3DFOGTECH©
Portable Fog Water Station for Water-stressed Environments

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ABSTRACT: 3DFOGTECH© is a water enhancement technology applied in fog collection. This study is focus on geo-climatic data collection in selected fog sites, including design and structural test. 3DFOGTECH© is a portable, lightweight and modular polyhedral space-frame with light-coloured and water-repellent textile screens that collects condensed water drops in 360° from fog promoted by physical surface effects such as cooling, coalescence and condensation following the multi-directionality of winds, without any active energy demand. It offers autonomous water management in water-stressed areas with frequent dense fog events. Previous experiments made by author and collaborators (2010-16) were focused in obtaining efficient forms and designs through lighter space-frames and affordable hydrophobic meshes to secure clean water for drinking and irrigation. 3DFOGTECH© can harvest at least six times more water than planar fog collectors. Tubular frames are made with aluminium, which is a light, strong, durable and recycling material, whilst modular meshes are made with textiles treated with water-repellent coating solutions, light coloured surfaces and natural, synthetic or remanufactured polymers. Advanced design, connectors and structural prototypes are tested digitally and physically. 3DFOGTECH© is an applied research project co-financed by EU H2020 Marie Skłodowska-Curie and ACCIO TecnioSpring Plus programmes.
KEYWORDS: Design science, Water technology enhancement, 3D fog collection, Portable water station, Space-frames

1. THE FUTURE OF WATER IS IN THE AIR

Fog is a result of a complex earth system embodying a delicate balance between ocean, atmosphere, and land processes that shape and alter fog and its liquid water content (LWC) over time. Among alternative water supplies, the potential to collect water from air is by far the most underexplored resource. Only a thousandth of 1% of the water on Earth is in the atmosphere as water vapour. As part of the natural global water cycle, at any given time, the amount of water in the atmosphere is 12,900 km3, which represents 0.001% of total water and 0.04% of freshwater existing in the planet [1]. Fog originates from the accumulation of water aerosols suspended in the air, which create masses of humid air over land or sea. At low levels, air may contain fog or suspended liquid water droplets with diameters typically from 1 to 50 µm.

In airflow crossing natural formations like cliffs, mountains or ridges, orographic clouds might occur below, at or above the top of the obstacle, i.e. Fohen effect. Orographic influence on wind leads to the development or enhancement of clouds on the exposed side, which generally dissipates on the protected side due to downward motion. A cross-barrier flow might produce waves on the sheltered side, depending on atmospheric conditions and the topographic features. Sometimes, the oscillations of air on the sheltered side form lenticular clouds on the crests of such waves, which is airflow alteration due to relief. The most common orographic clouds belong to the genera Altocumulus, Stratocumulus and Cumulus. It is critical to observe cloud formations in highlands because they may provide an indication of weather changes that could have implications on fog collection [2].

Fog collection can contribute to alleviate water scarcity in water-stressed regions harvesting fog water to supply clean water for drinking and irrigation during hot seasons in arid lands like coastal deserts being viable solutions in remote locations with high fog occurrence. As potential source of water in coastal arid environments, fog collection is achievable by the collision of fog on a vertical mesh, where they coalesce, after which water runs down into a collecting drainage system and harvesting tank.

2. NEW CHALLENGES AND POTENTIAL USES OF FOG COLLECTION IN THE MEDITERRANEAN REGION

Nowadays water provision is a fundamental challenge in many water-stressed environments, natural, rural or urban. Risks associated with water shortage increase as the limited surface freshwater resources gradually diminish as result of rapid transformations and ineffective water grid distribution in the built environment. By 2050 2.3 billion more people than today (in total over 40% of the global population) will live in water-stressed regions [3]. Circa 14 million people in Europe do not have access to basic drinking-water source, in 2015 more than 62 million lack access to an adequate sanitation facility and 14 million do not use a basic drinking-water source Seven out of ten people without

access to basic drinking water sources live in fragile rural areas [4].
Fog collection is a simple, affordable and sustainable technology to obtain fresh water for irrigation and drinking in remote arid areas -nearby the coast- where surface water is limited [5]. Usually, users of fog collection are low-income farmers or rural villagers. In doing so, author has established a viable terrace-down model for fog water distribution, which follows natural slopes and water cycles. This scheme is well-adapted to both local water management and traditional agricultural techniques applied in dry and arid coastal zones in Mediterranean regions, including the Western Mediterranean reliefs of the Iberian Peninsula [6]. The harvested water is stored in tanks and then filtered and distributed via gravity through two separate pipelines: One branch supplies settlement with drinking water and the other extension is for irrigation of ecological restoration (native flora) and farms to prevent and mitigate the ongoing effect of desertification [7].

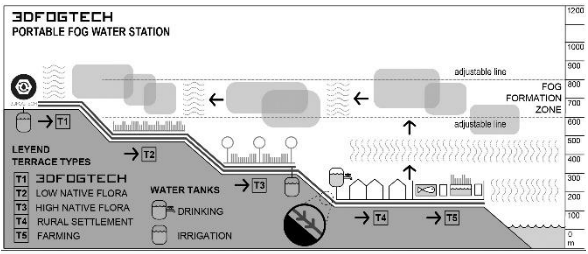


Figure 1. 3DFOGTECH© passive water distribution using gravity and slope to supply water for agricultural irrigation, ecological restoration and drinking. Source: author (2018).

3. RESEARCH, WORK PLAN AND OBJECTIVES

The duration of the overall project is two years. It is divided in three working packages (WPs) with distinctive tasks, milestones and deliverables. WP1 (ongoing stage; 8-month duration) is about climatic analysis, selection of fog sites and structural frame development. The next WP2 (10-month duration) will explore advanced textile development. WP3 (6-month duration) will test water capacities, yield and quality by monitoring, evaluating and disseminating technology.
The initial phase of this project (ongoing working package) is to (a) collect and map relevant geo-climatic data (selection of fog sites in Catalonia) and (b) develop a 3D fog collector, which is both adaptive and modular. Form follows climate. Climatic and geographic parameters are used to develop the design of portable fog water station (hexagonal array), which is made of lightweight metal structures that support strong winds and, through condensation, collect atmospheric water in water-repellent meshes facing multidirectional upwinds.
The objectives are to (a) explore innovative eco-design solutions (C2C) applied in advanced frames and screens with remanufactured materials like recycled and reused metal structures, remanufactured polymers, etc.; (b) develop modular, portable and lightweight frames and hydrophobic screens through digital and manual simulations, mock-ups, and proof of concepts; and (c) Integrate systemic design with high structural, textile and water yield performances during experimentation.

4. METHODS

The overall research encompasses six disciplines: eco-design, climatology, geography, structural engineering, materials science and textile chemistry.
The applied methodology in WP1 is research-by-design using theoretical, empirical and design-based tools. It is supported by literature review; precedent studies; fieldwork and site visits; digital design simulations; physical mock-ups; and workshop, lab and onsite tests of pilot project developed in labs and selected climatic stations and disseminated in relevant scientific media:
a. Literature review on precedent studies (study of planar vs. 3D fog collectors in Spain and worldwide).
b. Geo-climate data collection and analysis taken from the automatic/manual stations of AEMET (Spain) http://www.aemet.es; SMC (Catalonia) http://www.meteo.cat); and Wunderground https://www.wunderground.com. Real-time satellite maps from EUMESAT are used. Refer to EUMESAT-view, fog: https://www.eumetsat.int Fog and low clouds are based upon infrared channel data from the Meteosat Second Generation satellite. It is composed from data from a combination of the SEVIRI IR3.9, IR10.8 and IR12.0 channels. It is designed and tuned to monitor the evolution of night-time fog and low stratus. Individual survey includes fieldwork and site visits to all selected fog sites to measure, document visibility, wind, RH and temperature and climate parameters through photography and portable weather station. Psychrometric charts, spreadsheets and tables were used.
c. 3D Structural design and tests using AutoCAD & Sketch Up Pro to model space-frames; details and views. Design includes manual and digital representation in sketches, diagrams, CAD technical drawings and components; physical models. Each screen size is $1M^2$. They are elevated 2-3 metres above ground. Final prototype will be built in 1:1 scale and monitor by a Davis Pro 2 portable weather station with wireless integrated sensor, console and Weatherlink software.
d. 3D-printing. Connectors (joints) were modelled scales 1:5 and 1:1 using Flashforge 3D printer
e. Structural and CFD (Computational Fluid Dynamics) simulations using model making. Two structures were chosen and build in physical wiring models 1:5 scale (timber and aluminium bars). COMSOL Multiphysics 5.3 tools is used in both structural mechanics to measure axial, moment, shear and torsion and fluid flows to map lift and drag forces hexagonal prisms.

f. Open demos and citizen science talk in Barcelona Science Festival (June 2018).
g. Textile tests: Demonstration not achieved yet (WP2). Experiments will analyse wettability, surface area and adsorption parameters of selected textiles in a fog chamber at lab and then in-situ.
h. Water yield and quality test: Demonstration not achieved yet (WP3). Chemical and microbiological analysis of water samples.

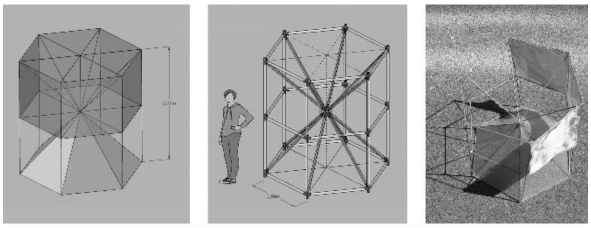


Figure 1. 3DFOGTECH© snowflake type: a. Concept; b. Frame and c. 1:5 Model. Source: Source: author, 2018

5. FOG ANALYSIS, MAPPING & SITE SELECTION

The Mediterranean Region (Cfb) is experiencing a significant shortage of rainfall, with severe impacts on rainfall-dependent settlements, farms and natural parks. In Spain, fog formations with high LWC are mainly located in Canary Islands and the Western Mediterranean Basin of the Iberian Peninsula, with annual rates of fog water yield between 3-10 l/m2/day average. Water needs will double by 2021 in Catalonia (Agència Catalana de l'Aigua, 2015). In Catalonia, frequent fog formations occur between 10km and 50km distance far from the Mediterranean coastline.

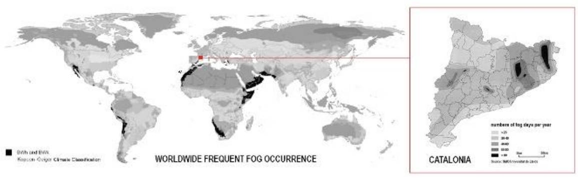


Figure 2. Map of frequent fog occurrence in Catalonia and worldwide (fog in black / dark grey). Sources: author (2018).

In Catalonia, advection fog (from sea to land) is mainly a phenomenon of cyclone episodes that occur in the Mediterranean littoral and pre-littoral zones, especially during cold seasons, between October and January. Prevailing wind direction is N and NE with wind speed between 2 and 5m/s. RH is higher (>80%) and temperatures are lower (<12°C). The average dew point temperature is between 7.1°C and 7,8°C [6]. Between 2006 and 2017, Montserrat Observatory (MO) recorded 96.1 foggy days per year, reaching 162 foggy days in 2001, and 2,7 m/s wind speed average.
The optimal places to catch advection fog are situated in Barcelona, Girona and Lleida provinces, mainly in high formations such as national parks and the Mediterranean Pyrenees. The best massifs or are Montserrat, Montseny and Albera [7]. However, the period for harvesting fog varies from site to site not offering a consistent pattern but rather randomized. The best fog harvesting point is Puig Neulós in Albera massif with 27.2 $\boldsymbol{l} \times \boldsymbol{m^2} \times \boldsymbol{day}$ of fog water in cold seasons, including Springtime, whilst in Montseny massif roses 11.6 $\boldsymbol{l} \times \boldsymbol{m^2} \times \boldsymbol{day}$ during Autumn [8].

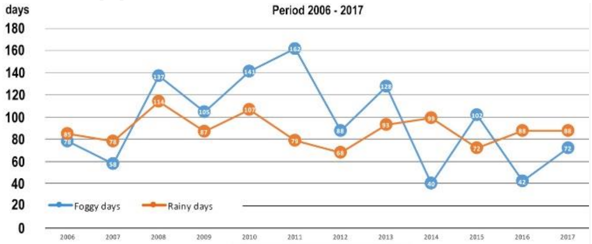
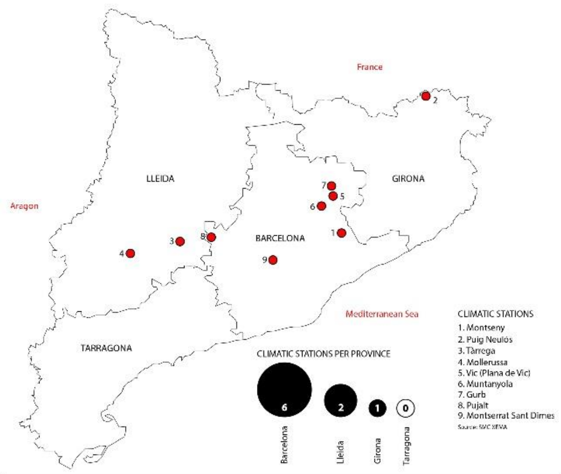


Table 1. Comparative table between foggy and rainy days in Montserrat abbey, 2006-2017. Source: MO (2018)

For instance, Puig Neulós offers the best conditions for setting experiment. It is a remote climatic station at 1256m a.s.l. (42° 28′ 51″ N; 2° 56′ 47″ E) with 7.1°C dew point; over 75% RH; and 3.9 m/s wind speed. Fog water is 22.3 $\boldsymbol{l} \times \boldsymbol{m^2} \times \boldsymbol{day}$, annual average [9]. The other suitable locations to set onsite experiments are Observatory and Sant Dimes stations (740m a.s.l. and 916m a.s.l. respectively) in Montserrat massif and also Turó d'Home (1712m a.s.l.) in Montseny massif. There is great potential in the rural landscapes of Gurb, Muntanyola, Vic (Plana de Vic), Pujalt, Mollerussa and Tàrrega.



3DFOGTECH Psychrometric table selected sites

location	Dry bulb Td °C	RH %	Dew point Tw °C	Abs. Humidity W (kg/kg)	Enthalpy h (kj/kg)	Sp. Vol (m3/kg)	Atmospheric pressure b	Wind speed m/s	Altitude meters	Köppen categories
Puig Sesolles Montseny	7.1	75.5	7.1	0.007	21.7	0.98	82827	4.86	1668	Cfa
Puig Neulós	13.5	86.8	7.8	0.006	36.2	0.88	87119	3.89	1256	Cfa
Tàrrega	14.1	77.5	7.8	0.006	34.8	0.87	96299	2.59	427	Cfa
Mollerussa	14.7	71.4	7.8	0.006	34.1	0.85	98393	1.44	247	Cfa
Vic (Plana de Vic)	13.4	79	7.8	0.006	33.7	0.87	95472	1.41	498	Cfa
Muntanyola	12	83	7.8	0.006	32.2	0.9	91954	1.50	811	Cfa
Gurb	13.5	86.8	7.8	0.006	36.2	0.88	94753	1.04	562	Cfa
Pujalt	12.2	79	7.8	0.006	31.6	0.9	92455	1.52	766	Cfa
Montserrat - Sant Dimes	12.2	88.4	7.8	0.006	34.3	0.91	90794	2.60	916	Cfa
TOTAL (average)	12.522	80.822	7.722	0.006	32.756	0.893	92229.556	2.273	794.667	n/n

Table 2. Comparative table of selected fog sites in Catalonia using psychrometric and climatic data calculations. Source: SMC XEMA & author (2018).

The potential beneficiary population represents circa 900,000 inhabitants, which means up to 12% of the population in Catalonia (IDESCAT, 2016). The Catalan Weather Service (SMC) employs different terminologies and methods to define and measure fog occurrence. Regarding weather data constrains, fog episodes are not recorded by automatic stations in Catalonia. Fog occurrence is measured in terms of visibility. In Catalan, Boira means dense fog (less than 1km of visibility); boirina is fog (visibility between 1-10km); and calitja means mist (visibility between 1-10km). The regional weather observation network (XEMEC) was founded in 2009, so it cannot offer retrospective data. Records of period 2010-18 have helped to identify trends in areas with frequent fog. As the fog observation points (i.e. airports) did not coincide with the location of the automatic stations, author has interpreted the general climatic data available in Osona, Urgell, Pla d'Urgell, Bages and Vallès Oriental regions. This study unfolds an updated climatic map of best sites for fog harvesting in Catalonia. Based on findings and permissions, two trials will be tested in the next research stages.

6. DESIGN & STRUCTURE ADVANCEMENTS

Problem: Planar fog collectors are structurally fragile tensile structures. They frequently fail under the heavy load of strong wind events. Meshes keep using polyolefin sun-shading nets with poor mechanical and spanning properties. Nets tear, gutters and pipes leak, and wind blow the whole structure over. Steel frames and tensile cables normally rust, and birds wreck textiles spoiling the process of fog water harvesting [10]. If wind changes its perpendicular direction, yield of fog harvesting decreases. This inefficiency is mainly due to the lack of fog-responsive design integration between dynamic weather factors; forms and geometries; and new materials and textiles advancements.

FOG COLLECTOR		CONVENTIONAL	3DFOGTECH
Structure	Form	2D planar	3D polyhedron
	Frame	tensile canvas type	modular space-frame, air-frame
	Connectors	tensors only	timber nods gutter clips column clips
	Foundation	permanent concrete pad	portable metal pad
	Manufacture	in-situ construction	off-site prefabricated construction
	Materiality	timber or metal posts	metal, Plastic, Timber, Paper
	Weight	heavyweight	lightweight
	Permanence	fixed	demountable
Mesh	Screen Ratio	1:2 / 1:3 / 1:4	1:1 / 1:2
	Fibre Texture	higher porosity	lower porosity
	Fog Collection	unidirectional (prevailing wind only)	multidirectional (windrose based)

Table 3. Comparative scheme of planar vs. 3D frames on textile and structural capacities. Source: author (2018).

Form follows multidirectional winds: The more wind, the more harvested fog water. In order to develop a high fog-responsive design, should integrate these multiple parameters: (a) Climate: Relative humidity, liquid water content (LWC), wind speed and direction, air temperature (wet bulb, dry bulb and dew point), visibility and atmospheric pressure; (b) Topography: Altitude, wind orientation, slope clearance (physical obstacles), soil mechanics and accessibility; (c) Shape: Screen ratio (height/length); height from ground, volume geometry, and structure types; and (d) Textiles advancement: Mesh pattern, textural porosity (spacing), colouring, polymer types, hydrophobic features and coating solutions.

In this early phase, throughout CFD simulations (computational fluid dynamics), model making and structural design, author is testing several experiments with light space-frames by eliminating tensors; reducing the amount of embracing elements; and creating a catalogue of connector including anchorage solutions following presumptive bearing capacity values for three different types of soils.

Design experiments: FOGHIVE© [11] is a 6-side fog collector that was tested in Atacama (Peña Blanca, Chile) in August 2014. Three mesh experiments were carried out: T1 (day 1) with 6-side insect nets (HDPE); T2 (day 2) with 6-side 3D mesh nets of polyester (PES); and T3 (day 3) with 5-side insect nets and one-side 3D mesh. Experiments examined (a) affordable insect net with lower porosity (white) and (b) 3D specialised fabric with higher porosity (black). Six PVC U-shape gutters and 10l tanks were installed, one gutter and one tank per 1m x 1m screen ratio. All fog collecting screens harvested equal fog water volume per screen regardless uniform and mixed meshes (T1, 4,1 $l \times m^2 \times day$ per mesh; T2, 3,8 $l \times m^2 \times day$ per mesh; and T1, 5,7 $l \times m^2 \times day$per mesh). Due to geometry and form of the selected volume and its wind multi-directionality, FOGHIVE© harvested six times more water content than planar devices.

Figure 3. FOGHIVE© test in Atacama Desert, Chile (2014). Source: author, 2018

3DFOGTECH© is an upgraded portable, lightweight and modular polyhedral space-frame with light-coloured and water-repellent textile screens that collects condensed water drops in 360° from fog promoted by physical surface effects such as cooling, coalescence and condensation following the multi-directionality of winds, without any active energy demand. This hexagonal cylinder consists of six screens (ratio 1:1 or 1:2). It can easily be installed on flatten or uneven grounds. It uses advanced polyhedral frames (towers), advanced textile materials and surfaces formed by coating processes, and remote wireless weather monitoring.

Shape and fluid dynamics: Relevant literature review on wind effect on solids with hexagonal cross section and computational fluid dynamics tests conducted by mechanical and wind engineers denotes that the pressure coefficients are calculated from the measured values of the surface static pressure distributions on the cylinder. Both drag and lift coefficients are obtained from the pressure coefficients by numerical integration methods [12].

As result, the hexagonal cylinder shows that there is significant drop in the drag coefficient values for the single hexagonal cylinder in comparison to that of the single square cylinder and the values approaches to that of the circular cylinder [13]. In addition, the drag coefficient for a single hexagonal cylinder at zero angle of attack is about 0.95 in contrast to that of 2.0 for a single square cylinder at the same angle of attack. The variation of the lift coefficient on the single hexagonal cylinder is not appreciable and they are close to zero value except at angles of attack of 100 and 500, where some insignificant values are observed. Drag coefficients become remarkably smaller compared with sharp-edge square cylinder The hexagonal cylinder offers a variation of lift and drag coefficients (c_d) facing airflows at various rotational angles respectively.

Structural types: Doing the most with the least. Mimicking scaffolding modules, author simplified structural elements of previous hexagonal cylinders eliminating tensile wires and screen cross-bracing; reducing the number of connectors and bars; and allowing stacking and honey-comb expansions. The experiments are tested in 1:5 models made of timber rods and aluminium tubes prior 1:1 fabrication.

As result, there are two distinctive modules made with aluminium tubes (33mm outer diameter; 2-4mm thickness; and 1000-1600mm length).

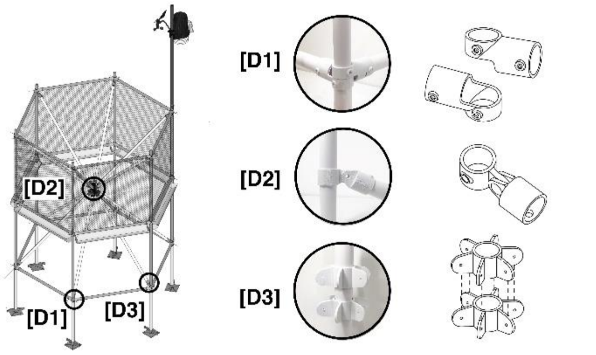


Figure 4. 3DFOGTECH© snowflake type: Details of rigid connector digitally designed and then made in 3D-printing. Source: author (2018).

(a) *Snowflake type:* It is a hexagonal prism with a core node of inner 12-way hub connector branching out and embracing the structure through the repetition of six large triangles spinning 60° around central axis. It is a double height volume with adjustable anchorage.

(b) *Tower type*: It is a hexagonal with an inner triangulated tower, which provides self-embracing to six perimeter screens. It is a double or triple height volume with adjustable anchorage.

Both types are horizontally embraced with triangular rings at bottom and top positions to avoid torsion and secured 100% stiffness.

Connectors, tubes, gutters and anchorage: Prior the fabrication of the 1:1 prototype, author is designing optimal joints. All connectors are rigid. They are made with plastic using 3D-printing. Being accurate and affordable, 3D-printing is quite slow. Plastic joints do not resist high heat. They have poor mechanical properties. Then chosen connectors are made in galvanized steel, which is also cheap but good with UV and oxidation. In addition, gutters are made of copper (high antibacterial qualities). Based on presumptive bearing capacity values for different types of soils, aluminium posts will rest on six adjustable jack screws (500mm) or shallow pad foundations. The four types of soils are: (a) soft rock and coarse sand (4.4 kg/cm2); (b) medium sand (2.2 kg/cm2); (c) stiff/soft clay (1 kg/cm2); or (d) rocks (>32.40 kg/cm2) where they are replaced by climbing anchors [14].

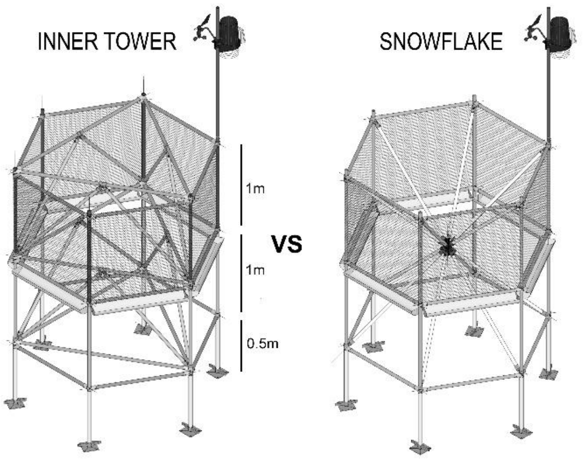


Figure 5. Comparative study between snowflake and tower structures. Source: author (2018)

6. CONCLUSION

Nowadays water management remains heavily dominated by conventional mechanised and human-built infrastructures. 3D fog collection is an adaptive water enhancement technology that uses horizontal precipitation to mitigate the effects of climate change on remote water-stress environments, particularly Mediterranean natural parks and rural settlements. Its synergy is aligned with the shifting towards sustainable development in rural areas in Catalonia and the Mediterranean Region allowing the preservation and promotion of biodiversity whilst fostering the creation of liveable, diverse and balanced ecosystems for the primary and tourist sectors.

The main achieved tasks of WP1: (a) process geo-climatic data collection in nine fog sites chosen for advanced experimentation; (b) obtain design efficiency through (i) finding optimal forms, geometries and structural frames with high portability, lightness and modularity and (ii) developing building components and connectors with great mechanical strength and air permeability. This study bridges design, climate, and structural by (i) Integrating site-specific climatic conditions in various simulations; (ii) augmenting mechanical properties of space-frames using lightweight metal bearing and spanning elements; (iii) simplifying connectors, including modularity, portability and montage; and (iv) minimizing visual and ground impact of immediate surroundings, mainly using reflective surfaces and adjustable anchorage.

3DFOGTECH© is the first 3D portable fog water station in the world (EUIPO community design registered). It is an autonomous water management solution for water-stressed areas with frequent dense fog events. New structures provide greater stability and stiffness against strong winds and rocky soils.

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The development of 3DFOGTECH© began with the experimentation of FOGHIVE©, ART ART© and AIRDRIP© at ECOFABRICA and associated (2010-2015) followed by the preliminary idea of 3DFOGTECH© project developed in Studio Pop (2016). Author expresses his special gratitude to Laura Petruskeviciute and collaborators.

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