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SIMULATION AND ANALYSIS OF A COMBINED ENERGY & WATER SYSTEM

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Abstract

The present dissertation has as its objective the description of the design and production analysis of a complex system comprising a 20 MW concentrated solar power plant with biomass support system and an advanced wastewater treatment facility. This large scale engineering project is to be installed in Fuentes de Andalucía, a town located 57 km away from the Spanish province of Seville, with the purpose of evaluating the viability of this kind of power plants in one of the most water and energy demanding areas of the Iberian Peninsula.

Hybrid power plants appear as a present solution with a promising future due to its electrical manageability, which enables the storage and regulation of energy production. Central receiver technology allows to work at higher temperatures arising from its greater concentration ratios and reducing at the same time the size and cost of storage systems. Likewise, molten salts system represent one of the most effective technologies for electricity generation with respect to costs. Hybrid power plants entail a bright alternative to increment the energetic production at a relatively low additional cost with fewer pollutant emissions.

The solar block of our power plant consists of a heliostats field controlled to concentrate the incoming solar radiation towards a receiver located at the top of a tower. Molten salts sent through the receiver work as the heat transfer fluid collecting the thermal energy used to generate electricity. For its part, the biomass block uses olive pomace as biomass material to serve as a backup for the power plant when necessary. Major components of a central receiver power station are defined and selected as well as the most suitable configuration for each part of the generation plant.

Similarly, the implementation of a direct potable reuse facility enhances the renewable potential of this project. The idea is that, urban sewage from the region is collected and subjected to a series of purification procedures until it becomes drinkable water ready to be directly blended into the potable distribution system. A specific treatment train is proposed to fulfil the desired water requirements and a sensitivity analysis is carried out in order to determine the feasibility of this kind of regeneration systems.

Once the main components of the power plant have been defined and taking into account the data of solar irradiation at this specific location, outcomes show that the plant is capable of generating 20 MW of electric power. Assuming a capacity factor of 85 % and the use of biomass, the operation period of the plant reaches a value of 7446 hours per year. Regarding these figures the annual electric production of the solar power plant can be calculated supplying the region with 148,92 GWh and avoiding the emission of tons of CO_2 into the atmosphere.

Furthermore, an exergetic and economic analysis of the power plant are conducted.

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1 Introduction

1.1 Introduction

Before proceeding with the analysis, it is essential to completely understand the general circumstances surrounding the studied subject, as well as the motivations to carry out this work and the set of objectives to achieve that purpose.

The current global context is characterized by a progressive economic recovery, the unceasing increase of population density and the further technological development of new countries, resulting in a constant growth of the electric and water demand worldwide. Within this ongoing energy framework renewable sources of energy, specifically thermosolar power stations, have a great potential to meet the existing electricity demand of numerous countries. On their behalf, water reclamation plants enable the maintenance and increase of the much-needed hydric resources, which are fundamental for this type of energy generation projects and life itself.

Emergent regions of the so called terrestrial Sunbelt consist of several countries, including Spain, with common ideal solar features as a result of their specific geographic location, which spans from 40° above the Equator and 35° below the East. These countries present the highest solar radiation levels per year of the planet providing them with diverse benefits regarding energy matter. As a result of their weather conditions, solar potential allows the production of remarkable amounts of energy to not only supply this region but for exporting to other areas of the world. In light of the actual situation, hybridization of conventional sources of energy with renewable energies represent an interesting alternative for the growing electricity demand while contributing to the reduction of greenhouse gas emissions. It is clear that during the last years, generation as much as installation of renewable energies is rising not only as a direct consequence of the associated technological development but for the clear political commitments and the consciousness-raising of the population.

In conclusion, investment on solar projects has become an attraction for the electric energy trading as hybrid power plants partially solve the current energetic challenges while more efficient renewable technologies are developed. All this, combined with water recycling becomes a unique and innovative alternative for emerging global problems.

1.2 Objectives

This thesis has two key objectives. The first is to undertake an exhaustive state of the art on renewable energies and their different technologies, specifically the ones regarding concentrated solar power (CSP). Water management and generation will be also dealt in order to have a clear and precise description of the current wastewater treatment framework. This research work aims to give a general answer to the lack of condensed knowledge on the main topic and a broad review of its real applications.

The second one, consists on the implementation of the previous concepts to simulate the realization of a renewable project based on a CSP-biomass power plant and the further use of part of the generated electricity to run a water reclamation plant. The impact of energy nature on the continuity of supply, economic efficiency and renewable penetration is studied and discussed by comparing the results obtained from the plant simulation and analysis. The principal objectives in doing so are the achievement of economic sustainability, lessening of pollutant emissions and the highest possible renewable spreading across the world.

1.3 Software and Tools

Two different software programs have been used to draw up this work: EBSILON® Professional and MATLAB.

EBSILON® Professional has been used to model the entire thermodynamic cycle process of the power plant and for that purpose the version 13 of 64 bit was installed. Evaluation of the efficiency and load behavior of the power plant is performed by means of this tool which allows to choose among a great variety of thermal components to create the most suitable configurations for our project. Concerning MATLAB, the version R2018a of 64 bit has been used to implement specific energy balances of few components for the successful completion of the power plant exergetic analysis.

1.4 Stages of Development

The development of this thesis has been carried out in four main sections. Research and documentation reading, explanation of the followed methodology, design and simulation of the whole renewable system and, ultimately, an economic and exergetic analysis of the project including a final discussion of the results.

1.5 Structure

Second section will cover the overview on the two main topics of study: Water and energy. It is mainly divided into four subsections each dedicated to the various energy sources, solar concentration technologies, energy hybridization and wastewater management respectively. Apart from the conceptual review and the explanation of the most significant terms regarding the matter, it also presents a compilation of different actual case applications and implemented examples of the exposed issues.

The third section of this work describes the specific methodology followed within later chapters to analyse the viability of the project proposal. The two main procedures needed to evaluate this include, among others, an exergetic and economic analysis. Both of them presenting the detailed steps required to be carried out successfully. Another form of feasibility study involves the calculation of the levelized cost of energy, a parameter used to compare unitary costs over the economic life of power plants.

Fourth section includes an overall description of all systems and subsystems comprising the CSP-biomass plant simulation and water reclamation facility. Numerical evidence as well as compelling reasons are provided for choosing the most suitable location for the project implementation, the thermodynamic cycle of the power plant to be modelled in EBSILON® Professional as well as the design points required for its correct operation. With respect to the water regeneration plant, an efficient treatment train required to generate safe drinking water is discussed based on existing direct potable reuse technologies. This section along with the economic and exergy analysis, constitute the core of this work.

Finally, within section five economic and exergetic analysis are conducted respectively with the intention of estimating and evaluating the real feasibility and productivity of a project of this scale. Exergetic balances of every component comprising the cycle are calculated providing with valuable information about the real amount of work yielded by the power plant. Similarly, a breakdown of the costs associated to each subsystem and water treatment is carried out to accurately estimate the necessary initial investment to bring the combined plant into operation. In addition, a sensitivity analysis is conducted in order to conceive at what price this potable water could be brought to market. In conclusion, chapter six will present the definite arguments and discussions based on the results obtained throughout the entire dissertation.

2 State of Art: Water and Energy

Water is a vital resource we use every day, it is fundamental to life and health. In order for people to have access to a guaranteed service of safe drinking water and adequate sanitation it is necessary to consume energy. Energy is required to extract, treat and distribute potable water as well as to collect and treat sewage. Likewise, water is crucial for energy production and generation; it is used for extraction, refining, and electric power generation, even though it usually seems less obvious.

This way, water and energy present a narrow interrelation determined to a large extent by multiple factors [1]. Actions taken and choices made in one field can lead to huge impacts on the other, positively or negatively. Consequently, both scarce and strategic resources have to be addressed together. The future of sustainability depends on the achievement of efficiency optimization for both resources to give a way out for the future requirements of energy production.

Water and energy are two of the most basic resources worldwide. Both face a future situation of new challenges in its management due to the increasing demand, the depletion of the traditional sources of extraction and its environmental consequences. The fundamental difference between water and energy resides in its renewable origin. Energy can be renewable while water resources are not, so we have to take care of the amount of fresh water currently available. For this reason, sustainability and investment on renewable alternatives become even more indispensable.

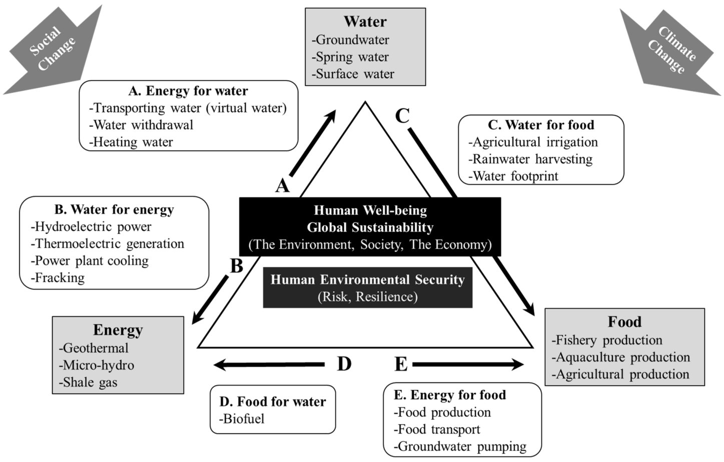


Figure 1: Water-energy-food nexus [2].

Difficulties will arise as a result of future population growth, economic development, climate change, food production and industrialization. All these circumstances put a lot of pressure on water and energy reserves. In the future, both resources are expected to deal with a continuous increase in the demand. As much for human consumption as for the industrial sector, intensifying the possible conflicts between them [3]. In fact, the energy sector may be the largest water consumer within the industry. Water does not only allow the direct production of electricity, but it is necessary to feed thermal power plant cooling systems, water biofuel cultivations and even to generate electricity by means of hydro-electric power plants and steam turbines [4].

Concerning water, the future situation seems to be complicated due to an increase of its demand major to 55% in 2050. As for energy, it is foreseen that in 2035 the demand will suffer an increase of approximately 70% [5]. Within this context of great pressure on the resources, the risk of global climate change adds a level of further complexity. Climate change will bring modifications in the hydrological cycle. Alterations are expected in the temporal and geographical fresh water availability, further decreased by pollution and contamination. In the same way, predicted raise of temperatures as a consequence of global warming will also involve changes in the energy demand [6].

Dependence of water in the energy sector and of energy in the water treatment revolve around fundamental issues like water management and infrastructure systems, sustainable energy or systems efficiency. Integrated development of energetic and hydrological policies is quite important. Together with the high risks to which the energy sector is exposed nowadays, the incorporation of water on its strategic plans turns out to be more essential than ever.

2.1 Energy Production and Generation

Energy is an essential element for global sustainability. Ensuring access to reliable, affordable and sustainable energy is fundamental for improving living standards, development and economic growth. Design of our cities, homes and domestic appliances as well as our life-style has a great implication for energy consumption. Every operation providing us daily life comforts requires an energetic expense. Industrial processes for power generation need as a base the use of different energy reserves.

Energy resources around the world can be mainly classified as renewable and non-renewable, having achieved the first ones a major relevancy in the last years. Renewable or clean energy is obtained from unlimited natural sources, either for the vast amount of energy they contain or because they are capable of being regenerated by natural means. On the contrary, non-renewable energy sources are the ones whose speed of consumption is higher than that of its replenishment. Their presence in the planet is limited and might cease to exist if they keep on being highly exploited.

2.1.1 Non-renewable Energy Sources

Since the beginning of energy production, humans have been making a reiterated use of non-renewable resources to satisfy the enormous energy demand worldwide. Fossil fuels and nuclear energy constitute the two main types of this kind of resources.

Fossil fuels are basically hydrocarbon compounds comprising of coal, oil and natural gas. They are originated from the accumulation over millions of years of great quantities of vegetable wastes and other living organisms in lake depths and other sedimentary basins. Under specific conditions of pressure and temperature biomass is transformed into compounds provided with energetic properties. Fossil energy is obtained from the combustion of these resources.

Fossil fuels can be directly burnt inside boilers and engines to produce movement and heat. They can also be used to generate electricity within thermal or thermoelectric power plants. Heat from the combustion of these fuels produces steam which starts up an electrical generator, usually a turbine.

Currently, about 80% of all primary energy in the world is derived from fossil fuels with oil accounting for 31.7%, coal for 28.1% and natural gas for 21.6%. Consumption of fossil fuels for heating, lighting and ventilation in buildings represents approximately half of the energy used in the world [7].

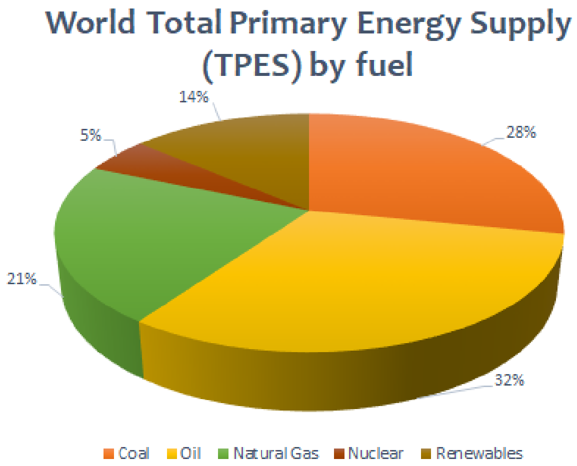


Figure 2: Global primary energy supply.

Coal was the first fossil fuel used by man. It is the principal fuel source for electricity generation in thermal power plants and accounts for about 56% of the energetic world reserves of fossil fuels currently known [8]. To give an idea of the relevance of this energy source, around 40% of the global electric power is generated within coal combustion power plants [9]. However, extraction along with combustion of coal originates a series of important ecological deteriorations. The most important is the emission to the environment of several pollutant elements like SO_2, NO_x and highly toxic CO_x [10]. This way, coal consumption contributes to the intensification of the greenhouse effect, acid rain and the alteration of the ecosystems.

Oil is the basis of a great number of products like cosmetics, paintings and solvents, but it is even more important for the production of fuels. Roughly 95% of the transportation sector worldwide depends on oil derivatives [11]. Given current levels of oil production, its global reserves are estimated to last 68 years [12].

In the same way as coal, oil exploitation releases to the atmosphere highly toxic pollutants, especially CO_2.

For its part, **natural gas** provides an abundant additional source of energy with high calorific value and appears to be relatively clean if it is compared with coal and oil. It serves as fuel for vehicles and power plants and offers great advantages within industrial processes where clean environments, controlled processes and high reliability fuels are required. Natural gas combustion, as other fossil fuels, produces CO_2. However, it generates almost 50% less emissions than coal and oil and presents a higher energetic efficiency due to its high molecular proportion of hydrogen-carbon [10].

Another way of non-renewable resource for energy generation are **nuclear fuels**. Principally obtained through the mining and refining of uranium for nuclear power plants. Uranium consists on a radioactive metallic element extracted from the earth which it is not rapidly replaced. Nuclear energy is generated by means of the disintegration of uranium atoms. Heat produced by the atomic disintegration boils water located inside the nuclear reactor turning it into steam. Later, steam drives the turbines within the reactors producing in this way the desired electricity. Apart from electricity, these atomic reactions can also provide with thermal and mechanical energy. At present, nuclear energy contributes to about 5% of the global primary energy supply [7]. The principal characteristic of this kind of energy is the high energy quality and quantity that can be reached per unit of material mass in comparison with other sources. Routine health risks and emissions of greenhouse gases provoked by nuclear power are almost negligible when compared to those of fossil fuels. Nevertheless, additional catastrophic risks exist as well as the dangerous storage of its radioactive wastes.

During the last decades the energy system has been based on the intensive exploitation of the previously mentioned non-renewable energy sources. Even though great amounts of energy can be obtained from these compounds, their hazardous environmental impact must be taken into account. The continuous release of several pollutants to the atmosphere, where they are accumulated, contributes to global warming, acid rain and the contraction of respiratory illnesses among other environmental and health effects. In addition, climate change derived from the combustion of fossil fuels will have an important long-term impact on the availability and quality of the water worldwide.

This situation leads to think about the reason to keep using these harmful resources. The answer is quite simple, they are cheaper than other environmentally-friendly alternatives already existing. However, these non-renewable fuels are being consumed at a major rate than they are produced. They are limited resources and will only be available for a finite period of time, leading to an increase on its market prices and causing multiple conflicts before its depletion. For this reason it is important to open the way to renewable energy sources, being eco-friendly and globally distributed, offering our planet a chance to clean its air reducing carbon emissions and serve as a fundamental key for an overall strategy of sustainable development.

2.1.2 Renewable Energy Sources

The increasing and unceasing decline of the environment together with the depletion of fossil fuel reserves are the main consequences of the current energy system. During the last years, renewable energy sources have been making their place within the energy sector. Nowadays, renewables account for 13.7% of primary energy supply worldwide and keep on growing [7]. Renewable energy can be defined as the energy sources that are continuously regenerated by natural processes as fast as we use them. They provide an inspiring alternative to fossil fuels as they will always be available for energy generation on a large-scale. At the same time, they constitute a clean way of energy production fundamental for the preservation of the so valued environment.

These alternative sources come ultimately from the sun. Solar power is the origin, in a more or less direct way, of all other current energy sources in the Earth. We can make use of solar direct radiation, indirect solar power (wind, waves, biomass, hydraulics. . .) and geothermal energy. Renewable energy technologies are in charge of transforming these resources into functional forms of energy, commonly electricity, but also heat, chemicals, or mechanical power. The most significant renewable possibilities will be briefly described below, including their main characteristics, potentials and limitations.

Solar energy comes directly from the power of the sun. It is associated with solar radiation and constitutes the principal source of energy of our planet. It is used to produce electricity, heat and for light. As renewable energy source, it does not produce any kind of noise neither pollution during its normal activity.

Solar power can be generated in two different ways, by means of photovoltaic (PV) solar panels or directly using the heat coming from the sun within power plants [13]. PV technology works in the following way; radiation emitted by the sun is absorbed by solar cells and transformed directly into electricity to be used, stored or returned to the grid.

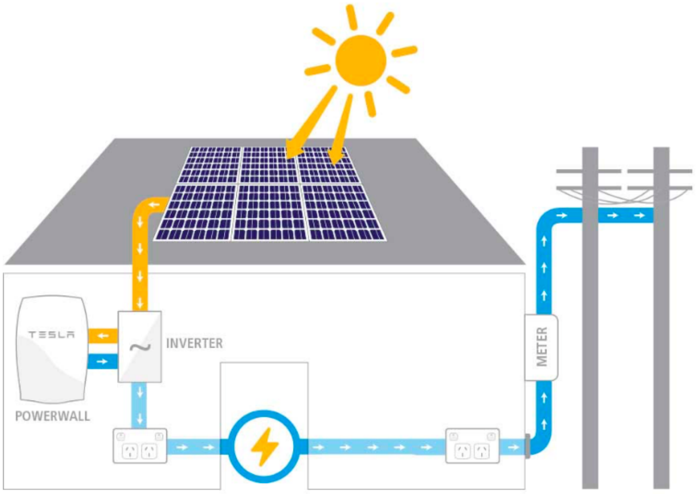


Figure 3: Solar PV system with TESLA powerwall storage [14].

Likewise, electric power can be produced within power plants using straightaway the heat coming from the sun. Thermoelectric energy uses solar radiation to heat a fluid, usually water, until it generates steam and runs a turbine to generate the desired electricity. These kind of systems can be either active or passive. In the first ones, air or liquid flows through solar collectors and carries heat to where it is needed. In passive systems, windows and heat-absorbing surfaces are installed in buildings for solar heating. Both technologies are practical for residential use.

Wind Power is obtained from the draughts of air. Wind is produced as a result of the temperature difference existing within the different air layers of the atmosphere. Masses of air at distinct temperatures generate pressure differences which lead to the movement of air currents from places with major pressures to minor ones. That is when turning aerodynamic blades of wind turbines take advantage of the wind.

Wind turbines are mounted to a hub, which is connected to a shaft that powers a generator to produce large amounts of electricity. Technology of wind turbines may appear to be simple but in fact they are highly sophisticated power systems designed to capture the energy of the wind by means of airfoils. Wind energy is converted into electricity thanks to modern mechanical drive systems combined with advanced generators.

Wind farms consist of several wind turbines usually located in areas characterized by high wind effects. In general, these wind turbines are placed on top of an elevated tower, considering that the wind velocity is bigger at higher elevations. Capacity of large utility-scale wind turbines extent in size from 50 kW to over 4 MW. However we can also find isolated wind turbines which are smaller in size (under 50 kW) but provide enough energy to remote places for residential and agricultural use [15]. Today, wind energy is the renewable energy source with the highest growth representing already a great part of the electric production.

Biomass energy results from the organic matter coming from microorganisms, plants or animals through natural processes. Yet, biomass energy use is principally based on agricultural waste, wood, and bark. Photosynthesis is the process through which energy from the sun is collected by plants. The term biomass refers to this conversion of the solar energy into organic matter by means of vegetation. Animals also obtain this energy when they ingest plants. Wastes such as crop remains, harvests, manures and many other diverse organic wastes are excellent biomass resources to be used as fuel. Biomass is considered a renewable source of energy as long as it is not being misused. Problems arise when the total production of the exploited ecosystem is lower than the amount of biomass being consumed leading to deforestation, biodiversity loss or even desertification.

Biomass provides a wide range of uses. It can be directly used as a fuel through combustion to obtain heat or generate electricity by means of steam turbines. Biomass is burned straightaway in specially designed power plants, or even used to replace up to 15% of a fuel such as coal in ordinary power plants [15]. This kind of renewable energy burns cleaner than coal because of its lower sulfur content, which means less amount of this noxious element will be emitted into the atmosphere.

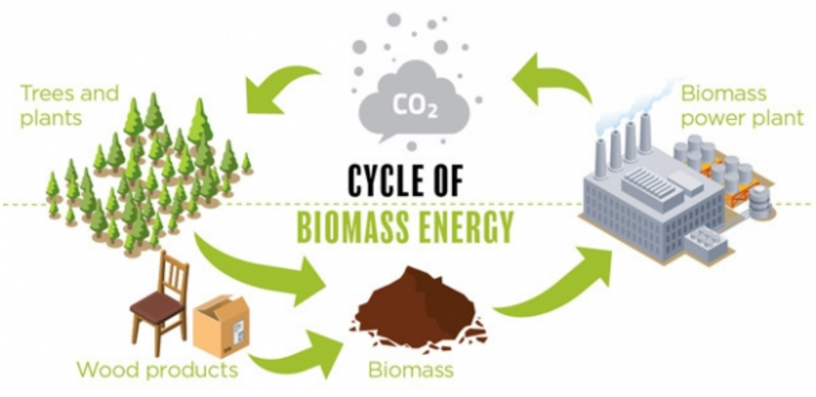


Figure 4: Biomass energy cycle [16].

Biomass is also indirectly expended for the production of methane gas (CH_4), biodiesel and other fuels. Methane can be slowly generated as biomass decays or more rapidly through a modern process called gasification. CH_4 is used to produce power by combustion within a boiler to create steam subsequently driving a steam turbine or through internal burning in gas turbines and reciprocating engines.

Another possibility of biomass would be the production of biogas. This fuel gas is produced inside special tanks where organic wastes are accumulated. Fermentation of these remainders by the action of microorganisms produces a mixture of gases that can be stored or transported to be used as fuel.

Geothermal energy takes advantage of the existing heat retained inside the Earth to acclimatize and obtain sanitary hot water in an ecological way. The center of the Earth basically consists of an incandescent mass that irradiates heat from the interior to the exterior. For this reason, as we go deeper into the Earth temperature increases progressively. As water reaches a sufficient depth it is heated and changes its state to steam. Consequently, this steam ascends and leaves the surface at high pressures in the form of streams or thermal springs.

Applications of geothermal energy depend on the characteristics of each resource. High temperature resources (superior to 100 - 150 °C) are fundamentally used for electricity production [17]. These deep underground high temperatures are used by geothermal power plants to produce steam, which then powers turbines to generate electricity. Hot water from underground reservoirs can be directly extracted or even heated by pumping it into hot, dry rock. When the field temperature is not hot enough to produce electricity, it is exploited for thermal purposes within the industrial, services and residential sector. In the case of temperatures below 100°C, hot water can be directly used or by means of geothermal heat pumps. As last resort, possible applications for very low temperatures of the resource (below 25°C) include acclimatization and hot water extraction [17].

In one sense, geothermal energy could be considered as non-renewable since the core of the Earth will keep on cooling as time goes by. However, that time is so far off that it is assumed to be renewable. In fact, this kind of energy is contemplated as clean, renewable and highly efficient to be used as much in large buildings as well as in homes.

Hydroelectric power consists on the electricity generated by the energy of water in motion. Rain or even water from melting, usually coming from the mountains, create streams and rivers with considerable currents of water flowing into the ocean. Energy is originated by the water fall from a certain height which creates a rotation movement to be converted into mechanical energy. Later on, all this energy passes through a series of generators where it is transformed into electricity.

In order to obtain energy from water, a hydroelectric power plant is required. These kind of power plants are located in areas characterized by frequent rain and geographical slopes. Energy is produced by water usually accumulated in great reservoirs known as dams. Dams retain water until it is required and afterwards this water falls to a lower level generating kinetic energy. This energy is later extracted by the turbines and transformed into mechanical energy. This makes turbines to rotate at a high speed and transfer the energy to a generator that turns it into electricity. The quantity of hydraulic energy depends on the water flow and the height from which it falls.

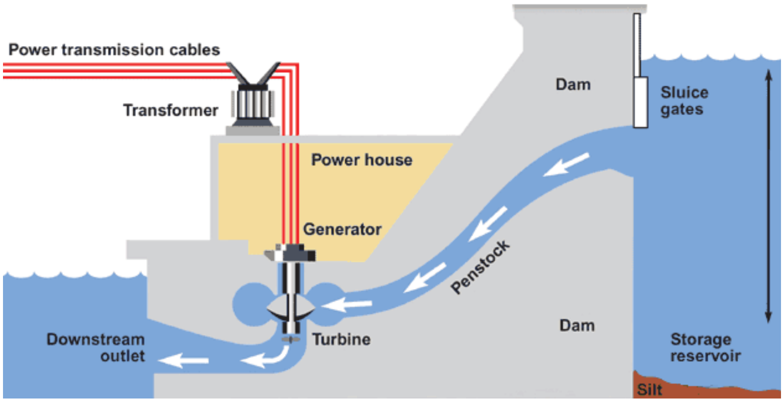


Figure 5: Hydroelectric power diagram [18].

Hydropower energy is to be considered a renewable resource as it does not produce any emissions and constitutes an endless source of energy. However, we must be aware that the process of damming a river may lead to important ecological problems affecting wildlife habitats as well as water quality.

Up to here, the most relevant and widely used renewable technologies have been discussed. With the aim of achieving the maximum utilization of these renewable energy sources and supplies, their various forms must be efficiently integrated within the energy sector. All efforts to reduce pollutant emissions and alleviate climate change must be included. It is true that in recent years, a fundamental shift has taken place in the way governments are approaching energy-related environmental issues around the world. This is significant, as energy accounts for almost 2/3 of total GHG emissions and around 80% of CO_2 [10]. Increasing concern about air pollution, energy security and climate change opens the way to future environmental sustainability. The objective is the creation of a clean, accessible and affordable global energy system.

2.2 Concentrated Solar Energy

Among all renewable energy resources, the sun constitutes a great opportunity for energy generation as it can be harnessed almost everywhere in the world due to its distributed nature. It can be easily captured and directly transformed into electricity or heat. The main components of solar energy are direct or beam radiation and diffuse irradiance. The first one comes directly from the sun's disk creating shadows, while diffuse radiation is scattered and does not have a preferred direction. There is yet another directionless radiation component that depends on the ground reflectivity, known as reflected radiation [19]. The term global irradiance refers to the aggregate of these three solar components.

The solar resource is immense compared to our energy needs. The sun provides a noteworthy amount of power; about 885 TWh are sent every year to the earth's surface, rather 6200 times the commercial primary energy consumed by humankind in 2008. Following up on the estimation 4200 times the energy mankind would consume in 2035 [20]. In other words, it only takes the sun one hour and 25 minutes to send us the yearly amount of energy we are consuming at the moment.

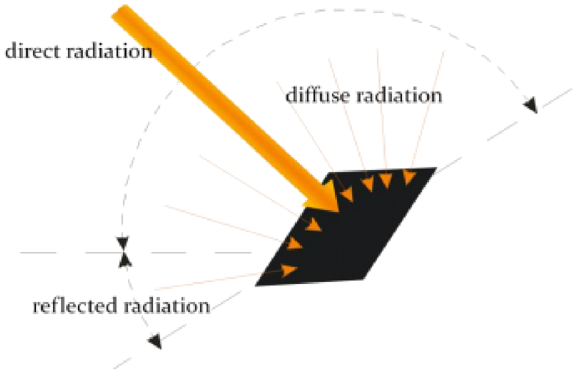


Figure 6: Irradiance components [19].

Capturing the incoming energy from the sun as heat can be done with great ease and by means of a significant number of devices. Our case of study is based on solar energy, more specifically concentrated solar energy. Concentrated solar power systems are based on the generation of heat or electricity by the concentration of solar irradiance onto a specific small area through mirrors or lenses to heat up a fluid. This fluid can be water vapor, pressurized air, oil or even some types of molten salts. In the case of having water vapor as the heated fluid, it will be directly introduced in the steam turbine or go through a heat exchanger in the first place if we use pressurized air or molten salts. Electricity is produced then as a result of the conversion of the concentrated sunlight into heat which subsequently drives a steam turbine coupled to an electric generator.

It must be taken into account that significant concentration of solar rays allows the collection of solar energy at higher working temperatures that vary between 400 and 1000 °C [21]. In the case of power plants, these elevated temperatures provide superior efficiencies of the heat conversion to electricity and may be necessary to run industrial processes or even for fuels manufacturing. CSP systems only take advantage of direct radiation as non-directional irradiance cannot be concentrated and therefore, used within this kind of systems. Precise tracking along with concentration ratios are also required.

Hence, two kinds of concentrated solar technologies can be distinguished; linear devices and point focus designs. First ones follow the sun on one axis, such as linear Fresnel reflectors and parabolic troughs, whereas the latter track the sun on two axis, like solar towers and parabolic dishes.

2.2.1 Parabolic Troughs

Among all concentrating technologies, parabolic trough collectors (PTCs) are characterized by competitive collection performances at delivering high temperatures with great efficiencies. Arranged in rows and facing north–south, parabolic troughs track the sun all day long always oriented towards it. PTCs display a parabolic cylinder shape formed by bending a sheet of reflective material. This way, incoming solar rays are concentrated onto a metal black tube located along the focal point of the parabola. Radiation is absorbed by the receiver tube and heat is transmitted to the working fluid circulating through until it reaches temperatures that oscillate from 50 to 400 °C [22]. Pumped along the pipes, high temperature fluid goes through a series of heat exchangers to produce overheated vapor subsequently transformed into electric energy by means of conventional steam turbines.

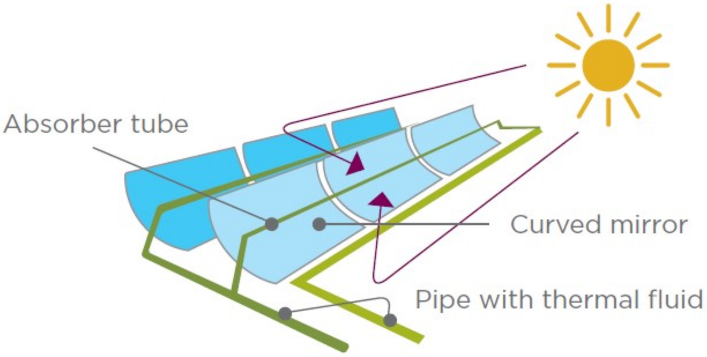


Figure 7: Parabolic trough collector [23].

Thermal oil reaches maximum temperatures of approximately 400 °C in liquid and steam operating conditions, which limits the conversion efficiency of the turbine cycle. For this reason, new alternatives are being studied and research of more developed fluids is taking place, such as direct steam generation within the absorber tubes and the use of molten salts as working fluids [24]. Energy storages are usually incorporated within this type of technology, the most commonly used include molten salts storage tanks where energy is accumulated to be distributed when required. Presence of storage tanks improves significantly the efficiency of the system, extending the production time even in the absence of direct solar radiation and guaranteeing a constant pressure level to power the turbine. These power stations also allow simple hybrid solutions when combined with other traditional fossil fuels or biomass to generate electricity at night, during cloudy days or even to support the solar operation.

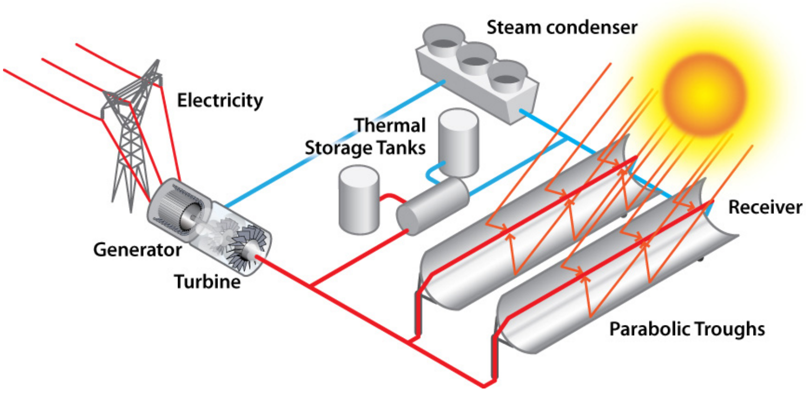


Figure 8: Parabolic trough power plant [25].

Located in South California, the Solar Energy Generating System (SEGS) constitutes the largest linear solar installation worldwide. It comprises a 9 plants complex with a combined capacity of 354 MW which supply enough electricity to meet the energy needs of approximately 500000 people [26]. Regarding Spain, two main solar power stations must be highlighted, the 200 MW Solaben located in Extremadura and the 150 MW Andasol 1 placed in Andalucía [27]. During the last decades, several new parabolic trough plants have been built or are currently under development as it has been demonstrated to represent an important renewable energy source. In addition, within the available power options of these days, parabolic troughs are one of the cheapest technologies and present significant potential for further cost reduction.

2.2.2 Linear Fresnel Reflectors

Linear Fresnel reflector (LFR) technology claims to pave its way in the direct competition with concentrated parabolic troughs. In fact, LFRs are relatively similar to the parabolic form of trough systems but with long rows of slightly curved or flat mirrors to redirect the solar radiation towards a fixed receiver. They consist of line-focusing collectors, that is to say, sun rays are concentrated along one line directed to an adsorption tube through which a thermal fluid circulates.

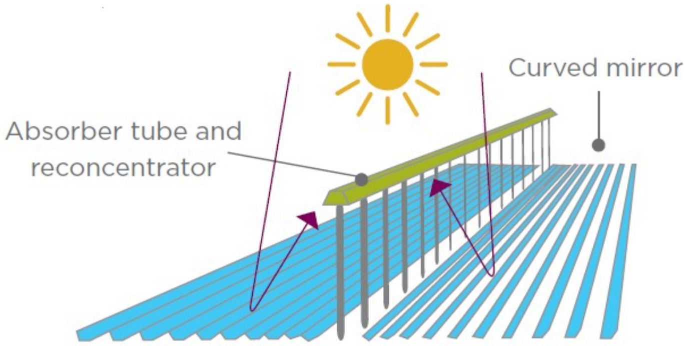


Figure 9: Linear Fresnel reflector [23].

The linear Fresnel system consists of a series of reflected surfaces with an elevated curvature ratio which intercept, concentrate and reflect the solar radiation towards a receptor tube, located in a different plane than reflection. This concentration system must include a control mechanism to allow the monitoring of the sun's path to ensure the proper concentration of solar rays on the receptor surface. Once the concentrated radiation reaches the receptor, it is converted into thermal energy by means of an energy transfer to the working fluid.

Power plants based on Fresnel technology consist basically of a primary field of mirrors, a receiver tube and a secondary cylindrical concentrator. The primary field comprises various series of flat mirror rows arranged in straight line at about one meter height above the land. Solar rays are reflected towards an absorber tube which hangs above the reflective surfaces and is the responsible of the radiation conversion into thermal energy. The secondary cylindrical mirror is located on top of the receiver tube, concentrating the solar light that has been slightly deflected from its trajectory and therefore has not collided yet into the lineal absorber.

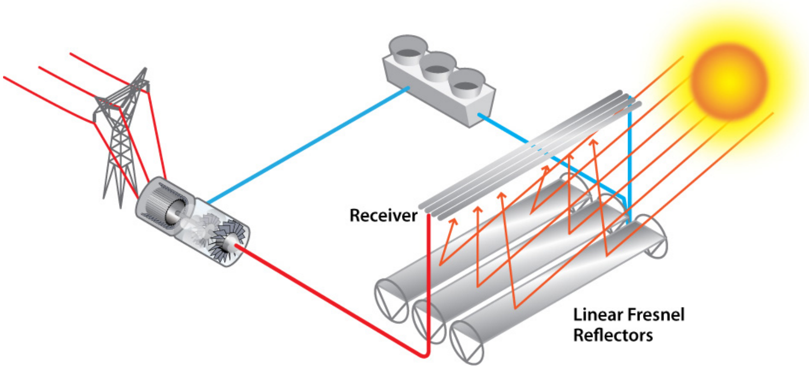


Figure 10: Linear Fresnel power plant [25].

Among the main disadvantages of these kind of power plants highlights the lack of maturity of this technology as well as its significant inferior performance compared to troughs. However, flat shape of these reflectors mean cheaper costs over curved mirrors and smaller footprints than other technologies. In the same way, fixed receivers permit higher pressures and thus direct steam generation [20].

Numerous power plants are currently under construction, especially in Spain and the USA. Kimberlina was the first compact LFR project by Ausra in North America. Construction of the power plant began in March 2008 entering into operation during October of the same year. Kimberlina generates up to 5 MW of electricity at full capacity to help meet California's peak summer demand [28]. Soon thereafter, the first commercial Fresnel power plant in Europe Puerto Errado 1 started operation in Murcia having an electric power of 1.4 MW. Power capacity of this Spanish power plant was highly surpassed after the construction of a second power station Puerto Errado 2 (PE2) by the same technological company Novatec Solar with 30 MW of electric power [29]. PE2 turned into the largest Fresnel power plant worldwide, record it held until March 2014 when the Dhursar power plant started operation in India with 125 MW.

2.2.3 Parabolic Dishes

Parabolic dishes consist of a reflective dish with parabolic shape which concentrates solar rays towards a receiver positioned at the focal point above its center. Both, the receiver and the dish move together tracking the sun and obtaining a concentrated map of energy. Parabolic dishes involve no cosine losses providing the best optical efficiency among the concentration technologies [20].

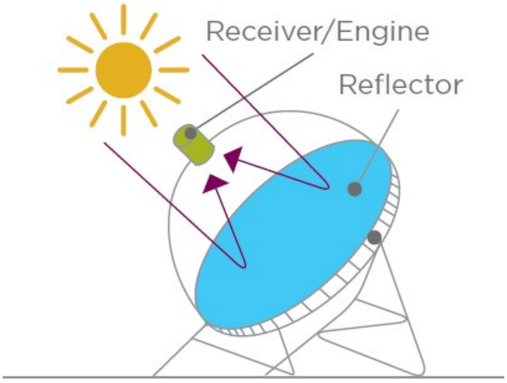


Figure 11: Parabolic dish collector [23].

These individual units include an engine generator located at the focal point of the reflector. The generator engine unit can incorporate a Stirling engine or a small size gas turbine. Two types of Stirling engines can be distinguished: Free piston and kinematic engines. Free piston engines use helium as working fluid and during normal operation do not cause friction, which reduces maintenance. On the other hand, kinematic engines work with hydrogen and present higher efficiencies than free piston engines [30]. The Stirling engine usually consists of two cylinders, one located at the cold focal point and another one at the hot, both connected by a pipe. The working gas shifts then between the hot cylinder, which receives the radiation, and the cold one by means of a set comprising pistons and connecting rods coupled to a common flywheel.

Parabolic dishes avoid the need of water usage for energy production which implies an advantage with respect to other technological designs. As each unit constitutes an individual system, these parabolic dishes do not seem to be suitable for large power plants but quite serviceable for the energy supply in remote and distant areas from the main grids, being modular and easy to connect within uneven lands. Parabolic dishes with Stirling engines have demonstrated high conversion efficiencies on the order of 30% although they generally have a limited power of 25 kW [31].

Within parabolic dish power plants incident solar radiation is concentrated towards the receiver placed on the focal point, where the transformer is connected. Energy absorbed by the receiver brings the thermal fluid flowing through it to operation temperatures around 550-750 °C [30]. The heated fluid runs a Stirling engine or micro-turbine installed in the same receptor, generating electric energy to serve directly to the grid.

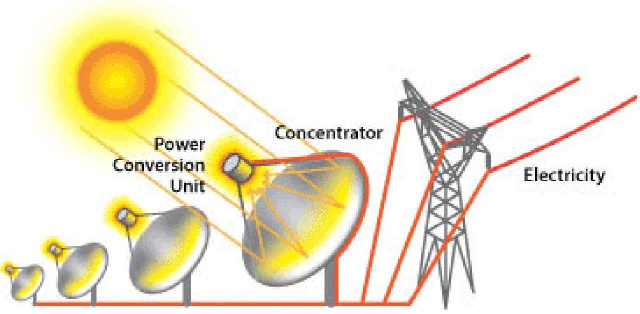


Figure 12: Parabolic Dishes power plant [25].

Among the existing projects around the world is one of the first power plants built at the beginning of the 80's in Australia composed of 14 parabolic dishes reaching 40 kW. Another relevant project which deserves special attention due to its substantial results is Solar 3 in New Mexico (USA). This power plant constructed in 2005 comprises 6 parabolic dishes which altogether generate 150 kW of power. Concerning Spain, the 10 kW Eurodish system located in Seville, became the first European solar thermal generator connecting to the grid on 24 March 2004 [30].

2.2.4 Solar Tower

Within the framework of the main solar concentration technologies currently used, this work focuses on a central receiver system. These kind of systems concentrate the solar radiation by means of a collector system composed of hundreds or thousands of flat reflectors known as heliostats. Individually orientated depending on the position of the sun, these flat mirrors concentrate solar irradiance with a ratio of about 1000 suns towards a central receiver located at a certain height above the ground on top of a tower [30]. Radiation focused towards an accurate focal point allows to reach higher concentrations and effective operation at higher temperatures. Heat is transmitted within the solar tower to a fluid with the objective of generating steam and spreading it subsequently in a turbine connected to an electric generator.

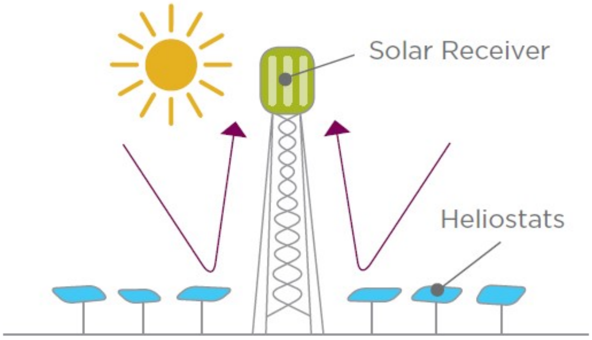


Figure 13: Solar tower system [23].

Heliostats arranged in circle reflect and concentrate the solar rays towards a central receiver located at the top of a tower. Inside the solar tower a fluid is heated up to temperatures higher than 500 °C and pumped afterwards trough a heat exchanger which absorbs the extremely concentrated radiation transforming it into thermal energy [20]. Pressurized steam generated within the heat exchanger drives a conventional turbine for the production of electric energy. The cycle comes to an end by means of a condenser which cools down and recovers the steam before starting again the whole process pumping it towards the heat exchanger.

The elevated temperatures that can be reached by the fluids of this technology allow its application not only to drive steam cycles, but also to run gas turbines and combined cycle systems. This kind of concentration system permits the storage of steam within a suitable tank which allows to increase the amount of energy generated beyond the direct exposure hours to solar radiation. Solar tower technology can incorporate an energy storage from up to 15 hours, this way the system is able to provide energy under cloudiness conditions or even at night [30]. At present, the most widely used solution consists of a steam or molten salts storage tank which accumulates the energy to be distributed at the right time. In this way, continuous operation of the power plant is possible throughout the 24 hours of the day.

Since this type of technology is taken as a case study, a detailed description of all subsystems making up a conventional central receiver power plant is provided within this subsection. Heliostats field and solar tower constitute the main distinction elements of this type of thermosolar power plants.

Solar Field

Central receiver systems use a specially distributed field of plane mirrors, known as heliostats, responsible for concentrating the solar radiation onto a common focal point. Each heliostat consists basically of a reflective surface, support structure, alt-azimuth mounting, foundation pedestal and control system. The support structure works as a bond between the collector and its foundation. This structure must withstand the worst case loads it may undergo, as much for the weight and dimensions of the mirror as for the wind load.

Heliostats work individually following the solar movement in order to focus light beams onto the fixed receiver located at the top of the solar tower. They can vary greatly in size, from about 1 to 160 m^2, and present reflective surfaces formed by several mirror modules which must be slightly curved if they are sufficiently large [20]. It must be taken into account that enlargement of the heliostat size can result in lower optical yields, greater maintenance difficulties as well as other side issues like its transportation and installation.

Solar Tracking System

Supporting structure of heliostats includes an electric engine to allow the orientation of the mirror by means of azimuth and height rotations, this is what is recognized as solar tracking system. This system is unable to perform an accurate solar tracking guidance for itself, but requires constant communication with the central control system of the power plant. In this way, it is guaranteed not only the energy consumption optimization of the heliostat's drive mechanism but the optimum distribution of the incident solar flux on the receiver. Even so, every heliostat must correct its position from time to time depending on the distance to the focal point it is heading at.

Solar Tower Receiver

Central receiver of a CSP plant is the device where conversion of concentrated solar radiation into thermal energy takes place. In most cases this is translated into the enthalpy increase of a specific fluid. Tubes receive radiation on its external section, conduct the energy straight through its walls and finally transmit it to the thermal fluid flowing through them.

Dimensions of the receiver must allow not only a reasonable thermodynamic performance but a homogeneous distribution of the incident radiation flux on its surface. A uniform distribution prevents flux peaks to exceed the maximum temperatures materials of the receiver can withstand without affecting its service life. At the same time, it enables minimal radiation overflow amongst the edges of the receiver, what is known as spillage.

In essence, fixed central receivers constitute the real core of any solar tower system for being the most complex technological element, its cited necessity to absorb incident radiation with the minimal losses and demanding conditions of concentrated flux.

Solar Tower

To ensure good system performance of the heliostats array, solar receivers must be installed at a certain height above the solar field. In other words, with the aim of achieving the maximum possible concentration, shadow effects and blocks of the heliostat field are reduced by placing the receiver at a certain height on top of a tower.

The height of the tower is one of the most important parameters within the optimization process of the solar field. This results from the fact that there exists an optimum elevation from which an increment in the tower height may harm the general performance of the field.

Working Fluid

Working fluids are generally defined as a liquid or gas which absorbs or transmits energy. In this sense, the working fluid of our power plant receives the energy reflected by the heliostats and concentrated onto the receiver. Then, the fluid transports the received heat from the receiver towards demand point with or without thermal storage. The most typically used working fluids within this type of concentrated power plants are briefly described below.

Water/Steam: Is the most common heat transport medium within the industry. At the exit of the receiver steam reaches temperatures in the range of 300 °C [32]. The main advantage of this working fluid is the fact that having reached the design conditions of the receiver, steam directly expands within the turbine without the need of intermediate heat exchangers to produce the desired steam.

Molten Salts: These usually consist of a binary mixture of sodium and potassium nitrates ($NaNO_3$-KNO_3) having appropriate melting points for steam generation. Molten salts constitute a relatively cheap and nontoxic transfer fluid having high heating values and conductivity. The mixture in liquid state circulates within the primary circuit, usually pressurized with nitrogen. Then heat is transferred to the secondary circuit being in charge of producing steam and powering the turbine. Molten salts provide an adequate medium as working fluid within the receiver as well as for thermal storage. This is the result of being a really stable fluid until 565 °C approximately and its capacity of remaining in liquid state until 238 °C [33]. Previously mentioned high solidification temperatures may lead to some problems. Therefore, provision should be made in order to avoid fluid solidification inside pipes, heat exchangers and storage tanks.

Liquid Sodium: Use of liquid sodium as high temperature fluid has been particularly developed within the nuclear industry. Sodium presents excellent properties for heat transfer allowing the use of extremely compact receivers having higher performances than the ones used by other working fluids. Sodium remains stable in liquid state until 540 °C and present melting points of the order of 98 °C [32]. The problem with sodium lies in its high reactivity with air and water, hence extreme caution should be exercised to avoid dangerous sodium leaks to the atmosphere. Due to its hazardousness, liquid sodium has now fallen into disuse.

Air: Last one joining the list of working fluids for solar receivers is air. Its use is intimately linked to volumetric receivers and presents the advantage of an easy operation and maintenance of the equipment. In addition, air is able to reach really high temperatures of about 1100 °C at the outlet of the receiver [32].

Control System

Primary role of the control system of a solar central receiver is to run the daily startups and shutdowns of the power plant. Shifting from one operation mode to a different one involves several stages and considerations, consequently control systems are required to automate the proper operation of the plant. For these reasons, design of the control system must be completely integrated within the process design of the entire power plant.

Thermal Energy Storage System

One of the main drawbacks of solar energy lies in its unsteady continuity over time. As concentrated systems only make use of direct solar irradiance a second constraint adds up, they require cloudless skies. This kind of radiation cannot be stored, but thermal energy transported by the heat transfer fluid. To overcome these problems thermal storage systems are available, allowing power plants to operate during periods of absence or high solar radiation variability. Traditionally, storage can be brought about in various ways described in the following paragraphs.

Sensible Heat Storage: Thermal energy captured at the receiver is stored within a given volume by a medium having great sensible heat properties. Most widely used fluids on today sensible heat storage tanks include thermal oils, molten salts and air (when volumetric receptors are being used). In the case of molten salts, storage systems involve two tanks where hot and cold fluids are separated and pumped towards the steam generator or the receiver respectively as needed for nominal operation conditions.

Sensible heat storage systems are commonly used within the industry of energy generation and can be implemented in two different ways: direct or indirect storage. Same working fluids are used at the receiver as well as for storage when discussing about direct storage. On the contrary, indirect storage utilizes different high heating fluids for the receiver and storage.

Lantent Heat Storage: Latent heat associated to phase changes of a substance provides another potential way of heat storage. However, it must be taken into account that temperature at which phase changes of the given substance occur must be compatible with the power plant requirements. That is to say, phase changes must take place at a temperature allowing steam generation at design conditions.

Thermochemical Heat Storage: Thermochemical storage is based on the accumulation of heat produced as a result of certain reversible chemical reactions. An appealing feature of thermochemical storage is the possibility of storing and carrying constituents of the system at ambient temperature. Nevertheless, only a few elements have sufficiently low costs to be considered as viable.

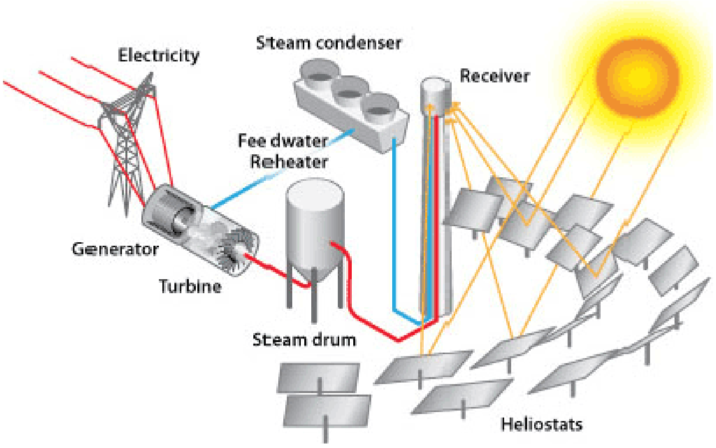


Figure 14: Central Receiver power plant [25].

In the world of countries at the vanguard of this type of technology, the most relevant ones include the American state of California and Spain. The first one was pioneer in the generation of electric energy on a large scale by means of a solar tower system thanks to the development of the well-known projects Solar

One (1982-1988) and Solar Two (1997-1999). Both with an installed capacity of 10 MW, differentiated by the fluid of the heat exchanger: it started with ordinary water and ended up being a mixture of molten salts, whose main physical property allows to keep an elevated temperature for long periods of time [31]. Furthermore, Spain has recently positioned cutting edgily within this technological sector thanks to a political investment relating to renewable energy sources. Nowadays, three major power plants of this type can be found in the surrounding areas of Seville; PS10 and PS20 with water as working fluid and Gemasolar with molten salts technology and 15 hours storage. PS10 consists of a solar field composed of 624 heliostats with a receiver tower of 115 meters tall and whose installed capacity reaches 11 MW. For its part PS20 and Gemasolar report an installed capacity of 20 MW and 19.9 MW respectively [31].

There exists a great variety of mirror shapes, solar tracking methods and ways of generating useful energy, as much for its immediate application as for its storage. Currently, concentrated solar power plants report about 50 and 280 MW of power capacity and even higher [21]. Storage can be integrated within these kind of power stations or hybrid operation with other fuels, offering solid power and large amounts of energy to answer the global demand.

2.3 Hybrid Power Plants

Most energy production systems currently in operation are not sustainable. Either because they are swiftly exhausting the planet resources or because they affect the environment in a dangerous way. Expected future increase of the energy demand worldwide will only worsen this situation. Thus, more efficient and clean ways of giving response to these energetic needs are required. Research advances become vital and development projects dealing with emergent technologies are needed to achieve these further objectives.

Hybrid power plants play an important role in the future of sustainable energy generation and suppose an attractive alternative to get rid of its adverse consequences. Combination of ordinary thermal power plants based on fossil fuels combustion with renewable energy sources allow the reduction of organic combustibles consumption. Use of primary fossil fuels such as coal or gas is reduced as part of the energy required to heat up the steam comes from renewable sources. Due to this combination, advantages of both fuels and renewable energies are banded together. Hybridization results then into constant energy production, savings on combustible and reduction of pollutant emissions.

Solar energy is one of the most undervalued renewable energies even though it provides a great number of technological alternatives. Further developments need to be promoted as that of the thermoelectric concentrated solar power plants and its possibilities of hybridization with combined cycles. As it has been previously explained, thermoelectric solar power plants generate heat or electricity by means of hundreds of large mirrors that concentrate solar light in a line or specific point. In this way, solar radiation is transformed into pressurized steam or gas at high temperatures to power up a turbine or a motor and supply the energy demand.

Today, CSP plants generate electricity in a similar way to the one used by conventional power stations. The difference resides in the fact that fossil fuels are completely or partially replaced by a renewable energy source, in this case solar power. Although solar radiation intermittence presents several challenges, technological advancements such as hybridization and the addition of thermal energy storage systems put forward a solution when facing those inconveniences.

Since sustainability and contamination lessening are the primary goals for CSP hybridization, emerging technologies are to be classified according to the renewable factor of the generated power: High, medium and low CSP hybrids. Hybridizations of CSP with renewable sources are presupposed to present the slightest environmental impact as approximately 70% of their power output has a renewable origin. For its part, effects of ordinary hybrids are mainly determined by their solar contribution, that is to say, a renewable energy fraction lower than 20% [34].

2.3.1 High Renewable Hybrids

CSP-biomass hybrids offer an encouraging renewable extension for the achievement of continuous plant operation as well as an attractive alternative to the thermal energy storage in places where long periods of energetic generation are required. Although initial investments of these kind of hybrids are high, biomass feedstock is available almost in every environment for CSP. Nevertheless, power plants must be located sufficiently near the renewable resource for them to be economically feasible. Global warming potential of energy production can be reduced up to 10 times thanks to these hybrid power plants with biomass extension [35]. Among the great variety of possible CSP-biomass technological combinations, solar tower and gasification result in maximum energy efficiencies of up to 33.2% [36]. Installed capacity of these plants is limited between 5 and 50 MWe as a result of the constant biomass supply required and overall cost considerations [34].

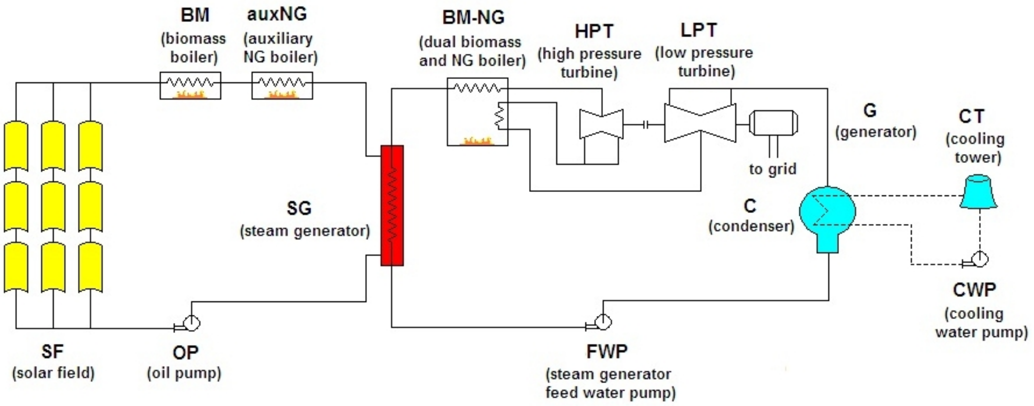


Figure 15: Termosolar Borges power plant diagram [37].

Termosolar Borges became the first operating commercial CSP-biomass hybrid plant located in Lleida, Spain. With a capacity of 22,5 MW and an electrical production of 98.000 MWh/yr, this power station has been in operation since December 2012 [34]. For this project, the solar unit uses parabolic troughs technology with thermal oil to generate power. For its part, the biomass block comprises two boilers in charge of supplying the required energy to the power block enabling the production of electricity with low or even absence of solar radiation. This allows uninterrupted operation of the steam turbine as well as an increase in the overall efficiency. These thermal units are compatible with both biomass and natural gas fuels. For this reason, although its main biomass resource comes from agricultural waste, supplementary natural gas can be used when required.

It is important to note that the objective of this work is the study of this kind of renewable plants and as a result an in-depth analysis will be carried out discussing the main subsystems conforming its power block.

Rankine Cycle

Generation system of a CSP plant consists essentially of the same elements that can be found within a conventional power plant system working with a Rankine cycle. In other words: Steam turbine unit, condenser, condensed steam pumps and steam boiler. This last component can be totally or partially substituted by the solar receiver. In the event of using steam, water is pumped through the solar receiver instead of using a boiler to evaporate water. Likewise, when using molten salts or air, steam boilers are replaced by intermediate exchangers where heat is transferred from the working fluid to the water.

Depending upon the type of designed power plant, different cycle configurations may be used. In general, larger base load plants need from reheating and/or regeneration stages, improving cycle performances but raising its cost.

Grid Conversion System

Outlet of steam turbines is directly connected to an electric generator, electric substation, distribution lines and support system. The electric generator is the device responsible for transforming mechanical energy into electricity by the action of a magnetic field onto the electrical conductors placed on the provisions of an armature. For its part, the electric substation is used for the transformation of grid voltage, by means of transformers, into the best adequate voltage to the needs.

Biomass Block

CSP plants often include small natural gas-fired boilers for startups or guaranteed controlled shutdowns. Thus, the biomass boiler itself is not really considered as an incorporation to the power plant. Needless to say, biomass fired steam boilers present and additional complexity, as they require the installation of a combustible storage and must be designed to prevent particles from entering the air. In the same way, further adjustments will be needed for each type of biomass.

Combustion chamber refers to the whole area where combustion within a boiler takes place and three main parts can be clearly distinguished. First one includes the zone where biofuel is blended with primary air and by means of a partial combustion, biomass is gasified becoming fuel gas. Within the second part of the boiler, a flame can be clearly seen and is the place where secondary air is introduced. Finally, third one consists of the remaining chamber with no visible flame. Combustion goes on but oxidation concentrations are low and invisible to the plain eye, although it is a key area for CO and combustibles reduction. In certain boilers this part can be separated and known as post-combustion chamber.

As a general rule, biomass combustion chambers present temperature ranges for optimum performance between 600 and 900 °C [38]. Below that temperature combustibles as much as CO increase dramatically. On the contrary, above that temperature NO_x levels soar as a result of nitrogen oxidation evoking to the need of more resistant and expensive materials for the construction of chambers.

Auxiliary System

Numerous elements are necessary for the proper functioning of any power plant. These components provide assistance to the main components of the power plant to fulfill their duties in an efficient, reliable and secure way. Some of these auxiliary components include: Compressed air systems, fire protection systems, refrigeration units, water storage and supply and auxiliary power supply.

CSP-geothermal hybrids take advantage of the thermal energy beneath the surface of the Earth to produce electricity. Conditional upon the kind of geothermal resource and the temperatures reached, several ways of using this energy are possible. Geothermal wells can be directly used to generate power, these natural water resources produce dry steam which operates a turbine. On its behalf, flash systems make use of pressurized hot water to generate steam within flash chambers capable of driving a turbine to produce the desired electricity. These kind of geothermal systems are the most widely known and used within geothermal power stations. Lastly, binary geothermal plants leverage on low temperature resources to generate vapors from an organic fluid with low boiling points. Despite the fact that these power plants are characterized by high capacity factors due to the steady supply of energy, efficiency of the plant is reduced as temperature of the resource goes down [39]. Therefore, hybridization with CSP technologies holds a promise to overcome some of the existing challenges geothermal plants have to face independently.

Stillwater was the first power plant to combine the mean enthalpy of a geothermal binary cycle with photovoltaic and solar thermal technologies in the same place. Located in Nevada (USA), this triple hybrid power plant integrates 33,1 MW of geothermal energy with 26,4 MW of photovoltaic power and 2 MW of solar thermal capacity. The combined plant is expected to produce about 200 GWh/yr of electricity [40]. Solar and geothermal energies are complementary, that is to say, solar energy production is higher during sunny and hot days when thermal efficiency of the geothermal plant is lower. Simultaneously, sharing the existing infrastructure reduces costs and the environmental impact of the plant by generated and delivered unit of energy.

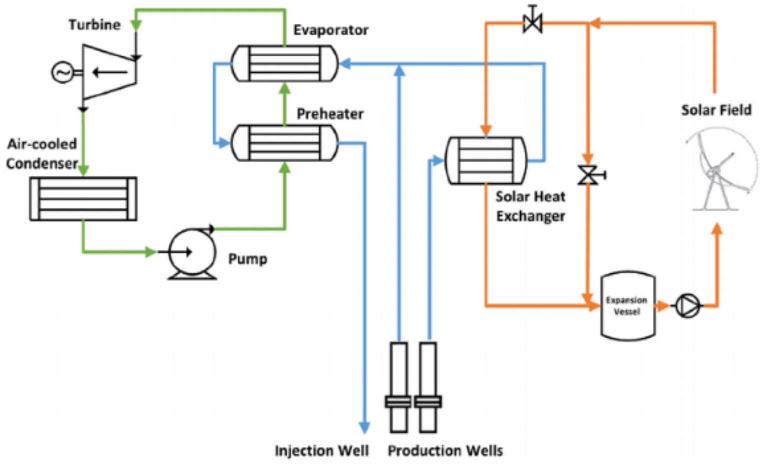


Figure 16: Stillwater power plant diagram [41].

CSP-wind hybrids are increasing their potential as an excellent renewable alternative for energy generation. Wind is widely available all over the world and provides the cheapest cost renewable energy, which increases its attractiveness for hybridization. The truth is that, combination of wind energy and CSP is a field that has yet to be explored in depth. This is mainly because both renewable energies do not have a wide synergy in terms of successful share of infrastructure, contrary to other thermal energy sources. In spite of their interference problems, they naturally complement each other as solar energy is more abundant during the day and summer while wind energy is more uniform in winter and at night. As far as wind and CSP is concerned, the exploitation of these energies can be carried out on a small scale as back-up or assistance for a reduced system, but not on a major scale as an alternative to conventional power.

2.3.2 Medium and Low Renewable Hybrids

Medium renewable hybrids relate to power plants taking advantage of fossil fuels as backup, especially natural gas, to keep a steady operation mode of the plant during low radiation periods. Nevertheless, in some countries there exist limitations on the maximum usage of these combustibles as an auxiliary energy source. This is the case for USA, where fossil fuels can represent only up to the 25% of the total output power, while in Spain the value is restricted to 12-15% [33]. Two main examples of these type of solar plants have been previously mentioned, the 19,9 MWe Gemasolar located in Seville and the 354 MWe SEGS in California, both including natural gas support.

Low renewable hybrids integrate solar power within conventional fossil fuel power plants for supplementary purposes such as preheating or steam injections. Solar energy within Brayton cycles can be used either to preheat the compressed air before it enters the combustion chamber or to produce solarized steam injections introduced into the heating appliance as high temperature fluid. In both cases, higher inlet temperatures lead to reductions in the fuel rate of consumption while increasing cycle performance.

The first model of this kind of solar hybrid gas turbine electric power system was analyzed under *SOLGATE* project located at Plataforma Solar de Almería in Spain [42]. The system comprised a solarized gas turbine, a modular receiver and auxiliary components. Principal objective of this first prototype was the development of a solar-powered gas turbine system with direct solar preheating of pressurized air for a gas turbine. The project successfully demonstrated the technological performance, feasibility and cost reduction potential of such power plants. Still in Spain, the first solar hybrid driven gas-turbine on a pre-commercial scale *SOLUGAS* was developed. The system receiver heats the pressurized air up to operation temperatures of 800 °C and later sent into the combustion chamber of a 4,6 MWe gas turbine [42]. This way, part of the required heat is added or even the entire combustion can be replaced if the solar input is sufficiently high to guarantee the inlet temperature of the working fluid at the turbine. Nevertheless, during days where solar radiation is weak or completely absent the system can still operate by means of the pure combustion mode.

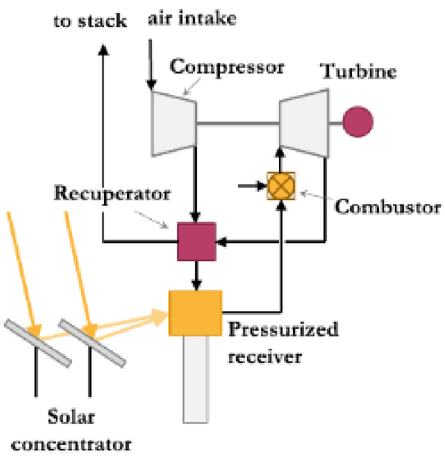


Figure 17: Solarized gas turbine plant scheme [34].

Solar-aided coal power plants represent a different method of solar energy usage within coal-fired power stations for preheating, boiling or both applications. Solar power substitutes the purge steam used for feed water preheating within a regenerating Rankine cycle. Boiling is suggested to be the best configuration if we are looking for a reduction in the fuel consumption, whether other indicators such as performance depend on the position of integration and the size of the plant.

Two main projects can be highlighted within the framework of solar-aided coal power plants although both of them are currently non-operational and near closure; *Liddell* power station in Australia and the *Colorado Integrated Solar Project* located in the USA. Both systems use compact Fresnel reflectors to produce solar steam for feed water heating. Liddell power plant commissioned between 1971 and 1973 produces 2 MWe of electricity with a solar capacity of about 3 MWe [43]. For its part, the Colorado Integrated Solar Project reduces coal consumption by 900 tons due to solar integration and generates about 2 MWe [34]. These projects demonstrate that ordinary power plants can be replaced by a combination of newer and cleaner technologies to provide with superior affordability and reliability improvements.

Regarding **Integrated Solar Combined Cycles (ISCC)**, operation is similar to that of a conventional combined cycle power plant, fuel is burnt as usual inside the combustion chamber of the gas-fired turbine. Heat from the solar field is added to the exhausted gases that head for the heat recovery system. Consequently, steam generation capacity as well as fuel savings increases with the corresponding emissions reduction. In the same way, this solar integration leads to higher operation and global costs of the solar thermal electricity. At present, various ISCC plants are functional or under construction across the globe.

In the end, the idea is combining the environmental benefits of solar energy along with the operating advantages of an ordinary combined cycle with steam and gas turbines. Basically, it benefits from an existing infrastructure within an ordinary thermal power plant including the connection of the energetic transmission lines to the power grid. This makes hybridization profitable and creates a path to less pollutant energy generation.

2.4 Wastewater Management

Water is both a right and a responsibility. It has economic, environmental and social value. Everyone must be aware that fresh water is a scarce natural resource needed not only for economic development but essential to support any form of life in the nature. From 60% to 80% of safe drinking water is transformed into sewage. If water coming from rainfall is added, higher numbers could be reached to those of consumption [44]. For this reason, reutilization of available water resources is indispensable to satisfy the basic human needs.

2.4.1 Definition and Sources of Wastewater

Sewage or wastewater is a certain consequence of human activities. From complex industrial processes requiring large amounts of water to simple household uses. Rainfall and subterranean infiltrations can be also considered contaminated water, especially when global warming presents direct impacts on its quality and availability. All these activities modify the characteristics of fresh water, polluting it and invalidating its later application for other uses. In general, wastewater contains organic matter, fats, industrial wastes but also detergents and toxic substances among others.

On account of the great quantity of substances and microorganisms they carry, effluents can be the reason for the pollution of places where they are spilled without previous treatment. Sometimes release of wastewater can even cause irreversible damages to the environment. What is more, not treated liquid waste supposes important risks for the public health. For this reason, sewage needs to be subjected to a series of physical, chemical and biological processes with the objective of reducing its concentration of pollutant content. Subsequently purified water can be discharged or reused minimizing the risks as much for the environment as for the population. Suitable treatment of wastewater and its later reuse for many different applications contributes to the sustainable consumption of water and environmental regeneration of the ecosystems.

2.4.2 Wastewater Treatment Levels

Before being spilled or reused in a safe way, sewage must receive an adequate treatment according to its specific composition. By means of wastewater treatment plants, sufficient quality can be returned to water so that it can be used again. The aim of this process consists on the elimination of pollutants of natural, industrial and domestic origin present in water.

Selection of specific treatments depends also on a series of water characteristics such as suspended matter, toxic substances and BOD (Biochemical or Biological Oxygen Demand) [45]. BOD parameter determines the amount of dissolved oxygen demanded by microorganisms to break down the organic matter contained within sewage. Depending on the quality of the received wastewater, more or less treatments will be required, though essential ones consist on: Collection, pretreatment, primary, secondary and advanced or tertiary treatments.

First phase of the purifying process consists on the collection and guidance of sewage towards the purification plant through a complex network of pipes. This is known as **wastewater collection**. Depending on the topography of the region, water can flow towards the facility location by gravity or necessary pumping might be required. Once the plant is reached, the first thing the flow encounters is a preliminary treatment.

Within **pretreatment** several physical and mechanical operations are carried out in order to separate from wastewater the major quantity of coarse suspended solids and grit that might cause problems in the course of posterior treatments. This type of matter include garbage, grease and oils among others.

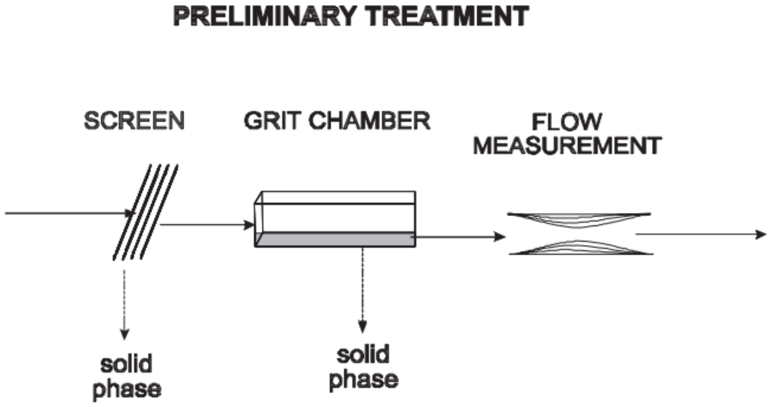


Figure 18: Preliminary treatment diagram [46].

Coarse solids removal is frequently done by screens or racks, even though comminutors and rotating or static screens can also be used. During screening, large materials which do not fit between bars are removed either manually or in a mechanized way. Basic purposes of coarse solids removal include the protection of wastewater transport devices, such as pumps and piping, as they can clog processes or damage machinery. In the same way, subsequent treatment units and receiving bodies are protected due to this preliminary treatment.

Removal of sand and gravel contained in wastewater is carried out by special units known as grit chambers. Sand removal mechanism is based on sedimentation; settlement of sand grains at the bottom of the tank takes place due to their larger density and dimensions. Meanwhile much lighter organic matter stays suspended at the top and goes on towards downstream units. Removal and transportation of settled grid can be accomplished by means of many processes, from manual to completely mechanized units. Grid is removed from sewage in order to avoid abrasion and reduce the possibility of plugging within pipes and mechanical equipment.

This preliminary process usually includes a flow measurement unit so that the amount of wastewater to be treated is quantified. It consists on a standardized channel where the controlled liquid level can be linked with the flow. Closed-pipe measurement mechanisms and weirs of different shapes can also be adopted. In addition, sampling equipment is often used to enable the identification of influent pollutants entering the plant. Eventually, raw sewage pumps drive the flow to the next treatment phase.

Primary treatment seeks to remove precipitable suspended and floating solids present in sewage by means of physical and chemical procedures. After moving past the preliminary treatment units, wastewater still carries non-abrasive suspended solids which can be partly eliminated within circular or rectangular sedimentation tanks.

Wastewater flows slowly into the sedimentation tanks, allowing the settlement of the suspended solids due to its greater density with respect to the surrounding liquid. Resulting accumulation of solids at the bottom of the tank is known as raw primary sludge that is to be subsequently removed. Lighter materials, such as oil and grease, tend to have lower densities than the enclosing liquid and therefore these substances rise to the surface and float at the top of sedimentation tanks. In the same manner as for sludge, these floating materials are collected and removed from the tank for succeeding treatment.

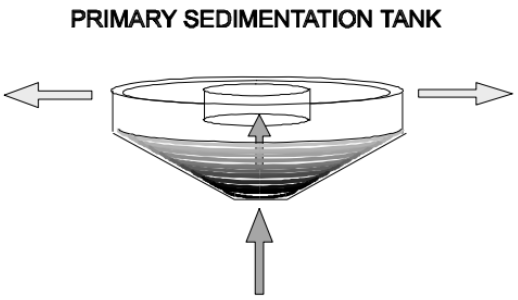


Figure 19: Sedimentation tank [46].

A meaningful part of these removed suspended solids is comprised of organic matter. For this reason, its mere removal through sedimentation implies as well a reduction in the BOD load of wastewater. Effectiveness of primary treatment may be intensified by the addition of coagulants and flocculants. Coagulant agents consist of chemical substances like aluminium sulphate ($Al_2(SO_4)_3$) or ferric chloride ($FeCl_3$) which are added to neutralize system loads, while flocculation is carried out by organic polymers [45]. These compounds are absorbed and work as bridges between particles with the aim of increasing the size of the created clots and thus, improve the decantation speed of suspended solids.

Physical treatments are applied to wastewater containing suspended inorganic pollutants or not biodegradable organic matter. For its part, chemical processes are used to eliminate soluble substances by means of chemical agents such as flocculants and coagulants which improve the separation of particles. Removal of these components reduce the risk of incidents within the next units of treatment.

Secondary treatment consists of the removal of dissolved and suspended organic matter that remains in sewage. While preliminary and primary treatments involve physical procedures, second operational levels require the action of microorganisms to undertake a series of biochemical reactions in order to eliminate the remaining organic matter. A diverse group of microorganisms participate in this process such as bacteria, fungi, protozoa and others. Most common and efficient existing secondary treatment processes are to be discussed below.

Stabilization ponds: Waste stabilization ponds comprise a series of different man-made water bodies modelled by simple ground movements which can be used separately, or connected in sequence for a more enhanced treatment of sewage. Three basic types can be distinguished; Anaerobic, facultative and maturation ponds, each one presenting different kinds of treatments and characteristics of design.

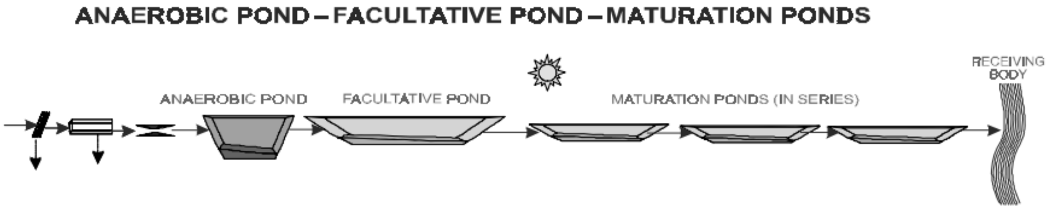


Figure 20: Typical flowsheet of a system of stabilization ponds [46].

Firstly, raw sewage enters the primary treatment stage known as anaerobic pond. The entire depth of this earthen basin is anaerobic and is the place where removal of BOD and solids occurs. Due to the slower rate at which anaerobic bacteria decompose organic matter, BOD is not removed completely during this first stage. However, this partial reduction of BOD up to 60% [45] contributes considerably decreasing the amount of organic matter load for the facultative pond located downstream. Effluent flows then from the anaerobic towards the facultative pond where further BOD is eliminated.

Within facultative ponds settleable solids and particulate organic matter accumulate and are digested at the bottom of the pond. This organic decomposition takes place in an anaerobic environment as oxygen is deprived of this lower layer. On its behalf, dissolved BOD together with fine particulate organic matter in suspension stays spread out in the liquid mass. Both components are aerobically stabilized by bacteria which generate an oxygen demand supplied to the medium by wind mixing, natural diffusion and algae driven photosynthesis. Aerobic and anaerobic organisms work together inside facultative ponds to achieve a reduction of BOD of about 70-90% depending on the application or not of a filtered basin [47].

Last step of the treatment consists of a shallow aerobic pond generally known as maturation or polishing pond. Its main objective does not include the additional removal of BOD, but the elimination of pathogenic organisms contained in sewage. Principal mechanisms of fecal bacteria and viral decay are driven by the algae activity along with photo-oxidation.

Anaerobic reactors: They are essentially bioreactors where microorganisms transform organic matter into biomass that is to be removed from the treatment system. Nowadays, anaerobic reactors represent a cutting-edge technology regarding the adequate processing of domestic wastewater and a variety of industrial sewage. Most widely used reactors include anaerobic filters and UASB (Upflow Anaerobic Sludge Blanket) reactors [46].

Generally, a system of septic tanks precede anaerobic filters. This is where most solids in suspension undergo anaerobic reactions and are removed by settling. Septic tanks are basically sedimentation tanks, and thus, BOD removal is not complete. Sewage, still containing high concentrations of organic matter flows towards the anaerobic filter, where further elimination of these components is carried out in the absence of oxygen. Anaerobic filters consist of biofilm reactors in which wastewater flows through a mass of biological solids located inside the reactor. This way, dissolved organic matter contained in the effluent come in contact with the biomass, being scattered through the biofilm surfaces or the granular sludge.

UASB reactors consist essentially of an ascending stream of sewage crossing through a dense sludge bed with important microbial activity. These reactors allow the conversion of influent wastewater with high organic load into a biogas or even a stabilized fertilizer. Sewage enters the reactor at the bottom, where it meets the sludge blanket, easing the adsorption of organic compounds by the biomass. On the other hand, effluent exits the unit through an inner sedimentation tank located at the upper part of the reactor. Organic matter conversion occurs in every sludge area, the system combination is fostered by the ascending flow of sewage and gas bubbles.

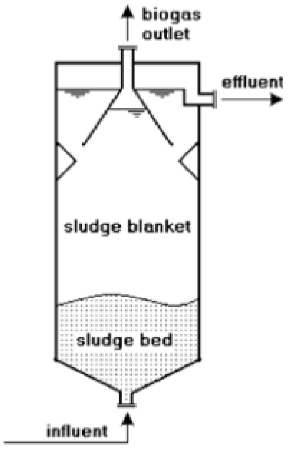


Figure 21: Scheme of an USAB reactor [46].

In order to reach higher BOD removal efficiencies some form of post-treatment must ensue from the anaerobic processes. These succeeding treatments may have a biological or physical-chemical origin. Their objective is the compliance of the main existing discharge and reuse standards. The most common biological procedure regarding UASB post-treatment is known as activated sludge process.

Activated sludge system: Activated sludge processes refer to a multi-chamber reactor unit that make use of microorganisms to feed on organic contaminants contained in sewage. This results in a high-quality effluent caused by the degradation of organic matter and nutrients removal. To keep activated sludge in suspension and the demanded aerobic conditions, oxygen is uninterruptedly supplied.

Conventional activated sludge systems comprise an aerated reactor and a secondary sedimentation tank. Pumps for sludge recirculation are also required as well as the removal of biological sludge excess. Inside aeration tanks, oxygen demand within the liquid mass is reduced by means of biological processes. Microorganisms make use of organic matter as nutrients converting them into biological mass like cellular material, water molecules and carbon dioxide. These aerobic systems require continuous aeration as a consequence of the high oxygen consumption required by the microbial oxidation. Oxygen is provided at the aeration tank either by diffusers and blowers or by a mechanical mixing process. Generated biomass is separated later within the secondary settling tank as a result of its flocculating property.

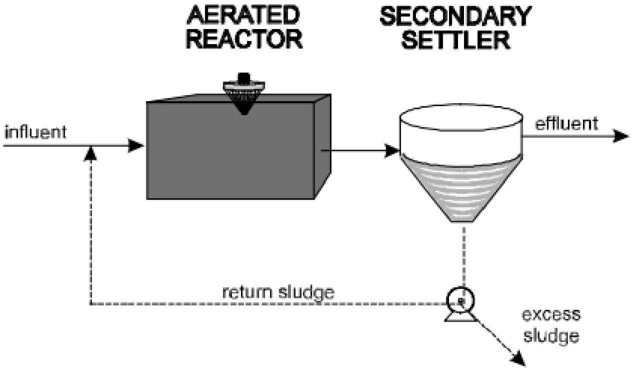


Figure 22: Conventional activated sludge system [46].

A variation of the activated sludge process that is becoming more popular nowadays are Sequential Batch Reactors (SBRs). This process differs from the conventional system in the incorporation of all units comprising the activated sludge process within a single tank. This way, the process consists of a complete mix-reactor where all these processes and operations occur in sequence. Use of the aerator as a settling tank is achieved by turning off the air towards the diffusers and allowing solids to separate from sewage. Nevertheless, for the proper treatment of residual wastewater more than one SBR would be required since only during tank filling time incoming effluent can be received.

Activated sludge processes may also include the removal of nitrogen and phosphorous. This treatment consists of biological reactors presenting two main removal zones. Anoxic area is located all along the aerated zone and characterized by the presence of nitrates. Nitrates generated within the aerobic zone are reduced to gaseous molecular nitrogen, which is later released into the atmosphere. In the same way, there exists an anaerobic zone situated at the upper part of these biological reactors, where phosphorous contained in the liquid is absorbed by microorganisms. Withdrawal of these microorganisms along with the excess sludge leads to the removal of phosphorous.

Lastly, **tertiary treatment** aims at the elimination of specific compounds not removed yet by primary and secondary stages. This advanced process, also known as disinfection, basically consists in killing or inactivating pathogenic organisms so they can not reproduce. Natural processes include treatment mechanisms previously mentioned such as maturation ponds and land treatments. However, most processes applied for the total removal of disease causing microorganisms consist of artificial methods comprising chlorination, ozonization, ultraviolet radiation and membranes. Each disinfection technology present unique strengths, limitations and costs. In fact, no single disinfection method is suitable for all circumstances, a sequence process may be required to meet specific treatment objectives.

Water *chlorination* is one of the most usual and effective disinfection methods. It is capable of destroying great amounts of bacteria, mildews and other dangerous microorganisms such as fecal traces, Escherichia coli and legionella. Chlorine is a relatively low cost treatment option used to enhance water flavor and clarity while eliminating the previously mentioned microbes. Chlorination can be applied and achieved in several forms.

Chlorine is stored in liquid state within pressurized containers and directly injected in gaseous form into the water. This process needs to be controlled and carefully applied, due to the fact that elemental chlorine (Cl_2) is a hazardous even lethal toxin.

Another alternative of major cost is the sodium hypochlorite solution ($NaClO$) treatment [48]. This corrosive solution, also known as liquid bleach, is much less harmful and easier to manipulate than chlorine gas. This liquid is simply diluted and afterwards mixed with water to conduct disinfection.

Chlorination can be also fulfilled by means of a water-soluble solid disinfectant, dry calcium hypochlorite ($Ca(ClO)_2$) [48]. This corrosive material can go off when it enters into contact with organic materials. Nevertheless, all these powders, granules and tablets can be stored in bulk and used efficiently up to a maximum of one year.

All chlorination methods discussed above take their time to come into effect, disinfection does not occur instantaneously. While varying in concentration and form, each option produces “free chlorine” to attack microbes present in water. Necessary doses change as well along with water quality variations so that monitoring of the water source becomes an essential part of the treatment process. Disinfection processes may also use other oxidants such as ozone, and ultraviolet radiation.

Ozonization is widely used within water treatment, both drinkable and sewage. is widely used within water treatment, both drinkable and sewage. It allows the elimination of organic as much as inorganic compounds, diminishing smell, color, flavor and turbidity of waters. In spite of its higher initial costs, ozonization is a powerful disinfecting agent due to its high reactivity and low solubility. Corona discharges are the most common mechanism for the on-site generation of ozone (O_3), also known as silent electrical discharges [49]. Oxygen in gaseous form or dry air passes through a system of high voltage electrodes separated by a dielectric and a hollow of discharges. Voltage is applied to electrodes, causing the flow of an electron across the discharges hollow. These electrons supply the required energy to separate oxygen molecules, resulting in the formation of O_3. Ozone is more often applied for oxidation rather than disinfection alone.

Ultraviolet (UV) radiation consist of a non-chemical process where microorganisms are neutralized at once as they go through ultraviolet lamps plunged within the effluent. UV radiation efficiently deactivates germs as this kind of light damages genetic material within cells preventing their reproduction [50]. This process only requires the use of UV light and therefore does not have any influence on the chemical constitution of water or its dissolved oxygen content. Efficiency of UV light depends on the characteristics of the effluent, the radiation intensity as well as the exposure time of microorganisms to radiation.

Membrane filtration constitutes a physical barrier for pathogenic microorganisms as well as other suspended solids having larger dimensions than membranes. Membranes act as a filter allowing the flow of treated sewage through extremely small pores which remove these microscopic substances. Costs of this process are still high but it does not bring any chemical into the liquid. Membrane processes can be pressure driven, or dependent on electrical potential gradients, concentration gradients, or other driving forces [51].

Pressure-driven membrane processes include ultrafiltration and reverse osmosis. Ultrafiltration is characterized by its ability to remove suspended solids, bacteria and viruses in order to obtain water with high purity levels and low sediments density. Particles of about $0.001 - 0.1\ \mu$m can be retained within this kind of membrane filtration process [51]. Low pressure is used to force fluids through the membrane, which results in minor operation costs. In addition, it is quite effective as a previous treatment to reverse osmosis.

For its part, Reverse Osmosis (RO) constitutes a process where water is demineralized or deionized by forcing it under pressure through a semi-permeable membrane. This membrane allows the passage of water molecules but not predominant organics, dissolved minerals and microorganisms. In this way, majority of pollutants are retained securing pure water. As stated before, RO can eliminate most suspended elements contained in water including pathogens. It is mainly used within industrial processes as well as for the production of drinkable water.

2.4.3 Water Quality Requirements

Oceans take up three quarter parts of the Earth's surface and contain about 97% of its water. However, only 3% of the existing water is fresh, which ultimately makes it an essential scarce resource in certain areas, as much in quantity as in quality. On the previous percentage, only 1% accounts for consumable water since great part is frozen in glaciers as well as present within soil humidity or remaining inside inaccessible underground aquifers [52]. Fresh water resources around the world are constantly being replaced by a continuous cycle of evaporation, rainfall and overflow. Hydrological cycle determines in this way the distribution and availability of fresh water across time and space.

Awareness of global water scarcity has changed the general plans of wastewater. Today, the main objective is not only the achievement of a sufficiently purified water to be spilled in a natural bed, but leverage of these waters for different uses, that is to say, its reuse. According to its origin and application, various types of water can be distinguished; treated, regenerated and potable water.

Treated water consists of the water coming out from the filter system, where it arrives originated from our houses, industries and other commercial establishments. Within the filtering system water undergoes the required processing to serve a specific end use. However, the term treated water refers to sewage that once treated and having good quality conditions is returned to receiving bodies such as rivers and seas.

Regenerated water is defined as the purified water that has been additionally treated in order to take advantage of its in non-direct uses. In this sense, we can distinguish three main applications for regenerated water: Urban, agricultural and industrial use.

Potable water is the natural water that has been previously treated to be suitable for human consumption. Either through physical processes to clarify the water or by means of chemical treatments to eliminate bacteria carrying diseases. As previously stated, the most common chemical treatment to obtain this desired drinking water is the addition of chlorine.

Applied treatment processes to obtain the above kinds of water are related to a large extent to its future reuse. Therefore, there exist purifying treatments whose destination is merely human consumption and wastewater processes bounded for agriculture, irrigation, industry and others. Imposition of different treatments is necessary to generate water having high salutary conditions and the required level of purification to be suitable for its various applications. Compliance and regulation of the specific quality standards of water is a basic duty to guarantee the absence of pollutants and microorganisms that pose a risk for public health.

INTENDED USE OF WATER	Maximum Acceptable Value (MAV)			
	Intestinal Nematodes (egg/10L)	Escherichia Coli (CFU/100mL)	Suspended Solids (mg/L)	Turbidity (NTU)
1. Urban Uses				
Quality 1.1: Residential a) Irrigation of private gardens b) Supply to sanitary appliances	1	0	10	2
Quality 1.2: Services a) Landscape irrigation of urban areas b) Street cleansing c) Fire hydrants d) Industrial washing of vehicles	1	200	20	10

INTENDED USE OF WATER	Maximum Acceptable Value (MAV)			
	Intestinal Nematodes (egg/10L)	Escherichia Coli (CFU/100mL)	Suspended Solids (mg/L)	Turbidity (NTU)
2. Agricultural Uses				
Quality 2.1: a) Direct crop irrigation	1	100	20	10
Quality 2.2: a) Indirect crop irrigation b) Irrigation of pasture land for milk c) Aquaculture	1	1000	35	No set limit
Quality 2.3: a) Tree crops irrigation b) Ornamental flowers irrigation c) Industrial non-food crops irrigation	1	10000	35	No set limit
3. Industrial Uses				
Quality 3.1: a) Process and cleaning water (except for use in the food industry) b) Other industrial uses	No set limit	10000	35	15
c) Food industry process and cleaning water	1	1000	35	No set limit
Quality 3.2: a) Cooling towers and evaporative condensers	1	-	5	1
4. Recreational Uses				
Quality 4.1: a) Golf course irrigation	1	200	20	10
Quality 4.2: a) Ornamental ponds and lakes	No set limit	10000	35	No set limit
5. Environmental Uses				
Quality 5.1: a) Aquifer recharge by percolation	Not set limit	1000	35	No set limit
Quality 5.2: a) Aquifer recharge by direct injection	1	0	10	2
Quality 5.3: a) Irrigation of woodland and green areas b) Silviculture	No set limit	No set limit	35	No set limit

Table 1: Quality criteria for the non-direct reuse of water [53].

2.4.4 Potable Water Generation

As the saying goes, “wastewater is not a waste, wastewater is a resource” and increasingly valuable. As a direct consequence of global overpopulation safe drinking water demand will increase significantly in the future. However, ever-present availability limitations pursues this water demand. This is the case for aquifers and surface waters such as reservoirs and rivers whose natural refill depend on rainfalls. A further alternative water resource is the one coming from the sea, practically infinite, but presenting two great issues: the need of proximity of the recipient to the sea and the high cost of exploitation to desalinate water. These factors fuel that within the last decades water reuse was seriously considered an inexhaustible and necessary source to satisfy water consumption worldwide. Safe water reuse takes place in two different ways: Indirect or direct potable reuse.

Indirect Potable Reuse (IDR) projects include the application of a non-potable regenerated water, previously filtered and disinfected by means of a superficial infiltration. In other words, the application of purified water previously subjected to a multi-barrier treatment system for its incorporation to a superficial water reservoir. IPR is considered as indirect as it requires the use of an environmental buffer in between the incorporation point of regenerated water and the point from which is it later extracted for its reuse as safe drinking water.

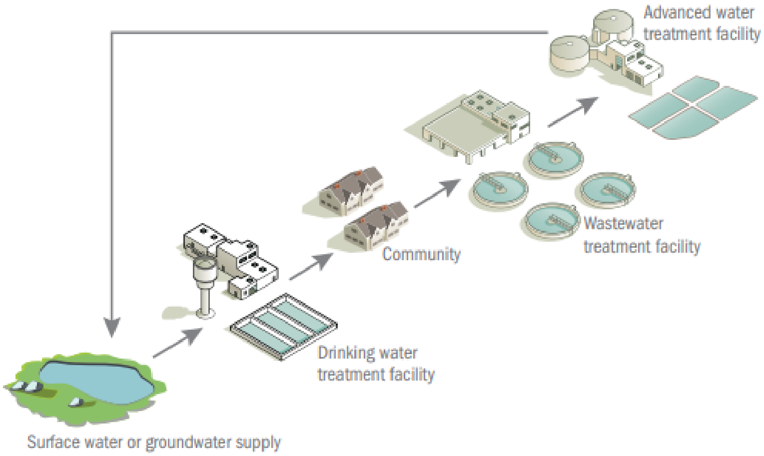


Figure 23: Flow schematic of indirect potable reuse [54].

Aquifers recharge with wastewater has served for rivers supply. Such is the case of *Orange County Water District (OCWD)*, located in California’s southern coast between Los Angeles and San Diego. The facility manages a large aquifer from which water is extracted to satisfy 75% of the total county demand, providing service to approximately 2,3 million people. Due to rising water demand, extraction was increased leading to the reduction of water level and salt water intrusion from the Pacific Ocean. In pursuing the recovery of the aquifer as well as its proper management OCWD was formed in 1933 [55]. Apart from increasing water supply, since then, water district of the Orange County undertook the development of the subterranean water replacement using highly treated regenerated water.

Scottsdale Water Campus reclamation plant was designed to enhance the capacity of treated water to recharge the aquifers of Arizona since 1980. Two treatment systems are currently operating in Scottsdale to regenerate sewage: Water Campus and Gainey Ranch. These installations have the capacity to produce more than 20 mgd of regenerated water 365 days per year [55]. Most of the treated water within Water Campus of Scottsdale is distributed over several golf courses in North Arizona. The remaining water is subjected to an additional treatment, using a combination of advanced technologies for subsequent pumping to the aquifer by means of recharge wells or infiltration at unsaturated zones.

NEWater treatment plant represents a promising strategy for drinking water supply in Singapore. This small island has an average annual rainfall of 2,4 mm and water consumption of 1,36 million m3 of which 50% is used by the industry, while the rest is intended for trade and domestic use [56]. NEWater takes advantage of the multiplier effect of water reuse to provide with high quality water to meet the criteria for human consumption. Nevertheless, this water is mainly used for non-direct applications as well as recharge of superficial reservoirs for potable reuse.

Direct Potable Reuse (DPR) implies the absence of any environmental buffer. Purified water is directly blended into the existing water supply system. Two different approaches can be distinguished when implementing DPR, both applying advanced treatments but differing in the location of blending. First one blends purified water with raw water supplies before undergoing additional treatment process within reclamation plants. Second approach involves direct blending of finished water produced within this advanced water treatment facilities into the potable distribution system.

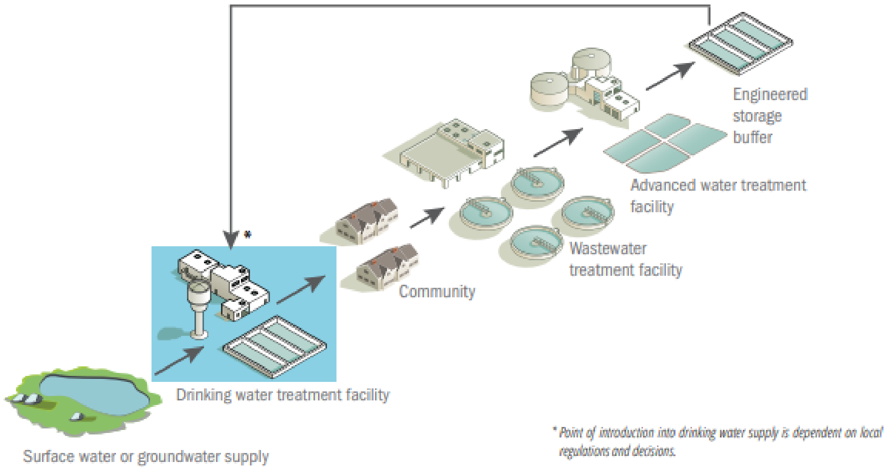


Figure 24: Flow schematic of direct potable reuse [54].

On account of potable reuse, especially high-quality water is provided and as a result the type of end-users are more diverse than for other kinds of reclaimed water. Apart from drinking water, applications may include industrial processes, landscape and agricultural irrigation and other municipal uses. At present, various DPR projects are in operation or under construction.

Wichita Falls River Road wastewater treatment plant located in the American state of Texas began its operation in July 2014 as an emergency potable water supply in response to severe drought conditions [57]. Chlorinated secondary effluent is subjected to microfiltration, reverse osmosis and ultraviolet disinfection, and finally combiined with other fresh water sourcings before being conventionally treated at the DPR facility. Microfiltration and reverse osmosis advanced treatment systems were originally installed to treat salty surface waters and will recover its initial application in the future. This facility is currently decommissioned as a consequence of significant rainfall events during 2015.

Colorado River Municipal Water District Raw Water Production Facility Big Spring purification plant provides an additional clear example of this kind of DPR facilities in Texas. This DPR process has been operating since spring 2013 [58]. Filtered secondary effluent is treated with microfiltration, reverse osmosis, UV radiation and advanced oxidation process. Afterwards, treated water is mixed with raw water within a transmission line for being subjected to further treatment at a drinking water treatment facility before its distribution.

Goreangab Reclamation Plant constitutes the only known real example of direct potable reuse at present, located in Windhoek (Namibia). Within this advanced treatment plant reclaimed water is directly blended into the potable water distribution system providing with supplementary water for human consumption. It started operating in 1968 with the aim of averting water shortages in the region, becoming the first place in the world where this kind of process was introduced [58]. However, throughout the years its treatment train has been continuously evaluated and upgraded in order to find the most effective processes and barriers to safe drinking water. Furthermore, regular samples and monitoring became also part of these plant improvements.

Potable reuse offers diverse benefits including a local and trustworthy water resource in the presence of drought, a reduction in the dependence of water transfers, a general improvement of water quality and a lower water discharge to the seas. Nevertheless, it also entails various requests such as the acceptance of the participants, public perception and the relative concern to a major exposition before the emergent pollutants. Lessons learned from consolidated water purification programs provide a magnificent starting point for water companies considering potable reuse by describing the different stages to be followed within its development and implementation.

3 Methodology

This section covers the specific procedures used to conduct the extensive analysis of the designed system proposal. As a general rule, most engineering projects follow this kind of methodology. This proceeding bases its success on a good background documentation with the aim of having a major source of information to work with. Accurate material provides not only advanced identification of the principal necessities to study subsequent requirements but the approach of different alternatives and solutions for the project application.

Conduction of the following technical, exergetic and economic analyses supports the final decision concerning the type of thermosolar plant to be developed.

3.1 Exergetic Analysis

Exergy is the thermodynamic name of energy quality. Exergy of a system can be defined as the “Minimum theoretical useful work required to form a quantity of matter from substances present in the environment and to bring the matter to a specified state” [59].

Exergy concept is derived from the joint application of the First and Second Thermodynamic Principles. It is quite useful for knowing the amount of work that can be obtained from a specific source. When applied to the different streams of the system being analyzed, it provides valuable information impossible to obtain just by the energy concept application. All required balances to conduct the required exergetic analysis of the designed power plant are contained within this chapter.

3.1.1 Solar Exergy

Exergy of solar power received by the sun can be calculated using the following equation.

$$\dot{E}_s = \dot{Q}_s \cdot \Psi_s \tag{1}$$

where, $\dot{Q}_s$ is the direct solar irradiance available onto the solar field, defined by the DNI and the reflective surface occupied of the heliostats, and Ψ_s is the ratio between exergy and energy calculated as:

$$\Psi_s = \left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right] \tag{2}$$

where, T_a is the ambient temperature and T_s is the apparent black body temperature of the sun with a value of 5,600 K.

3.1.2 Exergetic Efficiency

A major use for exergetic efficiencies includes the performance evaluation of the principal components comprising the power plant. From this thermodynamic point of view, exergetic efficiency provides a real measure of the productivity of a power system.

Before determining the exergetic efficiency of the analyzed thermodynamic system it is essential to note first both a product and a fuel. Products describe the desired outcome originated from the specific system. For its part, fuel is defined as the supplies consumed to give rise to the final product and is not limited to being an actual fuel but the required amount of work to carry out the desired process. Therefore, the exergetic efficiency ε represents the existing correlation between the product and the fuel of the thermodynamic system being analyzed:

$$\varepsilon = \frac{Product}{Fuel} \tag{3}$$

Determination of the exergetic efficiency of an energy system requires the previous calculation of the exergy provided by the fluids crossing them, which mainly constitute the products and fuels of every component. Exergy of the different fluids involved needs to be obtained at both entry and exit of each device. Equation 4 allows the calculation of the exergy provided by any kind of fluid going through a component.

$$\dot{E}_f = \dot{m}_f \left[(h_i - h_o) - T_a \left(s_i - s_o \right) \right] \tag{4}$$

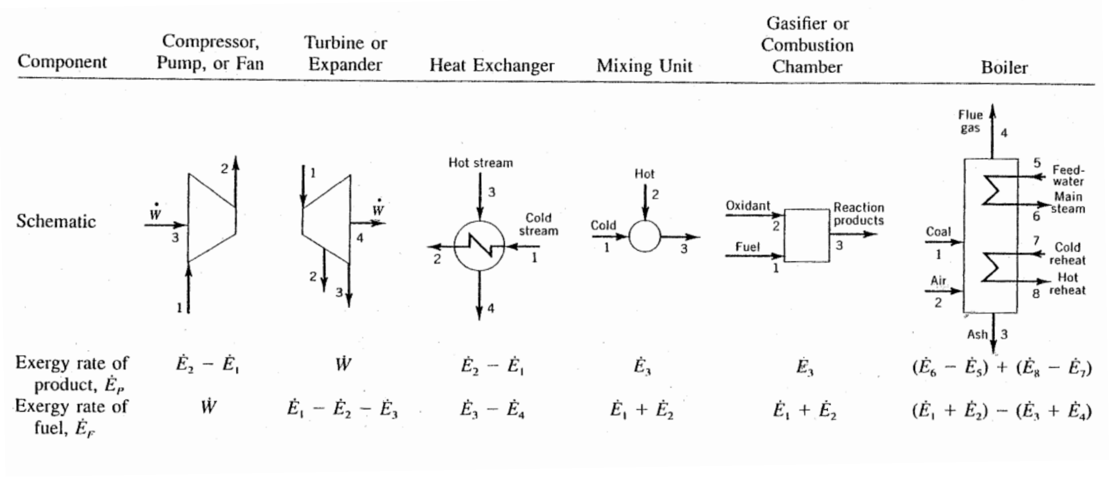
Being:

- $\dot{m}_f$, fluid flow rate going through the specific component in kg/s
- $\dot{E}_f$, exergy of the fluid at the entrance and exit in kJ/kg
- $h_i - h_o$, enthalpy increase of the fluid in kJ/kg
- T_a, ambient temperature in K
- $s_i - s_o$, entropy increase of the fluid in kJ/kg·K

When Equation 3 is applied to a specific component, decisions must be made concerning what is to be counted as the fuel and as the product of the system. Exergy rates used for selected components can be found in Figure 25.

With regard to the following definitions, it is assumed that heat exchangers aim to raise the temperature of the cold stream. On the contrary, if the purpose of the heat exchanger is to provide cooling the hot stream is cooled by the cold stream. In other words, in refrigeration applications exergy is calculated assuming that the product is ($\dot{E}_4$ - $\dot{E}_3$) and the fuel ($\dot{E}_1$ - $\dot{E}_2$) and as a result:

$$\varepsilon_c = \frac{\dot{E}_4 - \dot{E}_3}{\dot{E}_1 - \dot{E}_2} \tag{5}$$



Component	Compressor, Pump, or Fan	Turbine or Expander	Heat Exchanger	Mixing Unit	Gasifier or Combustion Chamber	Boiler
Schematic						
Exergy rate of product, $\dot{E}_P$	$\dot{E}_2 - \dot{E}_1$	$\dot{W}$	$\dot{E}_2 - \dot{E}_1$	$\dot{E}_3$	$\dot{E}_3$	$(\dot{E}_6 - \dot{E}_5) + (\dot{E}_8 - \dot{E}_7)$
Exergy rate of fuel, $\dot{E}_F$	$\dot{W}$	$\dot{E}_1 - \dot{E}_2 - \dot{E}_3$	$\dot{E}_3 - \dot{E}_4$	$\dot{E}_1 + \dot{E}_2$	$\dot{E}_1 + \dot{E}_2$	$(\dot{E}_1 + \dot{E}_2) - (\dot{E}_3 + \dot{E}_4)$

Figure 25: Exergy rates associated with fuel and product for selected components at steady-state [59].

This way, all exergies involved can be determined by the previously stated balances allowing every component to be energetically analyzed by means of the exergetic efficiency.

3.2 Economic Analysis

One of the most important factors within the implementation of an engineering project of this scale is the total capital investment required for its construction. This parameter gives an idea of the true sustainability of this kind of power plants. When the economic analysis of a power plant is conducted, different approaches can be used. In this work the Total Revenue Requirement (TRR) method is applied. Detailed steps and guidelines of this procedure can be found in ref [59], while specific assumptions for the analyzed scenario are presented below.

3.2.1 Purchased Equipment Cost

In the first place, an estimation of the required expenses associated to equipment purchase conforming the power plant is needed. For a more accurate assessment, guide prices for the equipment and its subsequent installation within the solar block are taken from the reference document IDAE [31], which evaluates the potential of the main thermoelectric technologies in Spain. This way, the final project investment will be closer to reality giving an idea of the magnitude of this kind of power plant implementations.

When it comes to the economic analysis of a power plant, one of the main challenges concerns the estimation of all major process components. This results from the fact that most available cost sources tend to refer to relatively small scale facilities. Therefore, when large equipment is considered these values are difficult to adjust.

One of the quickest ways to make an order of magnitude estimation of large scale component costs is the use of a scaling exponent and its application on the reference equipment of different capacity. This exponent, α, is supposed to remain constant within a given size range and it usually takes values below unity, stating that percentage increases of equipment costs are smaller than capacity percentage increases.

$$C_{PE,1} = C_{PE,2} \cdot \left(\frac{X_1}{X_2} \right)^{\alpha} \tag{6}$$

Equation 6 allows the purchase cost of an equipment component at a given capacity or size to be calculated when the purchase cost of the same equipment item at a different capacity or size is established. If a lack of specific cost information is faced, an exponent value of 0,6 may be used.

3.2.2 Cost escalation

As in most cost-estimating methods, historical data is used to forecast future equipment costs. For this reason, it must be taken into consideration that prices of materials for construction and labor costs are subjected to inflation. Inflation refers to the general and sustainable increase of the price of goods and services within a specific country. Therefore, some method needs to be applied in order to update old cost data used during estimation at the design stage and forecast the future construction of the power plant. Most common method used to keep historical cost data up to date takes advantage of published indices to bring all costs to the same reference year.

$$C_{ref.Y} = C_{calc.Y} \cdot \frac{Index_{ref.}}{Index_{calc.}} \tag{7}$$

By equation 7, all historical cost calculations on conditions at a different time can be related to a present base year. Needless to say, all data involved in the calculation of these indices are based on material, energy and labor costs published within government statistical digests.

3.2.3 LCOE

Another way to determine relatively well the feasibility of a power plant project is the so-called Levelized Cost of Energy (LCOE). This parameter is used to compare unitary costs over the economic life of power plants. These are the costs investors would face within a stable environment of electricity prices and assuming a reasonable certainty of the production costs provided. In other words, costs are defined in the absence of the risks related to the market or technology.

Ultimate investment decisions of the power plant are affected by the local and technological specific characteristics of the project. In the same way, reliability of capital and operation costs, the inherent uncertainty of fuel prices and future energy policies constitute a set of factors varying the final value of this parameter. LCOE can be determined by means of the succeeding equation which includes the required initial investment, fuel, operation and maintenance costs and naturally the annual energy generation.

$$LCOE = \frac{TRR}{E_{gen}} = \frac{C_{capital} + C_{O\&M} + C_{fuel}}{C_f \cdot t \cdot P_{gen}} \tag{8}$$

Being:

- $C_{capital}$, capital costs of the reference plant in €
- $C_{O\&M}$, operation and maintenance costs of the reference plant in €
- C_{fuel}, fuel costs of the reference plant in €
- C_f, capacity factor
- t, number of operating hours in h
- P_{gen}, power generated by the reference power plant in kWh.

LCOE calculation provides us with the price per generated kWh so that a comparison could be made with the generation price of the market. This information gives a clear idea about the economic sustainability of power plants for electricity production. The significant investments required by solar thermal plants lead to less competitive energy costs than the ones produced by other kinds of plants. Weather variations must be added to this hindrance although the use of storage systems seeks to reduce this drawback.

3.2.4 Wastewater Treatment Cost

Currently, there are no reliable approaches to the associated costs to wastewater treatment systems. It is for this reason that a mathematical model was developed to establish for each technology the behavior of its associated costs with the aim of providing a useful tool to calculate the investment required by a water reclamation power plant.

The type of function used to adequately adjust available cost data over numerous orders of magnitude of system scale correspond to the equation found in ref [60]. Based on the Levenberg-Marquardt algorithm and SigmaPlot® version 12.0 version, developed functions to calculate the principal wastewater treatment costs depend mainly on the water volume entering the facility.

$$log(y) = a\,[log(x)]^b + c \tag{9}$$

Cost information for the aforementioned sewage processing and reuse unit processes will be calculated differentiating between capital equipment and operation and maintenance (O&M) costs.

Water Reuse technologies	**Capital Cost**	**Annual O&M**
Activated Sludge	$\log(y)=0.256\cdot(\log(x))^{1.556}+4.545$	-
Membrane Bioreactor	$\log(y)=0.569\cdot(\log(x))^{1.135}+4.605$	$\log(y)=0.639\cdot(\log(x))^{1.143}+2.633$
Coagulation and Flocculation	$\log(y)=0.222\cdot(\log(x))^{1.516}+3.071$	$\log(y)=0.347\cdot(\log(x))^{1.448}+2.726$
Reverse Osmosis	$\log(y)=0.966\cdot(\log(x))^{0.929}+3.082$	$\log(y)=0.534\cdot(\log(x))^{1.253}+2.786$
Ultraflitration	$\log(y)=1.003\cdot(\log(x))^{0.830}+3.832$	$\log(y)=1.828\cdot(\log(x))^{0.598}+1.876$
Peroxone	$\log(y)=0.405\cdot(\log(x))^{1.428}+4.528$	$\log(y)=0.845\cdot(\log(x))^{1.057}+2.606$
Granular Activated Carbon	$\log(y)=0.722\cdot(\log(x))^{1.023}+3.443$	$\log(y)=1.669\cdot(\log(x))^{0.559}+2.371$

Table 2: Summary of cost functions of water reuse technologies [60].

Being:

- y, cost in €
- x, capacity in (m^3/day)

4 Simulations

This chapter outlines the main parameters and programs used to achieve the objective of this work, including the 20 MW power plant and water facility description as well as the undertaking of its simulation. Most important systems and components are presented for the correct operation of the simulated CSP plant. The aim is to obtain a general diagram of the functioning of the plant to be modeled. Besides the thermosolar plant and making use of part of the electricity generated a wastewater reclamation plant is implemented. Main treatments and procedures required to obtain the desired water quality are described for a better understanding of the potable reuse process.

4.1 CSP-Biomass Hybrid Power Plant

4.1.1 Project Location

A key aspect regarding the design and construction of a power plant is the selection of a suitable location. Determination of where to place the facility is an important and advisable decision-making for any company as significant investments are made on building and machinery equipment. Before the ultimate location of a power plant is decided, long range forecasts concerning the most critical factors that are likely to affect the project should be made to predict accurately the future needs of the facility.

Accordingly, our CSP plant with biomass backup system should be located somewhere in the Iberian Peninsula registering **high levels of radiation** and substantial sources of the utilized biomass. These values are quite achievable in large areas of the southern half of the peninsula such as Extremadura, Andalusia and Castilla La Mancha as a consequence of the elevated number of daily solar hours.

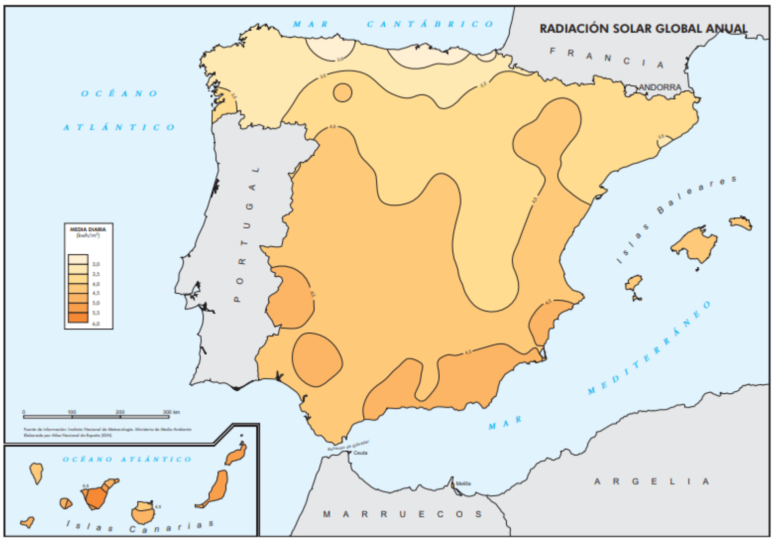


Figure 26: Annual global solar radiation in the Iberian Peninsula [61].

As it can be observed Andalusia shows a large solar resource availability offering more than 3000 solar hours a year in certain regions, thus an untapped potential for energy use awaits for its exploitation [62]. In addition, fossil fuels shortage as well as their low heating value lead to a strong dependence of imported oil within the energy sector. Fortunately, the energetic scenario of Andalusia has changed during the past years. Currently evolving from a centralized generation system based on fossil energies towards a more efficient system of distributed generation. This way, renewable resources are seized to a larger extent and contribute to the reduction of external energetic dependence. Abundance of native renewable resources within the region is allowing, through active policies, the development of clean energy generation now accounting for the 18.4% of the primary energy consumption [63]. For this reason, Andalusia has been pioneer in the production of heat and electricity from solar energy and therefore a great place to carry out our renewable project.

Within an energetic framework where sustainability, diversification and an elevated degree of self-sufficiency prevails, **biomass** plays an important role too. From an energetic perspective, biofuels contribute significantly to the energy system in Andalusia. Consequently, the different national and regional governments strongly support this renewable source of energy.

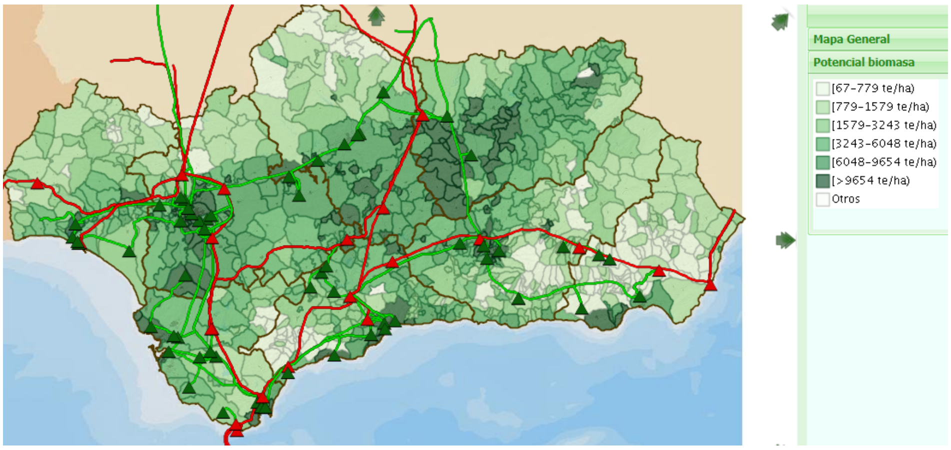


Figure 27: Biomass potential in Andalusia [64].

Andalusia currently holds an important biomass wealth, largely originated from the olive cultivation and its surrounding industry. Energetic utilization of this kind of biofuels allows the substitution of fossil fuels and activity maintenance in rural areas. Olive biomass stands out from other biological materials given that olive oil is one of the most valuable products of the country. Furthermore, it is the source of numerous secondary products having great energetic aptitudes such as the olive pomace, olive pit, almazara leaf and olive trimmings. Through the appropriate technology, thermal as well as electric energy can be obtained from them or even biofuels for transportation.

Once dried and subjected to an oil extraction process, olive waste turns into olive pomace. This derivative contains an average moisture of approximately 10% and great properties as fuel such as heating values of about 4200 kcal/kg on dry basis

[65]. Due to this fact, olive pomace is used within industries to generate thermal as much as electric energy. In the case of our suggested power plant, it has been stated that in the event of having continued absence of sunlight the plant will rely on an auxiliary biomass system. Therefore, regarding its outstanding characteristics as a fuel, it would be desirable to make use olive pomace as biofuel to address this concern.

At the same time, there exists not only at global scale but in the specific case of Spain a growing awareness about the **scarcity** of water resources and the importance of the integral management of the water cycle. The lack of rain along with the rising temperatures has resulted in a reduction on the availability of fresh water reservoirs. This may lead to alert or emergency levels of water shortage in several areas especially at the south of Spain. Climate in Andalusia is typically semi-arid Mediterranean, characterized by clearly defined seasons with dry and hot summers and milder winters. Periodic droughts result from years of very few rainfall added to an uneven water distribution throughout the territory.

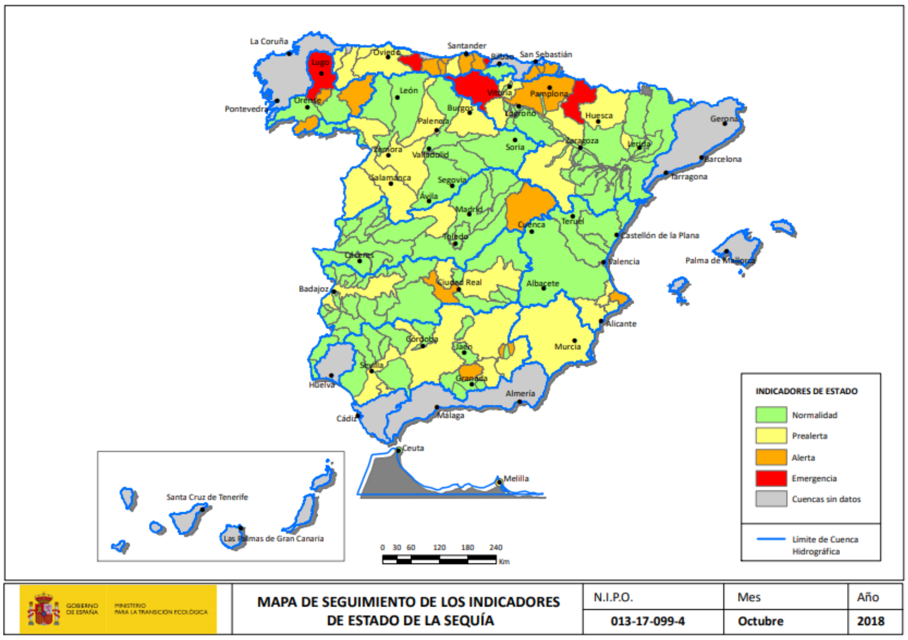


Figure 28: Tracking map of drought condition indicators [66].

Water in Andalusia is a hostage of irrigation. Water application for irrigation is of common sense especially in these regions determined by agriculture. Demand within this sector is insatiable and therefore scarcity continues growing even though available resources and several possibilities have been on the rise. Water scarcity is then a crucial aspect to have in mind as our renewable project will include a wastewater treatment facility to provide with purified water for many purposes including potable reuse and the much-needed irrigation.

Once again it is reaffirmed that Andalusia, specifically the province of Seville, meets the minimum demanded requirements and provides a desirable place to implement our project. The main purpose of this location study was to find an optimum site that will result in the greatest advantage to the organization.

4.1.2 Power Plant Sizing

The whole thermodynamic cycle was modelled using the commercial software - EBSILON® Professional - considering basic project rules. This program allows plant-wide access to a large set of input variables allowing to describe in detail the working characteristics of the system. In this way, processes can be modelled and controlled to carry out optimization and sensibility analysis of the power plant. Immediate results obtained from the simulation can be exported or opened by different spreadsheet applications, making this software a very useful tool for plant analysis.

Design Points

Power plant components are to be specified for the 21st of March when the sun reaches its peak height in the sky, known as spring equinox. Radiation levels within the software are represented by the DNI (Direct Normal Irradiance) coming from the sun, as concentration technologies can only make use of this kind of radiation. According to previous radiation studies among the Iberian Peninsula average irradiance in Seville is close to 850 W/m^2 [67]. This DNI value is quite similar to the selected design points for the PS10 AND PS20 power plants located in Sanlúcar la Mayor.

Likewise, ambient temperature is a significant input affecting the efficiency of CSP systems. The higher the local temperature, the worse the cycle first-law efficiency. This results from the fact that cycle performance is based on the temperature difference between the hot source from the receiver and the cold one from the environment. In this region, average ambient temperature can be assumed to be 20 °C [67]. The table below shows the main solar parameters used within the sun component of the simulation.

Location	**Seville**
Latitude	37.23 °N
Longitude	-5.58 °E
Date	21/03/2019
DNI	850 W/m^2
Ambient Temperature	20 °C

Table 3: Solar parameters.

Working Fluid

With regard to CSP plants, different working fluids may be used to capture and transmit heat within the solar receiver. However, best results were obtained by using a mixture of 60% sodium nitrate ($NaNO_3$) and 40% potassium nitrate (KNO_3) molten salts [33]. This combination of salts works not only as the high temperature fluid but as the cooling system of the receiver. They are heated up between 290 – 565 °C at the receiver, from there they are transported through pipes towards the thermal storage.

Afterwards, they are extracted and leave storage tanks to generate steam within heat exchangers. As stated in previous sections, molten salts present melting temperatures ranging from 150 – 250 °C at which they crystalize [33]. For this reason, tracing of the system components becomes vital as well as keeping storage temperatures below 250 °C to prevent from solidification problems and pipeline blocking.

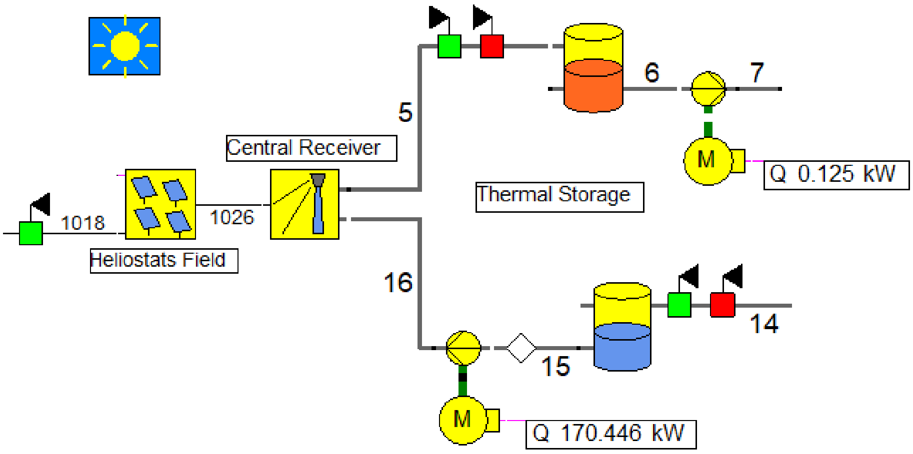


Figure 29: Solar block with thermal storage simulation.

Maximum operation temperatures for a safe process can reach up to 600 °C, at higher temperatures the working fluid turns into nitrites [32]. These molten salts are totally non-toxic although they can be considered a powerful oxidizer. This characteristic is quite significant when selecting the storage tank materials and other system components.

Solar Energy Capture System

Receiver, solar tower and heliostats field dimensions are strongly related to the final thermal power of the receiver at the design point and therefore key enablers for production optimization. Certain aspects must be considered within the solar field like the number of heliostats as well as their shape and size. It is also necessary to optimize the vision of the heliostats field from the receiver and all factors involved in energy loss like heliostats reflectivity, receiver absorbance and convective losses. Reflectivity of the heliostats is a significant characteristic with a powerful effect on the system behavior as it directly affects to the amount of flux reaching the receiver. In this way, the higher the reflectivity, the higher values for thermal power will be obtained within the receiver.

Our power plant comprises a solar field of 110 ha composed of 1458 mirrors made of high reflective glass. Heliostats having a rectangular design of 120 m^2 with an average reflectivity of 0,9, makes mirror surfaces to completely cover the heliostat area leading to a total solar field reflective area of 174960 m^2 [31]. Table 4 provides the main parameters for the heliostats field design.

Heliostats field	
Number of Heliostats	1458
Dimensions	120 m^2
Solar Field Area	110 ha
Average Reflectivity	0,9
Reflective Area	174960 m^2

Table 4: Heliostats field parameters.

For its part, the cylindrical receiver composed of several tubes is located at the top of the solar tower allowing high ratios of heat transference and reducing thermal gradients to increase its performance. As stated before, one of the most determining parameters of the solar tower is the optical height. In other words, the distance from the average height of the receiver to the heliostats level which in our case reaches 127 m. Moreover, the receiver aperture area is defined by the heliostat field matrix having a value of 247 m^2. Thermal power of the receiver at the design point is 100 MWt, inlet and outlet temperature of the molten salts goes from 290 to 565 °C respectively, which makes the mean wall temperature of the receiver to be 480 °C.

Solar receiver	
Receiver Type	Cylindrical
Optical Height	127 m
Working Fluid	Molten Salts (KNO_3-$NANO_3$)
Inlet Temperature	290 °C
Outlet Temperature	565 °C

Table 5: Solar receiver parameters.

Thermal Storage System

Storage tanks provide autonomy to the power plant and furthermore cushion transitory periods of the system resulting from power variations of daily radiation. Thermal storage working principle is simple; throughout the day excess heat diverts to the molten salts. When energy generation is required beyond sunset or during cloudy days, stored heat flows through the steam cycle to continue operating.

Depending on the aimed purpose of the solar installation design, thermal storage requirements will differ. Storage capacity variation is a way of adjusting CSP plants to satisfy its numerous needs. Our storage system will consist of two tanks of molten salts where hot and cold fluids are separated. From there molten salts are pumped either towards the steam generator or the receiver respectively as required from the system operation. Regarding energy storage parameters, the use of a storage system having a total capacity of 200 MWt will provide the plant with an autonomy of up to 4 hours when needed to meet the demand. An overview of the most important thermal storage parameters is included in table 6.

Thermal energy storage	
Storage Medium	Molten Salts (KNO_3-$NANO_3$)
Type	2 tanks
Capacity	200 MWt (4 hours)
Cold Tank Temperature	290 °C
Hot Tank Temperature	565 °C

Table 6: Thermal energy storage parameters.

Biomass Auxiliary System

Due to its thermal nature, every solar technology can be hybridized and work simultaneously with fossil fuels or other renewable energy sources. Hybridization has the potential to increase the concentration value of solar thermal energy with further enhancement of its availability and manageability. At the same time, is reduces costs as it provides a more effective use of the energy generation systems.

Practically all CSP plants with or without thermal storage are equipped with support systems that help regulate energy production and guarantee plant capacity, especially at demand peaks. This kind of systems consist of a boiler fueled with fossil fuels, natural gas or biomass which can provide calorific energy not only to the working fluid, but the storage medium and even directly to the energy generation block. In addition, energy would be generated at a lower cost than if it were depending solely on the solar field and storage systems. There are other plants continuously working on hybridization mode. This means that the additional boiler works increasing the efficiency of solar heat conversion into electricity due to the higher temperatures of the working fluid.

Our support system will consist of a biomass boiler fired with olive pomace which enables plant production capacity during periods in which direct solar radiation is far from ideal. This allows the differentiation of two operating modes, either the use of solar radiation or energy production from biomass combustion. Olive pomace is introduced inside the combustion chamber after being fitted up and dried up to about 10% moisture content. Olive pomace chemical composition characteristics on dry basis are presented in the following table.

Olive Pomace (wt %)	
Volatile Matter	74,4
Fixed Carbon	17,1
Ash	8,5
C	52,5
O	39,53
H	7,1
N	0,8
S	0,07

Table 7: Main characteristics of olive pomace on dry basis [68].

Power Block

Electricity generation is the main purpose of CSP plants. Generally, electric energy is centrally produced by means of a power conversion unit, known as power block. In other words, the functional combination of an electric generator with a steam turbine as primary drive mechanism.

In the case of our study, the power block of the plant is designed following the basic operational characteristics of an Integrated Solar Combined Cycle (ISCC). This type of thermodynamic configuration consists of a combination of renewable technologies which makes use of an ordinary cycle to generate electricity and where hybridization confers mutual benefits. However, unlike conventional ISCCs, fossil fuels are completely replaced by the solar resource becoming the only renewable source for energy generation. For its part, the biomass auxiliary system works as an energy support in the event of having continued lack of solar radiation and low levels of thermal energy within storage tanks.

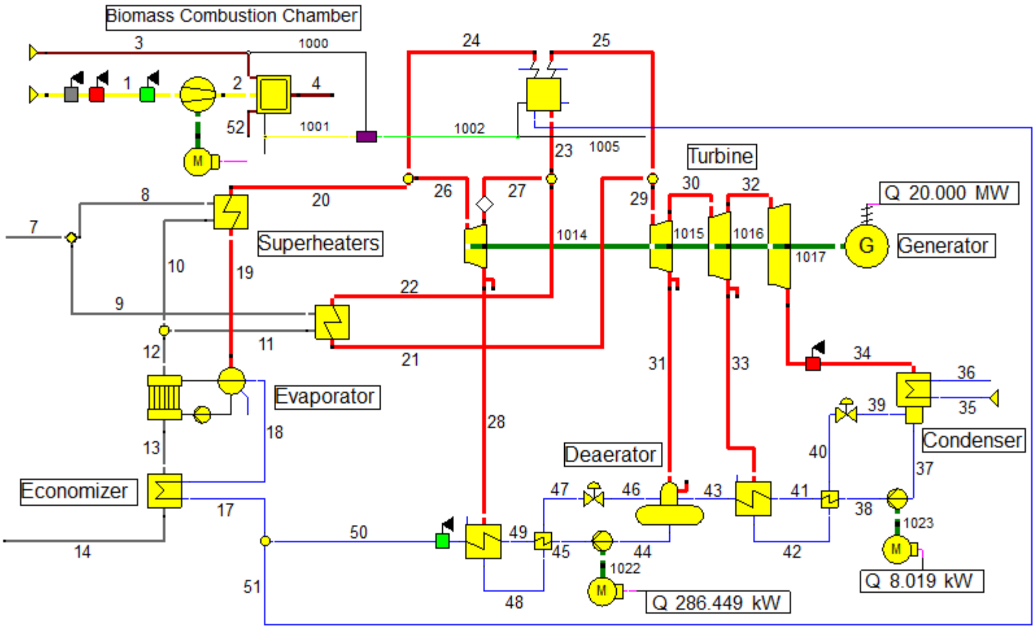


Figure 30: Power block with support system simulation.

Once heated, molten salts are driven from the hot storage tank towards the power block located at the center of the power plant where it flows through the different heat exchangers. Steam produced as a result of this heat transfer runs a train of turbines going from higher to lower pressures, all connected to the electric generator. Steam turbines relieve high energy steam which turns thermal energy into mechanical energy driving the generator. Then, by means of electromagnetic forces induction within a conductor, the generator converts mechanical energy into electricity. Exhausted steam leaving the turbines goes through the condenser in order to get back to liquid state and start the cycle all over again. Selected operating parameters for the thermodynamic cycle sizing of the power plant can be found in Table 8.

Operating Parameters
Ambient Air
20 °C, 1 bar, 80% relative humidity
Composition (mol%): N_2 (77,3), O_2 (20,73), CO_2 (0,03), H_2O (1,01), Ar (0,93)
Fuel
3,52 kg/s, 20 °C, 1,029 bar, LHV=16,4 MJ/kg
Olive pomace composition (mol%): C (52,5), O (39,53), H (7,1), N (0,8), S (0,07)
Biomass Auxiliary System
Compressor: isentropic efficiency 85,0%, mechanical efficiency: 99,0%, pressure ratio: 1,03
Steam Cycle
HRSG: 1 reheat stage, 1-pressure-level: 1,007 bar
HRSG pressure drop: hot side: 7 mbar, cold side: 2%
SH, ECON: ΔT_{min}: 20 °C
EVAP: approach temperature: 276 °C, pinch point: 278 °C
Live steam temperature: 545 °C
Steam turbine isentropic efficiency: HP (86,0%), IP (86,0%), LP (82,0%)
Condenser operating pressure: 0,1 bar
Pumps: efficiency 0,8% (incl. motors and mechanical efficiency: 99,8%)
Cooling water temperature: 20 °C

Table 8: Power block operating parameters.

Large number of these numerical values are taken from existing reference plants and technical reports concerning this kind of hybridization projects.

4.2 Wastewater Treatment Plant

Besides the energy generation plant we would also like to contribute to water care within the region, as both resources are equally essential to humankind. The idea is that part of the electricity produced within the CSP plant will be used to power a wastewater treatment facility seeking to increase hydric resources in nearby towns. Water reuse gives a great opportunity of providing clean water for irrigation as much as for human consumption. It seems clear that demanded water quality requirements for potable reuse are much more strict and extensive than the ones required for irrigation. Thus, our sewage treatment plant will include the main water treatments followed by existing direct potable reuse (DPR) facilities.

4.2.1 Direct Potable Reuse Treatment Train

DPR was discussed in previous sections of this work. At this stage we will only focus on the second approach of this reuse process in which purified water is directly blended into the potable supply system without the need for an environmental buffer. To ensure positive results of this type of recovery train, advanced water treatment facilities are required. At present, the longest-operating and only known real example of DPR system is located in Windhoek, Namibia. For this reason, the Goreangab Water Reclamation Plant seems to be the best benchmark when it comes to design the main technical characteristics and multi barrier concepts of our water regeneration facility. Nevertheless, modification and development of water reuse technologies enable the enhacement of the reliability and potable water quality of the reclamation treatment process.

Primary and Secondary Treatment

Once wastewater has been collected and guided towards the treatment plant it undergoes a series of physical, biological and chemical procedures during the first stages of the purification process.

- Primary Sedimentation
- Membrane Bioreactor
- Maturation Ponds

In the first place sewage enters a sedimentation tank where **primary settling** takes place. The aim of this physical operation is to concentrate and eliminate as much suspended solids as possible under the sole action of gravity. Resulting sludge from the accumulation of these solids at the bottom of the tank is removed for receiving separate treatment. Likewise, lighter organic materials such as oils and grease float on the surface where they are skimmed off.

As stated in previous chapters, effectiveness of primary settling tanks can be enhanced by the addition of coagulants and flocculants such as $FeCl_3$ and other polymers respectively [45]. Removal of these settleable solids within primary sedimentation is important because otherwise they would result in high BOD concentrations within the following treatment stages of the plant.

Thereafter, activated sludge would be a recommended DPR procedure to remove organic and nitrogen constituents of wastewater. However, **Membrane Bioreactors (MBRs)** appear as relatively new modification of this process providing with higher quality effluents for water reuse [60]. MBRs (biological reactor + UF) are included in the denominated membrane technologies, whom have witnessed a great development within the last decade. Application of this technology allows the separation of sludge from water by means of membranes, gaining significant advantages over traditional secondary clarifiers.

Its operation is based on the filtration of water throught the walls of a membrane within the biological reactor. Filtered water is extracted from the system while sludge and other components of larger size than membrane pores are retained and remain or return to the biological reactor. This way, suspended solids and microorganisms responsible for biodegradation are confined within the system, providing a perfect permanence time tracking of pollutant substances in the reactor and the desired effluent disinfection.

On the completion of these very first treatments treated water is dammed in **waste stabilization ponds** for about 3-4 days. Maturation ponds consist of large artificial water bodies where sewage is treated by means of natural procedures driven by algae activity along with photo-oxidation. In order to make this possible, they operate with low organic loads and under favorable conditions for solar radiation penetration. Stabilization ponds succeed at the elimination of pathogenic microorganisms and certain removal of nutrients for a clarified well-oxygenated effluent.

Advanced Treatment

So far, treated water has already been subjected to conventional procedures regarding the first steps of the reclamation plant. On their behalf, the following treatments correspond to much more advanced operations required to fulfil the established quality requirements for irrigation and potable reuse.

- Ozonization
- Biological and Granular Activated Carbon
- Reverse Osmosis
- Ultraviolet Radiation
- Chlorination

In order to increase the efficacy of the entire process, secondary effluent reaching the advanced treatments can be a mixture of fresh water resources and treated water from the maturation ponds. However, both sources can be combined at any ratio or used separately to reduce pollutant content and optimize water quality.

Ozonization: Raw water accesses ozone and is disinfected with the off gas for bacteria and viruses inactivation as well as algae control. At the same time it is used as pre-oxidant of organic and inorganic matter for the elimination of components providing the water with taste, odor and color. Oxygen is produced on-site by means of a Pressure Swing Adsorption (PSA) technology to generate high concentration ozone. Action of this natural oxidant gas in water presents high bactericidal, virus and fungicidal power destroying microorganisms by oxidation of their protective layer. During ozonization, a dosage of hydrogen peroxide (H_2O_2) is applied to increase oxidation.

Biological and Granular Activated Carbon (BAC & GAC): With the aim of protecting the biological activated carbon steps of this stage a second dose of H_2O_2 is added to remove any ozone residuals. During the main ozonization organic load in water is extensively oxidized producing easily biodegradable molecules subsequently removed by BAC consisting of seven filters [69]. It is favorable to have BAC process before GAC filters as larger fractions of organic load are lessened during the BAC level and the remaining organic constituents are later reduced at the GAC. This last step consists of a primary and secondary filter to reduce the bulk of organic matter and carry out a final polish respectively. While these processes are not regarded as microbiological barriers, they are seen as a significant treatment stage for water quality.

Reverse Osmosis (RO): This procedure was not included within the actual treatment train at Windhoek potable reclamation water but provides a significant polishing step for water purification. It works in a similar way to membrane filtration but water must be pressurized to a greater value than the osmotic pressure for this effect. Partial or full reverse osmosis would be a desirable process to reduce disinfection byproducts, salt concentration and removal of dissolved organic carbon to lower than 0.1 mg/l [70].

Ultraviolet Radiation (UV): As in the previous case, UV light was not present within prior systems but nowadays constitutes a key stage for final disinfection. Unlike other chemical water disinfection methods, UV radiation provides a fast and powerful inactivation of target microorganisms by means of a physic process. When bacteria, viruses and protozoa are exposed to certain germicidal wavelengths of UV light they become unable to reproduce and infect. It has been demonstrated that UV has developed effective responses against multiple pathogens and other bacterial illnesses.

Chlorination: The final disinfection barrier concerns the dosage of chlorine gas (Cl_2) for the ultimate inactivation of pathogens. This procedure is heavily affected by contact time as greater amount of microorganisms will be inactivated if higher contact times are applied. The aim is achieving pH values of about 8, contact times of 1 hour and residual chlorine concentrations of 1 mg/l [71]. In the end, a method called breakpoint chlorination is applied to guarantee the effectiveness and concentration of Cl_2. Finally, before being directly blended into the potable supply system, caustic soda (NaOH) is added to the purified water for a final pH adjustment and stabilization.

The plant should be operated and constantly monitored to avoid failures or problems within the treatment train. In the event of an error water can be rejected or even recirculated to the beginning of the treatment train.

5 Analysis Application

This section includes the principal details of the implemented methods and the obtained results. Application of the methodology discussed within section 3 requires the specific properties of each stream resulting from the simulation of the power plant. These values can be found in Appendix A.

5.1 Exergetic Analysis

Exergetic analysis allows the identification of components or equipment systems presenting the highest thermodynamic performances, locate them, quantify inefficiencies and understand the sources and processes causing them. Once all exposed balances within the methodology chapter have been solved different exergies are obtained for each block of the power plant, where fuels and products need to be previously determined for every component. Tables containing the results as much for the solar field as for the power block are described below.

Solar Exergy

Exergy of solar power received by the sun in Fuentes de Andalucía is estimated assuming direct solar irradiance at this place has a value of 850 W/m^2 and ambient temperature is 20 °C. Likewise, reflective surface of the heliostats field is needed, which in accordance with our calculations takes a value of 174960 m^2, resulting in 138 MW of solar exergy.

$$\dot{Q}_s = A_{refl} \cdot DNI = 174960\, m^2 \cdot 850\, \frac{W}{m^2} = 148,7\, MW$$

$$\Psi_s = \left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right] = 0,93 \qquad \{T_a = 293\, K,\, T_s = 5600\, K\}$$

$$\dot{E}_s = \dot{Q}_s \cdot \Psi_s = 148,7\, MW \cdot 0,93 = 138,3\, MW$$

Components Exergy Efficiency

Exergetic efficiency of the components conforming the solar block is included in Table 9. According to the data obtained, and taking into consideration other previously published studies it can be noticed that generally, exergetic efficiencies of the power plant components exceed 80%. An important aspect to be considered within this analysis is exergy destruction, which measures the importance of irreversibility within each component.

As it can be observed, the biomass combustor is a highly destructive system of exergy, especially when combustion chemical reactions take place. However, part of this exergy loss can be minimized by preheating of the reactives and the reduction of excess air. When calculating the exergetic efficiency of the biomass combustor it must be taken into account that, apart from physical processes, this component includes changes within the chemical composition of its streams. As a result, not only physical exergy must be considered but chemical exergy of the biomass fuel used. Chemical exergy is defined as "the maximum useful work that can be obtained when a substance is brought from the reference-environment state to the dead state by a process including heat transfer and exchange of substances only with the reference environment" [59]. Estimation of the chemical exergy of olive pomace is conducted providing the biomass combustor with a fuel exergy of 18,05 MJ/kg.

▷	**Stream Balances**		**Stream Values (kW)**		◁
Component	E_P	E_F	E_P	E_F	ε (%)
Air Compressor	$\dot{E}_2 - \dot{E}_1$	$\dot{W}$	114,98	139,58	82,38
Biomass Combustor	$\dot{E}_{24} - \dot{E}_{51} + \dot{E}_{25} - \dot{E}_{23}$	$\dot{E}_{Biomass}$	26979,72	63536,00	42,46
Pump 1	$\dot{E}_{38} - \dot{E}_{37}$	$\dot{W}$	6,41	8,02	79,89
Pump 2	$\dot{E}_{45} - \dot{E}_{44}$	$\dot{W}$	240,87	286,45	84,09
HPST	$\dot{W}$	$\dot{E}_{26} - \dot{E}_{28} - \dot{E}_{27}$	5.200,00	5.542,65	93,82
IPST 1	$\dot{W}$	$\dot{E}_{29} - \dot{E}_{31} - \dot{E}_{30}$	7.600,00	8.199,54	92,69
IPST 2	$\dot{W}$	$\dot{E}_{30} - \dot{E}_{33} - \dot{E}_{32}$	5.600,00	6.384,020	87,72
LPST	$\dot{W}$	$\dot{E}_{32} - \dot{E}_{34}$	2.100,00	2.605,15	80,61
FWH 1	$\dot{E}_{43} - \dot{E}_{38}$	$\dot{E}_{33} - \dot{E}_{40}$	289,91	347,95	83,32
FWH 2	$\dot{E}_{50} - \dot{E}_{45}$	$\dot{E}_{28} - \dot{E}_{47}$	115,39	151,13	76,35
Economizer	$\dot{E}_{18} - \dot{E}_{17}$	$\dot{E}_{13} - \dot{E}_{14}$	3.421,20	4.024,58	85,01
Evaporator	$\dot{E}_{19} - \dot{E}_{18}$	$\dot{E}_{12} - \dot{E}_{13}$	11.414,74	12.880,55	88,62
Superheater	$\dot{E}_{20} - \dot{E}_{19}$	$\dot{E}_8 - \dot{E}_{10}$	7.080,78	7.621,87	92,90
Reheater	$\dot{E}_{21} - \dot{E}_{22}$	$\dot{E}_9 - \dot{E}_{11}$	3.787,17	4.105,00	92,26
Cold Pump	$\dot{E}_{16} - \dot{E}_{15}$	$\dot{W}$	163,76	170,45	96,07
Hot Pump	$\dot{E}_7 - \dot{E}_6$	$\dot{W}$	0,1195	0,125	95,62

Table 9: Exergetic efficiencies of the power plant components.

Other significant source of irreversibilities is the heat transfer between great difference temperatures. This way, the higher the temperature of the hot stream, the higher the efficiency of the heat exchanger as more heat is absorbed and the amount of exergy destroyed. Such is the case of feedwater preheaters which tend to have lower exergy efficiencies, as a result of the temperature difference between steam turbine extractions and water.

▷	**Stream Balances**		**Stream Values (kW)**	
Component	E_D	E_F	E_D	E_F
Condenser	$\dot{E}_{34} + \dot{E}_{40} + \dot{E}_{35} - \dot{E}_{36} - \dot{E}_{37}$	$\dot{E}_{34} + \dot{E}_{40} - \dot{E}_{37}$	1.951,47	2.262,92

Table 10: Condenser exergy balance.

In addition, it should be noted that the exergetic efficiency of the cooling system cannot be defined as there exists no product. This results from the fact that the sole objective of the condenser is to cool down and reduce the exergy of steam, enabling the closure of the Rankine cycle. In other words, refrigeration does not have a productive function but is required to increase the total performance allowing lower pressures at the turbine exit, which makes this exergy loss necessary for the correct operation of the power plant.

In conclusion, although most irreversibilities cannot be avoided, as in the case of the combustion process, actions can be incorporated to mitigate these effects. Aforementioned actions may be improved with the development of solar technology. In the coming years, advances within components and working fluids are expected as to increase the total efficiency of power plants.

Power Plant Efficiency

As mentioned in previous sections, the power plant has been designed to work in two different operating modes; the first one takes as energy source the solar heat received from the heliostats field while the other makes use of the energy released from the combustion of a biofuel, specifically olive pomace. This means, the biomass combustor works as an auxilliary system being only used when the climatological conditions do not allow the utilization of solar radiation and having lack of thermal storage disposal.

Firstly, the **biomass efficiency** will be calculated. To determine the efficiency of the hybrid plant working on this mode the net calorific value (NCV) of olive pomace is needed as well as the required mass flow to power the plant and maintain the electricity generation in the abscence of solar radiation.

$$\eta_B = \frac{P_{gen}}{NCV \cdot \dot{m}_b} = \frac{20 \cdot 10^3 \, kW}{16403,61 \, \frac{kJ}{kg} \cdot 3,52 \, \frac{kg}{s}} = 0,34$$

With regard to modern thermoelectric plants making exclusively use of biomass, values of exergetic efficiencies take values ranging from 30-40% [72]. Therefore, an efficiency of 34% for our power plant is considered far more than acceptable for this kind of renewable proposals.

For its part, in the event of having high levels of solar radiation for successive days, which at the same time leads to the filling and potential use of the thermal storage, the **solar efficiency** for the correct operation of the plant can be determined. For this purpose various items of data are needed including the direct normal irradiance, the total reflective area of the heliostats field and the exergy/energy ratio.

$$\eta_S = \frac{P_{gen}}{P_{solar}} = \frac{P_{gen}}{DNI \cdot A_{refl} \cdot \Psi_s} = \frac{20 \cdot 10^6 \, W}{850 \, \frac{W}{m^2} \cdot 174960 \, m^2 \cdot 0,93} = 0,15$$

It can be observed that on this occasion the efficiency of the power plant is slightly lower in comparison with other concentration technologies [30]. However, this value is enhaced by the use of a thermal storage which provides autonomy to the plant and guarantees its proper operation.

5.2 Economic Analysis

Throughout this subsection feasibility study of the power plant is conducted as well as the necessary investment for construction. It is worth mentioning that this concentration technology is not mature enough in comparison with other solar options within the energy market. Even so, a high degree of analysis detail was achieved due to data availability.

For a more illustrative analysis, costs have been divided according to the main functional subsystems described in Chapter 4. Costs incurred in each subsystem conforming the plant will be analyzed separately with the objective of showing their importance on the total investment required for the plant.

Solar Energy Capture System

Solar energy capture system carries an important weight on the total investment of the plant. As stated in previous chapters, it mainly consists of the heliostats field and the solar tracking system controlling the mirrors. To ensure the solar position and adequate rigidity of the components, a solar tracker and metal structure are needed respectively for each heliostat.

It must also be taken into account the conditioning tasks of the location called upon to accommodate the plant as well as the required foundations for its proper assembly. Table 11 shows the total measurements and unitary costs of the previously defined components.

Component	**Cost**	**Investment (€)**
Mirrors	12 (€/m^2)	1.995.924,00
Metal Structure	84 (€/m^2)	13.971.469,00
Solar Tracker	7000 (€/heliostat)	9.702.409,00
Land Movement	10,5 (€/m^2)	1.746.434,00
Foundations	7 (€/m^2)	1.164.289,00
Assembly	20 (€/m^2)	3.326.540,00
Assembly Unit	5 (€/m^2)	831.635,00
Total Investment (€)		32.738.699,00

Table 11: Solar Energy Capture System investment.

Solar Energy Conversion System

Another subsystem with great impact on the final investment of the power plant is the conversion system of solar radiation into thermal energy. Solar towers present significant differences when compared with other technologies, since in this case the solar receiver constitutes the essential element of the system. This implies new considerations due to the receiver location at a considerable height from the ground, leading to additional investment costs on both materials and construction. Furthermore, the need for molten salts pumping to reach the receiver requires more powerful equipment within the salts mechanical system.

Component	**Cost**	**Investment (€)**
Working Fluid (Molten Salts)	0,72 (€/kg)	82,00
Solar Tower Receiver	210 (€/kWt)	21.361.270,00
Mechanical System	29,17 (€/kWt)	2.967.182,00
Fire Protection	540.000 (€/unit)	513.355,00
Inertisation System	300.000 (€/unit)	285.197,00
Solar Tower Construction	801.490*$e^{(0,012*h)}$ (€/he)	3.497.735,00
Total Investment (€)		28.624.822,00

Table 12: Solar Energy Conversion System investment.

Thermal Energy Storage System

Despite the great number of operational hours thermal storage systems can supply, they also imply relevant investment costs within power plants. As stated before, thermal energy is accumulated within two storage tanks with different temperatures having its corresponding insulation to minimize heat loss. In addition, vertical pumps are required for each tank to boost the fluid towards the fixed receiver and steam generator respectively. However, these costs were previosly included within the mechanical system calculations of the solar energy conversion system.

Component	**Cost**	**Investment (€)**
Transfer System: Tanks & Pipes	14,8 (€/kWht)	2.813.946,00
Initial Filling System	1,41 (€/kWht)	268.085,00
Construction	3,53 (€/kWht)	671.164,00
Total Investment (€)		3.753.195,00

Table 13: Thermal Energy Storage System investment.

Power Block Components

Under this second half of the analysis, several sources of information are brought together and an extensive data collection and economic indicators have been used as reference. Design characteristics for all components, reference data and their sources are contained in Appendix B. Size exponents applied to aptly recalculate costs based on sizing parameters and have been estimated by means of cost analogies with the equipment found in the references. Another relevant factor within investment calculations would be the construction materials employed. Nevertheless, plant components within this work are assumed to be made of similar materials as the reference components.

Component	**Investment (€)**
Air Compressor	970.173,00
Biomass Combustor	1.196.008,00
Economizer	414.050,00
Evaporator	2.947.812,00
Superheater	482.861,00

Component	Investment (€)
Reheater	1.021.964,00
Deaerator	14.728,00
Condenser	487.326,00
Pump 1	8.890,00
Pump 2	60.931,00
HPST	1.365.160,00
IPST	5.237.489,00
LPST	1.102.629,00
FWH 1	650.061,00
FWH 2	26.197,00
Total Investment (€)	15.986.369,00

Table 14: Purchase Equipment Costs.

Wastewater Treatment Train

Following the previously described wastewater treatment train and applying the modelled equations exposed within the methodology we can determine the required investment for this part of the project.

The reclamation plant is intended to provide with safe drinking water to the region and as a consequence involves a series of specific procedures focused on enhancing the final quality of the so much needed resource. Hence, incurred costs for the application of these methods tend to be high as most of them consist of relatively new purification techniques within potable water management.

Water Reuse Technology	Capital Cost (€)	O&M Cost (€)
Membrane Bioreactor	10.217.287,00	229.452,00
Ozonization	78.849,00	-
BAC & GAC	1.228.629,00	582.089,00
Reverse Osmosis (RO)	1.676.546,00	255.365,00
Ultraviolet Radiation (UV)	99.918,00	12.551,00
Chlorination	11.838,00	8.893,00
Total Investment (€)		14.401.416,00

Table 15: Wastewater treatments investment.

Total Net Capital Investment

Net investment can be defined as the sum of the initial capital investment and the payable interests during its construction. Therefore, the total net capital investment of the engineering project reaches a value of 211.526.743,00 €. It is evident, that this final cost includes as much the outlay for the implementation of the hybrid plant as for the water reclamation plant, resulting in a significant investment. Future expenses are not considered as they will be financed with the benefits obtained from power plant trading of water and electricity.

If compared with other projects of the same magnitude, such as the Gemasolar power plant which shares location and presents similar operating characteristics, it can be noted that the required investment is actually within the range of this kind of thermosolar plants [73]. However, it can be seen that our final investment is slightly higher as a consequence of the hybridization and the water reuse technologies applied [60].

LCOE

The last factor within the analysis of a power plant is the levelized cost of electricity. LCOE shows the relation between the total revenue requirement based on current euros and the total amount of generated electricity over the 20 years of the plant economic life. Following equation 8 with the results obtained from the previously calculated TRR and the electricity production of the hybrid plant, a LCOE of 0,307 €/kWh is obtained.

$$LCOE = \frac{TRR}{C_f \cdot t \cdot P_{gen}} = 0,25\,\frac{€}{kWh}$$

$$\{TRR = 738738981\,€,\; C_f = 0,85,\; t = 175200\,h,\; P_{gen} = 20 \cdot 10^3\,kW\}$$

If this information is compared to the levelized cost for this kind of CSP technologies with a thermal storage of up to 15 hours (0,14 to 0,36 €/kWh)[30], the LCOE of the studied hybrid plant is found to be is framed within the set limits. Thus, it can be considered that cost values and established assumptions are correct.

5.3 Sensitivity Analysis

Conduction of a sensitivity analysis concerning the reclamation plant aims to determine the level of feasibility of this kind of regeneration projects. It is important to bear in mind that once water has been treated and returns to the supply system it becomes once again a valuable good with a defined price.

By means of simple equations and assumptions, we can limit the minimum price at which potable must be sold in order to prevent money losses from the entire project. Equation 10 provides the required price adjustment based on the equalization of production costs for both electric energy and water generation.

$$Price_{water} \succeq \frac{Price_{electricity} \cdot Energy_{net}}{Mass_{water}} \tag{10}$$

To carry out this analysis several parameters are required including the net amount of energy generated in the event of sacrificing part of the electricity to purify sewage. In addition, final price of safe water basically depends on the treated water capacity of the reclamation plant and the resulting energy required to carry out the whole purification process.

Advanced Treatments	**Energy (kWh/m^3)**	**Energy (kWh/day)**
Membrane Bioreactor	0,920	3339,60
Ozonization	0,080	290,40
BAC & GAC	0,010	36,30
Reverse Osmosis	0,800	2904,00
Ultraviolet Radiation	0,030	108,90
Chlorination	0,002	7,26
Total Energy (kWh/day)		6686,46

Table 16: Energy requirements for advanced treatments [60].

In accordance with the aforementioned wastewater procedures, Table 16 provides the energy requirements by volume of treated water and per day needed for each treatment. We seek to supply with safe water to the same amount of people provided with electricity, that is to say, about 27500 homes. In the view of the above, a total water capacity of 3630 m^3/day is to be treated. Another significant data for the correct calculation of this analysis is the price of electricity, which in Spain has a current value of 0,13 €/kWh.

Water & Energy Parameters	
Treated Water	3630 m^3/day
Energy Required	1,84 kWh/day
Electricity Price	0,13 €/kWh
Generated Power	20 MW
Annual Power	148,92 GWh
Price of Water (€/m^3)	
14,61	

Table 17: Water price calculation.

In the event of sacrificing the required part of electricity to run the water reclamation plant and having applied the above sensitivity equation the selling price of safe water amounts to a high cost of 14,61 €/m^3. This means that in order to be regarded as a viable proposal either the necessary energy for water production or the price of electricity should be lowered.

6 Conclusions

Water and energy face a future situation of new challenges in their management as a result of the increasing demand, the depletion of the traditional sources of extraction and its environmental consequences. Within this context of great pressure on the resources, the risk of global climate change adds a level of further complexity. For this reason, the introduction of renewable solutions is essential for the achievement of short and mid-term sustainable objectives.

In this project we have studied the characteristics of a power plant that can address future challenges in the nexus of energy and water. The plant is namely a 20 MW solar tower power plant and advanced wastewater facility were considered as the reference scenarios to be implemented in the province of Seville. The principal reasons for this location proposal include high levels of registered radiation, great amounts of biomass wealth and water necessity within this region. As a result, 850 W/m^2 of DNI reach the solar field of our CSP plant composed of 1458 heliostats and a total relective area of 174960 m^2. Molten salts were chosen as the working fluid going through the central receiver achieving temperatures that go from 290 to 565 °C. With the aim of providing the plant with an autonomy of up to 4 hours, two thermal storage tanks were included having a total capacity of 200 MWt. In the event of solar radiation absence and inability to obtain energy from the storage tanks, the biomass auxilliary system takes action. Fueled with olive pomace, the support system enables the continuous operation of the power plant when required. This allows distinction to be made between the two different operation modes; the use of solar radiation and biomass combustion. This results in an advantage over conventional CSP plants, bridging the generation discontinuities which present the biggest downsides of renewable energies.

Water management part of the plant consists of a direct potable reuse system with the objective of treating urban sewage and generate clean water within the region. The specific treatment train is composed of different physical, biological and chemical procedures such as membrane bioreactors, ozonization, BAC & GAC, reverse osmosis, ultraviolet radiation and chlorination among others.

According to the results obtained from the simulation and taking into consideration other previously published studies on the subject, the following key conclusions can be drawn from the complete system.

The application of an exergetic analysis to the plant shows the location and magnitude of irreversibilities within the plant. Special attention must be paid to exergy destruction. It was shown that the component presenting the highest values is the biomass combustor, resulting from the great temperature differences reached within heat exchangers. Regardless of these inefficiencies, solar technologies development seeks to increase the overall efficiencies within energy generation. In relation to the global efficiency of the hybrid plant a value of 15% was obtained in the event of making use of the solar field and 34% if the biomass support system is required to meet the energetic demand.

Another significant study to determine the feasibility and convenience of carrying out this kind of large scale projects is the economic analysis. Net capital investment required for the construction and implementation of the whole plant amounts to 211.526.743,00 €. Most relevant functional subsystems include the solar energy capture and conversion systems, which represent approximately the 70% of the total power plant investment costs. Likewise, many other factors contribute to these costs such as the complexity of working with two different technologies and the use of a large thermal storage. For its part, advanced treatment technologies used to supply drinkable water within the water reclamation facility involve considerable financial efforts affecting the final investment required. To this mmust be added the resulting rise of interest rates due to the risk arising from the relative inmaturity of these kind of renewable projects. As discussed above, obtained results are consistent with existing reference plants and therefore established data and assumptions can be accepted as valid.

The last economic factor to be analyzed is the levelized cost of electricity. This parameter enables the comparison of different sources of electricity creating a relationship between the amount of energy generated and the required costs to produce it. A value of 0,25 €/kWh is reached by the designed hybrid plant, which can be considered as a correct result contained within the set limits for the LCOE within solar tower power plants. However, it is supposed that the future cost of electricity for renewable energies will decline over time due to the underselling of solar components and associated costs.

Lastly, a sensitivity analysis of the water reclamation plant is conducted with the purpose of evaluating the feasibility of this kind of resource recovery project. Selling price of potable water amounts to 14,61 €/m^3, which at present involves an excessive cost that can only be normalized either if the required energy for its regeneration or the electricity price is lowered. However, surely in the future this price might not be too elevated specially in certain places with lack of water resources.

Within the technological environment, investment reductions on solar equipment are expected especially of mirrors and storage. Higher component efficiencies are foreseen as well as the development of working fluids capable of reaching hotter temperatures and reducing storage costs. The same applies to water reuse technologies, as time goes by more advanced and innovative alternatives will be developed reducing its price. Considering all above-mentioned exergetic and economic aspects it is provided that hybrid technologies as well as water reuse constitute a great opportunity for future global sustainability and environmental care.

A Simulation Results

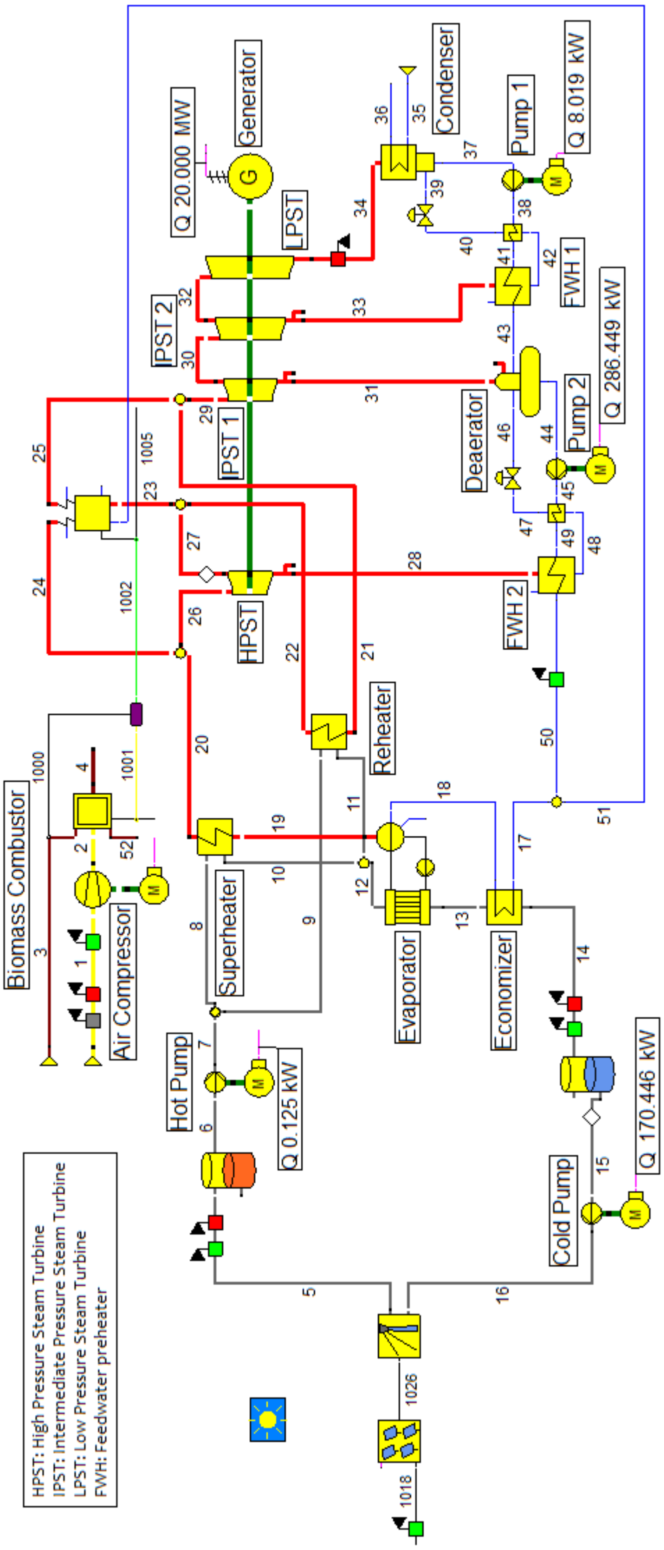


Figure 31: Diagram of the reference plant.

Stream Number	Mass Flow (kg/s)	Temperature (°C)	Pressure (bar)	Enthalpy (kJ/kg)	Entropy (kJ/kg·K)	Quality (x)
5	119,53	565,00	1,00	845,22	1,67	0
6	119,53	565,00	1,00	845,22	1,67	0
7	119,53	565,00	1,01	845,23	1,67	0
8	59,77	565,00	1,01	845,23	1,67	0
9	59,77	565,00	1,01	845,23	1,67	0
10	59,77	428,29	1,01	635,67	1,39	0
11	59,77	493,70	1,01	735,53	1,53	0
12	119,53	461,06	1,01	685,60	1,46	0
13	119,53	337,80	1,01	498,73	1,19	0
14	119,53	290,00	1,01	426,96	1,06	0
15	119,53	290,00	1,00	426,96	1,06	0
16	119,53	290,92	21,99	428,34	1,06	0
17	15,51	155,00	136,00	661,83	1,88	0
18	15,51	276,37	133,28	1214,91	3,01	0
19	15,51	332,80	133,28	2655,01	5,41	1
20	15,51	545,00	126,00	3462,47	6,61	1
21	15,38	545,00	33,25	3555,23	7,31	1
22	15,38	360,01	35,00	3128,95	6,70	1
26	15,51	545,00	126,00	3462,47	6,61	1
27	15,38	360,01	35,00	3128,95	6,70	1
28	0,13	360,01	35,00	3128,95	6,70	1
29	15,38	360,01	30,00	3555,23	7,36	1
30	13,63	298,07	4,50	3061,88	7,50	1
31	1,75	298,07	4,50	3061,88	7,50	1
32	12,97	81,04	0,40	2646,38	7,70	1
33	0,66	81,04	0,40	2646,38	7,70	1
34	12,97	45,81	0,10	2477,29	7,81	0,96
35	341,13	20,00	1,01	84,01	0,30	0
36	341,13	40,81	0,51	170,95	0,58	0
37	13,63	45,81	0,10	191,81	0,65	0
38	13,63	45,85	4,60	192,38	0,65	0
39	0,66	45,81	0,10	204,55	0,69	0,01
40	0,66	48,85	0,40	204,55	0,69	0
41	13,63	47,16	4,55	197,86	0,67	0
42	0,66	75,86	0,40	317,57	1,03	0
43	13,63	74,16	4,50	310,77	1,01	0
44	15,51	147,91	4,50	623,22	1,82	0
45	15,51	150,14	136,10	641,07	1,83	0
46	0,13	147,91	4,50	647,65	1,88	0,01
47	0,13	153,14	35,00	647,65	1,87	0
48	0,13	242,56	35,00	1049,76	2,73	0
49	15,51	150,93	136,05	644,43	1,84	0
50	15,51	155,00	136,00	661,83	1,88	0

Table 18: Solar stream simulation results.

Stream Number	Mass Flow (kg/s)	Temperature (°C)	Pressure (bar)	Enthalpy (kJ/kg)	Entropy (kJ/kg·K)	Quality (x)
1	46,74	20,00	1,00	20,30	6,92	1
2	46,74	22,82	1,03	23,16	6,92	1
3	3,52	20,00	1,03	21,35	0,43	0
4	49,96	170,00	1,03	178,98	7,41	1
23	14,65	390,00	35,00	3199,80	6,81	1
24	14,77	580,00	126,00	3552,96	6,72	1
25	14,65	580,00	30,00	3637,42	7,46	1
28	0,12	390,01	35,00	3199,80	6,81	1
30	13,02	326,05	4,50	3119,54	7,60	1
31	1,63	326,05	4,50	3119,54	7,60	1
32	12,40	100,18	0,40	2684,03	7,80	1
33	0,62	100,18	0,40	2684,03	7,80	1
34	12,40	45,81	0,10	2511,16	7,92	0,97
35	330,89	20,00	1,01	84,01	0,30	0
36	330,89	40,81	0,51	170,95	0,58	0
37	13,02	45,81	0,10	191,81	0,65	0
38	13,02	45,85	4,60	192,38	0,65	0
39	0,62	45,81	0,10	204,55	0,69	0,01
40	0,62	48,85	0,40	204,55	0,69	0
41	13,02	47,14	4,55	197,78	0,67	0
42	0,62	75,86	0,40	317,57	1,03	0
43	13,02	74,16	4,50	310,77	1,01	0
44	14,77	147,91	4,50	623,22	1,82	0
45	14,77	150,14	136,10	641,07	1,83	0
46	0,12	147,91	4,50	647,65	1,88	0,01
47	0,12	153,14	35,00	647,65	1,87	0
48	0,12	242,56	35,00	1049,78	2,73	0
49	14,77	150,91	136,05	644,34	1,84	0
51	14,77	155,00	136,00	661,83	1,88	0
52	0,30	850,00	1,03	898,00	1,42	0

Table 19: Biomass stream simulation results.

B Data for economic calculations

	Ref. Cost	**Ref. Year**	**Size Exponent**	**Reference**
Air Compressor	-	2010	0,9	Towler and Sinnott, 2013
Biomass CC & SG	-	2010	0,9	Towler and Sinnott, 2013
Economizer	-	2010	0,87	Towler and Sinnott, 2013
Evaporator	$3{,}7\cdot10^6$	2005	0,87	Javier Pisa, pers.com
Superheater	-	2010	0,87	Towler and Sinnott, 2013
Reheater	-	2010	0,87	Towler and Sinnott, 2013
Deaerator	$0{,}9\cdot10^6$	1990	1,00	Tsatsaronis et al., 1991
Condenser	$9{,}0\cdot10^6$	1999	0,87	Buchanan et al., 2000
Pumps	-	2010	0,8	Towler and Sinnott, 2013
Steam Turbines	$26{,}0\cdot10^6$	1999	-	Buchanan et al., 2000
Feedwater Preheaters	$2{,}0\cdot10^6$	2005	-	Javier Pisa, pers.com

Table 20: Data for purchased equipment cost calculations.

Parameter (units)			**Value**
Average general inflation rate (%)			2,5
Average nominal escalation rate (%)			2,5
Average nominal escalation rate for Biomass (%)			3,5
Beginning of design and construction period			2018
Date of commercial operation			2020
Plant economic life (years)			20
Plant life for tax purposes (years)			15
Plant financing fractions and required returns on capital			
Type of financing	**Common equity**	**Debt**	
Financing fraction (%)	60	40	
Required annual return (%)	12	8	
Resulting average cost of money (%)		10	
Average combined income tax rate (%)			38
Average property tax rate (% of PFI)			1,5
Average insurance rate (% of PFI)			0,5
Average capacity factor (%)			85
Labor positions for opening and maintenance			50
Average labor rate (€/h)			30
Annual fixed operating and maintenance costs (10^6 *€)*			5,748
Annual fixed operating and maintenance costs at full capacity (10^3 *€)*			530
Unit cost of fuel (€/MJ-LHV)			0,002
Allocation of plant facilities investment to the individual years of design and construction (%)			
Jan. 1-Dec. 31, 2018			40
Jan. 1-Dec. 31, 2019			60

Table 21: Assumptions involved in the economic analysis (reference year: 2018).

References

[1] G. Olsson, *Water and Energy. Threats and Opportunities*, 1st ed. London: IWA Publishing, 2012.

[2] A. Endo et al., “Methods of the Water-Energy-Food Nexus”, *Water*, vol. 7, n.º 10, pp. 5806–5830, 2015.

[3] E. Cabrera, M. Á. Pardo, E. Cabrera Jr. and R. Cobacho. “Agua y energía en España. Un reto complejo y fascinante”, *Ingeniería del agua*, vol. 17, n.º 3, pp. 235-246, sep. 2010. [Online]. Available on: https://polipapers.upv.es/index.php/IA/article/view/2976

[4] L. Hardy and A. Garrido, ”Análisis y evaluación de las relaciones entre el agua y la energía en España”, in *Papeles de Agua Virtual*, 1st ed. n.º 6. Madrid: Fundación Marcelino Botín, 2010.

[5] WWAP, “The United Nations World Water Development Report 2014: Water and Energy”, Paris, UNESCO, 2014.

[6] P. Linares and Z. Khan, *Agua, energía y cambio climático*, 1st ed. Madrid: Fundación Canal, 2015.

[7] IEA, “Key World Energy Statistics.”, Paris, IEA, 2017. [Online]. Available on: https://www.iea.org/publications/freepublications/publication/KeyWorld2017.pdf

[8] H. Andruleit et al., “Reserves, resources and availability of energy resources”, Hannover, BGR, 2016. [Online]. Available on: https://www.bgr.bund.de/EN/Themen/Energie/Downloads/energiestudie_2016_en.pdf;jsessionid=F518F6A3F3700C8521CE94FB00D216FB.1_cid292?__blob=publicationFile&v=2

[9] S. Jiménez, “Combustión de carbón”, Laboratorio de investigación en tecnologías de la combustión, LITEC, 2012. [Online]. Available on: http://www.energia2012.es/sites/default/files/Combustion_de_carbon.pdf

[10] IEA, “CO_2 Emissions from Fuel Combustion - Highlights”, Paris, IEA, 2017. [Online]. Available on: https://www.iea.org/publications/freepublications/publication/CO2EmissionsfromFuelCombustionHighlights2017.pdf

[11] IEO, “Transportation sector energy consumption”, 2016. [Online]. Available on: https://www.eia.gov/outlooks/ieo/pdf/transportation.pdf

[12] IEA, ““Resources to Reserves: Oil, Gas and Coal Technologies for the Energy Markets of the Future”, 2013. [Online]. Available on: https://www.iea.org/publications/freepublications/publication/Resources2013.pdf

[13] K. Tromly, “Renewable Energy: An Overview”, in *Energy Efficiency and Renewable Energy Clearinghouse*, National Re-

newable Energy Laboratory (NREL), 2001. [Online]. Available: https://www.nrel.gov/docs/fy01osti/27955.pdf

[14] “Tesla Powerwall 2”. Solahart. [Online]. Available on: https://www.solahart.com.au/products/battery-storage/tesla-powerwall-2 (Accessed: 04-Mar-2018).

[15] “Renewable energy sources and other alternative energy sources”. [Online]. Available on: https://www.dmme.virginia.gov/DE/LinkDocuments/HandbookAlternativeEnergy.pdf

[16] A.J. Marshall, “Any renewable energy solution requires extracting the full value of biomass”. Canadian biomass. [Online]. Available on: https://www.canadianbiomassmagazine.ca/biofuel/any-renewable-energy-solution-requires-extracting-the-full-value-of-biomass-6499?jjj=1538557410845 (Accessed: 04-Mar-2018).

[17] ERENOVABLE, “¿Qué es la energía geotérmica? Fuentes, usos, ventajas y desventajas de la energía geotérmica”. Erenovable.com, 2018. [Online]. Available on: https://erenovable.com/energia-geotermica/ (Accessed: 04-Mar-2018).

[18] A. Wilson, “The Grand Inga Dam Project”, Physics 240, 2010. [Online]. Available on: http://large.stanford.edu/courses/2010/ph240/wilson1/ (Accessed: 05-Mar-2018).

[19] M. Günther et al., “Advanced CSP Teaching Materials Chapter 2 Solar Radiation”, 2011. [Online]. Available on: http://www.energy-science.org/bibliotheque/cours/1361469594Chapter%2002%20radiation.pdf

[20] IEA, “Solar Energy Perspectives”, in *Renewable energy technologies*, Paris, IEA, 2011. [Online]. Available on: https://www.iea.org/publications/freepublications/publication/Solar_Energy_Perspectives2011.pdf

[21] C. Richter, S. Teske, and R. Short, “Energía Solar Térmica de Concentración’, 2009. [Online]. Available on: http://www.aperca.org/temppdf/concentracion_2009.pdf

[22] S. A. Kalogirou, “Solar thermal collectors and applications”, Progress in Energy and Combustion Science, Cyprus, Tech. Rep. 213-295, 2004. [Online]. Available on: http://www.ercba.ntu.edu.tw/weifang/eBook/heat/%20pump/HP%20for%20desalination/Solar%20thermal%20collectors%20and%20applications.pdf

[23] M. Qader and S. Stückrad, “Concentrated solar power”, IASS (Institute for Advanced Sustainability), Postdam (Germany), 2016. [Online]. Available on: http://publications.iass-potsdam.de/pubman/item/escidoc:1914914:5/component/escidoc:1914917/IASS_Fact_Sheet_2016_2_en.pdf

[24] Z. Rongrong, Y. Yongping, Y. Qin and Z. Yong, “Modeling and Characteristic Analysis of a Solar Parabolic Trough System: Thermal Oil as the Heat Transfer Fluid”, in *Journal of Renewable Energy*, vol. 2013, Article ID 389514, 8 pages, 2013. [Online]. Available on: https://doi.org/10.1155/2013/389514

[25] “Power Tower System Concentrating Solar Power Basics”, in *Solar Energy Technologies Office*, US Department of Energy (DOE), 2013. [Online]. Available on: https://www.energy.gov/eere/solar/articles/power-tower-system-concentrating-solar-power-basics (Accessed: 03-Oct-2018).

[26] S. Lab, “Solar Trough Systems”, US Department of Energy (DOE), Tech. Rep. 363-3732, 1998. [Online]. Available on: https://www.nrel.gov/docs/legosti/fy98/22589.pdf

[27] Solar Millennium AG, “The Parabolic Trough Power Plants Andasol 1 to 3, The Largest Solar Power Plants in the World—Technology Premiere in Europe,” pp. 1–26, Erlangen (Germany), 2008. [Online]. Available on: http://large.stanford.edu/publications/power/references/docs/Andasol1-3engl.pdf

[28] “Kimberlina Solar Thermal Power Plant - Solar generated, superheated steam for clean, reliable energy”, AREVA Solar, Mountain View (California). [Online]. Available on: http://us.areva.com/home/liblocal/docs/Catalog/Renewables/Areva_Kimberlina_flyer_HR.pdf

[29] R. Pitz-Paal, K. Hennecke, P. Heller, and R. Bucl, “Solar thermal power plants - Utilising concentrated sunlight for generating energy”, BINE Information Service, vol. 2, ISSN 1610-8302, Germany, 2013. [Online]. Available on: http://www.bine.info/fileadmin/content/Publikationen/Englische_Infos/themen_0213_engl_Internetx.pdf

[30] L. Crespo et al., “Concentrating solar power”, in *Renewable energy technologies: Cost analysis series*, vol. 1, IRENA, 2012. [Online]. Available ON: https://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-csp.pdf

[31] V. Ruiz et al., “Evaluación del potencial de energía solar termoeléctrica - Estudio Técnico PER 2011-2020”, IDAE (Instituto para la Diversificación y Ahorro de la Energía), Madrid, 2011. [Online]. Available on: http://www.idae.es/uploads/documentos/documentos_11227_e12_termoelectrica_A_fd47d41f.pdf

[32] K. Vignarooban, X. Xu, A. Arvay, K. Hsu, and A. M. Kannan, “Heat transfer fluids for concentrating solar power systems-A review”, in *Appl. Energy*, vol. 146, pp. 383–396, 2015. [Online]. Available on: https://doi.org/10.1016/j.apenergy.2015.01.125

[33] D. A. Baharoon, H. A. Rahman, W. Z. W. Omar, and S. O. Fadhl, “Historical development of concentrating solar power technologies to generate clean electricity efficiently – A review”, in *Renew. Sustain. En-*

ergy Rev., vol. 41, pp. 996–1027, Jan. 2015. [Online]. Available on: https://doi.org/10.1016/j.rser.2014.09.008

[34] S. Pramanik and R. V. Ravikrishna, "A review of concentrated solar power hybrid technologies", in *Appl. Therm. Eng.*, vol. 127, pp. 602–637, Department of Mechanical Engineering, Bangalore (India), Tech. Rep 602-637, 2017. [Online]. Available on: https://doi.org/10.1016/j.applthermaleng.2017.08.038

[35] M. B. da Fonseca, W.R. Poganietz, and H.J. Gehrmann, "Environmental and economic analysis of SolComBio concept for sustainable energy supply in remote regions", in *Appl. Energy*, vol. 135, pp. 666–674, Dec. 2014. [Online]. Available on: https://doi.org/10.1016/j.apenergy.2014.07.057

[36] J. H. Peterseim, U. Hellwig, A. Tadros, and S. White, "Hybridisation optimization of concentrating solar thermal and biomass power generation facilities", in *Sol. Energy*, vol. 99, pp. 203–214, Jan. 2014. [Online]. Available on: https://doi.org/10.1016/j.solener.2013.10.041

[37] "First commercial CSP-Biomass Hybrid Power Plant in Spain". [Online]. Available on: https://biomasspower.gov.in/document/flipbook-pdf-document/Solar%20Biomass%20Hybrid%20Plant%20in%20Spain.pdf

[38] "Cómo funciona una caldera de biomasa", IMARTEC: Biomass Energy Revolution, Jun. 2014. [Online]. Available on: https://www.imartec.es/como-funciona-una-caldera-de-biomasa/ (Accessed: 09-Jan-2019).

[39] S. J. Zarrouk and H. Moon, "Efficiency of geothermal power plants: A worldwide review", in *Geothermics*, vol. 51, pp. 142–153, Jul. 2014. [Online]. Available on: https://doi.org/10.1016/j.geothermics.2013.11.001

[40] "Stillwater power plant - Enel Green Power North America's Stillwater power plant is a first-in-the-world innovator twice over", (EGP-NA) Enel Green Power North America, 2016. [Online]. Available on: https://www.leg.state.nv.us/App/NELIS/REL/79th2017/ExhibitDocument /OpenExhibitDocument?exhibitId=30862&fileDownloadName=0411ab52a_pagt.pdf

[41] M. Ciani Bassetti, D. Consoli, G. Manente, and A. Lazzaretto, "Design and off-design models of a hybrid geothermal-solar power plant enhanced by a thermal storage", in *Renew. Energy*, vol. 128, pp. 460–472, Dec. 2018. [Online]. Available on: https://doi.org/10.1016/j.renene.2017.05.078

[42] M. C. Cameretti, G. Langella, S. Sabino, and R. Tuccillo, "Modeling of a hybrid solar micro gas-turbine power plant", pp. 1876–6102, 2015. [Online]. Available on: https://doi.org/10.1016/j.egypro.2015.11.820

[43] EPA, "Review of coal fired power stations air emissions and monitoring,", EPA, 2018. [Online]. Available on: https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/air/18p0700-review-of-coal-fired-power-stations.pdf

[44] M. Espigares and J.A. Pérez, "Aguas Residuales: Composición", p. 22, 1985 [Online]. Available on:

http://cidta.usal.es/cursos/EDAR/modulos/Edar/unidades/LIBROS/logo/pdf/Aguas_Residuales_composicion.pdf

[45] K. Skibinski, P. Smith, D. Cross and B. Skidmore, “Introduction to Wastewater Management,” in *Handbook on Wastewater Management for Local Representatives*, NYWEA, Jan. 2013. [Online]. Available on: http://efc.syr.edu/wp-content/uploads/2015/03/Chapter1-web.pdf

[46] M. von Sperling, ”Wastewater characteristics, treatment and disposal” in *Biological Wastewater Treatment Series*, 1st ed. London/ New York: IWA Publishing, 2007.

[47] M. Peña, “Waste Stabilisation Ponds”, IRC (International Water and Sanitation Centre), Delft, 2004. [Online]. Available on: https://www.sswm.info/sites/default/files/reference_attachments/VARON%202004%20%20Waste%20Stabilistion%20Ponds.pdf

[48] “Drinking Water Chlorination”, WCC (World Chlorine Council), 2008. [Online]. Available on: https://www.worldchlorine.org/wp-content/themes/brickthemewp/pdfs/WCC_Policy_Paper_Water_Chlorination.pdf

[49] M. J. McGuire, “Drinking Water Chlorination: A review of U.S Disinfection Practices and Issues”, ACC (American Chemistry Council), Santa Mónica (California), 2016. [Online]. Available on: https://chlorine.americanchemistry.com/Chlorine-Benefits/Safe-Water/Disinfection-Practices.pdf

[50] EPA, “Folleto informativo de tecnología de aguas residuales - Desinfección con luz ultravioleta”, Philadelphia, 1999. [Online]. Available on: https://www.epa.gov/sites/production/files/2015-06/documents/cs-99-064.pdf

[51] B. Tansel, “New Technologies for Water and Wastewater Treatment: A Survey of Recent Patents,” in *Recent Patents Chem.*, Eng., vol. 1, pp. 17–26, 2008. [Online]. Available on: http://www.aimme.es/archivosbd/observatorio_oportunidades/new_technologies_for_water_and_wastewater_treatment_-_Patents.pdf

[52] “Water for people, water for life”, in *Executive summary of the UN World Water Development Report*, UNESCO, París, 2003. [Online]. Available on: http://www.un.org/esa/sustdev/sdissues/water/WWDR-spanish-129556s.pdf

[53] España, Real Decreto 1620/2007, de 7 de diciembre, de Régimen Jurídico de la Reutilización de las Aguas Depuradas. BOE, 8 de diciembre de 2007, núm. 294, p. 50639-50661 [Online]. Available on: http://www.boe.es/boe/dias/2007/12/08/pdfs/A50639-50661.pdf

[54] A. Gerling, “Potable Reuse 101”, in *An innovative and sustainbale water supply solution*, AWWA (American Water Works Association), 2016. [Online]. Available on:

https://www.awwa.org/Portals/0/AWWA/ETS/Resources/Potable%20Reuse%20101.pdf?ver=2018-12-12-182505-710

[55] "Case study summaries", in *Best practices for developing indirect potable reuse projects*, Water Reuse Foundation, USA, 2004, pp. 21-26. [Online]. Available on: https://www.waterboards.ca.gov/water_issues/programs/grants_loans/water_recycling/research/01_004_01.pdf

[56] *Manual de Agua Potable, Alcantarillado y Saneamiento. Alternativas tecnológicas de tratamiento de aguas residuales para la recarga artificial de acuíferos*, CONAGUA (Comisíon Nacional del Agua). [Online]. Available on: http://aneas.com.mx/wp-content/uploads/2016/04/SGAPDS-1-15-Libro38.pdf

[57] J. Lahnsteiner, P. Van Rensburg and J. Esterhuizen, "Direct potable reuse - a feasible water management option", in *Journal of water reuse and desalination*, 2018. [Online]. Available on: https://doi.org/10.2166/wrd.2017.172

[58] G. Tchobanoglous et al., "Framework for direct potable reuse", AWWA (American Water Works Association), Water Environment Federation and NWRI (National Water Research Institute), 2015. [Online]. Available on: https://watereuse.org/wp-content/uploads/2015/09/14-20.pdf

[59] A. Bejan, G. Tsatsaronis, and M. Moran, *Thermal Design and Optimization*, New York: J. Wiley, 1996.

[60] T. Guo, J. Englehardt, and T. Wu, "Review of cost versus scale: water and wastewater treatment and reuse processes", in *Water Science & Technology*, 2014. [Online]. Available on: https://pdfs.semanticscholar.org/dcfa/b49323dd0aeb5474c797c3aa3b582f39c4e1.pdf

[61] "La radiación solar global anual", Instituto Nacional de Metereología. Ministerio de Medio Ambiente and IGN (Instituto Geográfico Nacional). [Online]. Available on: https://www.ign.es/espmap/mapas_clima_bach/pdf/Clima_Mapa_12texto.pdf

[62] "Radiación solar — Agencia Andaluza de la Energía", Consejería de empleo, empresa y comercio. [Online]. Available on: https://www.agenciaandaluzadelaenergia.es/es/la-energia-en-andalucia/recursos-energeticos/radiacion-solar (Accessed: 12-Nov-2018).

[63] "Datos energéticos de Andalucía 2016 — Agencia Andaluza de la Energía", Consejería de empleo, empresa y comercio, 2016. [Online]. Available on: https://www.agenciaandaluzadelaenergia.es/es/la-energia-en-andalucia/datos-energeticos (Accessed: 12-Nov-2018).

[64] "GEA Biomasa - Agencia Andaluza de la Energía - Mapa de Potencial de Biomasa en Andalucía", Consejería de empleo, empresa y comercio. [Online]. Available on:

https://www.agenciaandaluzadelaenergia.es/biomasa/biomasa/init.do?prefix=/biomasa&name=potencia (Accessed: 12-Nov-2018).

[65] "La biomasa en Andalucía", Agencia Andaluza de la Energía - Consejería de empleo, empresa y comercio, 2017. [Online]. Available on: https://www.agenciaandaluzadelaenergia.es/sites/default/files/documentos/la_biomasa_en_andalucia_diciembre_2017.pdf

[66] "Mapa indicadores sequía hidrológica", Informe - Resumen sobre la situación de la sequía hidrológica, 2018. [Online]. Available on: https://www.miteco.gob.es/es/agua/temas/observatorio-nacional-de-la-sequia/informes-mapas-seguimiento/

[67] G. Augsburger, "Thermo-Economic Optimisation of Solar Tower Thermal Power Plants", in *PhD Thesis*, vol. 5648, pp. 1–171, 2013. [Online]. Available on: https://infoscience.epfl.ch/record/183139/files/EPFL_TH5648.pdf

[68] S. Kyritsis, *1st World Conference on Biomass for Energy and Industry: proceedings of the conference held in Sevilla, Spain, 5-9 June 2000*, James & James, 2001.

[69] H. Andersson and M. Forss, "Microbiological Risk Assessment of the Water Reclamation Plant in Windhoek , Namibia", Master Thesis, pp. 1–106, Sweden, 2011. [Online]. Available on: http://publications.lib.chalmers.se/records/fulltext/150138.pdf

[70] P. Du Pisani and J. G. Menge, "Direct potable reclamation in Windhoek: A critical review of the design philosophy of new Goreangab drinking water reclamation plant", in *Water Sci. Technol. Water Supply*, vol. 13, no. 2, pp. 214–226, 2013. [Online]. Available on: https://doi.org/10.2166/ws.2013.009

[71] J. Menge, "Treatment of wastewater for re-use in the drinking water system of Windhoek", 2005. [Online]. Available on: http://www.wastewater.co.za/images/files/Treatment_of_wastewater_for_Drinking_Water_in_Windhoek_J_Menge.pdf

[72] IEA, "Biomass for power generation and CHP", 2007. [Online]. Available on: https://www.iea.org/publications/freepublications/publication/essentials3.pdf

[73] "20MW Gemasolar Plant: Elegant, But Pricey", Energy Central, Jun. 2011. [Online]. Available on: https://www.energycentral.com/c/ec/20mw-gemasolar-plant-elegant-pricey (Accessed: 06-Feb-2019).