux too and needs to be withdrawn via passive radiative cooling. Convection and conduction from the air (Q_a), as well as conduction via the back insulation (*Qi*), deliver heat to the radiator. Diffusion and convection transports water vapour towards the air layer at the condensing surface at the same time. The latent heat (*L*), multiplied by the condensation rate (*E*), is transmitted to the radiator per unit time during condensation (Nilsson et al. 1994, 311). Knowing the latent heat of water being 2453 kJ/kg the condensation rate can be predicted for this simplified physical model. This matter of principle describes the object of this study in a sufficient way and is considered throughout this thesis in calculations and design. Thus, the energy balance for an enhanced dew harvesting surface is as follows:

$$0 = LE + Qa + Qi + \Delta S - Rn \qquad (3—2)$$

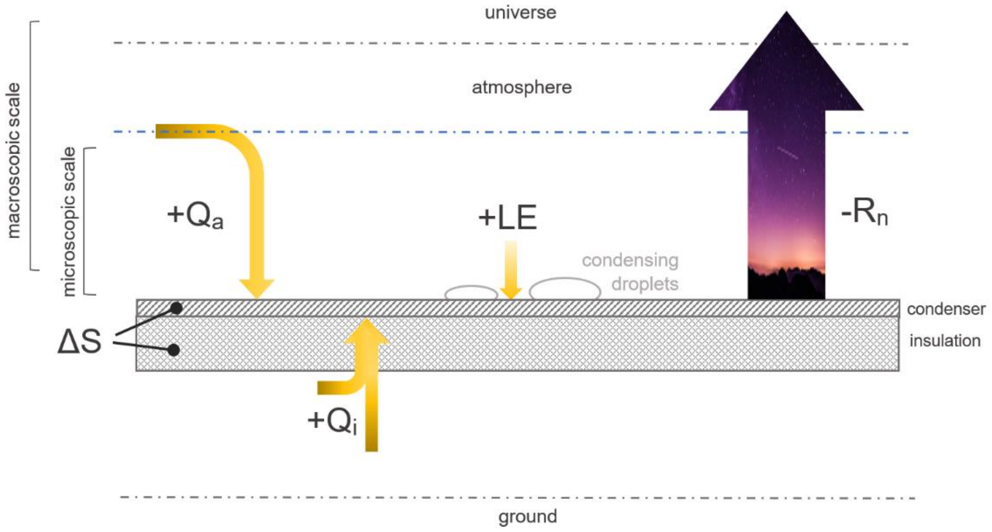

Figure 5 – energy balance of an insulated condensing surface comparable to the studied object

LE – latent heat flux of condensation

L being the enthalpy of condensation of 2453 kJ/kg. E the condensation rate in e.g., L/s or L/(m²s) or mm/s equals the amount of condensed water on the surface after the condensation period. The latent heat flux is one of the biggest fluxes due to the relatively high enthalpy of water. For the purpose of dew harvesting this term should be as high as possible to yield a fair amount of water.

Q_a – heat flux by air layer

The humid air in contact with the condensing surface conduct heat to the condenser and winds amplify the heat exchange. On a microscopic scale this air layer is the source of droplets forming on the condenser. Qa can be introduced by convection or conduction, which one represents the higher flux depends on wind speed and air temperature.

Q_i – heat flux through insulation

The sum of a heat flux entering through the insulation Qi is to be retained minimal. The ground radiation and the surrounding air heat act via conduction and convection as heat fluxes and migrate by conduction through the insulation to the condenser. The specific design in figure 5 describes the study object in a sufficient way. There is a plenitude of other designs where the insulation acts as a condenser or inflatable condenser where the insulator is a body of air. The bigger the insulation the smaller this heat flux is but the thermal mass increases at the same time.

ΔS – stored energy

An energy storage in materials that heat up during the day is considered here by the change of the stored thermal energy ΔS. This can be considered by knowing the material thermal storage capacity and mass of the condenser.

4. Applied dew harvesting

A high rate of radiative cooling is key to a higher yield but as figure 5 implies dependency on environmental as well as internal factors. The water quantity as well as quality is subject to numerous considerations such as positioning, materials in use and many more. In figure 6 the numerous elements are bound into mechanisms affecting yield and quality of the collected dew.

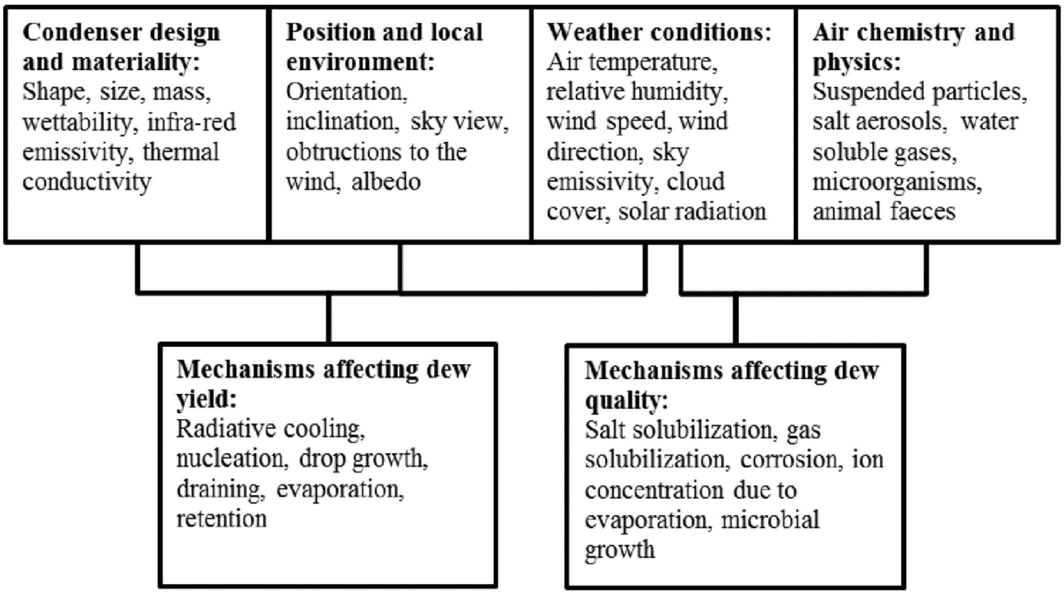

Figure 6 – overview of factors influencing dew water quantity and quality (Khalil et al. 2016)

Since the focal topic is the dew yield and enhancing dew formation artificially the water quality will not be discussed here. Augmenting dew yield can be either achieved by optimizing the design (e.g. windbreaking) and materiality (e.g. high emissivity) or is dependent on the local weather conditions (e.g. cloud coverage). Sharan investigated a variety of materials, including galvanized iron and aluminium sheets, and discovered that sheets of a unique plastic produced by the OPUR that were just 400 micrometres thick performed even better and were less expensive than the metal sheets (Girja Sharan and Beysens 2005). OPUR has produced a mineral filler containing titanium dioxide and barium sulphate ready to be mixed with conventional paintings (Daniel Beysens, Owen, and Muselli 2007, 13). The particles are UV stable and have been recognized as safe for use in food contact and have been patented for radiative cooling purposes and natural water condensation. The paint inhibits a highly hydrophilic character that retains over time and effectively promotes the condensation of atmospheric water vapour. This highly hydrophilic character also favours the gravity flow of the condensed water on the surface.

CFD offer simulations for various shapes like funnels or complex roof structure. Energy fluxes and moving and cooling air can be used for temperature analysis, so that the condenser surface temperature can be determined. For this purpose, real world experiments can be compared with the CFD results on an empirical basis. Experiments have been carried out for several pilot systems in accompaniment to CFD simulation (Owen et al. 2007). Wind speed (v, m/s), relative humidity (RH, %), cloud cover (N, octas), ambient temperature (T_a, °C), and dew point (T_d, °C) are now well understood and can relate to a minimal number of meteorological parameters. These correlations are fed in CFD simulations for a more predictive modelling for shape, materials and positioning of dew harvesting devices. Out of a set of shapes the funnel shaped object was showing less impact on dew yield by higher wind speeds which sets it as preferable for the windy environment on Tinos Island.

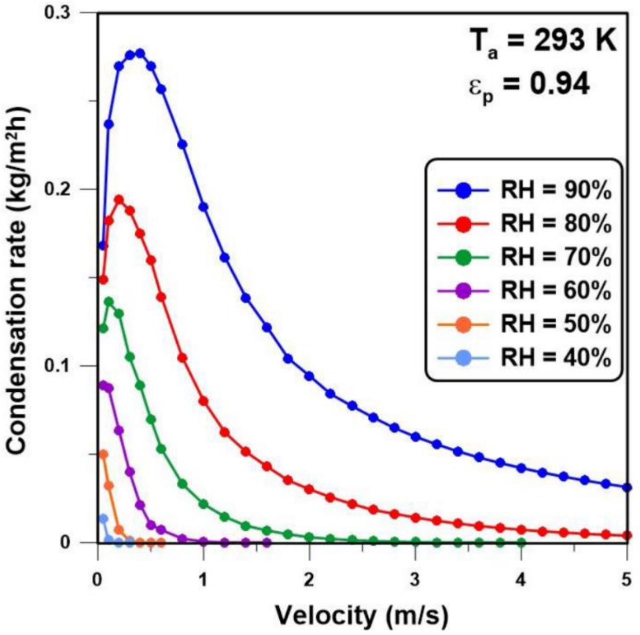

Figure 7 – Variation of condensation rate at different wind speeds and different relative humidity

However, predicting the condensation pattern and finally the water yield in dew harvesting remains complex. The temperature drop compared to dew point of the surrounding air gives a good correlation to the water output. Wind carries water vapour to the surface if it is present; hence, a modest wind velocity of <1 m/s is advantageous (Babaei et al. 2020, 7) for water condensation. Some simulated results and numerical models are verified within a real environment and observed by physical parameters that were proven to have great influence in dew formation. Figure 8 is a reference and summary for the most influential elements discussed in applied dew literature and will be considered in material and methods for the design as well as evaluation of results.

Element	***Optimal***	***Unit***	***Effect***	***Comment***
Wind speed	0,15 – 1	m/s	– ~	High speed winds inhibit dew formation whereas a steady breeze can increase dew yield
Cloud cover	0	okta	– –	Highly covered night sky hinders long wave emittance and radiative cooling
Relative humidity	>80	%	+ +	A high relative humidity is recommendable unless clouds start to form inhibiting radiative cooling
Dew point	>15	°C	+ +	The higher the dew point the less temperature drop of the surface is needed to start condensing
Wind direction	0 – 360	degree	~ ~	On a rotative design the wind direction has no effect on the condensation process
Day time	00 – 05	hour	~ ~	Dew formation can only happen during night and increases by time beginning from the sunset

Figure 8 - environmental quantitative parameters and influencing factors for dew formation

Element	*Optimal*	*Unit*	*Effect*	*Comment*
Surface area	>10	m²	+ +	A greater surface directly correlates to a higher yield
Surface emissivity	>0,94	1	+ +	High emissivity in the infrared spectrum and hydrophilicity and -phobicity should be in balance (see Figure 4: Rn – net radiation)
Insulation layer	1 – 5	cm	~ +	Incoming energy fluxes from the ground are hampered but contributes to higher thermal mass (see Figure 5: Qi – heat flux through insulation)
Condenser mass	<<	kg	– –	The higher the mass of the condenser device the more energy is stored during the day and needs to be withdrawn before dew occurrence (see Figure 5: ΔS – stored energy)
Wind protection	/	/	+ +	To ensure a high yield even during windy days, a structural form of wind braking which allows humid air to enter but restricts high wind speeds (see Figure 5: Qa – heat flux by air layer)

Figure 9 – overview on design and material elements influencing dew formation for planar condensers

However previous applied dew harvesting always depended on passive radiative cooling and thus on the weather conditions. Applying an actively cooled condenser surface widens the limitations by environmental conditions providing a more reliable dew harvesting method.

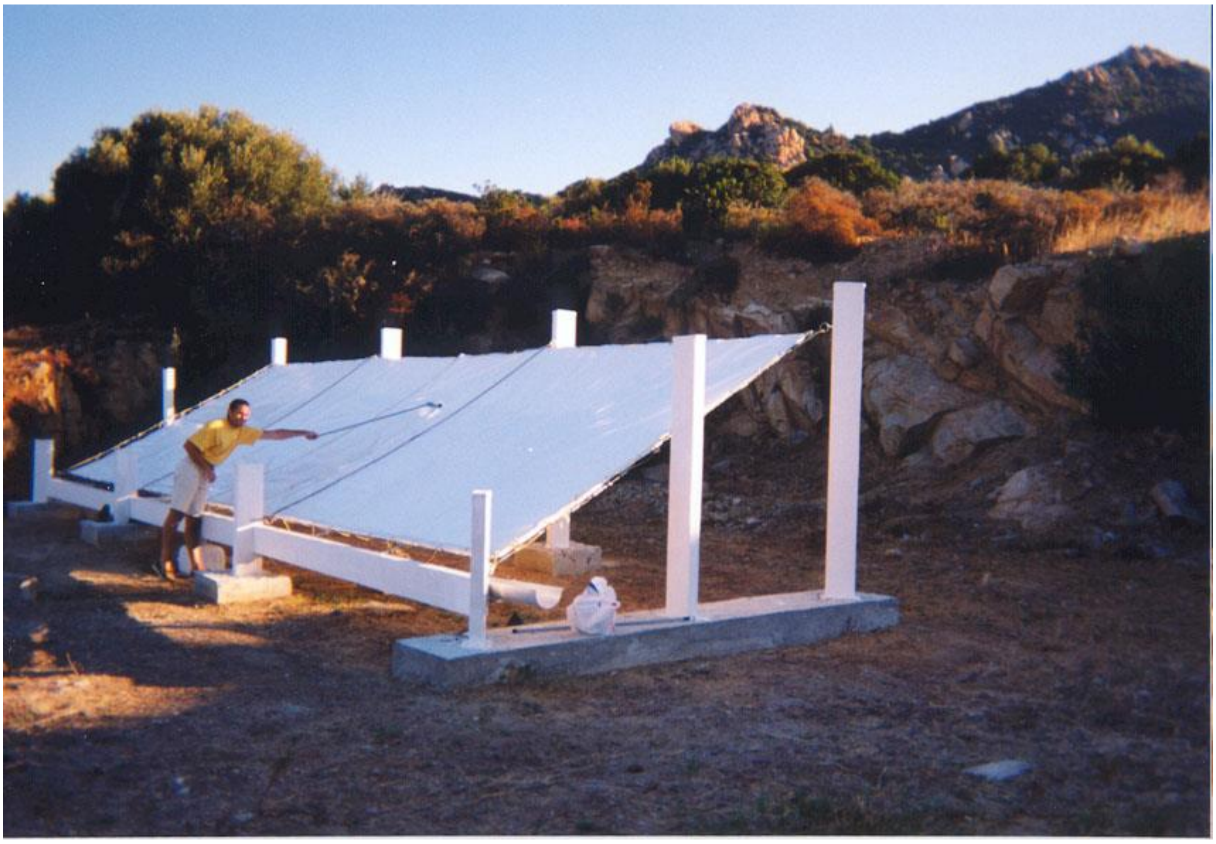

Figure 10 – Big OPUR Dew Condenser in Corsica

5. Societal aspect and economics of dew harvesting

The non-technical aspects of unconventional water resources are just as essential as the technical side because an enabling environment is required to facilitate the uptake of these water resource augmentation potential in a region or country. The non-technical aspects include governance, policies and institutions, economics and financial feasibility analysis in the context of circular economy, education and capacity building for skilled human resources and community, culture, and gender aspects. Most AWG devices employ this technology in conjunction with filters to deliver potable water. These devices are promoted as environmentally friendly alternatives to bottled water. This claim is unsupported by evidence because such systems require a lot of energy to run. Bottled water outperforms these AWGs, but if the AWGs are powered by renewable energy sources, they can be an environmentally friendly alternative to bottled water.

Although economic valuation of unconventional water resources is complex, it remains an important aspect to guide policymakers and investors to make informed decisions. The valuation if the benefits of action or, alternatively, valuation of the costs of no action is necessary to justify suitable investments in harnessing the potential of unconventional water resources. The perceived high costs of technology for using unconventional water resources without undertaking comprehensive economic analyses and innovative financing mechanisms restrict developing such water resources and scaling up their use. Such economic analyses do not consider the alternate water supply options such as tankers or water transportation from wells from far distances including the costs in the form of women’s time, labour, and poor health. With the aim at eliminating or minimizing waste and recycling and reusing products, materials, and resources, circular economy is a path forward towards harnessing the potential of unconventional water resources.