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Numerical simulation and analysis of Atmospheric Water Harvesting Prototype for Concentrated Solar Power (CSP) plants

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Abstract

The water physical scarcity due to increasing consumption and the water economic scarcity affecting the most disadvantaged populations are increasing in many regions of the world. In a future in which water will be considered a precious and limited commodity, many scientists are investigating and developing new technologies and alternative solutions to the rising problems of water scarcity.

This thesis aims to fully study the potential applications of the Atmospheric Water Harvesting Prototype in Concentrated Solar Power (CSP) plants technology. For this purpose an overview of the existing CSP plants, the most water intensive renewable technology, is carried out with particular attention to water management and consumption.

Thanks to the prototype, which uses low temperature heat in an absorption bed, realized in the laboratory of the Politecnico di Torino, based on the simulations of tests operating in arid or semi-desert environments, it has been possible to quantify the performance of a complete adsorption-desorption cycle. Besides, employing a Matlab code simulating the adsorption unit, energy consumption, water yield for different efficiency conditions and condensation temperatures for different Rankine cycles have been evaluated.

Furthermore a techno-economic analysis of CSP plants in terms of levelized cost of Electricity is conducted and emphasis is given to the water consumption impact on operations and maintenance cost (OPEX).

In conclusion, the results achieved with the model developed in this thesis provide information for the future development and improvement of the prototype as well as potential uses in a CSP plant: on the one hand a reduction of the water demand producing it directly on site; on the other hand, a consequent decrease in water costs and Operations and maintenance (O&M) costs that are relatively high for CSP plants.

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1 Introduction

Water represents life on this planet: it generates and feeds ecosystems and regulates the climate, but it is a limited resource. Although it covers three-quarters of the surface of our planet, slightly less than 97% is seawater and of the remaining 2.5%, about 1% is in the form of ice at the poles. The freshwater directly accessible for human activities is, therefore, less than 1% of the world's water supply.

During the 20th century, while the population tripled, water consumption increased about tenfold, and in recent decades it has become increasingly evident that due to increasing demand, freshwater scarcity is becoming a problem for the sustainable development of human society. The first consequences of prolonged periods of drought are, unfortunately, and dramatically, already before our eyes [1].

With population growth around 8.9 billion in 2050, approximately 3.5 billion people could face severe water shortages; There are already more than a billion people in the world who do not have access to a continuous supply of drinking water, and 3 to 4 billion those that do not have sufficient water and in stable quantities.

Water consumption has increased worldwide by about 1% per year since the '80s and will continue to increase until 2050, due to the exponential increase in population, rapid socio-social development and the growing demand in the industrial and domestic sectors, reaching 20-30% compared to the current level of water use. By continuing to these rhythms, as the increasing demand for water and the intensification of the effects of climate change, 1/3 of the population will live in areas where water is scarce by 2030 and 2/3 of the world population will be in conditions of "water stress" already by 2025.

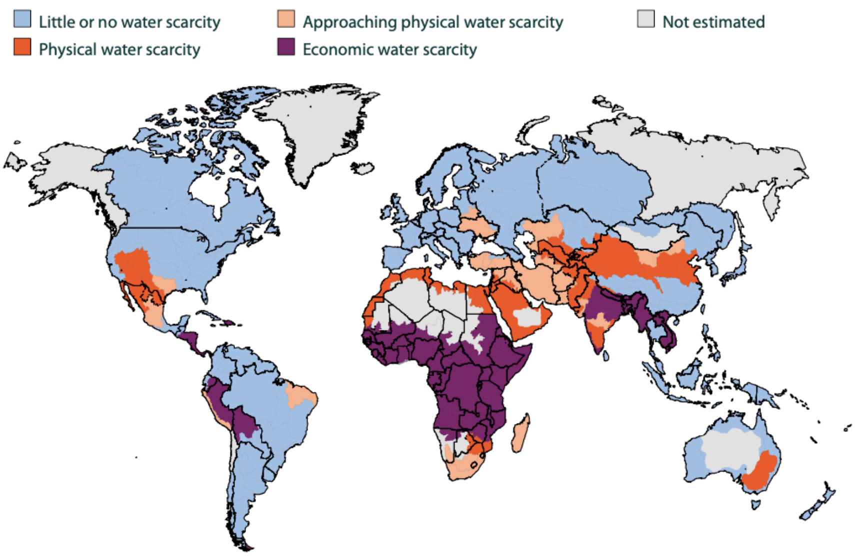


Fig. 1 water scarcity across the globe [2].

Water scarcity is generally divided into physical scarcity and economic scarcity.
The former estimates the total quantity of surface water and the extraction of groundwater; the latter refers instead to areas where water is abundant but there is a lack of infrastructures or water storage systems which make it inaccessible to the majority of the population. The above map (Fig. 1) shows that physical water scarcity is prevalent in arid regions like North Africa, Middle East, and Central America, while the economic water scarcity represents a more widespread phenomenon, and is prevalent in sub-Saharan Africa, where often water is abundant but contaminated and not suitable for anthropic activities. Currently, about 1.6 billion people, live in areas with low physical water availability[3] .
The United Nations Global Agenda for Sustainable Development, which set 17 Sustainable Development Goals (SDGs) to be achieved by 2030, sets the objective of «ensure the availability and sustainable management of water and sanitary facilities». Safe drinking water and sanitation are recognized as basic human rights, as they are indispensable to sustaining healthy livelihoods and fundamental in maintaining the Dignity of all human beings [4].

Unfortunately, there's a huge difference in the per capita water availability among the inhabitants of rich and poor countries [5] as evidenced by the 250 cubic meters annual per capita use of water in Africa, against the 1700 cubic meters per capita annual use of water in the United States. We should also consider the irregular geographical distribution of the water resources on the planet: 60% of the earth's fresh water is concentrated in just 9 countries, while nations such as India and China, which together represent 36% of the world's population, have just 11% of the drinking water on Earth.

According to the Falkenmark Water Stress Indicator, regions getting an annual water supply of below 60,035 cubic feet per person experience "water stress" [6].

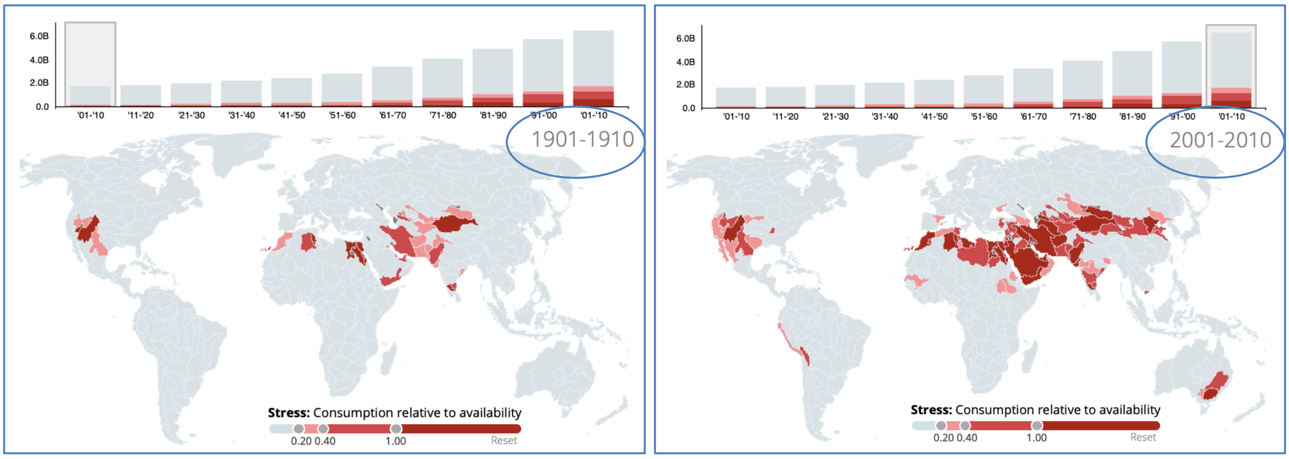


Fig. 2 Evolution during the 20th century of global population living in water stress [7]

The water stress evolved from being a local phenomenon to having visible global consequences in many and vast areas including all the Central Asian, Middle East, North Africa, India, Pakistan, and the United States. In particular northern and eastern India, the Middle East, Australia, and California are the macro-regions classified as the most water-stressed countries in the world, where the availability of freshwater per capita is less than 1,700 cubic meters [5] and the consumption represents more than twice the actual water availability.

1.1 Global Water Demand

Global water demand in terms of withdrawals is projected to increase by 55% towards 2050, mainly due to a growing demand from manufacturing (400%), thermal electricity generation (140%) and domestic use (130%). As a result, freshwater availability will be increasingly strained over this time period, and more than 40% of the global population is projected to be living in areas of severe water stress by 2050 [8]. This rapid increase is due also to economic development and industrialization and consequently the increase in consumption and production of raw materials and energy.

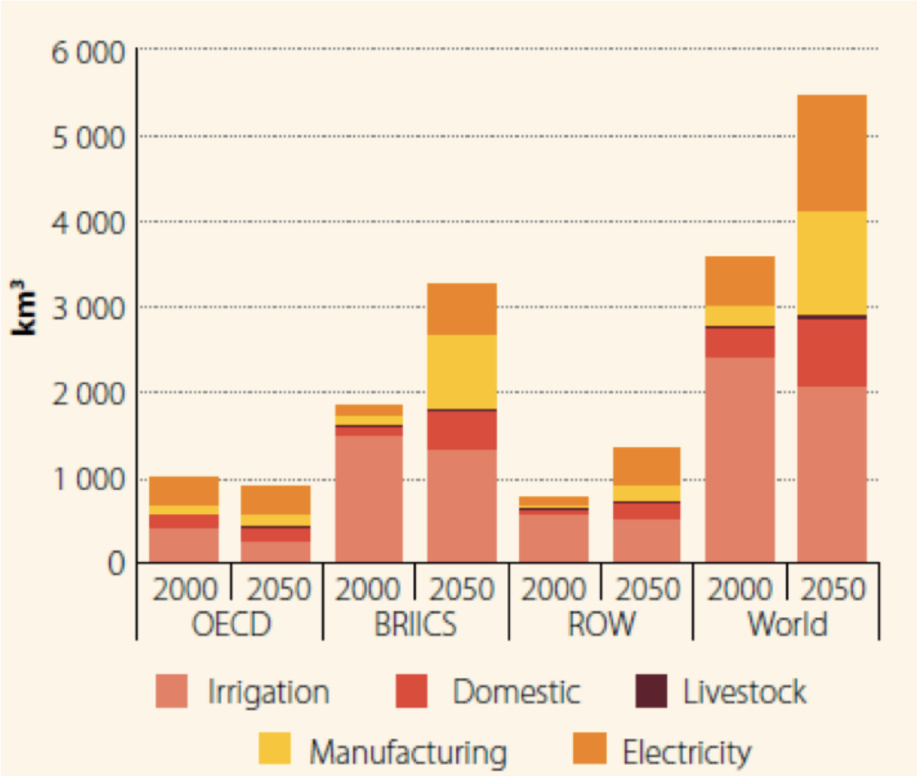


Fig. 3 Global water demand: Baseline scenario, 2000 and 2050.

Pollution and climate change are also factors that unavoidably reduce water availability, especially in areas with low rainfall and in arid or semi-desertic areas. This will affect not only developing countries but also Europe: according to the World Health Organization (WHO), 16 % of Europe's population has no drinking water and 140 million have no access to clean water and sanitation.

Nowadays in the world 70% of water is used for agriculture, 22% for industry and 8% for domestic use. The overall water consumption is around 1385 m3/year per capita, of which industrial products represent 4.7% and domestic water usage 3.8%. Industrialized countries have water consumption per capita in the range of 1250-2850 m3/year [9]. But in general, it varies higher for developing countries than for industrialized countries, as there are greater differences in consumption models and lower water fertility, as confirmed by countries as Central Asia and North Africa.

The European continent has abundant water resources respect to the others, but they are not equally distributed across countries; this creates different levels of water stress during the seasons and between regions. This stress is more sensed by the countries of southern Europe, due to the lower rainfall and the more frequent periods of drought. Spain, Portugal, and Greece have already experienced severe droughts during the summer months, but this phenomenon is also becoming a problem in the UK, Germany, and Italy.

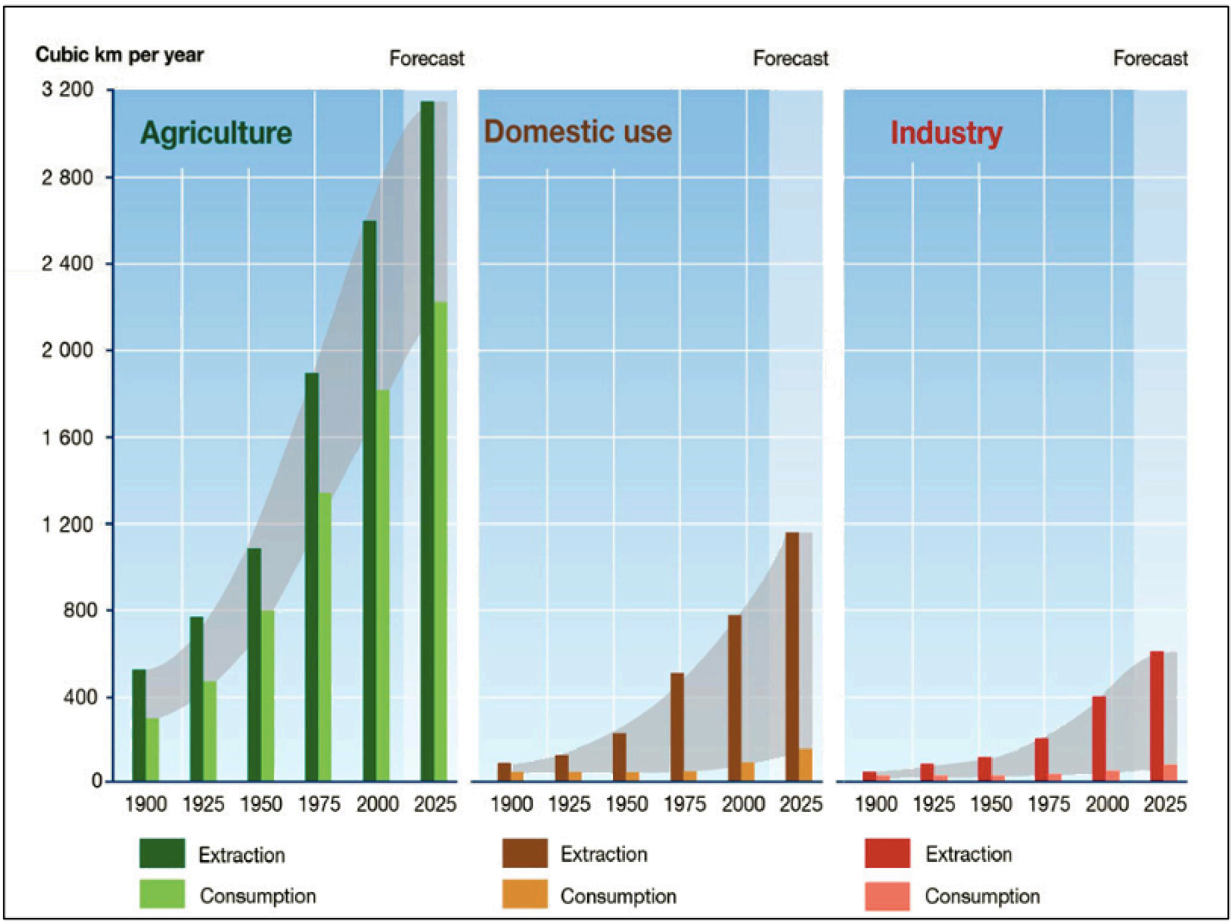
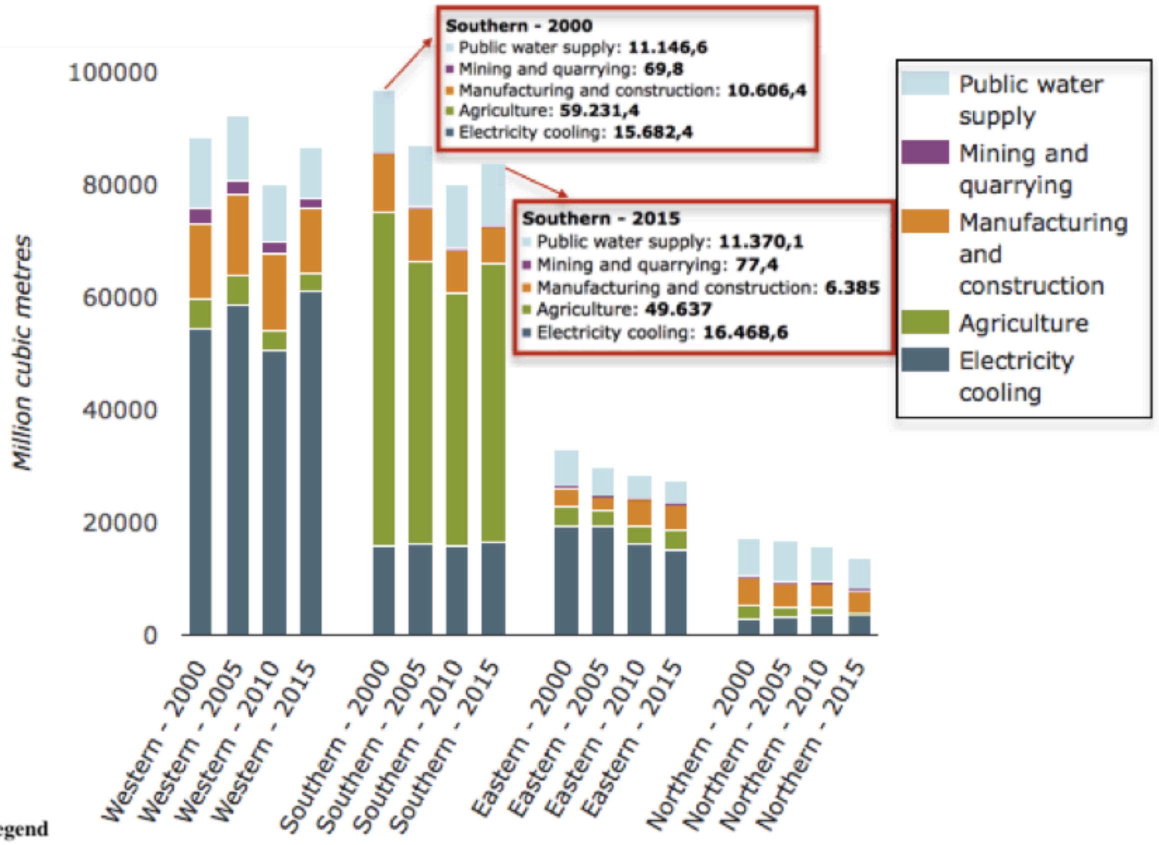


Fig. 4 Water extraction and consumption in industrialized countries[10].

Europe manages for economic activities on average about 243000 cubic hectometres (CIT SITO IEA) and about 57% is discharged into the environment. However, this water contains impurities or pollutants and should be also considered consumed water as it is no longer available for direct reuse and no longer drinkable. It contributes to increased waste, also caused by inadequate water management, especially in the agricultural and domestic sectors. As agriculture is responsible for the greater use of water, with about 40 % of the total annual consumption in Europe, the EU encourages nations to improve water management practices to enhance water efficiency through the use of water-saving technologies. Another sector that uses a lot of water is energy, which accounts for around 28 % of annual consumption. The mining and manufacturing sector accounts for 18 % of consumption, followed by around 12 % of domestic consumption.



Legend

Eastern Europe: Bulgaria, the Czech Republic, Hungary, Poland, Romania and Slovakia.

Southern Europe: Albania, Bosnia and Herzegovina, Cyprus, Greece, Spain, Croatia, Italy, Montenegro, the former Yugoslav Republic of Macedonia, Kosovo (under United Nations Security Council Resolution 1244/99), Malta, Portugal, Serbia and Slovenia.

Western Europe: Austria, Belgium, Switzerland, Germany, France, Liechtenstein, Luxembourg and the Netherlands.

Northern Europe: Denmark, Estonia, Finland, Iceland, Ireland, Latvia, Lithuania, Norway, Sweden and the United Kingdom.

Fig. 5 The development of water abstraction since the 1990s (Adapted from [11]).

In general, the following trend can be found: Southern Europe consume more water for agricultural purposes, the Western and Eastern Europe spend more water for the electricity cooling in energy production, while in Northern Europe it is the manufacturing industry that consumes the most.

1.2 Energy-Sector Water Demand

Approximately 90% of today's global power generation is water intensive. Energy production represents the second sector for consumption after agriculture, with about 580 billion m3 of fresh water absorbed each year. Energy production already accounts for 15% of the world's total water consumption and this percentage is destined to rise rapidly and should increase by 35% by 2035. This increase will result in an 85% increase in the volume of water consumed [10].

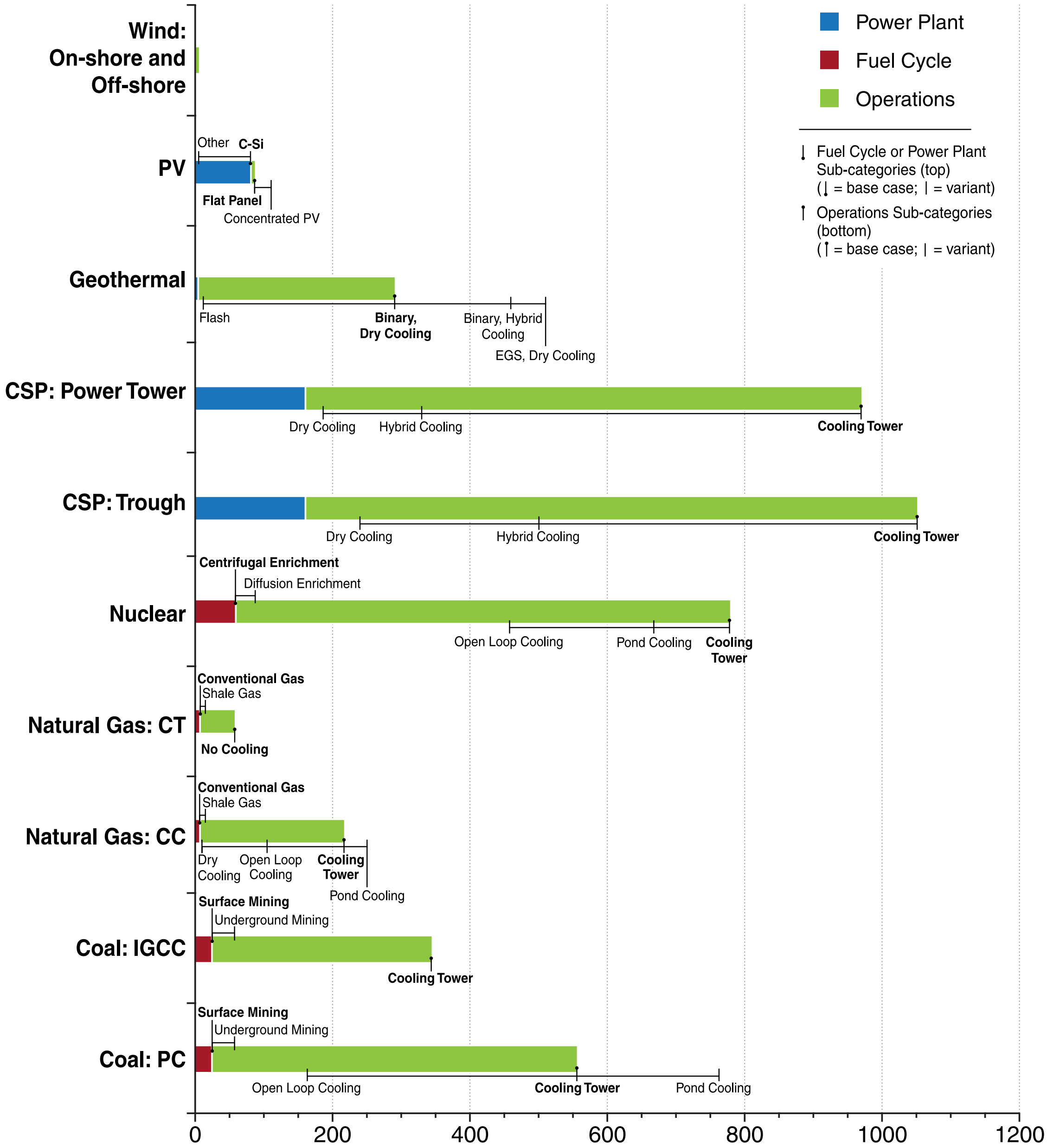


Fig. 6 Water consumption [gal/MWh] for different electricity generation technologies[13] .

As can be seen from the figure above, the CSP and nuclear technologies need a higher water quantity, respectively 5 m^3/MWh and 3 m^3/MWh: for CSP Operations represents 80% of the life cycle, for the nuclear the 90%. Furthermore, for coal, natural gas, and nuclear, power plant equipment life cycle water demands are negligible in relation to the life cycle total. In contrast, the power plant contributes a large portion of the total water use for the thermoelectric renewable technology of CSP, and represent the majority of life cycle water use for non-thermoelectric renewables (PV and wind) [11].

The consequences of the increase in energy demand will be observed especially in Africa where electricity generation by 2050 will grow rapidly by 700% increasing water demand by 500%. In

South America and Asia, the increase in energy production will be slightly more contained, 550% and 350% respectively, with a consequent increase in water demand of 350-360%.
In fact, in the countries of South Africa, projects are being arranged to switch to dry cooling systems, using air instead of water, in order to reduce water consumption. For these countries, another aspect should be taken into account: while electricity production is expected to increase exponentially, water scarcity will produce serious economic consequences, particularly in terms of rising electricity costs.
The close connection between water consumption and energy production will increase in the coming years, with significant implications for both energy and water security: more water will be required to increase energy production, more energy will be necessary to extract, distribute and treat water resources [8]. In the period between 2014 and 2040 water sector energy consumption will experience an increase of 130%, mainly due to alternative water sources, while water consumption in energy sector will grow by almost 60% to over 75 billion cubic meters (bcm), in part due to a switch to advanced cooling technologies in the power sector that withdraw less water, but consume more.

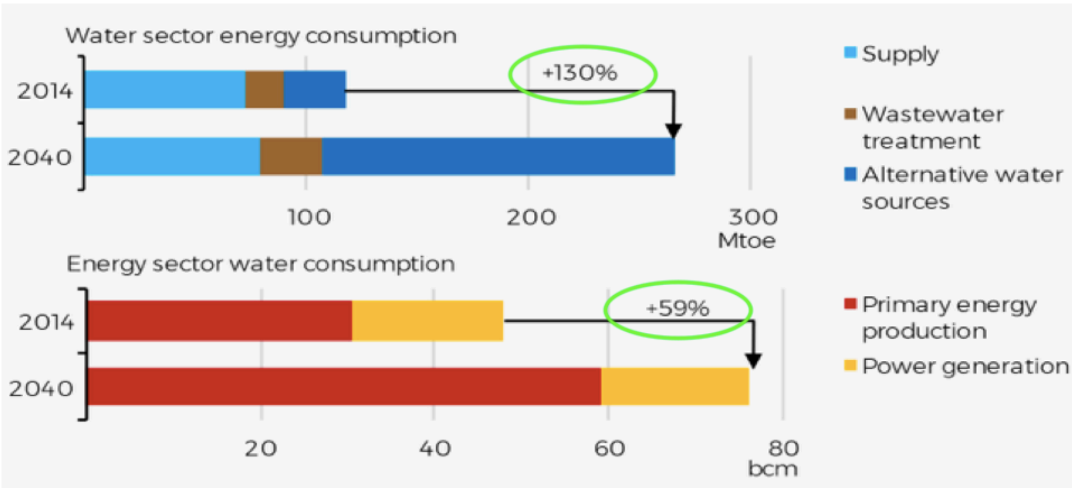


Fig. 7 Interdependency of water and energy in the period 2014 – 2020.

The electricity production is heavily affected by the water scarcity through a parameter, defined vulnerability index described by the equation:

$$\mathrm{TPVW} = \sqrt{\mathrm{WaSSI} * \frac{\mathrm{TPWW}}{\mathrm{TWA}}}$$

in which:

- TPVW represents the vulnerability of thermoelectric power plants to water scarcity;

- TPWW represents thermoelectric power plants' water withdrawal;
- TWA represents total water avail- ability;
- WaSSI represents water supply stress index, which is defined as the ratio of total water demand (TWD) to water availability (TWA) .

$$\mathrm{TPVW} = \frac{\sqrt{\frac{\mathrm{TPWW}}{\mathrm{TWD}}}}{\mathrm{TWA}}$$

The vulnerability index is a value varying from 0 to +inf , with significant vulnerability to water scarcity for high index values; very low or negligible vulnerability with values smaller than 10%, a potential vulnerability with values in the range 10-20% and high vulnerability with values above 20% [12].

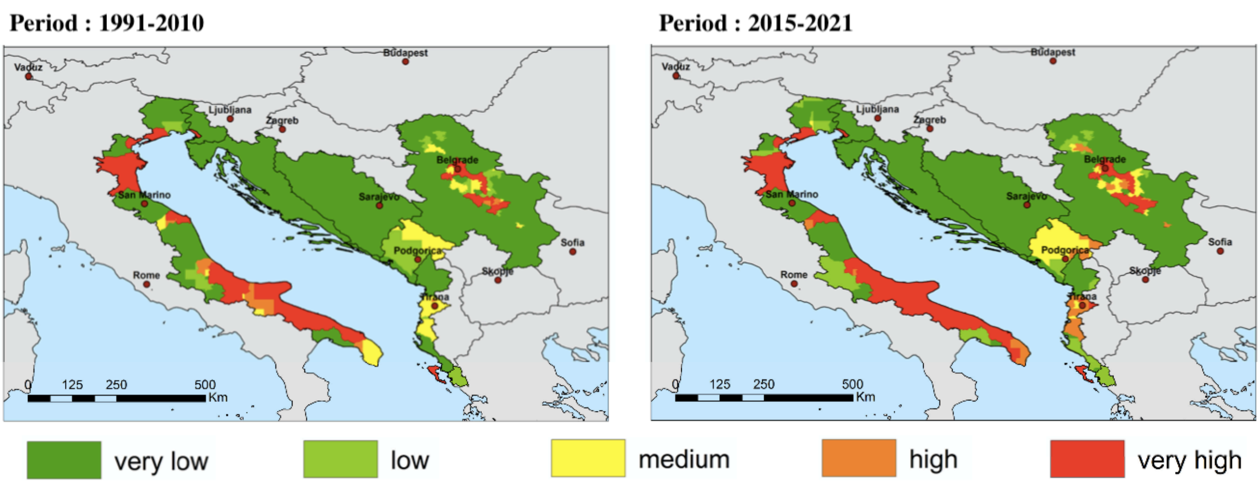


Fig. 8 Water vulnerability index in the Adriatic sea regions (Adapted from [15]) .

Focusing with particular attention to the Italian situation, in a few years, under the hypothesis of an increase of 25% in water demand, some areas of the southern national territory will move from high risk with index in the range 60-80% to very high vulnerability, greater than 80%.

2 CSP Technology

The Solar concentration technology, known as CSP (Concentrating Solar Power) allows converting the solar radiation into thermal energy, through a concentrator formed by reflective surfaces of suitable geometry that focus the Sunlight on a highly absorbent receiver tube. The set of

concentrator and receiver takes the name of the solar collector. There is than the presence of a system of movement of the collector that allows a constant pursuit of the sun.
Concentrating Solar Power uses mirrors to concentrate direct-beam solar irradiance to heat a liquid, solid or gas that is then used in a down-stream process to generate electricity. Typically concentrating solar thermal systems concentrate solar radiation on a thermally absorptive pipe, or receiver, which contains water or a heat transfer fluid (typically oil or salt).

The Heat transfer fluid flowing inside the receiver heating at high temperature can be of different nature whose choice depends obviously on the operative temperatures: starting from pressurized water for applications lightly higher than 100 °C, from mineral or synthetic oils for industrial thermal uses up to 400 ° C, it is possible to reach mixtures of sodium and potassium salts usable even over 600 °c. The Heat transfer fluid is the subject of intensive research to improve its characteristics and performance up to special cases for which it is possible to reach and exceed 1000 ° C.
When water is used, a direct steam generation (DSG) converts the water to steam by heat from the sun's radiation. When a heat transfer fluid ("HTF") is used, it passes through a series of HTF-to-steam heat exchangers and convert water to steam acting as an intermediate thermal energy carrier.

There are four primary CSP technologies: Parabolic Trough, Linear Fresnel, Solar Tower, and Dish Stirling. Those technologies can be divided into two groups depending on whether the monitoring is done in one or two axes.

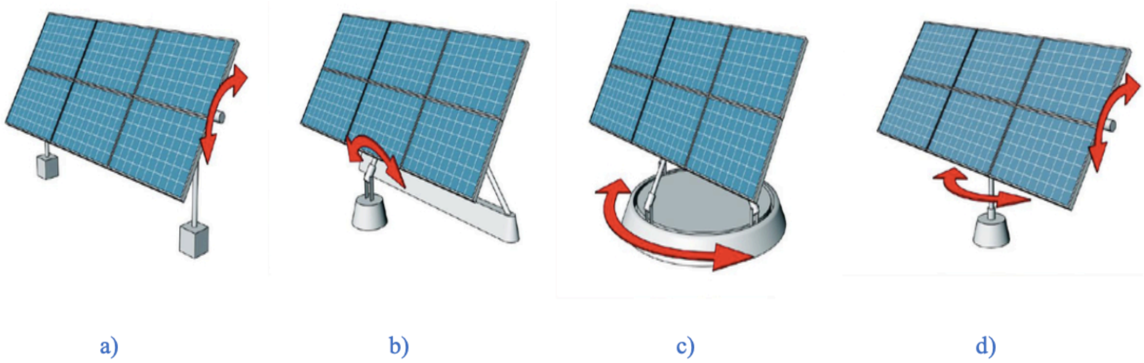


Fig. 9 Main types of trackers : a) Horizontal single axis tracking , b) Tilted single axis tracking, c) Azimuth tracker , d) Dual-axis tracker.(Adapted from REDIS – The Renewable Energy Data and Information Service)

CSP technologies that use one-axis tracking are Parabolic Trough Plant and Fresnel Plant, while those that use two-axis tracking are Stirling Plant and Central Receiver System. The former ones are characterized by concentrating solar radiation along a linear surface absorbing and transmitting energy to the working fluid; while the latter ones focus solar radiation on a single point [13].

Except for Dish Stirling, solar radiation is not converted directly into electricity but is collected in the form of thermal energy that can be easily accumulated in suitable storage systems. The opportunity to modulate the distribution of the collected energy is a peculiar characteristic of CSP that distinguishes this technology and makes it particularly advantageous compared to other renewable energies.

The thermal energy collected, available at high temperatures, can be destined to many applications among which the principal one is, obviously, the conversion into electricity by means of Rankine cycles or applications in the form of thermal energy: heating of fluids in the process industry, air conditioning of large environments by absorption cold generators, desalinated water production or more advanced applications such as the production of Hydrogen.

2.1 CSP Plants

2.1.1 Parabolic Trough plant

Parabolic trough is the most common CSP system and consists of reflecting surfaces with a parabolic cross-section, which when properly oriented reflect the sun's rays on a focal line along which a receiver is positioned. Inside the receiver there's a fluid (HTF) that is pumped through a series of HTF-to-steam shell-and-tube heat exchangers ultimately producing approximately 400°C superheated steam, which drives a conventional steam turbine to generate electricity through a Rankine cycle[14].

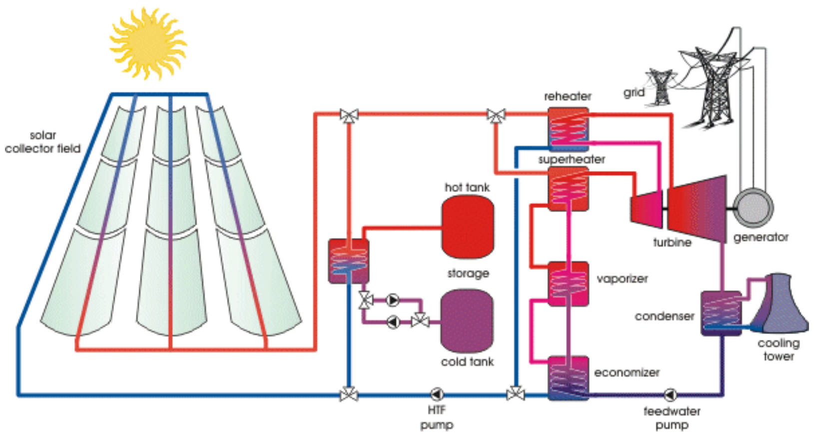


Fig. 10 Schematic of a Paraabolic Trough Power Plant.

Parabolic Trough Collectors (PTCs) operate in a temperature range between about 150° C and 400° C. The working temperature of the system is very significant, as it allows to define also the nature of the HTF, which can be principally diathermic oil, water/steam or molten salts. Concerning oil or molten salts, the most important parameter to consider is temperature, since they are incompressible, while, using water/steam, pressure also plays a central role and consequently affects the temperatures that can be reached. Systems operating at temperatures above 200° C do not use demineralized water as heat transfer fluid, but synthetic thermal oils to limit excessive pressures that would result in high mechanical stresses. Nevertheless, it is advisable to keep the system slightly pressurized, since many types of oils thermal, at atmospheric pressure, boil at relatively low temperatures (about 250° C). Yet, the use of thermal oils has some disadvantages, such as a specific heat lower than water, a higher viscosity that makes pumping more difficult, they can be inflammable or toxic, and often the solidification temperatures of these fluids are relatively high.

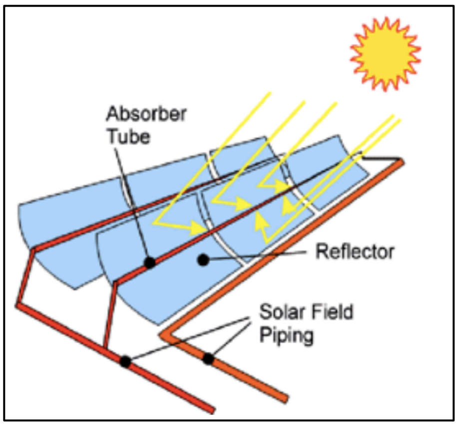


Fig. 11 Parabolic Trough Collector [18].

The receiver tube, usually made of steel, is coated with a selective varnish characterized by high absorbance (> 90%) and low emissivity (<30% in the infrared). The receiver, on the other hand, is embedded inside a glass tube in which a vacuum is created to minimize convective energy losses. The glass cover, however, reduces the amount of radiation absorbed, due to its transmittance, equal to about 0.9 (with clean glass) which is increased with an anti-reflective coating. In some models the absorber is covered by a vacuum coat, to reduce more convective losses. This system is usually adopted when temperatures are higher than 250°C, since for lower temperatures the losses are negligible.

In PTCs, the reflector and receiver tube move in tandem with the sun in order to keep solar irradiation focused on the receiver tube throughout the day [15].

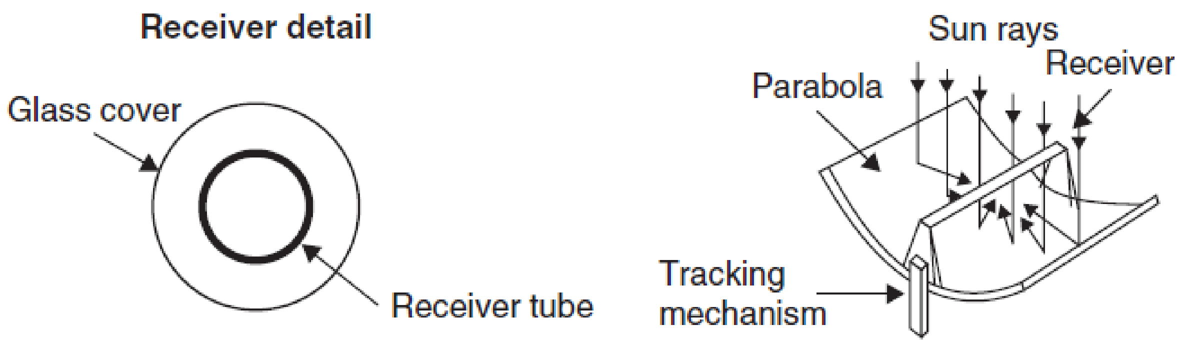


Fig. 12 Schematic of PTC collector (Kalogirou 2014, p.143).

The parabolic collectors are usually installed to enable the orientation of the axis along the north-south or east-west direction. An orientation in an east-west direction allows to track the sun from north to south and has the advantage that only minor adjustments are needed during the day and the collector faces with maximum opening towards the sun at midday, but the collector's performance is significantly reduced during the first and last hours of the day, due to the large incident angle, which reduces the efficiency of the system.

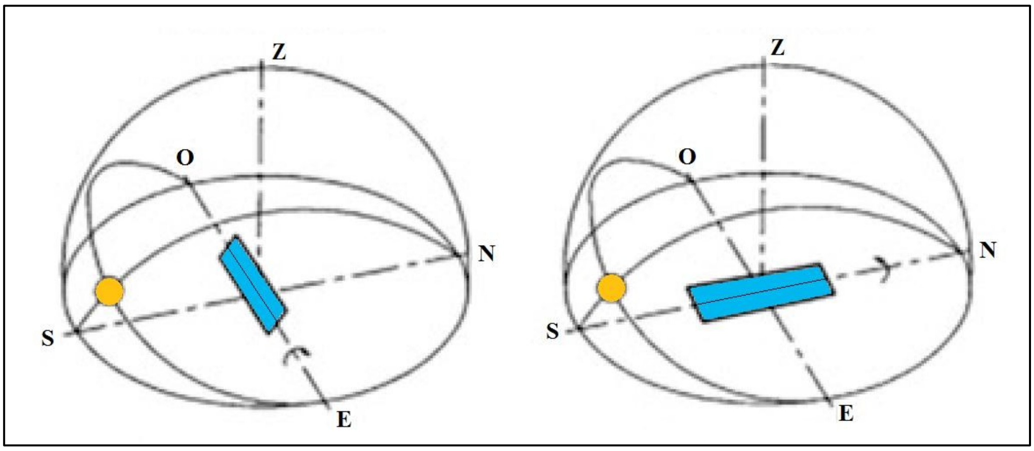


Fig. 13 Orientation with the east-west and north-south axis for a PTC. (adapted from Brian Norton, Leveraging Solar Heat, Springer)

A north-south orientation, though, following the sun from east to west has the maximum losses at noon and the minimum in the first and last hours of the day. It is consequently clear that by evaluating an annual production a north-south orientation provides more energy collection compared to an east-west orientation and, absorbing much more energy in the summer compared to winter, produces a less constant trend during the year.

As for the daily production, with an orientation of the east-west type, there is a large variation in the incident angle that takes very high values at sunrise and sunset and is equal to zero at midday, but there is a low seasonal variation of the energy generated. With a north-south orientation, there are minor daily variations but considerable seasonal variations on energy generation. The orientation option, hence, depends mainly on the type of energy demands that the plant must satisfy.

A typical power plant that uses PTC consists essentially of solar collectors, a steam generator and the energy conversion unit. The oil at high temperature (about 390° C) that comes from the solar collectors is sent to the steam generator, transfers part of its thermal energy to the water that flows in the heat exchanger, and thus turns into high-pressure steam and at high temperature. The thermal oil coming out of the steam generator has a temperature of about 290°C, and is so reintroduced into the solar collector system to restart the cycle. The steam produced is conveyed to a turbine and, after expansion, is reheated and condensed. The condensed water is then sent back to the steam generator. Condensation can take place either by water cooling or by air cooling, depending on the water availability of the site.

Since solar energy is intermittent, concentrating solar systems often make use of storage systems, which allow the storage of the excess of heat accumulated when solar radiation is available in large quantities, to use it during periods when solar radiation is limited or completely absent. It also allows improving the plant performance keeping the working temperatures stable in the energy conversion when the sun is clouded or under difficult weather conditions. The thermal storage system generally consists of one or more containers in which the heat is stored in the form of sensible heat in some material, generally a molten salt, which can provide the heat input to the thermodynamic cycle in the absence of solar radiation. In general, it is not possible to use water to store heat, because the temperatures involved would generate too high pressures, inducing the installation of robust and more expensive tanks.

Compared to systems using synthetic oil such as HTF, there are three fundamental advantages:

- The molten salts work at much higher temperatures, up to 550 ° C, thus allowing to increase the temperature difference between the inlet and outlet of the collectors and the storage volume reduction. Commonly a molten salt plant works between 290 ° C and 550 ° C, while a diathermic oil plant works between 290 ° C and 390 ° C;
- The thermodynamic cycle works with a much higher average temperature difference, increasing its efficiency;
- The intermediate exchanger between the oil and the storage heat transfer fluid is not necessary, hence the overall thermodynamic efficiency of the cycle increase [16].

The concentration ratio is one of the fundamental parameters of the collector. It is defined as the ratio of solar radiation entering the collector to solar radiation collected by the receiver.

Typically the concentration ratio for a parabolic troughs reaches maximum values of 100 or 200. This parameter is important since it sets the working temperatures of the power plant. Generally, it is approximated to the ratio of the collector and receiver aperture area:

$$C = \frac{A_{ap,collector}}{A_{ap,receiver}}$$

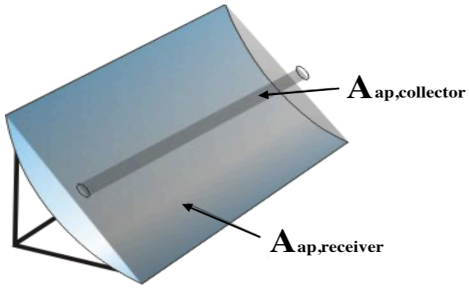


Fig. 14 Collector aperture and receiver aperture area.

PCT is currently the most popular technology: it represents more than 90% of the solar concentrating plants installed in the world. These plants produce a typical capacity between about 10 MW to over 200 MW and can achieve average efficiencies of 18% with a peak value of 22%.

2.1.2 Linear Fresnel plant

The Linear Fresnel Reflector technology(LFRs), from a constructive point of view, is simpler and cheaper than PTCs, so while a parabolic trough plant costs about 4,5 million € per MW installed, a plant based on Fresnel mirrors costs around 3,1 million € per MW installed, nearly a third less [17]. Nevertheless LFRs is slightly less efficient than PTC and have not reached their full industrial maturity as only a few of the existing and planned CSP plants use LFRs as collectors [15].

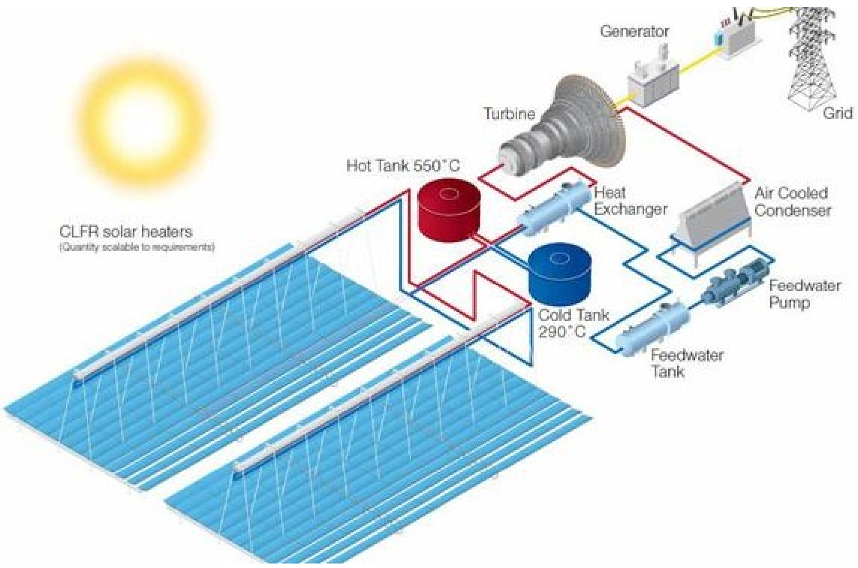


Fig. 15 Schematic of a Linear Fresnel Plant.

One of the main advantages of this technology is the lowest supply chain risk, the simpler structure with consequent reductions in material and construction. Linear Fresnel technology systems, reducing the volume of material required for the reflector, decreases the system's cost.
Additionally, LFs is the most land-efficient solar technology thanks to the much better ground utilization: in fact, it can produce 1.5 to 3 times more power per acre of land respect other solar technologies.
The operating temperature of the heat transfer fluid is usually lower than PTC, typically between 150°C and 350°C, but can achieve almost the same performance of parabolic troughs with lower costs.
A fundamental problem of Fresnel collectors is the shading between facing mirrors. It can be reduced by increasing the height of the receiver but increasing the cost and size of the system. A solution developed by Sidney University in Australia involves the use of multiple receivers, varying the orientation of the mirrors between the two receivers, hence reducing the shading [18].

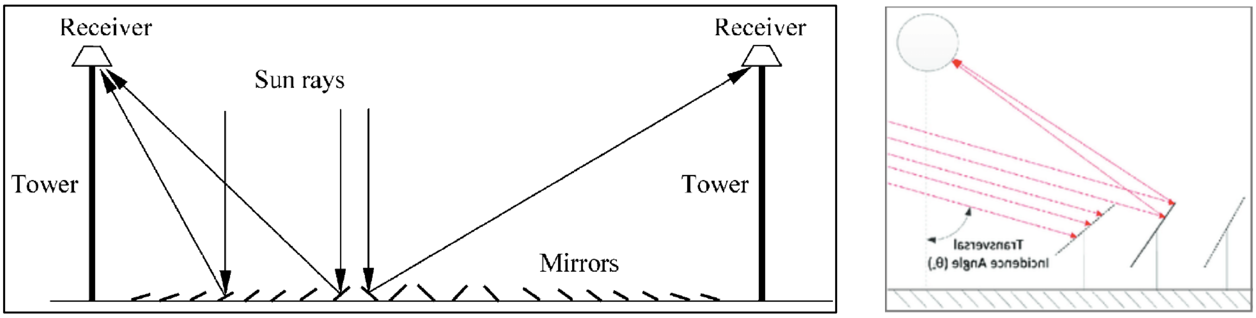


Fig. 16 Scheme of the Fresnel collector developed by Sydney University [23] and shading effects in LFC.

2.1.3 Solar Tower plant

Solar Tower which is also referred to as Central Receiver consists of a series of flat mirror (heliostats) having a dual axis control system. The aperture areas of the heliostats employed in many plants vary considerably from 1 m^2 to 120 m^2.
The heliostats concentrate the sun's rays on a fixed receiver placed at the top of a tower. This concentrated solar energy incident on the receiver is turned into thermal energy, which is carried by the HTF passing through the receiver. The thermal energy of the HTF is transferred to the working fluid of the power cycle, thereby generating electricity. The receiver is one of the most important parts of tower plants.

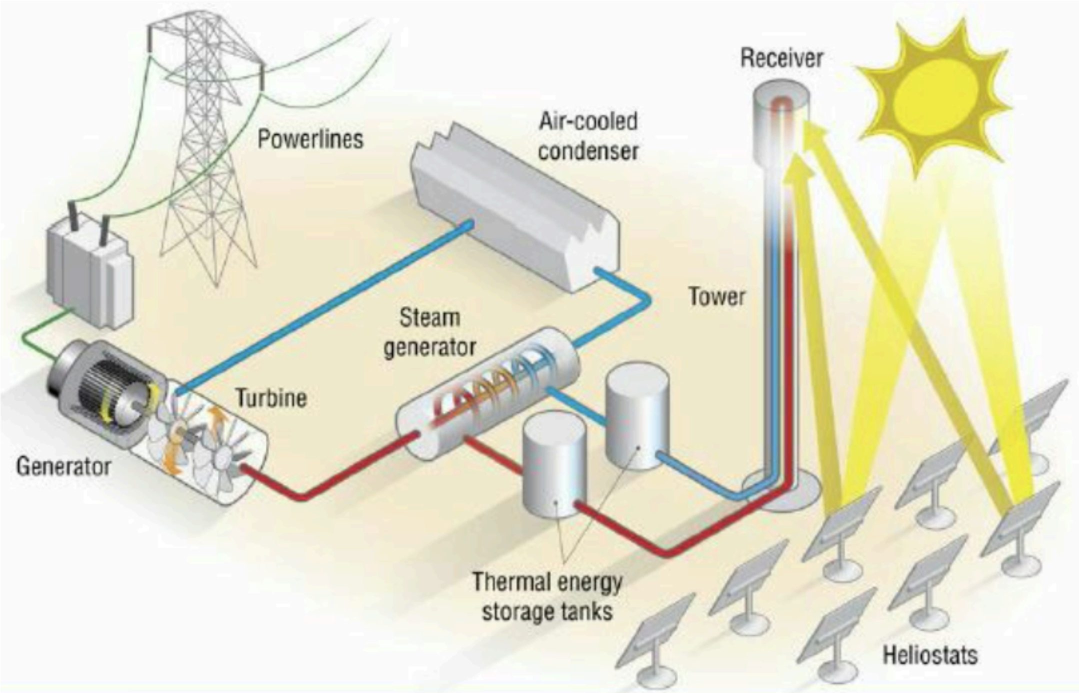


Fig. 17 Schematic of a Solar Tower Plant

There are two types of receivers: tubular and volumetric. Tubular receivers are used for HTF such as water, molten salt, thermic oil, liquid sodium, and Hitec salt, and volumetric receivers use air or supercritical CO2 as HTF. The type of receiver depends on the type of HTF and power cycle (Rankine or Brayton) used in the system.

This technology allows to reach higher temperatures than parabolic through and Linear Fresnel collectors, and that depends on the type of fluid used to collect the heat: usually, the temperature range varies between 500 and 600 ° C, but can also reach higher temperatures, greatly increasing the efficiency of conversion into electricity. By concentrating the sunlight 600–1000 times, they reach temperatures from 800°C to well over 1000°C. The plant efficiency is generally higher than parabolic trough plants because fluid temperatures are higher.

A meaningful weakness of this technology is the maximum distance between heliostats and the tower, which limits the power that can be installed for each system. The very large land area required, hence, make them suitable for areas like the desert. In addiction they need rigid structure and more support because of the large number of mirrors used.

Some developers (for example, eSolar) use small heliostats and claim that the advantages are mass production, easy handling & installation, smaller wind loads because of size and proximity to the ground. Heliostats of 1 m^2 have a single flat mirror. However, if such small mirrors are used, the number of heliostats and controllers will increase [19].

Central tower systems are less sophisticated than Parabolic Trough systems but allow higher efficiency and better energy storage capacity. One disadvantage to consider, however, is the larger environmental impact from the landscape point of view. The size of thermodynamic solar power plants with a central tower is limited by the possibility of keeping the heliostats pointed in the presence of wind at a distance of more than 1000 meters from the receiver, corresponding to a height of about 220 meters of the tower and a nominal power limit of 50-100 MW.

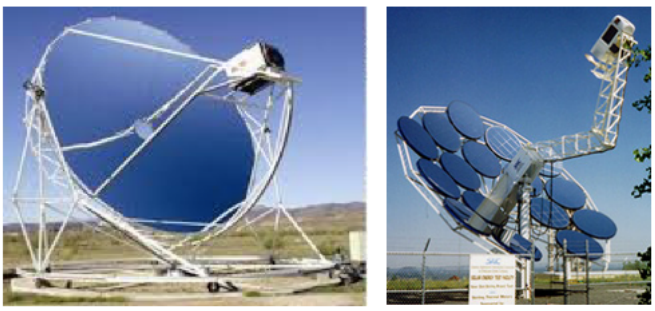
2.1.4 Dish Stirling System

A solar dish Stirling (DS) system consists of a paraboloid-shaped reflective surface, a solar receiver and a motor-generator block, in which the engine is in most cases a Stirling-type engine.

The dish solar collectors have a diameter that can vary from about 5 m up to more than 10 m. The reflective surface of the paraboloid can be realized in different ways, through the union of many sub-mirrors, or through multiple elastic membranes placed in such a way as to obtain the desired shape. Dish Stirling solar collectors allow achieving concentration ratios between 600 and 2000, which allow reaching working temperatures over 750°C and reflectivity values up to 94%. According to the shape, various types of concentrator can be employed:

- Glass-faceted concentrators with spherically curved glass mirror mounted on a parabolic-shaped structure. This design is characterized by high concentration ratios, more complex and massive structure and significant costs due to the required alignment accuracy.

- Stretched-membrane concentrators that can be a single-facet or multifaceted. The design incorporating thin membranes stretched over both sides of a metal ring. The membranes may be thin plastic sheeting or thin metal sheeting with a reflective coating applied to one of the membranes [20]. This type of system is principally adopted for rural and isolated applications.



a) b)

Fig. 18 a) single-facet b) multifaceted Stretched-membrane concentrators

The solar receiver, located in the focal point, is generally a cavity receivers with a small aperture to allow concentrated sunlight to enter. The receiver aperture is optimized to be just large enough to admit most of the concentrated sunlight but small enough to limit radiation and convection los [20]. The solar cavity receivers used in DS collectors can be classified into two distinct species:

- Direct-illumination receivers (DIR) that adapt the heater tubes of the Stirling engine, so the same fluid is used for both collects heat from solar radiation and for the Stirling cycle inside the engine. Normally, the heat transfer fluid is hydrogen or helium at high pressure.
- Indirect receiver (Liquid-metal, heat-pipe solar receivers) Uses a liquid-metal intermediate heal-transfer fluid, the liquid sodium metal is vaporized on the absorber surface of the receiver and condensed on the Stirling engine's heater tubes [20].

The motor-generator block is directly connected to the receiver. There are two types of Stirling engines: kinematic one works with hydrogen as a working fluid and has higher efficiencies, and free piston that work with helium avoiding friction during operation.

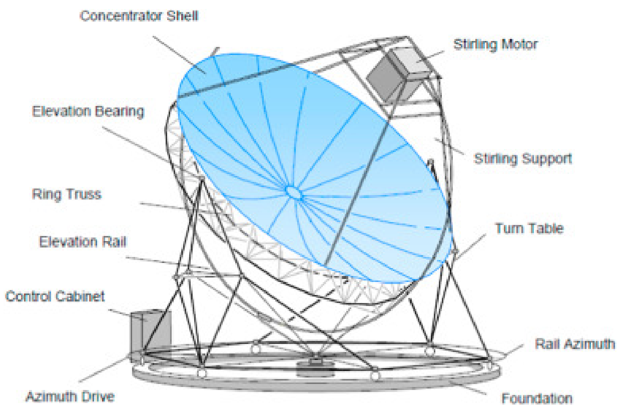


Fig. 19 Schematic of a Solar Dish Stirling Plant with components

The entire system is installed on a structure that, adopting a dual tracking solar mechanism, allows the solar parabolic dishes to be directed toward the sun and collect as much energy as possible. This improves the efficiency of these systems reaching values of approximately 24%, and peak efficiencies of more than 30%, representing the highest efficiency of any solar power generation system. This type of system constitutes an autonomous unit of electricity production, capable to provide 5 KW even to more than 25 KW of power for larger models.

Despite this technology allows achieving very high efficiency, the construction complexity, and the high realization costs, as well as the thermal storage system hard use, without which is not possible a continuous electricity supply, have limited this technology diffusion, in fact, commercial power plants that adopt this technology are rare.

3 CSP Water management

Water consumption is an important issue for the power sector, since all electricity generation technologies, including those that do not require cooling systems, need some amount of water for operational processes .This means that the power sector can be vulnerable to constraints caused by drought conditions and other changes in water resources [11].

This aspect is more significant for CSP power plants where water consumption is higher than for the non-renewable thermoelectric technologies. A wet-cooled CSP system needs more water than many other wet-cooled technologies, except for wet-cooled coal systems; while dry-cooled CSP systems have lower water use rates than conventional plants adopting cooling towers and similar water impact to natural gas facilities employing dry cooling [21].

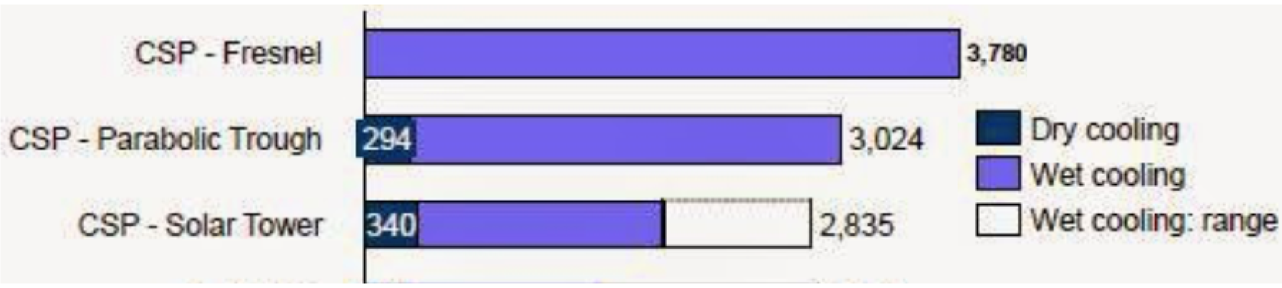


Fig. 20 Maximum Water consumption of various plants [liters/MWh] (Adapted from [22]).

Focusing specifically on the different CSP technologies, it is possible to observe that CSP-Fresnel requires a larger amount of water, reaching almost 4000 l/MWh. Based on thermodynamic principles, a water-cooled Parabolic Trough plant requires less water than a LF plant because of its lower working temperature and efficiency, and more frequent startup and off-design operation. A solar tower plant with a traditional Rankine cycle, instead, need a lower amount of water thanks to the higher operating temperature and efficiency. Stirling systems are not considered since they don't ordinarily need water for cooling or steam cycle operations, but just for concentrators washing.

All types of CSP technologies can require hundreds of thousands of cubic meters of water during construction depending on their size and type of technology [21].

3.1 CSP Water consumption

CSP technologies have four main water consumers, if water during construction is not considered:

1. steam cycle
2. mirror cleaning
3. cooling process
4. miscellaneous activities (that however can be considered negligible).

3.1.1 Steam cycle

Parabolic trough, linear Fresnel, and power tower CSP technologies require demineralized water for the water-steam Rankine cycle, that are essentially the same as those used in coal and nuclear power plants [3], while Stirling or small solar tower technologies use air or gas as HTF. The water used for this purpose is not very high, however it has very specific purity requirement and a salinity of 0.001 g/l to avoid fouling or scaling of the steam turbine.

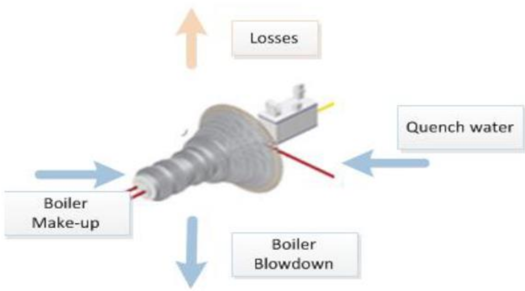


Fig. 21 Steam Rankine cycle water requirement [23].

Since most of the water is reused in the cycle, the consumption is usually identified with the losses in the cycle: flashing of steam generators and blow-down leakage to maintain a specific condensate quality, quench water, steam cycle make-up, that consumes about 100-200 l /MWh and spillages during startup.

3.1.2 Mirror cleaning

CSP collector systems experience more severe temporary performance degradation due to weathering, especially because most CSP plants are built in desert areas with frequent dust storms. Thus a periodical mirror cleaning is required, on average every 1-2 weeks depending on the site, dust properties, cleaning technology, etc.

For this type of plant, washing frequency and water quality conditions are much rigorous than for other technologies, because power production depends on the optical and thermal efficiencies. Commonly, due to soiling and dust, a power loss to 25 % per week can occur.

Consequently, choosing the most suitable cleaning methods is an economical decision based on the cost of cleaning versus the loss of energy resulting from soiled reflectors.

For cleaning purpose water jet and/or high-pressure air can be employed by sprinkling it on the soiled reflectors surface, that consume around 7-8 l/m^2; or in combination with a contact cleaning tool used for brushing, wiping or scrubbing the surface of soiled reflectors [24].

There are two different Washing processes: Contact cleaning or Non-Contact Cleaning:

- Contact cleaning consist of brushing, wiping or scrubbing the soiled surface and is capable of restoring full initial reflectance. This method consumes less water offering a better result, but is frequently slower and can scratch or delaminate the reflector's surface, degrading it irreversibly.
- Non-Contact Cleaning method consists of spraying high-pressure water onto the dirty surface. It is effective in removing dust, but not in eliminating the soil cemented to the mirrors. For non-Contact Cleaning it is possible to identify :
    - High-Pressure Spraying method in which high-pressure water is sprinkled restoring the 98% of their initial reflectance. This method requires 0.19 gallons/m2 of aperture area.
    - Deluge Spraying method that uses deluge-type spraying, which is four times faster than the high-pressure method and consumes 0.23 gallons per square meter of aperture area [24].

Cleaning method	Water Consumption [l/m²]		Cleaning Factor
	Heliostats	PT	
Water jet	0,85	0,75	95%
brushes	0,8	0,7	99%

Fig. 22 Water consumption and cleaning factor for different cleaning methods [23].

The average water consumption, nevertheless, depends on the type and quantity of soil and the CSP plant: for instance, in wet parabolic trough plants mirror washing influence the total consumed water by only 4%, while in the case of dry cooling, cleaning reflectors consumes up to 62% of the total consumed water[24].

3.1.3 Miscellaneous activities.

Besides water consumption due to steam cycle, mirror cleaning and cooling process, in a CSP plant, there are also miscellaneous activities, such as bundle cleaning, filter backwash, auxiliary machine cooling, flocculent hydration, ozone generator cooling, centrifugal cleaning, etc., requiring a very small amount of water, around 0.007 m3/MWh.

Fig. 23 Miscellaneous activities consuming water [23].

3.2 Cooling Systems

The two key processes in a steam turbine system are the steam cycle, already covered by paragraph 3.1.1, and the cooling process, required to condense steam back into water. Fossil and nuclear power plants use the same wet-cooling technologies as those for CSP [22]. There are three steam cycle cooling systems possible: wet, dry and hybrid-cooled.

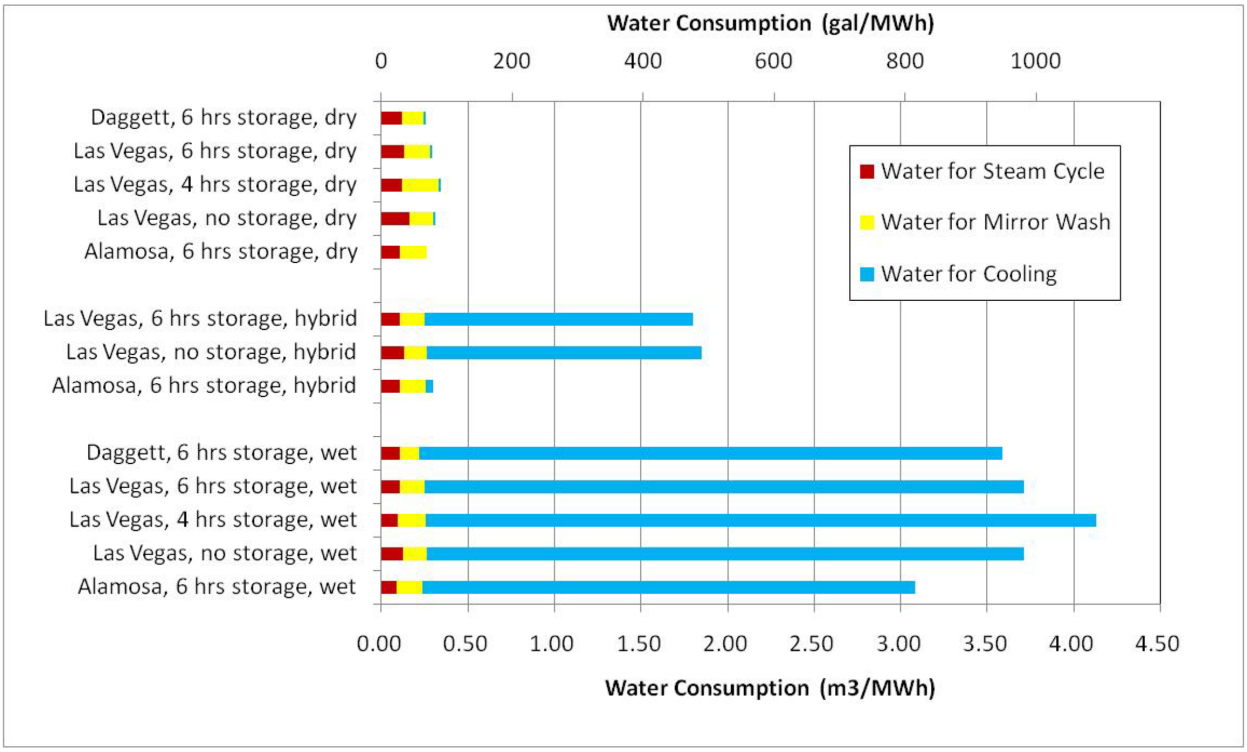


Fig. 24 Estimated water consumption for the 13 US plants.

The commonly used cooling system is the wet-cooled system, that can require 3.5 m^3/MWh comparable to 2.2 m^3/MWh for coal and 3.2 m^3/MWh for nuclear wet-cooled Rankine [22]. However, in very hot environments or in regions where water supplies are inadequate, a dry cooling technology, which adopts an air-cooled condenser, can be a more suitable choice. Despite the use of air instead of water for cooling, dry-cooled plants spend slightly more water than wet-cooled in the steam-cycle due to the lower total efficiency, but these effects are overwhelmed by eliminating the cooling tower [22]. The actual disadvantage of dry cooling is that air has a lower ability to carry heat than water; consequently, the efficiency decreases considerably. Where this parameter is essential a hybrid combination of wet and dry cooling technologies may be used. A hybrid system can make use of both wet cooling and dry cooling that can be used separately or simultaneously depending on ambient temperatures, or alternatively can use water sprays or deluges in a dry-cooled system to reduce ambient temperatures [21].

3.2.1 WCC systems

Water-cooled condensers (WCC) make use of water as heat transfer fluid because it is relatively cheap, easily accessible and reusable for many cycles. The wet-cooling system has the highest water consumption level, but is also the most compact and efficient method of cooling; in fact, more than 67% (62 plants) of world installed CSP capacity is equipped with WCC. Additionally, it is essential to remember that while dry-cooled processes rely on air cooling and are limited by the ambient dry-bulb temperature, wet cooling processes use evaporation to reject heat and can achieve minimum temperatures that approach the ambient wet-bulb temperature [25]. Wet-bulb is always lower than dry-bulb temperature, except under the condition of 100% relative humidity in which the two temperatures have the same value. Since the Rankine cycle efficiency depends on the condenser temperature, and lower temperature values improve the power-cycle efficiency, wet cooling is the most advantageous heat transfer method.
Water cooling for power plants is can use two types of condenser systems: once-through WCC and circulating evaporative WCC

3.2.1.1 Once-through WCC systems

Once-through cooling systems can be employed when a power plant is located next to rivers, lakes or the sea since its water is pumped through the pipes' condenser, remove the heat from the stream and discharges all of it back into the source at a higher temperature.

This open loop cooling system does not consume any water for cooling purposes, but has considerable environmental consequences: it increases the temperature and hence the evaporation rate from the body of water [26], as well as reduce the quantity of oxygen with potential mortality of marine creatures. This cooling method is rarely employed in CSP power plants, commonly located in deserts or arid regions with water scarcity. The plants that adopt Once-through cooling system tends to be more efficient, it withdraws 10 to 100 times more water per unit of electric generation than cooling tower technologies, yet cooling tower technologies consume at least twice as much water as once-through cooling technologies [26].

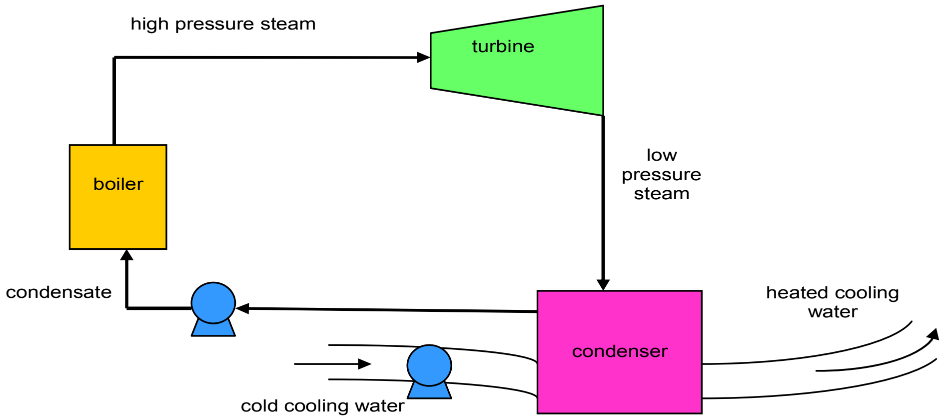


Fig. 25 Scheme of Once-through cooling system

3.2.1.2 Circulating evaporative WCC systems

Circulating evaporative WCC system, also called cooling towers, is the most common power plant cooling technique, given that it is economical and more efficient than dry cooling thanks to the less water temperature variations respect to air. This method employs approximately the same volume of water as a coal-fired or nuclear power plant; more specifically, a typical CSP parabolic trough plant with circulating evaporative WCC uses water at a rate of 2,955 – 3,030 l/MWh, of which 98% is used for evaporation, boiler blow-down and water make- up and 2% for mirror washing, compared to 1,890 – 2,840 l/MWh for a CSP solar tower plant [26].

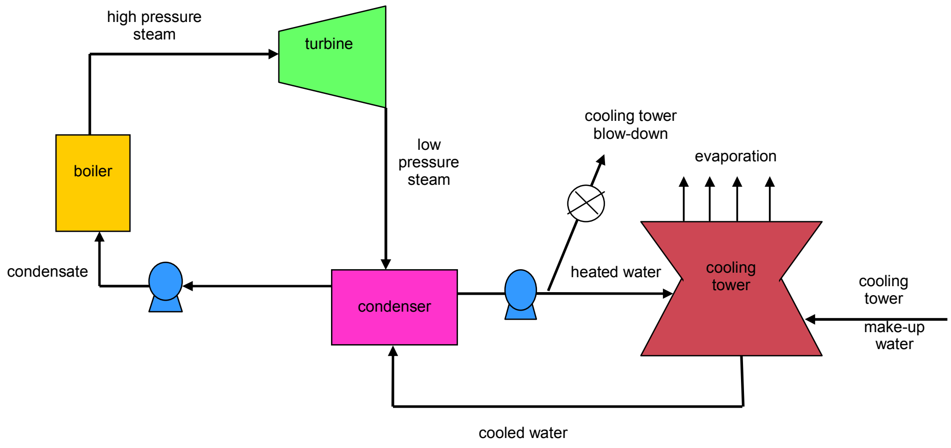


Fig. 26 Circulating evaporative WCC systems

There are two kinds of cooling towers: forced draught and natural draught.

Natural draught absorbs the heat from the sprinkled water through a cooling tower and discharges it into the air. This method uses around 1800 l/MWh of water and considering that 2.5% of the total used water is evaporated, this may represent a good choice mainly for plants installed near an available water source.

The Forced draught cooling method is similar to the natural one, essentially changes because air is sucked up from the tower's base and contemporary, the water droplets flowing down the fills opposite to the air direction. The counter flow of air and water cause heat transfer in a continuous cycle. This technique costs less but spends more energy since making use of Draught fans, that are used to cool the water in the cooling towers.

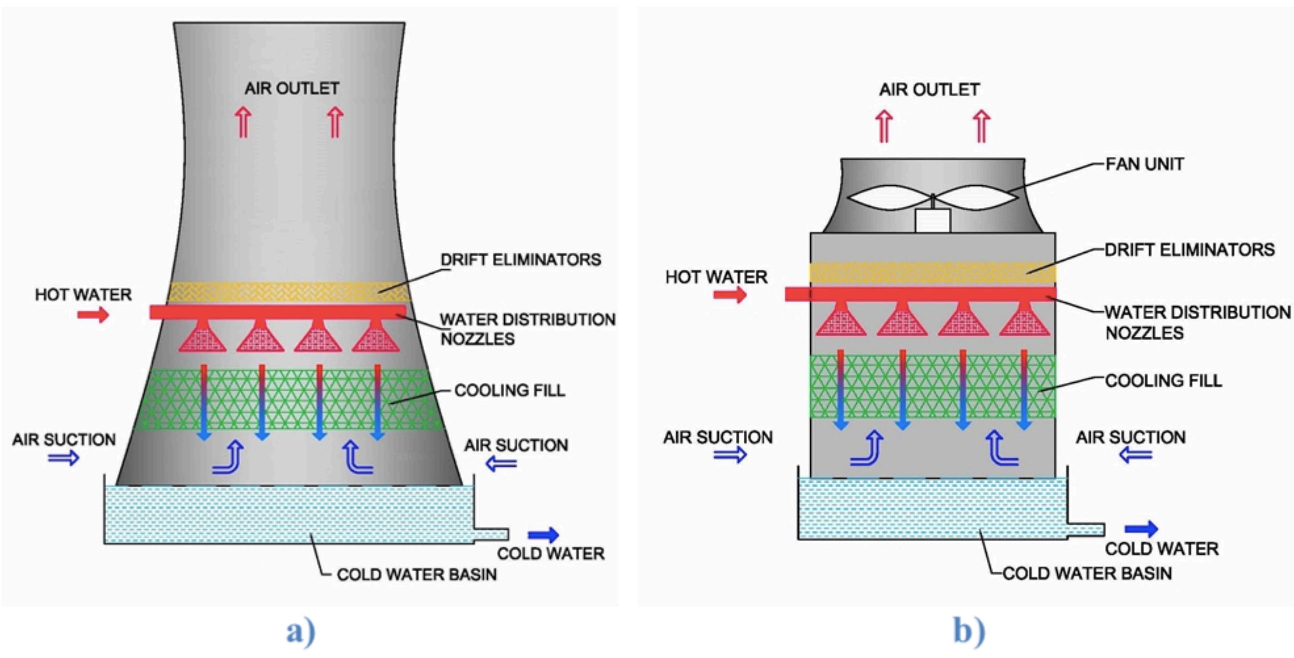


Fig. 27 Forced draught and natural draught cooling tower.

3.2.2 ACC systems

Air-cooled condensers (ACC) is a dry cooling system, which employing air to condense the steam exits the turbine over a bundle of finned tubes, so don't add additional water consumption.

This allows ACC systems to install power plants in regions without enough water supply sources, as frequently happened for CSP plants. Nevertheless, in desert areas where ambient temperatures are higher, the ACC performance is lower, while for low temperatures the efficiencies are almost comparable to wet cooling. Indeed a fundamental working parameter for this technology is the cooling range: the increase of cooling range gives extended temperature potential in the heat exchanger of the dry cooling system [27], in particular, the performance particularly decreases for ambient air temperatures above 38°C.

The dry condensing system consumes amounts of water usually an order of magnitude lower than a wet system. Dry cooling is distinguished by high capital cost, generally increased by 7 to 9% and produces 5% less annual electricity. Other limitations of dry cooling are higher capital costs, higher auxiliary operating power requirements, fan noise, and an overall lower plant performance [26]. The ACC is a closed-loop system not having evaporation or blowdown. Steam cycle makeup is supposed to be slightly higher for the dry condensing system than the wet [25].
ACC systems are classified in direct ACC systems and indirect ACC systems.

3.2.2.1 Direct ACC systems

In direct ACC systems, the saturated steam from the steam turbine is carried directly to a very large array of A-framed fin tube bundles, which are externally cooled by ambient air [28]. The ambient air used for condensate cooling can circulate with the use of fans, known as mechanical draft, or can circulate thanks to a hyperbolic tower with a series of heat exchangers, known as natural draft. The latter is more expensive in terms of investment cost and would result in significant operational problems.
Steam discharged from the turbine exhaust flows into a steam distribution manifold placed on the head of the construction. The steam is then distributed into the fin tube heat exchangers arranged in a roof structure with an A-shape configuration [26]. Then ambient air, which is drawn over the external finned surface of the tubes by the fans, placed at the bottom part of the A-shape

framework, is cooled and condenses the steam inside the tubes. The condensate is drained to a condensate tank, before being pumped to the conventional feed heating plant [28].
The direct ACC systems employ two types of heat exchangers, multi-row and single-row, advantageous in freezing ambient conditions.

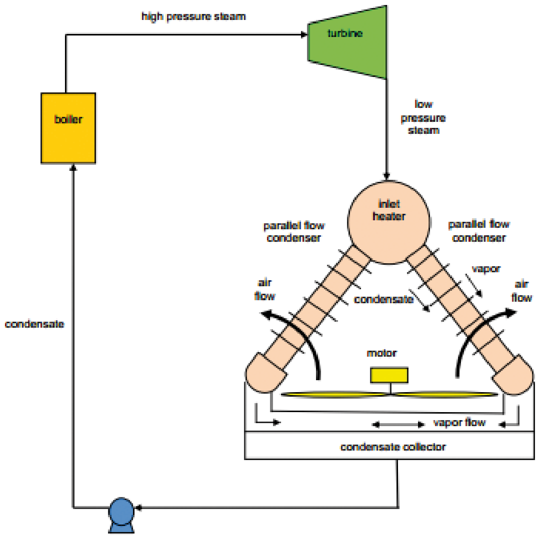


Fig. 28 Direct ACC systems

There are, also, different kinds of tube shapes and fin shapes possible.
Among all the shapes (round, oval, flat), oval and flat tubes work better but are more elaborate and need more complex construction techniques

3.2.2.2 Indirect ACC systems

In indirect ACC systems, however, the condenser consists of a traditional water exchanger but the hot water coming out of it is sent to air-cooled tubes batteries. These batteries are positioned tilted to ensure the maximum exchange surface inside the hyperbolic cooling tower.
The steam is condensed by spraying water directly into the exhaust flow of the steam turbine in a ratio of about 50:1 [28]. In this way, a large amount of water can be pumped to bundles of tubes arrayed at the bottom of the cooling tower. The cooling process is achieved by natural convection and is enhanced by the characteristic shape of the tower, realized in this way so that the vertical motion of the air is accelerated.

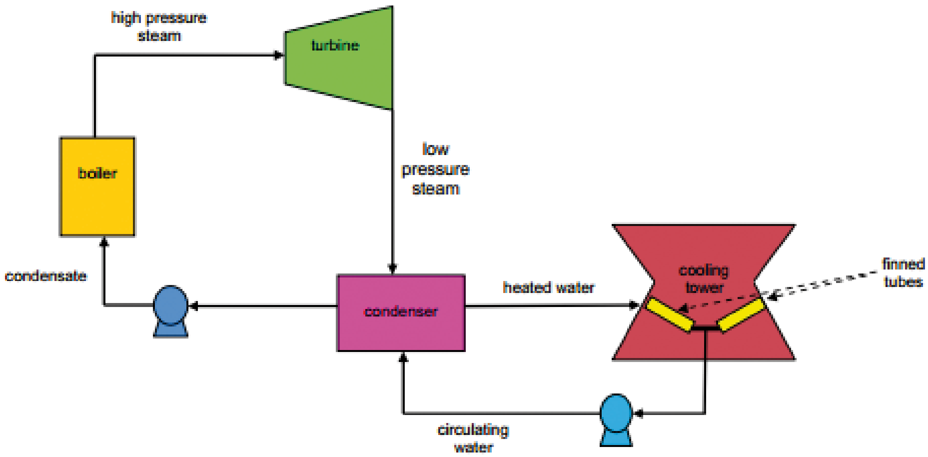


Fig. 29 Indirect ACC systems

Accordingly, indirect ACC systems have less limitation on what concerns the positioning of the cooling tower, which can be separated from the CSP system without modifying the steam pipes design and so reduce considerably environmental impact.
In the case of the indirect ACC systems, either mechanical or natural draft can be used [26]. For large-scale plants the natural draft is a more suitable option since avoid fan power demand and so costs.

3.2.3 Hybrid systems

Hybrid cooling systems typically include both ACC and WCC units, two facilities are sized depending on the operating strategy of the plant, that work in parallel or use water to evaporatively cool the air going to the air-cooled condenser [29](the parallel cooling system is shown in Figure 30). There is also the opportunity to combine wet cooling and dry cooling with a serial layout. However, this design is not applied because circulating water cooling requires a potential difference between wet bulb temperature and process water [27], forcing the position of wet cooling at the ending step of cooling.

Usually, wet cooling operates only on hot and less humid regions, in which the cooling tower requires to be employed with logical higher plant efficiency but higher water consumption.

Investigations have revealed that CSP hybrid-cooled systems spend less water than existing (wet-cooled) coal, natural gas, and nuclear power plants in some areas [22], but it depends of course on the frequency of wet cooling utilization. Typically, with this kind of technology, there is a reduction of water consumption by 50% with almost stable turbine efficiency and annual generation: a hybrid cooling system in the Southwest USA using 50% of the water of wet cooling would maintain 99% of the performance of a wet-cooled facility; while a hybrid cooling system using 10% of the water of wet cooling would maintain 97% of the energy performance [22].

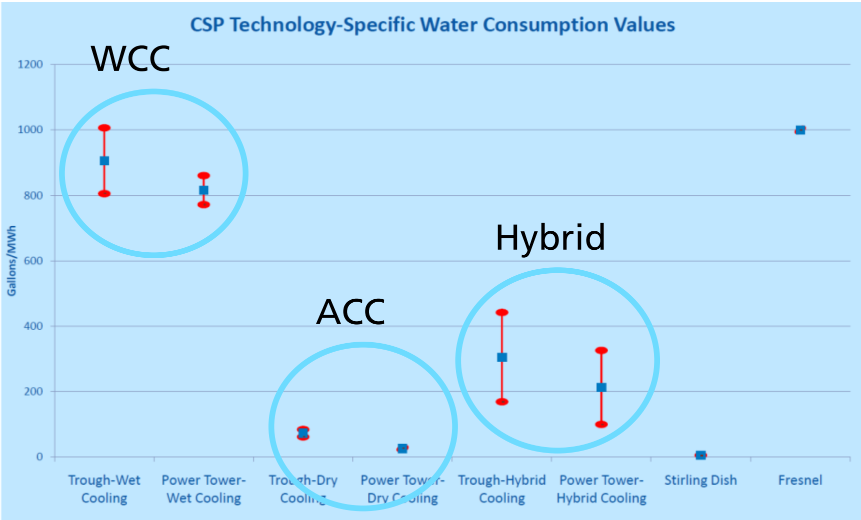


Fig. 30 Hybrid Cooling water consumption respect WCC and ACC [23].

However, this method has the highest operational complexity and installed price. The higher cost results in raising the Levelized cost of electricity (LCOE) and is due to the larger number of components and elaborate processes to shift from a wet-cooled system to a dry-cooled system. On the other hand, this possible switching operation enables to reduce water consumption over 92%–93% but unavoidably reduce the annual electricity output.

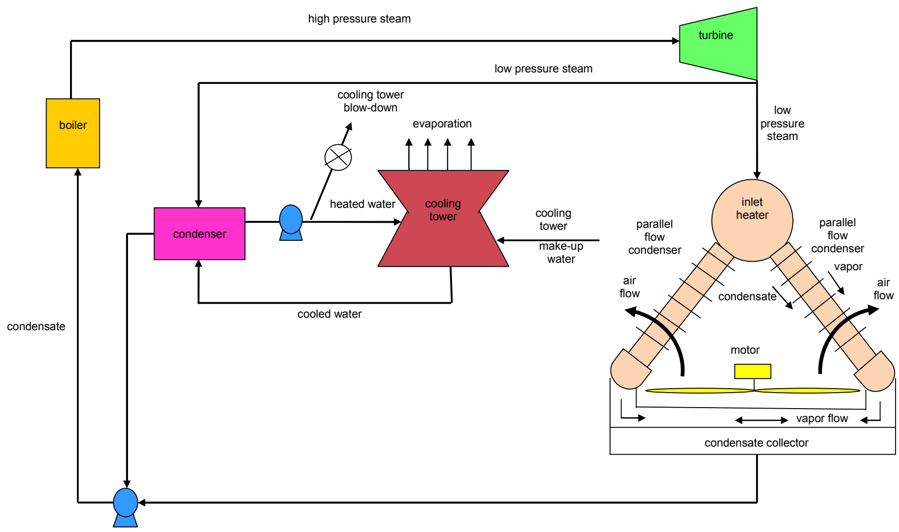


Fig. 31 Hybrid wet/dry cooling system

A hybrid wet/dry cooling systems, not only are applied to reduce water consumption but also to decrease the water vapor plume. This aspect is however trivial for CSP plants, which are typically placed in desert, or dry isolated areas.

To summarise the key aspects of the three different systems, a table with the principal advantages and disadvantages is reported below (Tab. 1).

Cooling method	Advantages	Disdvantages
Wet (cooling tower)	Lowest installed cost Low parasitic loads Best cooling (i.e., lowest cooling temperature), especially in arid climates; gives highest power cycle efficiency	High water consumption Water treatment and blowdown disposal required Cooling tower plume in cold weather
Dry (ACC)	No water consumption No water treatment required No cooling-tower or blowdown pond Lower O&M costs	More expensive equipment Higher parasitic loads Poorer cooling at high dry-bulb temps (cycle efficiency falls)
Hybrid	Reduced water consumption Potential for lower levelized energy cost compared to dry cooling Maintains good performance during hot weather	Complicated system involving wet and dry cooling; often highest capital cost Same disadvantages of wet system, but to lesser degree

Table 1 Advantages and disadvantages of different cooling types (Adapted from[25]).

4 Water extraction technologies' state of the art

The increasing deficit of drinking water, which already afflicts millions of people, is going to get worse with the intensification of energy production and the dramatic consequences of climate change. To remedy this situation, science is trying to investigate alternative approaches to tap into (even non-potable) water sources on the planet or extract it from unconventional sources. The main existing methods are groundwater extraction, desalination of seawater and water harvesting from the atmosphere.

4.1 Groundwater extraction

Groundwater is the water located underground in the holes and spaces in soil, sand, and rock, and run through aquifers. The groundwater represents 96% of the accessible drinkable water on the Earth, while the remaining 4% of the freshwater is found at the surface in rivers or lakes.

This source of water can be found near the surface or deeper, around 9000 m, according to the U.S. Geological Survey (USGS).

Groundwaters allow relieving demands on existing surface sources and increase water quantity and water security in areas where freshwater is inaccessible and have the benefit of reduces water treatment requirements. In addiction the water coming from aquifers has a good quality and is not at contaminated.

Groundwater contained in aquifers can naturally come to the surface at a spring (a point where the water table meets the ground surface) or outflow in springs, rivers, lakes and the sea, otherwise, it can get on the surface by human artificial abstraction. Aquifer recharge comes from infiltrations induced by snowfall or rainfall or conjunction with other water bodies. If groundwater abstraction exceeds groundwater recharge for an extended period of time, overexploitation or persistent groundwater depletion can occur, for this reason, sustainable management of aquifers is an important issue.

Groundwater is mostly used for drinking and domestic applications, in agriculture and power production, which can, however, harm groundwater quality and future constraints because of massive extraction and wasteful use, especially in the last decades. Besides the fact that groundwater sources are rapidly decreasing, another obstacle, resulting from this is described by the deterioration of water quality and groundwater depletion. The effects can be already visible in some regions of the world, such as northern China and India, North Africa and the western United States.

As we can notice the majority of these countries have a high quantity of arid and semi-arid lands. In these regions, in fact, surface water supplies are limited and unstable, hence groundwater represents the only freshwater potential source.

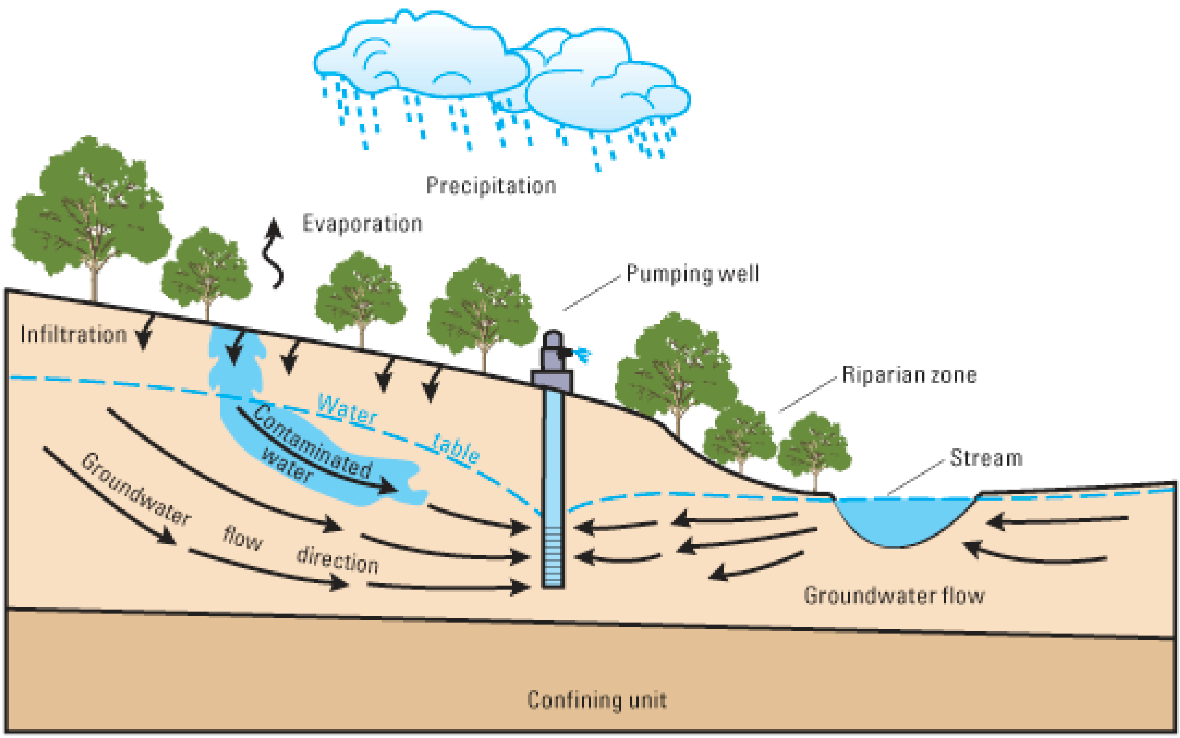


Fig. 32 Groundwater extraction

India, China, the United States, and Pakistan alone extract groundwater in the order of 325 km^3 every year [30]. In Saudi Arabia the non-renewable groundwater, used for urban water- supply and irrigated agriculture, is 84% of the country total water resource, while in Libya it is 67%.

Different extraction methods are employed to obtain groundwater and they depend on the depth at which water is detected, desired water quality, its final utilization.

As groundwater sources are becoming more and more limited, more shallow wells are draining, requiring deeper tubewells, and increased pumping costs. As the depth to water increases, the water must be raised higher to reach the land surface, with consequent more energy demand and more expensive equipment.

4.2 Desalination

Geographic regions where seawater is abundant or freshwater supplies are limited can adopt desalination technologies to satisfy water needs. Desalination is a method of extracting salts and other chemicals from seawater.

In 2013 the total capacity of installed desalination plants was about 80 million m3/day, by 2015, it grew to nearly 97.5 million m3/day and it is expected to reach 192 million m3/day by 2050 [31].

The principal concerns with this technology are that it is an energy-intensive and expensive process and has diverse environmental impacts, including high greenhouse gas emissions and waste products that can affect aquatic animals.

Seawater desalination technologies can be classified into two types which are separation or membrane methods and thermal methods.

4.2.1 Thermal seawater desalination technologies

Thermal methods providing thermal energy, evaporate seawater and produce water vapor (distillate) that is condensed into clear water. Thermal technologies, marked by higher costs, tend to be used in regions where water salinity levels are high and energy costs are low, such as in the Caribbean and the Middle East, while membrane technologies are becoming more popular in areas like the Middle East due to their lower specific energy consumption, lower environmental footprint, and more flexible capacity [31]. Thermal technologies are divided into Multi-Stage Flash Distillation (MSF), Multi-Effect Distillation (MED), and Vapor Compression Distillation (VCD).

4.2.1.1 Multi-Stage Flash Distillation (MSF)

Multi-stage flash distillation (MSF) is the most common desalination method, accounted for over 22% of the world's desalination capacity and is generally connected to other power plants.

In MSF process salt water is heated up to a specific temperature around 90 and120 C. Then the water is pumped and distilled through consecutive under vacuum chambers, each one at a progressively lower pressure to maximize water recovery. Saltwater temperature decreases from chamber to chamber so that the vacuum pressure keeps reducing to guarantee flash evaporation in all the chambers. The water vapor, rising from the chambers, is condensed on the outer surface of the feed water tube bundle, produces desalinated water and preheat the feed water before entering the brine heater. This allows reducing the energy needed for successive heating. The tubes are cooled by the incoming cooler feed water. Generally, only a small percentage of the feed water is converted into vapor and condensed.

MSF plants can make use of 15 -25 stages and can produce about 12.8 billion l/day globally, which is about 50 percent of the worldwide desalination capacity [32].

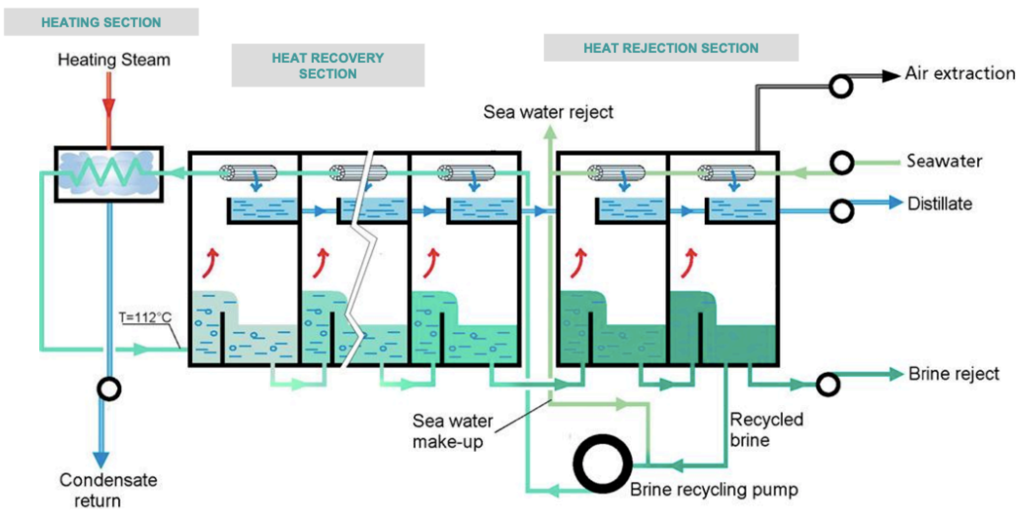


Fig. 33 Schematic of Multi-Stage Flash Distillation process

The most advantages of using multi-stage flash distillation are:

- the high-quality water produced, which contains less than 10 mg/L of salt (salt concentrations in drinking water limit is 499 mg/L)
- the relatively simple to management as it requires much less seawater pre-treatment.

Some disadvantages of using multi-stage flash distillation are:

- the corrosion, caused by direct exposure to the feed water, unless stainless steel is used
- the erosion generated by the turbulence of the feed water in the flash chamber
- the cost of installation and operation
- the high energy consumption
- the energy costs, that represent the majority of the plant operation cost
- a quite low water recovery rate, about 8-10 tons to provide 1 ton of desalinated water.

4.2.1.2 Multi-Effect Distillation (MED)

Multiple Effects Distillation (MED) method also called Multi-Effects Evaporation (MEE), similar to MSF, is formed by multiple stages with successively lower pressure to improve efficiency. In the multiple stages, saltwater boil repeatedly providing heat only in the first chamber, since the condensed vapor in the first chamber releases its latent heat that is capable to boil seawater in the second stage. MED is slightly different from MSF because the vapor formed in one chamber condenses in the next chamber with the heat released acting as a heating source [33].

The vapor outgoing on the first step is forced to circulate inside the tube bundle of the second step and so on for all the other steps. The pure distillate from the first stage does not join the main distillate stream to avoid mixing it with the boiler chemicals. For this reason, the brine is accumulated at the bottom of each effect.

Water vapor generated in the last stage is finally condensed in the condenser which is cooled by seawater and works also as heat reject section for the unit.

Part of the seawater at the final condenser outlet is filtered and used as feed water for the different effects by spraying it equally over the tube bundles [34].

The low temperature of the plant benefits reduce corrosion and scaling and allows the usage of low-grade waste heat, which are the main disadvantages of this process. The efficiency of the MED method is higher than MSF thanks to better thermal performances.

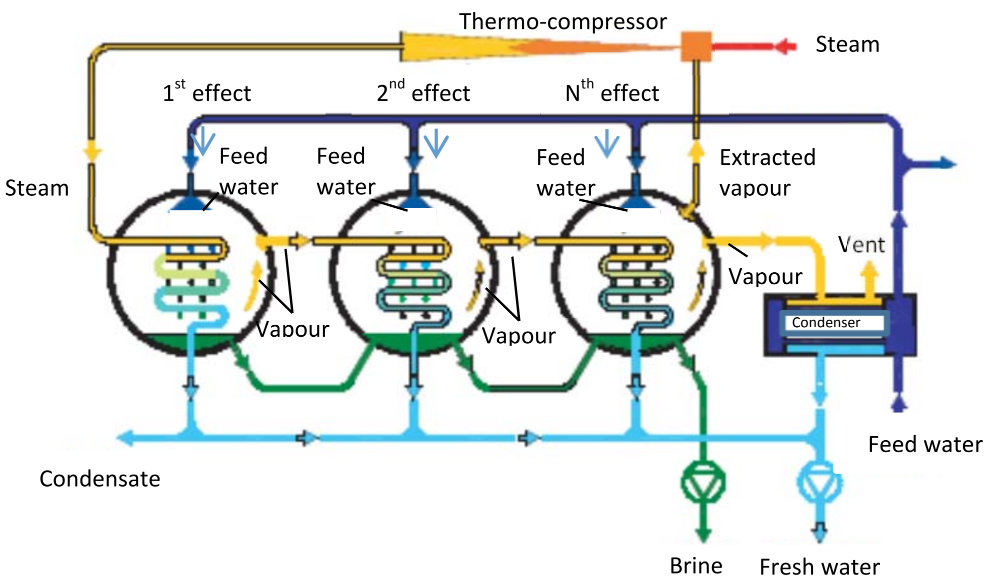


Fig. 34 Schematic of Multi-Stage Flash Distillation process

MED is the most mature water desalination technique since it is the first one to have been employed in the 1970s. Alike to MSF, MED requires few pre-treatment of seawater and can generate high-purity water. Yet it has a higher water recovery rate than MSF, needing about 5-8 tons of seawater to provide 1 ton of desalinated water.

4.2.1.3 Vapor Compression Distillation (VCD)

The Vapor compressor distillation (VDC) process is used in small and medium capacity units to desalinate seawater. In general, the capacity of desalination units employing a compressed vapor process varies between 20-2000 m3/day [34], depending on the number of stages, which if increased results in greater thermal efficiency and so a higher capacity. VCD method is used alone or matched with other processes, such as the MED.

Vapor compression consists of evaporating the feed water, compressing the vapor obtained, which after pressurized becomes the heat source to evaporate additional feed water.

In this process, the water evaporates at the feed water temperature thanks to a compressor that generates vacuum inside the evaporation chamber. The produced vapor is compressed by means of a mechanical vapor compression (MVC) or a steam ejector thermal vapor compression (TVC). Habitually, the mechanical compressor is used to compress the water vapor, which temperature increasing makes it the heat source needed to evaporate another part of feed water. The pressurized vapor is pumped to the shell side of tubes containing salt water making the vapor condense on the outer surface of tubes and also heating the salt inside the tubes providing supplementary amounts of water vapor which will be compressed again so the cycle will continue to produce condensed water as product water [34].

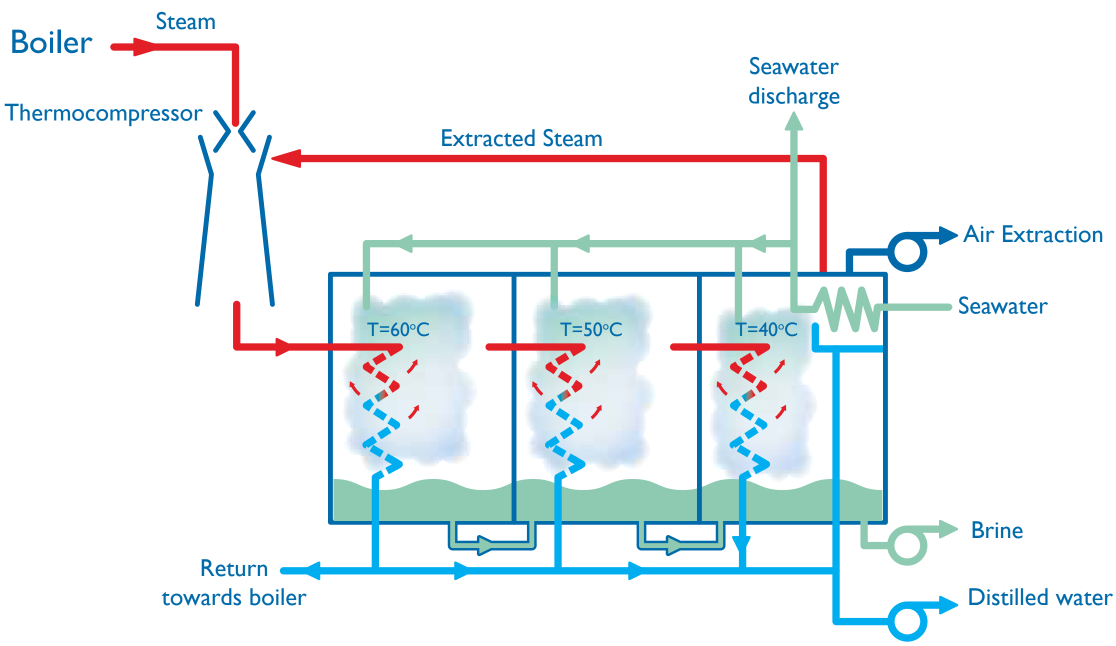


Fig. 35 Schematic of Vapor Compression Distillation process

The VDC plants are very compact and its capital cost is moderate. The desalination process is manageable and reliable, however, it requires large, expensive steam compressors and suffers especially from scaling and corrosion problems.

4.2.2 Separation seawater desalination technologies

Separation methods, such as reverse osmosis (RO) and electrodialysis (ED), work with appropriate filters (membrane) to separate salt from water using electrical or mechanical forces. In membrane processes, a membrane divides the feedwater into two phases, the wanted permeate and a higher salinity concentrate one, preventing the flow of the dissolved salts and other undesired substances. The driving force for transport can be a pressure gradient, a temperature gradient, a concentration gradient or an electrical potential gradient [35].

4.2.2.1 Reverse osmosis (RO)

RO desalination process consists of four major steps:

1. a) Pretreatment system, to remove dissolved solids
2. b) High-pressure pumps, necessary to force water passing through the membranes and separate it from the dissolved salts
3. c) Membrane systems, composed by a pressure vessel and a membrane inside of it
4. d) Post-treatment, to make obtained water proper for drinking.

Pre-treatment is essential in RO to eliminate particulates so that the membranes rest clean and last longer. This first step extracts all suspended solids. Pre-treatment may involve traditional methods such as a chemical feed followed by coagulation/flocculation/sedimentation, and sand filtration [32]. The choice of a specific pre-treatment method depends on feed water quality features, space availability, RO membrane conditions, etc.

High-pressure pumps allow the water to pass through the membrane and be desalted. The operating pressure for seawater is about 25 bar [35]. The value of the required pressure depends on the temperature and salinity of feed water and the expected generation [34].

The membrane system can use two different kinds of permeable or semi-permeable membrane inside the pressure vessel: Spiral wound, assembled from flat sheet membranes, and Hollow fiber, formed of cellulose acetate or other composite polymers.

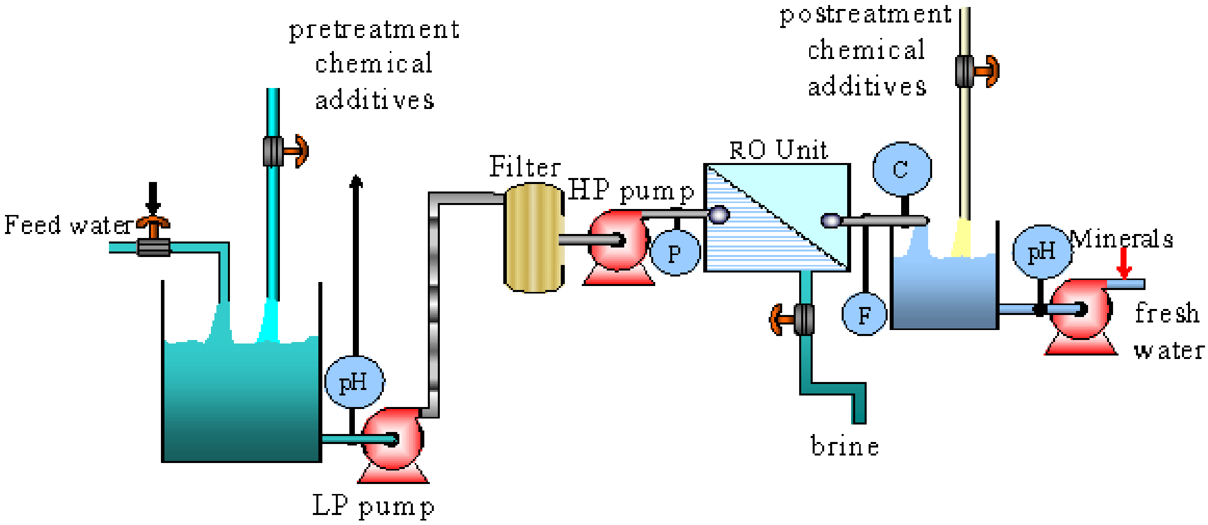


Fig. 36 Schematic of Reverse Osmosis process [36].

The Strength of RO are that: ordinarily spends less energy than thermal desalination, has high water recovery rate, as one ton of desalinated water can be provided starting from 2.5-3.2 tons of seawater, no heating or phase change occurs, can handle a large range of flow rates, from a few liters per day 4.0×105 L/day for seawater [35], chemicals used for cleaning goals are low.
However, the weaknesses are: membranes are costly and have a life expectancy of 2-5 years [35].
Reverse osmosis (RO) is the principal method of membrane desalination. RO is currently the most universally adopted process for desalination. In 2012, it accounted for 63% of the desalination production capacity worldwide, followed by MSF (23%) and MED (8%) [33].

4.2.2.2 Electrodialysis (ED)

Electrodialysis (ED) is a voltage-driven membrane method, in which voltage is used as a driving force.
Electrical potential allows dissolved ions, positively charged (sodium) or negatively charged (chloride) moving to the opposite electrodes passing through specific membranes that allow only a type of ions to pass through it, leaving fresh water behind as product water.
This separation happens in membranes organized in an alternate pattern, with anion-selective membrane followed by a cation-selective membrane forming cell pairs, consisting of an anion transfer membrane, a cation transfer membrane, and two spaces between the membranes. Hundreds of cells attached create a stack and the number of cells inside a stack depends on the system [35].

As the resistance changes along the stack, a sequence of short steps are required. This makes the process cheaper and simpler to regulate. ED systems effectively purify water with low salinity, up to 2000 ppm [34]. A critical concern in ED systems is the inability to separate the organic matter, colloids and dissolved solids.

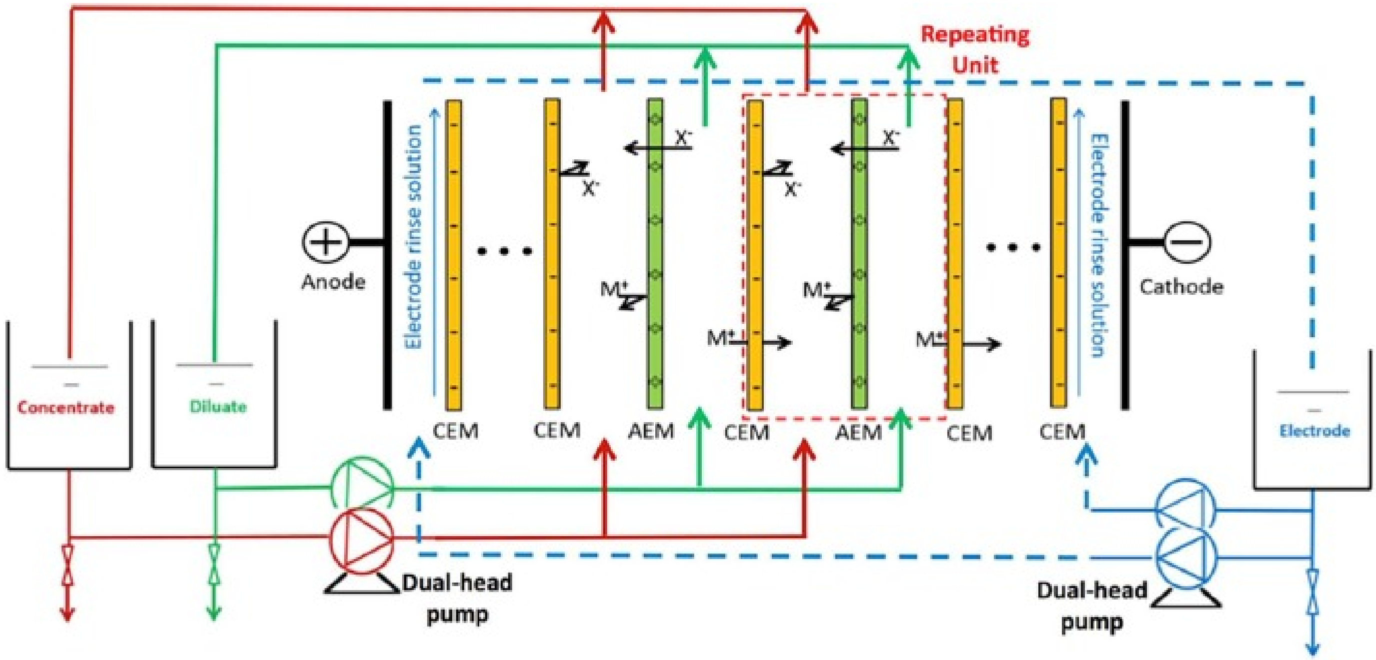


Fig. 37 Schematic of Electrodialysis process [37].

4.3 Water harvesting from atmosphere

Atmospheric Water Harvesting (AWH) is an attractive and innovative answer to water scarcity. Reflecting that in the atmosphere 12,900 km^3, in the past 20 years AWH gained significant interest compared to other water extractions methods. Besides, AWH installations could be competitive with desalination plants of similar water output and have the advantage of being simpler and less expensive to operate and maintain [38]. However, compared to desalination, which requires around 23 kWh to remove salt ions from seawater, AWVP consumes, in theory, 681 kWh to condense water vapor out of air to produce 1 m3 of liquid water [38].

This technology captures the water vapor /moisture from thin air and condense it into liquid water; it is largely practiced in regions with a good humidity rate, in arid or desert areas where water is scars, for agricultural and irrigation purposes.

In AWH technologies 3 indexes are examined to evaluate the performances [39]:

- specific energy consumption per unit mass water production (SEC)
- the specific water production per day per unit collector area (SWP)
- the recovery ration of the feed air (RR)

SEC and RR are described by the following equations:

$$SEC = \frac{Q_{cond}}{m_{H2O}} \approx C_p \left(\frac{\varepsilon_T}{\varepsilon_d}\right)\left(\frac{T_i - T_{cond}}{d_i - d_{cond}}\right) + h_{fg}$$

$$RR = \varepsilon_d \left(1 - \frac{d_{cond}}{d_i}\right)$$

where:

- T_i =temperature of the inlet air of the condenser
- d_i =humidity ratio of the inlet air of the condenser
- T_{cond} = condensation temperature
- m_{H2O} =water production per unit mass dry air (kg/kg)
- ε_T = heat-exchange effectiveness of the condenser
- ε_d = mass exchange effectiveness of the condenser,
- Q_{cond} = total cooling load of the moist air (sum of the sensible heat load)
- hfg= latent heat load, associated with the enthalpy of condensation

A low value of Q_{cond} result in a smaller SEC, which require a higher relative humidity of the inlet air. Low T_{cond} and T_i values and a high d_i are optimal.

Mankind realized that the atmospheric water could be a source of fresh water ages ago, already in 1600s many studies of possible ways to extract moisture was carried out, based on the ability of animals(such as beetles, frogs, lizards, spiders, etc…), or plants(cactus, Pottiaceae, etc…). Another source of water derives from the artificially harvested dew provided by big stones, that take benefit of the temperature variation during day and night: at night the stones are cooled down by the chilled air, while during the day the condensation occurs when the warm air saturated with water vapor touches this chilled surface.
Nevertheless, this natural and simple way limits the amount of water condensed because of its low heat capacity.

During the 20th researches has experienced great improvement and different technological atmospheric water harvesting systems have arisen, principally during the last few decades.

AWH can be divided into three different classes, according to their moisture-capturing systems:

- artificial rain collection
- fog water collection
- dew water collection.

4.3.1 Artificial rain collection

Artificial raining is a weather alteration by provoking or developing precipitation through clouds by adding external agents, typically Dry Ice(solid carbon dioxide), Silver Iodide, Salt powder. It may produce strong precipitation but only in the troposphere, at earth level, this process could not be obtained. Unfortunately, this method has bad effects on the environment since many animals, as mammals, or plants, like algae, are affected by these substances.

4.3.2 Fog water collection

Fog collection is a consolidated technology in arid regions Africa and Southern Asia, as it is technologically easy and can produce a good amount of fresh water. To collect fog water, a structure with a wire mesh should be placed with a normal direction to respect the wind direction. In this way, water droplets carried by the wind are forced to cross the mesh and become trapped. While the process advances, the droplets grow and when the dimensions are large enough they fall by gravity and stored into a tank.

Usually, this method is applied in windy areas where fog is frequent, is distinguished by high liquid water content and lasts relatively long to reach greater performance. The efficiency is defined as the ratio between water reaching the collector's mesh and the liquid water produced.
This method suffers from low efficiency caused by the wire mesh size: if it is too coarse it decreases the number of trapped droplets, while if too fine it can't catch microscopic fog droplets.

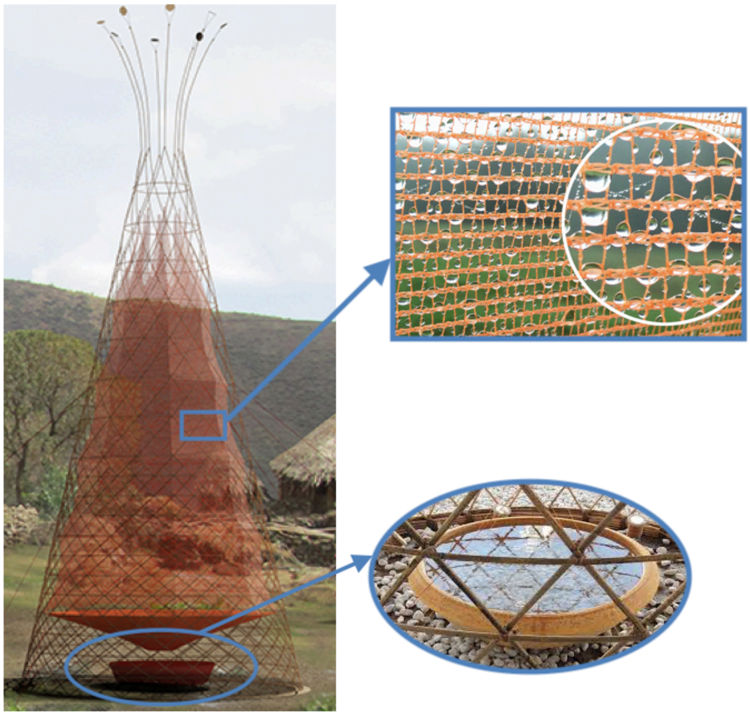


Fig. 38 Warka Water project based on fog water collection process (Adapted from [40]).

4.3.3 Dew water collection

Respect fog collection, dew water collection method isn't influenced by climatic and geographical restrictions and is cheaper in less cloudy zones, but depend on the rate of radiative heat exchange, the weather conditions, that determine the ratio of latent to sensible heat exchange between the surface and the air, and the surface characteristics.

Two kinds of approaches can be adopted for dew water collection: passive radiative condensers, which do not need any source of energy for the condensation process, and active condensers that require additional energy for the extraction of water from the air. The energy consumption of active condensers depends on heat pumps energy demand as well as the system configuration, at present, AWH processes use conventional air-conditioning with efficiencies of around 650–850 Whe/kg with peaks of 250 Whe/kg [41].

Another method for AWH is a sorption-regeneration process in which desiccants are employed to capture the moisture from the air. The desiccants can be used in liquid or solid phase.
Generally employed liquid desiccants are lithium chloride (LiCl), lithium bromide (LiBr) and calcium chloride (CaCl2). Calcium chloride has a lower absorption ability related to the others but

is more affordable. Lithium chloride has low vapor pressure but is more stable, lithium bromide has better regeneration performance.

Surface vapour pressure is one of the most significant parameters in liquid desiccant since it drives to heat and mass transfer in the dehumidifier. Liquid desiccants' disadvantages are to be expensive and a lower drying capacity respect sold desiccants, that are generally cheap, non-flammable, non-corrosive and environmentally friendly [42].

The most common solid desiccants are silica gel, zeolites and metal-organic framework (MOF), a porous crystalline material with a rigid networked structure, composed of both organic and inorganic components. Silica gel has low adsorption capacity and requires a high regeneration temperature, zeolites have low water capacities and a greater regeneration costs, while MOFs have a great performance because it is distinguished by extremely high surface areas, more than 7000 m2/g.

The benefit of working with a solid desiccant is that is easy to clean compared to liquid desiccant, cost less, except for MOF that is still quite expensive, but needs approximately higher regeneration temperature.

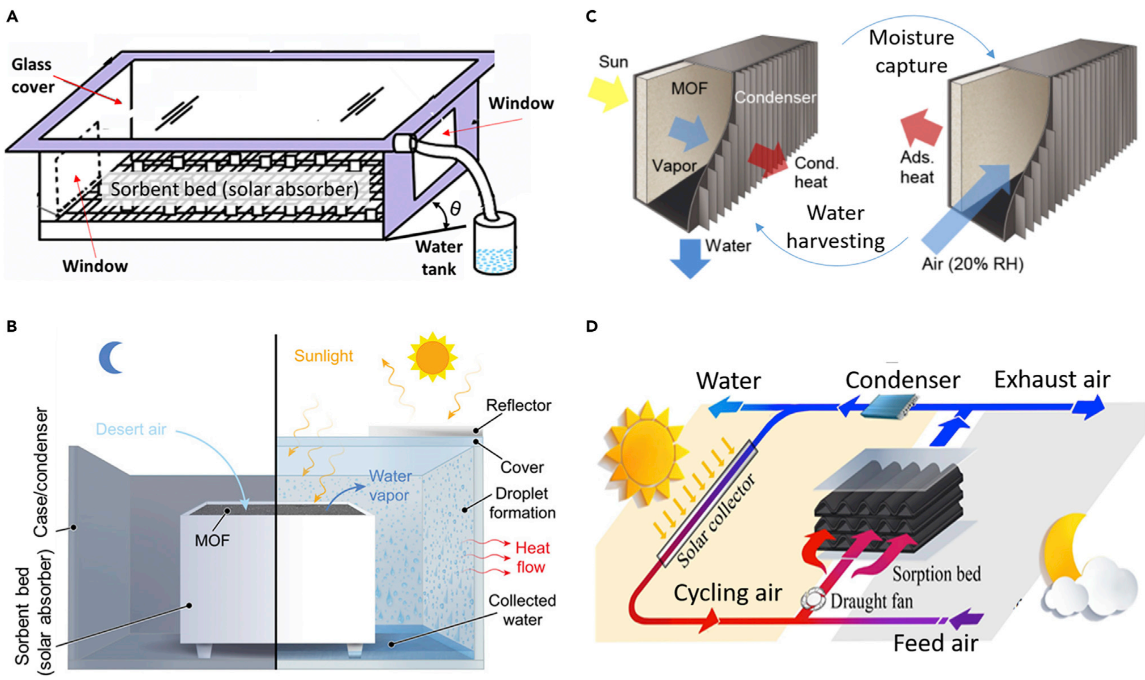


Fig. 39 Dew water collection: a)passive radiators condensation and b),c),d) sorption-based AWH

Water can be produced also in HVAC (heating, ventilation, and air-conditioning) systems. These systems condense a high quantity of water, which is a sub-product that is not used. Therefore, an integration of an air-conditioning system and a water-harvesting system could be a beneficial alternative not only to use the cooled air for refrigeration but also to produce water resources.

5 AWH prototype

The prototype introduced in this work, based on sorption-regeneration method, was developed in the laboratory of the Energy Department at Politecnico di Torino. It operates with solid desiccant (silica gel) to extract water vapor from the atmospheric air.
The main components of the experimental prototype under examination are:

- a hot water tank
- an adsorption system
- a cross-flow heat exchanger
- a condenser.

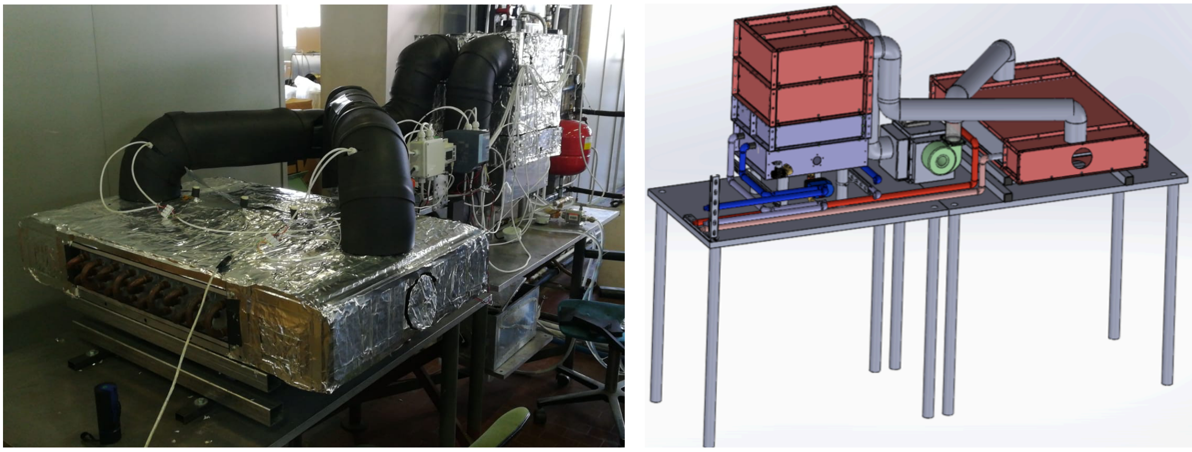


Fig. 40 Prototype assembled and prototype model

The adsorption system is filled with approximately 20.5 kg of silica gel, contained in a finned heat exchanger. The system heat supply comes from water, which thanks to electric resistance, reaches a temperature of 50-80 °C. The condenser is made of an air to air heat recovery system, allows exchanging sensitive heat with the output air, taking advantage of a portion that otherwise would be lost, increasing thus the efficiency of the process, and an air to water radiator used to condense the hot and humid flux with a cold water flow rate of nearly 600 m^3/h at 20°C, taken from the network.
The adsorption/desorption packed bed and the condenser, are joined by a flexible pipe, with a cross-flow arrangement: the outlet and inlet of the adsorption heat exchanger, respectively with the condenser's inlet and outlet.

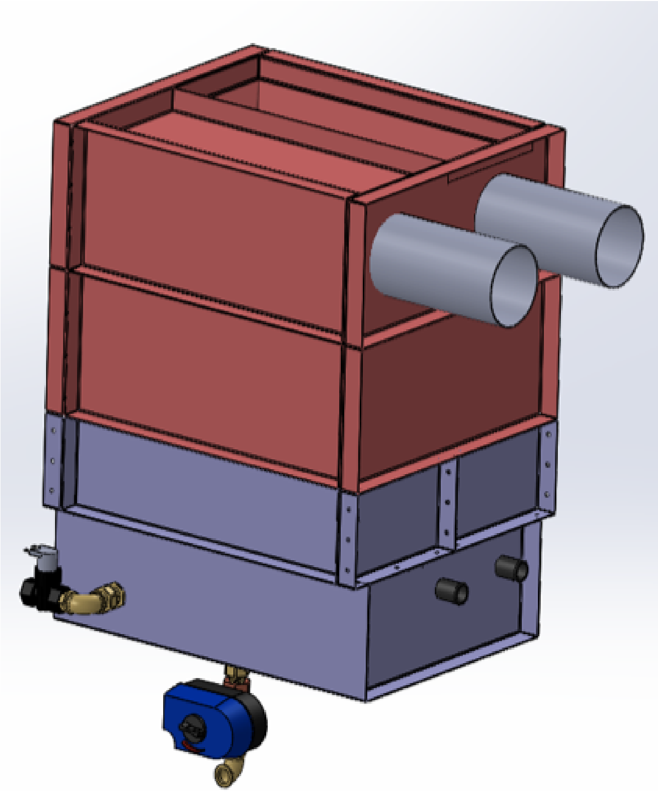


Fig. 41 Condenser prototype model

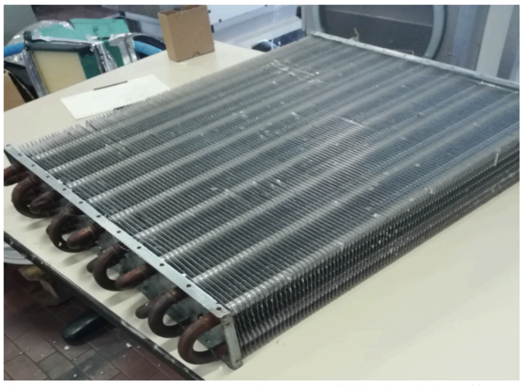


Fig. 42 Finned heat exchanger filled with silica gel

Fig. 43 Basin for water collection during condensation

5.1 Prototype operation description

The prototype showed works alternating two different phases:

- Adsorption: during this process, with the help of a fan, the air flows in the heat exchanger filled with silica gel absorbing water vapor contained.
- Desorption: during this process water vapor captured in silica gel is heated up, using a low-temperature energy source, and condense.

A schematic of the thermodynamic cycle is given in figure below:

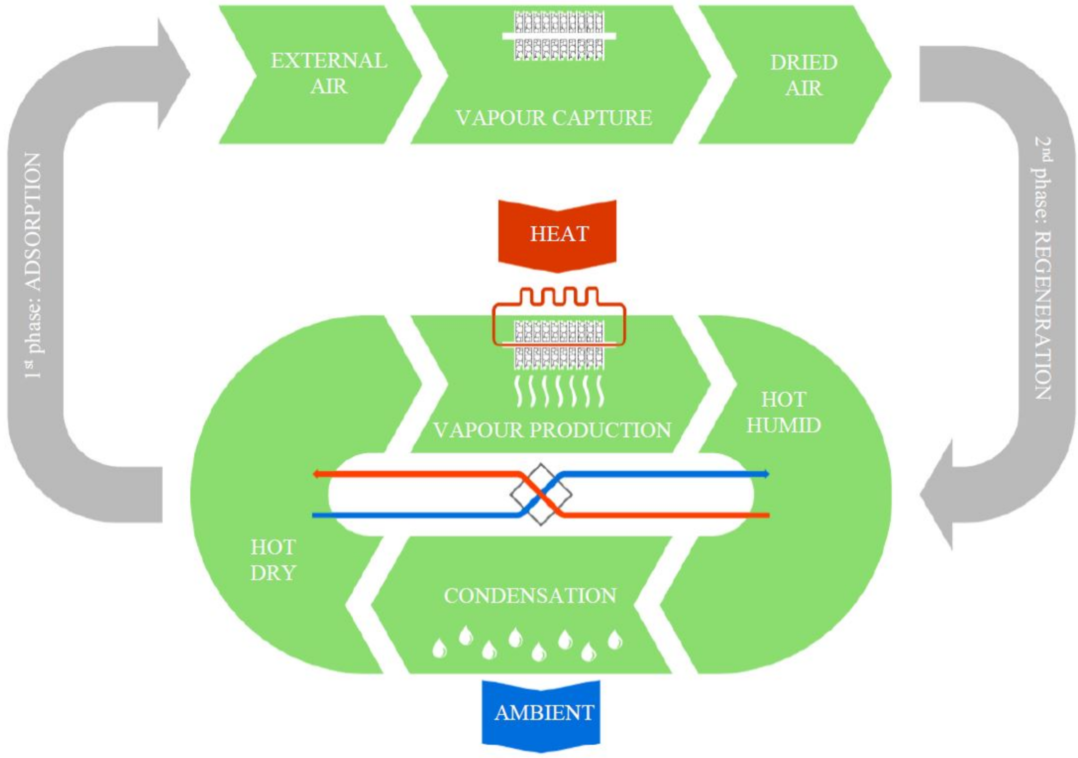


Fig. 44 Schematic of Sorption - Desorption cycle

5.1.1 Adsorption phase

The adsorption process operates as an open system since air is exchanged with the external environment. Airflow is taken from the atmosphere and forced to pass through the heat exchanger, where the solid desiccant adsorbs the water vapour embedded into the humid air. In the initial phase of absorption, the air temperature tends to rise a bit because of the isenthalpic dehumidification that releases latent heat which increases the temperature. The adsorption rate depends on the temperature and moisture content, which obviously varies according to climatic conditions and geographical location. The outlet flow released from the heat exchanger is dry air with a lower temperature, close to the recirculating water temperature around 20°C.

5.1.2 Desorption phase (Regeneration)

After the heat exchanger, the air enters into a dry cooler at ambient temperature, exit as hot and dry air condensing the water which is lastly collected in a condenser. At the end of the regeneration process, this hot and dry air circulates again into the heat exchanger and recommence the cycle. The heat sources enabling the condensation is provided by hot water flowing into the pipes, coming directly from the hot water tank. It has a temperature range from 50 to 80°C, obtained by means of electric resistance of 1.25 kW_{el}.

The heat source for the condensation process can be produced also with solar collectors, principally in arid-desert regions where solar radiation is extremely available. Another heat sources at low temperature attractive alternative are waste heat or thermal cascade from other technologies.

5.1.3 Thermodynamic cycle

The adsorption and desorption processes of the thermodynamic cycle described earlier moves along isenthalpic transformations in which temperature and moisture content variation are inversely proportional: during adsorption, moisture content decreases because more and more water is adsorbed by the solid desiccant as the process proceeds, and air temperature increases as a consequence of the latent heat released.

The opposite behavior takes place during regeneration processes, where the latent heat is absorbed to condense water increasing water vapor rate and decreasing temperature.

Considering that for a significant production of water the air temperature and moisture require to be lower than dew point of the stream, if we consider a condensation at an ambient temperature of 35°C corresponding to a saturation point of 36.5 g/kg (point 3, Fig.45), following an isenthalpic transformation (iso-H) (blue dotted line) to reach the saturation, a starting air temperature of 50 C is requested (point 1, Fig.45). Notwithstanding, following this line, a really modest amount of water is obtained (4-5 g/kg), since moisture content difference at the saturation is very low (≈ 7 g/kg).

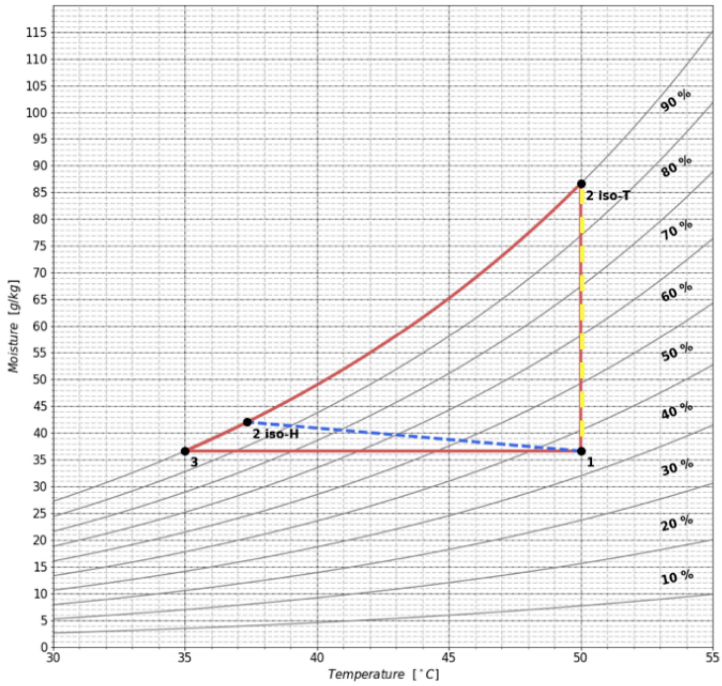


Fig. 45 Schematic of thermodynamic cycle

In order to increase the water production, an isothermal transformation can be followed (iso-T) (yellow dotted line), thanks to which the moisture content variation on the saturation line is much higher(≈ 50 g/kg). However, this increment has a comparable energy cost related to the energy required for water molecules transport from silica gel to the air.

5.2 Simulations and results

To analyze the performance of the prototype realized in the laboratory of the Politecnico di Torino, tests under different environmental conditions have been made through a Matlab code simulating the adsorption unit. Each test, according to the thermodynamic cycle, is formed by two consecutive stages, the regeneration and adsorption processes, handled distinctly.

For both processes, tests have been carried out varying the fan regulation getting a regression that permits determining the airflow rate. Second-order polynomials extracted are:

$$\text{for ADSORPTION} \qquad y = -\,0.0029 * X^2 + 0.9621 * X - 5\,.8062 \qquad (1)$$

$$\text{for REGENERATION} \quad y = -0.0042 * X^2 + 1.0017 * X - 7.9956 \qquad (2)$$

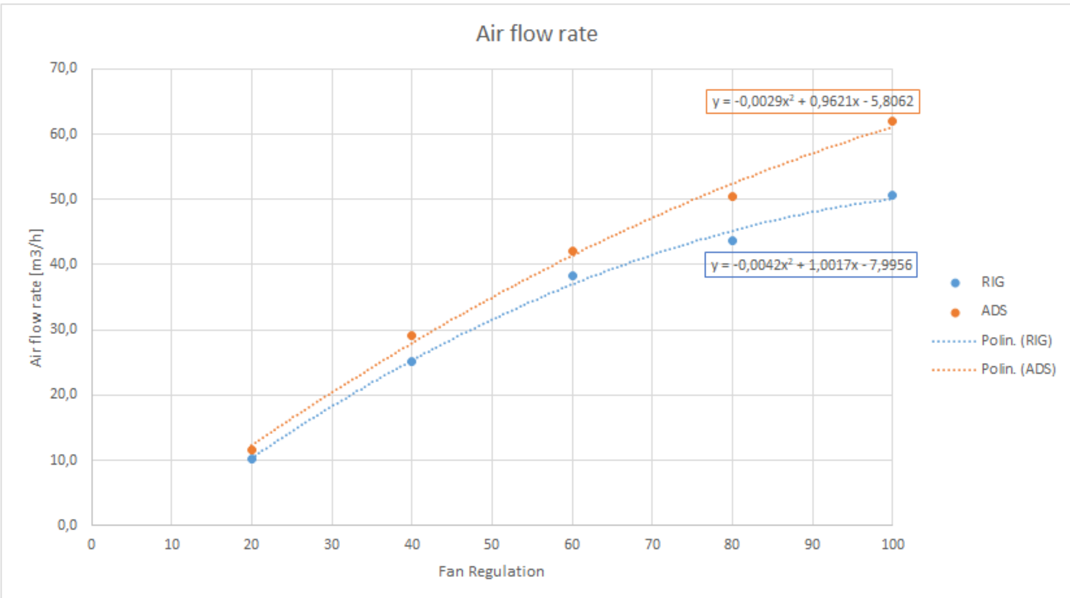


Fig. 46 Air mass flow rate

The parameters calculated in the Matlab code are:

- the air conditions, calculated using the following equations:

$$p_{vs} = 0.0004677 * T^4 + 0.02444 * T^3 + 1.359 * T^2 + 45.98 * T + 604.6 \quad [Pa] \quad (3)$$

$$\chi_a = 0.622 \frac{RH * p_{vs}(T)}{P_a - RH * p_{vs}(T)} \quad \left[\frac{kg_w}{kg_a}\right] \quad (4)$$

$$\rho = \frac{P}{R * T} = \frac{101325}{287.05 * (T + 273.15)} = \frac{352.98}{T + 273.15} \quad \left[\frac{kg}{m^3}\right] \quad (5)$$

$$\mu = 10^{-7} * (2.43 * T + 157.5) \quad \left[\frac{Pa}{s}\right] \quad (6)$$

$$cp_a = 1884 * X_a + 1004 * (1 - \chi_a) \quad \left[\frac{J}{kg\ K}\right] \quad (7)$$

- the mass balance, calculated in three ways, using the formulas:

1. $mr_{i+1} = ml_1 - ml_{i+1}$ (8)

   Where:

   mr_i : mass released at time i+1

   ml_1: mass measured by the load cell at the start of the test

   ml_{i+1}: mass measured by the load cell at time i+1

2. $dm = \left(\left(\rho_{out}(i+1) * \chi_{out}(i+1) - \rho_{in}(i+1) * \chi_{in}(i+1)\right)\right) * Q * dt$ (9)

   $mr_{i+1} = mr_i + dm$ (10)

   Where:

   Q: mass flow rate calculated with (2)

3. $dm = \left(\chi_{out}(i+1) - * \chi_{in}(i+1)\right) * \rho_{ave} * Q * dt$ (11)

   Where:

   ρ_{ave}: average density calculated in function of average temperature between the inlet and outlet flow

- Energy consumption of the test at each time step

$$e_{th} = \frac{E_{th}}{V_w} \qquad \left[\frac{kWh}{m^3}\right] \qquad (12)$$

$$E_{th} = \sum_{i=1}^{N} P_{th,i} \Delta t_i \qquad [kWh] \qquad (13)$$

$$P_{th,i} = G_w c p_w \left(T_{w,in} - T_{w,out}\right) \qquad [kW] \qquad (14)$$

Where:

e: Specific thermal consumption per unit of water produced

E_{th}: Energy consumption during desorption

P_{th}: thermal power consumed for water condensation

The graphs of the tests carried out are reported as follows:

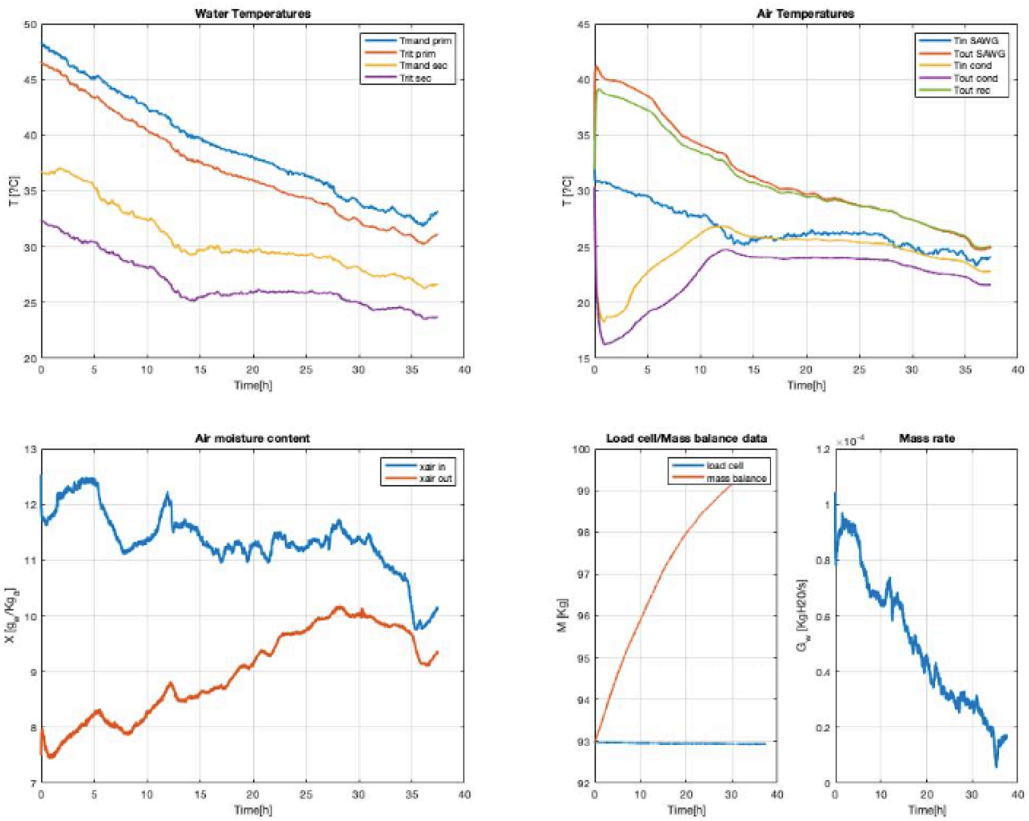


Fig. 47 Test 8-ADS

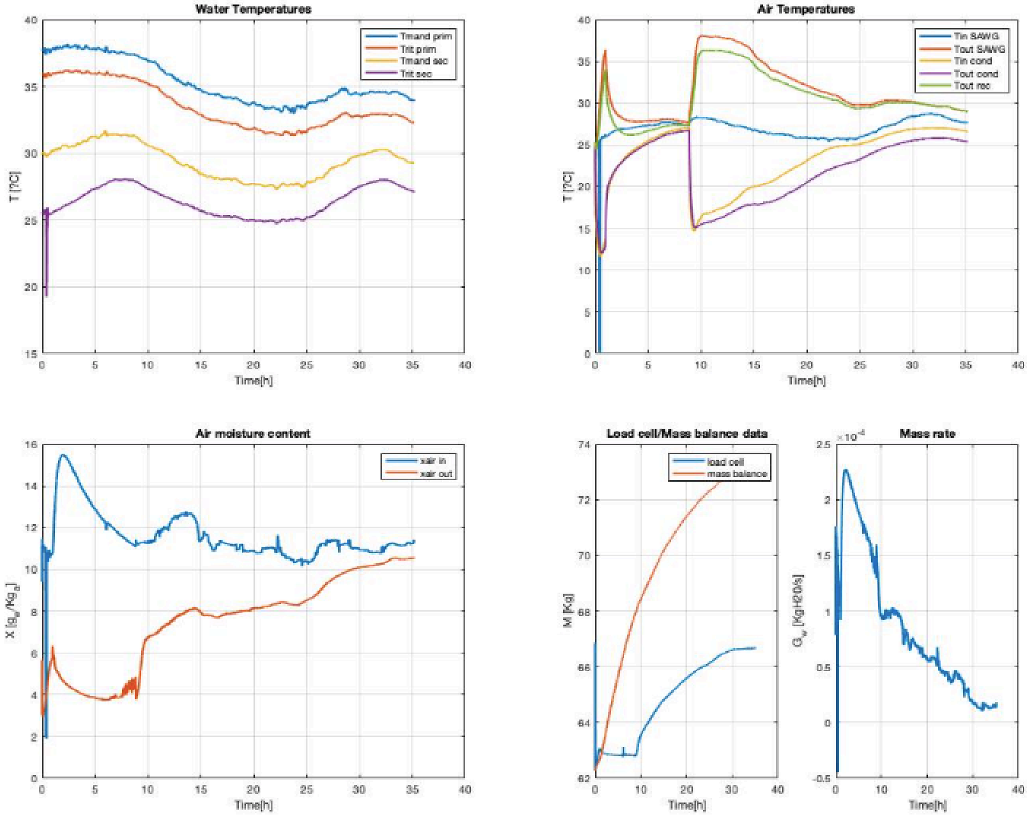


Fig. 48 Test 16-ADS

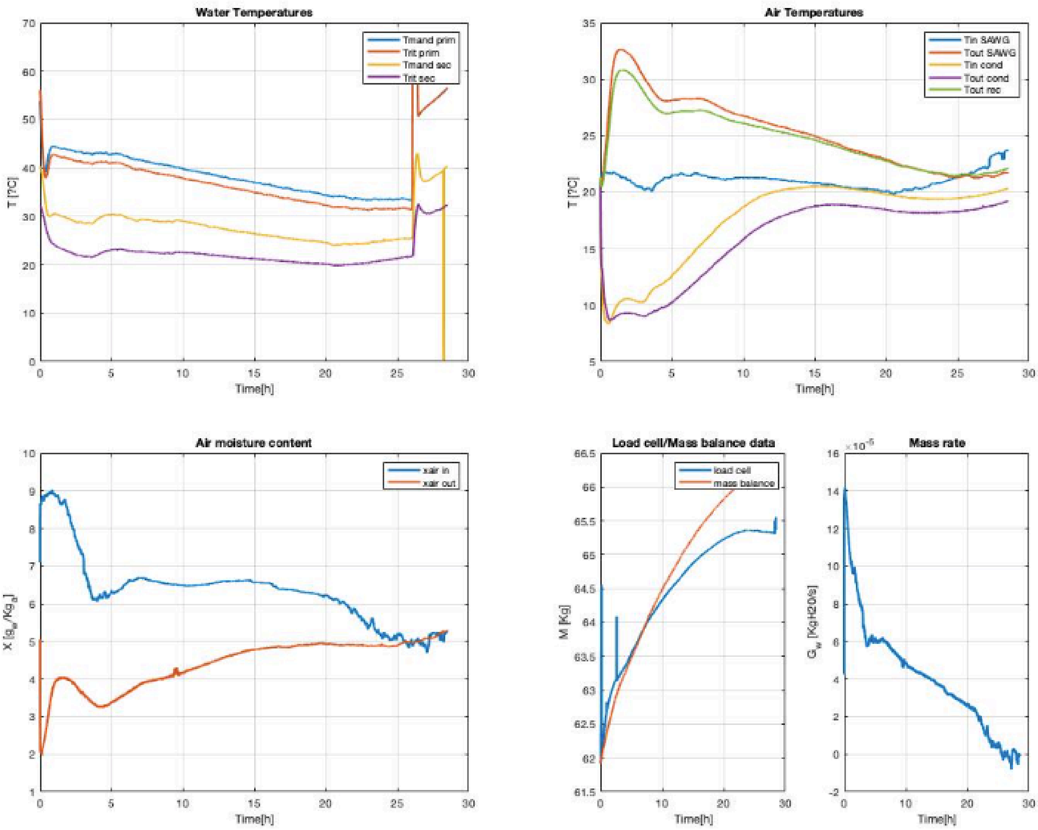


Fig. 49 Test 20-ADS

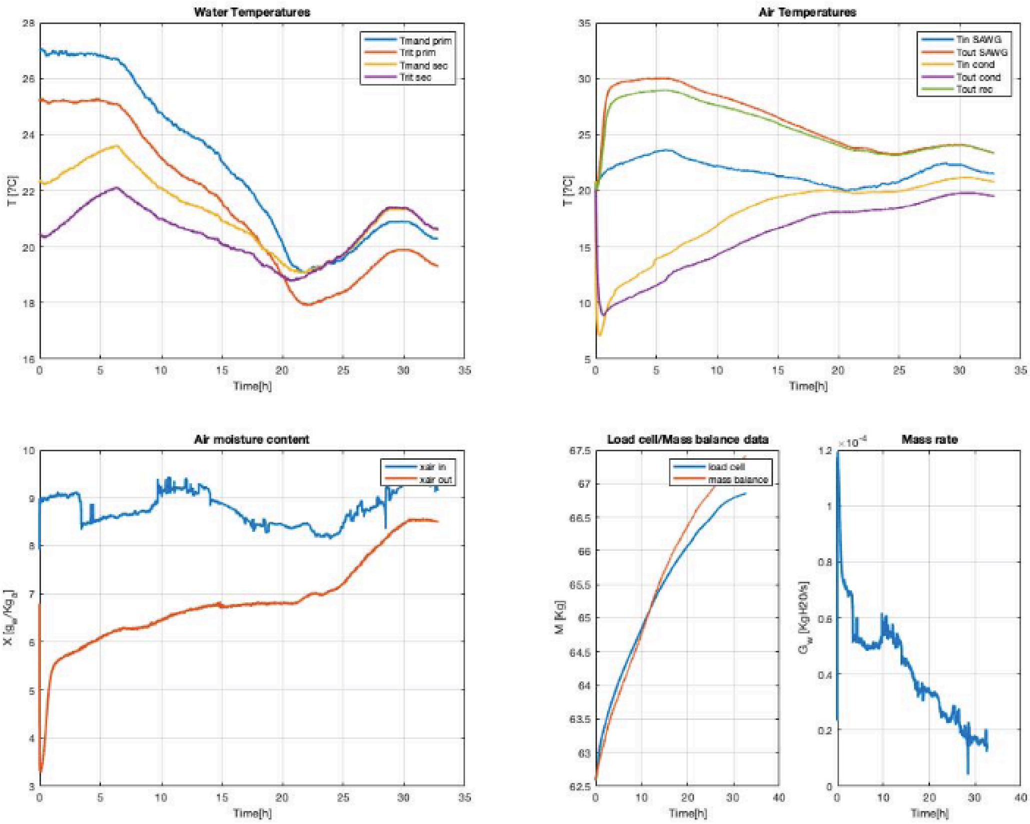


Fig. 50 Test 28-ADS

During adsorption tests energy is required only for the fan operations, calculated with equation (13). This phase last more respect to regeneration phase, because there is no thermal force to promote adsorption, in contrast to desorption which is assisted at lower operating temperatures. Besides, the heat generation is not a continuous process, since it depends on the humidity: in the initial phase water vapor is absorbed faster increasing air temperature but, as it can be seen from the trends reported in the graphs, in a second phase, as the silica gel saturation progressively increase, the air temperature drops again to the ambient conditions.

Lastly, it should be remembered that the adsorption process depends essentially on the ambient conditions of temperature(T) and relative humidity (RH). In effect the first tests (i.e. Test 8) were carried out at the end of summer with warmer and drier air, succeeding in extracting more water, while the last ones (i.e. Test 28) were performed in winter with cooler air but also more humid.

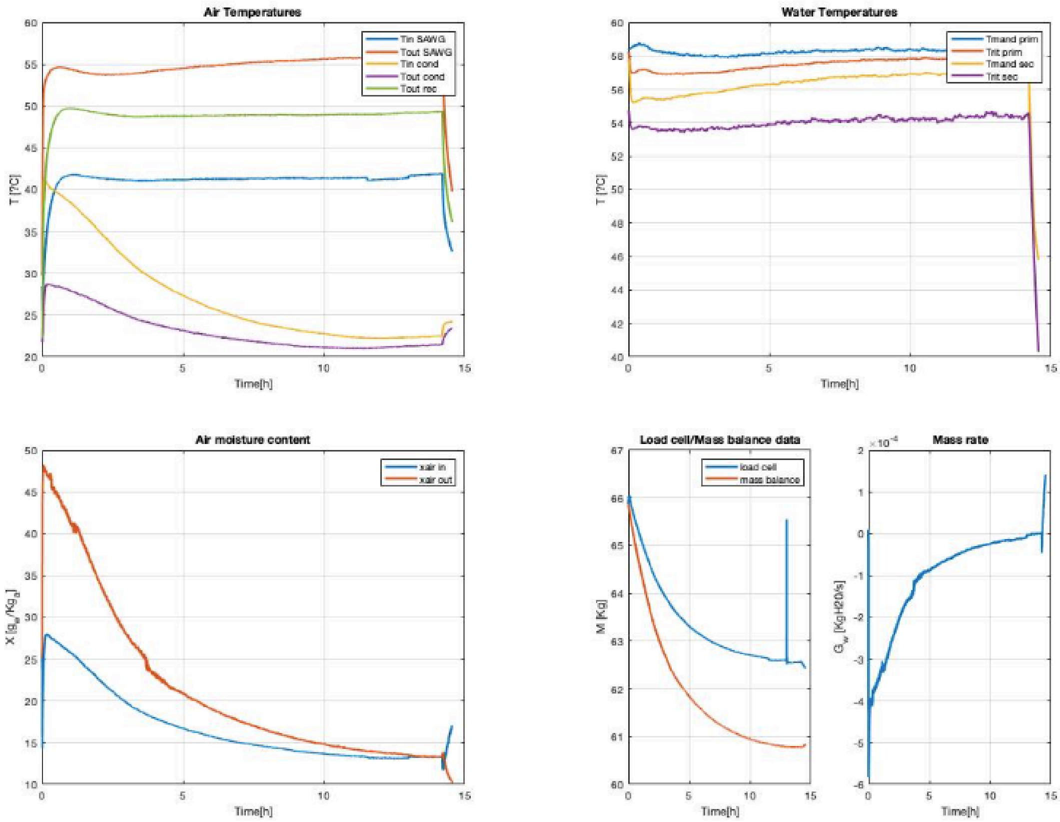


Fig. 51 Test 17-REG_fan90

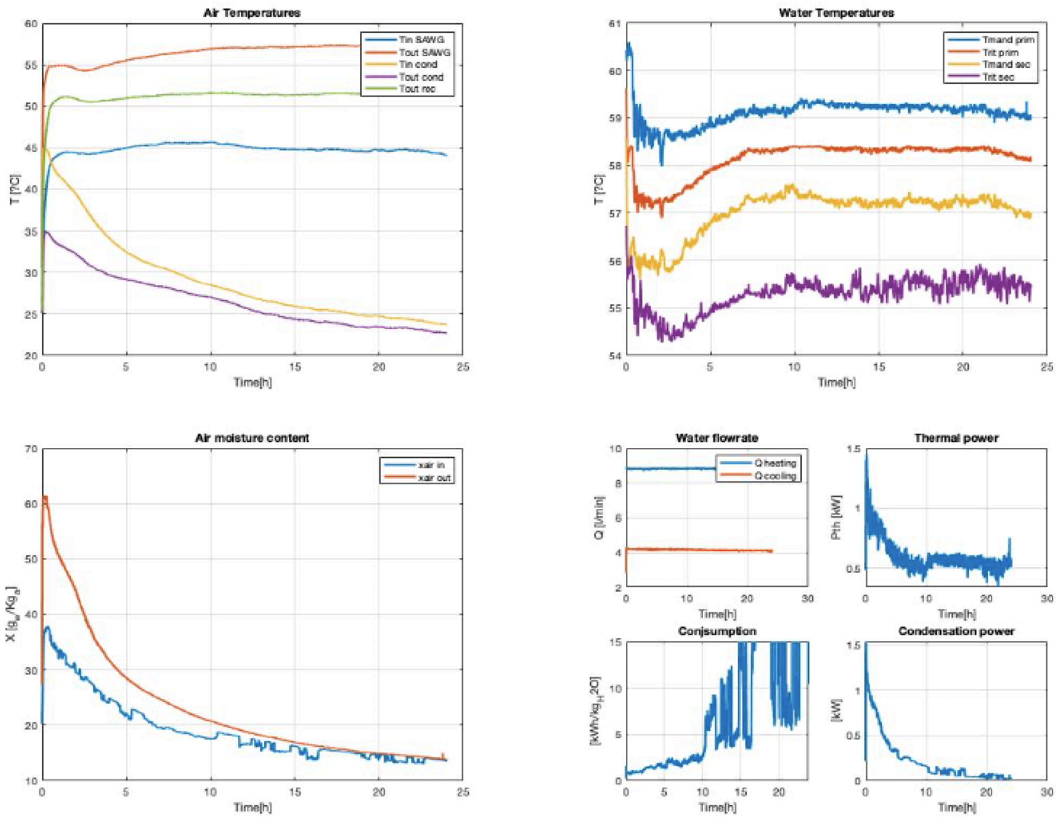


Fig. 52 Test 21-REG_fan70

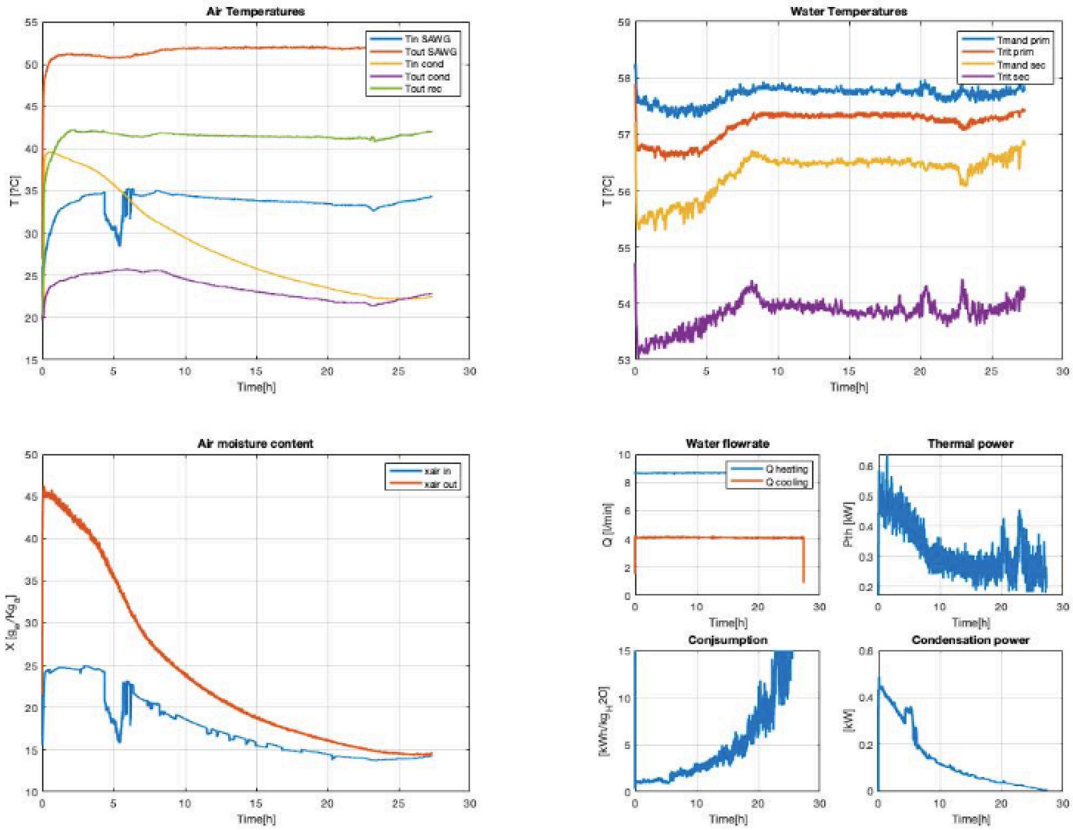


Fig. 53 Test 23-REG_fan30

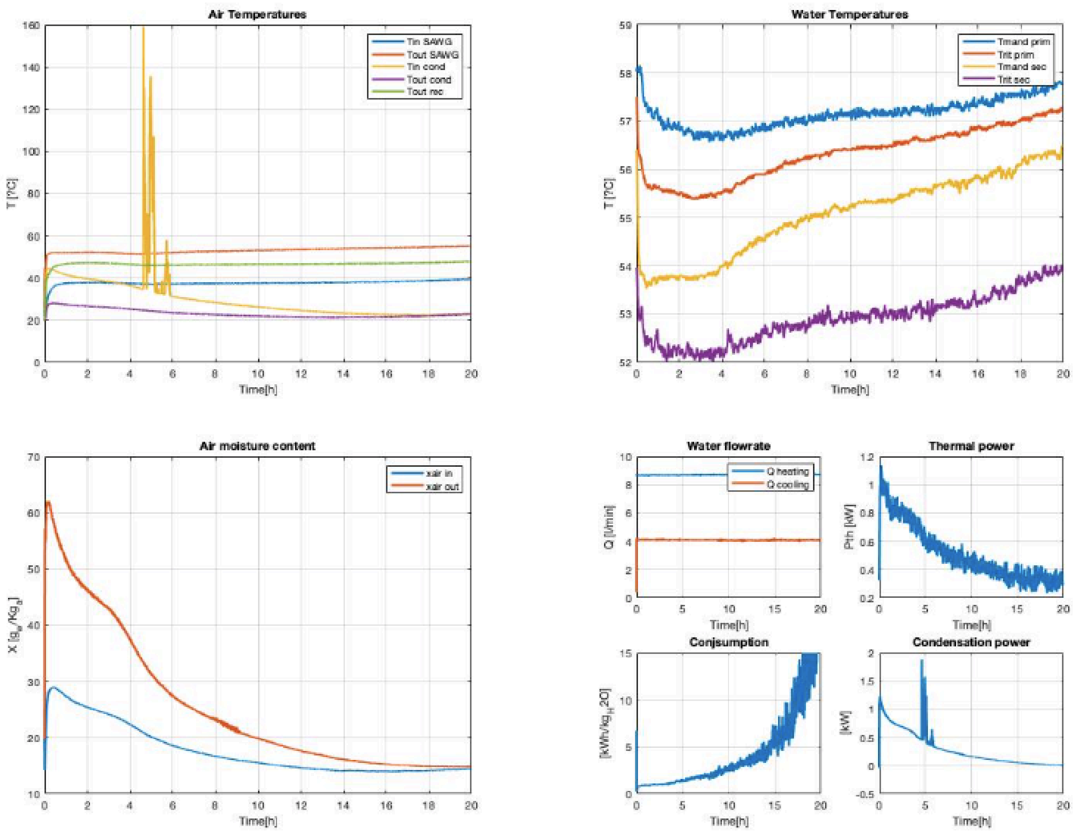


Fig. 54 Test 25-REG_fan50

During regeneration, the energy demand is due to the fan operation but also the pump and condensation circuits electricity consumption. In addition, in this process a further energy input is needed since the desorption is endothermic. This heat sources, necessary for the condensation, is provided by hot water flowing into the pipes, coming from the hot water tank and has been evaluated using equations (12)(13)(14). In the tests performed, the regeneration completes when an equilibrium between humidity and temperature of the absorbent bed is verified. This leads to having a small residual amount of moisture that would require higher temperatures to be extracted. Regenerative tests are faster than absorption tests because they take place in the presence of constant temperature drive and reach an equilibrium condition before adsorption tests. The desorption process strongly depends on the dehumidification temperature and condensation conditions. In the first tests, being the temperature of the air higher and the moisture content lower, the condensation is more demanding as it is more difficult to go under the dew point; while in the last tests the lower ambient temperature favors the condensation phase. The tests were carried out by also varying the temperature to the condenser, set at 30°C and 35°C, to study the effects on the performance. Furthermore, this process is influenced by the fan flow rate. For this reason, the tests were carried out by regulating the fan from 30% to 70%. From the results, it is evident that the process is faster with fan regulation rates close to the nominal one.

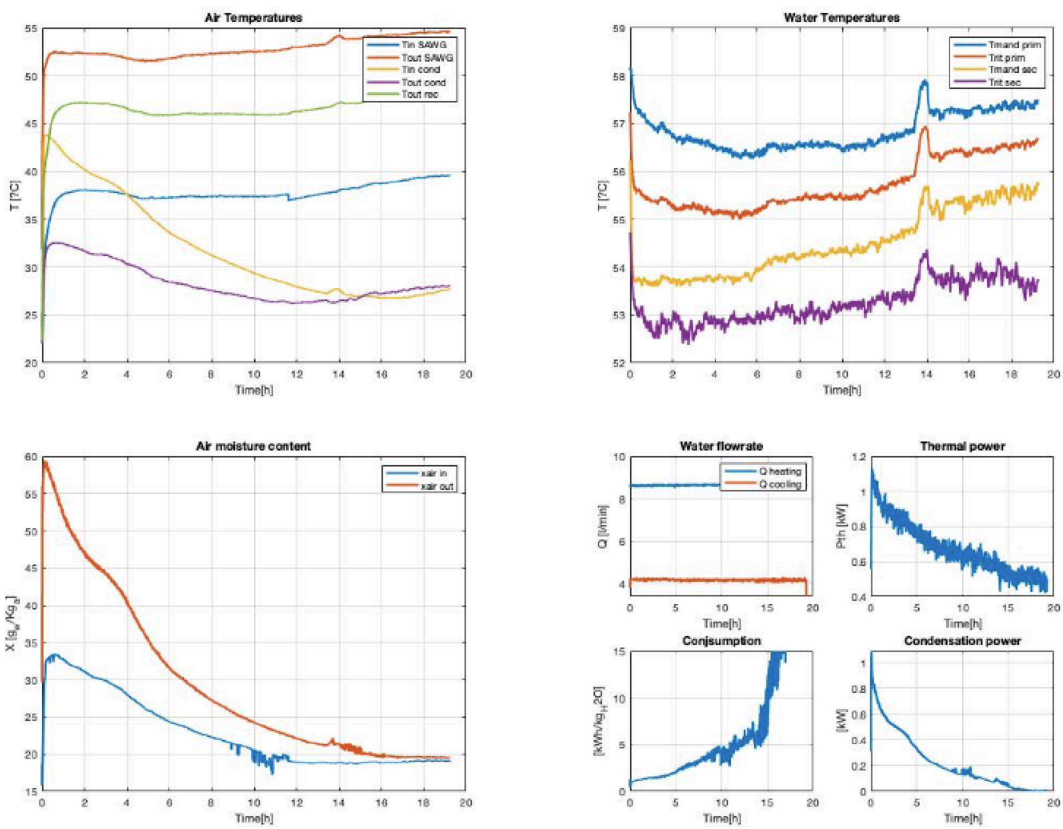


Fig. 55 Test 29-REG_fan50_Tc 30°C

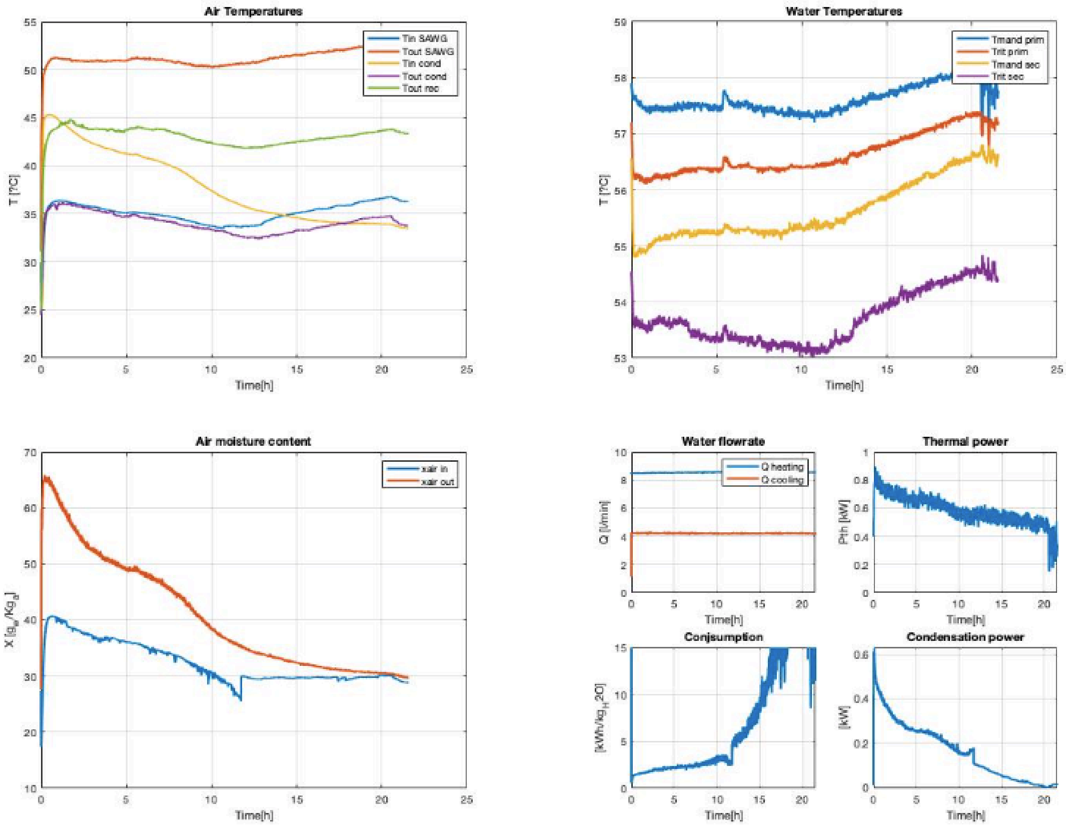


Fig. 56 Test 35-REG_fan90_Tc 30°C

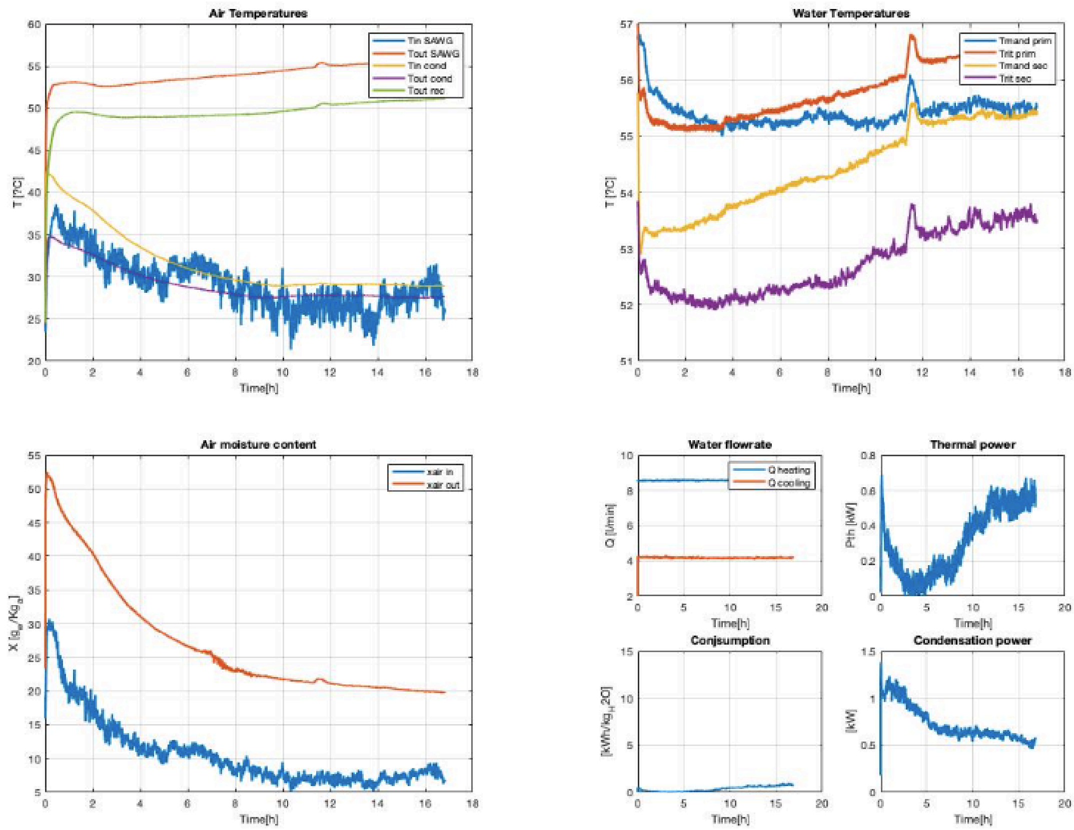


Fig. 57 Test 37-REG_fan30_Tc 35°C

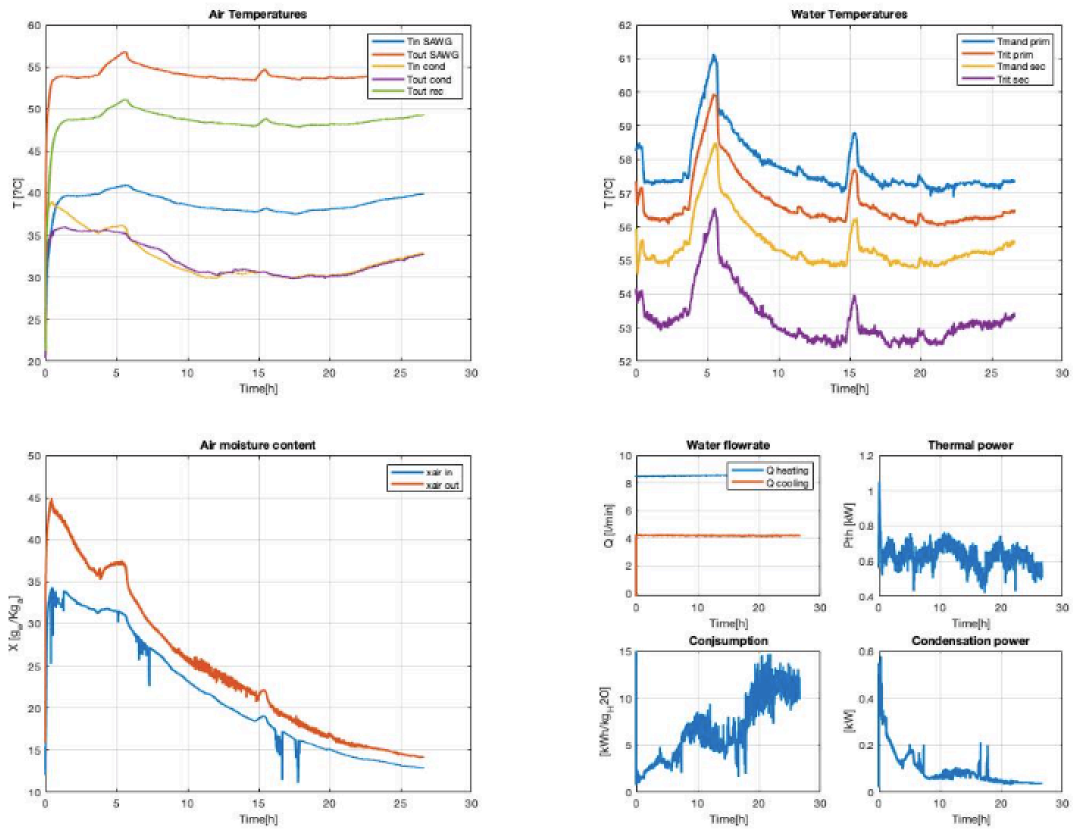


Fig. 58 Test 41-REG_fan50_Tc 35°C

5.3 Case study

The desorption phase, as previously told, requires a heat sources for the condensation process, that in case of the prototype was provided directly from the hot water tank, where water temperature is raised to 50-80°C. In case of CPS plants this source can be obtained from the Rankine cycle condensation process.

The Rankine cycle four processes are:

- *isentropic compression*: working fluid is pumped from low to high pressure
- *isobaric expansion*: high-pressure liquid enters a boiler, where it is heated at constant pressure to become a dry saturated vapour
- *isentropic expansion:* dry saturated vapour expands in a turbine
- *isothermal and isobaric:* compression: wet vapour is condensed at constant pressure in a condenser and turn into a saturate liquid.

The heat extracted from the condensation, evaluated as enthalpy difference between condenser inlet and outlet, and the mass flow rare [kg/s] allow to evaluate the power as follow:

$$P_{th} = G * (h_{in} - h_{out}) \qquad [\text{kW}]$$

In this work tree different Rankine cycle has been considered to analyze the performance of the machine coupled with a CSP plant.

○ Rankine- Goswami cycle

CSP Rankine cycle works with steam at low pressures that decrease the efficiency of the thermodynamic cycle, increasing the solar power plant costs. A possible way to improve the overall efficiency of a Rankine Cycle based power plant is to replace the traditional condenser stage of the Rankine cycle by a multicomponent mixture bottoming combined cycle [43]. This last one permits the reduction of the energy losses in the condenser and eliminates the problems related to vapor quality.

In this work, a combined Rankine–Goswami cycle (RGC) of a parabolic trough solar thermal plant is examined.

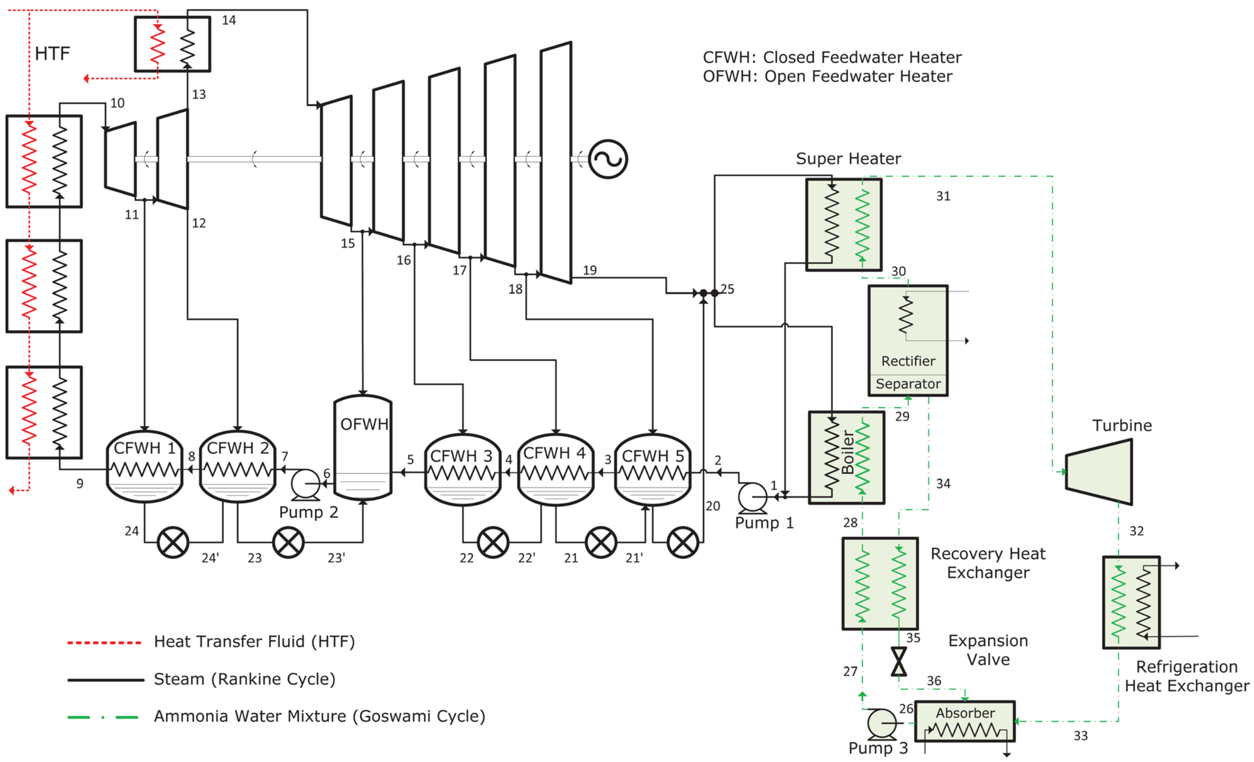


Fig. 59 Schematic of Rankine–Goswami combined cycle

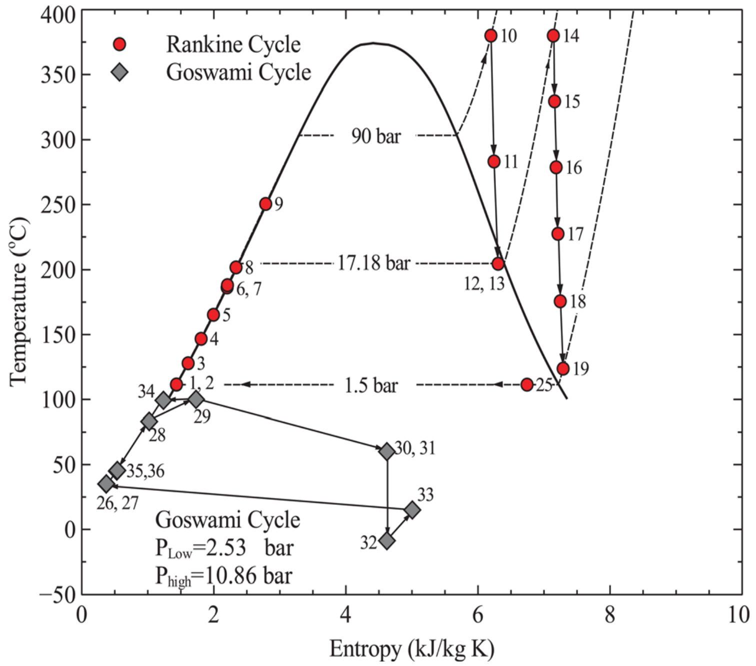


Fig. 60 Operating conditions for the Goswami-Rankine cycle

The Rankine-Goswami cycle condenser pressure is 1.5 bar, while the condensation temperature is 111.35 °C. For this paper, however, the condenser temperature is decreased in an adequate range since the prototype works using a low temperature energy source. Once the values of Q_{out} have been obtained calculating the enthalpy (with CoolPack software) of condensation, respectively the points 25 and 1, the amount of water that can be extracted has been evaluated varying the yield in a range from 0.6 k/kWh to 5 l/kWh.

p_con(bar)	1,5							
T_con(°C)	111,37	110	105	100	95	90	85	80
h1 (KJ/Kg)	467,49	461,72	440,7	419,71	398,74	377,78	356,82	335,86
h25 (KJ/Kg)	2693,22	2690,36	2679,92	2669,42	2658,86	2648,23	2637,54	2626,77
G (Kg/s)	62,41	62,41	62,41	62,41	62,41	62,41	62,41	62,41
P_con (KW)	138907,809	139089,422	139749,72	140404,401	141054,089	141698,785	142339,735	142975,6931
eff (l/KWh)	yield [m3/h]							
0,6	83,3446856	83,4536534	83,8498321	84,2426407	84,6324535	85,0192707	85,4038411	85,78541586
0,7	97,2354665	97,3625957	97,8248041	98,2830808	98,7378624	99,1891492	99,6378146	100,0829852
0,8	111,126247	111,271538	111,799776	112,323521	112,843271	113,359028	113,871788	114,3805545
0,9	125,017028	125,18048	125,774748	126,363961	126,94868	127,528906	128,105762	128,6781238
1	138,907809	139,089422	139,74972	140,404401	141,054089	141,698785	142,339735	142,9756931
1,5	208,361714	208,634134	209,62458	210,606602	211,581134	212,548177	213,509603	214,4635397
2	277,815619	278,178845	279,49944	280,808802	282,108178	283,397569	284,67947	285,9513862
2,5	347,269523	347,723556	349,374301	351,011003	352,635223	354,246961	355,849338	357,4392328
3	416,723428	417,268267	419,249161	421,213203	423,162268	425,096354	427,019206	428,9270793
3,5	486,177333	486,812978	489,124021	491,415404	493,689312	495,945746	498,189073	500,4149259
4	555,631237	556,35769	558,998881	561,617604	564,216357	566,795138	569,358941	571,9027724
4,5	625,085142	625,902401	628,873741	631,819805	634,743401	637,64453	640,528808	643,390619
5	694,539047	695,447112	698,748601	702,022006	705,270446	708,493923	711,698676	714,8784655

Table 2 Input data Goswami-Rankine cycle analysis

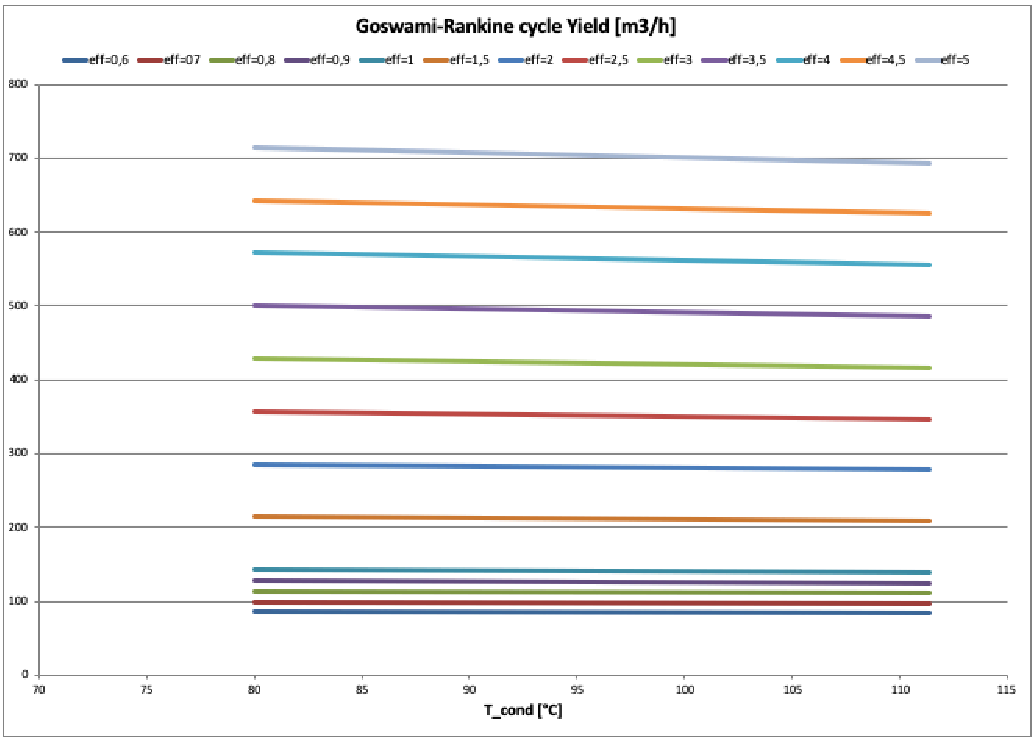


Fig. 61 Yield [m3/h] for Goswami-Rankine cycle

With a condensation temperature of 80 °C and an efficiency of 0.6 l/kWh, corresponding to a specific consumption of 1.7kWh/l, the machine could extract around 100 m^3/h of water, while for an efficiencies of 2 l/kWh the amount of water produced rise up to 300 m^3/h.

- ## Rice (Mojave) power plant Rankine cycle

The second cycle examined is the Rankine cycle of the Rice CSP facility.

Fig. 62 Race (Mojave) solar power plant

This Solar Tower power plant is located in Rice, California, in the Mojave Desert where the solar radiation reaches 2,598 kWh/m2/year. The steam Rankine power cycle used in this plant has a maximum pressure of 115 bar, at the condenser the pressure is 0.1034 bar and the condenser temperature for heat rejection is 45°C.

The schematic of the investigated solar power plant Rankine cycle is reported in the figure below:

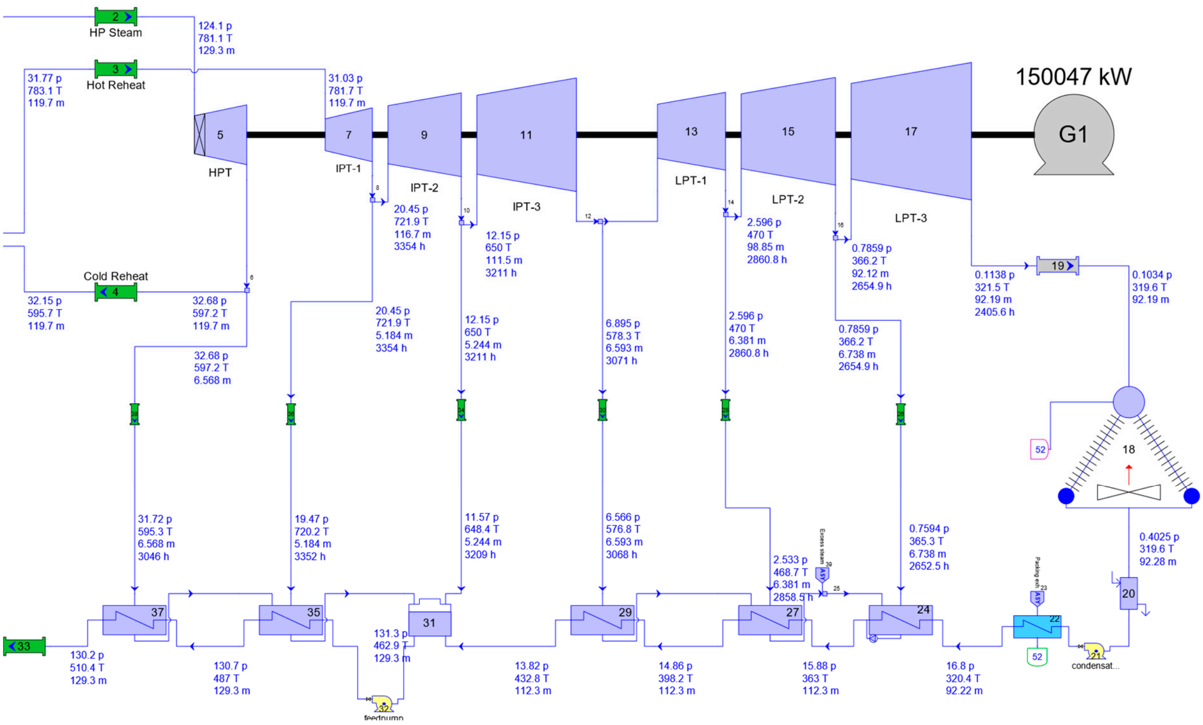


Fig. 63 Operating conditions for the Rice ST facility

Again the temperature condensation has been regulated from 45 to 80 to analyze the influence of temperature in the water yield.

p_con(bar)	0,1034							
T_con(°C)	45	50	55	60	65	70	75	80
h1 (KJ/Kg)	188,58	209,69	230,78	251,84	272,88	293,89	314,88	335,86
h25 (KJ/Kg)	2582,7	2592,17	2601,64	2611,12	2620,6	2630,08	2639,57	2649,07
G (Kg/s)	92,19	92,19	92,19	92,19	92,19	92,19	92,19	92,19
P_con (KW)	220713,923	219640,831	218569,583	217502,023	216436,307	215373,356	214313,171	213254,83
eff (l/KWh)	yield [m3/h]							
0,6	132,428354	131,784499	131,14175	130,501214	129,861784	129,224014	128,587903	127,952898
0,7	154,499746	153,748582	152,998708	152,251416	151,505415	150,761349	150,01922	149,278381
0,8	176,571138	175,712665	174,855667	174,001619	173,149045	172,298685	171,450537	170,603864
0,9	198,642531	197,676748	196,712625	195,751821	194,792676	193,83602	192,881854	191,929347
1	220,713923	219,640831	218,569583	217,502023	216,436307	215,373356	214,313171	213,25483
1,5	331,070884	329,461247	327,854375	326,253035	324,65446	323,060034	321,469757	319,882245
2	441,427846	439,281662	437,139167	435,004046	432,872614	430,746712	428,626342	426,50966
2,5	551,784807	549,102078	546,423959	543,755058	541,090767	538,43339	535,782928	533,137075
3	662,141768	658,922494	655,70875	652,50607	649,30892	646,120068	642,939513	639,76449
3,5	772,49873	768,742909	764,993542	761,257081	757,527074	753,806746	750,096099	746,391905
4	882,855691	878,563325	874,278334	870,008093	865,745227	861,493424	857,252684	853,01932
4,5	993,212653	988,38374	983,563125	978,759104	973,963381	969,180102	964,40927	959,646735
5	1103,56961	1098,20416	1092,84792	1087,51012	1082,18153	1076,86678	1071,56586	1066,27415

Table 3 Input data Rice(Mojave) Rankine cycle analysis

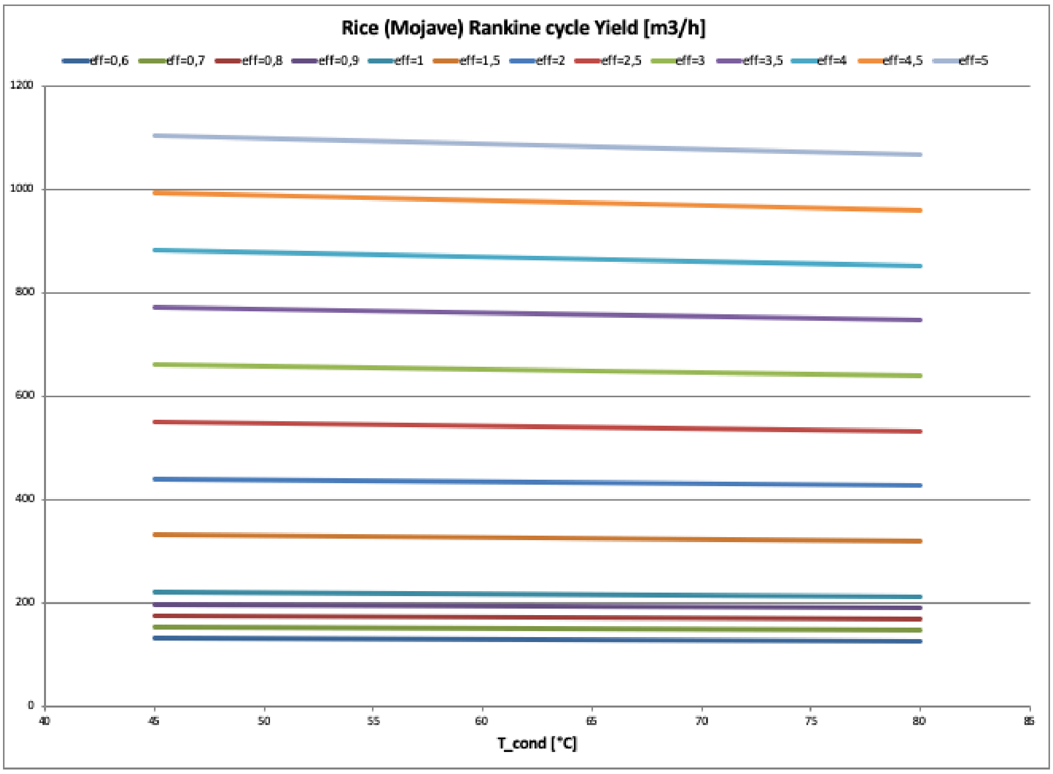


Fig. 64 Yield [m3/h] for Rice (Mojave) Rankine cycle

The coupling with this ranking cycle enables obtaining significant water yields. In the real operating conditions of pressure and condensation temperature, approximately 130 m^3/h of water can be extracted if a reduced efficiency (0.6 l/kWh) is considered, but the production of great quantities of water can be achieved, in the order of 500-1000 m^3/h, with higher efficiencies (2-3 l/kWh).

This Rankine cycle works in similar conditions to others SRC, therefore an economic comparison has been analyzed in order to estimate the economic saving consequent to a reduced water consumption, mitigated by on-site production with the prototype. For this purpose, several ST power plants based on the Rankine cycle, in regions with water scarcity or water stress have been considered, such as Spain, China, United States and Morocco.

Country	water price [€/m^3]	Source	water produced [m^3/y]	economic saving[€/y]
Spain	0,3638	[44]	2708,855	985,481376
China	0,2500	[45]	1861,500	465,375000
United States	0,7700	[46]	5733,420	4414,733400
Morocco	0,7170	[47]	5338,782	3827,906694

Table 4 Economic saving for countries in water stress/scarcity

6 Techno-Economic analysis

The Levelized Cost of Electricity (LCOE) is an indicator that evaluates and confronts the socio-economic costs of electricity generation. It is an effective tool to compare different electricity production technologies based on fossil, nuclear or renewable energy. LCOE estimates the average lifetime cost of power generation, expressed in €/kWh or $/kWh. In other words, it is the evaluation of the amount of money spent to produce 1kWh during the plant lifetime (over 20 to 40 years life). LCOE is calculated taking into account investment costs, fuel costs, operation and maintenance costs, environmental externalities, system costs, and heat revenue for combined heat and power plants [48].

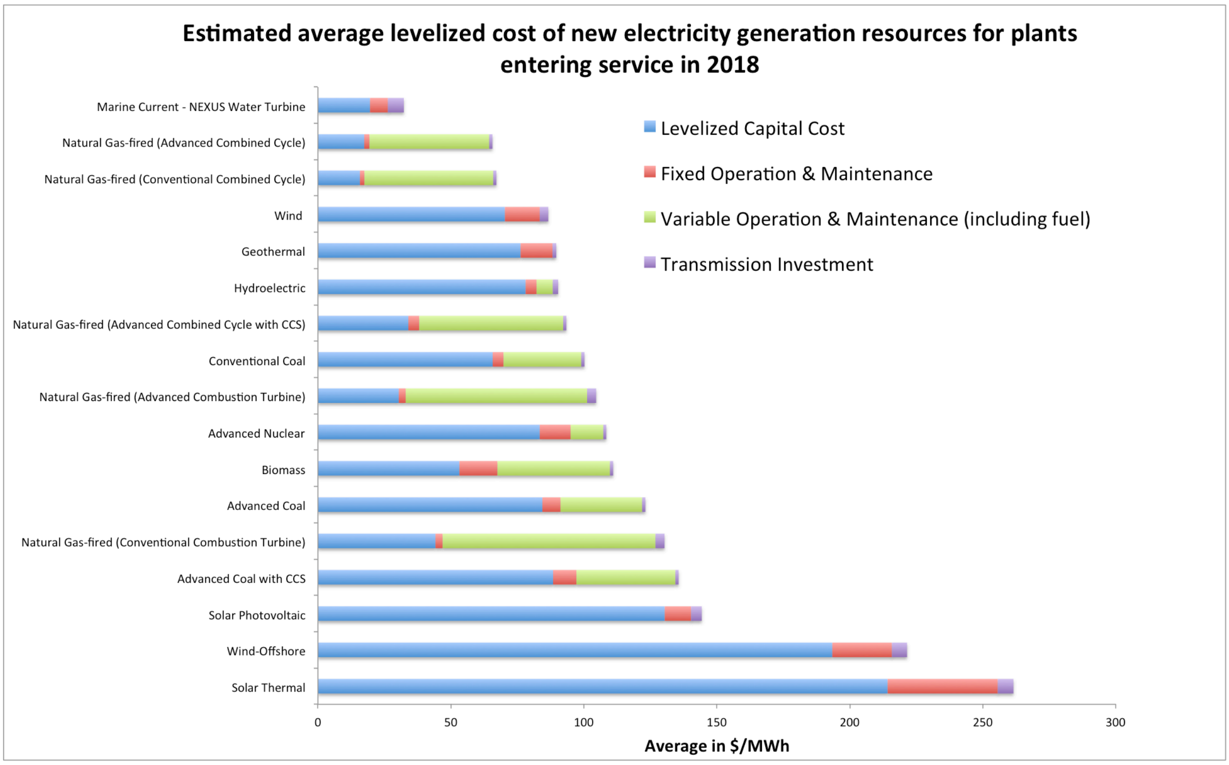


Fig. 65 Levelized Cost of Energy of different electricity production resources [49].

The solar electricity generation costs for PV and CSP is nearly double or triple the cost of the other electricity production. Also wind offshore has a high value of LCOE, dominated by initial investment cost, but CSP is the higher one with LCOE about 0.26 $/kWh.

6.1 Water costs in CSP plants

CSP plants are capital intensive but have virtually zero fuel cost. The LCOE of renewable energy technologies depends on the technology, the country, capital and operating cost, and the efficiency of the plant, for instance the LCOE of parabolic trough plants today is in the range of 0.2-0.36 \$/kWh and that of solar towers in the range of 0.17-0.29\$/kWh [49]. In this work, the procedure used to evaluate the LCOE does not take into account any CO2 pricing.

The equations used for estimating the LCOE of renewable energy technologies are [50]:

$$LCOE = \frac{\Pi_{capital\ cost} * CRF * O\&M_{fixed}}{8760 * CF} + O\&M_{variable} + HR * \Pi_{fuel}$$

$$CRF = \frac{i * (1+i)^n}{(1+i)^n - 1}$$

Where:

- LCOE = the average lifetime levelized cost of electricity generation;
- Πcapit cost = Capital cost(\$/MW)
- CRF = capital recovery factor
- CF = average capacity factor
- HR = heat rate (GJ/MWh)
- Πfuel = price of fuel(\$/GJ)
- i = interest rate
- n= number of years

For LCOE calculation the following variables have been considered:

- capital costs (CAPEX, costs to build the plant itself, [\$/kW])
- debt service costs
- fixed Operations and Maintenance costs (O&M, costs associated with the operations and maintenance of the plant, [\$/MW])
- variable O&M costs (costs associated with each unit of electricity generated, [\$/MWh] including costs related to water consumption)
- the heat rate (how much heat it takes to produce a unit of electricity, [kJ/kWh])
- the fuel cost (on a per unit of heat basis, [\$/GJ])

- the capacity factor (ratio between actual electrical energy output and maximum possible electrical energy output).

In contradistinction to power plants working with fossil fuels, dominated by fuel costs and variable operational and maintenance costs, in CSP plants is prevalent the initial investment cost, which represents approximately four-fifths of the total cost.

Parabolic trough plant :	**capital cost [$/kW]**
without thermal energy storage	4600
6 hours thermal energy storage	7100 - 9800
Solar tower plants :	**capital cost [$/kW]**
6 – 7,5 hours thermal energy storage	6300 - 7500

Table 5 Capital cost for different CSP plant types

As can be seen from the Table. 2, CSP plants with thermal energy storage have higher investment costs because of additional prices due to the storage system, yet if more electricity is produced, the LCOE will decrease. Considering that most CSP projects nowadays under construction or in operation are based on parabolic trough technology and solar tower, Dish Stirling and Linear Fresnel systems are not considered, and an average value of 5000 $/kW is been fixed for CAPEX.

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For the estimation of OPEX costs I have separately estimated:

- **Fixed O&M cost**
    - Solar field & HTF system (material and maintenance)
    - TES system (material and maintenance)
    - Power block and aux. heater (material and maintenance)
    - O&M personnel
    - Administration & management
    - Land lease (if applicable)
- **Variable O&M costs**
    - Fuel
    - Water
    - Electricity

Variable O&M costs are almost negligible respect to Fixed O&M, respectively assumed as 70 $/kW and 0,0028074 $/kWh. The operating costs of CSP plants are substantially high, especially compared to fossil fuel power plants.

Water price has been fixed to 0,5 $/m3, a lifetime of 30 years for the plant has been assumed.

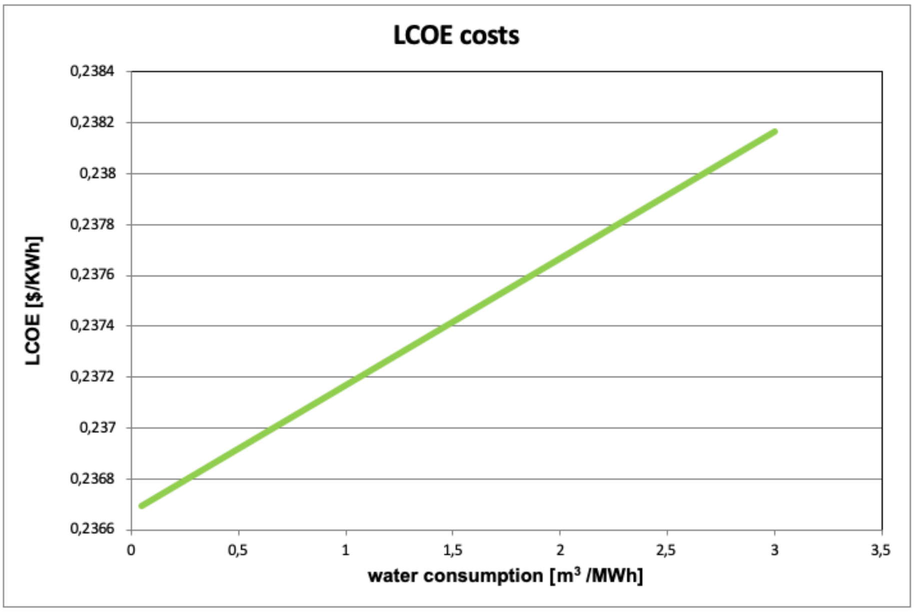

Fig. 66 Influence of water consumption in LCOE

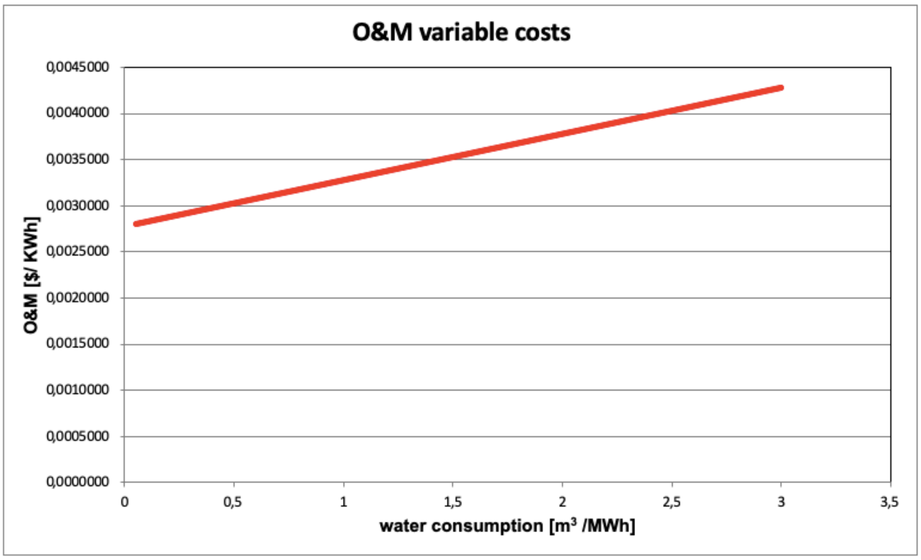

Fig. 67 Influence of water consumption in O&M costs

Water consumption does not affect LCOE, which varies from 23,67 cent/kWh to 23,82 cent/kWh.

In particular, in the analysis carried out, LCOE has been evaluated studying how water consumption variation affects the overall electricity generation costs.

The consumption of water has been varied in a very large range, in order to make a representative estimation taking into account all the CSP types, also considering the cooling system employed. More specifically, the following values have been considered:

- Parabolic Trough water consumption varies from 0.3 m3/MWh for dry cooling to 3 m3/MWh for wet cooling
- Solar Tower water requirement varies from 0.25 m^3/MWh for dry cooling to 2-3 m^3/MWh for wet cooling
- Linear Fresnel water utilization change between 0.2 m^3/MWh for dry cooling and about 3 m^3/MWh for wet cooling
- Dish Stirling water consumption, only due to mirror washing, fluctuates from 0.05 m3/MWh to 0.1 m^3/MWh according to the cleaning method adopted.

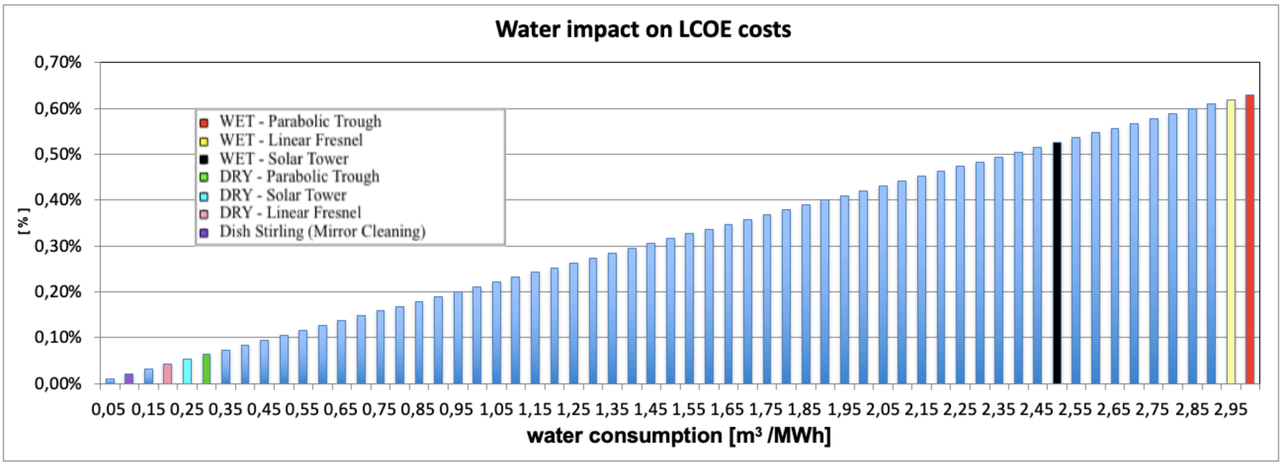

Fig. 68 Water impact on LCOE

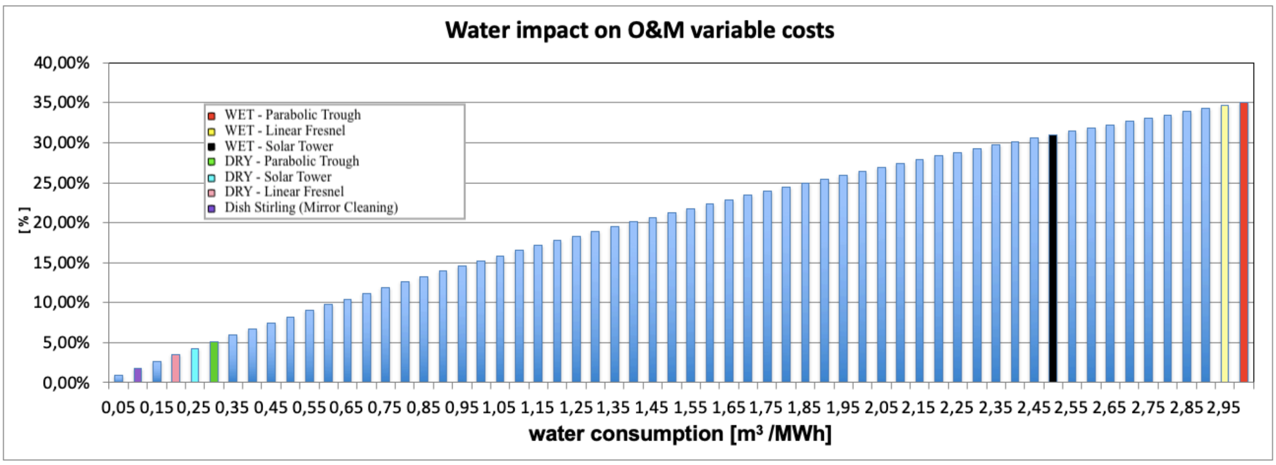

Fig. 69 Water impact on O&M variable costs

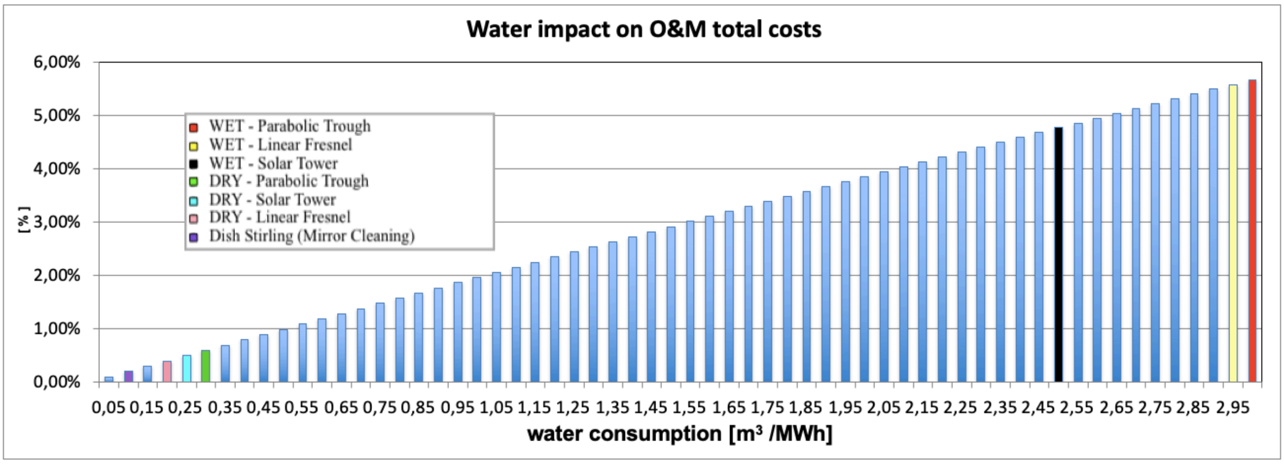

Fig. 70 Water impact on O&M total costs

Water can significantly affect O&M variable costs, especially the wet cooling system technology, for which water cost represents up to 30% of O&M costs. Water O&M costs are less than 1% of LCOE cost.

	WET			DRY		
CSP Plant	variable O&M	totl O&M	LCOE	variable O&M	totl O&M	LCOE
Parabolic Trough	35,03%	5,66%	0,63%	5,12%	0,60%	0,06%
Linear Fresnel	34,65%	5,58%	0,62%	3,47%	0,40%	0,04%
Solar Tower	31,00%	4,77%	0,53%	4,30%	0,50%	0,05%

Table 6 Results of Economic analysis

As we can see from Table 3, for CSP plants (mostly parabolic troughs and solar towers) the:

- initial capital investment (CAPEX)costs constitute ≈ 84% of the LCOE
- fixed O&M costs account for the 10% - 11% of the LCOE
- O&M costs represent around 12% - 15% of the LCOE
- total O&M costs are more or less the 2% of CAPEX
- personnel costs affect by 4% - 5% the LCOE.

Since the LCOE depends primarily on capital costs and less on O&M, water consumption represents a small fraction of O&M total costs(< 6%), a significant fraction of O&M variable costs (up to 30%), imperceptibly affect LCOE (≈ 0,6%) which does not tend to decline with higher water use.

7 Conclusion

This work aimed to prove the potential of a system that extracts liquid water from water vapor contained in the air through the condensation with low-temperature solar heat (50-80°C). Thanks to the prototype introduced, tested in the laboratory of Energy Department (DENERG) of Politecnico di Torino, an ideal water amount of 3-5 l can be achieved.

The outcomes of the simulations conducted allow evaluating the phenomena of heat and mass transfer taking place to quantify flow rates and specific consumption; major interest has been given to inlet and outlet temperatures, relative humidity and moisture content of the air, as well as the dew point temperature fundamental to investigate the condensation process. In particular different tests with several external temperatures and moisture contents have been conducted to reproduce arid and semi-arid regions weather conditions; and different condensation temperatures, between 20-35°C, have been examined.

In addition, also the issue related to the heat sources required for desorption phase has been analyzed considering as alternative several CSP solar Rankine cycle, for which the water yield has been established considering different efficiencies of the system in the range 0.6 - 5 l/kWh.

The second part of this work presents the techno-economic analysis related to the CSP plants, conducted in terms of the Levelized Cost of Electricity. In this case, more emphasis is given to the water consumption impact on operations and maintenance costs (O&M). In the model water requirement has been ranged from 0.3 m^3/MWh to 3 m^3/MWh in order to analyze the economic weight of water intake on CSP plants, distinguishing between different plant technologies and cooling systems. The results show a strong influence on wet cooling system technologies that affect up to 30% O&M variable costs and around 5% O&M total costs, while dry cooling system technologies influence in minimal part O&M variable costs(≈ 4%) and inappreciably O&M total costs (<1%).

In conclusion, the prototype can be further improved in order to produce more potable water by the use of new desiccants, such as nanoporous inorganic materials or metal-organic frameworks (MOFs) that show a higher potential for water-harvesting systems, or other geometries and working configurations to improve the desorption phase; also different fan regulations can be used during regeneration to optimize air dehumidification. Solar water harvesting can be used with excellent results in arid regions of the world, like MENA countries, not only for energy-efficient water technologies but also for water-efficient energy technologies which clearly can reduce the energy consumption and the water stress of power plants and agricultural applications.

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