Politecnico di Torino

Laurea Magistrale in Architettura Sostenibile

Water for Life

An experiment on fog water harvesting for the Po Valley in northern Italy

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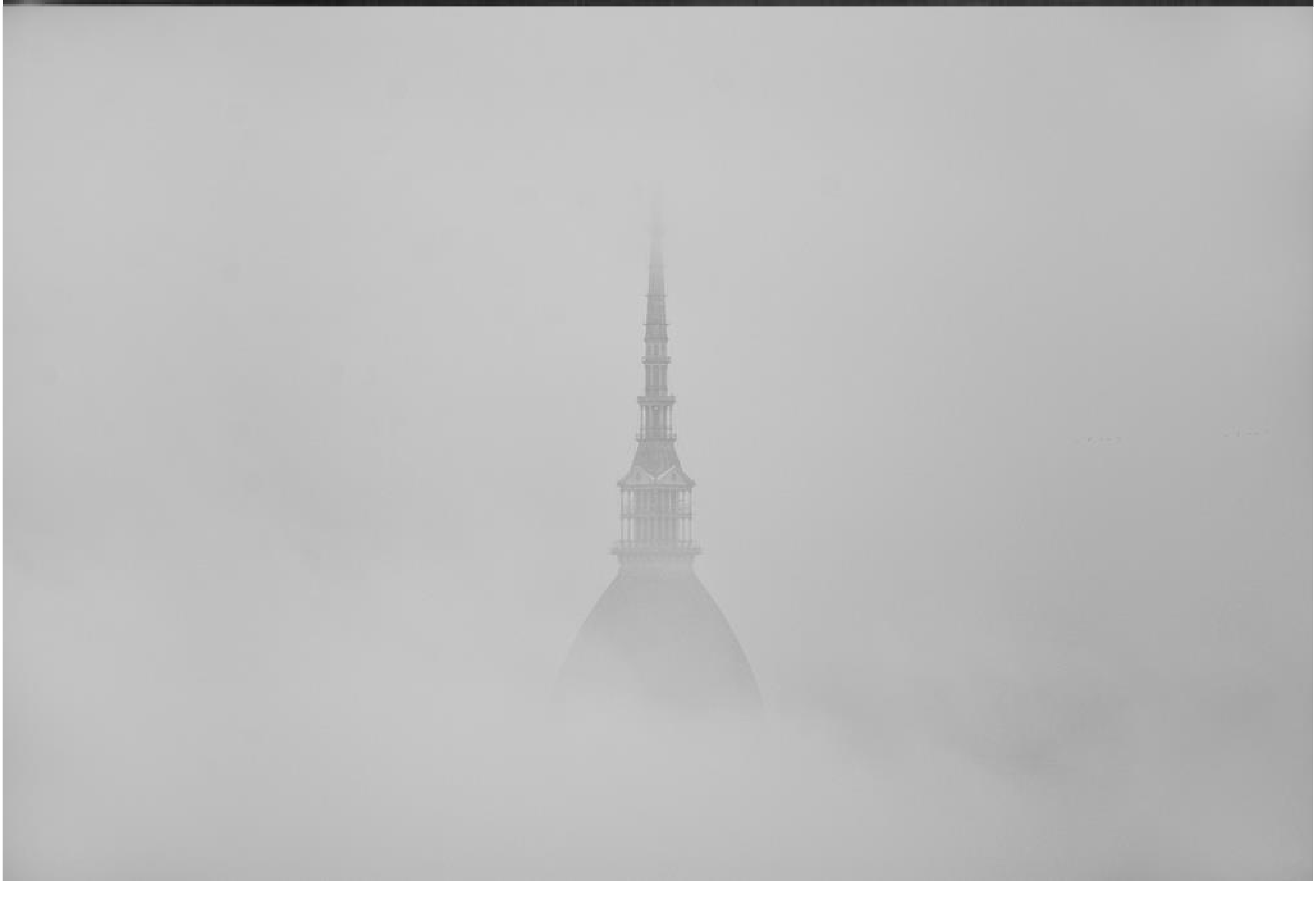
All water is alive. It is our most fundamental essence. The bond between everything that can trace its origins to the early Earth. The canvas of history's ever-changing painting. The memory of the earliest beings which lives on, flowing around, never resting, and sculpting our planet.

Yet we must face a water crisis. The highest value resource, the sustainer of life is threatened. A water crisis is the crisis of life – our life. And so, must be dealt with the highest priority. Two ways out are possible: the perpetuation of us, or the ruin of an era.



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Finally, my sincerest thanks to the Polytechnic University of Turin that gave me the opportunity to be one of its students for two and a half years, enriching my knowledge and improving my skills as a professional, which ultimately culminated in this thesis.

Torino, 21 Febbraio 2018

To my beloved mother, who even amongst the strongest of storms, never ceased believing in me.

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Abstract

Water for Life: An essay on fog water harvesting for the Po Valley in northern Italy

by Lucas BANDEIRA CALIXTO

The thesis aims to evaluate the potential of harvesting water from the fog present in the Po river valley in northern Italy, and eventually propose a project with such nature to enhance dynamicity, flexibility and sustainability of the water provision services of the region. For such, a thorough analysis of the economic impact of the project's final yield, water, is conducted in order to identify in which sectors of the economy could a water surplus make a major contribute. Then, the nature of fog itself is investigated, and its dependent factors, characteristics and behavior are reported. The state of the art of the fog harvesting technology – which has been in constant development since 1989, mostly in developing countries – is explained and critically evaluated, in order to identify its strengths and weaknesses to propose a novel solution for the Italian context which is highly contrasting to past fog water harvesting experiments, of which two in particular are studied and commented.

The problem framing arises from the consideration of every single data collected previously, and the new project's goals determine that passive, state of art technology is insufficient for the Po valley. Therefore, the creation of the Dynamic Fog Harvester (DFC), powered by electricity and possessing a wind current generator in order to compensate for the weak local winds, is proposed. To maximize efficiency, an analysis of alternative fog harvesting methods aligned with shape studies proposes a more compact, but taller collector. The DFC's versatility will allow it to be located not only on the urban and semi-urban environments, but also as a building component, provided the building is immersed in an area where fog can provide water that falls within World Health Organization's drinking water standards for pH and heavy metals. The proposal's calculated theoretical efficiency results as more than 10 times that of an average fog collector.

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Riassunto

Water for Life: An essay on fog water harvesting for the Po Valley in northern Italy

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Questa tesi vorrà valutare il potenziale di raccolta dell'acqua della nebbia presente nella valle del fiume Po nel nord Italia, ed eventualmente proporre un progetto di tale natura per conferire dinamicità, flessibilità e sostenibilità ai servizi di provvisione d'acqua nella regione. Per raggiungere tale obiettivo, viene condotta un'analisi approfondita dell'impatto economico del prodotto finale del progetto – l'acqua – al fine di identificare in quali settori dell'economia un ingrandimento della fornitura dell'acqua possa dare un contributo importante. Successivamente viene studiata la natura della nebbia stessa e vengono riportati i suoi fattori dipendenti, le sue caratteristiche e il suo comportamento. Lo stato di fatto della tecnologia di raccolta della nebbia (detta Fog Harvesting nella letteratura) - che è in costante sviluppo dal 1989, soprattutto in paesi sottosviluppati - è spiegato e valutato criticamente, in modo tale da identificarsi i suoi punti di forza e debolezza, per proporre una nuova soluzione per il contesto italiano, che è altamente contrastante con gli esperimenti di Fog Harvesting passati, di cui due in particolare sono studiati e commentati.

Il *problem framing* è emerso dalla considerazione di ogni dato raccolto in precedenza e gli obiettivi del nuovo progetto determinano che la tecnologia passiva dello stato di fatto non soddisfa i requisiti del contesto della Pianura Padana. Pertanto, viene proposta la creazione del Dynamic Fog Harvester (DFC), alimentato dall'elettricità e dotato di un generatore di corrente del vento per compensare le deboli correnti d'aria locali. Per massimizzarne l'efficienza, viene condotta un'analisi dei metodi alternativi di raccolta della nebbia, con studi di forma allineati suggeriscono un'apparecchiatura più compatta, ma più sviluppata in altezza. La versatilità della DFC consentirà di installarsi non solo negli ambienti urbani e semi urbani, ma anche come *building component*, purché l'edificio sia immerso in un'area in cui la nebbia può fornire acqua che rientra negli standard di acqua potabile dell'Organizzazione Mondiale della Sanità per pH e metalli pesanti. L'ipotetica efficienza teorica della proposta per quanto riguarda la raccolta dell'acqua della nebbia è del 10 volte quella di un collettore comune.

Preface

This thesis concludes a two-and-a-half-year period of studies at the Polytechnic University of Turin (known as Politecnico di Torino, or simply as PoliTO), in the field of sustainable architecture. During the course, important insights on the idea of energy efficiency, resource use optimization and notions of cost efficiency were given to me, which constitutes the theoretical foundations of this work.

Fog harvesting first came to my knowledge when I was a participant in the Alta Scuola Politecnica (ASP), a multidisciplinary program between the Politecnico di Torino and the Politecnico di Milano, two of Italy's top universities. There, the idea was introduced to me by Chilean professor Juan Carlos dall'Asta, whose speech convinced me to join his WaLi (Water for Life) project. A multidisciplinary team composed of engineers and architects was formed, and that kickstarted our researches on the topic of fog harvesting technology.

During researches for WaLi, several foggy places in the world were identified by the team, most of whom were located in Latin America, Africa and Asia. The island of Tenerife caught our attention for it was dry and foggy, which could be a possibility of intervention. Largely neglected, however, was the very region where we were at that moment, the north of Italy. I did not know just *how foggy* it could get. The first fog harvesting experiments, as identified, were in Chile, in high altitudes, and at that time the author had little knowledge of fog, since his native Brazil isn't exactly the foggiest place on the planet – *anzi.*

During a bus ride from Turin to Milan in 2016, I slept about 20 minutes, and when I woke up, I couldn't help but notice how the landscape was extremely foggy – to a point that all you could see was about 60m around where you were, beyond of which god knows what lied. I immediately thought "oh well, look at this! I am either dead and walking on the clouds because the bus had an accident on the road, or this is an extremely thick fog. I think I rather believe the second". At that time, it had completely caught my attention, immediately prompting me to think that intervening with a project near home wouldn't be so unthinkable.

Thus, the idea of this thesis started as a conviction of the author – rather than an *a priori* verified feasibility – who thought that the Po Valley could host a major fog harvesting experiment even if it had enough water to meet its demands, even if its people did not *need* to harvest the clouds for water as did those folks in the arid Moroccan villages. The idea quickly shown to be challenging as researches in the ASP progressed, when it was found that wind was a major factor in securing fog harvesting efficiency – which the Po Valley had scarcely any. Fog harvesting was considered as an option only when other fresh water resources were either rare or insufficient. The Po Valley sat in a very humid region with several water flows and channels. Community involvement was deemed crucial for the success of the project. Could I convince the people of the area to take care of an array of tensile nets to harvest a water they were not in dire need of?

Even if all odds seemed contrary to intervention in Italy, I archived the idea for myself, for when the ASP project would be finished, I would quickly start my own, this time proposing a more daring approach to the problem. I was well aware that I was sailing on dangerous waters, in contrast to the calmer, already backed by literature, waters of the state of the art of fog harvesting technology. But complex situations require complex solutions, and so, I realized that a simple boat might navigate well in calm seas, but for agitated waters, you need a stronger, well-equipped ship.

A huge deal of time and effort in this thesis' design phase was dedicated to solving the wind-less fog problematic of the Po Valley. As an architecture student – and therefore not so familiar with the engineering side of life – the composition of the final design solution of this thesis proved to be a challenge greater than initially thought. As my researches were not finding any acceptable material combination to energy-free harvest fog water, I started to think that the device wasn't possible at all. Fortunately, in the last stages of writing this thesis, literature stemming from China served me well with biomimesis – that is, taking inspiration on nature to seek better solutions for a problem – and the end device was, under every aspect, a product of natural mechanisms of fog harvesting.

This thesis is the result of all my efforts in trying to innovate within a field of study that is not only dominated by technicians, but that seems rather exotic, "out of reach" for an architecture student. I sincerely hope to have produced relevant knowledge to make a positive contribution not only in the fog harvesting field, but also in the field of architectural design, when I tried to unite both to create my new conceptual solutions.

Lucas Bandeira Calixto
Torino
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III. List of Abbreviations

FWH:	Fog Water Harvesting
SFC:	Standard Fog Collector
LFC:	Large Fog Collector
DFC:	Dynamic Fog Collector
SPFC:	Standard Passive Fog Collector
SDFC:	Standard Dynamic Fog Collector
EEA:	European Environmental Agency
GDP:	Gross Domestic Product
UN:	United Nations
NGO:	Non-Governmental Organization
PC:	Pavilion Collector

1 Introduction

Water is – as cliché as it might sound – an indispensable resource for life. So vital it is, its scarcity can halt development, if not bring stagnation and retrocession to nations and communities. The XXI century is witnessing a seemingly unavoidable population growth and unprecedented stress on fresh water resources. It is estimated by the UN that by 2050 the world population will be at 9.1 billion people, placing an enormous burden on hydric resources, and as early as 2030 around half of the population will be living in water-stressed regions[1], all of which recalls the XVII economist Thomas Malthus' geometrical populational growth compared to arithmetical resource growth. In many places of the planet, populations cannot count on the presence of an available, "easy" source of fresh water, e.g. rivers or lakes, and must spend much time and effort in bringing water to satisfy their daily needs.

The problem of water stress and scarcity, although in a way globally present, is much of an issue in populous and/or arid regions. The solutions available to the water problem are restrained: Desalinization is expensive and complex, and ground water extraction, although a short-term solution, can cause resource depletion, as well as problems over public/private ownership of underground water sources that are situated below and within private properties. Rain seems to be the only viable water alternative, but not every region of the planet is blessed with abundant rainwater sources. The only remaining potential, yet not sufficiently explored water resource is **fog**. It is already in use not only since ancient times by some human populations, but also constitutes a vital part of many ecosystems.

The nascent modern fog harvesting technologies received large contributions from NGO's in partnership with universities and research institutions, as well as independent researchers. FogQuest and Dar Es Salaam are some important names to be mentioned that fostered and assessed water harvesting potential in many different regions of the planet, quantitatively demonstrating how efficient such technology can be. The introduction of an evaluation process – as for determining if a given place is ideal for fog collection – and quantification of the average liters of water a fog harvester can catch per day were done in multiple locations by Schemenauer and Cereceda in their many studies carried on together. In Oman, South Africa, Peru, Colombia, Spain and Nepal – to mention a few – a number of academics innovated and contributed to enrich and make Fog Harvesting more than a mere promise.

[1] UNESCO, United Nations World Water Development Report, 2015

Perhaps the greatest contribution given by professors Schemenauer and Cereceda was the assertion, over 10 years, of the impact of abundant, additional water supply: their experiments in Chile oversaw the growth of small villages, attracting more people to live in them, slightly easing migration flows to bigger urban centres and diversifying its economy, being able to grow more crops than before and saving public resources that previously were utilized to costly transport water to the village. These experiments provided these peoples their desired water surplus, buy maybe most importantly, it laid seeds for the growth of a promising sustainable water provision technology.

Yet there seems to be an important gap to be filled in the field of fog harvesting experiments: nearly all of them were conducted in developing countries. Their very nature was rather clearly directed to providing water for a vital, immediate use, since previously little fresh water was available, and infrastructure was insufficient to meet people's necessities. The developed world wasn't quite the object of many experiments, maybe because water supply is largely sufficient and currently is not severely threatened in the short run, therefore being "less in need" of such technology. Such assumption, however, fails to recognize the current trends experienced by Europe, as migration currents are as intense as ever, big urban centres are being overwhelmed by the influx of people and existing hydric resources are becoming heavily stressed even in rain-abundant countries.

Conscient of this void and understanding the opportunity it offers, the objective of this thesis will be the implementation of a fog harvesting project in a developed country context and assert its success. The country chosen was the Italian Republic, as it fulfills several criteria to host such project since its northern macro-region experiences heavy, consistent fog through long periods of the year. The Valpadana, as it is known locally, is the region under direct influence of the Po river that flows from northwest of the country to the coast of Emilia Romagna, and its fog occurrences and nature have been the subject of documentation and scientific literature which positively supported the necessary theoretical justification and basis for an innovative approach on providing society with water through fog harvesting.

The nature of a project conceived and conducted for a more economically developed context **must** be different from an underdeveloped one. First, financial output is primarily high, the latest technology is usually available and governments – both national and local – could show interest in the project as long as it provides enough **value** for the city/region. Second, existing infrastructure – especially water distribution networks – is already extensive and developed, meaning that it is less of a problem to reach a considerable portion of society. Finally, there is this very society, a.k.a. the people. Clearly, they could live their lives without fog harvesting. But the implementation of such technology could not only help securing their already high quality of life, but could also help foster environmental and sustainability consciousness, as some sort of creative warning to their own ecological footprint on the planet – and how the authorities had to recur to such technology to “contour” it.

In addition to the above statements, a project in a developed context will bear multiple different stakeholders, be made of different, desirably more efficient materials, have a different and unique symbolism and provide water for a different purpose. One that can at first seem less noble than providing water for the needy, but definitely a significant step towards a more cordial relationship between that human society and their colonized natural environment, which has, in silence, been withstanding every aggressive anthropization, particularly in the last 200 years.

2 A discussion on water as an economic power

Riassunto:

Prima di iniziare a discorre sulla tematica della colletta dell'acqua della nebbia, una discussione più approfondita sul suo output finale – l'acqua – si fa necessaria. Tale discussione, di natura economico-legislativa, non è altro che, innanzitutto, la discussione sul concetto di valore in economia e la caratterizzazione dell'acqua in quanto agente economico attivo ed input indispensabile per una serie di processi di produzione di beni. Tale risorsa essenziale non solo per il funzionamento dei sistemi economici ma alla vita nel pianeta non può essere dotata di un prezzo – anche se tutta la sua infrastruttura ne avrà uno. Il costo di questa infrastruttura ed eventuali sussidi pubblici hanno un ruolo predominante nel determinare il costo finale di una risorsa che, anche se sprovveduta di prezzo, sicuramente ha un costo. La legislazione internazionale e le azioni pubbliche che trattano di questo tema hanno convergenze – notabilmente nel carattere del prezzo dell'acqua – ma enormi divergenze nel riguardo alla posse delle risorse idriche.

Note: This chapter relies heavily on Water Crisis: Myth or Reality? By multiple authors, 2005.

Before starting to discuss fog water collection and additional water supply properly, it is necessary, in the author's view, to conduct a thorough research about this project's final output that is water, and analyze its role as a resource and economic agent. The reason might look quite obvious, but in reality, could be more complex than appearances: water, despite being a necessary factor for most economic production, in reality can be an economic vector itself, and while it is indispensable for life, it is also subject to a variety of laws of ownership that, in some cases, restrict its accessibility and have severe socioeconomic implications.

Water has many peculiar characteristics that differs it not only from most resources that are in use, but also among substances – to the elementary level – that are present on the planet. It is an indispensable and vital requirement for all known life on Earth – both in its fresh and sea variations – yet it is very unevenly distributed, not always being enjoyable or present (Gleick, 1993). Nevertheless, water has its own fantastical tendency to be dynamic – that is, to not hold its form, being present as water vapor, liquid water, ice glaciers and so on. All being essentially different variations from the same resource, and all of which have at least some importance for every single life process that takes place on the planet.

As with every marketable good, water is subject to a variety of laws of ownership around the world. Many different societies and governments dealt and deals with the problem of hydric resources ownership in their own manner, although displaying a significant convergence in many forms of regulations on ownership and usability rights. These laws have been fundamental factors in facilitating or complicating water accessibility, ultimately affecting their economic production and social balance. One such convergence is when States make water a State property, taking direct possession of every water source within its borders but conceding its usability rights differently. In most countries, it is an enjoyable resource legally conceded for all its citizens – although access to it can be in some cases limited – and in another handful of countries, water usability rights are strongly linked to the notion of private property.

Assessing, therefore, water's economic potential can help identifying scenarios of water usage. Who will – or could – have the right of using the water harvested from the fog? To whom it will go and how will it reach its final destination? Which kind of **costs** does it imply? And above all: is it economically *viable*? All such questions must be answered before carrying such project that, according to Cereceda et al (1997), Fog Water Harvesting[2] projects can represent an investment risk if a thorough analysis on the site's potential is not sufficiently conducted. And in the case of the project to be discussed in this thesis, that deals with material experimentation and more dynamic technology than regular fog water harvesters, such analysis can help creating an undesirable deficit in public finances.

2.1 Economic characterization of water

A discussion of the economic role of water on contemporary economy is rather complex. Countries' necessities of water vary according to their population density and size, standard of living and degree of economic activity. Elementarily, water is the primary resource of life. It is not only an input at the basis of every single need of human beings (and also animals,

[2] In this thesis, the abbreviation FWC will be also used as a way to shorten the term. The notion of "Harvest" might not seem to be appropriate to define this technology – as it implies that a "seeding" of the fog took place a priori. However, due to the fact that the term harvest is hitherto used and accepted in the literature, this thesis will use the term as it is so to avoid confusion.

plants, and other forms of life) but also constitutes the unreplaceable element for producing other elementary survival resources, like agricultural products, and also modern needs like power generation and navigation. Given its notorious importance, its commercial value is a topic of discussion on whether water should be treated like any other commodity or if it rather deserves its special status, like it currently is in many countries. Laws governing water use, ownership and availability to society varies widely across countries and cultures, and it is ultimately a decisive factor on water sustainability and security.

As an introductory concept, explaining some economic terms like commodity and value is necessary, in order to correctly determine water's economic role. A commodity is mostly any primary good that is substantially the same regardless of place of extraction or production. Agricultural products, minerals, petroleum and energy are some examples of some well traded commodities. The economic concept of value has a more subjective definition. In many ways, it is a given, not an intrinsic, value[3]. Historically, it has basically always been the monetary value that the seller wants for a product, and the value the buyer is willing to pay, something that is highly determined by the law of offer and demand. However, one can easily infer that some products are more immediate; more essential, rather basic, for human survival. Following the law of offer and demand, water should be something whose value is rather small, yet it is much more essential for living than, say, a car. There comes the paradox of value: Intrinsically valuable products not always cost the highest monetary value. Adam Smith, well-known English economist of the XVII century, wrote in his book The Wealth of Nations about his definition of value:

> "The word value, it is to be observed, has two different meanings, and sometimes expresses the utility of some particular object, and sometimes the power of purchasing other goods which the possession of that object conveys. The one may be called value in use, the other, value in exchange. The things which have the greatest value in exchange have frequently little or no value in use. Nothing is more useful than water, but it will purchase scarce anything; scarce anything can be had in exchange for it. A diamond, on the contrary, has scarce any value in use. But a very great quantity of other goods may frequently be had in exchange for it"[4]

Understanding, then, that water can be treated as a good with a characteristic and intrinsic value, an assessment over water's price has to be made. Which factors influence water's

[3] Many economists throughout the centuries have passionately debated about the concept of value, for which the definition of this concept is rather abstract. Intrinsic value, value in exchange and value in use are just some of the numerous definitions of the word value in economics.

[4] SMITH, Adam. Wealth of Nations, book I, chapter IV

final price? Is it the infrastructure or the water itself? This approach is especially important for fog water harvesting for two reasons: one, it will be part of the initial evaluation over if is it possible to install such project in Milan, economic-wise; two, it is important to understand the economic impact that a water surplus could have for the commune.

2.2 Is water a commodity?

The question to be made now is whether water should be treated as a marketable good or should it be considered as something on the outside of the global market. On that topic, divergent views exist among economists and scholars alike. Notoriously, the 1992 International Conference on Water and the Environment, Dublin concluded that "Water has an economic value in all its competing uses and should be recognized as an economic good". Barlow & Clarke (2002), however, treat the resource in a different and unique way, stating that "The Earth's freshwater belongs to the Earth and all species, and therefore must not be treated as a private commodity to be bought, sold, and traded for profit (…) the global freshwater supply is a shared legacy, a public trust, and a fundamental human right, and therefore, a collective responsibility". In many countries in the world, water is indeed a value-less resource. What citizens usually pay as a monetary value for the water they consume are transportation and treatment costs, which can be lower or higher depending on the infrastructure quality, complexity and reach.

In economics, the concept of **essentialness** applies well into this context. Essentialness is basically the notion of such a high degree of importance of a good – both as an input or an output – that without it, there is a strong damage to, or total disappearance of, a given economic system. Goods that also can't be produced and are of widespread use also are included in this description. It is needless to say that water fits well into this concept, as it is the single most important building block of life, and absolutely **nothing** – as far as we know – can replace it. Views of such essentialness however differ from culture to culture, between income levels and educational background and level of instruction, as households in more developed societies with access to abundant water tends to think of water as an important resource, but not an **essential** one; Conversely, poverty-stricken areas could exchange a good amount of their goods for a regular water supply, which they deem to be essential to their survival.

If we are to classify water as a commodity and attributing a price to it, we must be ready to also "commoditify" other essential resources for life, such as the air we breathe or the sunlight we receive, all of which look absurd. In agriculture, crops don't only depend on water supply but also on sunlight and good air quality. Similarly, sunlight is a virtually zero-cost energy source for multiple uses, and many countries that can rely on such source are shifting towards an electricity matrix increasingly sunlight-based to avoid environmental degradation. How could these essential resources, so available and so free, have a price? The case of air is minimally understandable, as it is bulky and available worldwide. Hardly could any argument be structured well enough to justify a price for it. However, in cases where this very abundant fresh air is an increasingly rare commodity – such as in the highly polluted industrial regions of the world – it seems reasonable to convert it in a consumable good under the laws of market, to attribute a price to something whose level of scarcity could no longer fulfill everyone's basic needs. In capitalism, the law of offer and demand is omnipotent. Every action to prevent a scenario where an essential resource becomes progressively scarce must be taken.

Beyond the notion of essentialness, water has also multiple other uses. Taking its notion of production good – such as water for agriculture, industry and household consummation – away, water can be also a recreative good. That can explain why, for example, in the United States, water consummation per capita averages 455-530 Liters/day per person, a number of several magnitudes higher than an imaginary "threshold" of essentialness of water. Additionally, water as a recreative good may also include lakes, that can either offer a relaxing panorama for someone walking in a park or a bathing, crowd-gathering location for summer days, as an example. Such usage of water as a recreative good has a notorious and disproportional enjoyment from more affluent classes than to poorer ones[5].

Summarizing, the fact that water is a necessity may not imply that people are conscious of its indispensability. This observation can take us to the question of how much people in a developed country would value an improved water supply. Of course, this depends of several factors, such as present-day service quality, and overall consciousness of people.

2.3 Infrastructure and cost of water

[5] In a study carried by Sérgio Koide, in the city of Brasilia, Brazil, residents of wealthier areas would consume more than 4 times the amount of water consumed by the city's poorer areas. In the city's wealthiest region, the consummation would average 800 Liters/day per person.

Water costs has nothing to do with availability. When water costs less in one place than another, this has to do with inexpensive infrastructure (Hannemann, 2005). That is also to say that a given city or region can have inexpensive water if they are well served by bodies of water and a relatively short-distance, efficient water transportation infrastructure. Water treatment also has an impact on water bills, for the process of cleaning and regularizing the ions that are present in drinking water sometimes can be difficult and expensive, as is the case with desalinization. This is to say that, although water does not have a direct price, it does have a cost[6], like every other resource.

Construction of water infrastructure may represent an investment risk if careful studies aren't carried before on the site's water demand, available ground and surface water and construction of storage facilities. The latter is especially important, for it is a major factor in the reducing of water costs. Contrary to electricity, water is inexpensive to store, but no so to transport, relative to its cost per unit of weight. When water transportation systems rely on free-flow through gravity, the transportation costs tend to zero. This water-electricity comparison is important to state, for both are valuable indispensable resources nowadays. Hannemann (2005), on the overall economic functioning of a water infrastructure system, states:

> "The capital intensity, longevity, and economies of scale mean that water supply and sanitation costs are heavily dominated by fixed costs. In a simple surface-water supply system with minimal treatment of drinking water, minimal treatment of sewage prior to discharge, and a heavy reliance on gravity flow, the short-run marginal cost of water supply and sanitation may be almost zero except for small costs associated with pumping to move water through the system. Even in a modern system with full treatment of drinking water and sewage discharges, the short-run marginal costs are extremely low. There is thus an unusually large difference between short- and long-run marginal cost in water supply"[7].

The final cost of water is also very influenced by the entity that owns it and that oversees its distribution and system maintenance. Usually, when a water system is heavily fragmented, i.e. many companies/entities working on different processes at the same time, a considerable monetary and resource loss is experienced, directly impacting, also, water quality, as it can differ among providers. Government subsidies on water bills usually tends to be adopted to compensate its very own

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[6] Here, the concept of price is that of value in currency exchange, while cost deals with the requirements for obtaining a given resource, which cannot be ignored.

[7] HANEMANN, W.M. The Economical Conception of Water. Water Crisis: Myth or reality? CRC Press, pp.61 – 88)

infrastructure flaws, an unsustainable approach to the problem, especially in the long-run.

2.4 Water and economic processes

As mentioned above, water is at the core of almost every single economic activity, either directly or indirectly. As the world population increases and countries develop their economies, water use and stress on water resources becomes more and more evident, a situation that may lead to chronic water scarcity in some regions of the world. The term "water scarcity", here, can be defined as a lack of water quantity, not quality. "Domestic water scarcity" is defined as a lack of sufficient water for domestic use. As a matter of fact, since many people are inclined to think that domestic water use is the main consumer of water worldwide, this is fundamentally wrong. To better explain why, the concept of embodied water must be characterized.

Embodied water is the water needed to produce a desired output. Especially in the case of agriculture and cattle raising, this water footprint is largely invisible to the final consumer of such goods, since these products' final water volume is much inferior than the actual volume of water needed for their production: for instance, to produce one cubic meter of wheat, irrigation and water consummation during the cultivation process will have consumed more than 1000 cubic meters of water as of the harvesting moment in some cases. This variable is a function of weather, technology level and soil conditions, but mostly as a rule of thumb, it "costs" much more water to produce food than its own final water mass percentage.

Agriculture is the overwhelming leader of water consummation worldwide, at 70% of all water use globally (UNESCO, 2001). New irrigation methods and their widespread use since the 1960's are largely responsible for such high numbers (Frederick, 2005). Although essential for production, the assumption that abundance of water past the required levels for cultivation of crops is false. It has been demonstrated through experiments that little to no difference in the final agricultural output is seen between abundance and sufficiency of water (Hannemann, 2005). However, insufficiency of water will lead to a production deficit. Most agriculture developments that took place during the last century were done so in a time where the water crisis was not perceived as a relevant threat, and therefore unsustainable water usage practices took place which either badly affected or depleted fresh water resources (Frederick, 2005).

The usage of water to produce food constitutes an important case-study for every person concerned with the water crisis: the high demand of water by such economic sector is not expected to diminish anytime soon, as the world population grows at fast paces and resources do not grow in equal proportions, a case of Malthusian economics. Maintaining resource production at current levels will only lead to increased famine, and it is virtually impossible, in the short run, to contain population growth. Therefore, a sustainable approach to water management and obtainment is more and more a dire necessity and less a vanity worldwide. Sustainable agricultural practices are recommended to avoid ground pollution, which can ultimately contaminate ground water (Boberg, 2005).

Water in the secondary sector of the economy is used for numerous applications, from cooling reactors in nuclear power plants to the production of certain durable and non-durable consumer goods. In the case of Industrial and manufacture processes, heavy industry – such as construction materials – is responsible for high percentages of water consummation globally, especially in fast-developing countries such as China, and is the subject of much international controversy regarding not only its water consume, but also its high land, water and air pollution. In an ecologic footprint approach, the foodstuffs industry is one of the highest water-consuming human activities in the world, for it sums all the water needed to produce its primary inputs – crops, cattle among others – with the water needed to transform them into different industrialized food products. Perhaps the manufacture sector's relation with water is by far the most uncordial of every human economic activity, for it not only requires water to function, but also progressively pollutes its surroundings, of which water absorbs a considerable part, contaminating ecosystems and food chains.

The tertiary component of the economy consumes proportionally much less water than both primary and secondary sectors and represents the overwhelmingly dominant GDP component for post-industrial or Newly Industrialized countries. Though it displays an enormous diversity of activities and finalities, it can be said that water consummation by this sector falls within domestic urban water provision and management, as water usage levels are proportional or often even less than household domestic water use. Considerably high water-consuming tertiary activities might include cleaning services, especially that of vehicles and of large structures, as well as that of provision of water for recreational uses, such as in water-themed parks. Most of the tertiary sector, especially those of financial, legal and other services, however, do not directly *require* water to be offered and traded; this economic sector is dominantly dependent of other commodities such as electricity to be properly run, as well as more indirectly of fuels.

2.5 Structure of water management

Water management must take on consideration water availability, regional concentrations and easiness of extraction. As explored before, water costs are directly influenced by its infrastructure of distribution and extraction, and thus may end up having an unsustainable cost in a distant region/community which relies on equally distant water sources. Additionally, water management and governance are indissociably responsible for an adequate supply: they constitute several layers of administration of hydric resources, the efficiency and hierarchy of which are determining to assure system coverage and continuous water flow. A case to be observed of inefficient water management was the Brazilian city of São Paulo's 2014 water crisis, a city whose metropolitan area of 20 million inhabitants sits on a country that owns a considerable proportion of the world's fresh water, yet has poor water services caused by bad, irresponsible governance – all that led to a massive water scarcity that lasted well into 2016 (Kelman, 2014).

As a vital component of nearly every economic process, both directly and indirectly, water management establishes priorities, proportions and resource reallocation based on different economic sectors, in the short and long term (Hanneman, 2005; Groves et al., 2013). It is to be understood as a stratified procedure rather than a unidirectional approach to the water supply problematic: starting from economic sectors, diving within one of its sectors, exploring geographical and climatic conditions, and ultimately establishing criteria based on the previously explored strata are quintessentially the core of water management (Hannemann, 2005). It requires major governmental actions, problem-solving on various levels of society and public administration and conflict-easing measures (Al-Saidi, 2017), all of which may be proven to be particularly hard to accomplish, especially in politically and socially unstable countries.

Another fundamental characteristic of water management is water quality management. Not every economic activity requires fresh water to yield outputs, and so a large margin of finances can be spared from water treatment sometimes (Hannemann, 2005). For farming uses, irrigation water is left mostly untreated, very unlike water for domestic consume in urban and semi-urban areas. Within the industry sector, different water quality levels are required to produce different goods. Brewery industries requires fresh, readily available water, which often leans the installation of such industries next to water courses and bodies, whereas water for heavy industry does not need to be pure, as long as its chemical composition won't alter their manufactured products.

Population size is fundamentally linked to water use, even if this relation is not linear – that is, for an x number of people, not necessarily a directly proportional y resources are consumed, since populations use resources differently, regarding income level, availability and culture (Boberg, 2005). Studies have shown that a higher number of households with fewer people – contrary to fewer households inhabited by more people – does more environmental damage than simple population growth (Liu et al., 2003; MacKellar et al., 1995). In one, the researchers looked at 141 countries, including 76 countries containing biodiversity hotspots, such as Australia, India, Kenya, Brazil, China, Italy, and the United States. The worldwide increase in the number of new housing increased at fast rates, faster than population growth – particularly in these countries, of which a notorious example is China (Liu et al, 2003).

2.6 International laws regarding water control

Water crisis has often been dubbed a management crisis instead of a proper resource scarcity. Water governance is concerned with those political, social and economic organizations and institutions (and their relationships), which are important for water development and management (Rogers, 2005). Although immaterial in nature, the power of law has an incredibly high material impact. Law over ownership and use can be crucial for maintaining water quality, availability and distribution. Since water use by an individual can affect both the quantity and quality of water available for others, it seems rather clear how adequate legislation is a crucial factor for preserving the infrastructure of water distribution, as well as to reduce the environmental impact of water extraction. Accessibility rights plays a huge role on social equity and individual quality of life, a key pillar of sustainability.

Water is different from other commodities such as land. A key characteristic of land is its stability and easiness to partition; as for water, that is not the case. Water tends to flow around nature, it evaporates, condenses, rains, snows… It is the very soul of Earth, and what has been shaping and reshaping it since prehistoric times. Therefore, our first providence tends to lean towards collectivization of water resources, making it accessible for all. This approach is widely diffused throughout the world, as generally the ownership of water belongs to the state.

International laws regarding water control vary across the world. As countries observe the tendency of the exhaustion on water resources – and some already experiencing water stress – centralized water control more and more becomes a reality in order to protect hydric resources. In most countries of the world, for an example, water is a state property (Rogers, 2005). That means that no other entity has any power over hydric resources in these countries but the State itself, not even if an individual's property is located next to, or englobing a hydric resource such as rivers, lakes or aquifers. That, however, may ultimately not exclude rights of use, which is to be distinguished from rights of ownership.

In India, surface water is under centralized control. Ground water is under the *de facto* control of individual farmers, as those hydric resources can be located immediately below one's land property (Saleth, 1994). Given the large Indian demand on water, conflicts over who definitely has the rights of use water resource are not uncommon, spurring a race to extract greater amounts of water from aquifers, a rate above its replacement rate – which only deepens the water stress problem – and negatively affecting water quality. That brings a simple conclusion that water ownership and control is an important factor in water management and overall system efficiency and sustainability.

Communist countries – nowadays most of them being formerly communists – despite what might come to mind, have different approaches regarding water management. China (law of 1988) asserted complete and centralized water control and administration. In the Hungarian (1964) and Czechoslovakian (1973) laws from the beforementioned years, water management is carried on an independent local level decision-making, while emphasizing centralized control. The Czech law declares some large water and natural reservations as protected areas to protect water quality and availability. All those countries above mentioned impose the request of a permit to draw from water resources.

The United Kingdom and United States, however, follow the opposite direction, as water tend to be privatized for the largest part. This have severe implications from an economic point of view and especially for social equity, because although the precise nature of ownership is immaterial for economic efficiency as long as the water rights are private and transferable, it has fundamental equity implications as the issue of who has the user rights of water determines actually to whom the benefits of such a transfer should go (Hanemann, 2005). However, these *rights of use* are not to be confused with *rights of ownership*, since American and English law follow the same principle of the Roman *res communis omnium*, in which water is treated as a common good.

2.6.1 Italian laws and State of Art of water infrastructure in Italy

According to Eurostat Data (2014), in Italy in 2005 the total freshwater abstraction from the public water supply was the largest in Europe. Data from the OECD (2008) also shows that Italy is becoming increasingly water-stressed, being one of the most of such countries among the OECD members. Italy is also plagued with system leakages that amounted to 37.4% of total water withdrawals, an increase from the previous census, when it stood at 32.1%[8]. Such leakages do not go to water bills, becoming a public deficit. Furthermore, water bills in Italy are underpriced – and has been so for a long time – thanks to government subsides (Barba et al, 1997), which makes it cheaper than in many other European countries of the same income levels. The country has an average water consummation of 240 liters/person/day, a number higher than other European countries, and higher than Spain and France, where it is about 160 liters/person/day.

Italy has a very different approach to water management when compared to its European neighbors. Historically, municipalities (*comuni*) were the main responsible for water management and services, and remained highly fragmented until 1994, when the law n.36 of 1994, most famously known as the Galli Law (named after Giancarlo Galli, its main proponent), bold reforms on the SII (Servizio Idrico Integrato) were made. The law filled important fragilities of the Italian water sector: it allowed for private and public stakeholders to coexist and to share responsibility, in different levels, of the water sector, which contributed to major cost-recovery for the service's providers – which, conversely, Romano and Guerrini (2014) argues that it didn't necessarily brought about a relevant change in the efficiency of the services, which could benefit more from the board dimensions of the responsible water providers than its public-private nature. Another interesting feature of the law is its humanitarian dimension: it postulates that water uses must be prioritized for human consummation first, and other uses second.

The Galli law has many purposes, albeit as a synthesis to its enunciate it basically seeks to improve water sustainability, assuring that future generations won't quite suffer with water scarcity. In addition, it created optimal management areas (Ambiti Territoriali Ottimali or ATO), to better manage geographic division according to natural water basins, and to regulate private stakeholders' actions, which could be motivated by profit only and not so much for the service's quality. The ATO is further regulated by the local regulatory authority (Autorità di

[8] ISTAT Urban Water Census, 2014 (data from 2012)

Ambito Territoriale Ottimale or AATO), which are the responsible bodies for the planning of finances, operational measures and the objectives to be reached by each individual region as to ensure adequate water services. AATO had three main objectives. The Italian law considers water as a good for the satisfaction of public needs (Barba et al, 1997). It also establishes a revenue limit for water bills, that is, discounting inflation and other costs, revenues with water services cannot exceed from 6.5% to 9%. The former quota is conceded especially for local distributors that makes significant water infrastructure projects in their own local context (Romano et al, 2015).

Italy has also a notorious north-south divide even among hydric resources, where in the north 86% of water requirements are made whereas in the south the number drops to only 30% (Barba et al, 2017). The funds required to accordingly modernize water services in Italy are over 60 billion euros, but Italy’s high public debt severely undermines its spending capacity, making it hard to sustain such investments in its water supply sector (Guerrini and Romano, 2014). Particularly in Milan, much of the piping network dates from the beginning of the last century, and some hundreds of cities in the south of the country are yet to be connected to proper sewing.

3 Fog: Nature, characteristics and potential

Riassunto:

La nebbia è un fenomeno atmosferico definito da certi parametri che la distinguono dalle nuvole e dalla foschia, fenomeni questi che condividono caratteristiche comuni. Può essere formata da diverse condizioni meteorologiche, il cui insieme ne cambia la natura ed il tipo – alcuni dei quali non servono alla raccolta dell'acqua secondo le tecnologie esistenti oggi. L'acqua raccolta della nebbia ha l'importante caratteristica di essere adatta alla consumazione diretta, rientrando nella WHO drinking water standards, anche se con una proporzione delle particole dissolte in essa leggermente diversa. La Pianura Padana del nord Italia è una delle regioni più nebbiose al mondo, e bensì la sua nebbia non sia adatta alla raccolta dell'acqua dagli LFC (Large Fog Collectors), è ricca di Contenuto Acquoso Liquido (Liquid Water Content in inglese) e ne è nota l'assiduità durante l'anno, specie durante la stagione invernale. Tutto ciò rappresenta un'opportunità di intervenzione che richiama un aggiornamento della tecnologia esistente per tale scopo.

Fog is, in a short description, a low-lying cloud (Fuzzi et al, 1996; Mariani, 2009; Klemm et al, 2012). It is composed of water droplets suspended in the air that forms around condensation nuclei, whose chemical properties, shape and dimension significantly influence fog's characteristics (Mariani, 2009). These water droplets are too small to fall rapidly and can easily be carried on by the wind. Fog is substantially a microscale phenomenon, in which local conditions such as ground temperature and air currents plays a determinant role in its creation. Fog can form and dissipate in the arc of a few hours, and sometimes can persist over many days or weeks[9]. Fog formation processes are well discussed in the academic literature and its types are numerous, but for pragmatic reasons, this thesis will discuss only a handful of them, who are pertinent to fog water harvesting: radiation, orographic and advection fog.

[9] Extraordinary cases where a foggy scenario persisted for uninterrupted 18 days at Linate airport in Milan, was observed by Eichenberger (1973)

Radiation fog is common in autumn and winter in temperate latitudes; it is formed when the lowest layers of the atmosphere cools down during clear and cool nights during calm wind conditions. If this air contains sufficient water vapor, or there is a liquid surface, fog is formed and becomes visible. The fact that this type of fog is formed in an environment where wind speed is insufficient for fog collection – as of the state of the art of the technology – most projects carried around the world does not rely in this type of fog occurrence.

Orographic fog is formed when warm, damp air moves toward a mountain; as it rises along the slope, it expands and is cooled. If it is sufficiently humid, then fog will be formed on the surface. From a distance this will appear as a cap cloud covering the summit of the mountain.

Advection fog results in two different manners. Advection means movement and both processes involve motion. The cooling of surface air can occur when warm, humid air moves across a cold surface. If the air is cooled to the dew point, fog is produced. The other type of advection fog can also be termed high-elevation fog. It is produced when the wind blows clouds over mountains or hills. When the cloud touches the ground, it is fog. This fog will persist as long as the cloud is forced over the terrain.

Also according to Mariani (2009), fog also has a curious characteristic of being able to aggregate particles in suspension in the air – like gases, pollutants and solid particles – and its droplets can act as a vector to chemical reactions between these various particles, which results, as time progresses, in a fog with droplets whose chemical composition are very different from its initial state, sometimes causing the so-called smog phenomenon. It is also to be noted that such chemical reactions can also not be maleficent, and in many parts of the world, water harvested from the fog meets the World Health Organization’s drinking water standards for heavy metals and other soluble organic compounds (Cereceda et al, 2015).

To further discuss this subject, it is necessary to define some important concepts, such as visibility, haze, mist and fog. The definitions hereby presented are those of the World Meteorological Organization (WMO) and reported on their same manual.

Visibility is defined as the greater distance at which an object of specified characteristics can be seen and identified with the unaided eye in any particular circumstances or, in the case of night observations, could be seen and identified if the general illumination were raised to the normal daylight level.

Haze is a phenomenon that might seem at first glance like mist, or foggy-like in appearance, but is something entirely different. It is composed of non-aqueous particles in suspension in the air that somehow gives a milky-ish aspect for the atmosphere. It is not defined by visibility or horizontal and vertical coverage.

Mist is made of water droplets that are significantly sparsely distributed in an air mass. By definition, "mist" is when visibility is higher than 1000m and no more than 5000m. **Fog**, in turn, reduces visibility to less than 1000m, with some thick fogs reducing it to less than 100m.

A fog's thickness will depend on the amount of condensation nuclei formed, which are dependent on some substances in suspension in the air, such as heavy metal ions and some other inorganic substances that together are responsible for a different pH of fog water in comparison with water found elsewhere. These nuclei acts as droplets aggregators, ultimately responsible for the fog's Liquid Water Content (LWC), a measure of water (in grams) contained in a cubic meter of air. This last feature is one of the most fundamental fog properties for its harvesting, for it determines the amount of liquid water that is harvestable. A relation between visibility and LWC in a specific case of study is identified by Fea (1988), reported in the table below.

Visibility (m)	***LWC (g/m^3)***
400	0.05
20	10

As it can be inferred, the Liquid Water Content is inversely proportional to visibility, which prompts us to consider that the least visibility a fog can offer, the best it is for water collection. It is known that the LWC in fogs may usually vary between 0.05 and 10 g/m^3 (Mariani, 2008). An empirical mathematical formula can be deduced that correlates visibility with Liquid Water content, which is:

$$Visibility = 50\ x\ 1/(LWC^{3/4})$$

In which LWC is expressed in g/m^3 and visibility is expressed in meters.

For fog harvesting, when there is no fog, there is no possible collection. Rain is a vital water resource when fog formation is weak or absent. Rain collectors are often thought to be necessarily oriented along a horizontal direction, but that is only efficient in calm conditions. Rain associated with the wind has a horizontal component, a reason for which fog collectors are also good rainwater harvesters (Schemenauer et al, 2015).

However, that potential hasn't been fully explored yet. The amount of water that can be harvested depends on the fog's Liquid Water Content (LWC) and of wind speed, usually ranging from 2 to 10 m/s. An optimal value is 6 m/s. Wind is the agent that will transport water to reach the collecting meshes, and in case it is weak or absent, collection will largely fail to meet expectations. Empirically, it can be defined as:

$$Hw = LWC \bullet Vo$$

In which Hw is the Harvestable Water, LWC is the liquid water content (expressed in g/m^3) and Vo is the unperturbed wind velocity, in m/s. The harvestable water is therefore expressed in $g/m^2 \bullet s$, or in other words as the mass of water that a meter square of net may capture per second.

Perhaps the most interesting fact about this technology is that, if the necessary environment criteria are met, fog can provide drinking water that falls within the WHO standards for water consumption, with often adequate pH levels. That means the water harvested is good for nearly every possible usage, from cleaning to drinking, if treated. This makes the technology very practical and versatile, since similar water providing sources might deal with complex processes of water cleaning, an illustrious such example being desalinization. Most fog harvesting experiments have been conducted in areas where little to no air pollution was present, such as in desert regions (ex. Namibian Desert, Atacama Desert and Oman), agricultural landscapes or mountain chains (Atlas Mountains in Morocco), and dealt with harvesting of advection and orographic fog.

3.1 Fog in the Po Valley, Italy

Fog represents a frequent phenomenon in the Po Valley during the autumn-winter season (Fuzzi et al, 1996; Mariani, 2009). The Po Valley (locally known as Pianura Padana) is confined in a geographical "bowl", surrounded by the Alps and Apennines mountain chains on the north, west and south, and with an opening on the east with contact with the sea, which drags in several air masses from Europe, creating an ideal place for fog formation. Indeed, the Pianura Padana is one of the world's foggiest places and Milan is Europe's foggiest large city. At Milan's Linate airport, for years considered the European airport with the largest number of shut downs due to fog, days in which fog is present are frequent and heavy, thick fog – with less than 100m visibility – occurs in about 29 days per year (Eichenberger, 1973). Throughout history, numerous narrations of the fog in the Po Valley was carried by numerous authors, and their subsequent analysis shows how much fog occurrence has been decreasing over the decades.

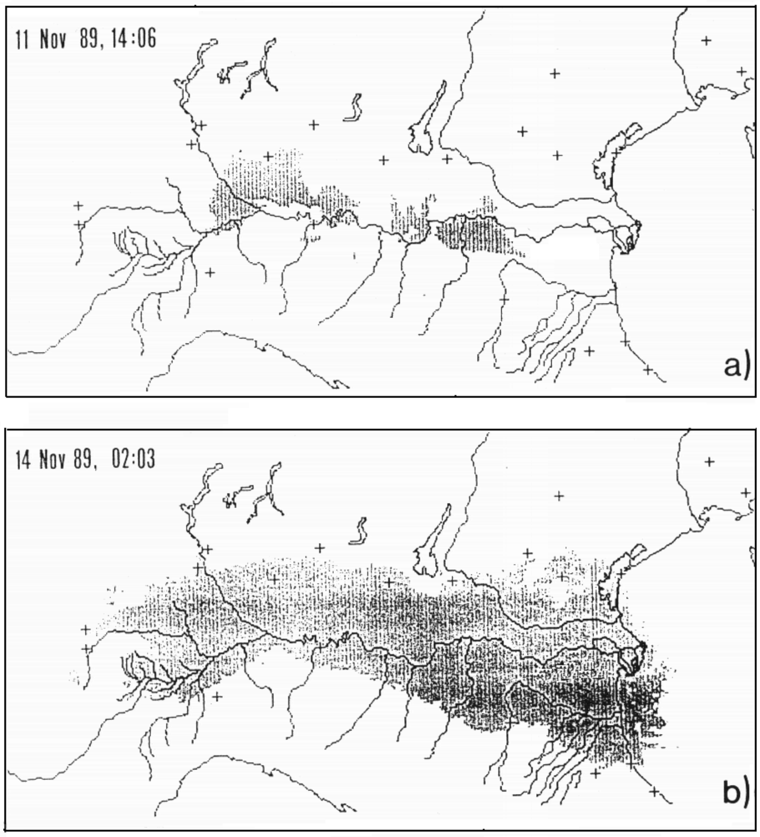

Figure 1: examples of local (a) and extended fogs (b) in the Po valley. Maps based on satellite images multispectral data from NOAA/AVHHR (Fuzzi et al., 1992)

According to Giulianelli et al (2014), the most prevalent type of fog in the Pianura Padana is the **Radiation fog**. It forms on the onset of the evening as temperature falls, and lasts until the early morning, when solar radiation gives fog droplets enough energy to evaporate, dissipating the fog (Mariani, 2008). However, during certain meteorological conditions – and especially in rural areas – fog can persist well into the afternoon, provided not enough heat is transferred for it to evaporate. In cities, especially large metropolises such as Turin and Milan, the heating island effect contributes for weaker fog and its earlier dissipation. The mean fog height in the Po valley is different from west to east, in which it ranges from 90m in the west from altitudes up to 209m a.s.l., to 72m for 191 m a.s.l. (Bendix, 1993).

During a time span of 20 years since 1989, it was assessed that the chemical composition of fog throughout the Po Valley is sufficiently uniform, and that its ionic strength has been decreasing over the years. Among the many ions that can be found in fog that act as condensation nuclei, the sulfates show a steep decrease, as other ions also decrease in frequency but not as strongly. This is partially due to improving air conditions in the region – and not due to changes in air humidity as one could hypothesize – and could be one of the reasons why fog occurrence in the Po Valley has been decreasing so vertiginously in the recent past, though this is not completely confirmed by the study, who only empirically correlated these two phenomena. Fog pH, on the other hand, has been slowly increasing (Giulianelli et al, 2014).

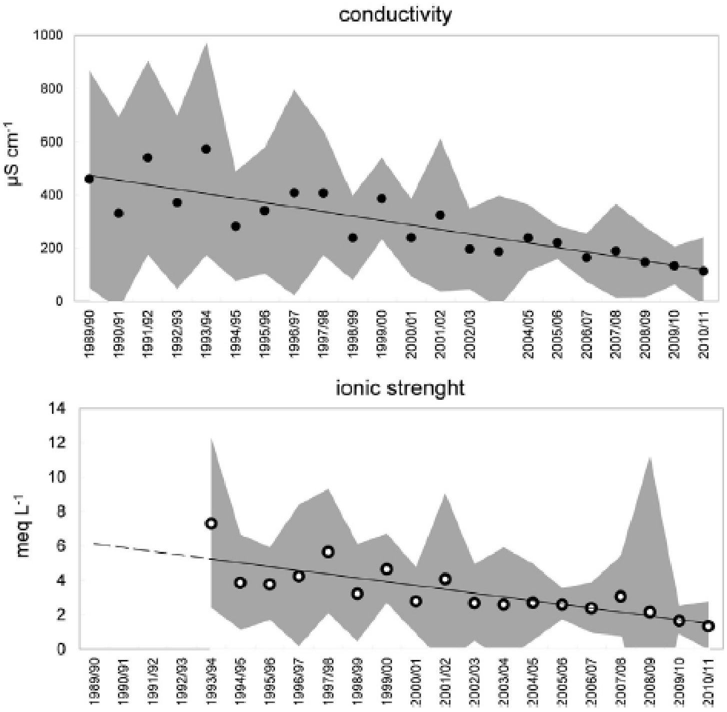

Figure 2: fog conductivity and ionic strength over the years as measured at San Pietro Capofiume. Shaded areas represent standard deviations of the volume-weighted means. (credits: Giulianelli et al, 2014)

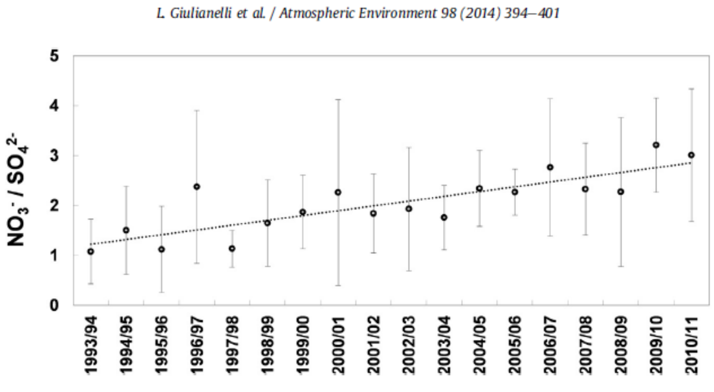

Figure 3: Fog pH as a result of the ratio NO3/SO4 2 (Credits: Giulianelli et al, 2014)

Several studies on fog biochemistry and composition had been carried in the Po Valley. Fuzzi, Mandrioli and Perfetto (1997) sampled fog droplets in the Po Valley and asserted that it manifests bacteria, yeast and moulds up to two magnitudes higher than when in clear air conditions, being an active vector of propagation of such biological agents. His arguments support the theory that fog might act as a culture media for some pathological flora, albeit most of the organisms found in the collected samples are, however, not dangerous to human health and are actually widespread on the soil, air and surfaces. pH value of water was also deemed to be largely unrelated to the presence of such microorganisms and be more due to the high level of pollutants in the region's atmosphere (Fuzzi et al, 1996).

Taking in consideration the Harvestable Water formula, which equates fog's Liquid Water Content times the wind speed, it can be noted that currently, the Po Valley's harvestable water is low – even due to the location's strong fog presence. That is due to weak wind speeds throughout most of the year (European Environmental agency, 2009), but especially during winter, the region's foggiest season[10]. Therefore, according to this mathematical definition of potential of hosting a fog water harvesting, the Po Valley would be quickly dismissed as a possible area of intervention.

Albeit mathematically deemed unsuitable, the fact that the Pianura Padana exhibits a heavy occurrence of fog is without a doubt an interesting opportunity. Fog that is predominantly of the radiation type is a challenge for any fog water harvesting project that could be carried in this foggy, densely populated area. The existing wind-reliant fog harvesting nets cannot operate with efficiency if there is not enough movement of clouds through them. Additionally, the smog phenomenon is often present in the region, a significant issue to be tackled. A novel, dynamically active solution therefore must be developed, and it has to be intrinsically more complex, aesthetically appreciable and user-friendly compared to previous devices. It must consider its context and comply with the particularities of the place, perhaps, more than any other fog harvesting project ever did.

[10] Further insights on this topic will be presented in chapter 6 – Milan, Italy: An Analysis of the City's Potential for Fog Harvesting

4 Fog Harvesting Devices: State of the Art

Riassunto:

Carlos Espinosa nel 1957 diede un importante passo rumo allo svolgimento della tecnologia raccolta dell'acqua della nebbia con l'invenzione del suo collettore "diamante", che si è semplificato negli sperimenti futuri condotti da altri ricercatori ed organizzazioni. Nonostante vi siano oggi numerosi progetti per la raccolta dell'acqua della nebbia, una maggioranza disproporzionale di essi usano un solo tipo di dispositivo: Gli LFC (Large Fog Collectors), che sono usualmente composti da una maglia per la raccolta dell'acqua, una struttura portante e un'altra per il suo stoccaggio e distribuzione. La manutenzione ne è una parte fondamentale, per cui il coinvolgimento della comunità servita dai dispositivi si fa importante. Così si presenta lo stato di fatto della tecnologia, che conta con vantaggi e svantaggi, fra i quali sono particolarmente noti il basso costo di costruzione e di operabilità, bensì il basso livello tecnologico e facile manutenzione; come svantaggi principali si citano l'assenza di fornitura d'acqua in caso di assenza di nebbia oppure di pioggia, e la necessità che certi parametri meteorologici vengano rispettati.

Fog collection has been around for a long time, but the modern usage of the technology only gained its necessary propel in 1987, in Chile. In 1957, Carlos Espinosa, a Chilean researcher, invented a "diamond-shaped" fog collector that is perhaps the predecessor to the current model of fog catcher used (Fig. 4). The device had surfaces faced on multiple directions, which could collect fog in varied wind conditions. The water collection was assessed at an average 3,9 Liters/m^{-2}/day^{-1}. It was of a complex geometry, which complicated its maintenance. Nevertheless, this pioneer experiment laid ground to future developments in the field of fog harvesting, which would take place initially in his very own country (Cereceda et al, 2014).

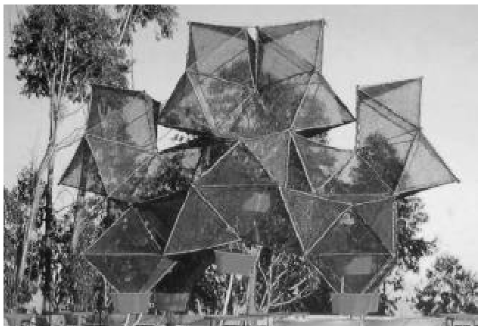

Figure 4: Espinoza's diamond collector

Nowadays, full-scale fog collectors are usually simple, flat, unidirectional rectangular nets of nylon supported by vertical poles at its lateral extremities and placed perpendicular to the predominant direction of the wind. Alternatively, the collectors may be more complex structures, made up of a series of such collection panels joined together in a more complex geometrical pattern. The number and size of the modules chosen will depend on local topography and the quality of the materials used in the panels. Multiple-unit systems have the advantage of a lower cost per unit of water produced, and the number of panels in use can be changed as climatic conditions and demand for water vary.

Formally, devices can collect water on 2D or 3D directions. The majority of the current and past fog harvesting projects rely and relied on simple, 2D surfaces for water collection due to the easiness of installation and maintenance, but bolder, sculpture-like collectors also exist, and some were assessed as particularly more efficient against strong wind pressures. Projects like Warka Water (2015 – present) made by the Italian architect Arturo Vittori, integrate rainwater and fog harvesting, while also incorporating Ethiopia's Warka tree features, a cultural symbol for some Ethiopian ethnic groups.

Figure 6: Vittori's Warka Tower (www.warkawater.org)

Collector panels have been designed to withstand the structural stresses imposed by wind, humidity, friction between their different constituent parts, and chemical or galvanic oxidation (Mukerji et al, 1993). The technology of fog collection basically works with a simple surface impaction process, in which fog water droplets hit a net, stick to it and slowly gather into larger drops, which in turn slips down the net by gravity, ultimately being collected by a gutter and taken to a reservoir. If sufficiently clean, this water can be used for domestic purposes, and with enough treatment, consumption; if impure to a certain extent, it can be used as irrigation water and for another couple different economic activities.

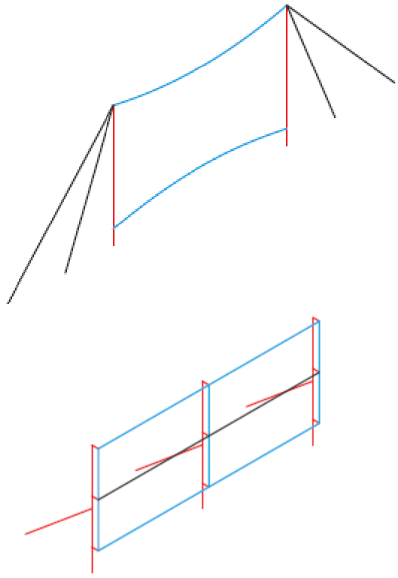

Figure 5: Usual typologies of fog collectors. From Top to bottom: simple 2D and rigid 2D collectors

4.1 Large Fog Collectors (LFC) components

Since the first studies made by Carlos Espinosa in Chile, fog water collection projects had relied on different designs of fog collection devices, where the flat screen Large Fog Collector (LFC) is the most common type of design used in the last decades (Schemenauer et al., 1988; Schemenauer and Cereceda, 1994b; Gischler, 1991). The materials used for the LFC are usually simple and locally available. Because the main focus of fog water collection projects has been to provide fresh water to poor communities in remote areas, it also implies in a low-cost technology with simple maintenance. Apart from fog frequency, wind speed is quintessentially the single most important feature for fog water collection, as it moves fog through the nets. Studies by several authors (Schemenauer and Cereceda, 1994b; Schemenauer and Joe, 1989; Bridgman et al, 1994; Marzol, 2008) place an ideal wind speed for fog collection at 3.5 and 9.0 m/s, and fog collection has been shown as being a direct function of wind speed (Schemenauer, Cereceda and Oases, 2015).

Most Fog Water Harvesting projects carried up to this day were made possible by NGO’s in partnership with universities and other technology/educational institutions, and names such as FogQuest, Dar Si Hmad are some of the responsible entities for fostering this water harvesting method. As of the state of the art, the maintenance of such fog harvesting panels has to be done by the community itself – that is a fundamental characteristic of such projects which are carried in undeveloped contexts: community involvement will determine the continuation of the project, which in turn determines the development and ultimately the impact upon the community itself (Fessaye et al, 2014).

The next subchapters will explain, in sufficient detail, the main components of an LFC. Since it is the main used device, it has been the subject of significant literature on its performance, mesh geometrical pattern, quantification of water collected and experimentation with materials – the latter one being less prevalent.

4.1.1 The Plastic Mesh

Figure 7 A Raschel mesh erected for fog collection of an LFC. (Credits: R. Schemenauer)

Dominantly, the mesh type used in different countries is a polypropylene or polyethylene Raschel mesh with a shading coefficient of 35%. The standard mesh that is generally used is a triangular pattern with flat fiber about 1mm wide and 0.1 mm thick, having a pore size of about 10mm. Schemenauer and Joe (1989) found out that the fiber width has direct effect in collecting fog droplets. This means that the ten 1-mm wide ribbons generate more water than a 10-mm wide ribbon. Usually a double layer of mesh is used to cover 7% of the surface are of the collector, depending on how the fibers overlap. This, in turn, facilitates run-off of the collected water as the two layers move against each other.

Although the Raschel mesh is the prevalent type of net – being used and tested in over 35 countries worldwide – different types of meshes and materials do however exist, and some haven't been the object of testing so far (Klemm et al, 2012). In South Africa, a different kind of mesh with a reticular, squared shape was used, to be more efficient against strong winds (Olivier et.al, 2015).

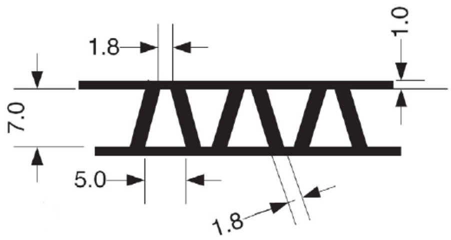

Figure 8: Dimensions (in mm) of a Raschel mesh commonly used for fog harvesting (www.marienberg.cl)

The mesh's primary function is to capture and condensate water from the fog, reuniting its droplets into larger drops, and letting gravity transport them to the bottom of the mesh till it can meet distribution pipes, ultimately leading water to its reservoirs. Such function as the main interceptor of fog droplets has been the object of a considerably large literature (Cereceda et al, 2014; de Dios Rivera and Lopez-Garcia, 2015; Batisha, 2015; Regalado and Ritter, 2016; Rajaram et al, 2016), both of its geometric pattern and of its materials.

Since it is the main receptor of horizontal stress due to the wind, meshes are usually strained and fastened, partially relieving the stress for the device's foundations and composing a vertical plane surface for water collection. Being a fluid, wind's natural flow is changed and considerably deviated by the presence of the mesh, which can cause efficiency loss (Holmes et al, 2015). Such surface has been observed to be also a good rainwater collector (Schemenauer et al, 2015), compensating water collection in days where fog is especially absent, a period of which no fog water is collected for obvious reasons.

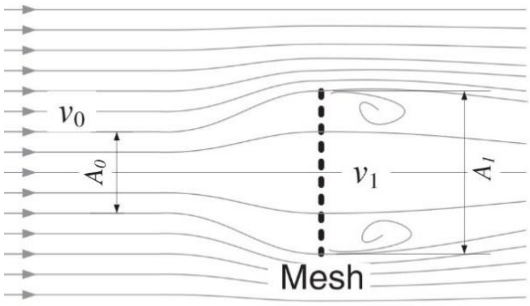

Figure 9: The presence of the mesh surface alters wind dynamics. In the figure, the total area A_1 of the mesh is larger than what it receives from the wind, A_0. V_0 is the unperturbed wind velocity and V_1 is the velocity that goes through the mesh. (Credits: Holmes et al, 2015)

A number of mathematical formulas – in an attempt to quantify fog water harvesting by the mesh were proposed by authors such as Rivera (2011), Imteaz et al (2011) and Kyoo-Chul et al (2013). More details on their elements and applicability will be discussed further in chapter 8, where the parameters taken into consideration for the design of this thesis' novel fog harvester will be identified and characterized.

4.1.2 The Supporting Structure: Posts and Cables

(most of this session is based on Schemenauer, Cereceda and Oases, 2015)

Figure 10: A mesh sustained by wooden posts and steel cables in Chile. (Credits: Klemm et al, 2012)

The structure of LFCs must withstand different types of forces. First, there are gravitational forces, corresponding to the dead weight of the wet mesh, cables, trough full of water and other structural elements. Also, there are dynamic loads corresponding to erection and maintenance of the system. Additionally, there may be seismic loads in places like Chile, which as of the state of the art of this technology, can't be countered. However, the most significant and present load is wind.

To secure the device's stability, it is not necessary to excavate deeply for the posts, as one could conversely think. The base of the post is normally only 15 cm in the soil, however it is necessary to excavate holes at least one meter deep for the installation of the anchors, who will give the posts their needed stability against horizontal loads. This means considerable time and effort must be put into the preparation of the holes for the anchors. If machinery is available for the task, the work will go much more quickly. Securing the device's stability is a fundamental part of its installation and may slightly reduce the need of structural maintenance of the devices.

The materials for the posts can be wood or metal. This choice should be taken in relation to the region's material availability, and the budget available for the project. Wood has the characteristic to absorb water and to suffer a reduction in resistance, however this phenomenon can be countered with surface treatments for the wooden posts, some of which are inexpensive. The posts also need to be desirably straight and free of knots. Metal posts need to have considerable strength as they can bend in cases where the cables are allowed to loosen. Galvanized steel is the preferred material. Aluminum, despite its lower cost, is improper for such structural means as it is not strong enough, complicating the device's stability. Materials that shows a tendency to rusting should also be avoided.

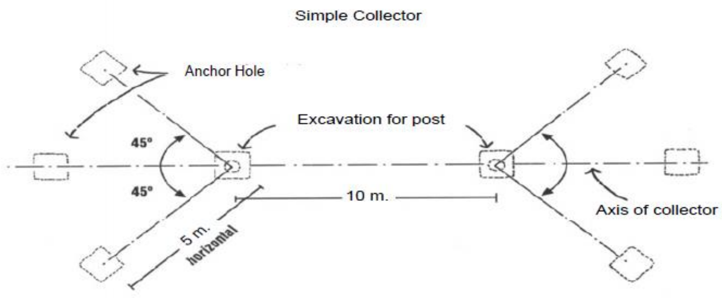

Figure 11: Plan view of an LFC. Credits: Schemenauer et al, 2015

Cables are a fundamental part of the device's stability, being the main counteractors of horizontal stress. It is essential that they are tight all the time (Schemenauer et al, 2015), otherwise the devices might start to bend down due to wind pressure. A combination of two – sometimes three – cables are usually used at every post, so to secure it from dislocating horizontally. Such cables are usually attached at the top of the posts, make a 45º angle with them and are attached to the soil by deep anchors. Materials traditionally used are galvanized steel. Weaker, cheaper materials should be avoided for they don't secure sufficient stability and may degenerate rapidly due to the cable's high tensions.

4.1.3 Water Conduction System

(most of this session is based on Schemenauer, Cereceda and Oases, 2015)

Figure 12: A raschel mesh with a collection gutter. (Credits: R. Schemenauer)

The water transportation to its reservoirs is usually made by a pipeline, collecting water drops from the mesh and leading them, through gravity, to storage facilities. It presents a considerably accentuated slope so as to facilitate such water downward movement. It can be made from different materials, depending on the local availability and the cost. The recommended materials are PVC, HDPE (High-Density Polyethylene) and galvanized steel. The diameter of the pipe depends on the number of LFCs, highest absolute fog-water production in liters per day (obtained from the evaluation done with the SFCs), and the mechanical resistance of the pipe. If there is a combination of water sources, and the volume of water changes strongly in different seasons, the pipe must be able to handle the peak flow rates.

Needless to say, these pipes can accumulate dirt and solid particles transported by the wind, as well as some small insects, and must be kept clean at all times. It is also important to prevent leakage, as it would significantly decrease the amount of water transported to the reservoirs.

4.1.4 Water Reservoir

(most of this session is based on Schemenauer, Cereceda and Oases, 2015)

Figure 13: Fog water being poured into a reservoir (credits: R. Schemenauer)

The reservoir is where water is stored and therefore is of crucial importance for water quality. It may be made of different materials such as cement, stone or plastic. Alternatively, a hole in the ground can be escavated and covered by a thick plastic sheet (2 or 3 mm) and electrically welded to seal the seams. The size of the reservoirs is an important concern for such project and must rely on several parameters, and according to Schemenauer et al (2015), they are:

- Maximum absolute production in liters from the SFC in one day multiplied by the total number of square meters of mesh installed in the LFCs;
- Maximum number of continuous days without fog water production;
- Average water demand by day and by week;
- Occurrence of rain during some seasons.

Before arriving into the reservoir, water also bypasses a sedimentation tank where its particles in suspension are deposited on the bottom of the tank. In order to have a zero-energy, gravity-flow conduction of water, the reservoir must be at a lower position than the harvesting nets, and above other buildings. This is such a sensible parameter that only a few meters of elevation difference are enough to abandon the needing of pumps or any other energy source to conduct water. A passive, zero-energy system enhances the cost-benefit relation of the project, and additionally may be a strong positive feature of such intervention on the eyes of its involved stakeholders.

4.2 Operation, maintenance and community involvement

Operating this technology can be very simple, especially with proper dialogues with the community. The main hazards that affect the LFC’s are sun radiation, strong winds which can destabilize the collectors, and eventual dust accumulated on the nets, for which also cleaning is an important factor to be considered. Projects that lack community involvement and commitment to maintenance are usually abandoned. For this reason, training of some local personnel is fundamental, for they will ultimately be the ones in charge for their own water supply. A routine quality control program has been said to be efficient in organizing maintenance sessions (Schemenauer et al, 2015).

People chosen to be responsible for the maintenance of the devices should bear in mind a sense of responsibility (Mukerji et al, 1993). Among important parts of the harvesting devices that should receive special attentions are the cables, which must be always very tight in order to hold the devices into their vertical position, and the mesh that must be tensioned enough to form a vertical plane. In case the net would tear and form holes for whichever reason, such damage must be immediately repaired, as such holes can increase in size, both due to the state of tension in the mesh and the wind.

Water quality must be assessed periodically to prevent major health problems to whom water is distributed. Generally, dirty water tends to have a cloudy aspect, caused by microscopic organic flora and solid particles altogether. This is mostly prevented through the cleaning of the devices, the distribution pipes and the storage tanks. In case the fog changes of nature and such pattern endures, it is to be inferred that new feasibility studies must be carried on, as major local or external factors are influencing water quality. The only justification for the using of the state of the art fog harvesting technology is its capacity of provision of fresh water with little to no operational costs. Therefore, if any experiment fails to meet such expectations, it will be in risk of discontinuation.

4.3 Large Fog Collectors' Advantages and Disadvantages

While it is true that the fog harvesting methods as of their current state of the art are a decisive plus in the direction of economic and social sustainability, they are nonetheless nowhere near being a flawless water supply. In fact, much of its criticism derives from the fact that it contains several voids which it couldn't so far satisfactorily deal with, such as, for example, the absence of a sufficient wind speed. Also, as a rather passive method for water collection, it is highly dependent on sometimes unreliable climate conditions that vary throughout the year, and even between years. That is not to mention the handful fog types suitable for water collection which also limits the intervention's geographic location.

Schemenauer (2015) states that only when other fresh water sources are scarce and/or difficult to obtain – which would imply a high cost, that the local government could not afford – then a fog water harvesting project makes sense. That is well exemplified by his first projects as the head of FogQuest, which took place in severely dry regions of South America. However, this condition is not as *quintessential* as proposed, as it can be strongly contested by some authors' findings, that have been studying fog collection in Tenerife, Spain, in recent years. Marzol (2008) studied Tenerife's fog nature, areas of higher frequency and potential for harvesting, and found results comparable to those of Lima, Peru. Ritter, Regalado and Guerra (2015) demonstrated that fog is more frequent than rainfall in the Canaries and assessed a potential of fog collection for the island up to 40 Liters/m^{-2}/day^{-1}. The fact that the Canaries are a dry region but economically more provided than previous application contexts – since it could rely on other means of acquiring its domestic water – is an important loophole for Schemenauer's statement, and an important evidence of the applicability of fog collection in non-economically-deprived contexts.

Another interesting factor to be mentioned is this technology's imagery: if this project is firstly successful in a country/region, it will be generally viewed positively. However, if it fails to comply with its goals, future investments in such initiatives might find extra barriers, more than the ones already present. Therefore, if one is intending to execute such project with state of the art technology, it is fundamental to carry feasibility studies beforehand, so to avoid an unnecessary failure scenario. The following are a list of the main advantages and disadvantages of the State of the Art of Large Fog Collectors, fundamental to be taken into consideration before any such interventions.

ADVANTAGES

- As of the state of the art, fog collection systems can be easily built or assembled on site relatively quickly, once every assessment of local conditions have been made.
- Assembling of standard LFC's do not require high-skilled manpower.
- No electricity is needed to operate the system or transport the water, being completely passive in nature.
- Maintenance and repair are easy and can be taught to the local community.
- Capital investment is much lower compared to most other water infrastructures.
- The technology can provide environmental benefits. Water can be used for reforestation, agriculture or cattle raising.
- It has the potential to allow human presence in places where conditions are harsh.
- The water quality, in the majority of cases, fits WHO drinking water standards, a factor of which was assessed through a number of available literature on the topic.

DISADVANTAGES

- Fog water harvesting can be an investment risk if enough feasibility studies aren't carried *a priori*.
- In most contexts that it has been applied so far, community involvement in the project has been proved to be fundamental. Without communitarian involvement, a project's chances of failure dramatically increase.
- If the harvesting area is not close to the point of use, a costly pipeline needs to be installed. The difficulty is accentuated if the topography of the region is made of irregular and steep mountains.
- The technology is susceptible to changes in climatic conditions which alter fog frequency and LWC.
- When there is no fog, there is no collection. A backup source of water is required in these circumstances.
- Not every fog can provide water that is adequate for direct consummation. In some regions of the world, fog chemistry can contain more accentuated ionic strength, and some may be heavy on pollutants, especially in industrialized areas.
- Caution is required to minimize impacts on the landscape and the flora and fauna of the region, all of which can be dependent on fog to exist.
- The installation of a huge array of such nets, even in the countryside, may be considered aesthetically unattractive.

Overall, it can be stated that the modern technology and its variants are not suitable for installation in urban and semi-urban contexts. It lacks an aesthetic appeal, and its systems of water storage are somewhat rudimentary for placement in, say, a public square. To make it adaptable for the dynamics of a city, it must not only be a part of the urban furniture, but also function in a way such that its usage is ultimately recognized as important and, above all, needed; If not, it will simply be considered a "visual disturbance", and will be quickly discontinued. For this project to be accepted among a city's public space, it must solve several of its critical disadvantages, if not every single one of them.

4.4 Pre-conditions for the implementation of fog harvesting projects

Before implementing a project, a series of feasibility studies must be carried, so to assess the place's fog harvesting potential. Apart from geographic essential conditions, another relevant factor is community unity and availability. Since the project must be maintained by the locals, it is important to train personnel, commit them to responsibility for maintenance and foster a conscience that this water supply is important and essential to them. That is most certainly not an easy task. Often, the language spoken won't be understood – as when local translators aren't available – and local ONG's won't be interested in being involved with the project. In many cases, that might lead to a high failure rate.

Once the potential of water harvesting is assessed and deemed sufficiently positive, accurate data from the local climate and weather must be collected. It must be borne in mind, however, that such data may not represent a short time span but a rather long one: in many foggy places around the world, fog incidence have been decreasing vertiginously over the last decades, as exemplified by most of such regions in Europe (Mariani, 2008). Therefore, the general analysis of the evolution of fog incidence must be considered before decisively carrying the installations of the devices *in situ*. Among the factors that will affect water collection are fog incidence and frequency, wind direction and speed and the LFC's overall design.

Little to no environmental impact or assessment is carried as of the installation of such devices, for it is deemed that, since only a small percentage of the fog's water will be collected by the nets, environmental damages are from minimal to dismissible (Schemenauer et al, 2015). This very environment might be, curiously, a positive natural indicator of fog presence in arid regions, for it can provide important insights on where fog can be more present. Borthagaray, Fuentes and Marquet (2010) observed that fog formation on the coast can spur vegetation growth of certain patterns, with little to no help of rainfall; and

Cereceda (2008) suggested that vegetation presence in dry areas could be linked to the presence of sufficiently dense fog.

Topography's influence on the topic can be resumed to the land formations' capacity to intercept cloud with are heavy in LWC, influence directly the type of fog that will be formed and the wind speed and direction. In some situations, a region's topography might facilitate fog formation in one place and difficult it in the other, within a handful kilometers apart. Among geographical conditions, a disproportional majority of past fog harvesting experiments were carried on high elevations due to the presence of fog ideal for water collection.

5 Past Fog Water Harvesting Experiments

Riassunto:

La tecnologia della raccolta della nebbia come oggi si presenta è nata in un primo momento in Chile, grazie alla collaborazione fra esperti e l'ONG canadese FogQuest. Il contesto di scarsità di acqua nel deserto dell'Atacama in Chile è allarmante, e il governo del paese forniva acqua agli abitanti tramite sistemi inefficienti e cari, economicamente inviabili. Lo sperimento di raccolta dell'acqua della nebbia ha fornito circa 15.000L di acqua potabile agli abitanti di Chugungo, un villaggio nel deserto dell'Atacama, sviluppandone l'economia e aumentandone la qualità della vita. Posteriormente allo sperimento cileno, numerosi altri simili sono stati tenuti in tutto il mondo, notevolmente in aree di clima desertico e con poche disponibilità di risorse idriche oltre alla nebbia. Un tale esempio è lo sperimento della Dar Si Hmad, l'ONG marocchina che è stato responsabile per edificare una serie di collettori nelle montagne Atlas del paese, provenendo acqua ai villaggi che prima soffrivano, sia economicamente che socialmente, della scarsità dell'acqua. Tali sperimentazioni sono stati imprescindibili alla continuazione di tale tecnologia, che già consta con alternative formali e tecniche diverse fra sperimenti.

Numerous fog harvesting projects have already been carried all over the planet. Notoriously, South America, Africa and Asia are major recipients of such experiments, in which NGO's team up with local subjects interested in such action and start executing fog harvesting projects. The projects' successful grade varies from project to project and from their nature – since some of them are made for scientific purposes and not for community use. The communitarian ones have a common goal: provide water to those whose basic water necessities cannot be supplied by conventional water sources. We are talking about, therefore, of peoples in a situation of economic disadvantage.

Among the noteworthy names that have been involved with fog water harvesting is FogQuest, Dar Si Hmad and Creating Water Foundation, NGO's that hail from Canada, Morocco and the Netherlands, respectively. Another number of international researchers are also actively involved in fostering these projects, especially in countries where a high degree of successful projects was met, such as Oman (Abdul-Wahab et al, 2010), where a high rate of water harvesting in a day was met at

30 L/m^{-2}/day^{-1}; in Colombia (Molina, Escobar, 2008), Namibia (Eckardt and Schemenauer, 1998; Shanyengana et al, 2002), Nepal (Schemenauer, Bignell, Makepeace, 2016), Guatemala (Schemenauer, Zanetta, Rosato, Carter, 2016) and South Africa (Olivier, de Raurenbach, 2002; Olivier, van Heerder, de Rautenbach, 2015). Important assessment of fog harvesting potential in Kenya was made by Muthama et al (2014) and in Tenerife by Marzol (2008). International conferences of this theme are also being held since the 1990's, which helps keeping the momentum of the technology.

Independent researchers in several universities around the world have contributed for the technology through laboratory experiments, novel shape concepts and material testing. Some experiments on fog harvesting were not directed towards the provision of fresh water for human consummation, but rather as an irrigation source or reforestation practices, such as in Spain (Estrela et al., 2009) and more recently Egypt (Harb et al., 2016; Salem, Omar and El Gammal, 2017). Fog harvesting potential was also assessed in Kenya by Ngaina et al. (2014), which stated that cities in the country have a high potential of harvesting water from the fog, with frequent fog presence in some areas and collection rates of up to 4.4 Litres/m²/day of net.

Table 1 reunites most fog harvesting projects carried up so far around the world. It is to be clarified that the intention of this chapter is not to compare previous and current projects' degree of success or their size, but to illustrate how the researchers interested in this subject tackled the fog water collection problem using their own means, all of which made significant contributions to this technology. It is not, also, intended to be a list of every single fog water project, but a selection of very bold, significant symbols of how a water surplus can cause major changes in the dynamics of the recipient societies. Profound discussion of technical details of such experiments are also limited in this section, for they have already been discussed in the previous chapter.

Current status of operational LFCs implemented worldwide						
Countries	**Site**	**Operational years**	**No. of LFCs**	**Purpose**	**Current status**	**Reason for success, continuation or termination**
Spain (Canary Islands)	Tenerife	2000-2010	4	Research on the characteristics of fog and its interaction with vegetation	Operational	Interest in the study of fog characteristics on the island of Tenerife
Cape Verde	Serra Malgagueta	2003		Community water supply	Not operational	Insufficient involvement of the communities and not enough support given by official service
Chile	El Tofo (Chugungo)	1987 – 2002	100	Community water supply	Not operation al	Local politics prevented upgrade to support the conventional water supply system
	Alto Patache	1997 – 2010*	2	Ecosystem and climate research	Operational	Interest for scientific purposes. Also, fog-water collected is used for greenhouse crops
	Padre Hurtado	1999 – 2004	10	Community water supply	Not operational	The church terminated staff appointments and operation of the sanctuary
	Falda Verde	2001 – 2010*	10	Grow *Aloe Vera*	Operational	Strong involvement and commitment by fishermen
Colombia	Andes Mountains	2008 – 2010	1	Rural water supply	Operational	Full involvement f the community, both in the experimental and operational stages
Ecuador	Pachamama Grande	1995 – 1997	40	Community water supply	Not operational	Lack of technical skills and involvement by local partners
Eritrea	Arborobu	2005 – 2010*	10	Community water supply	Operational	Strong will of the zonal and local administration to set it as operational model
	Nefasit	2005 – 2009	10	Community water supply	Not operational	Mesh damage, insufficient commitment by the school and community at large since new conventional water supply installed
Guatemala	Tojquia	2006 – 2010*	35	Community water supply	Operational	Strong community involvement
Nepal	Pathivara Temple	2001 – 2010*	2	Water supply for the temple	Operational	Addressed the strong need of the temple for sufficient water
Peru	Mejita	1995 – 1999	20	Research on rehabilitation of the lomas ecosystem by fog water	Project completed	Fulfilled the main objectives of the research project (verifying the possibility of rehabilitation of the lomas ecosystem through reforestation supported by fog water)
South Africa	Lepelfontein	1990 – 2001	1	Water supply for school	Not operational	Poor maintenance and gale force winds led to failure of the system
	Soutpansberg	2001 – 2008	7	Water supply for school	Not fully operational	Lack of required maintenance by recipients and strong wind
	Brook's Nek (Eastern Cape)	2010*	3-panel system	Research to test a new design for fog-water collection	Operational	The preliminary result indicates the system is stable and resistant to strong wind. It has a mesh made up of co-knit stainless steel and poly propylene yarn
	Lamberts and Doring Bay (West Coast)	2010*	9-panel system		Operational	
	Zondachsberg	2010*	3-panel system		Operational	
Spain	Valencia	2007 – 2010*	1	To irrigate 620 one-year-old seedings of *Pinus pinaster* and *Quercus ilex*	Project completed	Very successful for two years following which the adjacent trees grew tall and were able to collect by themselves
Yemen	Hajja	2003 – 2005	25	Community water supply	Not operational	Lack of maintenance; use of a non-standard mesh and strong wind

(Table 1: Past and current fog harvesting projects. The list does not show more recent projects. Information missing was either not available or not found. *operational as of data collection date. Fessehaye et al, 2014)

5.1 FogQuest, Chile

Figure 14: Large Fog Collectors made by FogQuest. (Credits: FogQuest: Sustainable Water Solutions)

Chugungo is a small fishing village in the Chilean northern coast, that was the stage of one of the first large-scale water-harvesting experiments in the world. The city's main water supply at the time was made by trucks, high in cost and inefficient in nature. Fresh water resources, other than fog, were rare. The villagers' quality of life was notoriously conditioned by this seemingly lack of improvement prospects, as the climate was harshly arid, fresh water was scarce and the local economy's development was slow. A significant migration towards larger cities was present, for there would be opportunities and much better services than locally in the village.

In 1987, FogQuest and several Chilean high-education institutes teamed up to produce, at its peak, 100 fog harvesting nets to supply the village some additional fresh water, partially to lower the economic costs and difficulties of having trucks transporting water to the village. The project was an initial success and had the involvement of the community, for they maintained the harvesting devices through a community committee, and paid a very small fare for the usage of the water. It is also to be cited that the continuous flow of water from the harvesting devices increased over time with the further installation of more devices, producing around 15.000L of fresh water a day and developing the village's agriculture, and even a park in the town centre was created. According to the project's leader, professor Pilar Cereda:

> "It is so important to involve the community not only so that people know about the project, but so that they are involved in building the collectors, in maintaining the collectors, in organizing a local water committee, and in donating their labor to keep water costs at a minimum. This system depends on the clouds, but if people know how to use this simple technology and organize themselves well it will really work."[11]

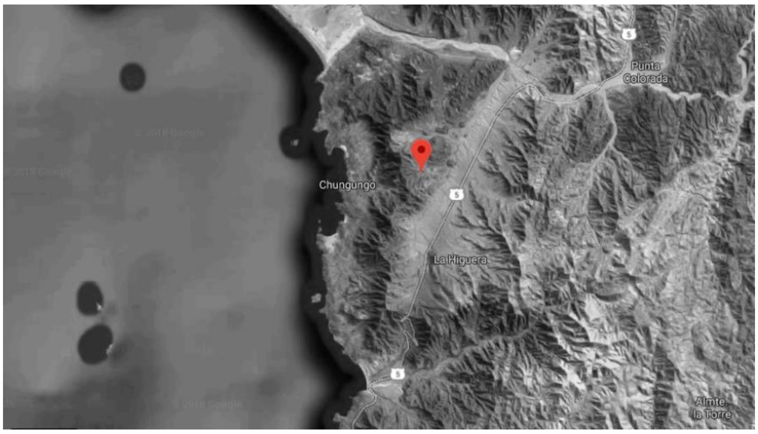

Figure 15: Approximate location of the experiment. Information from FogQuest's website (as of 10/02/2018), image obtained from Google Maps

The village experienced immigration from neighboring communities, growing from 300 to more than 900 inhabitants, clearly stating how the greater availability of water can really develop a community, slightly easing migration flows to bigger cities. Nearly every economic sector benefitted from the water surplus, and for many years continued to grow at somewhat stable rates. Community involvement in the project continued to be strong, until the village's ever larger population started having issues with creating consensus among the involved personnel, and a big blow to the project was dealt when the government announced the creation of an expensive water distribution pipeline to the city.

The devices at Chugungo, therefore, fell into disuse and the village again became dependent on trucks to deliver water. Out of 100 devices, 9 are said to be functioning properly, with most others falling between poor performance or having been completely shut down. Some explanation for this matter is the progressively insufficient community involvement, but definitely the relatively large population growth played a role. Politicians considered a 1.000.000 US dollars desalinization plant on the region to attend communities, in an opposite direction of financially mild, sustainable fog collection devices made before.

[11] http://www.pbs.org/pov/thirst/harvesting-water-from-the-sky/2/
(last checked: 12/09/2016)

The Chugungo model of acquiring water was nevertheless reproduced and tested in over 25 countries all over the world, and water harvesting technology remains under the spotlight of promising technologies to fight the water scarcity that some parts of the world currently faces. It was an important kick-starter experiment for this technology, both for the involved NGO's, as for the direct beneficiaries of such intervention. Currently, Latin America hosts dozens of fog harvesting projects (Klemm et al, 2012), largely concentrated in Chile, Peru and Ecuador, many of which relies on previous data collected at this first Chilean experiment, as well as the technology developed for such water collection.

5.2 Dar Si Hmad, Morocco

Figure 16: Fog catchers in the Atlas Mountains by Dar Si Hmad, with a resistant metallic frame. (credits: Dar Si Hmad)

Morocco faces problems with droughts as aquifers dry up and rainfall decreases, in a context of a country located in an already desert-dry, poverty-stricken area. Sustainable water management is much needed so as to help relieving pressure in communities for finding safe sources of fresh water, which are very scarce and distant from each other. Apart from these, fog is a frequent phenomenon in the Atlas Mountains (Marzol and Megia, 2008), a previously largely neglected source of water in the region, and a huge opportunity for a new fog harvesting project.

According to the state of the art of water usage in the region, an important social issue bounded to the economic problem of water emerged from the researches. Gender unbalance was associated with water scarcity where women – including children – were the ones responsible for gathering water in buckets and its transportation to the individual households, whereas men were free of such burden and could work in different economic sectors (Marzon and Megia, 2008).

Among children, a disproportional number of boys were given the right of going to school, whereas girls were mostly in charge of domestic affairs, such as water collection.

Since 2006, Dar Si Hmad, a Moroccan NGO, and the University of La Laguna from the Canary Islands, collaborated for the production of a large-scale fog water harvesting project for the Sidi Ifni region[12] in the Moroccan coast, as well as educating the youth in good water use practices. After nearly a decade, the fog project was inaugurated, collecting potable water from the top of the Atlas Mountains and distributing it for the villages located at its base. With a capacity of 600 m² of nets, each being 40 m², Dar Si Hmad's fog net initiative in Sidi Ifni is one of the largest in the world. Through advances in the fog net technology in the last decade, the systems that Dar Si Hmad was able to put in place yielded a large quantity of water per day, which was transported to the villages located in the bottom of the mountains via conduction pipes.

Since the project's early results, it has been observed how the previous social dynamics of the region were affected, also showing a noteworthy improvement in living standards. The abundance of water largely relieved the burden, for the female gender, to collect water from distant sources, allowing more free time that could be used for other activities, such as education (Babas, 2017). Expanded water management and greywater[13] recycling is the next step in satisfying the region's water needs.

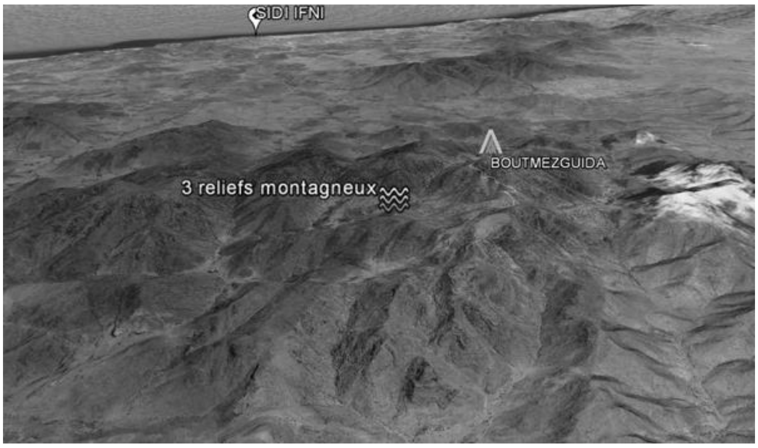

Figure 17: Approximate project's location at Boutmezguida, supplying water for Sidi Ifni. (Credits: Dar Si Hmad, retrieved from http://darsihmad.org/fog)

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[12] Ifni is a region located on the Atlantic coast of Morocco (29º N; 10º W), with a surface area of 1,310 km^2 and a population of 64,269 in habitants distributed among 348 villages (Marzol and Megia, 2008).
[13] Part of domestic household water is called greywater, water that is produced from "personal hygiene, laundry, washing and cooking (Paris & Schlapp, 2010)." Recycled greywater does not pose an immediate health risk if used for non-consumption household activities

6 Milan, Italy: An Analysis of the City's Potential for Fog Harvesting

Riassunto

La città di Milano in Italia, oltre ad essere il suo più rilevante centro economico, è anche la città più nebbiosa dell'Europa. Immersa all'interno della Pianura Padana, la città si colloca in un'area estremamente propizia alla formazione di nebbia, bensì sia praticamente sprovvista di vento, una situazione che, alleata all'emissioni di inquinanti nell'aria, difficolta la dissipazione di essi, che a loro volta si fondono alla nebbia generando un pesante inquinamento. Tuttavia sia una situazione di difficile rimedio, è in realtà una potenzialità di intervenzione, ed una significante lacuna nello stato di fatto della tecnologia del Fog Harvesting. La situazione della fornitura dell'acqua nella città metropolitana di Milano non ha ancora raggiunto livelli critici di stress sulle risorse disponibili, né presenta alti livelli di fuoriuscite; ma questa situazione non perdurerà per molto tempo. Un intervento per la raccolta della nebbia come fonte di acqua addizionale potrà significare non solo un sollevamento della pressione attuale nel sistema idrico della città, ma anche un'immagine estera positiva alla città in quanto facente parte dei simboli della sostenibilità.

The Metropolitan City of Milan is at the core of the Italian region of Lombardy, one of the Four Motors of Europe and Italy's strongest regional economy. The city is a major transportation hub, being the convergence point of several railways, motorways and air traffic. It is an alpha+ global city, being internationally known for its strengths in fashion and design. The city proper has a population of 1.369.000, and the Metropolitan City of Milan – of whom the *comune* of Milan is the anchor – had 5,270,000 inhabitants, as of 2015. The wider metropolitan area, which encompasses the Piedmont province of Novara and several of Lombardy's provinces, is over 8,123,000, ranking 4th in the European Union. The city's metropolitan area grew largely northwards instead of expanding in all directions, as usually experienced by cities around the world, reaching cities like Bergamo, Monza and Como to integrate them into Milan's sphere of influence.

Although Milan has been Italy's leading industrial powerhouse for at least since the late 1800's, since the early

1980's the city has been witnessing a reduction of its industrial output share in its GDP, being largely overtaken by the service component. Nonetheless it remains at the core of Lombardy, Italy's largest manufacture region. The Metropolitan City of Milan's GDP per capita is well above that of Italy, even if wealth in the city is markedly unevenly distributed when compared with other Italian provinces. It concentrates a huge share of Italy's multinational and national companies, being a world leader in fashion, design, industry, banking, commerce, education and more, characterizing the city as an Alpha + world city. The city recently hosted the international exposition of 2015, which left a legacy of an urban development in the outskirts of the city which will become its City of Sciences, designed by architect Carlo Ratti.

Beginning with the industrialization of Italy shortly after the country unified itself, Milan was the focus of many migration flows, especially from Italy's southern regions, due to the lack of labor force in the city and worse living conditions in the south of the country at the time, a fact that spurred the city's growth and significantly reshaped its cultural and demographic outlook. Not only immigration, the province of Milan and the rest of Lombardy also experienced considerable emigration towards the Americas, especially South America[14]. Nowadays, apart being home to Italians of many different origins, Milan is also home to several expatriate communities, adding to its multicultural and cosmopolitan makeup.

6.1 Climate and weather

Milan is the foggiest of Europe's large cities. On average, it experiences around 343 days of either fog or mist in a year[15]. Daily fog presence is heavier during the evening until sunrise, and fog is heavier during winter months (Sandroni et al, 1981), especially during January (Fuzzi et al, 1995). Fog's intensity and density diminishes as one moves from the suburbs inwards towards the city center, thanks to the urban heating island effect. Milan's fog incidence and overall fog "strength" have been decreasing in recent decades due to the removal of rice paddies from the city outskirts and the increased anthropization of rural

[14] For further reading: ALIANO, David. Brazil through Italian Eyes: The Debate over Emigration to São Paulo during the 1920s. Fondazione Giovanni Agnelli, 2005.
[15] Retrieved from http://www.holiday-weather.com/milan/, 12/02/2018.

areas (Mariani, 2009)[16]. Milan's heavy traffic contributes to air pollution, and when these pollutants mix with the fog – and eventually reach the ground as fog condenses – they generate both air and ground pollution (Fuzzi et al, 1995). The weak wind speed also contributes for the non-dispersion of pollutants (Vignati, Berkovicz and Hertel, 1996; European Environment Agency, 2009). Its climate is classified as Humid Subtropical (Cfa) according to the Köppen climate classification.

Milan's relative humidity can range from considerably high to very high – usually up to 95%, sometimes reaching 100%. Wind, like most of Northern Italy, is generally weak (Vignati et al, 1996; Mariani, 2008). This is largely due to its geographical position, confined between two mountain chains, the Apennines and the Alps, who both serve as a shield against Northern European and Mediterranean wind currents, respectively. Summers in the city can reach temperatures above 35ºC and winter temperatures often fall below the freezing point of 0ºC. Snow days are on average 6 per year, and rainfall amounts for an average of 970mm a year, with 77 rainy days, on average.

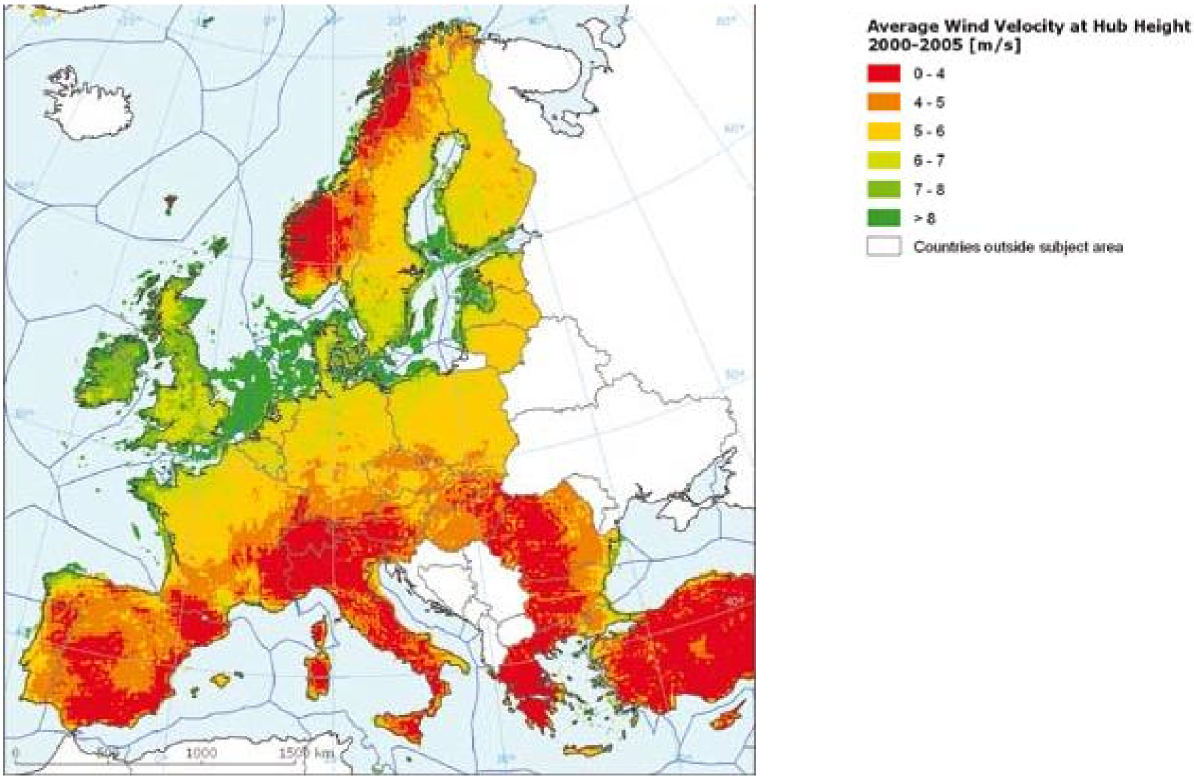
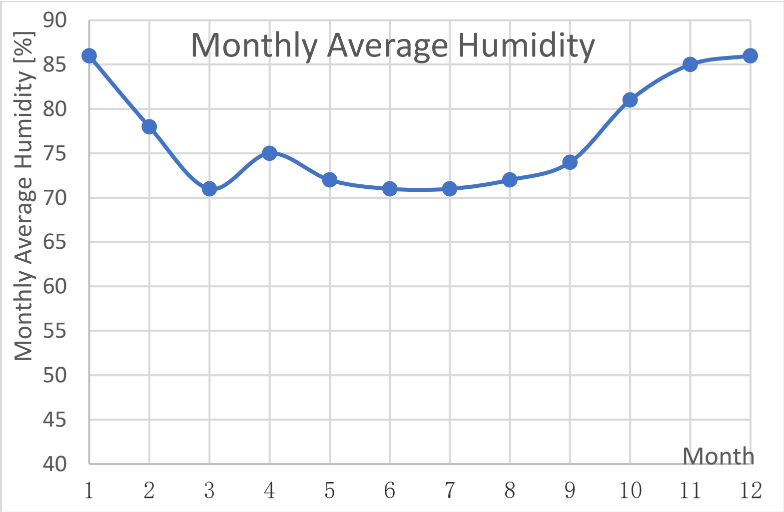
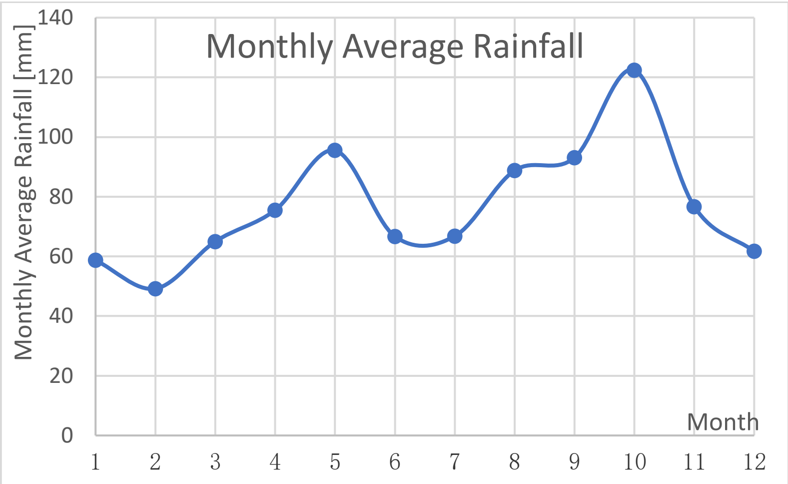


Figure 18: Wind in the city (and throughout most of the Italian peninsula) is largely absent, as identifiable by the weak wind speeds described in the figure. Credits: European Environmental Agency, 2008.

[16] This trend is in line with a general tendency of decrease of fog in Europe due to climatic alterations and an accentuated human presence throughout the continent.





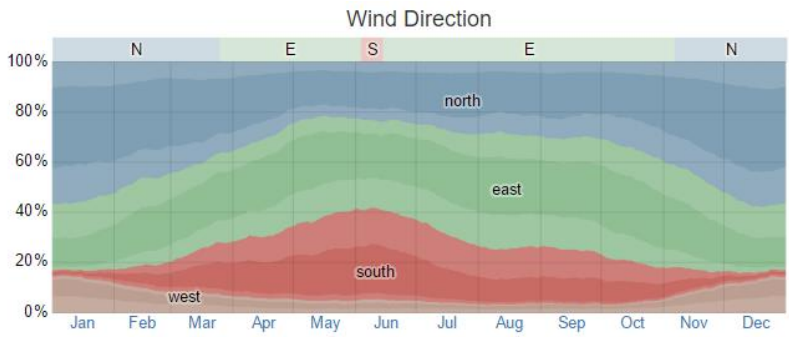


Figure 19: Milan's average humidity is always considerably high, and rainfall is not a rare resource either, as deducted from the two upper graphics. Predominant winds considerably shift direction from summer to winter: in the former, the south direction predominates alongside the east direction, and as the latter arrives, it slowly shifts starts coming from the north.

The metropolitan region of Milan sits within the wider Pianura Padana region of Northern Italy, half-way between the Alps and the Po river, in a sort of major topographical “bowl”, the result of which proportionate an ideal configuration for radiation fog formation which is heavy on LWC (Mariani, 2008; Giulianelli et al, 2014; Fuzzi et al, 1995).The topography of the city is mostly flat, with little altitude variation. However, a gradient, from north (~150 m.a.s.l.) to the south (~90 m.a.s.l.) is observed, making any water utility installed in the upper parts of the city to flow gravity-led down to the metropolis (Gama et al, 2015).

6.2 Water infrastructure in Milan: State of Art

Milan’s Water Distribution Network (WDN) presents a very low leakage level, as studies by Candelieri (2014) demonstrates. Thanks to this pattern, reliable data on water consumption could be deployed by the ICe project, an European-sponsored model of monitoring WDNs. A study on water use in Milan, both in a year and in each individual day – including an hourly study of water consumption, from the household level to the wider urban level – showed three distinct patterns: Spring-Summer, Fall-Winter and Summer break. This last period is especially characterized by lower water consumption, as it is “associated to the 15 days in the middle of August, when usually citizens of Milan have their summer holidays and leave the city”[17]. In a daily basis, for all patterns observed in the study, water consumption is highest in the morning from 07:00 to 09:00, slightly decreases till 19:00 – 21:00 and then sharply decreases during the late evening until early morning.

Although Milan is a heavily polluted city for European standards, a large deal of Milan’s urban air pollution stays in the city for reasons other than simply greenhouse gases emissions. A study by Marcazzan et al (2001) found that in Milan the concentration of pollutants, particularly aerosol, was higher in wintertime than in summertime. Such seasonal difference was largely attributed to the presence of fog and lower wind speeds during winter. Vignati, Berkowicz and Hertel (1996) compared the urban air pollution on Copenhagen and Milan and found that the former exhibits much higher levels than the latter mainly due to the weak wind speed, causing pollutants to station within the

[17] CANDELIERI et al. Urban Water Demand Characterization and Short-term Forecasting – The Icewater Project Approach. 11th International Conference on Hydroinformatics, New York, 2014 (p. 7)

city. When wind speeds are higher in Milan, pollution levels can be comparable to Copenhagen.

The water utility company responsible for the service operations in Milan is currently Metropolitana Milanese S.p.A. (Gama et al, 2015). Milan's Water Distribution Network system is divided in two parts: a sub-system, called Water Transmission Network (WTN), made of water extraction and transmission to storage and treatment facilities; and the distribution system which involves the distribution pipes present throughout the city. Currently, Milan obtains its water from groundwater only. Water is pumped to storage facilities from its sources (there are 26 active pumping stations in Milan), where it is treated. Metropolitana Milanese's greatest issue with its water services is its great cost and energy consume that groundwater extraction represents, and all the required pumping to transmit water (Gama et al, 2015). That, aligned with water bills in the city – the cheapest in the country – make running costs in Milan's water supply system difficult to sustain.

The ICe Project built an intelligent computer model for the city's WDN. Most importantly, it helped identifying ageing infrastructure, total number of components and altitude differences within Milan. Wells and water pumps to extract water from the ground amounted to 501, and 33 storage tanks. Milan's network functions with only one pressure zone, named Abbiategrasso, located in the south of the city (not to be confused with the *comune* of the same name located west of the city, next to the region of Piedmont)

Element type	Total count
Number of junctions	149,639
Number of Pipes	118,950
Pumping stations	26
Booster pumps	95
Wells and well pumps	501
Storage tanks	33
Valves	36,295
Check valves	602
Total base demand (m^3/s)	7,5 +-4,2

(Table 2: Element counting on Milan's WDF. Credits: Gama et al, 2015)

Figure 20: MIlan's WDN: counting of elements and overall map. (credits: Gama et al, 2015)

6.3 Potential areas of intervention within the metropolitan city

Figure 21: Milan's urban mesh disrupting fog. Photo: NASA, 2015.

Fog is not as strong in the central parts of the city as it is in its outskirts (Bendix, 1994). Major interventions in the central areas of the city will, therefore, be largely avoided, not only for the technical part of the project but also for its aesthetic one, since the aim of the intervention is not one of disturbing historical cityscapes but providing an aesthetic and functional addition to the urban environment. The implementation of the devices will be, therefore, either in the suburbs or in medium and small cities around the city of Milan, part of its metropolitan area.

Although the project is not thought of a "fog cleaner", intense harvesting of water from the fog means that trains, roads and transportation infrastructure in general could benefit of this new intervention, in case the collectors were positioned side by side with them. This implementation will be strongly conditioned to the presence of energy and water infrastructures nearby, as the devices cannot store too much water neither can function without electricity. This scenario is the least possible out of all due to these technical difficulties that goes beyond the need of maintenance.

In the territory of the metropolitan city in Milan, a curious characteristic is present: most of its south half past the actual city of Milan is much more sparsely inhabited in comparison to its north. Giving the fact that fog tends to be thicker outside the city center, the installation of a fog harvesting project in the small southern comuni of the city are a preferable option, since they could, perhaps, rely more on fog water provision.

The northern, semi-urban areas of the city, due to their denser urban mesh, are not an optimal zone of intervention.

However, in case an optimal fog harvesting zone is identified in this northern area, installation of devices there can significantly ease water transportation costs, for they can transport water to lower-lying reservoirs and treatment stations.

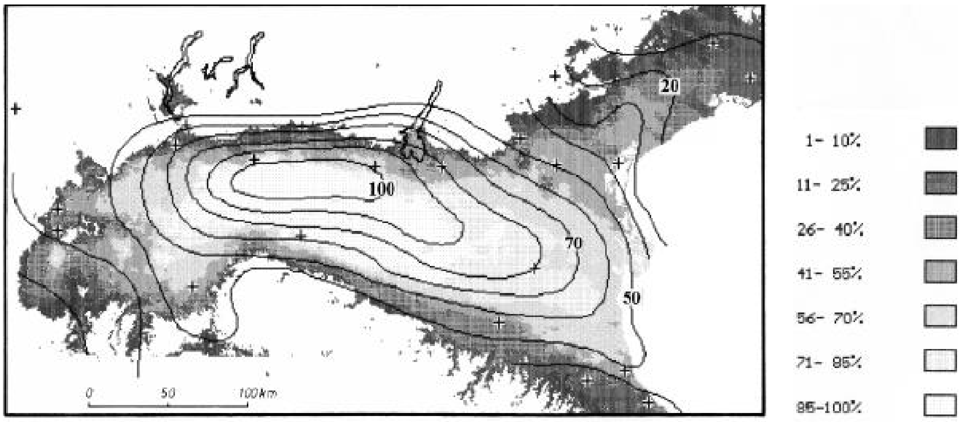


Figure 22: Fog incidence in the Po Valley. Milan's metropolitan area is immersed in the area with the highest fog frequency in the region. (Credits: Bendix, 1997)

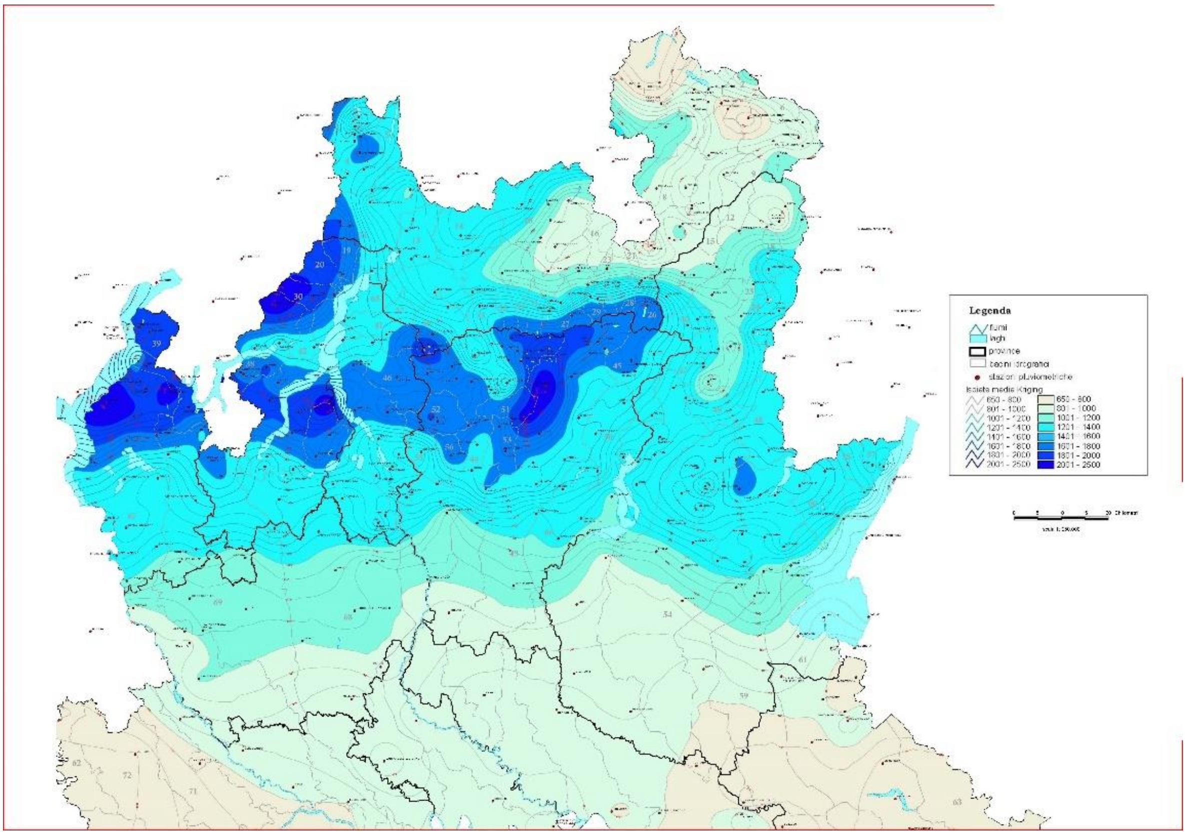


Figure 23: Average precipitation in Lombardy (2015).

7 Comparison between intervention scenarios and problem framing

Riassunto:

Per arrivare alla decisione di scegliere il locale di intervenzione per il progetto, le variabili prese in considerazione sono state così scelte per la loro rilevanza nel progettare un sistema per la raccolta della nebbia. Fra di essi, la presenza, incidenza e qualità della nebbia, bensì l'infrastruttura esistente, velocità del vento e specie l'opportunità di innovazione sono state elencate come essendo le più importanti variabili nel determinare il contesto di progetto. La scelta della progettazione nello scenario del nord Italia non trova tanti imbasamenti oltre la presenza della fitta nebbia della regione, una volta che presenta carenza di venti, la nebbia è spesso inquinata e l'attuale situazione di fornitura dell'acqua della regione non è critica. Tuttavia, anziché considerarle barriere non trasponibili, si nota questo scenario come essendo un'importante opportunità per iniziare e diffondere la pratica del Fog Harvesting in Italia. Siccome la maggior parte degli sperimenti a priori realizzati nel mondo furono sviluppati in un contesto di carenza di risorse idriche e con tecnologia passiva e zero costo energetico, l'applicazione innovativa del Fog Harvesting in Italia disporrà di un più alto livello tecnologico localmente disponibile che richiamerà una fornitura di energia per funzionare.

Having as a theoretical base all the research conducted so far, it is already pertinent to analyze, both individually and collectively, every component that influences fog water harvesting for determining the scenario of the project, its geographical location and make a problem framing, out of which a program of necessities will emerge to accordingly respond to the context's demands. For such, different variables will be analyzed, such as wind speed, presence and overall strength of the fog, the state of the art of fog harvesting technology and scenarios of application.

With every chapter before the present one, several information regarding the importance of water for society and economy were discussed, as well as fog harvesting's potential to be an alternative water source for many regions of the world that can count on such method. Water's role as a vital resource for social and economic dynamics, fog's nature, composition and frequency and the state of the art of fog harvesting were discussed in enough depth. The analysis that will be conducted now will be one to identify loopholes and unexplored potentialities in all the material presented before, so to emerge a set of opportunities for innovation through invention.

A fulfillment of such unexplored potentialities will be sought with the invention of new fog harvesting devices, a novel application that will imply on different dynamics than previously with state of the art technology. In the end of each subchapter, a table with the main findings in each section together with their related opportunities for innovation will assess the potentialities for each of the *dimensions* of fog harvesting. Their combined result will constitute the final problem framing of the thesis, which will originate the program of necessities of the new devices.

7.1 Water as an economic agent

Among every city or region that could be suitable for a fog harvesting project that exists in Europe, Milan and its surroundings was preferred due to its immersion in the Po Valley region, that presents frequent, thick fog during the autumn-winter season – whose potential as a secondary source of fresh water is enormous. Though it might contain several pollutant agents due to industrial and urban activities, water could still be harvested. Treatment is required to make it potable, especially when pollutants reach an undesirably high level, but nonetheless feasibility of the proposal will be reached by means of water yielded per collector, which will seek its maximum reach.

Determining which economic sector to intervene was deemed to be less adequate than choosing *scenarios* of intervention. In other words, instead of choosing between the primary (agriculture, mining), secondary (industry and manufacturing) and tertiary (commerce, services and finances) economic sectors, it was instead considered a rural, semi-urban and urban context of intervention, a set of economic sectors being present within each one of them. From that model, three application possibilities emerged, and that will be subsequently evaluated: Agriculture[18] and urban design – which represents the natural and anthropic environments respectively – and building components, which derived from a ramification of urban design, specifically directed towards architecture.

[18] Other primary activities, such as the case of mining, were dismissed since the activity is not relevant in the Po Valley region.

7.1.1 Agriculture

As analyzed in chapter two of this essay, agriculture is one of the human activities that most consume water to produce its outputs – about 70% of fresh water uses worldwide (UNESCO, 2001). Currently, it is not an activity – at least in the Po Valley – which is in danger of water scarcity that could lead to less crops, nor is it especially impactable with an extra water surplus past its required levels, as shown by Hannemann (2005). Additionally, fog is an atmospheric phenomenon, and radiation fog in particular covers a big deal of land with water droplets, both in width and in height (which will depend on the height of the thermal inversion layer) (Teixeira, 1997). That means that vegetation can easily intercept water droplets, and as they slowly fall on the ground, they accumulate on the plants' surface, effectively providing them with water. Though not sufficient in its own, this water source is literally cost-free.

The interaction between fog and vegetation is well documented and studied in the scientific literature (von Glasgow, 1999; Katata et al, 2010; Bothagaray, Fuentes and Marquet, 2010; Li et al, 2018). Particularly, in California, a study conducted by Ingraham and Matthews (1995) observed how fog water deposited in the plants of the Point Reyes peninsula in the proximities of San Francisco, is significantly richer than rainwater in terms of its isotopic composition. Vegetation was shown to have absorbed a huge deal of fog water.

Frederick (2005) suggests that perhaps a more efficient usage of water resources – instead of an increasing amount of them – is key for achieving more production with less water. In other words, his concept of *crops per drop* illustrates the idea that in an efficient irrigation system, less water is needed to grow a given desired number of outputs. Supporting this statement is a later study by Saccon (2017), who suggests that more efficient irrigation practices can reduce the volume of water consume in agriculture by 30–70% and yields by 20–90%. Such results could be achieved by efficient public policies and legislation, aimed at regulating water use so to prevent leakages in infrastructure, as well as maintenance and updating of old irrigation systems (Frederick, 2005).

Fog harvesting to provide water for crops are more efficient in arid countries or regions. Some such initiatives exist, as in the case of Egypt (Harb et al, 2016), where extreme desert aridity makes it hard to rely on any other water source but fog or the river Nile. Raschel meshes are used for some agricultural practices to provide shading and protection against excessive sunlight and insects. Fog water gathers around the surface of the greenhouse through the same collision phenomenon present in other fog collectors.

In the Italian case, this scenario is not a preferred one for intervention, given that wind is weak and air humidity is high. Though the field has potential for a fog harvesting project – and some researchers have already assessed it – it is not one whose effects are deemed to be an immediate, justifiable and visible benefit, both in the short and in the long run. Furthermore, maintenance of the meshes would have to be constant, since it would be exposed to environmental hazards all the time, a factor of which severely reduces its aggregated value as an irrigation alternative.

7.1.2 Urban design

Without a doubt, intervention in an urban context is a powerful and unexplored potentiality for a novel fog harvesting program. It has been continuously neglected – perhaps due to a technical restriction of the Large Fog Collector instead of pure rejection of the idea – by the enthusiasts of fog harvesting, who see the applicability of the technology to be more suitable and more necessary to rural and more sensible areas, where existing water infrastructure is little. Although sensate and reasonable, such limited application restricts both site and context of the projects, excluding a vast potential of intervention and innovation that are yet to be fully discovered.

Italy, being Europe's largest water consumer per capita, puts strains in its fresh water resources. Fog water harvesting, therefore, may come not to replace groundwater or surface water abstraction, but might act as a mean of reducing such water withdrawals at least during the foggiest months of the year, a period of which lakes, rivers and groundwater may replenish themselves.

Potentialities of intervention in such scenario may assume the form of urban furniture, in which a device could be placed in a public park, square or another sufficiently open area that may receive enough fog to be harvested. Such device will have to be an integral part of its landscape, and might not be a competition to the context, but a positive addition to it. Another possibility is the creation of a major network of interconnected devices that together constitute a sort of "water generator" (as compared to energy generators), that can collect more water from the air, but that are located distantly from central areas of cities, opportunistically for the fact that it won't aesthetically impact the historical architecture commonly present in Italy's urban nuclei, and will suffer less with the urban heating island effect caused by anthropization in cities.

7.1.3 Building components[19]

Conceiving building parts that can mechanically or passively harvest water from the fog is another interesting potential of implementation of fog harvesting in the Po Valley. Here, a peculiar characteristic connected with wind speeds is present, that contrasts with other possible applications: considering a high-rise building, as height increases, so does wind speed. Devices positioned high from the ground may rely little on mechanical ventilation to generate their air flow, if at all. In this framework, a fog harvesting building component may be similar in nature to a state of the art LFC: passive, wind-reliant and zero-energy.

Radiation fog may form with heights that are proportional to the thermal inversion layer of the atmosphere (Bendix, 1994). That being said, radiation fog may cover a wide area while stretching several dozens of meters above the ground, where wind speeds are notoriously greater. In the case of high-rise architecture, wind is a major concern regarding the building's stability. A device conceived for such heights must not act as a wind "catcher" – so not to collaborate to "push" the building laterally, weakening its aerodynamics – but rather, it should allow wind to free flow through it. Mesh's pore size will have to be notoriously larger, and the collectors' geometry must be made according to the expected wind speed. In the case of shorter buildings, or devices placed in the lower floors of a high-rise, mechanical ventilation is necessary.

Evaluation of intervention scenarios regarding water as an agent of socioeconomic dynamic in northern Italy				
Scenario	**Present water supply situation**	**Status within FWH**	**Other observations**	**Final avaliation**
Agriculture	Not in critical condition	Some major past experiments had it as one of their focus of action	This scenario could benefit more from politcs/legislation than from fog harvesting	Not desirable for intervention
Urban design	Not in critical condition	**Unexplored. Open for opportunities and innovation. Can help relieving pressure in existing groundwater sources.**	**Intervention could assume many shapes, including urban furniture or larger structures**	**Preferred choice**
Building components	-	**Largely unexplored. Open for opportunities and innovation.**	**May be used to supply green roofs, gardens in buildings**	**Desirable choice**

(Table 3: comparison between studied scenarios. Urban design and building components easily emerged as potentials of intervention)

[19] This application was first suggested by professor Lorenzo Matteoli, to whom I give partial credits for the idea.

7.2 Characteristics and presence of fog

Giving the fact that fog is present throughout the entire Po Valley, even if is the case of developing this project in only one city, it could be well developed for other places within this region due to fog's similar chemical features (Giulianelli et al, 2014), taking special care in selecting places where fog LWC and incidence is maximum, so to yield maximum outputs. Particularly, fog incidence in the Milan metropolitan area is the highest (Bendix, 1997), which justifies major interventions for the city. The city of Turin does not experience episodes of heavy fog as it used to. It is not envisioned an application of the project in the Torinese context, since it is not expected to yield enough outputs as to justify its investment.

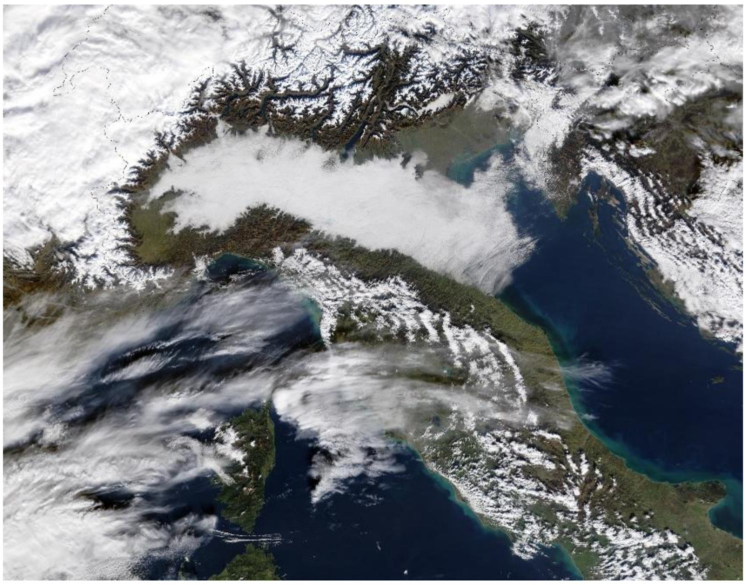


Figure 24: Satellite image of the north of Italy during winter, with a thick, dense fog cloud over the Po Valley. (Credits: NASA)

Fog in the Po Valley, as reported in chapter 3, happens majorly as a nocturnal phenomenon between sunset and the early morning, when the sun gives droplets enough heat to evaporate, dissipating the fog. This factor is especially important for the studies of functionality of the new devices: they will work mostly during the evening until morning, or at least until fog dissipates. Therefore, operability costs regarding electricity use may be largely concentrated during the fog hours of the day.

Fog, although a natural phenomenon, is connected to several environmental degradation processes in the region. One such problem is that, due to the intense anthropic presence in most of northern Italy nowadays, the region experiences considerable air pollution as a result of fossil fuels usage to provide energy for the many activities that take place in the region. The north of Italy – particularly the Lombardy region – is very industrialized, and emission of pollutants in the region may combine with fog and produce the undesired smog phenomenon, of public health concern.

Water harvested from a fog that contains numerous toxic substances is not at all deemed acceptable, and thus two solutions to contour the problem are possible: either the devices are turned off during smog episodes, or they may deliver contaminated water directly to treatment facilities, where an extra amount of care will be dedicated to treat that water, so to make it potable. Smog is a concern for public health authorities in the region since several years, and although it is not the scope of this thesis to deal with this issue directly, it is not unthinkable to hypothesize a fog harvester that will seek to absorb pollutants and release cleaner air in the atmosphere. That is an opportunity for another novel fog harvesting application, of a different kind.

Thick fog is responsible for major transportation hazards, not only in the Po Valley but also, reportedly, in the Bosphorus Strait in Istanbul, Turkey, and throughout California's Tule fog's area of influence. Since it isn't a function of the devices to be proposed to "clear" fog from the atmosphere, installation alongside transportation infrastructure with that specific purpose is not the goal of this thesis. However, the potentials and benefits that could emerge from the proposal of a major intervention that could increase visibility in roads, train tracks and airports during severe fog events are numerous and could have an immensely positive impact for the country/region. This could be, perhaps, a theme for the continuation of this work – or even of another master's thesis.

Evaluation of potentialities and weaknesses of fog in the region		
Fog	**Situation**	**Answer**
Incidence	In the Po Valley, the highest fog incidence is in Lombardy, in and around the metropolitan area of Milan	**Intervention within this region is preferred**
Seasonality	Fog largely forms during autumn and winter	**Devices will harvest much more water during autumn-winter. When there is no fog, they could collect rainwater.**
Daily formation and dissipation	Fog happens as a nocturnal phenomenon	**Fog harvesting by the devices will operate from early evening until fog dissipation in the morning**
Related infrastructure hazards	Transportation infrastructure problems due to thick fog	**Not a theme of this thesis**
Related health hazards	Smog phenomenon	**Cleaning smog from the atmosphere is not a theme of this thesis**

(Table 4: Fog evaluation and identified possible opportunities)

7.3 Fog water harvesting: state of the art and past experiments

From the research conducted so far, it is already possible – and pertinent – to collectively name some important characteristics about the intervention contexts of the vast majority of the past experiments on fog harvesting: a large number of them were executed in dry, relatively remote areas of economically undeveloped/developing countries[20]. As a consequence, some hardships met by the enthusiasts of fog harvesting technology were mostly repetitive throughout the many experiments conducted.

Figure 25: Wind pressure upon an LFC at Majada Blanca, Chile. (Credits: Holmes et al, 2015)

Fog was the strongest alternative for water provision that villagers could have. At times, it was the *only* fresh water resource locally available. Community involvement was quintessentially the life of the project, that kept maintaining the devices operational, clean and to the top of their efficiency. Furthermore, the LFCs were always placed at high altitudes, and distant from the villages. That not only makes it hardly inaccessible, but also leave them exposed to several environmental hazards such as exposure to intense sunlight, dust storms and strong winds that can often tear off the collectors' meshes. When there was no wind, there was no collection. Where there was a strong wind, there would be damages to the structures (fig.25 and 26).

Figure 26: Wind initially creates small ruptures in the mesh, and if these aren't fixed, may expand and ultimately destroy fog collection infrastructure. (Credits: Holmes et al, 2015)

The previous paragraphs of this subchapter were a synthesis of chapter 4 and 5 of this thesis. Important voids can be identified from these information: one, there has never been a major fog harvesting project in a developed context, which makes this Italian intervention pretty much unique in its kind; two, fog harvesting is at no means the only source of water available for the population, but a secondary source to help alleviating pressure upon existing fresh water resources; three, a project for the Po Valley could only effectively harvest fog during the autumn-winter season; therefore, in the absence of a strong fog, the devices could rely on collecting, for example, rainwater; and four, the devices won't have their meshes directly exposed to environmental hazards, being protected from them.

Conversely to previous experiments, this Italian project will not be maintained by volunteers trained locally. Since they would be owned and maintained by local water providers, they would be the direct responsible for the devices' maintenance and personnel training, generating jobs and possibly securing a

[20] For clarification purposes, no particular definition of "development" is meant to be enforced by this sentence, but rather a statement that these countries' economic level are below post-industrial.

longer duration of the project. One of past fog harvesting initiatives' major constraints was that, when local involvement was low or weak, the project was quickly discontinued; in the case the devices are owned by a company that bears responsibilities over them, chances are that this component of the project wouldn't be a major concern.

Finally, there is the place of intervention. The devices will be installed in urban and semi-urban areas, easing accessibility. That is a major advantage of the proposal in comparison with LFCs, for the latter is ideally best situated in hills and mountains, whereas the proposed devices will work well in both high and low altitude contests, as long as fog is present.

State of the Art weaknesses and loopholes	Opportunities for innovation
Most were in arid, undeveloped regions	**Potential of exploring a developed context**
Fog water was at times the only source of fresh water available	**Surface and groundwater are available, but not inifinite. Therefore, the project could help alleviate pressure on existing water resources.**
When there is no wind, there is no collection	**There is little wind in the Po Valley. The devices need to generate wind**
LFCs are constantly exposed to environmental hazards	**The new devices could be protected from degradation**
Community involvement is essential	**The devices would be maintained by the water provision service**
LFCs are always positioned at high altitudes, distant from urban centres	**Versatility of use; can be implemented pretty much everywhere where there is fog**

(Table 5: Most of the opportunities of innovation extracted from the state of the art are due to its limited applicability.)

7.3.1 Developed and undeveloped scenarios

This subchapter is meant to analyze and assess important differences between designing for people that can use a water surplus as a mean of direct social and economic change inductor, and people who certainly would benefit from an extra water supply – but, as discussed in chapter 2, may not be conscious of its importance. The scope, mechanic and impact of such project will have to justify its implementation, so it won't be an investment risk.

Beforehand, it is worthy stating that the so-called Third World is a very heterogenous macro-region. Since it encompasses everything that wasn't within the USA's and the USSR's zone of direct influence – e.g. the non-aligned countries of Latin America, Africa, Asia and Oceania – their economic development and societies differ widely even within a single country, even at the local level. The developing countries in which previous experiments were carried on were at very different levels of economic and social development, also belonging to widely different regional contexts. Nonetheless, the reasons for which entities executed fog harvesting projects in these countries remained basically the same: to provide an easier to obtain, extra fresh water resource.

Many procedures for implementing and maintaining a fog harvesting project in a developing, rural context cannot be recycled for the same application in developed, urbanized ones, since fog nature, composition and frequency widely changes. For that reason, an almost entirely new approach to the issue must be used, in order to fit this new context's own peculiarities. To start with, we are not dealing with impoverished, rural people whose nearly entire lives have been passed on a single location; instead, we must conceive a project that will fit the necessities of an urban, cosmopolitan and educated[21] population who might not immediately view this new intervention so positively, or even ultimately necessary.

Despite regional differences in income between its Northern, Central and Southern regions, Italy is regarded as being a developed, advanced economy. That is to mean it has a sizeable middle class, a developed and advanced infrastructure of sanitation, water distribution, transports and communication, as well as a very high standard of living, capable of cope with its people's basic needs. This single characteristic of being an advanced country is the single most influential factor here: most hardships experienced by former projects in developing countries will simply not exist in Italy, or at the very least, will be very different in nature. An Italian fog harvesting project will contrast heavily with the previously fog harvesting projects where insufficient infrastructure – if any at times – was commonplace.

Designing for the northern Italian context, which is a heavily populated region with an important manufacturing importance both for the country and for Europe as a whole, means an electrical energy supply is never far away. Also, to produce the new device, existing industries and manufacturing centres could be more than sufficient. Therefore, these factors will be taken into consideration for the material choices and features of the new device.

[21] For clarification purposes, the word here is used in the sense of "instructed" instead of "polite".

Developing world	Developed world
In some areas, the culture of maintenance and hygiene are not the norm and basic maintenance is out of reach.	**Although notions of hygiene may vary among countries, cleaning is usually culturally viewed as something necessary and fundamental for its own good;**
For the success of the project, maintenance must me constant and must be considered important for the project.	**Devices are owned by a water provision company that bear direct responsibility for the devices, maintenance may become routine.**
Water infrastructure is either insufficient or lacking	**Water infrastructure is good and already present (in most cases). Water distribution network well developed and far reaching;**
Education[22] levels that can range from satisfactory to very low	**An educated population means that no greater communication efforts shall be needed in order to implement the project;**
In certain cultures, a wide gender gap is present	**Gender gap is less evident and not critical**
Materials must be simple and locally available, so to easen costs	**Manufacturers locally available with a variety of usable materials**

(Table 6: comparison of economic scenarios of intervention.)

7.4 Problem framing

The before analyzed data and potentials are enough to build a program of necessities to whom seek a formal solution. From the scenario choice, urban design and building components emerged as promising and unexplored potentials for innovation within the fog harvesting field. Fog duration, seasonality and frequency also prompted the preferred location of this project in the metropolitan city of Milan and its surroundings. Environmental hazards that may reduce material durability of the devices will be countered by protecting them against aggressive agents. Intervention in an economically developed context means that distribution infrastructure, both of water and electricity, is widespread.

The lack of wind in the region mean that the devices will have to provide for their own air current. This, after every analysis conducted, appears to be an elementary characteristic of fog harvesting: the droplets *need* to be transported towards the collecting mechanisms of the devices, being these mechanisms either actively causing such air mass movement, or passively receiving fog droplets. The mechanism of wind generation is the

[22] Word used in the sense of formal instruction

single greatest difference between the new devices and every single previous proposals of Passive Fog Collectors (PFC). It seems opportune to name them as such, to stress their zero-energy fog harvesting mechanism. The PFCs are, therefore, a category and not a specific device.

To actively generate wind, fog collectors must be everything but zero-energy and passive. They require a special mechanism that produces enough and steady air flow to be able to function properly. Such feature is naturally energy consuming, for which the devices will have to be connected to energy infrastructure. Unfortunately, radiation fog happens at night, where there is no more sun radiation that could be absorbed by solar panels to generate sustainable energy to run the devices.

An inducted air flow offers another opportunity: the increment of the collection efficiency of the devices. It is known through the literature of fog harvesting, particularly as assessed by Schemenauer (2015), that a very little amount of fog water is deposited on the meshes' surface, most of them either deviating their course or passing right through the mesh's pores. Consequently, only a small 1 to 3% of all fog water is harvested by the meshes. In a wind-induction system where it is possible to manipulate wind currents, such percentage can be enormously raised, if two provisions are taken: increase the amount of meshes that intercepts fog – so as each one of them will intercept a small percentage of fog's LWC – and securing a steady wind pressure and speed throughout the device, so to maximize the Harvestable Water coefficient.

As far as community involvement is concerned, this project is a radical departure from traditional fog harvesting methods: if PFCs are located in hills of arid regions with community maintenance and supervision, the new devices are not as simple as to be maintained by locals. Also, since these very locals don't necessarily see any necessity of having fog water, if maintenance depended directly and entirely on them, the project would be quickly discontinued. Therefore, who will be responsible for maintenance and functioning of the devices will be technicians from the local water provision company, which bears responsibility for the hydric resources of the region, except in the case the devices are privately-owned.

The nature of this project, as can be inferred from previous deductions, is not as socially conscient as previous experiments. The goal of this project will not be one to provide water for the needy (there are none!), nor will it be one to provide better sanitation, social dignity or any kind of remedy for a social problem. This project, instead, have a more *environmental* appeal to contour a socioeconomic problem; it is an initiative to better preserve hydric resources and foster sustainability and equilibrium between resource use and availability, as well as a desired “conscientization” among the Milanesi who lives in an ever-growing megalopolis whose development, since its industrialization, has been swallowing every nature in its way. Though water provision is not yet in critical situation (Gama et al, 2015), even though all of the city’s inefficiencies, we definitely don’t want to reach such state to start conceiving sustainable, alternative ideas for fresh water provision.

Let the new devices be opportunistically named Dynamic Fog Collectors (DFC), since flexibility and dynamicity are their main features. Instead of being a sterile single device, it is rather a category of them, which can be expanded, improved and diversified as new ideas are conceived.

State of the art devices (PFCs)	**Proposed devices (DFCs)**
Cheapest and locally available materials	Cost-efficient materials with higher water collection capability
2d mesh, one or two layers	Multiple layers eventually composing a 3D collection
Reliance on natural wind, its speed and prevalent direction	Airflow generator and regulator yields water without natural wind
Limited applicability on high elevations and rural areas	As long as fog is present, anywhere is potentially adequate
Lack of existing distribution infrastructure	Placement in a context of very developed and far reaching distribution infrastructure
Socially-aimed intervention	Environmental appeal to correct a socioeconomic problem
Maintenance carried and owned by locals	Devices owned by either public or private parties
Virtually zero-energy	Energy-consuming
Predominant use as a fog harvester. Occasional (but not planned) rainwater harvester	Multiplicity of functions

(Table 7: comparison between the proposed genre of fog harvesting devices and state of the art. Under nearly every aspect, changing the context of actuation radically changes project nature)

8 Design principles of the new Dynamic Fog Harvesters

Riassunto

Questa sezione della tesi vorrà proporre una sperimentazione formale e funzionale di possibili nuove forme per gli adesso denominati DFC (Dynamic Fog Collectors). Partendosi dal programma di necessità ricavato dal problem framing dello scorso capitolo, importanti direttrici sono state ottenute, tali flessibilità di applicazione, meccanismo di creazione della corrente d'aria, una superficie di colletta che deve presentare una più alta efficienza rispetto ai metodi esistenti e apprezzabilità estetica.

Equazioni che descrivono la performance dei collettori vengono in primis individuata. Lo studio di direttrici formali viene eseguito e così si ottiene che il dispositivo dovrà essere capace di integrarsi nel suo contesto senza ripeterlo. Lo studio di un meccanismo di generazione del vento viene fatto e la scelta è ricaduta sul bladeless fan. L'analisi di fattibilità viene eseguita vincolata allo studio della LCA dei materiali del DFC., che attesta il suo basso impatto ambientale. Le tre proposte di DFC sono quindi caratterizzate, ulteriormente scegliendosi di approfondirsi di più sulla tipologia del Pavilion Collector.

From the previous chapter, it was possible to visualize a general framework of the current fog water technology, out of which weaknesses and potentials were obtained. From this problem-framing, a program of necessities emerged to which new ideas could propose a solution for such matters. That is the object of this chapter, which will deal with enough experimentation on shapes, materials, DFC categories and wind generation mechanisms and harvesting methods to respond to the north Italian demands. Above all, a harmonic relationship between the device's parts, both from the technical and the aesthetical point of view will be sought, as well as a reduced carbon footprint, and a great relation cost/benefit.

Intervention possibilities identified as unexplored and open for innovation were urban design and building components. During this chapter, yet another category that will seek farther reaches for the fog harvesting device is proposed: The Pavilion Collector. Initially thought of as a mean to hugely increase fog water collection by increasing both device number and funnel, the solution proved to be much more versatile than initially expected: the array of devices altogether produced a roof, under which a variety of activities more directly related to local citizens could be developed.

Next sessions will develop the methodology used to create the most optimal energy-demanding Dynamic Fog Collector as possible. Starting from the individuation of mathematical equations described by a series of authors, the first shape rules try to enhance as much as possible the device's efficiency. Then, a study of airflow creation mechanisms that could suit the fog harvesters is done and special attention is given to this mechanism's maintenance and energy consumption. Materials are discussed in regard to their carbon footprint, embodied energy and overall performance, so to find the optimal choice for the structure and the collecting meshes. A business model is proposed individuating possible stakeholders. Finally, at the end, the results are discussed, and the choice of detailing one specific type of DFC is made, which further develops in the next and last chapter.

8.1 Mathematical equations of fog collection performance

To better propose an efficient novel device, the need of quantifying efficiency and collection seems evident. To this purpose, a variety of authors have already proposed many different equations to measure fog collection by meshes, some of them being essentially empirical. Notably, Rajaram et al (2016) after several laboratory rests, proposed how the effects of coating and geometry can affect water collection. In his experiments, it became evident how a mesh coated with a hydrophobic surface could collect water at higher rates compared to a non-coated one, but a super-hydrophobic coating, contrary to what one might think, was less performant on efficiency. Additionally, he concluded that flat, knot-free surfaces are more efficient in collecting water and allowing for it to drop quicker to the gutters.

Efficiency, as described by Rivera (2011) is defined as the total surface area of the mesh divided by the total water collected by it, in a given period of time. The harvestable water is the fog's Liquid Water Content multiplied by the wind speed, generating a result that is expressed in g/m^2s.

Among the many mathematical quantifications of fog water collection, some coefficients are worth characterization.

- **Free Flow area ratio**: describes the portion of the area of the meshes in which air can pass through it and continue its course. It is indicated by $f = \frac{Aop}{A}$, in which A_{op} is the area of the pores, and A is the total mesh area.

- **Shade coefficient**: the inverse of the free flow area ratio, it represents the area of the collector capable of collecting water. It is defined by $s = 1 - f$, in which f is the free flow area ratio.
- **Water collection efficiency**: Obtained through $\eta coll = \frac{Wcoll}{\upsilon 0\,.\,LWC}$, in which W_{coll} is the water collection rate by the gutter referred to the mesh's area (measured in laboratory with prototypes, or in field studies), υ0 is the wind's unperturbed velocity and LWC is the Liquid Water Content.
- **Capture efficiency**: $\eta coll = \eta ac\,.\,\eta cap\,.\,\eta dr$, where ηcoll is the collection efficiency, ηac is the aerodynamic collection efficiency, the product of the shade coefficient and the interception efficiency η is the capture efficiency, e.g. the fraction of droplets that are actually captured by the mesh, ηdr is the total water that actually reaches by the gutter.

It must come as no surprise so far that both wind speed and mesh collection efficiency are important factors in determining how strong the fog harvesting solution can be. As seen before, Harvestable Water (Hw) is the fog's LWC multiplied by the unperturbed wind speed, but out of this potential of water collection, the real *collection efficiency*, that is, how much of this harvestable water can actually be collected, is perhaps the last assessment to be done in order to evaluate the devices' feasibility from the fog harvesting point of view.

8.2 Guidelines

To maximize water collection, the device's shape will have to facilitate both wind flow and water collection. Therefore, fluid dynamics plays an important role in shaping the final outlook of the devices, when it is conceived to optimize air flow and water collection. It is to be bore in mind that these proposed devices are not zero-energy as PFCs, and so must make the most out of their operational costs.

The generated vertical wind current imposes vertical stress on the collecting surface, as it normally does horizontally with PFCs. Not only will the mesh need to be of a different material other than the conventional plastic Raschel mesh, but also will need to assume shapes that better withstand vertical stress and bending moments. The fact that the mesh's hypothetically chosen material is of lower resistance than expected cannot justify an increase of the mesh's overall thickness to tackle the issue – that would actually reduce efficiency per unit of volume of the mesh and possibly complicate maintenance. Furthermore, there are currently no studies that states that thickness of the nets benefits water collection, which could lead to an unnecessary material use. Therefore, the use of a more resistant and durable material can be justified if the mesh's overall thickness is as little as possible – as long as resistance and efficiency are not compromised.

Filters and grates to retain eventual impurities will be needed, one at the top to prevent small animals to get inside the collectors, and another one located at the bottom of the collection tube, before the water drops reach its small reservoir. From the state of the art technology, only a sedimentation tank is present to purify the water, which in the current device proposal, will not be sufficient. The DFCs need to, therefore, have periodic inspections so to clean the filter and remove its impurities. Albeit retaining solid particles, the filter, is not capable of retaining pollutants eventually present in the water, a reason of which water yielded will not be directly drinkable. Water will need to go to a treatment facility, and that implies transportation costs – which would be minimal in case reliance in a gravity flow is possible.

From the above statements, it is already possible to identify some fundamental components of the device, from top to bottom: a resistant grid on top of the fan so to retain solid objects of considerable dimensions that could eventually be caught in the air flow, like leaves, trash and other things that could be transported by the air; a wind inductor, located immediately below such grid, is the responsible for the generation of the desired wind current that will pour inside the device; the water content of which will be subsequently captured by the intercepting meshes, distributed all along the length of the device's body, ending in a final collector unit that will conduce water to a small reservoir, then to the filter, and then to its destination – being the storage facilities through piping or to other water uses that do not require treatment.

The shape of the device must be one such to allow air movement to either maintain or increase speed. A shape where airflow is restricted or contained will fail in transporting fog droplets to the lower level meshes. A desirable airflow, throughout all the length of the device, is to be sought.

Since the installation of the devices will have to blend inside an urban environment, shape and aesthetics are of essential importance. Special care is given to the device's dimensions: it must not be as robust so to be a visual harm, nor so little as to not be seen. It cannot be, therefore, a 2-dimensional net such as the ones in nearly every fog harvesting experiment carried up to this day. From this principle, we can derive the assumption that the device will need to be either short and larger (like for example a functional bus stop) or tall and slender like a post. Giving the fact that fog's Liquid Water Content is highest from 2/3 of its height, it is safe to assume that the device will need to be tall in order to harvest the most of fog's water.

8.3 Fog harvesting in a wind-scarce context

The feasibility of a fog harvester in a wind-less context requires the development of a mechanical, energy-consuming wind generation component. This noteworthily increases the device's running costs, especially if compared to the PFC that yields water without any active energy consumption. However, such assumption is only but superficial. The real data that needs to be produced is, as suggested by Holmes et al (2015), the *total cost per unit of water produced*. Therefore, to compensate an increase in operational costs of such fog harvesting device and maximize its efficiency, water collection must be elevated to such a threshold previously deemed to be hard to achieve by using a simple, passive Large Fog Collector.

Since the wind generation mechanism will be a costly component of the devices – and to the fact they are strictly correlated with the water collection mechanism – the mesh's materials will need to be as economic as possible, while being much more efficient in harvesting water.

The device's wind inductor will have to be propelled by electricity. Consequently, it will need to be connected to energy infrastructure. Radiation fog has the characteristic to form during early evening and last well till sunrise – which means it is largely a nocturnal phenomenon. That, combined with the fact there is little wind in the region, equals no source of sustainable solar or wind energy can be used by the devices to properly function, which is a potential weakness of the solution. In other words, the devices will have to use energy directly from the city's existing infrastructure. Collecting solar energy during the day and storing it in a battery to be reused at night is expensive and not feasible.

8.3.1 Studies of mechanisms of wind generation

Wind, as a natural phenomenon, is the large-scale movement of air from one place to the other due to a difference in pressure between them (Makarieva et al, 2013). Air flows from the higher-pressure area to the lower pressure one, and such flow is maintained as long as the pressure difference is constant.

Several methods to generate airflow exists. Through different procedures and with different apparatus, they work to generate the flow of air particles between one point to another. Among every kind, it can be identified:

Fans, which are machines that works by creating a pressure difference in the air, propelling the movement of air particles. Both size and RPM matters in generating air flow and pressure. Fans usually move constant volumes of air while exerting a low pressure; compressors[23] on the other hand, usually move less volumes of air with higher pressures. There are two main types of fan: axial fans, which propel air perpendicular to its surface and parallel to its spinning axis, and centrifugal fans, which changes air direction while it spins. Both types are known for usually produce noise as a result of impeller[24] rotation and pressure fluctuation (Jafari et al, 2016).

Fans can be designed to deal with higher static pressure, a concept within fluid dynamics. Fans with this characteristic can move a given amount of air more strongly when compared to regular fans. To move air through a series of physical obstacles, a high static pressure fan is more ideal than a high airflow one, for it secures that air will blow stronger throughout the mesh's pores and will not be prevented to reach the lower meshes of the device.

The use of a regular fan as a mean of airflow generation has a series of disadvantages. As a physical element, a fan positioned at the top of the device to push air downwards becomes a physical barrier itself against fog flow, and also against rain. Additionally, it requires periodical cleaning, for their blades get covered in dust, especially in semi-urban areas. Their spin can be interrupted by solid objects that might be eventually carried up with the air and get stuck between the blades, such as small rocks, leaves, tree branches and others.

8.3.1.1. The bladeless fan

Bladeless fans, a.k.a. Air multipliers, were invented by Gammack et al (2009), who also holds its corresponding US patent. They are propelled by a brushless electric motor that spins an impeller inside its lower body, which sucks air in and deliver it to the frame of the fan, with an airfoil cross-section. This creates a pressure difference, and when air blows from the fan's

[23] Their usage as an airflow creator for the DFCs is impracticable for they are too robust and much more energy-consuming (Guo et al, 2017)

[24] Movable part of the fan responsible for the creation of pressure differences. Composed by the fan's blades and spinning axis.

frame, it drags surrounding air together with itself onwards, effectively multiplying the airstream and creating thus a smooth, laminar flow – as opposed to traditional fans' turbulent flow. Bladeless fans are neither centrifugal nor axial fans, but drags elements from both of them, for it changes airflow direction like a centrifugal fan and propels it forward to a similar way to axial fans (Jafari et al, 2015).

Although a relatively recent invention, literature on the topic was already produced to evaluate its performances with Computational Fluid Dynamics (CFD), so to verify its behavior as an air current inductor. Jafari et al (2016) narrated well the mechanism of a bladeless fans, in a passage of their article titled "Experimental and Numerical Investigation of a 60cm Diameter Bladeless Fan", which reads:

> "Surrounding air is sucked into the fan by rotation of radial impellers driven via a DC motor. Afterwards, the air is passed through an annular section and exited from a narrow ring-shape zone. The area reduction at the exit side increases the outlet velocity of airflow. Difference between the air velocity upstream and downstream of the fan leads to a pressure gradient according to Bernoulli equation. This created pressure gradient sucks the air from the back of the fan (upstream) towards the front side (downstream). The outlet flow of the fan includes the inlet flow (passed through the impeller), sucked flow from the upstream which passes through the annular part, plus surrounding airflow. So, total output flow rate measured at a distance of 3D (D is fan diameter) downstream is several times of the inlet flow rate (Gammack et al. 2009)"

Currently, the air multiplier technology it is mainly used for domestic appliances, however Jafari et al (2016) assessed through a study of a 60 cm diameter bladeless fan that this category of fans could serve a wide variety of other purposes, and that its potentials are still largely undiscovered. In the study it was obtained that the air flow generated by the fan were largely composed by sucked air from behind the fan and from its upstream. In another study conducted by Jafari et al (2015), an optimal profile cross section of the fan was individuated, that is the Eppler 473 airfoil (fig. 28), for its high curvature (good Coanda surface) and better capacity of suction of the air from back of the fan, a fundamental characteristic for its use in fog harvesting.

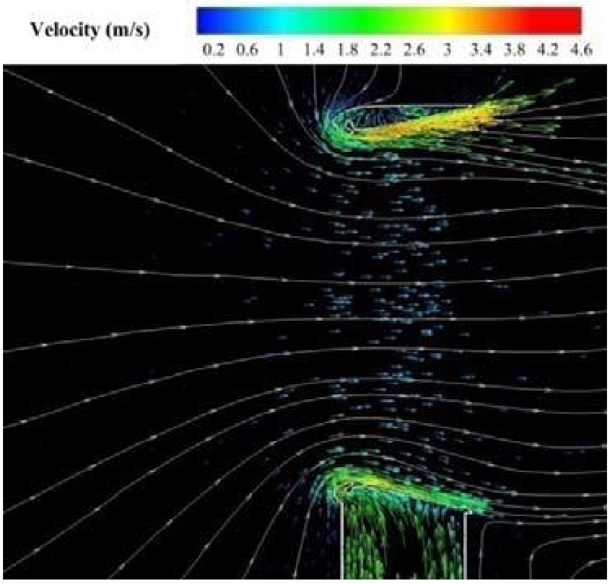


Figure 28: Vectors and flow lines of a bladeless fan. (Credits: Jafari et al, 2016)

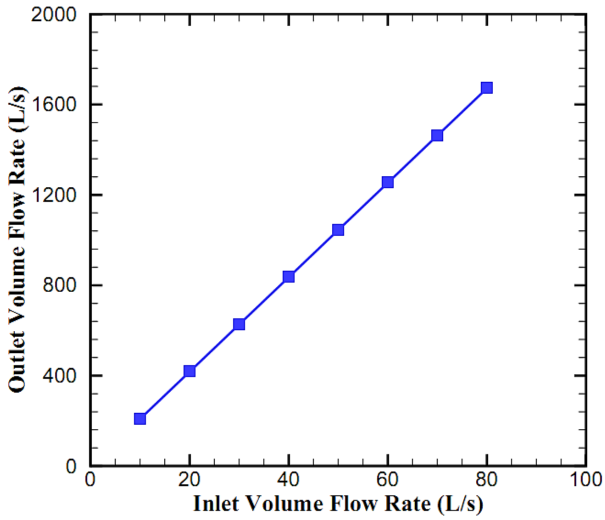


Figure 27: The increase of the Inlet Volume Flow Rate for a bladeless fan corresponds linearly to its outlet volute flow rate (Credits: Jafari et al, 2015).

The bladeless fan is easier to clean, presents no physical harm to people and is much more silent compared to virtually every other kind of fan. Its bladeless characteristic means its airflow is uninterruptable by solid particles as stones or pieces of other hard small objects (as it could happen with regular fans) and they produce an unperturbed, laminar wind flow. Giving all its notoriously strong features and superior airflow generation with one third of the energy consumption of other fan types (Fan, 2015), the bladeless fan is the preferred choice to be the air flow inductor of the Dynamic Fog Harvester.

Studies by Li et al (2014) attested that the dimensions of the Coanda surface[25] of the bladeless fan's airfoil has an important role in its performance, particularly in its blowing strength.

8.4 Water collection mechanisms

The most widely used mean of collecting water from the fog is the Raschel mesh (Schemenauer, 2015). Studies by Rajaram et al (2016) noted how reducing pore size in Raschel meshes led to an increase of water collection by 50% and using a hydrophobic material would further increase it by another 50%. He also noted that a knot-free mesh is more efficient than otherwise. Rivera (2011) concluded, conversely, that hard sheets of metal or plastic are not suitable for fog harvesting collection,

[25] The Coanda effect is a fluid jet's characteristic to stay attached to a convex solid's surface (Trancossi and Vucinic, 2013).

and that there is an optimal shade coefficient for the mesh that ranges from 0.5 to 0.6, whose distance from such range prompt efficiency to sharply decrease.

Raschel meshes have been extensively studied in the literature of fog harvesting (Rivera, 2011; Klemm et al, 2012; Park et al, 2013; Holmes et al, 2015; Rivera and Lopez-Garcia, 2015). Perhaps as a response to its repetitive use throughout most of the fog harvesting experiments, several types of meshes for fog collection were conceived by researchers, even though a large number of them have never been put to practical evaluation in field conditions (Rajaram et al, 2016).

Although the use of meshes to harvest water from the fog is widespread in the modern fog harvesting projects – as well as studied (series of authors), it is not the only existing way to collect most from the atmospheric air. Many of them are still under testing conditions, but nevertheless offer a new horizon in the available methods of harvesting water, especially in wind-less conditions (Peng et al, 2015).

Figure 29: Cactus thorns can efficiently harvest moisture from the air. Photo: Mars HIll, 2015

Biomimetic materials as collectors of fog water have recently been studied, conceived and proposed by a number of authors, taking inspiration on cactus, beetles and other forms of live that thrives in arid environments where fog is a vital water source. Ebner, Miranda and Roth-Nebelsick (2011) studied mechanisms of fog harvesting by the *Stipagrostis sabulicola*, a species of grass that grows in the Namib desert, and found that one such plant in average may collect up to 5 litres of water per fog event. White, Sarkar and Kietzig (2013) produced a series of hydrophobic surfaces inspired by the *stenocara* beetle and found that water collection rates among them was rather even, being wind and aerodynamics the most responsible for differences in water collection.

The Lotus effect is a characteristic of ultrahydrophobicity in a material, where its surface configuration prompts contact angles of over 160º. It is named after the lotus flower for its surfaces present an elevated degree of hydrophobicity (Rosario et al, 2004). Ultrahydrophobic materials have the property of being able to self-clean, due to water in their surfaces carrying dust as they slide down (Guo and Yang, 2017).

Inspired in cactus thorns, Xu (2016) produced in laboratory an artificial periodic roughness-gradient conical copper wire (PCCW). The thorn-like structure can harvest fog on evenly spaced points of its surface from the surrounding air and transports them without an external force, a phenomenon of which is attributed to dynamic as-released energy generated from drop deformation in drop coalescence, in addition to both gradients of geometric curve (inducing Laplace pressure) and periodic roughness (inducing surface energy difference) (fig. 31). The study further verified the great fog harvesting potential of the solution, related to the tilt-angle wires (angle formed with the horizontal) and subsequently proposes a fog collector with composed of several PCCWs. (Xu, 2016)

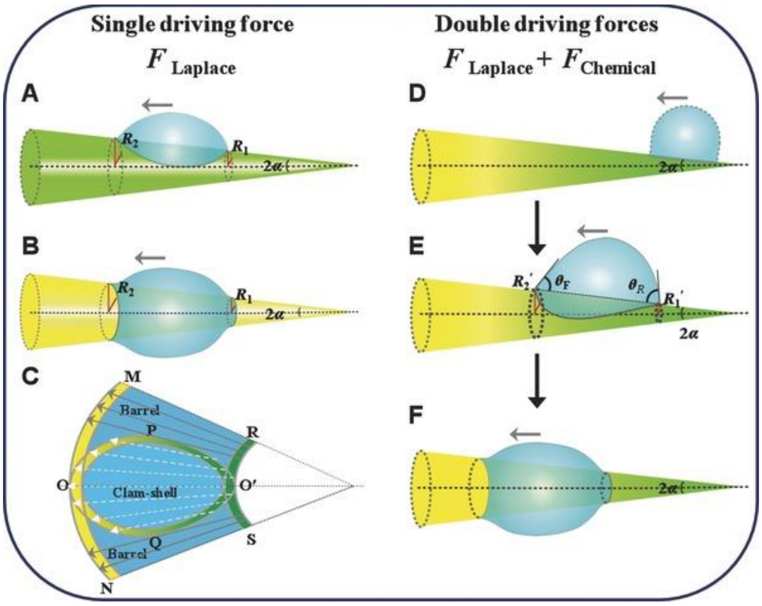


Figure 30: Scheme of water collecting by the PWWC. The water slides to the base of the needle due to surface changes of the material. Credits: Xu, 2016.

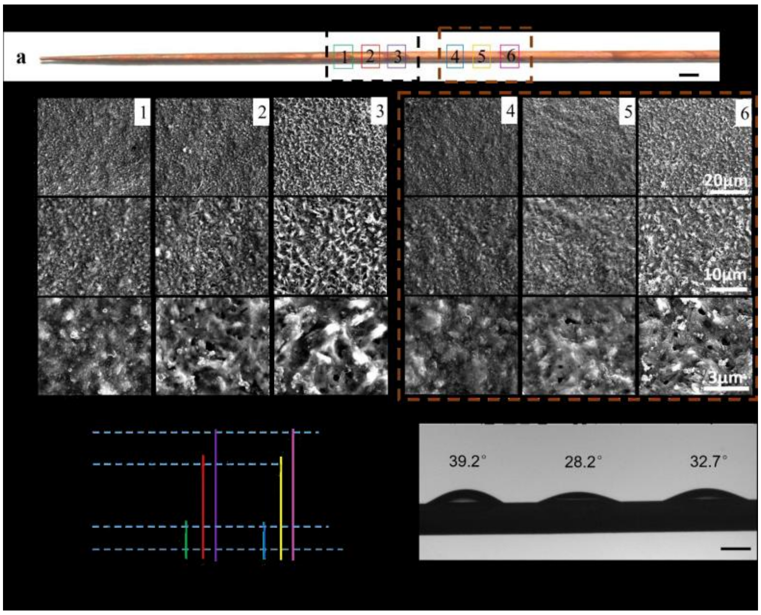


Figure 31: PCCW and surface changes. Credits: Xu, 2016.

The copper wires are conical in shape, thought so to facilitate drop movement along its length. Fabrication of their surface irregularities – gradient wettability, as described in the study – is realized through gradient electrochemical corrosion and posterior gradient chemical modification. The produced material is shown to be more efficient in fog collection than the untreated copper wire (Ju, Xiao and Yao, 2013).

The study made by Xu is characterized by Pinchasik, Kappl and Butt (2016) as being “a self-sustained water-harvesting system (…) which does not require additional external stimulus but makes use of a smart design and economic production.”. However, Xu herself assessed through her studies that air velocity has a direct impact in water collection by the thorns, and that the more air movement there is, more and more droplets can be captured (fig. 32). Presumably, combining this fog collection method with an airflow inductor (such as the bladeless fan) might yield enormous water outputs.

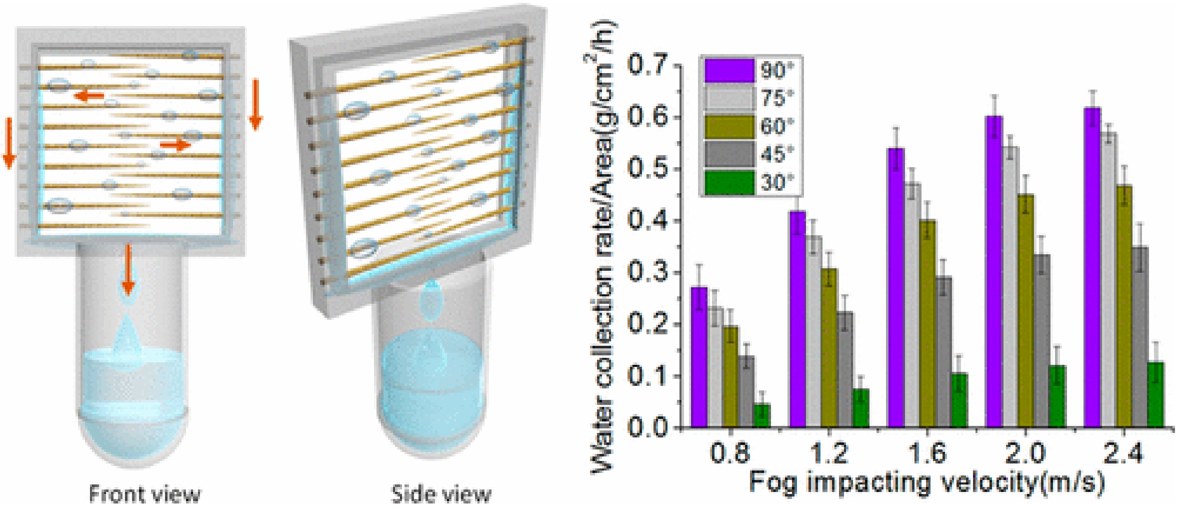


Figure 32: Overall view of Xu's design, as well as a performance graphic that correlates water collection rate and fog impacting velocity, attributable to airflow. (Xu, 2016)

The technology of Xu has not been, as of the publication date, been tested in a field condition. However, laboratory tests were performed that obtained extremely positive results for the technology, and the possibilities that it offers are immense. Considering its relatively easiness of production, a Dynamic Fog Harvester with a PCCW-based “mesh” collecting mechanism is a promising solution.

8.5 First device ideas

The idea starts from the three dimensions of space: the line, the surface and the volume. Each one of these covers a simple function, and one is a component of the other: lines constitute areas that constitutes volumes. The line corresponds to a single entity, from a start point to an end point, which are individual collectors not necessarily correlated to each other:

these are individual fog collectors that can be either Building Components or Urban Furniture. The “area” idea is when a number of lines are arrayed together, assuming a larger surface of intervention. the second-dimension scenario is, therefore, intervention in the urban mesh as Urban Furniture (UF). Lastly, the three-dimensional concept is when the device transcends its initial usage to incorporate a variety of others, located immediately below its collection surface, where different activities other than fog harvesting may take place. Such situation is possible when devices make a mesh-like array and sustain a roof above them, resembling an open pavilion.

One must consider Schemenauer’s statement, that remain true to Dynamic Fog Harvesters: when there is no fog, there is no fog water collection (Schemenauer, 2015). For a device whose running costs are not zero – and that has an energy-consuming mechanism of airflow generation – being solely capable to harvest fog does not justify investment for such intervention. Hence, the DFC’s letter “D” will have to include another different type of dynamism that goes beyond the mere active energy consumption: it must be multifunctional and serve to other purposes, especially when fog is absent.

Development of the proposals were carried largely based on the aforementioned observations. The DFC’s yields must represent a profit and not a resource consumption. Here, the word profit is used not in its economic sense – or, rather, not only in such sense – but in its benefits yielded meaning. That is to say the resulting advantages from the use of a DFC will greatly overwhelm its disadvantages, especially its number one weakness, energy consumption.

8.5.1 The Building Component

Being able to ease water consumption of buildings and reducing demands on the water utility provider is identified as a major field of potentiality. The Dynamic Fog Harvester that assumes the role of a building component – that is, it is an integral part of a building’s aesthetics and infrastructure – must be designed in a way such that it represents a positive addition to the architecture concept of its host building and, at the same time, sparing part of its demand for water from the city provision.

Buildings vary greatly in height, and with that, also their structure, appearance and function changes. In the Italian context, which is predominantly made of small to medium-height buildings, wind is not as a great structural preoccupation as it would otherwise be for a high-rise-dominated context. In fact, the latter is designed to withstand the increasing horizontal stress posed by the wind, whose speed and pressure upon the building's surface increases as of distance from the ground is reach.

Thanks to the increasing wind speeds in tall heights, the Building Component DFC is the only one who can have models that function as either Passive or Dynamic Fog Collectors, or even a hybrid, thanks to the bladeless fan's unobstructed surface. If the devices are going to be one or the other, that will be a function of height. Wind speeds increase notoriously with distance from the ground (Hussain, 2007)., and even in wind-scarce Po Valley this rule is not absent. Radiation fog's height is linked to the height of the thermal inversion layer (Bendix, 1993), therefore the positioning of devices in higher floors or rooftops of very tall buildings might prove to be an investment waste in case fog can't reach heights past the building's own (fig. x)

The Building Component category finds its great advantage compared to the other two DFC variations in which it does not *need* to ultimately provide drinkable water, for its water yields are not envisioned as for direct human consummation, but to provide irrigation for gardens – which does not require major treatment – sanitation water and cleaning in general, as well as any other use that does not include its ingestion. A fog harvester as a part of a residential building could provide water as a sustainable approach to irrigate green roofs and private gardens, since this typology of green building is currently increasing its presence among cities. In Milan, the Bosco Verticale is a notorious example of presence of such building type.

As seen before, when there is fog, it slowly deposits water droplets on the surface of plants. Also, although rain and fog provide plants with a natural, zero-energy and virtually free source of irrigation, storing fog and rainwater for later usage could be a major strength of the devices. Considering fog to be a nocturnal phenomenon, storing of collected fog water can take place during its presence and posteriorly reused during the day, when sunlight is present, enhancing benefits for the green areas of the building. Contrary to traditional agriculture, which in the Po Valley is never too far away from a source of irrigation, gardens and green areas in general of high-rise buildings are dependent on its water supply system, and. As a measure to reduce water consume in the building, therefore, gardens and green roofs could be irrigated using collected and stored rain/fog water from when episodes of such events take place.

Clearly, different plant species have different water needs, so the amount of water to be provided for green building areas must be determined through calculations, so to dimension the fog water reservoir accordingly. Gardens, albeit a water-consuming element, do not require extraordinarily huge amounts of water daily and fit well inside even a Passive Fog Collector's average collection rate.

DFC as Building Components' usage in high-rise could be also considered in a larger scale outside the Italian context, which does not, currently, count many of them. Especially in the English-speaking countries of Canada, Australia, New Zealand and the United States, where a number of tall buildings is annually built, such device would find higher feasibility. The State of California is a major recipient of strong radiation fog during the winter, and high-rise developments are present elsewhere in the State's numerous cities, and especially in its two biggest metropolitan areas: San Francisco and Los Angeles. Also known as Tule fog by locals, it is the leading cause of road accidents and transportation complications in California (NASA, 2018). Once verified the fog's pH and overall dissolved compounds, a major fog harvesting program could be carried in the region, with immense benefits for the water services, since California's dry climate complicates irrigation and water distribution.

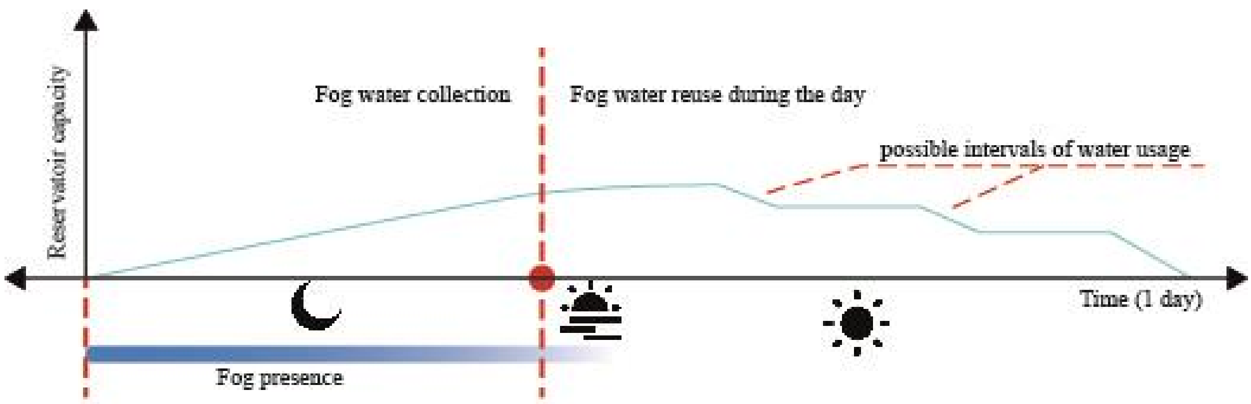


Figure 33: Schematic graphic on the dynamic water collection/reuse by a Building Component DFC serving green area irrigation purposes.

8.5.2 The Urban Furniture

The DFC as placed either in semi-urban or urban environments function as a piece of urban furniture, similar in nature to posts, benches and other similar city adornments that can be used by the population. To not become a visual impairment, shape must not be robust so to obstruct views, not also be of such contrasting, conflicting colors as to ruin the composition in its context. It must blend inside its space.

Applicability as an urban furniture finds in its technical justification the easier access to the energy network that supplies the city. Since the used mechanism of wind generator is quieter than traditional fans and compressors, it won't be a problem to place the devices in residential areas, although preferably they would better perform, on the technical side of fog harvesting efficiency, in a wider area where fog can accumulate and be both in greater density and volume.

In the Italian context, where big cities generate a considerably high heat island effect (Gama, 2015) and many small and medium cities in the Po Valley exist with proximity to each other, it would be more opportune to implement the device where fog is thicker and longer-lasting, such as the several smaller cities of the wider Milan metropolitan area. Preferred locations are parks, squares and other large open spaces. The reason is that, as a utility provider first and an embellishment second, their functional aspect must prevail above the aesthetical.

From the technical point of view, the meshes of the Urban Furniture Dynamic Fog Collector are made of a material that is ultrahydrophobic, so each fog water droplet that hits its surfaces will either bounce and "fall down" to the mesh below, or they will encounter the mesh's surface, slide down its length and be collected by the gutters, which provides the device with some resistance against possible horizontal stresses. Its verticality means that it behaves like a free-standing pillar, where only one of its extremities are connected to the ground. Therefore, to counterbalance momentum in its free extremity, foundations of the furniture must be designed to withstand such efforts, similarly as a street post.

Since water needs to be treated before it became potable, the UF does not provide water for direct drinking as the commonly found water fountains in Italy. To be drinkable, water must be transmitted to a treatment facility, for then it can be distributed to households and other buildings. Installation in parks and in green areas might allow water harvested to be transported to a reservoir where it can provide irrigation and cleaning water, to the same manner as the Building Component DFC. Its eventual recreational use is also envisioned, although in the Po Valley fog happens mainly in the coldest months of the year. However, its usage as in decorative fountains is also not dismissible.

8.5.3 The Pavilion Collector

The Urban Furniture device, as described in the previous subchapter, is equipped with a funnel for technical and aesthetical reasons. If it was the case of increasing this funnel dimensions till the Dynamic Fog Harvester nearly resembles a tree, the device alone would seem an "aberration" in a traditional, history-rooted Italian context. However, thanks to this much larger funnel, if you position one device close to another, their combination starts resembling an arcade, or a covered structure.

Further increment of their number makes it approach, shape-wise, to a series of porticoes.

The Pavilion Collector was created out of a necessity of providing the fog water collector genre with more versatility of use, making it a functional, usable structure for all its lifetime. From a cost point of view, the solution approaches the ideal situation of a device that pays for itself: its multiplicity of use beyond that of fog harvesting may strongly support its proposition. The covered surface originated by the pavilion, together with electricity infrastructure, allows it to be adaptable to a variety of uses. Depending on the size of the intervention, it could host fairs, a community garden, seasonal markets, itinerary events or perhaps even an open-air museum. These events would pay a small fee to use the space, which would go to the maintenance budget of the pavilion, directly controlled by the water company in charge.

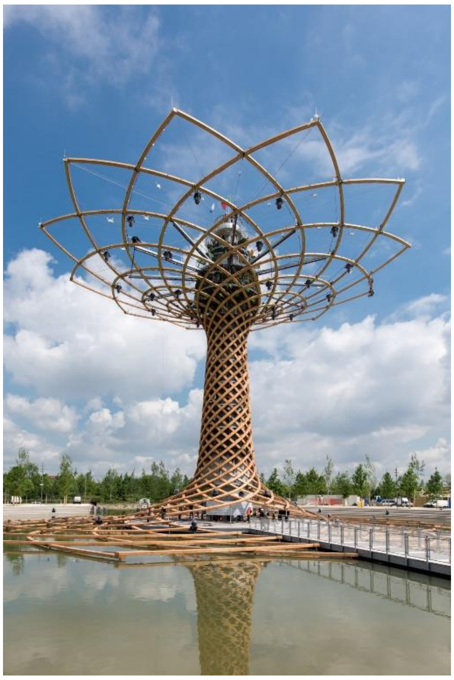


Figure 36: Milan Expo's tree of life. Photo: Dirk Werwoerd, 2015

Aesthetical composition of the pavilion drags inspiration from three major shape sources: the tree of life of Milan's 2015 EXPO (fig. 27), Singapore's Gardens by the Bay (fig. 28) and the traditional Italian *loggia*, more specifically the *loggia del mercato nuovo* in Florence (fig. 29). The tree of life provided the individual collectors' main formal inspiration, while Gardens by the Bay provided the idea of a "walkable" structure. Finally, *loggia del mercato nuovo* and its traditional architecture inspired much of the versatility of use of the pavilion. Compared to other conceived types of DFC which are free-standing structures, fog harvesters in the Pavilion Collector assume the structural role of a pillar, supporting a roof, and therefore needing to assume a shape that is more strictly connected to structural performance. The resulting building is notoriously more resistant than other standalone devices.

Figure 35: Supertree groves, Gardens by the bay, Singapore. Photo credit: Wikimedia Commons: http://commons.wikimedia.org/wiki/File:Supertree_Grove,_Gardens_by_the_Bay,_Singapore_-_20120712-02.jpg

In contrast to previous PFCs – whose harvesting plane was vertical and perpendicular to the wind direction – the Pavilion Collector's harvesting plane is a large horizontal surface, conceived to be capable of absorbing the largest amount of fog without having to exceed an aesthetically tolerable height. This characteristic, combined with the collectors' large funnel, makes the PC an excellent rainwater harvester, especially if compared to most other fog harvesting devices – which include both PFC and DFC models. The collectors in the pavilion are strategically positioned next to the borders of the roof, both from a structural point of view (to provide the structure with rigidity) and in order to be in closer contact with fog from outside its rooftop. Placement of a collector in the middle of the roof will cause its collection area of influence to intersect others, reducing its efficiency and its cost-benefit.

Figure 34: Loggia del mercato nuovo, Florence, Italy. Photo: Dan Kamminga, 2005

Out of every other device type, the Pavilion Collector is perhaps the strongest of its kind. Not only it accomplishes its goal more efficiently than the other purposes, but the fact that it efficiently corrects the DFC genre's largest disadvantage in comparison to the PFC – that is, the fact it is not a zero-energy, zero-running-cost device – puts it almost in a league of its own. During the foggy season, it provides water, during rain, it harvests rainwater. With or without fog, it is a safe roof under which a series of activities may take place, being them permanent (as in the case of a community garden, for example) or itinerant.

One of PC's peculiar but also strongest characteristics is that, although the DFC application in northern Italy is thought as an environmental rather than a social project, the Pavilion Collector manages to unite both spheres. Though maintenance of the facilities is not carried by local citizens, they are the absolute direct users of the structure, and their direct benefactors. Contrary to Urban Furniture, whose usage by the populace is a rather distant, impersonal relation, the Pavilion Collector is a gathering point for locals, a spatial reference and, wishfully, a symbol of the place.

8.6 Wood as a structural material

The structure of the device, vertical, needs to be made in a way such to resist wind pressure (admitted as low throughout the region), horizontal stresses due to various reasons, rain and snow loads, its own weight and non-constant loads. In order to both give more rigidity to the device and to be more aesthetically appealing, the configuration of the structural parts altogether resembles a lotus flower, in which its junction nodes provides the desired rigidity and resistance against external forces. The structural concept is hence derived from the Fibonacci spiral, widespread in many natural forms.

Wood is the most resistant construction material when regarding its mechanical resistance per its density (Raftery and Harte, 2011). It is a natural, renewable and durable material whose production is relatively low on carbon dioxide emissions – rather, production of timber has been observed to absorb CO2 from the atmosphere during the plant's growth (Fruhwald, 1995). Similarly to other organic substances, wood's elementary compounds are flammable. To prevent such risk, the material must be treated accordingly, with surface coating. Particularly, extruded timber parts are more susceptible to fire than Glued Laminated Timber (Kolaitis et al, 2014), which is also more resistant to structural loads and to moisture, due to its much-reduced internal cavities.

The structure of the devices will be, therefore, made of Glued Laminated Timber (GLT, or glulam), for it allows a multiplicity of shapes, and its color ranges are best at blending aesthetically with most traditional Italian buildings, which are of a light-yellow complexion. It has a much lower embodied energy when compared to concrete and steel, the two most used structural materials (Meil, 1995). A study by Petersen and Solberg (2002) found it takes up to three times more energy and up to twelve times more fossil fuels to manufacture steel beams than it does to manufacture glued laminated timber beams. The study also assessed that if the wooden parts are to be dismantled – at the end of their life cycle – they can be easily replaced and can be burned, producing, more energy than was used to manufacture them. That characterizes wood with the unique feature of being a net energy-provider, rather than an energy-consuming, material.

Since the structure is going to be situated inside a humid region – and ultimately will deal with water collection – wood will need to be finely treated to resist humidity. Such treatment is not only due to the high air humidity of the Po Valley, but also to fog's water droplets whose effects on wood represents a progressive reduction on its durability. Hence, superficial treatments must be considered both to prevent water from penetrating the wooden structures and to resist fire.

8.7 Other device components

The collection gutters and the reservoir are proposed to fit the device's needs. The Pavilion Collector has one small reservoir located inside its structure, that can be connected to a second, external, larger one depending on local necessity to obtain water for other non-drinkable uses. The material of the reservoir is the same of state of the art technology: plastic. Dimensioning of the reservoir, therefore, is made taking into consideration the following parameters:

- Maximum absolute production in liters from the SFC in one day multiplied by the total number of square meters of mesh installed in the LFCs: maximum water yielded in a single day is obtained;
- Maximum number of continuous days without fog or rainwater production;
- Average water demand by day and by week;
- Occurrence of rain during some seasons, and the strength of the episode.

Water is expected to condense in the copper needles, then run to their bases, enlarging themselves and falling at the bottom of the device, where a hydrophobic polyethylene blade with drippers (fig. x) ultimately conduct them to the reservoir). Enclosing the meshes and protecting them from physical damages from the outside, is a combination of one glass sheet and one tensioned transparent membrane.

8.8 Discussion

The results of this chapter are elementary for the DFC's feasibility justification. For that, different analysis on its possible characteristics was made, as a mean of obtaining the optimal configurations for the devices. Materials chosen were low on energy and carbon footprint. Wind creation mechanisms, which were a crucial point of reducing energy consumption for the device, ended up with the choice of a novel bladeless fan application, allowing a more laminar air flow inside the devices. Giving the materials chosen for the water collection and wind creation mechanisms, cleaning will not be a major issue of this project as it was with previous Large Fog Collectors, which needed frequent cleaning and monitoring. This is a significant reduction in this kind of inspection/maintenance.

Three categories of Dynamic Fog Collectors were proposed, that functions differently from each other (Table 8). Building components are proposed to reduce water consume of buildings from the utility provider; Urban Furnitures harvest fog from public spaces and may either provide water locally for non-drinking uses or transport it to treatment facilities in which water is then made potable; Finally, the last category of device represents a significant departure from previous categories. The Pavilion Collector yields more water and is usable as an open space building.

Although this chapter presented three possible natures of DFCs, one of them has proven to be by far the most cost-effective and most directly usable for the population: these are the pavilion collectors. Made of visually light materials, having large-scale harvesting properties and being a usable structure for all its lifetime, its positive points greatly outweigh all its energy consumption, cost of production and carbon footprint, which were made to be as minimal as possible. Its versatility of use and the possibility of reach cost-recovery greatly puts it ahead not only of other DFCs, but also of every other fog harvesting method. It is a technological, energy-driven building that can provide for all its investment.

The next and final chapter of this thesis will seek the further detailing of the Pavilion Collector, and a handful of hypothetical implementation scenarios in which it could successfully perform in all its spheres of usefulness. In order to optimize all its functions, ideal scenarios of local usability and functioning will also be established, as to make the proposal as realistically applicable as possible.

	Artificial Ventilation	Rainwater Harvesting	Other uses	Impact on context
Building Component	Yes, but not necessarily	Ranges from minimal to good	- Decoration element - Irrigation to green roofs and gardens - provides water for cleaning	Depends on the building. From minimal to relevant
Urban Furniture	Yes	minimal	- Aesthetic sculpture - reference point - Irrigation to vegetation - Provides water for cleaning	Relevant. Fixed urban furniture.
Pavilion Collector	**Yes**	**maximum**	**- Usable and flexible space delimited by its roof** **- Excellent rainwater collector**	**Major landmark. Site needs to be carefully chosen regarding its surroundings.**

(Table 8: main characteristics of the proposed DFC types. The Pavilion collector's capacity of coping with cost in a sustainable way makes it a much more justifiable option than the other two).

9 Final design concept and extended uses

Riassunto:

Dalle analisi fatte previamente sono emersi tre tipi di dispositivi: il punto (Building Components), la linea (Urban Furniture) e il solido (Pavillion Collector), fra di cui è stato scelto l'ultimo per ulteriori approfondimenti. Il Pavillion Collector si mostra particolarmente efficiente per quanto è un eccellente collettore di acqua sia della nebbia sia della pioggia, e pur in assenza di essi, serve da spazio fruibile. Tale *caratteristica viene investigata ed alcune attività che possano tenere luogo nel Pavilion vengono individuate e caratterizzate.. Attestata la sua efficienza nella raccolta della nebbia, scenari di uso della struttura vengono caratterizzati ed elencati in base alla loro natura.*

9.1 Final Shape and elementary components

The Pavilion Collector's geometry derives, as stated in the previous chapter, of three formal and functional references. Mathematical ratios found in nature such as the Fibonacci number inspired much of the fractal-like external appearance of the device's structure. Its modularity (fig. 38) allows it to be mass-produced in the case of multiple installations, or of a single installation that covers a larger area. Total height has been only empirically suggested, being adaptable – to a certain extent – to its context and design requirements. Parametrization of the shape mean that the structure is made from a single component which is repeated many times and increases in size as one moves from the base to the top of the collector.

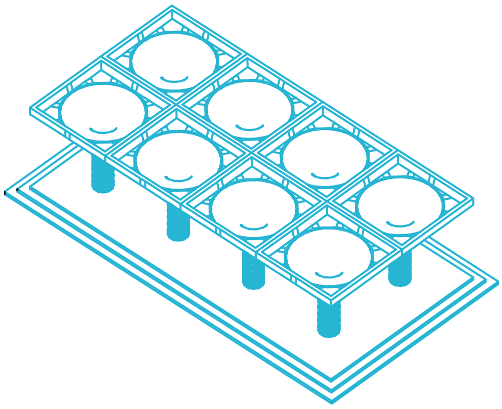


Figure 37: Illustration of a hypothetical pavilion configuration. Scale-less. The base seen here is merely illustrative and does not need to be designed if decided not to.

Structure was made not only to resist solicitations of various types, but also to be able to support a roof immediately above the collector. Flexibility is quintessentially the defining characteristic of the Pavilion and therefore the fog harvesting devices must be able to be organized in various shape arrays according to local demands. Total width of the pavilion must ideally not exceed the golden ratio proportions, and in case a greater vain is needed, a simple roof module can be added between one collector and the other.

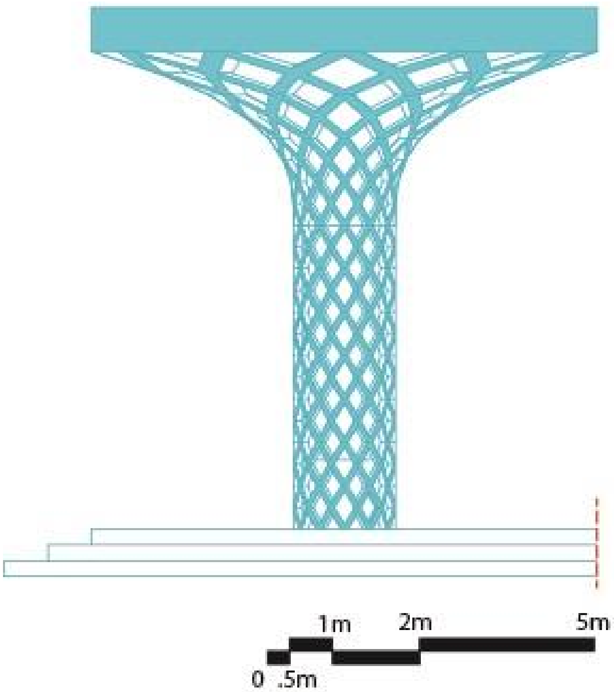


Figure 39: Frontal elevation of a Pavilion Collector DFC.

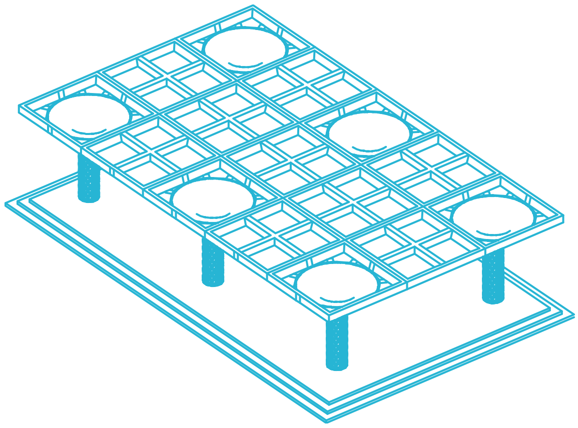
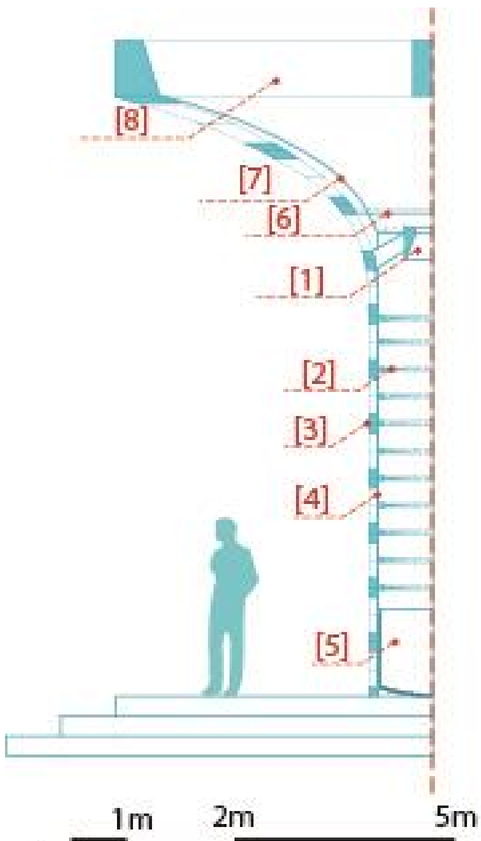


Figure 38: Pavilion Collector model with greater distance between its pillars. Roof modules are used to reach a freer space

The proposed design here is a preliminary project design rather than an executive one. Several factors are expected to influence its finished appearance, though not radically changing its concept. Worth mentioning such factors are soil resistance (having an impact on the device's foundation choices), expected external loads, characterization of the local environment according to its exposure coefficient (if aggressive), and expected total water collectable, both fog and rain.

A section depicted at fig. 40 shows the copper needles inside the device and their placement, which is conditioned by the position of the structural nodes of the outer timber structure. Interface between the elements located in the inner part of the device and its structure is mainly made through structural junctions, which are modular and radially symmetrical. The proposed Dynamic Fog Harvester hereby proposed is elementarily composed of:



- [1] Bladeless fan (dimensions: 50 x 50cm)

- [2] Periodic roughness-gradient Conical Copper Wire (PCCW) surface collection (R=30cm)

- [3] Structure, Glued Laminated Timber

- [4] Glass sheet. Openings in its lowest point allows for the exit of the air

- [5] Reservatoir, PVC

- [6] Protective grid

- [7] Impermeable tensioned membrane

- [8] Roof, wood-based

Figure 40: Section of the Pavilion Collector.

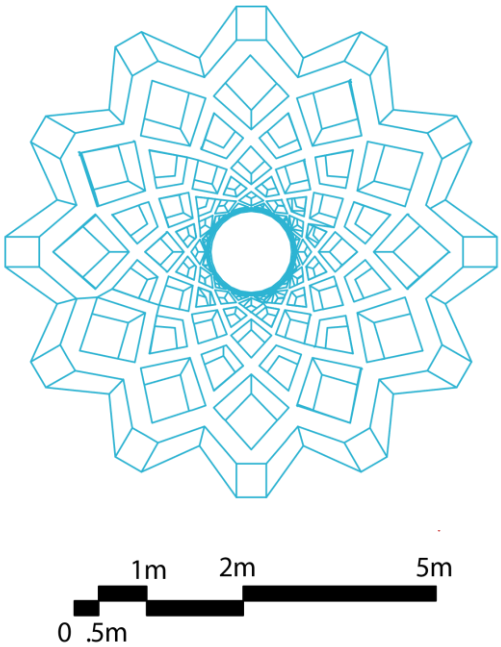


Figure 41: Plan view of the lotus-inspired structure

Wood is the dominant material, as a percentage of the single Pavilion Collector's total volume. The lowest participation on the devices is that of the copper needles. It greatly reduces the shading coefficient of the collection surface (therefore allowing more air to circulate in between the many collectors) while also having a greater efficiency of harvesting fog water compared to traditional methods even in the event of an impediment of airflow from the bladeless fan (caused by a cut on its energy supply, for example), therefore being crucial for the fog harvesting efficiency of the collector. It presents a tilt angle of 30º, as Xu (2016) assessed it had the greatest water collection rate.

Substitution of any wooden modules that may appear to be reaching its limit as a functional element can also be performed without major constraints. Feasibility of this proposal is strongly based in its modularity and possibility of mass-production of its elementary components.

Total height of the section depicted in Fig. 40 is 600 meters. Such value might be increased or reduced according to the statistically-obtained average height of the atmospheric thermal inversion layer, of which radiation fog's height is a function of. The structural module's cross section is a direct function of all the loads the structure has to bear and of the resistance of its wood type.

9.2 Theoretical performance and cost comparison

The cost of a Large Fog Collector, as assessed by Schemenauer (2015) is not high for its yields. Comparing such device with the DLC may at first make the latter appear less feasible than the former. However, such comparison is not sufficient to assess the actual cost efficiency of a Dynamic Fog

Collector. Here the concept of cost is the idea of cost *per unit of water produced*. In other words, a DFC's cost-efficiency can justify its adoption, provided that its water yields and extensions of use are compensated by their running costs. Since LFCs cannot operate well when wind speeds are insufficient, the DFC represent a definitive advantage in which they generate their own air flow, providing water whenever fog is present. Value is added when, through a fixed operational cost in a certain period of time, a huge water production is obtained due to technological use.

Water collection efficiency, as described in the previous chapter, is the water collection rate divided by the unperturbed wind speed times the fog's LWC. This inverse proportion is clear in every study conducted so far: if the fog is rich in LWC but the mesh cannot yield a good enough collection rate, it means that its efficiency is lacking. A standard Raschel mesh's efficiency is from 1 to 4% the harvestable fog's water, usually collecting about 5 litres of water from a medium-thickness fog, and wind speeds of about 6m/s[26]. When coated with hydrophobic substances, increased pore size and knot-free, its efficiency gravitates around 10%.

However, the PWWC needle of the Dynamic Fog Harvester is a whole different level of water collection. For a 2.4 m/s wind velocity (approximately the speed of a breeze), only 18 PWWC needles collects 0.6 $g/cm^2/h$, or in other terms, an astonishing $144L/m^2/day$. That multiplied by the amount of such needle arrays in the collection – which totals 11 – allow us to hypothesize that, in an ideal case where the wind speed is equal throughout the collector, each Dynamic Fog Harvester can produce 1584 $L/m^2/day$. To arrive at Chile's El Tofo levels of water production (which stood on an average of 15.000 liters per day with 100 Large Fog Collectors), all we need is an array with approximately 10 collecting devices – that is, with an extremely low wind speed.

Schemenauer never established empirically a relation water yielded/cost of the LFC. In Schemenauer, Cereda and Osses's 2015 Fog Water Collection manual, they establish a "rule of thumb" for the cost of a LFC: 150 US dollars for an iron-structured one, and 300 for its aluminum-structured preferred version. An array of 100 such nets are to cost about from 15000 to 30000 USD. Not only it is extremely economical giving that it takes little to no operational costs or energy consumption, but it also is a strong alternative to more expensive fresh water obtaining methods such as desalinization.

The Dynamic Fog Harvester, albeit being a theoretically powerful collector, has never been physically produced.

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[26] Much higher rates are found in places where fog is abundant and thick, such as in Oman where it was assessed a $30L/m^2/day$ of water collection by a standard Raschel mesh.

Therefore, a material cost estimation, running and maintenance cost estimates are only but superficial. Prices of its base materials – wood, glass, copper, PVC and a bladeless fan – are as unexpectedly fluctuant and diverse according to manufacturer and the region as is an LFC's expected water yields in a day. Since this thesis did not work with prototyping, discussion on the DFC's total production, operation and maintenance cost will end here.

The large water yielded by a 10-collector array Pavilion Collector is about the same yield of water than a 100 array of LFCs. Both forms of water provision are however far away from supplying a large population. As an example, the *comune* of San Donato Milanese, in the south of the metropolitan city of Milan with a population of 32.659 (as of 2017) consumed 2.480.651.000 Liters of water in 2016. Using the Dynamic Fog Harvester to supply a large city would require huge investments, and even so, although the device also collects rainwater, it can only provide but a little part of the local water demands. To compensate such weakness, the Pavilion Collector presents itself has extensions of use, which will be further discussed in the subchapter 9.4.

9.3 Business model

An identifiable vital partner of this project is the Metropolitana Milanese, the most interested party for this project. Local ATOs and *comuni* are also another important stakeholder to be involved, as they are the executive body of the region and would ultimately concede or deny permission for the intervention. The end users of this project are the citizens of Milan, that although won't be involved in the communitarian maintenance of the devices (as it requires technical maintenance), will be the ones enjoying its benefits. Jobs are expected to be created for the hiring of technicians for the periodic maintenance of the devices.

The value proposition of this project can be drawn from three main sources: one, the solution aims to ease the already heavy water abstraction from Lombardy's groundwater, considering that the scenario of the region in the upcoming decades is not a pleasant one. Two, the project is far beyond that of a single fog harvester and can assume multiple roles and host a variety of activities, of which local markets, art conferences and meetings, community urban garden and collection of fog water for experimental/research purposes. Since it is, in few words, a covered structure, it can be assembled in a seamlessly infinite array possibility, originating bus stops, train stations, *loggie*, among others.

The Pavilion Collector promotes the city's image as a sustainability innovator. Being the first host of an intervention of this genre, the host *comune* is expected to be better known and advertised by the media, both Italian and international. Such notoriety could prompt a higher tourism inflow, benefiting the economy, or research institutions both national and international creating partnerships of this nature in order to foster the development of the technology further.

<table>
<tr><th colspan="5"><u>BUSINESS MODEL CANVAS</u></th></tr>
<tr>
<td rowspan="2"><u>Key Partners</u>

- Comune di Milano
- Metropolitana Milanese S.p.A.
- Local manufacturers
- Research and education institutions and independent researchers
- Urban planning agencies</td>
<td><u>Key Activities</u>

- Water provision
- Open building</td>
<td rowspan="2"><u>Value Propositions</u>

- Alleviate the burden on groundwater
- Allow a different water source to be collected
- City's imagery as sustainability model
- Good cost per unit of water produced
- Versatile use</td>
<td><u>Customer Relationships</u>

- Direct contact with Metropolitana Milanese and manufacturers</td>
<td rowspan="2"><u>Customer Segments</u>

- End users: local citizens of Milan metropolitan area</td>
</tr>
<tr>
<td><u>Key Resources</u>

- Manageable wind stream
- Enhanced Aesthetic appeal
- More efficient collection</td>
<td><u>Channels</u>

- Television
- Newspaper
- Internet</td>
</tr>
<tr>
<td colspan="3"><u>Cost Structure</u>

- Production costs
- Operational costs
- Maintenance costs</td>
<td colspan="2"><u>Revenue streams</u>

- Public and private funds
- Extensions of use</td>
</tr>
</table>

9.4 Foreseeable activities

To better understand the effects that the proposal can have in its immediate context regarding versatility, each use that can be made of the Pavilion Collector will be classified according to certain parameters that better define its nature. These parameters are hereby denominated *dimensions of use*, conceived to characterize activities according to what benefits one expects to receive from them. It is to be mentioned that being less prominent in one dimension rather than the others do not represent a weakness but rather an individual characteristic of the use. The dimensions of use, along with their abbreviation, are four in total and are as follows:

Economic (ECN): as the name suggests it is the dimension connected to economic activities whose production can yield profits, of diverse natures.

Social (SOC): this dimension regards the potential of the activity to make the Pavilion Collector an intensifier of *urbanity*. In other words, this means a property of the activity that creates and foster community bonds between locals and visitors. This dimension also regards the generation of a flow of people in and out of the pavilion, whether intentional or not.

Functional (FCT): also interchangeable with “technical”, regards the fruition of the Pavilion Collector’s produced outputs, such as harvested fog and rainwater. In other words, it englobes the usage of the device as a Fog Harvesting Collector, its primary destination of use.

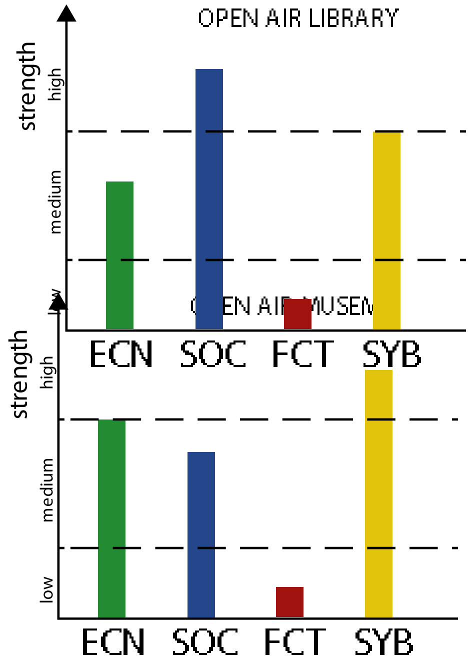
Symbolic (SYB): the pavilion has a shape and a spatial composition that are, in greater or lesser degree, different from its context. This is especially highlighted if the intervention place is close to historical buildings, whose contrast to the pavilion’s modern shape might be easily noticeable to anyone who visits the urban area where the pavilion sits. This contrast – the effect of making the pavilion an identifiable symbol of the place – is a variable that strongly depends on the context rather than the device itself.

The Pavilion Collector is, under every point of view, a covered structure that allows for a versatility of use. Therefore, it is potentially adequate for any activity that requires a space protected from harmful weather situations. One could enclose the Pavilion with walls, making it resemble a private building; However, such intervention severely harms the device’s initial purpose, which is one that gathers the social sphere and adds it to fog harvesting. Additionally, even if the Pavilion allows for a flexible use, it is not deemed to be positive that providing only one extra activity for all the building’s lifetime.

Proposed extended uses for the Pavilion finds their justification in aligning the building proper’s sustainability in providing a water surplus without resource depletion with further sustainable activities that enhances the building’s image and purpose. Such additional uses might or might not be directly correlated with fog harvesting, that is, does not necessarily needs to benefit directly from water collected by the building, but can act as a provider of a different usage for the building, one that enriches its functions. Results to the characterization of the extensions of use are reported to the right of each paragraph.

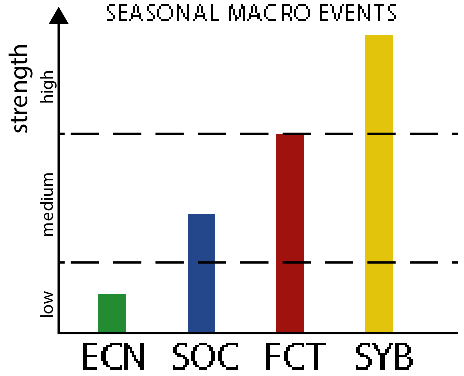
Among the individuated possibilities which are worth of consideration, we can name:

Open air library: A center for consulting books that is open to all and accessible to everyone. Under certain weather conditions, this activity could host a study area for students and common people alike, providing for a more cultural sphere of the social dimension. Though paying for staying in the space is not envisioned, certain books' loans could comprise a small fee which would go directly to the maintenance of the facilities of the library.



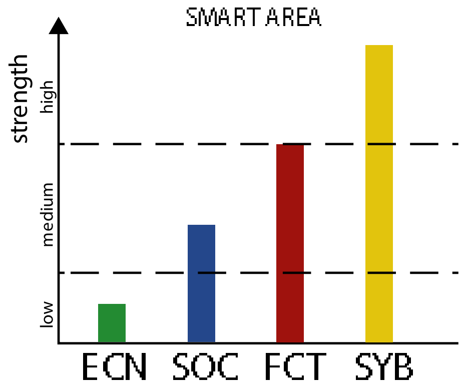
Since its main objective is to provide people with information, the collection of the library might also include other sources of material, such as digital content. Placement of the Pavilion Collector next to educational institutions might see its usage being overwhelmingly linked to providing complementary services to the educational sphere of the functional dimension. In case the educational institution agrees in providing for some of the costs of the library, this can potentially represent the desired cost-recovery of the Pavilion.

Open air museum and Seasonal exhibitions: The structure of the Pavilion Collector is suitable for art exhibitions of various natures. Such function could even attract people from elsewhere in the region to attend the exhibitions, bringing about an influx of tourism that would be beneficial for the local economy.



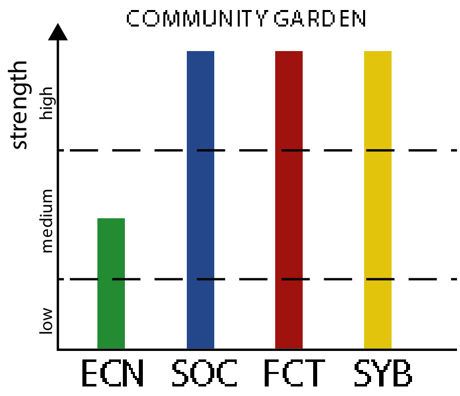
Seasonal macro events: big size events such as a major festival taking place in a large open area can make use of the pavilion to host part of its activities. The conception of a monumentally huge Pavilion Collector as to host the entire fair under its roof is impracticable from the aesthetic point of view, for it would be a strong presence in the landscape, stronger perhaps than the city/village itself where it is located.

From the financial point of view, since the macro event is a large installation, it would pay a significantly high fee to the local government, a cost such that could greatly benefit the maintenance of the Pavilion. Special care is advised against the depredation of the facilities, which could be fatal and represent major expenses with repairing the structure.

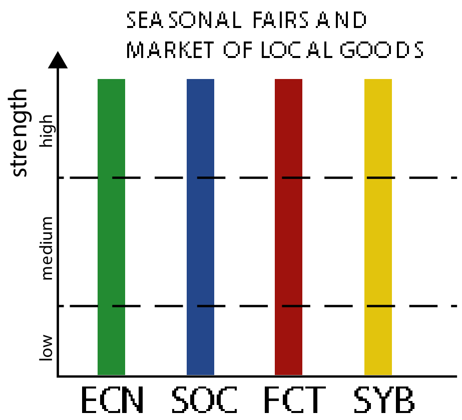


Smart area: the energy infrastructure present in the pavilion could support the installation of smart screens (that serves for a variety of purposes, desirably explaining also the pavilion's own components and fog harvesting functionalities), a free Wi-Fi service and several recharging stations for personal electronic devices such as phones and laptops. This use is not directly included in the base project as it represents an unnecessary extra construction and running cost for the pavilion, whose decision of having the service can be only justified if locals' opinions are strongly in favor of benefitting from it. The provision of such public services, which are not necessarily connected to water provision, may be owned by a different stakeholder of the project, namely the local *comune* government or the city's prefecture.

Community garden: water yielded from the pavilions, both from fog and from rain, can be used to supply a medium to large community garden, that can be either located immediately below its roof or be placed around the pavilion. It can be fix or movable, depending on the vegetable species that one wants to cultivate and to if plants' roots are anchored to the ground or contained inside a vase. This use is more strongly related to the social dimension of the pavilion collector, fostering cooperation between locals and a sense of "owning" the structure, therefore taking more care of it. This use, although providing for the cultivation of crops, yields more benefits in which community bonds between locals can be created, improved and stressed, representing a more social rather than an economic dimension of use.



Seasonal fairs and market of regional products: this use could be directly connected to the aforementioned community garden. Since the pavilion provides a considerably ample area underneath its roof, this covered space could be used to host weekly markets, as the former are common throughout Italy. This could make the pavilion to be a focal meeting point of its immediate surroundings, evidencing a social and economic dimension of use.



Multiple of the aforementioned activities can take place in the pavilion at the same time, being complementary and/or offering mutual support. Conflicting uses, such as an open-air library and the market of regional products, though being possible to coexist at the same time, are not a desired scenario since one might interfere in the quality of the other, reducing the pavilion's social efficiency (the library might not be used due to the market's noise, and the market might just move elsewhere if it finds the presence of the library uneasy). However, alternating uses are strongly advised for the building.

9.5 General project implementation methodology

When comparing once again with the implementation procedures of a traditional fog water harvesting project as described by some relevant authors (Fessaye et al, 2012; Batisha, 2014; Schemenauer, 2015), surprisingly, for the Pavillion Collector, the steps required for its efficient implementation does not need to be are a striking contrast with state of the art procedures. Many of Schemenauer's recommendations (2015) remain valid for the Pavilion's project implementation, especially when regarding field research and data collection. A major difference, however, is in involving locals with the project, which in the case of this DFC does not require the direct maintenance of the device by locals.

The natural first step of implementing a fog harvesting project is an assessment of the proper climatic conditions not only of the whole region, but for the specific area. This procedure is not different for DFCs. If a wrong assessment is made and the device is placed in a fog-less area, it might end up being everything but a fog collector. It might harvest rain, host fairs and exhibitions, but will fail to accomplish its main objective and wind generation technology will be a monetary loss.

To better collect data on how much water can be harvested by the devices, a typical Standard Fog Collector is needed, similarly to state of the art proceedings. This procedure is important because it will assess how the low-cost and zero-energy Passive Fog Collectors perform in the environment. The results of fog collection measurements will then be compared with the ones obtained through a Dynamic Standard Fog Collector (DSFC), envisioned to verify how much more water can be harvested with such alternative. The DSFC's meshes must be of the same material and type that is going to be used in the pavilion.

Next, studies on rain incidence – which includes total rainwater in a year and frequency of water – are performed to assess rainwater collection potential, a complementary water source to fog harvesting. Weather data needs to be obtained from local meteorological stations rather than from locals (as it otherwise is in most previous fog harvesting experiments), therefore allowing the design to take into consideration the fluctuations in water collection over time.

The next step, involving a more social approach, is to consult the local population – especially if the project is implemented in a relatively small city – about their receptiveness to such intervention. The design proposal is then shown in an assembly of dwellers of the surroundings of the pavilion, in which a list of possible and wishful extensions of use are then shown as possible to be hosted by the pavilion.

In case receptiveness to the intervention is positive, the starting point of effectively designing for the local context is to determine the modularity of the pavilion and the further design of its water distribution network that will connect it to the existing infrastructure. In the case the pavilion foresees extensions of use, for example, that of a community garden, local reservoirs need to be dimensioned according to the maximum expected water flow. This part of the project involves extensive collaboration with personnel from the water provision company, who will, after the intervention is realized, bear direct responsibility over its maintenance.

The conclusive step is to make a general frame of the total cost of the intervention and report it to the financing stakeholders of the project. This is the ultimatum of the project: financial feasibility will have to ensure and detail expenses and profits – of every nature – that implementing the Pavilion Collector represents. In case the population is strongly supportive of the pavilion, that can also be counted as a major pro-factor in deciding for its execution.

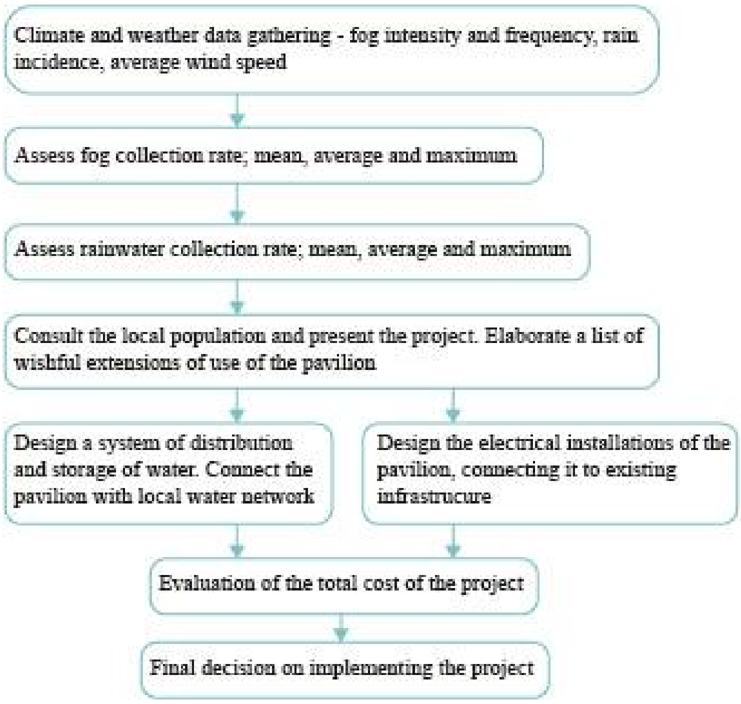


Figure 42: Methodology scheme to start the installation of the Pavilion Collector

Though construction of the device is a responsibility carried largely by the water utility provider, partnerships, including public-private ones (as it is common throughout Italy in its water supply system, as mentioned in chapter 6) can potentially offer a relieve for construction costs for the public sphere. A public-private partnership means that an external entity is going to own a share of the building's right to use, which implies in access to both its water collection and social functions.

Conclusion

This work aimed to present a comparison between previous fog harvesting projects and to offer a new horizon for the future of the technology in applying it for other contexts, with geographical, social, economic and meteorological features that were previously either unexplored or not considered. The region of choice did not present a substantial and immediate water availability problem, however as demonstrated, increasing population density and migrations together with the highest per-capita consume of water in Europe all can potentially make the north of Italy in a difficult situation regarding water resources in the future. Fog harvesting is a promising alternative for fresh water provision, and although the current technology is limited to certain context conditions, it could be adapted for the northern Italian region.

Even though several new technologies were chosen, combined and evaluated in this study, dissociating the social component of fog harvesting seems impossible. It is the very heart of this type of project, which shouldn't come as a surprise given water's role as a provider of better life conditions. The results of this thesis showed that fog harvesting in a developed context is a radical departure from the ones in developing countries. Even so, due to economical, technical, material, sustainable and functionality reasons, the act of providing water needed to keep its social component preserved for the Pavilion Collector.

This thesis relies heavily in the work of other researchers, and is intended, above all, to experiment with a novel context and novel technological combinations rather than producing its own. The Dynamic Fog Collectors were conceived to be a positive addition to environment, not representing a strong carbon footprint in its lifetime and not to representing an expense rather than a surplus, either. The DFC attends the needs of the Po Valley – which wind speed is insufficient for fog collection – but its application represents a step forward in implementing fog harvesting in other contexts where climatic conditions do not correspond entirely with the requested parameters by the state of the art technology. Further experimentation with Dynamic Fog Harvesters can take place in other regions of the globe where radiation fog is present, especially in Europe, the Central Valley in California and in some regions in English-speaking Oceania.

The DFC category still requires major real-life application and prototype testing. Its wind-speed regulator allows for a greater efficiency of collection when compared to standard Large Fog Collectors with the same or approximate mesh area. Mathematical justification and software simulation can provide only but a theoretical support for the device's correct functioning. Therefore, the natural step forward from the end of this thesis is the construction of physical models and their subsequent testing, so to evaluate, over determined periods of time, the device's performance.

Several areas of intervention of fog harvesting were intentionally left unattended in this thesis. Collectively, they offer a great opportunity for other innovative works in the field of fog harvesting.

Next phases of the work

This thesis was developed in concordance with the double degree procedure between the Politecnico di Milano, Italy, and the University of Brasília, Brazil. It aimed to develop the theoretical background necessary for a novel solution in the field of fog harvesting. Nonetheless, important assessments need to be made, such as a simulation of implementation in a *comune* of the Milan metropolitan area, the development of an executive project for the Pavilion Collector and possibly the creation of testing prototypes. Such procedures will be carried in the continuation of this work, in which the device's detailed design and implementation will be extensively characterized.

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