Final Master thesis

Titulacio

Market Potential Analysis of a Solar Hybrid Dish-Brayton System

Memoria

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ABSTRACT

In this study, the market potential of a solar hybrid dish-Brayton system has been analyzed, using a market analysis of four relevant industries and the techno economic analysis of the system, operating in a stand-alone configuration.

The industries assessed were desalination, produce drying, Steam Methane Reforming for Hydrogen Production and Compressed air for the mining industry. After taking into consideration, the various factors that affect each industry, the applicability of the technology in industrial processes varies.

It was found that the technology would be a good fit in small scale applications in remote locations for both desalination and for supplying compressed air in the mining industry. Produce Drying requires the targeted industries to be well-established, large-scale players wanting to decarbonize their processes. Owing to the prohibitive initial capital of the system, it would not be feasible with small scale market players. In locations where there was high DNI and higher costs of natural gas, the technology can be used in the thermal process in Steam Methane reforming for Hydrogen production.

The techno economic analysis was carried out in three different locations, that has high DNI and relevant industries present. It was found that the price of natural gas and the DNI plays the major role in determining the Levelized cost of Energy at a location. The biggest costs factor in the initial capital spent was the expense of the dish. Future developments in cheaper material with similar levels of reflectivity, and the economies of scale, due to increase of production, stemming from increased demand would reduce the cost of the technology.

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ABBREVIATIONS

CPV:	Concentrating Photovoltaics
CR:	Concentration Ratio
CSP:	Concentrated Solar Power
DNI:	Direct Normal Irradiance
HTF:	Heat Transfer Fluid
JPL:	Jet Propulsion Laboratory
KISR:	Kuwait Institute of Scientific Research
LCOE:	Levelized Cost of Energy
LFR:	Linear Fresnel Reflector
MDAC:	McDonnell Douglas Astronautics Cord
MED:	Multi Effect Distillation
MENA:	Middle East and North Africa
MGT:	Micro Gas Turbine
MSF:	Multi Stage Flashing
OMSoP:	Optimized Microturbine Solar Power System
OPEX:	Operating Expenditure
ORC:	Organic Rankine Cycle
PTC:	Parabolic Trough Concentrators
RO:	Reverse Osmosis
SAM:	Serviceable Addressable Market
SRTA:	Solar Reflector Tracking Collector
STEP:	Solar Total Energy Project
TES:	Thermal Energy Storage
TIT:	Turbine Inlet Temperature
LEC:	Levelized Electricity Cost

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1. INTRODUCTION

Human civilization is currently at a crossroads. The industrial revolution that came about with the use of fossil fuel such as coal and later on Oil and natural gas as a means of fueling machinery and that have overtime become a vital part of powering the rise of modern economy and society. However, it has been observed that the emissions from these fuels are increasing the greenhouses gases in the atmosphere, which retains more heat from the solar irradiation that irradiates on the earth. This has caused the earth to warm significantly over the course of this period and with the continued use of fossil fuels it is continuing to warm up. It is predicted that by 2100, that without any global policies to mitigate this issue, there will be a temperature rise of 4.1-4.8 ºC compared to pre industrialization levels in the atmosphere and with current policies and targets it may still rise up to 2.7-3.1 ºC compared to pre industrialization levels. [1] Therefore, it is evident that global warming is a legitimate concern that is threatening the survival of the human species.

One of the main ways governments and institutions are attempting to mitigate this issue, is to increase the share of non-fossil fuel based renewable energy resources in their energy consumption profiles. The world is already seeing a rapid increase in the deployment of photovoltaic solar energy power plants which extract the energy of the light that is irradiated on to earth from the sun, wind power plants which make use of the changes in pressure in the different regions of the world which causes wind, to convert to mechanical energy, which is subsequently converted to electrical energy, geothermal power plants which makes use of the thermal energy in the planet's core and converts into mechanical and eventually electrical energy, Biomass and biogas energy powerplants which use the either use incineration of biomass such as agricultural waste, wood, forestry waste, Industrial residue and animal waste or the anaerobic digestion of various biomass sources to produce biogas which can be used as either heat or produce electricity.

Another emerging renewable energy technology is Concentrated Solar Power (CSP) plants. There are different technologies used to extract the thermal energy that is irradiated on to the surface of the earth from the sun to generate both heat and electricity, combined with thermal storage, presents a clear opportunity to decarbonize industrial purposes and provide 24-hour electricity to the electric grid. Parabolic trough systems use arrays of troughs to concentrate solar rays onto an absorber tube, which collects the heat and transfers it to generate electricity through a steam turbine. Fresnel System is setup similarly, however in this case, instead of troughs, a series of glass panels are used to concentrate the solar rays. CSP Towers use a field of reflectors, named heliostats to reflect the solar rays to a receiver, where it is concentrated at the top of a central tower.

However, in this project, the objective is to focus on the techno-economic and market feasibilities of the parabolic dish CSP technology, which is a modular and a smaller scale powerplant than the previously mentioned CSP plants types. It uses a parabolic dish to concentrate the solar rays onto a receiver that extracts the solar heat and converts it into electricity. Conventionally sterling engines were used to convert the solar heat into electricity, however in this study the use of the Brayton cycle by means of a micro gas turbine (MGT) is used.

In this study, the fundamental principles, and the different types of the CSP systems have been explained. The different types of power conversion system that have been used in the dish CSP system in particular have been explored and subsequently the history and the evolution of the dish CSP system has been examined. The state of the art of the small CSP systems, the OMSoP project and the potential of the dish CSP system operating with a MGT system to be integrated with Biomass in various hybrid configurations are examined.

The market potential of four key markets have been explored with the use of market analysis, where each market's potential in terms of its relevance, predicted growth and the effectiveness of the proposed system as a solution to each market has been explored. Following the market analysis, three promising locations have been chosen in terms of its solar resource, industry and biomass availability and a preliminary techno economic analysis has been done to show the suitability of the technology in different high potential locations.

2. BACKGROUND

2.1 SOLAR RESOURCE

It is known that any object above absolute zero temperature, emits radiation. The Sun having an effective temperature of 6000 K, emits radiation over a variety of wavelengths, which are from high energy shorter wavelength radiation or low energy long wavelength radiation. 97% of the solar radiation falls in the range of 290nm to 3000nm, which is referred to as the Spectral range. Since the radiation power received from the sun is fairly constant, it is termed the solar constant.

The amount of radiation exchanged between two objects is affected by their separation distance. The Earth's elliptical orbit (eccentricity 0.0167) brings the planet closest to the sun in January and farthest from the sun in July. This annual variation results in variation of the Earth's solar irradiance of ± 3%. The average Earth-sun distance is 149,598,106 km (92,955,953 miles), or 1 AU. Figure 1: Effect of solar radiation on earth depending on the time of year. Figure 1 below shows the Earth's orbit in relation to the northern hemisphere seasons, caused by the average 23.5-degree tilt of the Earth's rotational axis with respect to the plane of the orbit. [2]

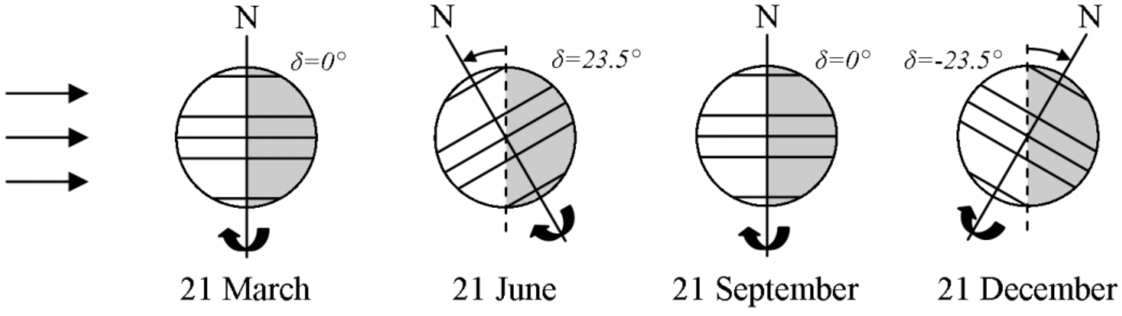


Figure 1: Effect of solar radiation on earth depending on the time of year. [3]

The direct sunlight that is radiating at a location is termed the Direct normal irradiance (DNI). The air mass between the surface of the earth and the atmosphere scatters this direct radiation to a certain extent. The more distance there is from the atmosphere to the surface of the earth, more scattering is observed.

DNI is one of the most important factors that needs to be considered when designing CSP systems. To maximize production CSP receivers are often equipped with tracking the DNI. The intensity of DNI at each location on earth can be measured by an Pyrheliometer.

The diffused radiation can vary, according to the weather and the cloudiness of the sky in addition to the relationship between the elevation of the earth surface. The percentage of diffused sunlight can vary from 10% on a clear to 100% on a cloudy day. The diffused radiation can be measured with a shadow-band Pyrheliometer that blocks the direct radiation. [4]

The global irradiance is the sum of both direct normal irradiance and diffused irradiance. This can be measured by a Pyrheliometer.

Equation 1, shows this relationship.

$$I_{t,h} = I_b Cos\theta_z + I_{d,h}$$

Equation 1: Global Solar Irradiance

Where $I_{t,h}$ is the global radiation on a horizontal surface, $I_{d,h}$ is the diffuse radiation on a horizontal surface, I_b is the beam radiation and θ_z is the solar zenith angle. The definition of the zenith angle in terms of solar irradiation is as below.

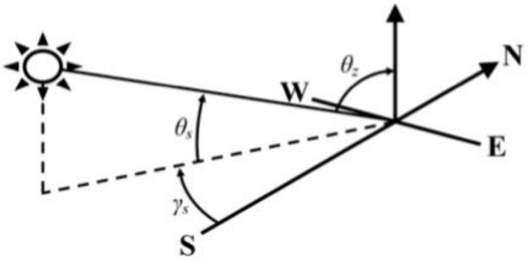
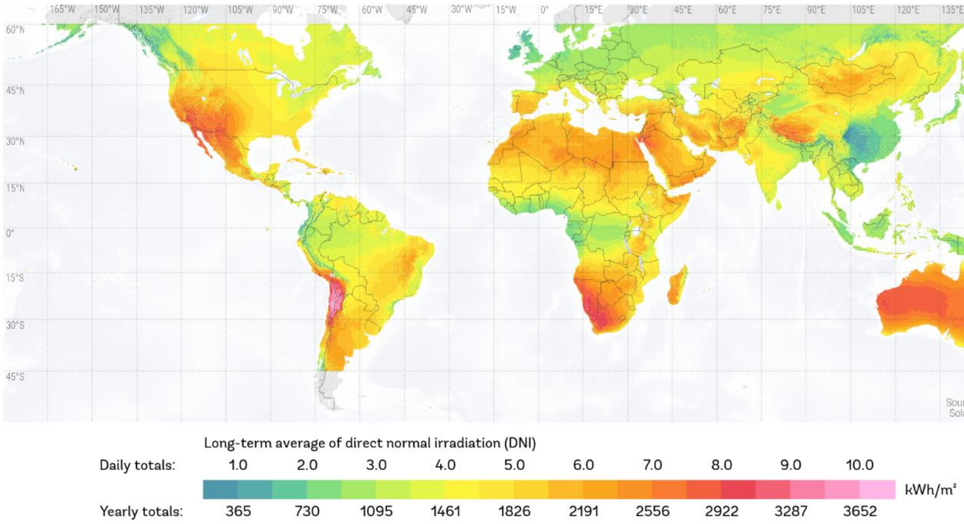


Figure 2: Solar Zenith Angle

The irradiation on the earth surface varies in different parts of the planet. Higher latitude or higher humidity in the atmosphere means that there is less solar irradiation at a particular location. The world map below shows the DNI intensities. When a location has higher DNI it fundamentally provides more heat for a CSP system to operate in.

The capacity factor of a power plant, which is defined as the ratio of the actual Energy Produced over a period over the energy that the system would hypothetically produce if it was operating at full capacity all throughout the said period. With higher heat due to higher DNI at a location, CSP system is able to operate at the nominal power for a longer period, that when it has low DNI.



© 2019 The World Bank
Source: Global Solar Atlas 2.0
Solar resource data: Solargis

Figure 3: DNI World map [5]

2.2 ENERGY BALANCE ON RECEIVER

The useful energy that comes from a CSP powerplant depends on the DNI and the energy balance of the receiver system of the CSP technology. The energy balance refers to the difference between the energy received at the particular location from the sun and the total losses incurred by the system. Where the first term is the useful energy extracted by the CSP system and the second term is the energy given by the sun and the third term refers to all the losses incurred in the system.

$$Q_{Useful} = Q_{Sun} - Q_{losses}$$

Equation 2: Useful heat

The losses refer to optical losses that includes any shading losses, soiling losses, losses incurred due to the effectiveness of the reflectors used in the specific CSP technology and power losses in both the generator and the power block.

2.3 CONCENTRATION TECHNOLOGIES

Over the years many types of concentrating solar power technologies have been developed. The technologies discussed below represent the most deployed and prominent technologies at present. Each technology possesses its own advantages and disadvantages and hence are suited for different applications.

The technologies that use solar heat yet does not use concentration, such as flat plate collectors are mainly used for domestic water or space heating purposes. The concentration ratio (CR) of a technology is defined as the ratio between the area of the receiver and the to the aperture area. In non-concentrating flat plate collectors this value is equal to Concentration increases density of the radiant energy flux, allowing more power to be absorbed for a given surface area and thus a more effective receiver operation at higher temperatures. [3]

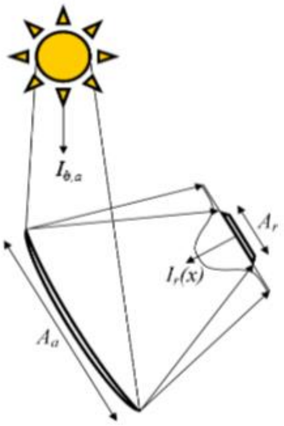


Figure 4: Concentration Ratio [3]

Where the concentration geometrically is given by the equation given below. Where the A_a refers to the area of the Aperture and A_r refers to the area of the receiver. CR_g refers to the geometrical concentration ratio.

$$CR_g = \frac{A_a}{A_r}$$

Equation 3: Geometrical concentration ratio [3]

However, when the optical efficiency η_{opt} is considered, the optical concentration ratio CR_o is given as below.

$$CR_o = CR_g * \eta_{opt}$$

Equation 4: Optical Concentration Ratio [3]

There are several advantages of operating with higher concentration ratios. Having a higher concentration ratio is that it is possible to reach higher temperatures, which means that the thermodynamic efficiency of the powerplant will be increased. Higher concentration ratios also mean that there are lower heat losses due to convection, conduction, and radiation. Concentrated solar thermal plants, especially with higher concentration ratios are dependent on DNI, rather than diffused radiation, therefore solar tracking is essential to ensure optimum performance of these technologies.

The Cosine effectiveness is another important factor to consider when considering the design of CSP systems. Below will explain the phenomenon.

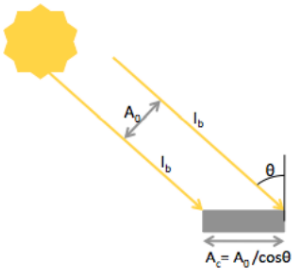


Figure 5: Cosine Effectiveness Illustrated [4]

The amount of energy irradiating from the sun, which is in the area A_o is equal to the multiple of that area with I_b, which is the same as the energy received by the collector which has area A_c.

$$I_b A_0 = I_c A_c$$

Equation 4a: Cosine Effectiveness

Where I_c is the effective direct normal irradiance on the collector.

$$I_c = I_b cos\theta$$

Equation 4b: Cosine Effectiveness

Therefore, cosine effectiveness is defined as

$$\varepsilon_{cos} = \frac{I_c}{I_b} = cos\theta$$

Equation 4c: Cosine Effectiveness

Concentrated solar thermal technologies can be mainly divided into two categories in terms of the irradiance collection points. Line collectors, as the name suggests concentrates the solar irradiance towards a collector tube. Fresnel and Parabolic trough concentration systems fall into this category. The point collectors concentrate the rays onto a single point. Solar tower and Parabolic dish technologies fall into this category. [4]

In terms of power plant configurations, it can be divided into modular systems and large-scale arrays. For remote small scale applications modular configurations can be more beneficial, whereas large scale MW scale power plants can be used to connect to the grid.

2.3.1 CSP Tower

The CSP Tower technology, works by reflecting a field of heliostats at a single point at the top of the tower in the middle of the field, which has a receiver that is usually composed of ceramics or metals that are capable of withstanding high temperatures. This receiver then transfers this heat to a working fluid that can transferred to a Rankine cycle to generate electrical power. Water/steam, molten salt, liquid sodium or air can be utilized as the working fluid in the system for large plants with capacity of 100–200 MW. [6] This technology is usually used with a thermal storage system as it is used to provide solar power to the grid during the hours when there is no solar irradiance.

Currently the main capital investment of these powerplants is the computer-controlled heliostat fields. The solar to electric efficiencies of these powerplants can range from 20% to 35%. These type of power plants also require a significant amount of water to generate steam in the Rankin Cycle operation and has the largest land footprint of the prominent CSP technologies. The efficiency of these types of plants varies with the optical characteristics of the heliostats, the accuracy of the heliostat tracking system and the cleanliness of the mirrors. The CSP tower technology is generally economically viable at a scale of 50-100MW [6]

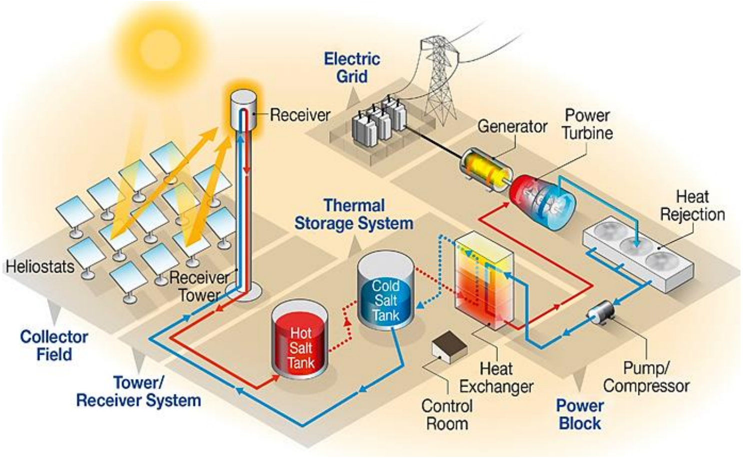


Figure 6: CSP Tower technology [7]

However, with the drastic reduction of cost of Solar PV technology, many CSP investors are turning towards PV technology. CSP Tower technology however carries the potential to integrate with emerging Solar PV powerplants as hybrid powerplants. Noor powerplant in Morocco which combines, CSP tower, Parabolic trough and Solar PV technologies and the Masdar City and the Mohammed bin Rashid Al Maktoum Solar Park in the United Arab Emirates are examples of powerplants that are being developed under this configuration.

One of the main advantages of this technology is that it can be integrated with thermal energy storage. Molten Salt can act as both the storage and the working fluid medium in this case, which reduces the issues related with more conventional heat transfer fluid such as thermal oil which is prone to ignition which poses a risk to the entire system.

2.3.2 Parabolic Trough

Parabolic Trough Concentrating System (PTC) CSP Systems are composed of large mirrors shaped in a semi-circular concave parabolic array which acts as solar receivers and concentrate the irradiance onto an absorber tube. The collector field comprises several hundred troughs that are placed in parallel rows aligned on a north-south axis. This configuration enables the single-axis troughs to track the sun from east to west throughout the day, ensuring that the solar radiation is continuously focused on the receiver pipes. [6] The absorber tubes are filled with heat transfer fluid such as oil or molten salt. Depending on the concentration ratio, solar intensity and working fluid flow rate, the temperature of the working fluid can reach up to 400ºC. As the solar energy is concentrated 70–100 times in the system, the operating temperature reaches 350–550 °C. The solar-to-electric efficiency is 15% for the system. [6]

The working fluid will transfer this heat to water in a boiler to produce steam, which in turn operates a Rankine Cycle to produce power. This method is known as the direct steam generation technology. Once the heat is transferred through a heat exchanger the fluid is again cooled and recycled in the same process. PTC system also do have the option of being integrated with thermal energy storage, which enables power production during intervals of cloudy periods as well as during the hours where the sun does not shine.

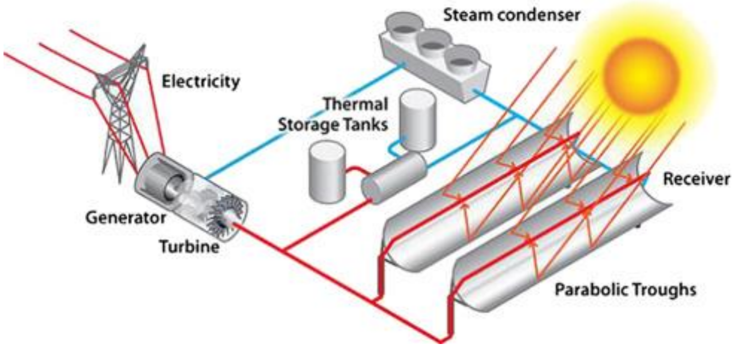


Figure 7: Parabolic Trough CSP System [8]

Parabolic trough CSP systems are the most mature CSP technology. As of 2018, 76% of the total global CSP deployment was done through Parabolic CSP technology. Parabolic trough is comparatively bankable, and the solar field is not limited by the tower as in CSP Tower technologies. This technology is especially suited to produce process heat. However, it can only be tracked on a single axis. The main failure parts occur at the flexible joints that enable the receiver to be tracked according to the sun’s trajectory. The Parabolic trough technology however is inferior to the tower CSP technology in a way that it can handle only up to about 500 degrees Celsius, and the concentration ratio, which measures the amount of solar flux energy that can be absorbed per a given surface area, is significantly lower than the tower technology. [3]

2.3.3 Linear Fresnel Reflector CSP

Linear Fresnel Reflector (LFR) CSP technology consists of an array of mirror strips as reflectors with receivers, solar tracking system. process and instrumentation system, steam turbine and generator. The reflectors are the most important components in the system and the mechanism of the reflectors is the same as that of the Fresnel lens. The sun's rays are reflected by the Fresnel lens and focused at one point, generally on to a permanent receiver on a linear tower. In the daytime, the Fresnel reflectors are directed automatically toward the sun, and from there the reflected solar irradiation carries on to the linear tower where a receiver shaped like a long cylinder contains a number of tubes filled with water. With the high solar radiation, the water evaporates and under pressure runs into the steam turbine that spins a generator that generates electricity. The capacities of the LFR CSP plants vary from 10 to 200 MW and the yearly solar-to-electric efficiency is estimated to be 8–10%.

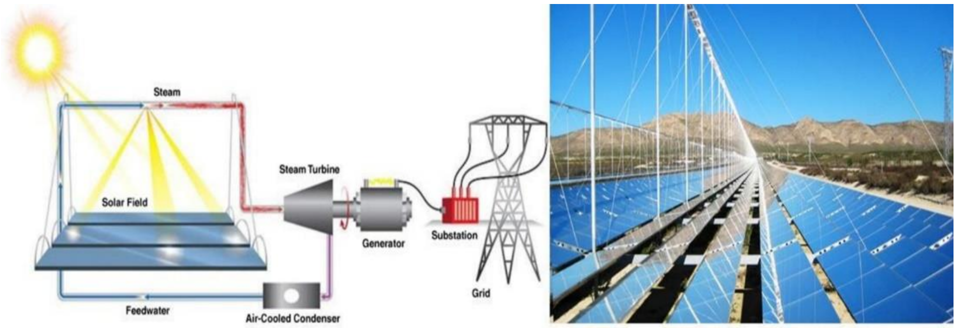


Figure 8: Linear Fresnel Reflector CSP Technology [6]

Poweplants such as the Kimberlina Solar Thermal Power Plant in the United States (5 MW), and the Rende-CSP Plant, Italy (1 MW) are the two linear Fresnel-reflector based CSP plants that were built for demonstration, whereas the Liddell Power Station, Australia (9 MW) and the Puerto Errado 2 Thermosolar Power Plant, Spain (30 MW) were built for commercial production in 2012. Out of the prominent CSP technologies, LFR CSP technologies posses the lowest range of concentration ratio and of 2018 the market share of these type of powerplants in the CSP market has reduced from 4% 2016 to 3% in 2018 in terms of the Capacity. [3] This is mainly due to the low capacity of the individual plants that LFR CSP technology possess.

2.3.4 Parabolic Dish CSP

Parabolic Dish CSP systems functions by concentrating the direct irradiance onto a receiver by the use of a parabolic dish made with either a uniform reflector or a series of reflectors assembled to resemble a concave semi-circular shape. The reflector dish and the receiver are typically assembled together and through a double axis tracking device, the sun is tracked throughout the day. At the receiver, the irradiance is concentrated and is used to heat working fluid, which in this case usually air to operate, either a sterling engine or a Brayton cycle device, which in turn generates electricity.

The concentration ratio of Parabolic dish CSP system can reach as high as 2000 and the working fluid can reach temperatures up to 750°C and 200 bar pressure [6]. Usually, the receivers are composed of silver or aluminum which is coated on a glass or a plastic surface, however higher efficiencies of reflectivity can be obtained if a glass surface coated with a 1µm layer of silver. The reflectivity can reach up to 94% and the nameplate capacity of Parabolic Dish CSP system can range from 0.01 to 0.5 MW. The electrical efficiency of the system varies according to whether a sterling engine was used, or a Brayton Cycle device was used. The efficiency for a Sterling engine-based system is between 25% to 30%. The reason for this efficiency is the double axis tracking that allows optimum cosine effectiveness at all times, which is not achieved with other CSP technologies at all times.

Figure 9: Parabolic Dish CSP Technology [9]

The advantage of this technology is that unlike other CSP technologies, it is modular and can be scaled up by simply increasing the number of installations of the units. It also has one of the highest concentration ratios, can reach higher temperatures and is considered the most efficient CSP technology to convert solar energy to electrical or chemical energy. The high temperatures make the integration of energy storage a possible configuration.

This technology can be applied especially in remote or small-scale scenarios which require both power and heat, such as small-scale industries that are further from away from the grid. The limitations are that the initial capital cost of this technologies is significantly high compared to other CSP technology options.

2.4 POWER CONVERSION TECHNOLOGIES

Since the study topic of this thesis is about the specific system of parabolic dish CSP with Micro Gas turbine used as a power conversion technology (which is a Brayton Cycle device), it is important to examine the main power conversion technologies currently available with regards to parabolic dish CSP systems, in terms of performance and economic parameters related to them.

2.4.1 Sterling Engine

Stirling engine is a reciprocating engine that uses both a piston and a cylinder, similar to an internal combustion engine in automobiles. However, in Stirling engines, the system is pressurized and sealed. Unlike the ignition happening inside, as in the combustion engines, the source of heat and cooling systems are external in Stirling engines. Commercial Sterling engines are smaller in range, which is about 1-25kW. In addition to being used in CSP Dish systems, it has been used in many Combined Heat and Power (CHP) systems.

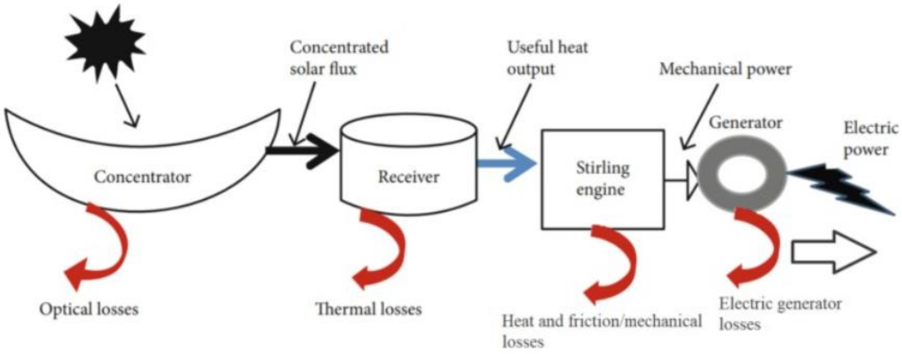


Figure 10: Dish Sterling Engine solar to electrical energy conversion chain [10]

Stirling engines are attractive for dish-electric systems because of their high-power conversion efficiency (30–45%) at small scale, with peak solar-to-electric efficiency exceeding 30%. Concentrated solar flux from dishes can provide isothermal, high-temperature (typically 650–800 °C) heat with good efficiency. Stirling engines have been both coupled directly to dishes or indirectly via a sodium heat pipe. Hybrid solar and gas systems have been tested to allow higher capacity factors and better performance during solar transients. [11]

2.4.2 Brayton Cycle Engine/ The Micro–Gas Turbine (MGT)

Brayton Cycle is a thermodynamic cycle where a fuel is used to heat a gas, of which the pressure is increased by using a compressor, the gas in turn expands in a turbine and thus performing mechanical work, which is then converted into electricity using a generator. Conventionally gas turbines have been used in larger scales and have been used in power generation applications.

A micro gas turbine has been defined as a gas turbine that has less than the 1MW of power outputs in literature, however the European Union refers a micro-cogeneration unit based on the electrical power output with a maximum capacity below 50kWe. [12]

A Micro Gas Turbine (MGT) includes a compressor, turbine, combustor, bearings, recuperator, high speed generator, power conditioning and control unit, enclosure,

and balance-of-plant. [12]

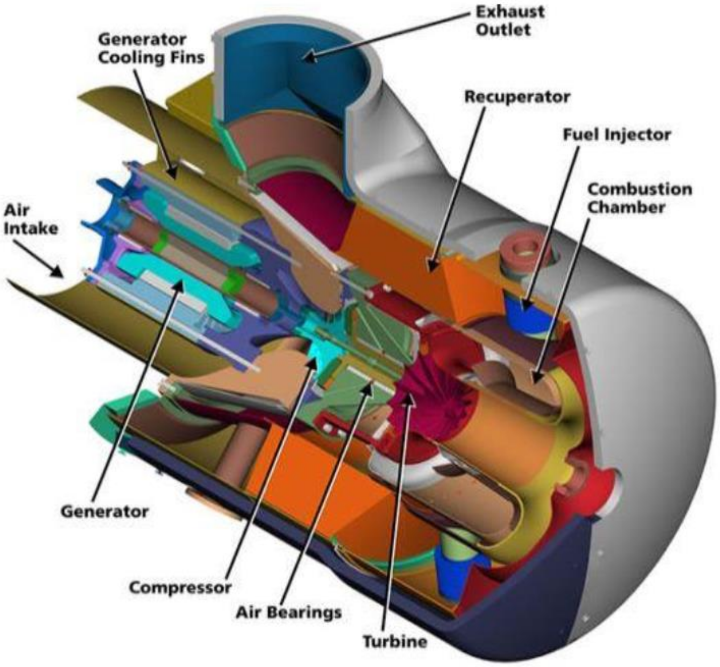
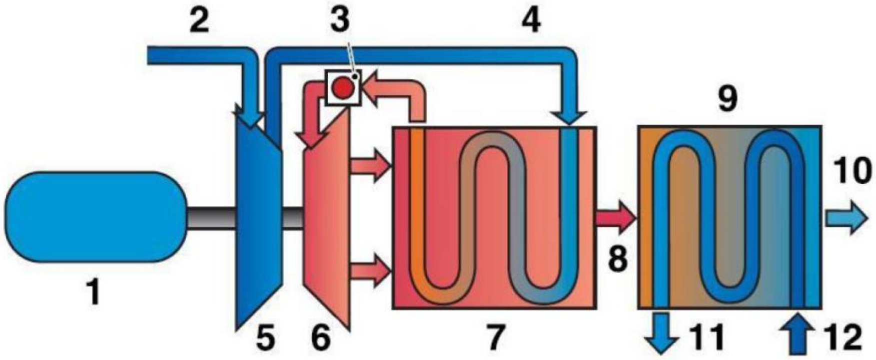


Figure 11: Micro Gas Turbine Components. [12]

Even though Sterling has been the conventional power extraction method that has been used in Dish CSP applications, there are certain drawbacks to this technology with regards to this application, which affects the lifetime of the system and hence the reliability of the system, which have led to increased costs and added complexity in design. There are issues such as cylinder seals, hot spots in the heater and problems with managing and controlling part load conditions.

However, with the use of a MGT for this application, there are several advantages that can be seen. Since MGTs are fuel flexible they can be used in a hybrid system in conjunction with solar heat and heat obtained from combusting a fuel such as natural gas. This is beneficial in maintaining a steady power output, to avoid the intermittent nature of solar heat obtained from direct solar irradiance. The dispatchable, continuous, and stable power output from such a system can be a more attractive prospect from a power purchaser's point of view, when compared with a solar PV system without energy storage. In comparison with other small scale power generation technologies, MGTs offer advantages such as lesser number of moving parts, compact size light weight, low emissions, low electricity costs, reliable operations and the potential for low-cost mass production and opportunities to be utilized waste energy recovery applications. Even though the electrical efficiency is very low, especially in small scale such as MGTs, the competitiveness is maintained through fuel flexibility, power density, low emissions, and low noise. [12]

The typical operation of the MGT can be seen from Figure 12 below.



1. Generator
2. Inlet air
3. Combustor chamber
4. Air to recuperator
5. Compressor
6. Turbine
7. Recuperator
8. Exhaust gases
9. Exhaust gas exchanger (PH vers.)
10. Exhaust gas outlet
11. Hot water outlet(PH vers.)
12. Water inlet(PH vers.)

Figure 12: Micro Gas Turbine operation [12]

2.5 EVOLUTION OF PARABOLIC DISH CSP TECHNOLOGY

John Ericsson is often acknowledged as the first person to couple a parabolic dish with an energy conversion system. He coupled a Stirling engine and developed and tested several prototypes of this technology in 1880s. [11] Ericsson also noted that his “solar-motor” produced steam that is several times costlier than coal produced steam at the time and noted that it will be a viable technology when the world coal supply is depleted. Even though the world’s coal reserves are yet to be depleted and that there has been interest in the technology since the 1970s, the costs remain the main factor that is inhibiting the widespread deployment of the technology, even though the technology currently is proven.

In 1973, with the oil crisis, there was a renewed interest in CSP technologies in general and there was investment from both and small-scale companies and research and commercialization funding through government research institutions. In the 1990s CSP Dish commercialization began to rekindle after being dormant for another decade. In the 1970s United States started the first design of the solar dishes. Previously dishes from telecommunication designs were used and along with it there were a few of unnecessary components in them. Jet Propulsion Laboratory (JPL) started the research on distributed CSP systems and by the late 1970s dedicated parabolic Dish CSP research was underway. This included both parabolic dish and mirror panel technologies, as well as adaption of power conversion units for dishes, including Brayton, Stirling, and organic Rankine cycles. [11]

From the early days of research there was a focus on bringing the production costs of the technology down. For example, one of the private companies who were involved in the research Zimmerman laid out three main objectives for its production techniques. First was to establish a design that is optimized for solar applications.

Second was to maximize the cost to performance ratio, where every additional dollar spent on improving the performance of the design had to be justified through a cost-benefit analysis. The third was to select approaches to the subsystem and component designs that were compatible with, and derived from, commercially available manufacturing techniques.

In the 1980s, two main types of designs emerged, Glass faceted concentrators and full surface paraboloid concentrators. Another important design that came about at this time was the stretched membrane concentrator, which was 17m in diameter and larger than the existing concentrators at the time.

In the pursuit of cost reduction further improved designs such as the fixed reflector / Tracking absorber solar collector (SRTA), where the reflector remains stationary during the day and the absorber moves to track the sun, and Scheffler dish which was the converse concept of the fixed reflector, where the absorber was fixed and the reflector would be solar tracking enabled through an east west tracking device, were invented.

The evolution of parabolic dish CSP also coincided with the power extraction technologies that were used. There are several technologies that have been used for this purpose throughout the years. Dish mounted options that were investigated include Organic Rankine Cycles (ORC) with toluene, Stirling engines with hydrogen or helium, and open and closed air Brayton cycle systems. Dishes have been also used with concentrating Photovoltaics (CPV) modules. Ground mounted technologies that have been investigated are power cycles suitable for small power stations, such as the Rankine Cycle with steam and power cycles suitable large power stations such as conventional Rankine Cycle steam turbines.

Figure 13: Raytheon design [11]

The in the early in 1970s companies such as Bomin Solar GmbH pioneered the concept of using large foil membrane mirrors and developed a parabolic dish mirror by stretching plane, metallized plastic membranes over hollow, drum shaped structures, to achieve Concentration ratio of 1000. One of the earliest companies to install Parabolic dish CSP was Omnium-G. The company started installing the units in 1978 in Colorado, USA. THECK 1&2 were constructed with triangular mirrors in the reflectors in 1987. Raytheon developed a reflector with spherical, heat sagged mirror segments in 1985. The solar total energy project (STEP) in Georgia, operated a powerplant with multiple units of Dish CSP with reflectors assembled with 21 doe stamped aluminum gores developed by General Electrical Cooperation. Messerschmitt-Boelkow-Blohm, together with the Kuwait Institute for Scientific Research (KISR) developed a technology with reinforced plastic for the reflectors with an ORC system for the power extraction. The Crosbyton project in Texas conducted by JPL, used a stationary reflector system in 1980, with a direct steam system. Companies such as Advanco corporation and McDonnell Douglas Astronautics Cord (MDAC) were focused on using mirror facets as the reflector.

Figure 14: MDAC design [11]

Later on, Companies such as Sterling Energy Systems and Solar Systems brought about their design of the technology. Heliofocus and Arun projects developed in Israel and India respectively were using a number of Fresnel reflectors similar to Linear Fresnel CSP technology in the early 2000s. ZED Solar and Repasso Energy were formed in the late 2000s and have developed their unique dish prototypes. Cleanergy is a company focused on developing sterling engine technology. Great Ocean Energy have installed Parabolic dish CSP a powerplant in Inner Mongolia with 10-10kW dishes that has a total capacity of 100kW in 2012, In 2015, Jiangsu Province in China, they have installed a development prototype of 25kW.

The capacity of the absorber and the sterling engine has determined the size of the dish size. In the early stages of development, dish with a diameter of 11m was used, to match the requirements of the 25kW sterling engine used at the time. When a smaller engine was used, smaller dishes have been used. There are also other factors such as the machines available to fabricate the reflectors and the transport modes available for the logistics during a project that makes a smaller dish size more feasible. Cost breakdown from the Australian National University big dish project which has a steam receiver, demonstrated that there is an optimum diameter of 7-20m for parabolic CSP dish receivers.

Both Carousel and pedestal tracking systems have been used in the past projects, however in the more products that were eventually commercialized pedestal tracking is more dominant due to its capacity to reduce the drive and foundational costs.

The mirror panel suitability depends on the performance and the cost, which in turn effects the cost of the dish itself. Higher optical errors in the mirrors contribute to the loss of efficiency in the system. Some of the early designs had highly accurate but expensive facets, later on low-cost fabrication methods such as reflective film adhered to die-stamped aluminum mirrors with rear ribs were developed, where the optical accuracy is good enough to be economically viable. Another development was the sandwich panel which are currently supplied by companies such as Toughtrough and Rioglass solar. Even though the sandwich panel was developed to make cheaper panels, the efficiency is lower than the stamped mirrors.

Energy storage both with latent and sensible heat storage methods have been explored in the past and dishes can be used in series or parallel with an auxiliary source of heat. Another strategy that has been explored is to hybridize with the use of fossil fuels.

2.6 POTENTIAL FOR POLYGENERATION APPLICATIONS

Polygeneration can be defined as the combined production of two or more energy services and/or manufactured products, seeking to take advantage of the maximum thermodynamic potential (maximum thermodynamic efficiency) of the consumed resources. [13]

CSP technologies in general have the potential to be used in CHP applications since the primary source of energy that it produces is heat and due to the inefficiencies in the thermodynamic cycles used such as the Rankine Cycle, Brayton Cycle and the Stirling Cycle, there will always be a differing percentages of waste heat energy after the electricity is produced. This waste heat energy can be used in a variety of other applications where heat energy is required.

The Polygeneration application will depend on the type of CSP system and the type of Heat Transfer Fluid (HTF) that is being used and the temperature the fluid will exit the turbine or the engine as waste heat. In CSP tower technologies, since the operating temperature is higher, the waste heat from the resulting Rankine cycle is higher compared to a PTC system or an LFR system. In the case of Parabolic dish CSP systems there is an additional challenge in converting exhaust heat into useful heat. This is due to the fact that in the main thermodynamic cycles that are used in this type of system, namely Brayton and Sterling cycles, the HTF used is air as opposed to other CSP such as PTC or LFR systems where steam is used.

Case study comparison has been done in both Northern Chile and Venezuela on the Polygeneration electricity and desalinated production of water. In both cases the power plant used was a PTC system with a two tank Thermal Energy Storage (TES) System and thermal desalination systems have been used in both cases to utilize the waste heat from the CSP system. The Figure 15 shows a configuration that was setup in these cases to analyze the optimization of the system. [14]

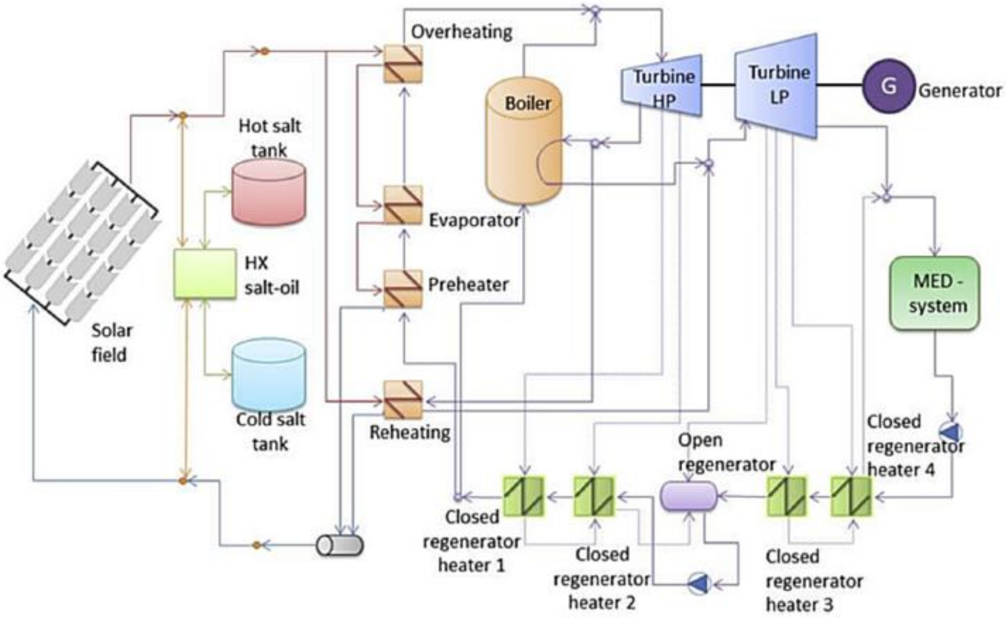


Figure 15: PTC CSP Polygeneration system with a Thermal Desalination System [14]

The thermodynamic performance has been measured in these cases with the thermodynamic efficiency of the entire system, which has been defined with Equation 2.

$$\eta = \frac{E_{electric} - Parasitic\ Losses}{Solar\ Energy + \frac{Backup\ Power}{\eta_{boiler}}}$$

Equation 2: Thermodynamic Efficiency of the Polygeneration System [14]

The $E_{electric}$ represents the electric power generated by the Generator from the Rankine cycle. Parasitic Losses constitutes all losses including the energy used in the internal energy consumption from pumps, the solar field, storage system, MED (Multi Effect Distillation) desalination system operation and pumping the water to the location of the plant. Solar Energy represents the total solar resource that is available at the location, which is calculated by the area of the aperture of the solar field, multiplied by the annual DNI of the location. The backup power represents, the reserve power provided by the boiler and η_{boiler} represents the efficiency of the boiler. [14]

Another Polygeneration application is to use the heat in space cooling and heating. It has shown that the Dish CSP with MGT system in conjunction with an Absorption chiller system serving a district energy network can save up to 20% in costs and 33.5% reduction in carbon dioxide emissions, compared to a system with an absorption chiller, without a Dish CSP system operated with an MGT. [15]

The configuration shown by Figure 16 shows the layout how the district energy network functions. The CSP case can be seen as an extension of the base case configuration and depending on the sizing of the MGT, the diesel generator can be completely replaced, or they can be used in parallel.

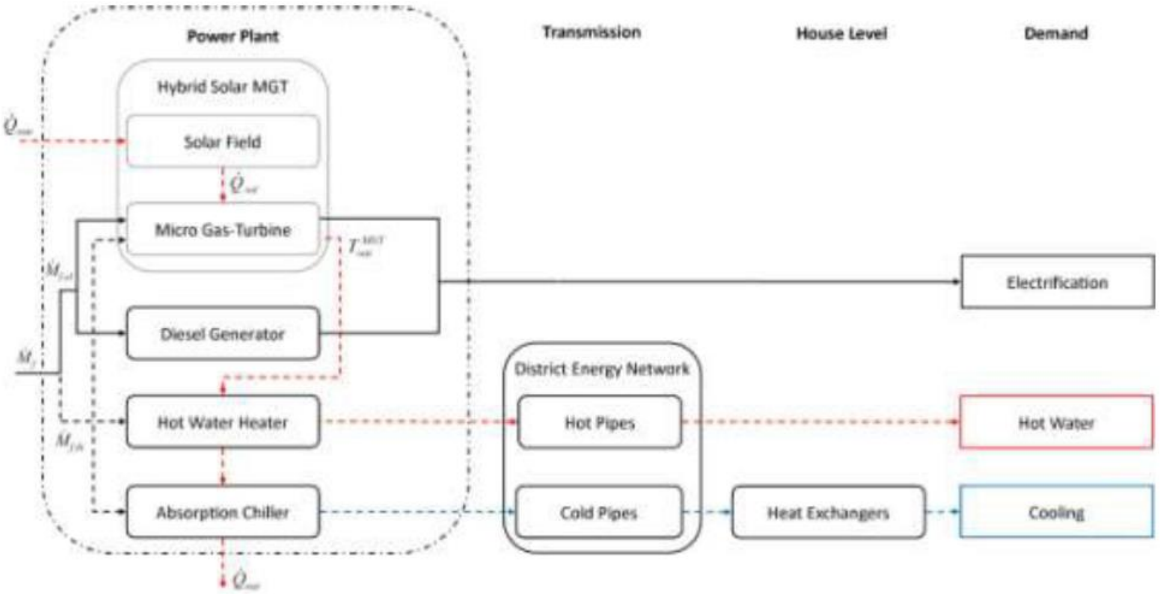


Figure 16: Layout of the CSP with MGT used for District Heating and Cooling [15]

2.7 POTENTIAL OF HYBRIDIZATION WITH BIOMASS

Due to the nature of both biomass and CSP in general, the operation of a biomass powerplant in conjunction with a CSP plant is technically feasible. This subject has been explored widely through researching the technical, thermodynamic, and economic feasibilities. In most cases PTC systems have been used as the CSP system that is in place and an ORC system has been used to convert the energy.

There are several advantages of this configuration in locations with suitable biomass supply and high DNI resource available. For a fixed plant size, the size of the solar field and the supply of biomass can be reduced. The flexible operation when modulating the biomass contribution and possibility to obtain dispatchable renewable energy from smart integration of intermittent solar and programmable biomass resources. It has the capacity to deliver a greater conversion efficiency compared to CSP only systems at the same plant size or scale. It also enables the modulation of the heat output to match the specific requirements of the energy demand. [16]

In the case of the dish CSP system with Brayton cycle MGT system, the heat required by the system to operate at nominal conditions can also be supplemented by Biomass fired heat in conditions that does not yield design load level solar heat, as MGT systems are fuel flexible. Therefore, for a Dish CSP system operated with an MGT, the hybrid mode of operation, offers several different options such as reduction of the size of the concentrator dish, the receiver being able to operate at lower solar heat, with a greater percentage of the heat being provided by biomass.

However, the source of biomass is a relevant parameter to consider in this mode of operation. In most cases biomass is sourced from forestry or monocultures that are present in the region. Many countries and regions that have high DNI, does not have an abundant source of biomass present, therefore if this mode of operation is to be considered, the biomass resource in the region also needs to be considered. It is possible to source biomass or biogas from a different region, however the costs of outsourcing the biomass such as logistics, shipping costs, taxes and regulations may deem the use of biomass, especially in remote hard to reach locations, unfeasible.

2.8 OMSOP PROJECT

The OMSoP Project was co funded by the European Union 7th Framework Program for Research and Development and was aimed to provide and demonstrate technical solutions for the use of state-of-the-art concentrated solar power system (CSP) coupled to micro-gas turbines (MGT) to produce electricity. The intended system will be modular and capable of producing electricity in the range of 3-10 kW. [17]

In February 2013, the OMSoP project kicked off with 8 partners from 5 countries with a total budget of 5.8 million euros. Successful dissemination and implementation of the project results was to result in the demonstration of the stand-alone-system, addressing the key innovation bottlenecks: the high temperature solar receiver, the stand-alone solar dish concentrator, and the more reliable micro-gas turbine. [17]

The primary objective of this project was to optimize the key components of the Dish CSP MGT system, in order to improve energy conversion efficiencies, compare different materials for components from a performance and costs perspective and find out what markets are best suited for this technology, in order for it to be economically viable and profitable. Figure 17 shows the basic layout of the technology.

1. Ambient air is compressed by the compressor, while the concentrator, concentrates and beams the solar heat to the receiver

2. The compressed air enters the regenerator, and the supplemental heat is absorbed by the air, preheating the compressed air

3. Preheated air enters the receiver to be heated to the maximum heat that is heated in the process through the direct heat extracted from the solar receiver.

4. Heated and compressed air enters the turbines, where the turbine expands the hot compressed air while converting the heat energy to electrical energy by means of the generator.

5.The exhaust air from the turbine, which is at low pressure and low temperature enters the recuperator once more to cool down further, expending it’s heat onto the incoming air from the compressor from step 2.

6. The low pressure, low temperature air exhausts out of the recuperator there off.

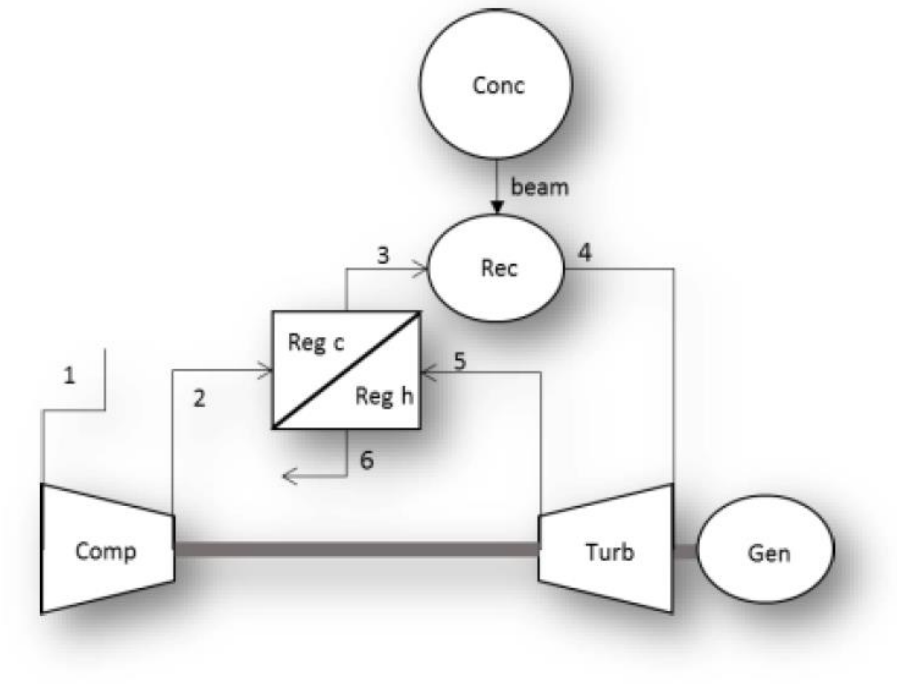


Figure 17: Base Case for OMSoP Project

3. MARKET ANALYSIS

3.1 SMALL SCALE CSP MARKET OUTLOOK

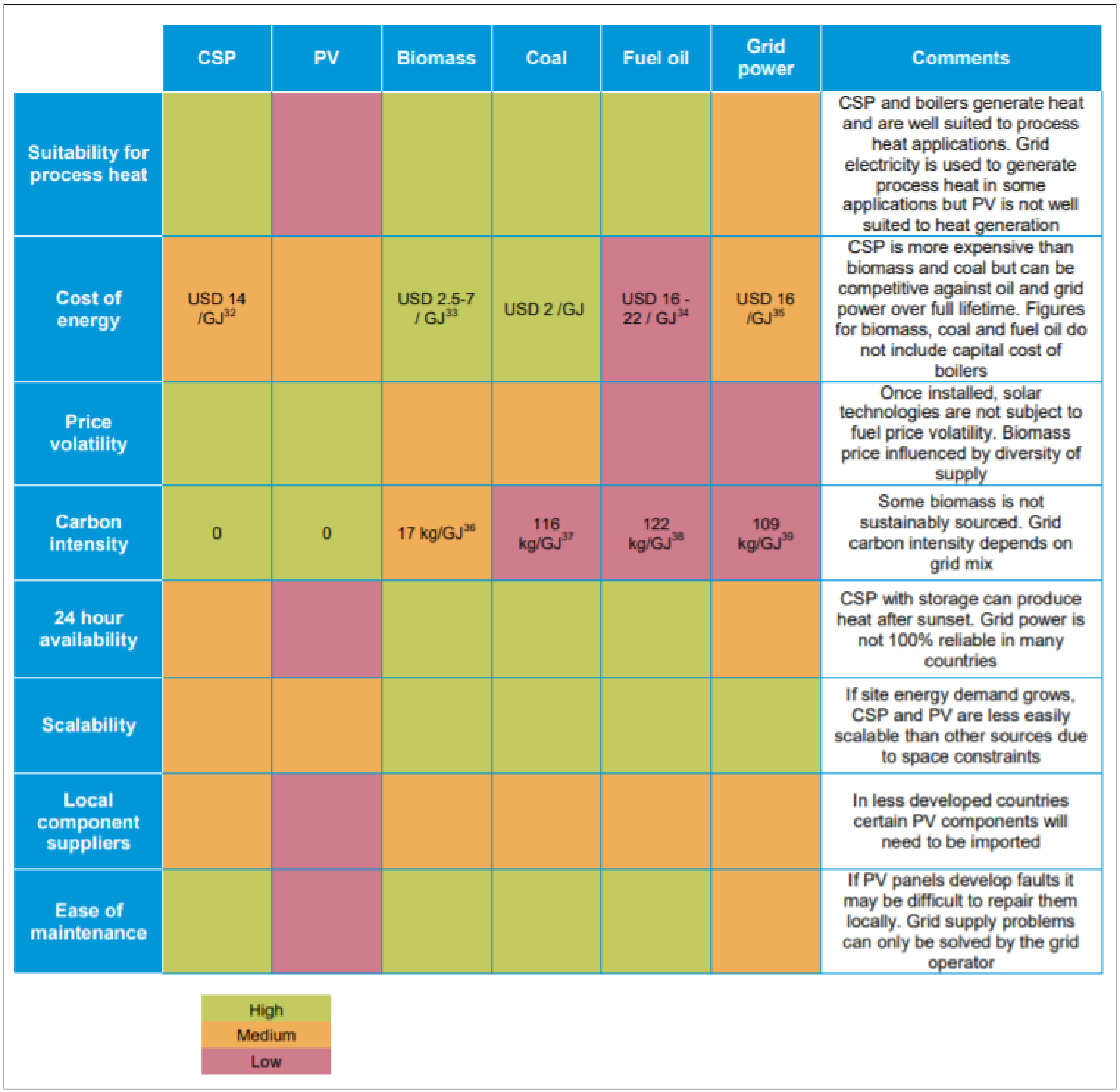
Before analyzing the market and the potential sectors that this technology can be applied to, it is important to review and understand the present-day state of the industry. This includes present market trends, the barriers to entry that it has, the state of the finances and the state of the small scale CSP sector in general and where it is placed in the present market in terms of technological suitability.

Small scale CSP can be defined as CSP systems that are less than 2MW in capacity as a powerplant and not less than 100kW. According to the report on review of activity and potential to accelerate deployment, submitted by the Carbon Trust in 2013. [18]

The case for small scale CSP will vary due to multiple factors, including the type and the cost of the fuel that the CSP system is replacing, the DNI resource a particular location may have, as with the case of utility scale CSP systems, degree to which the country of the selected location prioritizes CSP as a viable energy source in their energy policies, the nature of the market being such that the country has existing small scale industries that require mainly process heat as well as electricity and the need for off grid energy solutions (i.e % of the population without grid electricity access). [18]

In the report there are three countries that have been selected based on the above parameters, however in this report the electricity generation has not been considered and the potential for industrial heat generation has been the focus.

The Figure 18 below shows the comparison between different energy technologies in its capacity to generate process heat for small scale industries.



	CSP	PV	Biomass	Coal	Fuel oil	Grid power	Comments
Suitability for process heat	🟩	🟥	🟩	🟩	🟩	🟧	CSP and boilers generate heat and are well suited to process heat applications. Grid electricity is used to generate process heat in some applications but PV is not well suited to heat generation
Cost of energy	🟧 USD 14 /GJ[32]	🟧	🟩 USD 2.5-7 / GJ[33]	🟩 USD 2 /GJ	🟥 USD 16 - 22 / GJ[34]	🟧 USD 16 /GJ[35]	CSP is more expensive than biomass and coal but can be competitive against oil and grid power over full lifetime. Figures for biomass, coal and fuel oil do not include capital cost of boilers
Price volatility	🟩	🟩	🟧	🟧	🟥	🟥	Once installed, solar technologies are not subject to fuel price volatility. Biomass price influenced by diversity of supply
Carbon intensity	🟩 0	🟩 0	🟧 17 kg/GJ[36]	🟥 116 kg/GJ[37]	🟥 122 kg/GJ[38]	🟥 109 kg/GJ[39]	Some biomass is not sustainably sourced. Grid carbon intensity depends on grid mix
24 hour availability	🟧	🟥	🟩	🟩	🟩	🟧	CSP with storage can produce heat after sunset. Grid power is not 100% reliable in many countries
Scalability	🟧	🟧	🟩	🟩	🟩	🟩	If site energy demand grows, CSP and PV are less easily scalable than other sources due to space constraints
Local component suppliers	🟧	🟥	🟧	🟧	🟧	🟧	In less developed countries certain PV components will need to be imported
Ease of maintenance	🟩	🟥	🟩	🟩	🟩	🟧	If PV panels develop faults it may be difficult to repair them locally. Grid supply problems can only be solved by the grid operator

🟩 High
🟧 Medium
🟥 Low

Figure 18: Comparison of Different energy sources for the generation of industrial process heat [18]

CSP is especially suited for the industry process heat application due to it being price volatile and the ability to supplement the existing heat sources, however the scalability due to land availability constraints is an obstacle in deploying, where further expansion of facilities is planned out.

There are several barriers to entry into the market for the small scale CSP in general. The lack of awareness among local policymakers and industry of CSP being a viable option, not only for industrial process heat but also as a means of electricity generation has hindered the rapid deployment of small scale CSP. Compared to fossil fuel or biomass powered boiler systems, the use of CSP as a heat source is relatively new and currently there is a low level of confidence, especially where a reliability of the process heat is paramount in the profitability of the industry in question. This has historically dissuaded industry, especially small-scale industry to adopt CSP as a means of process heat. The DNI of a location is a big factor in determining the applicability of CSP and this limits the Serviceable Addressable Market (SAM) significantly to countries and regions with very high to excellent DNI as realistic prospects where CSP deployment for process heat would be profitable. One of the main barriers to entry is the longer, unattractive payback periods of CSP technologies, especially in smaller scale, where storage options are more expensive, compared to more conventional options, such as fossil fuel systems and biomass systems.

However, small scale CSP technologies do have the potential to operate in the rural off grid market with limited access to the grid, and favorable climatic conditions since it can be used in multiple basic requirements such as electricity, fresh water, process heat and cooling for communities and local manufacturing. Even though, some promising technologies exist but the lack of support programs keep them, in the better cases, at demonstration level. The potential market size is strongly affected by the cogeneration requirements of the specific application and the national policies such as economic incentives and micro credit programs. [19]

3.2 TARGET MARKET

Since the Dish CSP with MGT, can be deployed in multiple configurations due to the modular nature and the output of both power and heat, there are several applications that it can be used in. The industries identified below are some of the more promising industries for potential applications.

In addition to the industries discussed, with the lowering of cost from economies of scale, many other industries that require process heat, such as the dairy industry and textile industry, and other applications that require reliable steady power in remote applications at a modular level such as military applications can be looked into in the future. However, in the following sections 4 key promising industries, are considered for this study. Desalination has several processes that uses both power and heat in its processes as discussed below. Produce drying techniques require both heat and power, Steam methane reforming requires high temperature heat and the production of compressed air in the mining industry requires modular units that produce power to compress air.

In the following sections, these industries will be examined in detail, in terms of technology, current market players, state of the art technology and the direct and indirect competitors to the proposed technology.

3.3 DESALINATION

As the world's population continues to increase and more of the population moves into cities with a prediction that two thirds of the world population would be urbanized. With urbanization and the improvement in people's standards of living and with the Sustainable development goals which has set clean water and sanitation as one of the benchmarks, the need for clean potable water is increasing at a fast pace. With the natural water sources such as rivers and reservoirs drying out and being over utilized, desalination of both ocean water and water used for the industrial process cooling have been growing as a possible solution.

However, one of the main inhibiting factors of desalination has been the high energy intensity in converting salty water into fresh water. One of the most common technologies used in desalination are Reverse Osmosis (RO) and thermal desalination technologies such as Multi Effect Distillation (MED) and Multistage Flashing (MSF). Reverse Osmosis plants converting seawater has shown to hover around 1.5-4.0 kWh/m^3, depending on the salinity of the seawater and other external factors. [20] Complimenting this energy use with a renewable source that can provide electricity or heat (depending on the process used) through Dish CSP with MGT technology could reduce the amount of carbon emissions due to desalination and with remote places such as military bases and hotels that need desalination, the Dish CSP with MGT could prove to be a reliable, renewable, and economically feasible option.

Figure 19: Reverse Osmosis System in Ghana [21]

3.3.1 User characteristics

The desalination market is growing and even though it does not have clear established market leaders, there are emerging companies that are currently the market leaders, having deployed a considerable amount of desalination plants in various parts of the globe.

Veolia is currently the market leader in desalination plants with a daily production of 13 million m^3 of water, throughout 1300 desalination plants throughout the world in 108 countries. The country that Veolia has deployed their plants are in United Arab Emirates. Apart from the standard RO systems, they have also deployed a hybrid system with thermal membranes. [22]

SUEZ is another company that is heavily invested in desalination. They have a plant capacity to produce 4.2 million m^3 of water per day. Their main customer in terms of country is Saudi Arabia. Their plants mainly deploy RO systems to process the water. [23]

Doosan heavy industries and construction is a company that employs multiple technologies of desalination in the various desalination plants that they have built and operate. In addition to the RO technology, they have also deployed MSF and MED systems in their portfolio. The main countries that they have catered to are Saudi Arabia, Qatar, Kuwait, and Oman. [24]

Acciona S.A is another company that is a player in the desalination market and is mainly deploying RO systems and their main customer country is Saudi Arabia.

Few other notable players in the market are IDE technologies, Xylem and Aquatech international LLC.

The Main countries with major demand for this technology is Saudi Arabia, the majority the demand for desalination is coming currently from the Middle East and North Africa (MENA) region. As a result, 45.32% of the desalination plant capacity is in this region. [25] Figure 20 below shows a breakdown of the capacities installed. This is an encouraging sign, in terms of promoting dish CSP with MGT technology to power these plants as the MENA region is also a region with high DNI.

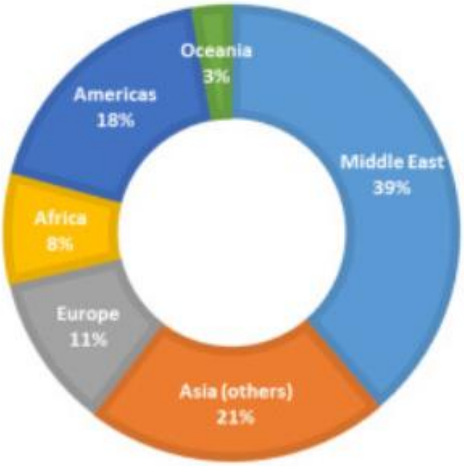


Figure 20: The installed capacity of desalination in terms of regions [25]

The main type of water uses that desalination is used for is municipal drinking use. The cumulative capacity of plants that currently serve municipal purposes is 57.3 million m^3/d, representing about 59% of global installed capacity. 61% of this capacity is served by plants in the Middle East and North Africa. Globally, the largest operational plants in terms of installed capacity are the Shoaiba 3 and Jubail Plants; these plants serve municipal drinking water purposes. Many industries also employ desalination but as a means for the reclamation of wastewater produced during industrial processes. The combined installed desalination capacity that serves industrial purposes is 35.3 million m^3/d currently, representing 36.3% of global installed capacity. [25] Figure 21 shows the breakdown of the desalination deployed as per water end use currently.

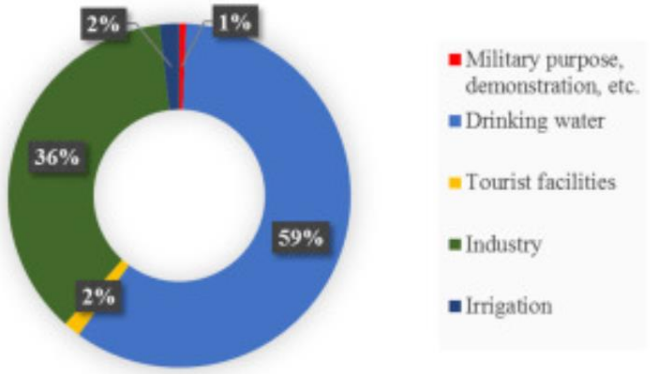


Figure 21: Desalination capacity as per final water usage [25]

3.3.2 Market Size

The global water desalination equipment market size was estimated at 12.8 billion USD, in 2019 and is anticipated to grow at a compound annual growth rate (CAGR) of 9.0% from 2020 to 2027. Rapid depletion in freshwater reserves and increasing water scarcity are expected to drive the demand for water desalination equipment over the forecast period. With the increase in population and economic activity, there are massive, expected increases in the desalination market, especially in the African continent. African desalination capacity was expected to increase by 1700% percent from 425,455 m^3/d in 1990 to a capacity of over 7.6 million m^3/d in 2020. Europe, although was not an early adaptor of the technology is now expected to increase the usage over 1600% from a cumulative capacity of 604,274 m^3/d in 1990 to a cumulative capacity of over 10.6 million m^3/d in 2019. [25]

Early desalination plants predominantly utilized thermal technologies, located in oil-rich but water scarce regions, especially in the Middle East. For example, prior to the 1980s, 84% of all global desalinated water was being produced by the two major thermal technologies (MSF, MED). The rise in the use of membrane technologies post-1980, in particular RO, gradually shifted the dominance away from thermal technologies. [25] However with the increased prominence given by these countries to move towards CSP technologies in making process heat required for these technologies and the hence as a result with greater deployment and economies of scale and lower Levelized Cost of Energy, using CSP applications to power thermal technologies of desalination will be an attractive prospect in a growing industry.

3.3.3 Competitive analysis

As seen in the industries that the technology can be applied in, it can be seen that there are wide ranging applications that it can be used in. However, these applications will have specific costs associated with it and competition from various other technologies and methodologies that can achieve the same goal. In this section, the other factors that affect the dish CSP and Brayton cycle technology, both in making it a more or less competitive will be examined. It is interesting to examine both the direct and indirect competition and their specific competencies and weaknesses, when compared to the Dish CSP with Brayton Cycle technology.

Direct Competition

Direct competition refers to the situation where multiple players, such as companies or in this case technologies that may offer solutions to the same potential market. The direct competition in this case can be segmented into mainly two categories, in terms of the type of solar technology used. Solar thermal related technologies and companies and non-Solar thermal related technologies.

Solar thermal based desalination technologies can be seen in many middle eastern countries currently and are operated at larger scale. Therefore, technologies such as CSP tower technology, parabolic trough and Fresnel systems have been mainly used. However, there are CSP Dish technologies that have been used in smaller scale. Since these countries have a significant need for desalination and the plant sizes are at large scale the solar thermal technologies that have been opted for, present technologies that have economies of scale.

In other cases, any renewable energy such as solar PV, Wind, or fossil fuels such as Natural gas, that can generate cheaper electricity have been used to operate RO desalination plants as this only requires electricity to operate and does not require heat.

Indirect Competition

The environmental impacts of desalination technology operation, such as expelling brine as by product back into the oceans and a wholistic view on the global water demand has prompted many different strategies to not only produce fresh water through techniques such as desalination, but also conserve and curb the increase in demand with building operation strategies such as grey water recycling, improving groundwater storage efficiencies, which may effectively curb the growth of the desalination industry, hence the growth of the demand for specialized dish CSP technology for the purpose of desalination.

Competitive strengths and Weaknesses

In direct solar thermal competing technologies, the strength lies in the ability to benefit from economies of scale and the usage of thermal energy in thermally driven desalination processes. Compared to Dish CSP technologies that are modular in nature, technologies such as Parabolic trough systems and CSP tower systems are well suited for larger scale, centralized applications, thus being able to produce cheaper desalinated water per m^3. However with the exception of the CSP tower technology, the other solar thermal technologies do not have the ability to achieve higher temperatures as the ones achieved by the Dish CSP systems, that results in the reduction of the amount of thermally driven desalination technologies, that they can be applied in.

Usage of fossil fuel such as natural gas, would mean that the user can produce the desalinated water at a cheaper rate than Dish CSP technologies, however this would also mean that the one of the main issues related with desalination, which is the carbon footprint due to the heavy energy use is still unanswered. Hence to an industry that is making efforts to decarbonize, an entirely fossil fuel driven desalination plant is unattractive.

Cost of Solar PV and Wind generated electricity is currently price competitive and the trend is continuing to improve. Hence the usage of these technologies specially in RO desalination plants are becoming more feasible. The usage of these technologies in thermally driven desalination technologies however would not be feasible. However, since many large-scale desalination plants recently opting to operate with an RO system or a combination of technologies that involves RO, in the large-scale desalination market, usage of these technologies are more competitive.

Barriers to Entry

Since the desalination industry in the large-scale projects are constructed or operated by large companies that have standard technologies that have been proven in the field, it would not be an easy to convince the industry that the technology proposed, would be a good fit for their operations. Since Dish CSP does not have many operational power plants, they are relatively less bankable compared to other technologies such as Solar PV, therefore the cost of finances is significantly higher.

Due to the intermittent nature of the solar resource, the Dish CSP system by itself would be unreliable specially in a RO desalination system, where the pressure needs to be applied to the water, therefore it would need to either be combined with a conventional fuel, such as natural gas, thereby increasing the carbon footprint of the device.

Window of Opportunity

As discussed previously, it is seen that in large scale applications, the modular nature and the lower bankability and reliability of solar resource, plays a part in the Dish CSP system being uncompetitive when compared to technologies such as large solar technologies such as CSP tower and large-scale solar PV. It is also seen that fossil fuels such as natural gas is a more economical choice of fuel when it comes to both thermally driven and RO desalination systems. Therefore, it can be said that the window of opportunity for dish CSP lies in the small-scale desalination applications, such as in remote micro grid systems with desalination, where both the heat and the power can be utilized, in military or resort applications where desalination is required.

3.4 PRODUCE DRYING

Produce drying is another promising technology where the CSP Dish with MGT technology can be utilized. The produce drying has many technologies associated with it. The main technologies currently used in the industry are Belt drying, Flash Drying system, freeze drying, Cabinet drying, rotary dryer, fluidized bed dryer. The type of produce being dried, and the desired end product determines the kind of technology that is used.

Flash drying refers to the removal of moisture by a stream of hot gas that goes through a stream of small particles that moves in the opposite direction. When drying large quantities of bulk powders, it can be important to better control the output characteristics of the powder. For this, combining drying, milling, and classifying steps in one piece of equipment can be beneficial. [26]

Freeze drying is the removal of ice or other frozen solvents from a material through the process of sublimation and the removal of bound water molecules through the process of desorption. Controlled freeze drying keeps the product temperature low enough during the process to avoid changes in the dried product appearance and characteristics. It is an excellent method for preserving a wide variety of heat-sensitive materials such as proteins, microbes, pharmaceuticals, tissues & plasma. [27]

Cabinet/tray dryers are used for batch drying of solid foods at small to moderate scale (Around, 2000 to 20 000 kg per day). They are inexpensive and simple to construct. Cabinet dryers consist of a closed compartment in which trays containing the food to be dried are placed. The trays rest on shelves with adequate spacing between them. Heated dry air circulates between the shelves. Very often, tray bottoms are slotted or perforated, in order to provide some air flow also through the trays. the moisture content of the material, depends on its position on the tray. The material located closest to the entrance of dry air has the lowest moisture content. In order to secure more uniform drying, the direction of air flow may be reversed, or the trays may be rotated periodically. The cabinet is usually equipped with movable baffles, adjusted so as to have uniform distribution of the drying air throughout the cabinet. Cabinet driers are frequently found in rural installations where they are used for drying fruits (grapes, dates, apples), vegetables (onion, cabbage) and herbs (parsley, basil, mint, dill). Air inlet temperatures are usually in the range of 60–80°C. Air velocity is a few $m.s^{-1}$ and must be adjusted according to the size, shape, and density of the food particles so as to avoid entrainment of dry particles with the wind. Depending on the product and the conditions, the duration of a batch is typically 2 to 10 hours. [28]

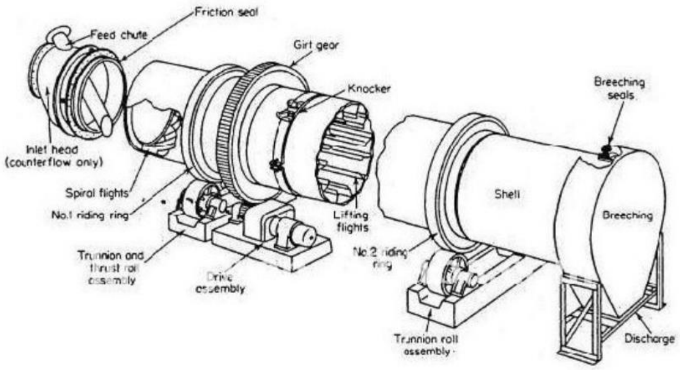


Figure 22: The components of a rotary dryer [29]

Rotary dryers are a class of dryer commonly used in industry to dry particulate solids. They are made of a long cylindrical shell that is rotated. The shell is usually slightly inclined to the horizontal to induce solids flow from one end of the dryer to the other. In direct heat rotary dryers, a hot gas flowing through the dryer provides the heat required for vaporization of the water. To promote gas-solid contact, most direct heat dryers have flights placed parallel along the length of the shell, which lift solids and make them rain across the dryer section. The transport of solids through the drum takes place by the action of the solids cascading from the flights, each cascade comprising the cycle of lifting on a flight and falling through the air stream. [30] Figure 22 above shows the components of a rotary dryer typically used in industry.

Fluidized bed dryers are used for drying materials such as granules, powders, tablets, fertilizers, and plastics. They are particularly popular in industries such as Chemical, Pharmaceutical, food, diary, Metallurgical, Dyes and other process industries.

Fluid bed dryers work on the principle of fluidization, a process where a material is converted from a static solid-like state to a dynamic fluid-like state. In this process, hot gas or air is introduced through a perforated distribution plate into the area holding the material. This hot gas pumps through the spaces between solid particles. As the velocity of the gas or air increases, the upward forces on the particles increase, causing them to equal the gravitational forces below.

This creates a state of fluidization where the particles are suspended in what appears to be a boiling bed of liquid. What once moved in a solid way can now flow like water. Each particle is in direct contact with, and surrounded by, the hot gas or air – creating an efficient and uniform drying process. [31]

In addition to these conventional types of dryers, there have been experiments and pilot projects with using solar heat as the primary heat source to dry produce. One of the examples is the solar crop drying demonstrations done by the Conserval systems, under a grant by the California Air Resources Board of the California Environmental Protection Agency. This was done using solar energy to dry crops grown in California using the low-cost unglazed transpired solar collector displacing fossil fuels. [32] SOLARWALL was a technology initially adopted to aid in space heating of buildings, however this demonstration proved that in large scales that the solar heat can be used to dry certain types of produce. The crops that were tried out in the demonstration included, prunes, apricots, pears, grapes, walnuts, peanuts, almonds, pistachios, pecans, rice, cotton, corn, seeds, spices, herbs, onions, and garlic.

In addition to this, mechanism to solar dry produce has been around for a long time and has been conducted successfully in non-industrial levels. However, with a Dish CSP system with a Brayton cycle output, there is a potential to use the exhaust gases from the recuperator after power generation is done to aid in the any of the produce drying types that have been mentioned above as when the processes are examined, many of the processes use steam or a hot air stream to complete the drying process.

3.4.1 User characteristics

Ajinomoto Co. is a Japanese company that produces packaged, readymade food as their primary product and since its inception has ventured into many other foods and produce related products that uses many drying processes. The main product which composes of Monosodium Glutamate (MSG) is processed fermentation od molasses or tapioca starch by using microbes. MASAKO® another product of theirs is produced using dried meat. Ajinomoto USA produces amino acids, where the final process involves vacuum drying of produce. As of end of March 2019, the parent company had a paid in capital of 79,863 million Japanese Yen.

Nissin is a company whose expertise lies in the dried instant foods. Their products need to undergo drying process to be market ready. Nissin group has also set a medium-term environmental target to reduce their process greenhouse emissions by 30% by 2021. The company has already identified several emission reduction initiatives such as replacing lighting with LED lighting, installing solar panels, but they also have considered the process heat part of their operations. [33]

The top players in the global fruit drying market include companies such as National Raisin Company is a company that specializes in fruit drying and mainly a Business that supplies dried to other businesses (B2B) which supplies dried fruit products all over the world. The products include various kinds of raisins, prunes, figs, blueberries, cranberries, cherries, dates, mango, bananas, pears, apples, pineapples, coconut, and strawberries. The company has an annual revenue of 126.16 million USD. [34]

Graceland Fruit offers dried fruit infused ingredients from produce such as apples, cranberries, blueberries, cherries. Their customers include food service manufacturers and other consumer packaged food manufacturers. [35] The annual revenue of the company as of 2018 was 60.72 million USD. [36]

Sunsweet Growers, who are a primarily cranberries, prunes and apricots growing company with the world's largest dried fruit plant in the world, while processing 50,000 tons of prunes per year. [37] and Ocean Spray cranberries is a marketing cooperative owned by almost 1000 cranberry and grapefruit growers in the United States and Canada, since the beginning it has operated as a grower owned agricultural corporative. The primary products include juices and drinks. [38]

Bühler, which is a company makes a wide variety of food products, but is also involved in producing alternative plant-based proteins, which in the production involves a thermal drying process [39]

3.4.2 Market Size

As the world population continues to grow, the demand for food and hence the demand for processing of seasonal produce to last year long is increasing at a rapid rate. The global Food Dryer market was valued at USD 1670.5 million in 2019 and it is expected to reach USD 2235.2 million by the end of 2026, growing at a CAGR of 4.2% during the forecast period. [40]

The fruit drying industry is valued at 10,570 million USD in 2020 and is projected to reach 15,080 million USD in 2027 and is projected to at a CAGR of over 6.1% in this period. [41]

Since most of the drying processes discussed earlier in the overview of the industry all include a step in the process where either hot gas or steam is used in drying, the potential for a solar thermal system to be integrated, that would provide substantial savings and replacement of fossil fuels used in the process. The potential of the Brayton cycle run dish CSP system is that it is modular nature can aid in sizing the system in according to the drying facility size and its particular drying demand.

However, it needs to be noted that, compared to facilities that use open air drying unfortunately, higher quality from solar driers does not always bring higher market prices than open-air drying. [42] However as discussed in the user characteristics, there are many companies that use machinery and processed air and thermal techniques to dry the produce. A system where the electricity is used to power the auxiliary needs of the drying facilities, with thermal drying processes would be an ideal candidate for the technology.

It also needs to be noted that solar drying can be suitable for a certain kind of produce that can be dried with the use of convection based drying techniques. Certain produce that has higher temperature drying requirements may need to be supplemented with more fossil fuel or biomass powered heat to achieve the desired dryness levels.

A solar heater is able to work 12 months a year displacing fossil fuels whenever it is in operation. It also needs to be noted that Firms which have driers dedicated to only one crop, may operate them for only a few weeks a year. The low utilization factor affects the economics of solar, as well as the cost of having driers sitting idle for most of the year. [43] Therefore, companies that have multiple crops that have varying seasons will profit more from an above-mentioned application.

3.4.3 Competitive analysis

As seen in the industries that the technology can be applied in, it can be seen that there are wide ranging applications that it can be used in. However, these applications will have specific costs associated with it and competition from various other technologies and methodologies that can achieve the same goal. In this section, the other factors that affect the dish CSP and Brayton cycle technology, that make it competitive will be examined. It is interesting to examine both the direct and indirect competition and their specific competencies and weaknesses, when compared to the Dish CSP with Brayton Cycle technology.

Direct Competition

There are many Solar thermal applications in the market with varying degree of success applied in the drying applications that were discussed above. In most research and pilot projects that are carried out, the usage of solar chimney with non-concentrated solar heat used as the primary drying agent. Pilot projects such as the UC Davis chimney dryer project [44] have shown success in drying produce that require lower temperature dry heat.

In addition, any dryer system that is powered by a renewable energy source such as solar PV or Wind generated electricity can be considered as direct competition as an emission free produce drying.

Indirect Competition

The emergence of alternative food preservation methods such as exposing the food to blue LED lighting that terminates bacteria cells that spoil food products [45] and exposing food and produce to cold plasma that terminates the bacteria has been developed and introduced into the food preservation industry can be considered as indirect competition to the produce and food drying industry. [46] However they do have certain temperature and food type limitations that they can be used in.

Competitive strengths and Weaknesses

Simpler techniques that do not have many mechanical or electrical components such as solar chimney that are used for process drying, have the advantage of having significantly lower Operating costs, for a produce drying application requiring a carbon free solution, with lower temperature requirements. Hence it is a more attractive solution. However, in high temperature and high-pressure applications, these technologies do not satisfy the necessary requirements. The applications that require electricity rather than heat, the electricity generation is more suitable. However, since the dish CSP system, expends most of the generated energy as exhaust heat from the MGT, the electricity generated from a source such as Solar PV and Wind would be more price competitive in producing the electricity required.

Barriers to Entry

The high capital cost of the Dish CSP with Brayton Cycle technology is a barrier to entry into this market, especially in remotely located small scale produce drying as the to obtain the financial paybacks from the system. Since the conventional drying systems are established technologies, there needs to be considerable retrofits and modifications to accommodate the heat and power generated by the proposed technology and since the technology is not widely used the farming corporations that operate drying sites may be dissuaded from taking risks.

Window of Opportunity

Opportunity lies in the remote applications with large scale farming corporations that have large scale sites with big volumes that are able to recover the cost of the units. The produce drying needs to require high temperature heat. Companies that operate high heat and high-pressure drying machines who are strategizing to decarbonize the operations is a market segment that the technology can be used in.

3.5 STEAM METHANE REFORMING FOR HYDROGEN PRODUCTION

Steam Methane Reforming (SMR) refers to the process of converting the methane gas into Carbon Monoxide (CO) and Hydrogen molecules (H_2). This is an endothermic reaction that requires high temperature heat. In steam methane reforming, superheated steam is exposed to the methane gas and thus causing a reversible reaction between the methane (CH_4) and the water molecules to produce hydrogen and Carbon Monoxide. The Carbon Monoxide formed subsequently reacts reversibly with the excess steam to produce Carbon Dioxide (CO_2) and Hydrogen molecules. Equation 3 below shows the summary of the reactions.

$$CH_4 + H_2O \leftrightarrow CO + 3H_2$$

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

Equation 3: Steam Methane Reforming

It is a mature production process in which high-temperature steam (700°C–1,000°C) is used to produce hydrogen from a methane source, such as natural gas. In steam-methane reforming, methane reacts with steam under 3–25 bar pressure in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. [47] This is the most common practice used in producing Hydrogen for industrial and energy purposes. The CSP Dish system's ability to reach very high temperatures compared to other CSP technologies such as parabolic trough makes it a viable candidate for SMR process. Methane reforming is currently the cheapest method to produce hydrogen. With a global renewed interest in Hydrogen and the explosion of demand in hydrogen through ambitious and fast deployment of hydrogen infrastructure, the methane reforming market is expanding.

Paper written on Integrated solar thermochemical reaction system for steam methane reforming, which was based on demonstration project, where a Dish CSP unit was used to measure the feasibility of methane reforming with solar thermal technologies shows that they were able to convert 69% of the solar energy to chemical energy efficiency. [48]

However, the intermittent nature of the solar resource means that the hydrogen production with a dedicated Solar thermal system to provide the heat for the steam in the refining process is unreliable. A possible workaround of this problem is to solar augment or compliment an already existing methane reforming system running on conventional fossil fuels to produce the heat needed, hence reducing the amount of greenhouse gas emissions involved in the production of Hydrogen.

1.5.1 User characteristics

There are many companies that are operating in the industry of steam methane reforming to produce hydrogen. The end product is usually a syngas (CO + H_2 Mixture) with a CO/H_2 ratio of about 3:1 to 5:1. It is usually used to produce Hydrogen or another syngas product. A heated mixture of the hydrocarbon feedstock and steam flows through catalyst filled tubes within a fired furnace called a reformer.

As discussed previously, many industries are looking at Hydrogen as a means of decarbonizing their processes and to reduce their sulfur, olefins, and aromatics content in their transportation fuels, with the tightening environmental regulations. This has created a rapidly increasing demand for Hydrogen.

Honeywell UOP is a company that operates in the oil refining and gas, petrochemical processing industry. The company has a revenue of 37 billion US Dollars. UOP uses a technology called Polybed™ to refine Hydrogen, which is highly reliable, leading to more production uptime. Currently they are using the tail gas from the SMR process to power the furnaces that provide the heat needed for the SMR process. [49] However using solar thermal heat to augment this process would further reduce the carbon footprint of the current process.

Air Liquide is another company that is a world leader in providing technologies and services in gases related to industries. They operate in 78 countries, with Oxygen, Nitrogen and Hydrogen being at the core of their business models. Air Liquide has pledged to produce 50% of their hydrogen by 2020 through carbon free processes by combining biogas (Methane) reforming, using renewable energy-based electrolysis and capture the carbon emitted in producing hydrogen in their current convectional processes.

Linde is a leading global industrial gases and engineering company with 2020 sales of 27 billion US Dollars. Their end markets include chemicals & refining, food & beverage, electronics, healthcare, manufacturing, and primary metals. Linde’s industrial gases are used in countless applications, from life-saving oxygen for hospitals to high-purity & specialty gases for electronics manufacturing, hydrogen for clean fuels.

Amec Foster provides design, consulting, and project management services for the natural resources (oil sands, oil and gas, and mining), nuclear, clean energy, water, and environmental sectors. Amec Foster Wheeler is responsible for maintaining large, complex facilities such as nuclear power stations and oil and gas production facilities.

Air Products is a company focused on serving energy, environment, and emerging markets, they provide essential industrial gases, related equipment and applications expertise to customers in multiple industries, including refining, chemical, metals, electronics, manufacturing, and food and beverage. Additionally the company is a major global player in the supply of liquefied natural gas process technology and equipment. [50] The company recorded 8.9 billion US Dollars in sales.

1.5.2 Market Size

Hydrogen is expected to play a key role in the future climate neutral economy, which enables reduced emission transport, heating and industrial processes as well as inter seasonal energy storage. Through the improvements in the Electrolyser technologies, through higher efficiencies and lower operating temperatures, the green hydrogen production through renewable energy generated electricity is becoming cheaper, however currently steam methane reforming production is the cheapest and most widely used technique to produce Hydrogen.

The steam reforming market is valued at 600 million US Dollars in 2018 and is projected to reach 890 million US Dollars by 2025 at a CAGR of 5.9% during the forecast period. [51] Therefore this is an industry that currently has the capacity to decarbonize the processes that are being used. Dish CSP used with Brayton cycle technology can be promising technology to be used in this decarbonization process as the temperatures reached in the systems are comparable to the temperatures needed to activate the endothermic reaction discussed in the introduction of this section.

3.5.3 Competitive analysis

As seen in the industries that the technology can be applied in, it can be seen that there are wide ranging applications that it can be used in. However, these applications will have specific costs associated with it and competition from various other technologies and methodologies that can achieve the same goal. In this section, the other factors that affect the dish CSP and Brayton cycle technology, both in making it a more or less competitive will be examined. It is interesting to examine both the direct and indirect competition and their specific competencies and weaknesses, when compared to the Dish CSP with Brayton Cycle technology.

Direct Competition

Competition for the proposed technology in terms of methane steam reforming as the end product could be classified as the direct competition in this market sector. Other solar thermal technologies such as CSP tower, CSP PTC and LFR technologies are the immediate direct competition. However, a source such as biofuels for this process can also be considered as a direct competitor in this regard.

Indirect Competition

Green Hydrogen through electrolysis from other renewable sources such as Wind and Solar PV through electrolysis technology can be identified as an indirect competition to the methane steam reforming and is considered to be carbon negative and does not require the use of natural gas or biogas. With the cost of electrolyzers decreasing with economies of scale of production, it can be considered as a major indirect competitor.

Competitive strengths and Weaknesses

Direct Competition methods have the advantage of scale over the proposed dish CSP with MGT technology. Technologies such as CSP tower can be a used in large scale SMR systems. However, in a smaller scale where land availability is a concern, the space taken for the solar field will be a concern. Green Hydrogen and the respective methods of production using electrolysis are currently more expensive than the grey hydrogen that is produced due to the high cost of electrolysis currently as the technology is still developing. However, green hydrogen provides the ability to store energy produced from renewable energy sources and improve the utilization of renewable energy powerplants, by making using of the energy generated during periods where the demand is less than the generation.

Barriers to Entry

The current method of SMR where Methane itself is combusted to generate the heat to activate the SMR reaction, is simpler and requires less operating labour and cost, is much more economical. Even though decarbonizing the SMR process is becoming an important factor, the strategies point towards, the deployment of green hydrogen and the long-term strategies include phasing out grey hydrogen. Hydrogen produced through SMR are proposed to be coupled with Carbon Capture and Storage (CCS), hence turning grey hydrogen to blue hydrogen. However, a Life Cycle Analysis (LCA) done by the Hydrogen council shows that the green Hydrogen production has the most impact in terms of decarbonization. [52]

Window of Opportunity

The opportunity lies in the applications where Natural gas price is high, the Dish CSP with MGT technology can provide the necessary heat to start the SMR while reducing the production cost of the Hydrogen produced and the amount of methane used in the process. Specially in small scale SMR generation applications such as in remote locations where hydrogen is needed, it may be more cost effective to produce the SMR produced Hydrogen than transporting it from a centralized production point in the long run.

3.6 COMPRESSED AIR IN THE MINING INDUSTRY

Mining industry needs compressed air for multiple purposes. Exploration drilling, where a percussion drill bit is slowly driven using compressed air. It is needed in pneumatic instrumentation and Agitation. Smelting facilities where metals are extracted through heating and melting the metal ore, are located close to the mines and the instrumentation needs compressed air for its processes. It is also needed in ventilation systems in mines where the compressed air provides fresh air and ventilation supply during hazardous events during the underground mining operations. [53]

There is a growing need to decarbonize the mining industry. The Mining industry produces 1.9 to 5.1 gigatons of CO_2 equivalent GHG emissions annually. The power consumption in mining contributes 0.4 gigatons of CO_2 equivalent GHG emissions. [54] The specific countries that need to be targeted in this sector are the countries that have mining industry with compressed air needs, where there is a high level of DNI, such as South Africa, Namibia, Australia, and regions such as California in the United States. Companies such as Rio Tinto aim to have 10% of their energy demands in one of the mines, which accounts to 20-25 MW from renewable energy. The company plans to reduce its diesel consumptions by 4 million liters. Therefore, it is a promising market to deploy the Parabolic-Dish CSP with MGT technology (Brayton Cycle).

3.6.1 User characteristics

The main operators in the mining industry through market capitalization as of 2018, include the BHP Group Group, Rio Tinto, and Glencore PLC. [55]

BHP Group Ltd, formerly BHP Billiton Ltd, is a global resources company. The Company is a producer of various commodities, including iron ore, metallurgical coal, copper, and uranium. Its segments include Petroleum, Copper, Iron Ore and Coal. The Petroleum segment is engaged in the exploration, development and production of oil and gas. The company recorded a 42.9 billion US Dollars of annual revenue in 2020. [56]

Rio Tinto PLC is a mining and metals company. The company specializes in finding, mining, and processing minerals. The Company's segments include Iron Ore, Aluminum, Copper & Diamonds, Energy & Minerals and other Operations. The Copper & Diamonds segment has managed operations in Australia, Canada, Mongolia and the United States, and non-managed operations in Chile and Indonesia, which includes countries that have high solar resources as well. They recorded a yearly revenue of 44.6 billion US Dollars in revenue in 2020. [57]

Glencore PLC operates through three market segments. Metals and minerals segment, which is engaged in copper, zinc/lead, nickel, ferroalloys, alumina/aluminum, iron ore production and marketing, as well the interests in industrial assets that include mining, smelting, refining and warehousing operations; Energy products segment, which includes coal mining and oil production operations and investments in strategic handling, storage and freight equipment and facilities, and Agricultural products segment, which is supported by controlled and non-controlled storage, handling and processing facilities in various locations, and is focused on grains, oils/oilseeds, cotton and sugar. The company recorded 142.39 billion US Dollars in 2020. [58]

3.6.2 Market Size

The global mining market size was valued at 1641.67 billion USD as of 2020. It is expected to grow to 1845.5 billion USD by 2021, at a CAGR of 12.4%. The market is expected to reach $2427.85 billion in 2025 at a CAGR of 7%. [59] This growth means that there is more demand for steam generation at these sites. However currently mainly coal and other fossil fuels such as natural gas and diesel fired boilers are used in producing this steam. However, with the current need to decarbonize, there is an opportunity for the Dish CSP with Brayton cycle systems to be used to decarbonize the steam generation process.

3.6.3 Competitive analysis

As seen in the industries that the technology can be applied in, it can be seen that there are wide ranging applications that it can be used in. However, these applications will have specific costs associated with it and competition from various other technologies and methodologies that can achieve the same goal. In this section, the other factors that affect the dish CSP and Brayton cycle technology, both in making it a more or less competitive will be examined. It is interesting to examine both the direct and indirect competition and their specific competencies and weaknesses, when compared to the Dish CSP with Brayton Cycle technology.

Direct Competition

In compressed air production in the mining industry, the direct competition to the proposed production of compressed air through Dish CSP combined with MGTs, are the diesel engine generator produced compressed air, which is the current industry standard. Another direct competitor would be Solar PV, Wind or Hydro power generated electricity used in generation of compressed gas.

Indirect Competition

Indirect competition would be that certain operations that are carried out using compressed air as a pneumatic power source in the mining industry being carried out with remote tools that are directly hardwired to an electricity source or equipment and mining accessories that have battery storage in them.

Competitive strengths and Weaknesses

An energy source such as Hydro has the advantage of being reliable throughout the day, that a CSP technology without thermal storage capability does not possess. PV technologies, although without storage have the same shortcoming of being intermittent, are lower in CAPEX and is easier to install in a remote setting. The diesel engines produce carbon emissions in the process of producing compressed air. The amount of energy needed from a source such as solar PV to produce the required levels or low to medium compressed air used in the mining industry would require a solar array that takes up a big land space, which is a disadvantage especially in hilly terrain. Hydro and wind power may not be available at all remote locations and all year long and is a limiting factor in this regard.

Barriers to Entry

The industry standard of diesel engine generators is the industry standard to produce compressed air and there will be reluctance to change the status quo due to its reliability. In a 24-hour operated mine where the compressed air is a vital component, which is a matter of safety, there could be push back from the industry to adopting an intermittent CSP technology without thermal storage. The annual DNI at a particular site can vary significantly and it is not the priority when selecting a mining site, therefore, the adaptability of the technology at various sites, besides being limited to remote locations can vary to a great extent, which results in an effective shrinkage in market application and market size.

Window of Opportunity

In the remote mines where there is no access to other powerplants due to being far from the grid, this technology can have a comparative advantage over other technologies. To produce the low to medium pressure needed in the mining industry CSP technologies are best suited for the application when carbon emissions are taken into consideration. However, the modular nature and the minimal footprint makes it ideal, in a small scale mine site or a remote mining location with elevation, where extensive solar PV array with higher land area use is not feasible.

4. TECHNO ECONOMIC ANALYSIS

4.1 LITERATURE REVIEW FOR TECHNO ECONOMIC MODEL

To model the techno economic analysis, and to define the boundary conditions and the layout the relevant assumptions in the model, a literature review was conducted.

First article referenced was a Thermodynamic survey and cost analysis of a CSP parabolic dish system working with an MGT in hybrid operation mode. In this paper, different locations have been considered, however all within Spain, namely Seville, Salamanca, and Santander.

The model has been developed taking into consideration the instant solar radiation reading, the ambient temperature of the locations. This has been used to get an estimation of the power output of the CSP system. It has also taken into consideration the associated fuel consumption, emissions linked to the said consumption of fuel and a comparison of Hybrid and combustion only operating modes at all the locations considered.

The Levelized Cost of Energy (LCOE) has been calculated in the end to compare the different outcomes from the different locations that have been analyzed. The article is done under the assumption that the technology has the potential to be cost competitive in locations with high DNI and lower access to water.

The modelling has been done using a mathematical model to get an estimation of the energy output from the system. Precise estimations of the hybrid operation have been obtained for time dependent conditions over a year and compared with the hybrid results. [60]

The LCOE in this paper was defined as below, where CI_o is the total capital investment, $C_{o\&m}$ is the cost of operation and maintenance of the system C_{fuel} is the cost of fuel during the hybrid operation strategies, n is the project duration and is defined as 25 years, EE is the energy generated throughout the project duration and r is the discount rate.

$$LCOE = \frac{\sum_{i=1}^{n}(CI_o + C_{o\&m} + C_{fuel})(1+r)^{-i}}{\sum_{i=1}^{n} EE_i(1+r)^{-i}}$$

Equation 4: Used to calculate LCOE [60]

One of the main factors that has not been considered in this paper is the cost of decommissioning of the system and the discount rate of the project is considered to be constant throughout the project lifespan of 25 years.

Another paper that was examined which dealt with a preliminary analysis of a solarized MGT application for a CSP Parabolic dish system. The net power of the system that is analyzed in this system is 31.5 kW and Turbine Inlet Temperature of 850°C.

It also assumed that a minimum DNI of 250 W/m^2 is needed to operate the system, in order to consider, the heating time of the system. This paper has based the conclusions on the results for the LCOE value that they obtained at the end.

The LCOE in this instance was calculated as below. C_{inv} in this case represents the total capital investment costs and FCR represents the fixed charged rate and $O\&M$ represents the total operating and maintenance costs of the system and E_{el} is the total electricity produced. [61]

$$LCOE = \frac{C_{inv} + FCR + O\&M}{E_{el}}$$

Equation 5: Used to calculate LCOE [61]

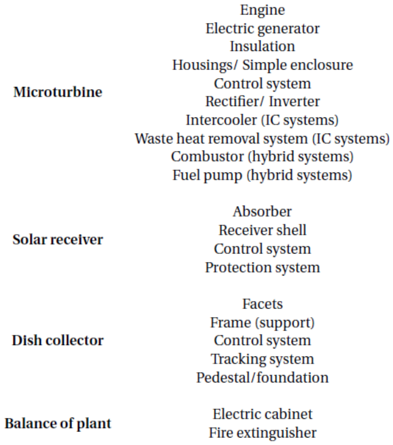
A PhD thesis that examined the techno economic optimization of a solar thermal power generator based on Parabolic dish and Micro Gas Turbine was examined. Even though the model of the said project was optimization, a model was created in this study, that was relevant to the scope of this study. The techno economic model used, the economic section and the parameters considered in the optimizations of the system was relevant to this study.

A non-dimensional (Lumped-Volume) models have been used for the main equipment and model with one dimensional(mean-line) design and performance of radial compressors and turbines have been developed and tailored to the OMSoP project specifications. Mainly three MGT configurations have been considered in this study.

- Simple Recuperated
- Intercooled and Recuperated
- Reheated and Recuperated

Each of the above three configurations have been also analyzed as a solar only operation and as a Hybrid system with natural gas.

In the economic sections, all costs including all the capital and operating and maintenance costs along the complete supply chain, i.e., Manufacturing, assembly, transport, import, erection, operation and dismantling of the components have been taken into consideration. These cost functions have been made sensitive to the size of the system, where specifications such as the Turbine inlet temperature, Recuperator effectiveness, plant size and production volume have been taken into consideration. Following the costs, a cash flow analysis for the project lifetime has been carried out. [62]



Microturbine	Engine Electric generator Insulation Housings/ Simple enclosure Control system Rectifier/ Inverter Intercooler (IC systems) Waste heat removal system (IC systems) Combustor (hybrid systems) Fuel pump (hybrid systems)
Solar receiver	Absorber Receiver shell Control system Protection system
Dish collector	Facets Frame (support) Control system Tracking system Pedestal/foundation
Balance of plant	Electric cabinet Fire extinguisher

Figure 23: Main cost items of the dish-microturbine stand-alone power-only systems. [62]

The Optimization of the system has been done, taking into consideration the LCOE and the environmental impact of the project, where subsequently an optimum size, dish quality and design normal irradiance have been concluded to.

Main takeaways from this study are that since the major cost of capital of the systems is from dish, improving the MGT efficiency, allows for a smaller dish, hence reducing the capital costs of the system. The site location plays an important part in the profitability of this system, not only because of DNI but also the cost of project so that design is done for the specific boundary conditions. The thesis report concludes that in specific applications, CSP dish system with MGT can be economically viable under certain boundary conditions. The optimization in this study has concluded that, a production and market volume of 10MW/year, solar only operation mode could be profitable. [62]

4.2 REVIEW OF PRODUCTION COST ANALYSIS OF OMSOP

A review of the OMSoP consortium cost data, shows that the increase in production volume in any variation of the MGT, when considering the Turbine inlet temperature (TIT), the recuperator effectiveness and the mass flow rate of the air into the turbine, there is a decrease in the specific cost of production of the MGT unit. Figure 24 shows this trend in a 7.5 kW MGT that has been tested out by Compower during the OMSoP costs analysis. [63]

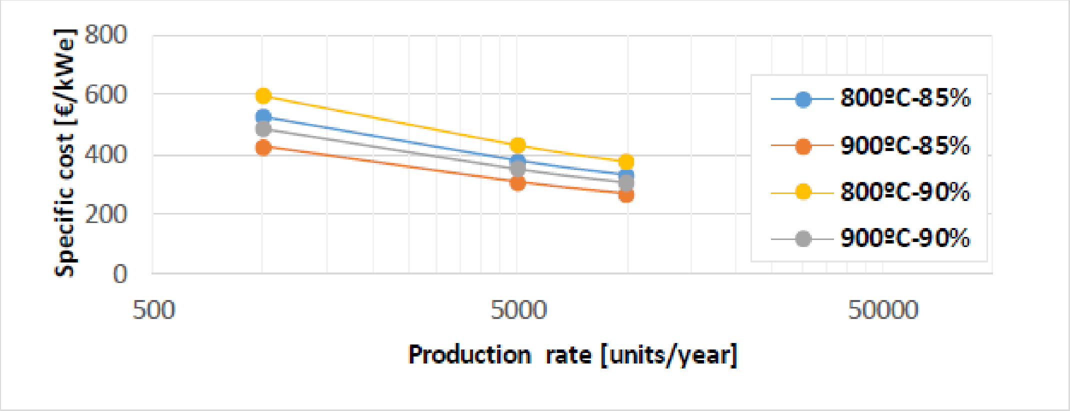


Figure 24: Specific cost vs Production Rate of a 7.5kW MGT [63]

This trend in economies of scale affecting the specific cost of the equipment in question, affects the other key components, such as the receiver, Concentrator. However, in the Balance of Power (BOP) systems, the specific costs depend on the configuration of the system, namely stand alone or farm type. It is also differentiated according to solar only operation and the Hybrid operation.

Figure 25, shows that the reduction in specific costs of a 31 kW_t Solar receiver with the increase in the scale of production at the two different TIT values. [63]

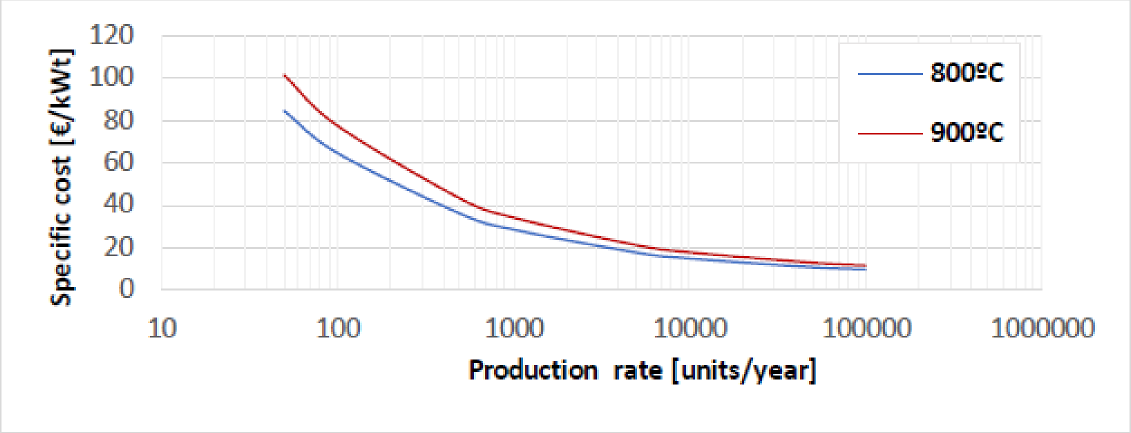


Figure 25: Specific costs vs Production rate of a 31kW$_t$ Solar Receiver [63]

In the case of the solar receiver in spite of the specific costs reduction with the increase in production rate, the aperture area, appears to have a critical point with regards to the specific costs according to the OMSoP report where a 1000 units per year production rate is considered as shown in Figure 26 . However, when this critical aperture area of $90m^2$ is projected to be manufactured at higher scale the specific costs of the receivers decrease as shown in Figure 27.

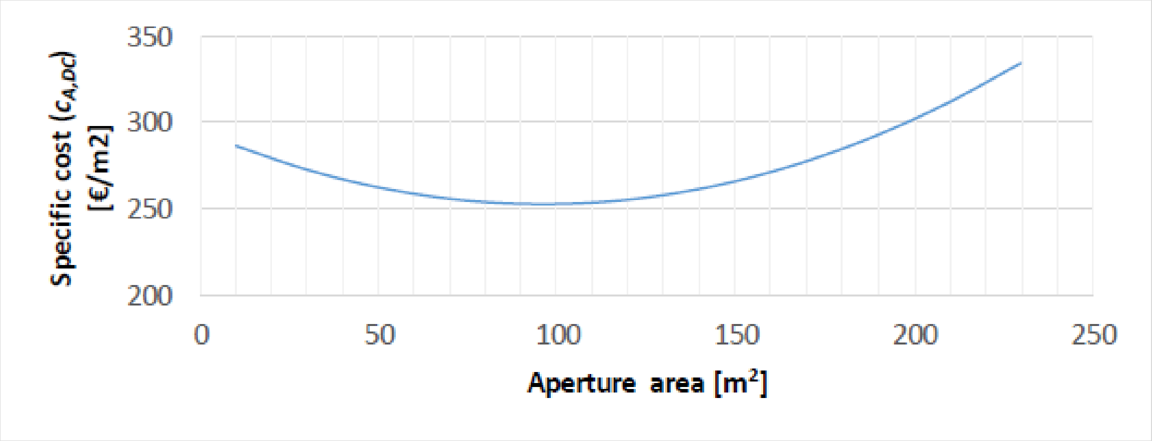


Figure 26: Aperture area vs Specific costs of dish collector [63]

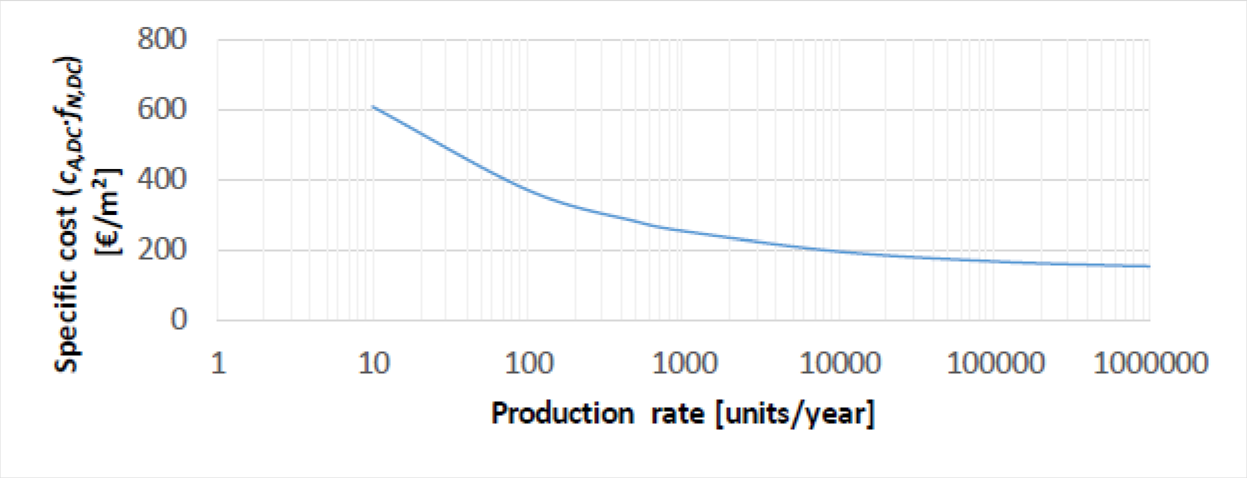


Figure 27: Specific costs vs Production rate of 90m^2 dish collectors [63]

Figure 28 shows the relative specific manufacturing costs of the BOC system when a 90m^2 standalone systems, against variation in production rate. The general trend is that with increase in production rate there is a reduction in the unit costs.

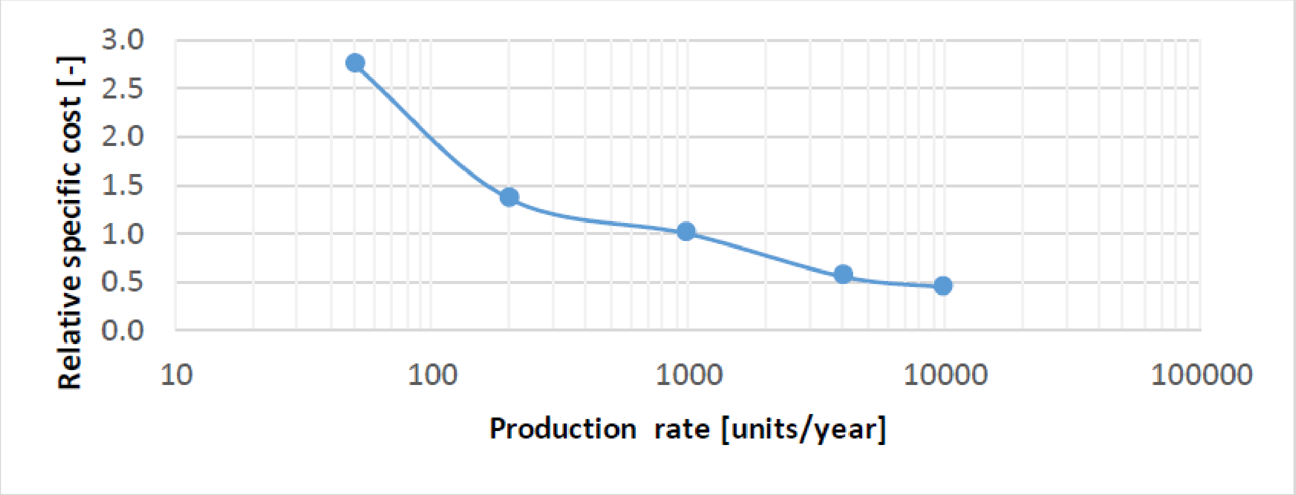


Figure 28: Relative specific manufacturing costs vs Production rate for BOC in a 90m² dish standalone system [63]

From Figure 29, it is seen from that the specific costs of the BOP increase in a farm configuration system with the increase in the total aperture area of the whole power plant. Each curve represents the value of the total power output of the system.

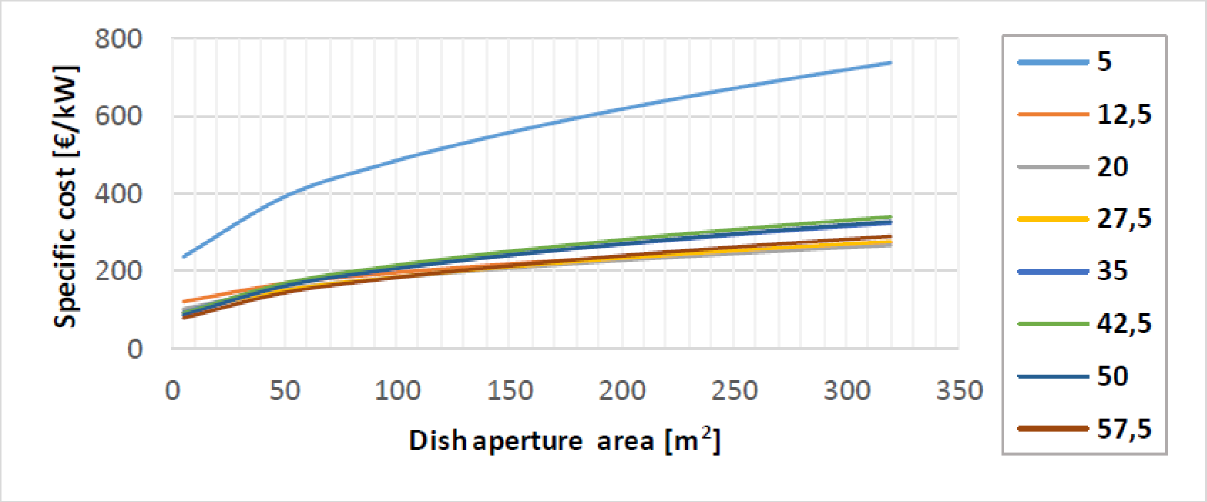


Figure 29: Specific Cost of BOP vs Total dish aperture area of a farm configuration system on solar only operation [63]

Figure 30 shows that with the increase in the total dish aperture area of the farm type plant, in hybrid operation with natural gas, the specific costs of the BOP of the system increase with the increase of the total plant size.

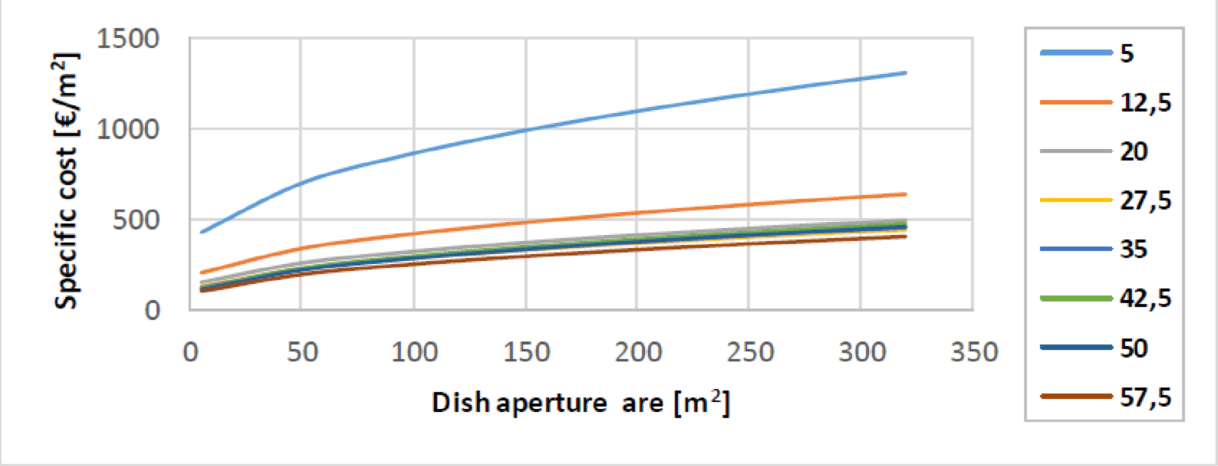


Figure 30: Specific costs of BOP vs Total dish Aperture area of a Farm Type Hybrid Operation plant [63]

4.3 LOCATION SELECTION

The Location selection for the analysis was done by a three-step process. As DNI resource is one of the vital factors determining the success and profitability of a CSP plant, it was decided that initially select 10 locations select 5 countries with the best DNI resource.

The initial countries selected were

- Khai Ma, South Africa
- Maan, Jordan
- New Mexico, United States of America
- Karas, Namibia
- Colombo, Sri Lanka
- Valdez, Equador
- Rabat, Morocco
- Western Australia, Australia

Region, Country	DNI (kWh/m2/year)	Elevation (m)
Northern Cape, South Africa	3083.9	1040
Maan, Jordan	2657.4	857
New Mexico, United States of America	2748.7	1847
Karas, Namibia	2949.9	763
Colombo, Sri Lanka	1392.6	18
Valdez, Ecuador	946	5
Rabat, Morocco	1799.3	26
Western Australia, Australia	2853.8	646

Table 1: DNI and Elevation comparison of selected locations [5]

Since the DNI resource in three of the locations were lower than 2000 kWh/year, they were no longer considered in the second level of deciding factors. Secondly, several key factors such as the existence of relevant small-scale industries that can take advantage of heat from dish CSP and the dissipated waste heat, the availability of biomass was taken into consideration and ranked based on a scoring system as seen from Table 1 and Table 2 below. The top three ranked countries were selected as the locations that were to be analyzed in this study.

South Africa possesses a thriving mining industry with gold and iron ore composing the two main types of mines. Northern Cape itself possesses many mining communities that this technology can be pitched to. The value of the mining industry in South Africa is 59.7 billion USD. [64] South African however has a declining desalination industry, of which the high capital costs have dissuaded governments and companies to look at desalination as a viable solution for the water scarcity issues ailing the country. [65] However, the main reason of the decline specially in the thermally driven desalination is the prohibitive cost of electricity, with the dish CSP system with Brayton cycle, this has the potential to be reduced. Produce in South Africa is done varying scales in South Africa, using mainly drying trays exposed to Sunlight, which is mainly done due to the high cost of electricity, therefore the technology can be attractive solution. Steam Methane reforming is also an industry present in South Africa, however the higher costs of natural gas prices as seen in Table 3 in the next section may prohibit the growth.

Desalination in Jordan is a relatively new enterprise, and the market size is small. Other water management strategies such as conservation have been actively pursued in the past and the dish CSP Brayton cycle system in addition to the high capital costs related with the desalination plants could prove prohibitive. [66] Jordan possesses a mineral and metal mining industry that has a wide range of products. Jordan has sparce vegetation, even though it does possess an agricultural sector. The steam generation from the technology can be used as a produce drying solution, however the market potential is limited. [67] SMR is not an industry sector that has been explored by Jordan currently and the technology in question has minimal potential of growth in this industry in Jordan.

Even though New Mexico is a land locked state in the United States, there are nearby states such as California where desalination plants have been rapidly deployed. Therefore, it can be justified that the Southwestern United states as a region, does have a sizable potential with the deployment of the dish CSP technology. There is a big Mining industry in New Mexico and the southwestern United States, the mining comprises of metals and minerals. Therefore, the small-scale mines with the need for compressed air needs, the dish CSP Brayton cycle system in question could be used as a method of decarbonization. [68] Red Chile and Paprika are produced dried currently in New Mexico with the use of mostly tunnel and belt dryers and the heated steam from the Dish CSP system has the potential to be integrated into this drying process. [69] New Mexico along with other Southwestern US states have ambitious plans for the deployment of Hydrogen production plants, that include the SMR process, therefore there is a major potential for the technology in this region.

Namibia possesses several large-scale desalination plants operated using RO systems that supplement the water demand of the population and industries such as mining. However, the small-scale desalination and the remotely located outposts and hotels still hold a market potential in a country with big mining potential. The main mining industry in Namibia is the uranium mining and the technology’s ability to be a solution in providing compressed air, creates a big market in Namibia. Namibia does not possess abundant biomass or forestry as seen by Table 2, however there has been a policy shift to improve the agriculture sector along the rivers, as a means of improving food security in the country and hence the produce drying in small scale can be deployed to improve the longevity of the local produce. The dish CSP system can be solution in providing the necessary heat for this process while in conjunction proving power to the farming facility or a microgrid. Even though there is potential in this regard, there is minimal existing systems that makes for an attractive market. SMR produced Hydrogen is a very attractive possibility in Namibia and there are already bilateral agreements with countries such as Germany to produce Hydrogen in Namibia due to the high solar resource and the straightforward shipping route into Europe. [70]

There are large scale sea water desalination plants, mainly using RO systems that account to up to 43% of the water demand in western Australian city such as Perth. However, the region is a has a big potential for remote applications of desalination due to the high DNI in the region. [71] Even though the produce drying in Australia exists, majority of the fruit production and drying is done in areas such as Victoria and New South Wales and freeze-drying techniques are being used. [72] There is a state governmental level focus towards the production of Hydrogen in Western Australia, that includes the SMR process and strategies to use waste biomass as a means of methane production for the process. This, hence, presents a big market opportunity for the dish CSP system. [73] Western Australia possesses a thriving mining industry with majority of the mining in Iron ore and Gold. WA’s mining industry consisted of 123 predominantly higher-value and export-oriented mining projects in 2019-20. The State’s mining industry also comprised hundreds of quarries and small mines producing clays, construction materials, dimension stone, gypsum, limestone, limesand, and spongolite for the local construction industry. [74]

Region, Country	**Availability of Biomass (Percentage of Forest cover)**	**Availability of suitable industries**
Northern Cape, South Africa	7.31	Desalination: 3/5 SMR Hydrogen: 4/5 Produce Drying: 4/5 Compressed air in Mining: 5/5 Overall Availability: 4/5
Maan, Jordan	1.0	Desalination: 2/5 SMR Hydrogen: 1/5 Produce Drying: 2/5 Compressed air in Mining: 3/5 Overall Availability: 2/5
New Mexico, United States of America	33.84	Desalination: 3/5 SMR Hydrogen: 5/5 Produce Drying: 4/5 Compressed air in Mining: 5/5 Overall Availability: 4.25/5
Karas, Namibia	9.29	Desalination: 3/5 SMR Hydrogen: 5/5 Produce Drying: 2/5 Compressed air in Mining: 5/5 Overall Availability: 3.75/5
Western Australia, Australia	16.0	Desalination: 4/5 SMR Hydrogen: 5/5 Produce Drying: 3/5 Compressed air in Mining: 5/5 Overall Availability: 4.25/5

Table 2: Location comparison based on the availability of biomass and suitable industries

When availability of suitable industries and available biomass are considered, three countries were selected to be analyzed in the techno economic analysis. South Africa, Western Australia and New Mexico, USA were selected for the analysis.

4.4 MODEL FOR THE TECHNO ECONOMIC ANALYSIS AND RESULTS

The cost data of the components for the techno economic analysis was obtained from several academic sources, including the OMSoP report on the cost analysis for this study.

The hybrid configuration 40% of the available energy for conversion by the MGT is assumed to be from Biogas or Natural gas was taken as the model for the study, and the costs and the performance parameters that are related to the specific dimensions.

The second case is the Hybrid Operation mode with 10% of the available energy to be converted by the MGT coming from Biogas or Natural gas.

The third case is the solar only operation of the system, where the only the heat from Solar Irradiation is considered. In this case the system components does not constitute a hybrid combustor, that is specifically used for Hybrid Operation.

The LCOE is calculated using Equation 6 as shown below and the same equation without considering the heat energy output as useful energy was used in calculating the LEC (Levelized Electricity Costs).

There are factors that varying with the location that is being analyzed which affects the outcome of the economic performance of the location.

Region, Country	**Natural gas price (EUR/MWh)**	**Land Price (EUR/m2)**	**Transportation costs (EUR)**	**Reference**
Northern Cape, South Africa	32.16	1.70	949.94	[75], [3], [76]
New Mexico, United States of America	10.97	105.04	8375.30	[77], [75], [78]
Western Australia, Australia	17.87	4.14	2946.53	[75], [79], [80]

Table 3: Factors varying at different location that are used in the techno economic calculations

4.4.1 Model Assumptions

Land area: The basic assumption is that the land area required by the dish is equal to a square with side dimension equal to 2.5 times the dish aperture diameter. [63] This assumption was made since the systems that are being analyzed are standalone systems.

Manufacturing of equipment are done in Spain, and hence the origin of the shipping costs is from the port of Barcelona. Since the main costs of transportation is freight shipping, the shipping quotations of a 20ft freight was taken as the cost of transportation. It was also assumed that the total system will be transported with the use of a 20ft freight container.

The funding for the project is assumed to be totally funded by the power producer or the owner and hence there is no cost of financing involved.

The replacement costs, the performance drop due to degradation of the components have not been taken into consideration in this model.

4.4.2 Levelized cost of Energy

The equation used to calculate the Levelized cost of Energy in this study is as below.

$$LCOE = \frac{CAPEX + OPEX}{E_e + E_t}$$

Equation 6: LCOE Equation used in the techno economic analysis

In this case, *CAPEX* refers to the total capital expenditure that is incurred for the system, *OPEX* refers to the operational and maintenance costs incurred throughout, the project lifetime which is defined as 20 years. E_e refers to the total electricity that is produced from the system. E_t refers to the total useful heat energy that is generated by the system.

CAPEX

Capital costs include direct costs and indirect costs. The direct costs include the cost of the components of the system and the costs of the services that are needed at the installation site such as transportation and the costs of the land. The indirect costs include the costs incurred that are not immediately needed at the site such as contingencies.

Direct Costs	**Indirect Costs**
MGT	Engineering and Design
Solar Receiver	Contingencies
Parabolic Dish	
Hybrid Combustor	
BOS (Balance of System)	
Transportation	
Installation	
Civil	

Table 4: CAPEX cost components considered

The CAPEX was calculated for the Hybrid operation scenarios with the reference costs obtained as seen in Table 6 in the annex. It is seen that from the direct costs involved in the project, majority of the costs are incurred due to the Parabolic dish.

Referring to the lowest specific costs from the OMSoP project, it is assumed that the dish is 90m^2 in reflector area and the MGT size used was 15kW in the calculations.

In the hybrid scenario is also seen that there is added costs incurred in the Hybrid combustor as shown Figure 31 below.

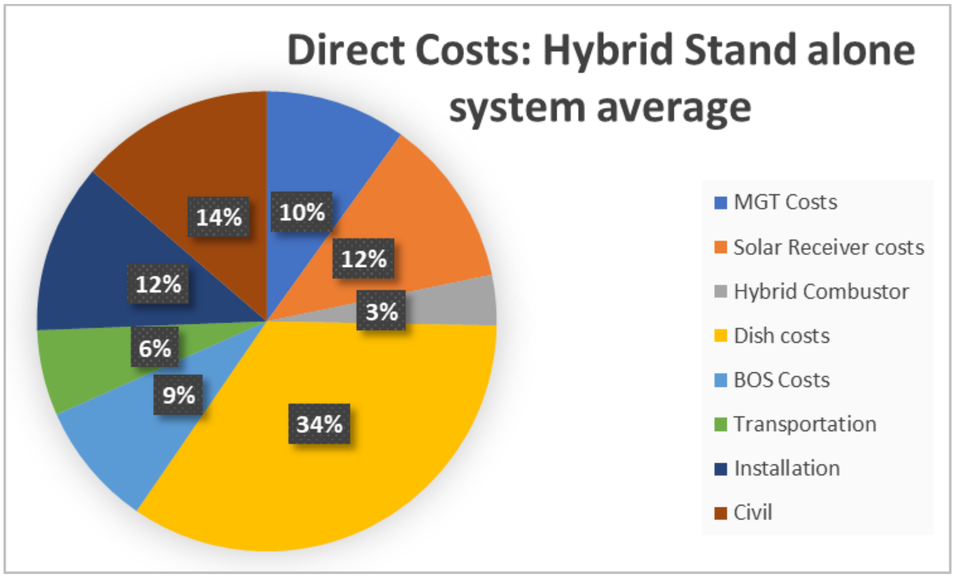


Figure 31: Direct costs of the Hybrid standalone system

Figure 32 shows the direct costs breakdown of the direct cost CAPEX of the solar only operation without the costs incurred by added components as discussed above. In all scenario it is seen that the major cost incurred is through the solar dish, hence it is paramount in further improvement of this technology and the scaling of the technology, the materials and the manufacturing techniques used, be optimized, in order to have a higher energy output per square meter of reflective dish.

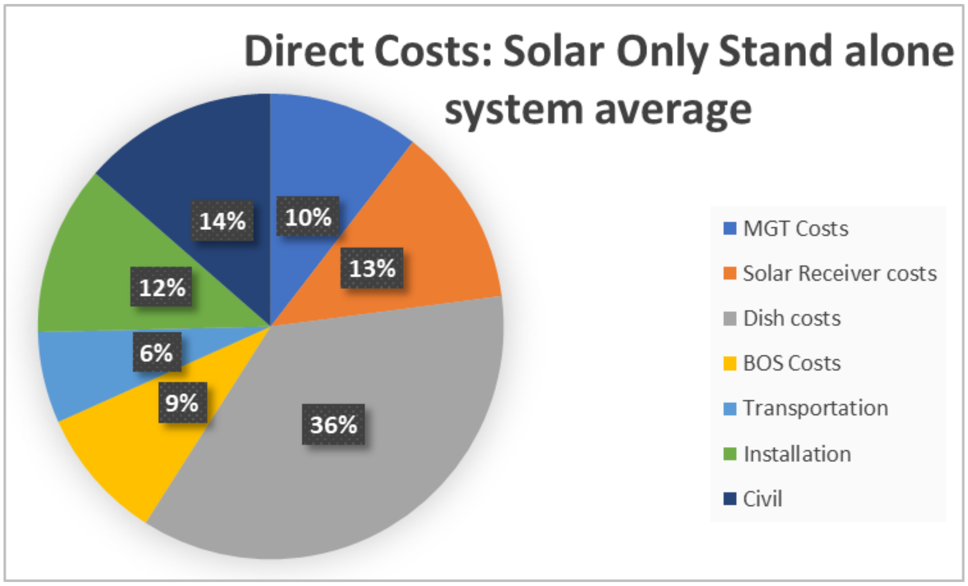


Figure 32: Direct cost CAPEX of Solar Only mode standalone system

The main indirect CAPEX involved in this project is mainly due to the engineering and design costs and the contingencies, the land costs are marginal due to the limited space, that is occupied by a standalone system.

However, in a farm type arrangement with multiple modular units connected, will require more land space. The indirect costs do not vary with the three different scenarios considered as shown by Figure 33.

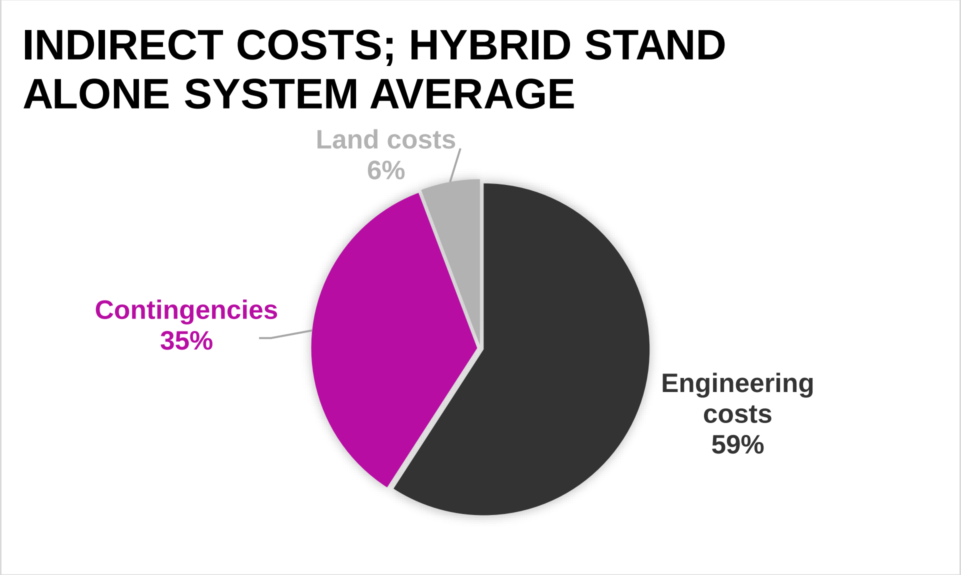


Figure 33: Indirect costs of a Hybrid Stand Alone system

OPEX

The Operational costs, refers to the operational and management costs. This includes the costs incurred during the project lifetime with maintaining the components throughout, for optimal performance, the insurance premiums, and the fuel costs in the case of hybrid operation.

In this case the maintenance and operational costs are assumed to be capital cost of 2% of the hybrid combustor and 4% of the dish annually. In the Hybrid operation, the cost of the fuel used is considered as well, which differs according to the location. For the purpose of the calculation of the first scenario fuel costs,40% of the total energy available for the power production and the second scenario 10% of the total energy available for power was assumed to be from fuel (Natural gas). Since three locations were selected for analyzed, the varying natural gas prices affected the OPEX in the first and the second scenario. Since the solar only operation does not involve the cost of fuel, the OPEX did not vary.

OPEX
Operation and Maintenance
Fuel Costs

Table 5: OPEX costs

The OPEX costs of the 40% Natural gas scenario and the 10% Natural gas scenario for the three different locations for the project lifetime of 20 years is seen as below.

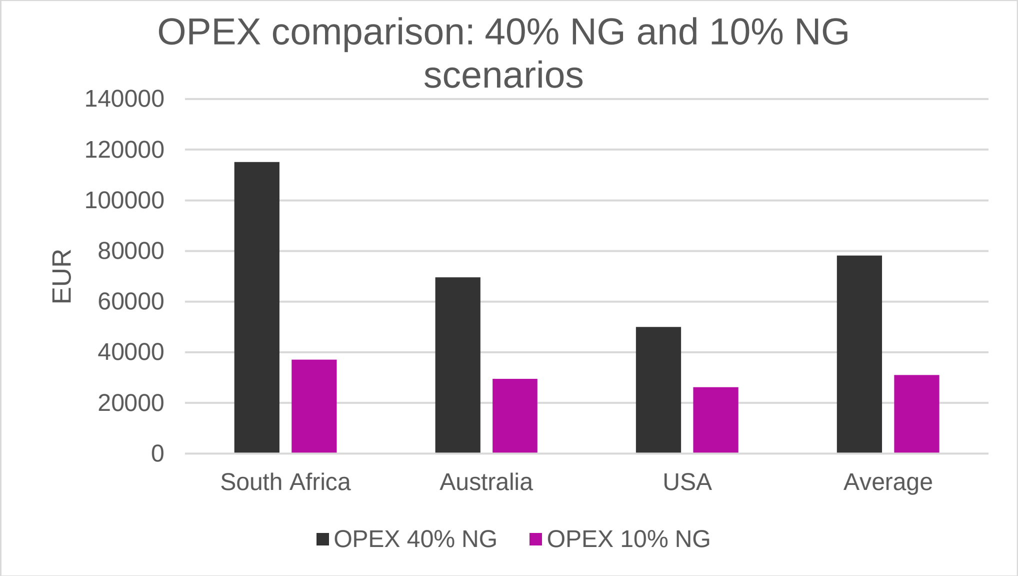


Figure 34: OPEX comparison of 40% Natural gas and 10% Natural gas scenarios

Energy Generation

Energy generation is calculated using the efficiencies values of each component involved in the system, referenced as shown in Table 10 and Table 11 for the three different scenarios. The profiles obtained give the average annual DNI at a particular site and it was multiplied by the surface area of the dish to give the initial solar resource. However, the available heat energy and the generated power was calculated after the reflectivity of the dish, efficiency of the solar receiver, efficiency of the MGT, mechanical and electrical efficiency of the shaft and the generator respectively were considered.

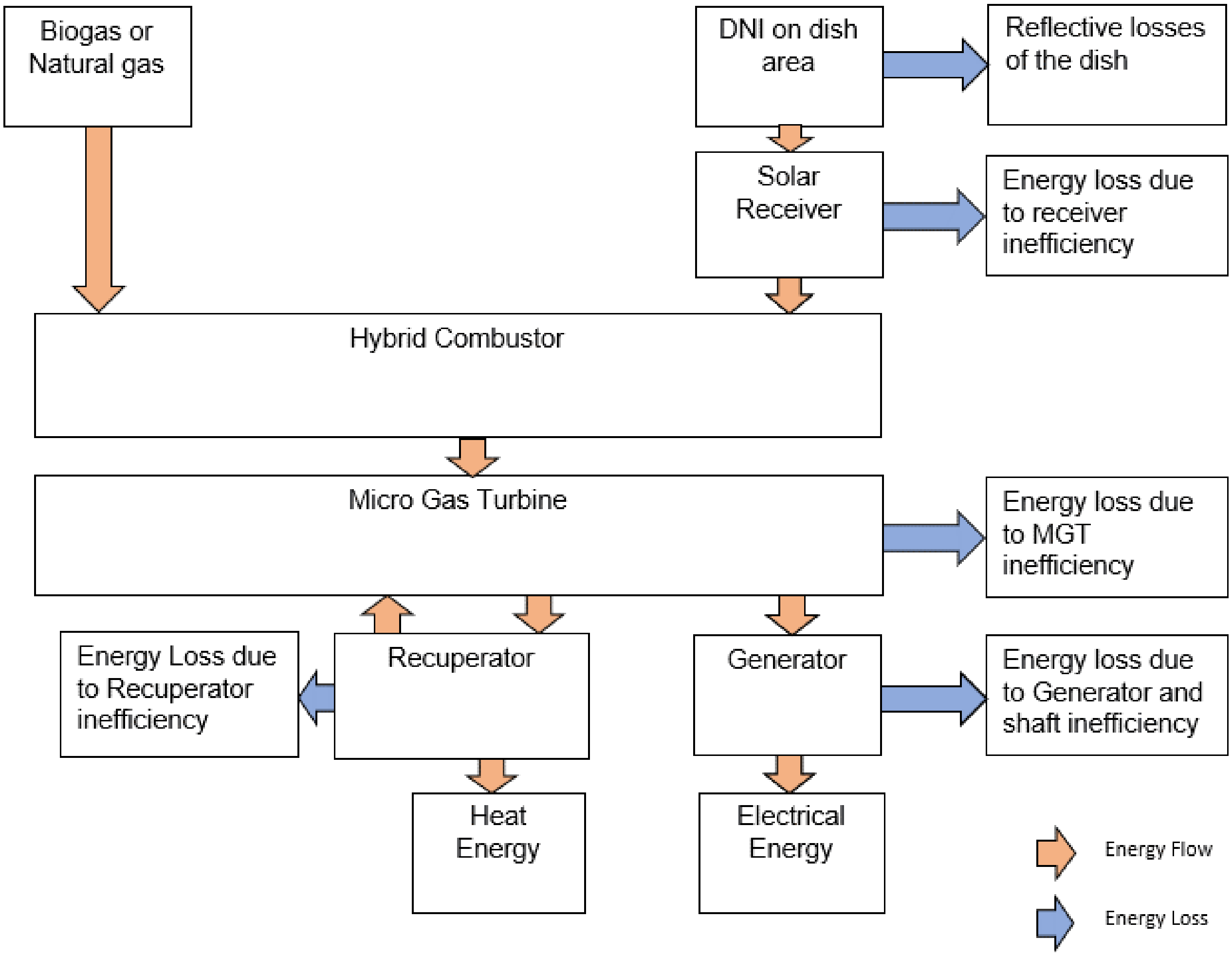


Figure 35: Energy Flow chart of the Dish CSP with MGT in hybrid operation

Figure 36 below shows the comparison of the generation of the three different locations with the three different generation system scenarios considered.

The first scenario with higher share of natural gas, yields the highest energy generation and the lower share of the natural gas used shows the second-best case and the solar only scenario shows the lowest energy generation.

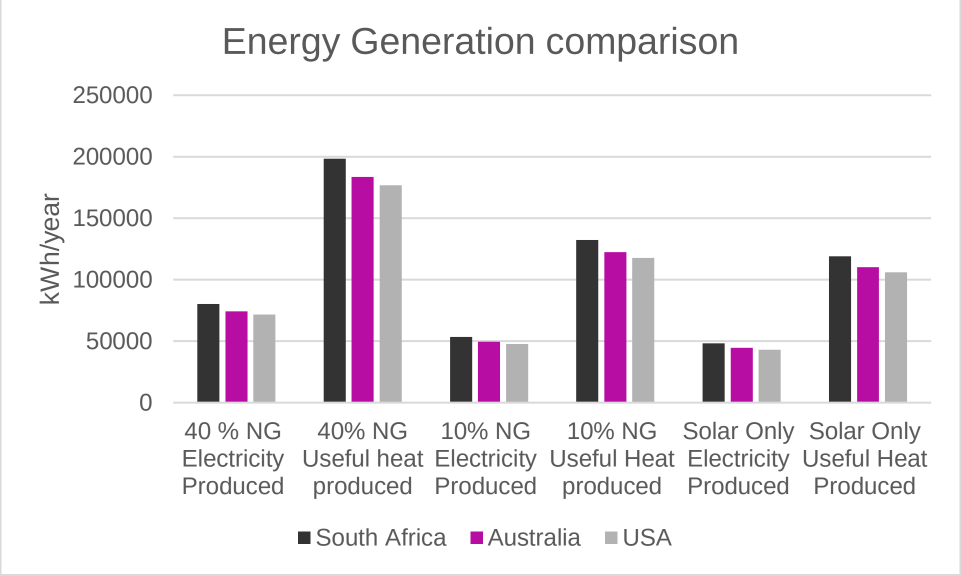


Figure 36: Energy Generation Comparison

After all the costs involved and all useful energy generated is taken into consideration, the LCOE and the LEC was calculated for each location for each scenario.

LCOE Results

The results of the LCOE and LEC were calculated, and the results were as shown in Figure 37. Table 12, Table 13 and Table 14 in the Annex shows the detailed calculation used to calculate LCOE and LEC.

It is seen that the varying price of natural gas plays a major role in the LCOE and LEC values. The higher costs of Natural gas paired with the higher utilization of natural gas in the first scenario results in an above average LCOE and LEC in South Africa, however this trend is reversed in the solar only case, due to the higher DNI resource available in Northern Cape, South Africa. The inverse is true for New Mexico, USA, due to the cheaper cost of natural gas and the higher transportation costs associated with the longer shipping route. It is seen that in Western Australia, the 10% natural gas utilization scenario results in the highest LCOE and LEC and the difference between the LCOE and LEC of the 40% Natural gas and Solar only scenarios is marginal, therefore in this case solar only is best suited due to the lower environmental impact, when the two operation modes are compared.

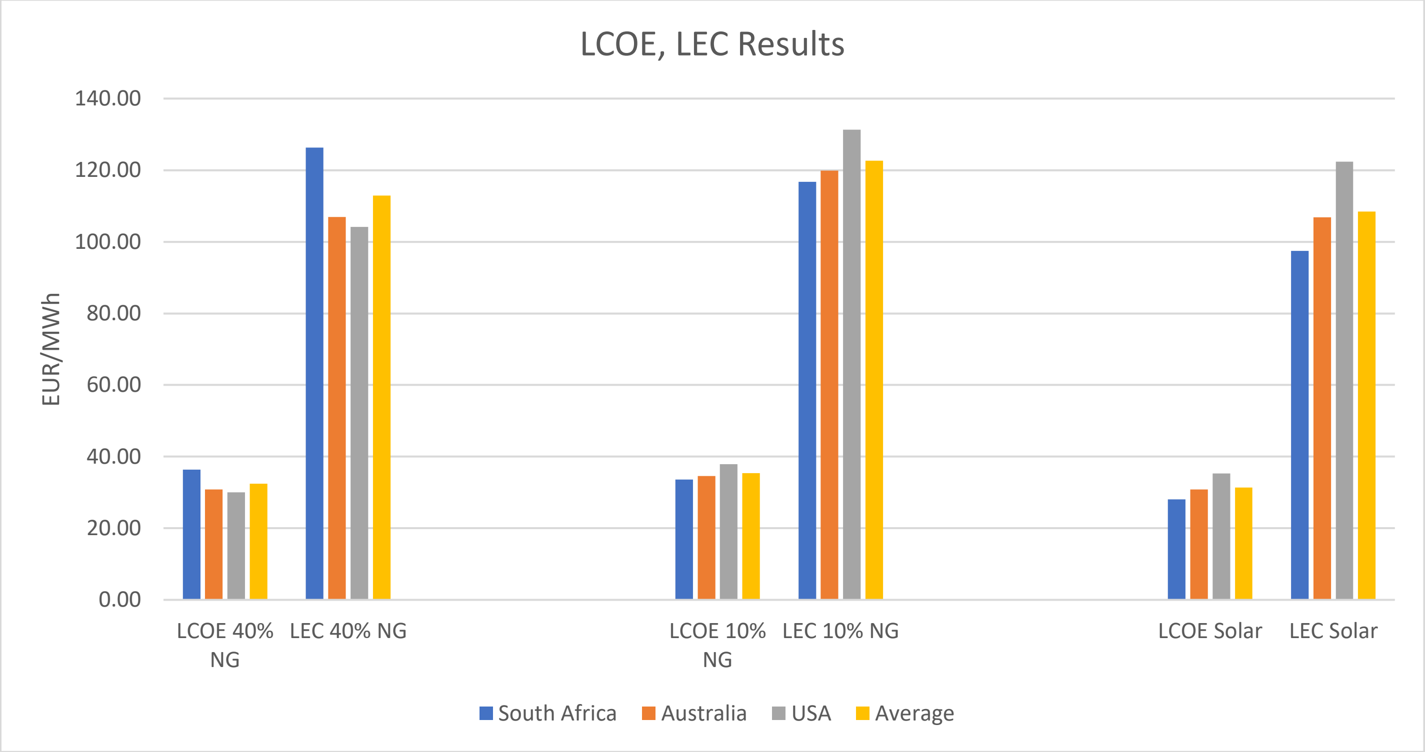


Figure 37: LCOE, LEC Results

5. ENVIRONMENTAL IMPACT

The environmental impact of this technology will depend on several factors, in which it is deployed. The materials and the processes used in the production of the components of the system such as the receiver, combustor and the parabolic dish will determine the environmental impact the production may have.

In operation, the solar fraction and the biogas or natural gas fraction will determine the environmental impact the system will have during hybrid mode. Higher solar fraction and hence a lower natural gas fraction means that the environmental impact would be lower since, there would lower carbon emissions released into the atmosphere.

Decarbonization through the use of the technology is a major positive environmental impact resulting from this technology. When a process that has conventionally used fossil fuels such as diesel, natural gas and gasoline is replaced by this type of technology, the amount of emissions saved that would, otherwise be emitted needs to be taken into account. Throughout this study it is seen that most of the applications that are proposed in the separate industries would replace an existing process that requires fossil fuel systems to operate, hence the positive environmental impact from this technology being deployed is significant.

However, the overall impact of this technology would be primarily dependent on the market penetration of the system in different industries and size of the demand. This would determine the amounts of units of each component in the system produced and the impact each system would have in replacing a conventional fossil fuel system.

6. CONCLUSION AND FUTURE WORK

It can be seen with this study that there are potential markets that this technology can be applicable and feasible, under certain conditions. The chosen markets show that the sectors each has promising growth potential and that hybrid dish CSP system with Brayton cycle could be used in all these markets at differing capacities.

Thermally driven desalination plants have a potential market due to, majority of the demand coming from the MENA region, where the DNI resource is high. The growth of the market is aided with the explosive 1400% growth in market size in Africa, where in both north and the south, the DNI resource is quite high. However, the maturity of the existing types of CSP plants, the large-scale desalination being a mature industry with big market players, the chances of integrating this technology in large scale applications is not feasible. The plummeting cost of energy of Solar PV and the increase in market share of RO driven desalination plants, compete for the sizable share of the growing demand for desalination. However, in remote locations with the demand for desalination, such as remote hotels and military bases, the modular nature of the dish CSP system and it’s ability to generate both heat and power with the use of the MGT, presents a specific market segment that can be targeted.

Even though Freeze drying is the method mainly used in produce drying, there is a considerable market with multiple food drying applications where dry hot air us used in the drying process such as in Cabinet dryers, rotary dryers. Fluidized bed dryers and in flash drying processes. Dish CSP with Brayton cycle can be used in drying with heating and power for auxiliary services in a produce drying facility. However, there is considerable competition that is posed by simpler methods such as solar chimney drying process and drying processes that are operated from other forms of renewable power such as solar PV and the growing market of alternative food preservation methods. Since the solar Dish CSP system operated with a MGT, expends most of its output as heat, it is more suitable for a facility that primary uses thermal drying processes. However, the need for extensive need to modify the facility to accommodate the heat from the MGT in an already operating facility, makes it an unattractive from a capital costs perspective. However, its niche in the produce drying market will lie in either facilities that are operated my farming corporations or companies that plans to decarbonize its operations in remote locations with a need for high pressure and high temperature heat in the drying process.

SMR is a promising market, mainly due to the increase in demand for Hydrogen due to the energy policy at governmental level and company level, turning to Hydrogen as an option. Direct competition in this market stems from other CSP technologies that are deployed in large scale and the economies of scale of such plants and hence the lower LCOE, makes them a stronger candidate than the modular Dish CSP system with a Brayton cycle system. Indirectly the green hydrogen produced from other power generating renewable energy sources and its applicability to be used as a means of energy storage in large scale power plants, makes it an attractive option for a utility customer. Since the SMR market is a mature existing market which mainly uses the Natural gas, both as a fuel to heat up to activate the methane reforming reaction, also as a fuel in the methane reforming, there is a barrier to entry to the existing market players to integrate the system to be used in the methane reforming systems and the intermittency of the heat generation of the system makes it an unattractive retrofit for existing large scale market players. In spite of the increase in demand for hydrogen, the long-term policies related to hydrogen point towards a decrease in cost of electrolysis and the rapid deployment of green hydrogen and the phasing out of grey hydrogen sources. However, the window of opportunity for the dish CSP with Brayton cycle system lies in the small scale SMR generated hydrogen in remote areas where the price of Natural gas is high and the high DNI.

Compressed air has multiple applications in the mining industry. The growing demand of the mining industry translates to higher demand for compressed air. Additionally, the move towards decarbonization of mines, makes the dish CSP technology to provide compress air, an attractive prospect. The competition includes the current industry method of producing compressed air, which is the diesel engine generators, this technology is not intermittent, however is not environmentally friendly. The fact that diesel generators are the industry standard is and the fact compressed air in mining need to be reliable, especially in life support applications, makes the dish CSP technology, unattractive as an alternative without any storage mechanism. However, when paired with storage it can be used in small scale mines, which are located in remote locations to produce low to medium pressure, compressed air applications.

It can be seen from the techno economic analysis that the highest production of energy, among the three different locations was in Northern Cape, South Africa. This was due to the superior DNI resource that this location possesses compared to the other two locations. Increase in the percentage of natural gas or biogas that is used in the systems, increases the amount of energy produced in the system.

However, both the LCOE and LEC are affected by primarily two factors, the price of the natural gas and the annual DNI resource. It is seen than in South Africa due to the higher costs of natural gas, the LCOE and LEC is higher in the higher 40% natural gas fraction scenario and lowest in the solar only scenario. However, in New Mexico, USA 40% natural gas fraction scenario yields the lowest LCOE and LEC due to the lower cost of natural gas.

The average LCOE in the 40% natural gas fraction scenario across the three locations yield 32.41 EUR/MWh and the LEC is 112.92 EUR/MWh. The average of the 10% natural gas scenario yields a LCOE of 35.35 EUR/MWh and the LEC is 122.65 EUR/MWh. The solar only option yields an average LCOE of 31.39 EUR/MWh and LEC of 108.44 EUR/MWh.

It can be concluded that, depending on the location, the share of fuel use needs to be changed to cater the specific costs sensitivities of the location.

A techno economic analysis that involves the cost of financing can be carried out to further understand the economic paybacks of the system at different locations with differing discount rates.

Further study needs to be carried out, which addresses lowering the cost of production, specifically of the parabolic dish. A comparative analysis needs to be done with different materials used for the production of the parabolic dish. Further improvements in the MGT technology and efficiency can be taken into consideration.

A comparative analysis of the performance of this system against other renewable energy plants such as Solar PV, Wind, Biomass should be carried out in regions with high DNI.

ANNEX

	Reference Cost unit	Assumption/Multiplier	South Africa	Australia	USA	Average	Reference
Direct Costs							
MGT Costs	450Eur/kWe	800TIT, 85% recuperated, 1000-unit production, 15kw turbine	6750	6750	6750	6750	[63]
Solar Receiver costs	125.45 Eur/kWt	1000 units/year, 64.14 kWt receiver	8046.363	8046.363	8046.363	8046.363	[63]
Hybrid Combustor	480 Eur/kW	15kWt combustor	7200	7200	7200	7200	
Dish costs	23319.4 Eur	90m^2 Dish	23319.4	23319.4	23319.4	23319.4	[63]
BOS Costs	398 Eur/kW	15kW System	5970	5970	5970	5970	[63]
Transportation	Eur	Location specific	949.94	2946.53	8375.3	4090.59	[75]
Installation	Eur	20% of Equipment cost	9063.15	9063.15	9063.15	9063.15	[61]
Civil	Eur	23% of Equipment cost	10422.63	10422.63	10422.63	10422.63	[61]
Total Direct Costs	Eur		71721.48	73718.07	79146.84	74862.13	
Indirect costs							
Engineering costs	Eur	14% of direct CAPEX	10041.01	9375.53	11080.56	10165.70	[81]
Contingencies	Eur	10% of Equipment, Civil and Installation costs	6034.89	6034.89	6034.89	6034.89	[81]
Land Costs	Eur	Location specific costs per m^2 multiplied by 2.5 times the diameter of dish	45.51	110.82	2811.78	989.37	[3], [77], [80]
Indirect costs	Eur		16121.41	15521.24	19927.23	17189.96	
Total CAPEX	Eur		87842.89	89239.31	99074.07	92052.09	

Table 6: Direct Costs Reference costs and calculations for Hybrid Operation scenarios

OPEX	Reference Costs	Assumption/Multiplier	South Africa	Australia	USA	Average	Reference
O&M Costs per annum	1076.776	2% of the hybrid combustor costs and 4% of the dish costs: energies paper	1076.776	1076.776	1076.776	1076.776	[61]
Fuel Costs per annum	Location specific	40% of available energy from Natural gas	4676.47	2404.64	1421.79	2834.301	[76], [67], [79]
Fuel Costs per annum	Location specific	10% of available energy from Natural gas	779.41	400.77	236.97	472.38	[76], [67], [79]
Total OPEX 10% Natural gas case			1856.19	1477.55	1313.74	1549.16	
Total OPEX 40% Natural gas case			5753.25	3481.41	2498.57	3911.07	

Table 7: Operational costs per Annum for Hybrid Operations

	Reference Cost	Assumption/ Multiplier	South Africa	Australia	USA	Average	Reference
Direct Costs							
MGT Costs	450Eur/kWe	800TIT, 85% recuperated, 1000-unit production, 15kw turbine	6750	6750	6750	6750	[63]
Solar Receiver costs	125.45 Eur/kWt	1000 units/year, 64.14 kWt	8046.363	8046.363	8046.363	8046.363	[63]
Dish costs	23319.4 Eur	90m2 Dish	23319.4	23319.4	23319.4	23319.4	[63]
BOS Costs	398 Eur/kW	15kW System	5970	5970	5970	5970	[63]
Transportation	Location specific		949.94	2946.53	8375.3	4090.59	[75]
Installation		20% of Equipment cost	7623.1526	7623.1526	7623.1526	7623.153	[61]
Civil		23% of Equipment cost	8766.63	8766.63	8766.63	8766.63	[61]
Total Direct costs			61425.48	63422.07	68850.84	64566.13	
Indirect Costs							
Engineering costs			8599.57	7934.09	9639.12	8724.26	[81]
Contingencies			5170.89156	5170.8916	5170.89156	5170.892	[81]
Land costs			45.509	110.8222	2811.778774	989.37	[3], [77], [80]
Total Indirect costs			13815.97	13215.80	17621.79	14884.52	
Total CAPEX			75241.45	76637.87	86472.63	79450.65	

Table 8: Direct Costs of Solar Only Operation

OPEX	Reference Costs	Assumption/ Multiplier	South Africa	Australia	USA	Average	Reference
O&M Costs per annum	932.776	2% of the hybrid combustor costs and 4% of the dish costs: energies paper	932.776	932.776	932.776	932.776	[61]
total			932.776	932.776	932.776	932.776	

Table 9: OPEX for Solar Only Operation

	South Africa	Australia	USA	Reference/Assumption
DNI (kWh/m2)	3083.9	2853.8	2748.7	[5]
Efficiency of MGT (%)	0.245	0.245	0.245	[61]
Reflectivity of dish (%)	0.883	0.883	0.883	[61]
Efficiency of the receiver (%)	0.89	0.89	0.89	[61]
Area of the dish (m2)	90	90	90	[63]
Mechanical efficiency (%)	0.98	0.98	0.98	[61]
Generator Efficiency (%)	0.92	0.92	0.92	[61]
Recuperator Efficiency (%)	0.85	0.85	0.85	[63]
LHV of Methane	55.5	MJ/kg	15.416679	kWh/kg
40% Natural Gas Case				
Total energy received by the dish (kWh/year)	277551	256842	247383	
Energy remaining after reflective loss (kWh/year)	245077.5	226791.486	218439.2	
Energy remaining after receiver loss (kWh/year)	218119.0	201844.4225	194410.9	
Energy from Natural gas/Biogas (kWh/year)	145412.7	134562.9	129607.3	Assumption: 40% of the total available energy
Energy available energy (kWh/year)	363531.7	336407.4	324018.1	
Energy produced after MGT losses (kWh/year)	89065.3	82419.8	79384.4	
Electricality produced after gen/shaft loss (kWh/year)	80301.2	74309.7	71573.0	
Useful heat Produced (kWh/year)	198302.0	183506.0	176747.8	
kgs of Biogas/Natural Gas used (kg)	9432.2	8728.4	8407.0	
10% Natural Gas Case				
Total energy received by the dish (kWh/year)	277551	256842	247383	
Energy remaining after reflective loss (kWh/year)	245077.5	226791.486	218439.2	
Energy remaining after receiver loss (kWh/year)	218119.0	201844.4225	194410.9	

Energy from Natural gas/Biogas (kWh/year)	24235.4	22427.2	21601.2	Assumption: 10% of the total available energy
Energy available energy (kWh/year)	242354.4	224271.6	216012.1	
Energy produced after MGT losses (kWh/year)	59376.8	54946.5	52923.0	
Electricality produced after gen/shaft loss (kWh/year)	53534.2	49539.8	47715.3	
Useful heat Produced (kWh/year)	132201.3	122337.3	117831.9	
kgs of Biogas/Natural Gas used (kg)	1572.0	1454.7	1401.2	

Table 10: Energy Generation for Hybrid operation mode

Solar Only Operation	South Africa	Australia	New Mexico	Reference
DNI (kWh/m2)	3083.9	2853.8	2748.7	[5]
Efficiency of MGT (%)	0.245	0.245	0.245	[61]
Reflectivity of dish (%)	0.883	0.883	0.883	[61]
Efficiency of the receiver (%)	0.89	0.89	0.89	[61]
Area of the dish (m2)	90	90	90	[63]
Mechanical efficiency (%)	0.98	0.98	0.98	[61]
Generator Efficiency (%)	0.92	0.92	0.92	[61]
Recuperator Efficiency (%)	0.85	0.85	0.85	[63]
Total energy received by the dish (kWh/year)	277551	256842	247383	
Energy remaining after reflective loss (kWh/year)	245077.5	226791.486	218439.2	
Energy remaining after receiver loss (kWh/year)	218119.0	201844.4225	194410.9	
Energy available energy (kWh/year)	218119.0	201844.4	194410.9	
Energy produced after MGT losses (kWh/year)	53439.2	49451.9	47630.7	
Electricality produced after gen/shaft loss (kWh/year)	48180.7	44585.8	42943.8	
Useful heat Produced (kWh/year)	118981.2	110103.6	106048.7	

Table 11: Energy Generation for Solar Only Mode

Hybrid Operation 40% Natural gas	South Africa	Australia	USA	Average
Total CAPEX (Eur)	87842.89	89239.31	99074.07	92052.09
n	20	20	20	20
OPEX per Annum (Eur)	5753.25	3481.42	2498.57	3911.08
Total OPEX (Eur)	115064.95	69628.32	49971.35	78221.54
Total Lifetime Costs (Eur)	202907.84	158867.63	149045.42	170273.63
Electricity Generation per Annum (kWh)	80301	74310	71573	75394.65
Heat Generation per Annum (kWh)	198302	183506	176748	186185.28
Total Energy per annum (kWh)	278603	257816	248321	261579.93
Total Lifetime Electricity Production (kWh)	1606025	1486194	1431460	1507892.99
Total Lifetime Heat Production (kWh)	3966040	3670120	3534957	3723705.60
Total Lifetime Energy Production (kWh)	5572064	5156314	4966417	5231598.59
LCOE (Total Energy) (Eur/kWh)	0.0364	0.0308	0.0300	0.0324
LCOE (Total Energy) (Eur/MWh)	36.42	30.81	30.01	32.41
LEC (Eur/MWh)	126.34	106.90	104.12	112.92

Table 12: LCOE Calculation for 40% Natural Gas Operation

Hybrid Operation 10% Natural gas	South Africa	Australia	USA	Average
Total CAPEX (Eur)	87842.89	89239.31	99074.07	92052.09
n	20	20	20	20
OPEX per Annum (Eur)	1856.19	1477.55	1313.74	1549.16
Total OPEX (Eur)	37123.76	29550.99	26274.83	30983.19
Total Lifetime Costs (Eur)	124966.65	118790.30	125348.89	123035.28
Electricity Generation per Annum (kWh)	53534	49540	47715	50263.10
Heat Generation per Annum (kWh)	132201	122337	117832	124124
Total Energy per annum (kWh)	185735	171877	165547	174386.62
Total Lifetime Electricity Production (kWh)	1070683	990796	954307	1005261.99
Total Lifetime Heat Production (kWh)	2644026	2446747	2356638	2482470.40
Total Lifetime Energy Production (kWh)	3714710	3437543	3310945	3487732.39
LCOE (Total Energy) (Eur/kWh)	0.0336	0.0346	0.0379	0.0354
LCOE (Total Energy) (Eur/MWh)	33.64	34.56	37.86	35.35
LEC (Eur/MWh)	116.72	119.89	131.35	122.65

Table 13: LCOE Calculation of 10% Natural Gas Operation

Solar Only	South Africa	Australia	USA	Average
Total CAPEX (Eur)	75241.45	76637.87	86472.63	79450.65
n	20	20	20	20
OPEX per Annum (Eur)	932.78	932.78	932.78	932.78
Total OPEX (Eur)	18655.52	18655.52	18655.52	18655.52
Total Lifetime Costs (Eur)	93897.0	95293.3948	105128.149	98106.17
Electricity Generation per Annum (kWh)	48181	44586	42944	45236.79
Heat Generation per Annum (kWh)	118981	110104	106049	111711.17
Total Energy per annum (kWh)	167162	154689	148993	156947.96
Total Lifetime Electricity Production (kWh)	963615	891716	858876	904735.79
Total Lifetime Heat Production (kWh)	2379624	2202072	2120974	2234223.36
Total Lifetime Energy Production (kWh)	3343239	3093789	2979850	3138959.15
LCOE (Total Energy) (Eur/kWh)	0.02808563	0.03080152	0.03527968	0.0314
LCOE (Total Energy) (Eur/MWh)	28.0856314	30.8015216	35.2796755	31.39
LEC (Eur/MWh)	97.4424251	106.865141	122.401989	108.436266

Table 14: LCOE Calculation for Solar Only Operation

BUDGET FOR THE THESIS

The cost of writing the thesis was calculated by taking into account the average monthly pay of an energy engineering professional in Spain. The duration of the thesis was defined as 6 months, referring to the months from February to July.

		Reference
Monthly rate	2,670 Eur	[82]
Duration	6 Months	
Total cost	16020 Eur	

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