Department of Mechanical Engineering

MUH 104 - An Introduction to Mechanical Engineering

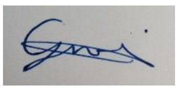
Electricity Generation Through Concentrated Solar Power (CSP)

by

Gökay, KART

21832009

I confirm that I have followed the Academic Integrity Rules.



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Abbreviations	
CSP	Concentrated Solar Power
PV	Photovoltaic
TES	Thermal Energy Storage
HTF	Heat Transfer Fluid
IRENA	International Renewable Energy Agency
R&D	Research and Development
SETO	The Solar Energy Technologies Office
TEİAŞ	Turkey Electricity Transmission Inc.
NREL	The National Renewable Energy Laboratory
TÜBİTAK	Scientific and Technological Research Council of Turkey
TTGV	Turkey Technology Development Foundation

Abstract

In the 21st century, the importance of renewable energy sources is increasing. Solar energy is at the forefront of renewable energy sources. There are many areas where solar energy is used and it is usually aimed to convert it into electrical energy. Although PV systems in solar energy have been preferred in industry and domestic use for many years, CSP systems have been developing gradually in the last ten years. It increases its market share. Because of the direct generation of electricity from PV systems, the cost of storage in large-scale facilities is very high. CSP systems, on the other hand, can store the energy obtained as heat energy in special liquids. With TES systems that work integrated with CSP systems, heat energy can store its energy with high efficiency in targeted periods. The production and maintenance cost of TES systems is cheaper than electricity storage systems in PV systems. The importance of TES systems is that they provide the opportunity to use energy when the sun goes down. A lot of R&D is being done to reduce the cost of the TES system and increase its efficiency. Experiments and new ideas are being developed by establishing experimental CSP systems in many laboratories for heat transfer fluids (HTF) used in CSP systems to increase efficiency. It is aimed to increase the market share with new generation concentrated solar power plants and to accelerate the process of transitioning the world to clean energy.

1.Introduction

In this article, why solar energy is important and solar energy systems used in the world are explained. The historical adventure of solar energy is explained. Technologies used with solar energy are compared. CSP technologies are explained. Advantages and disadvantages are explained according to usage conditions. The types and usage areas of CSP systems are explained. The need for renewable energy in the world is explained and the R&D activities of the countries are mentioned. It explains why CSP systems may be the first choice in the future. The ways to reach the optimum CSP technology are mentioned. Finally, the latest developments in CSP systems are described.

2.1 What is Solar Energy?

Solar energy is a radiation energy. The most important tasks in our world are heating and being a food for plants. Mankind first used the sun's rays directly to make fire in 7000 BC. The first solar device was made by Charles Fritts in 1883. This device is the first semiconductor selenium cell. However, this invention was born with high cost and 1 percent energy efficiency at that time.

In 1905, with Albert Einstein's discovery of the "photon", solar energy systems leapt into an era. In this discovery, Einstein said that photons eject electrons at a certain energy level, and this explanation won him the first and only Nobel Prize in 1921.

By 1954, Calvin Fuller, Daryl Chapin and Gerald Pearson at Bell Labs had produced the first modern solar cells and were used on the Vanguard-I satellite in 1958 as the first major project. The Vanguard-I satellite remains the oldest in orbit.

At the end of the 20th century, solar energy entered the stage of regular use and transitioned to the industrial dimension to generate electricity. Today, many researches and developments are carried out for more efficient use.

2.2 General Description of Concentrated Solar Power (CSP)

The idea father of this system is Augustin Mouchot. He started his work in 1860 with the idea that coal would decrease over time after the industrial revolution. He succeeded in providing a motive power in the steam engine with the steam obtained by heating a water-filled boiler with solar energy and developed the first solar collector in 1866. The product could not develop in the domestic conflicts of the period.

The general purpose of CSP systems is to convert energy into heat or electrical energy by using concentrated sunlight, and it is also used in water treatment (desalination) processes. In these systems, instead of using separate battery cells, rays are focused on a certain point or area with many reflection elements. Reflective film or mirror types are preferred as reflection elements. Reflection elements are in continuous R&D process for optimum efficiency. With the help of reflective elements, the absorbed solar energy is transmitted to the heat transfer fluid (HTF) used in the system. The oil used here contains complements such as water, salt, etc. For optimum efficiency, the elements used in the liquid are in continuous R&D process.

There are various CSP systems according to the type of liquid used, the positions of the reflection means and the energy conversion paths. There are four types of commonly used systems. These systems are examined in Section 2.3. They are systems that cover sunlight temperatures between 400˚C - 1000˚C, so household modeling is not intended as a target area of use. Large-scale energy production is aimed with large investments. The high-temperature liquid produced is transferred to storage tanks. When energy is needed, liquid is converted into steam and electricity is obtained by means of large steam turbines. It is a great advantage that storage tanks can save energy. Solar energy cannot be used 24 hours a day, 365 days a year, but with CSP systems, energy is stored as heat energy in warehouses and used when there is no sunlight.

2.3 CSP Designs and Applications/ Technologies

In CSP systems, there are models with the same purpose but developed from many perspectives. The main purpose in most systems is to generate electricity. It is also possible to use the heat directly together with electricity production. In addition, the distillation of sea water is an energy-intensive process. The process of heating and distilling sea water with direct concentrated sunlight is carried out with CSP systems. There are four types of CSP systems that have become widespread.

- **Parabolic Trough**

Picture.1 Parabolic Trough

• Special oil is passed through the heat absorber pipes made of stainless steel, then the high-energy oil is sent to heat the water and electricity is produced by means of steam turbines.

• It is used for electricity generation and to obtain process heat at medium temperature.

• Since linear condensation is made, their efficiency is low.

• Since it is the most used system among all CSP systems, it has been proven commercially, so its biggest advantage is the guaranteed energy conversion.

• Systems in desired dimensions can be produced.

• The tracking system is cheap and simple.

• Heat collection pipe and special mirrors are costly.

• Maintenance and repair is complex.

• It contains special technology.

• It uses very little reflection area.

• This CSP technology looks like in *Picture.1 Parabolic Trough*.

- **Linear Fresnel Collectors**

Picture.2 Linear Fresnel Collectors

• Water flows directly through the pipe passing through the focal point of the mirrors. It is a simple design that enables steam generation.

• It is used to generate electricity and to obtain process heat at low-medium temperatures.

• Since linear condensation is made, their efficiency is low.

• Low production cost is its biggest advantage since it contains flat mirrors.

• Systems in desired dimensions can be produced.

• The tracking system is cheap and simple.

• It is the most cost-effective system among all CSP technologies.

• Maintenance and repair is simple.

• It does not contain special technology.

• The reflection area it uses is very small.

• This CSP technology looks like in *Picture.2 Linear Fresnel Collectors*

- **Solar Power Tower**

Picture.3 Solar Power Tower

• It reaches the highest temperature level (1000 C°) among CSP technologies. This heat energy is transferred to the liquid in the tower and electricity is produced by means of steam turbines.

• It is used for electricity generation and to obtain high temperature process heat.

• High efficiency due to point condensation.

• Its biggest advantage is that it can produce energy when solar energy cannot be used due to its ability to store heat.

• It is carried out in large sizes.

• The tracking system is expensive and complex.

• The mirror it uses and the tower in the center are costly.

• Maintenance and repair is complex.

• It contains special technology.

• The reflection area used is quite large.

• This CSP technology looks like in *Picture.3 Solar Power Tower*.

•Dish Stirling

Picture.4 Dish Stirling

• Concentrated solar energy is supplied to a heat transfer fluid heated up to 750°C and electrical energy is generated by a stirling engine.

• It is used only for electricity generation.

• High efficiency due to point condensation. It has the highest efficiency among CSP systems.

• Its biggest advantage is that it complies with mass production conditions, does not need water, and contains high efficiency.

• It cannot be performed in large sizes.

• It contains special technology.

• The tracking system is expensive and complex.

• Stirling engines are used. The use of these engines is not common, so they are the most costly CSP system to manufacture.

• Maintenance and repair is complex.

• The reflection area it uses is very small.

• This CSP technology looks like in *Picture.4 Dish Stirling*.

2.4 CSP Economic Efficiency and Energy Storage

When we look at the past, the first solar energy cell allowed us to use energy with an efficiency of one percent. Considering that non-renewable energy resources will run out, governments provide significant support for renewable energy, and private energy companies develop solar energy technology. Since CSP systems require large investments, the location of the established business is very important. For high productivity, North America, Africa and Australia continents should be preferred as shown in the *Figure.1 Earth Sunlight Projection*. Most CSP systems have an efficiency of 7-25% depending on the type, but systems using a stirling engine have an efficiency of 30-35%. Although CSP systems cannot reach the efficiency of Hydroelectric and Wind Turbines, they have similar efficiency with other solar energy systems.

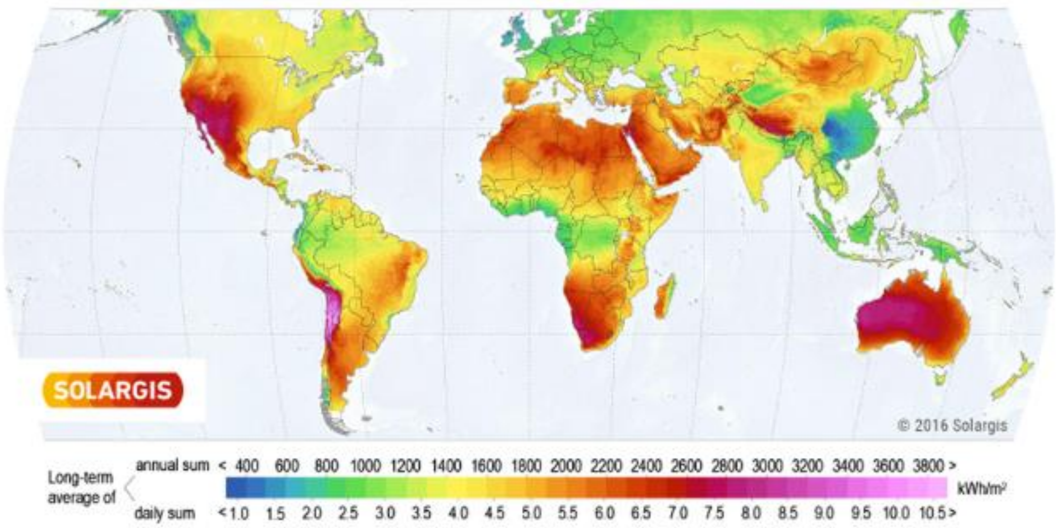

Figure.1 Earth Sunlight Projection

Although CSP systems have similar efficiency with other solar energy technologies, they have a great advantage in energy storage. Thermal Energy Storage (TES) systems are used in CSP systems and the efficiency of TES systems has reached 90%. or this reason, it provides the opportunity to collect energy when the sun's rays are intense and to use the energy in TES systems as heat or electricity when necessary. Today, short and long-term models of TES systems vary according to production capacity. Two types of TES systems are used as day-night or summer-winter depending on the purpose and place of use of the CSP system. Storing heat in TES systems is much cheaper than storing electricity in any power plant. Storage cost is very important in large enterprises, so the biggest advantage of CSP systems is to be able to store energy at low cost.

As can be seen in the *Figure.2 CSP Cost Chart*, according to the analysis of the US Department of Energy's Office of Solar Energy Technologies (SETO), the cost of thermal energy storage has decreased by 50% in the last ten years, with performance improvements and cost reduction. This process makes the cost of CSP systems more economical.

Figure.2 CSP Cost Chart

2.5 Concentrated Solar Power (CSP) Vs Photovoltaic (PV)

The first difference between CSP and PV systems is the way electrical power is generated. PV systems use sunlight while CSP systems use solar energy directly.

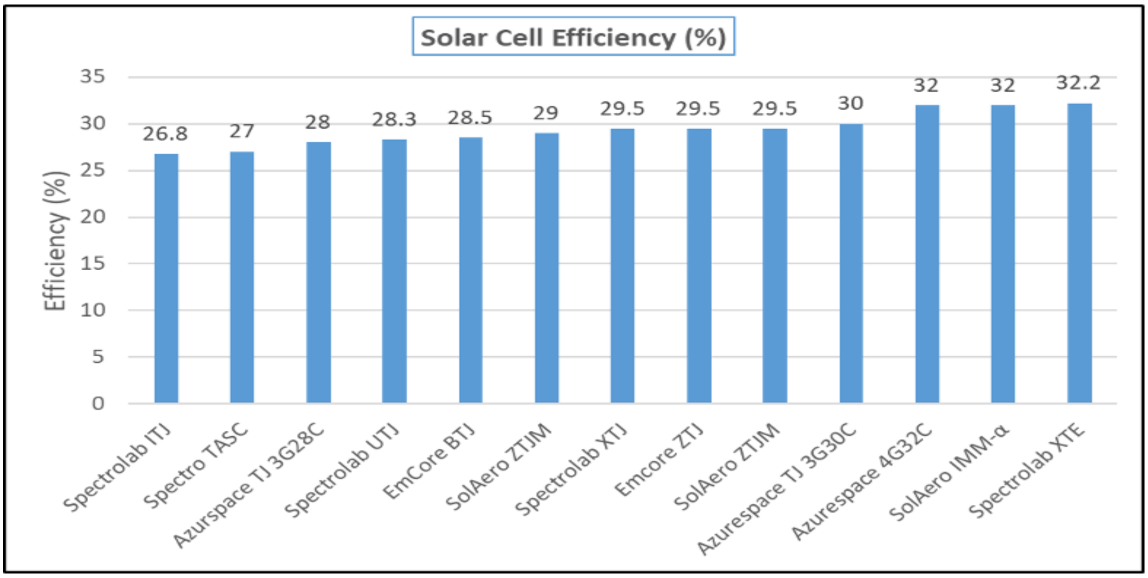

Figure.3 Solar Cell Efficiency in PV

The highest achieved efficiency of the PV system batteries developed in the industrial field belongs to the SunPower Maxeon 3 model with 22.3%. However, there are also solar energy cells, which have a very high production cost and are used in space vehicles. As seen in *Figure.3 Solar Cell Efficiency in PV*, the efficiency of the batteries developed by NASA is in the range of 26-32%. The last product developed is Spectrolab XTE and its energy efficiency is 32.2%. CSP systems, on the other hand, approached these rates with stirling engines. It is aimed to replace the industrially used PV systems when the idea of concentrating the sun rays in the CSP system reaches the optimum level.

The history of the PV system is older than the CSP systems. Today, PV systems are located on the roofs of many houses. There is a cost difference of 8-10 times as the initial investment cost. The fact that the cost of plant production is high in CSP systems ensures that R&D and development are slower than PV systems, that is, the biggest obstacle to the development of CSP systems is the establishment of only large investments.

According to the research conducted by the International Renewable Energy Agency (IRENA), PV systems produced 291 GW of energy in the process of generating 5GW of energy from the CSP system in 2016. Accordingly, today, PV systems still give more confidence to the investor, so they receive more investment. In addition, the area covered by CSP facilities requires 45-50% more area than PV systems, so the preference for big cities is in favor of PV systems.

There is a significant difference in the storage methods of the two systems. Since PV systems produce electricity directly, they need to store electricity. CSP systems store energy through TES and can then decide on the desired transformation. As we mentioned earlier, storing electricity is more expensive than storing heat, so CSP systems can be in the race for big investments.

When we look at all these, PV systems are still far ahead of CSP systems and CSP systems are one of the most expensive electricity generation methods available.

2.6 Global Status of CSP

The world is rapidly switching to renewable energy sources in the 21st century. They produce energy with PV systems, Wind turbines, geothermal systems or Hydroelectric power plants. As the newest, energy is produced with concentrated solar energy systems (CSP). Due to the high cost and newness of CSP systems today, the amount of renewable energy produced in the world is approximately 2%. Since TES technology can be used and energy can be used later, governments have increased their investment in CSP systems in the last 10 years. Although there are structures built in Africa and North America in general, Asian states have also made breakthroughs.

According to the latest data from the South African government, they doubled their installed power capacity and reached 400 MW with the facilities that were put into operation in 2017 and 2018.

Although the Chinese government could not reach its goal in its five-year project for the installation of CSP systems, which is important for 2011-2015, it added 350MW of power to its structure thanks to 6 systems that went into operation in 2019. Its capacity was 210 MW with 4 facilities it previously owned. China is the country with the highest number of CSP plant projects, so it will take the necessary position in the coming years.

There are many Asian and African states whose generation capacity does not exceed 50MW. Chile and Saudi Arabia, India and the United Arab Emirates also exceeded 100 MW levels.

The largest enterprise is the "Noor Solar Complex" in Morocco, which is still under construction. It achieves this title with its targeted 500 MW power. The Moroccan government plans to obtain 52% of its energy from renewable energy by 2030. When the facility is completed, it is aimed to provide electricity to more than one million people. The facility is being built by ACWA Power Ouarzazate on a build, operate, transfer model. The facility consists of 3 phases and the first phase started in 2016. The second and third phases started to be installed in 2018. The vast majority of CSP systems are Parabolic trough and Solar tower systems, accounting for 85-90% of all facilities. These technologies will also be preferred in the Noor Solar Complex.

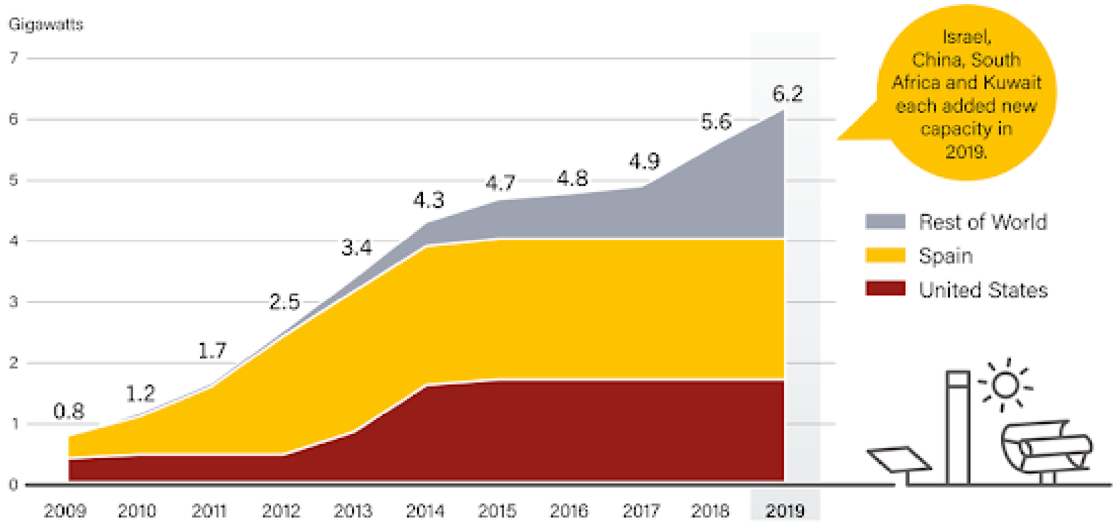

Figure.4 CSP Capacity in The World

Global Concentrated Solar Power capacity grew 11% in 2019 to 6.2 GW, with 600 MW of capacity coming online. Although this was well below the average annual increase (24%) of the past decade, Concentrating Solar Power continued to spread to new markets, including France, Israel and Kuwait.[1] As seen in the *Figure.4 CSP Capacity in The World*, the world leader in CSP capacity in the world is Spain. According to the data in 2019, it has a capacity of 2.3 GW. The second in production capacity is the USA with 1.7 GW.

Many states support the expansion of CSP systems. They provide tax incentives, fixed power purchase promises or capital loan support for private businesses. These supports accelerate the world's transition to renewable energy use.

2.7 National Status of CSP

As seen in the *Figure.5 Turkey Sunlight Projection*, the region that receives the most solar energy in Turkey is the Southeast Anatolia Region, followed by the Mediterranean Region.

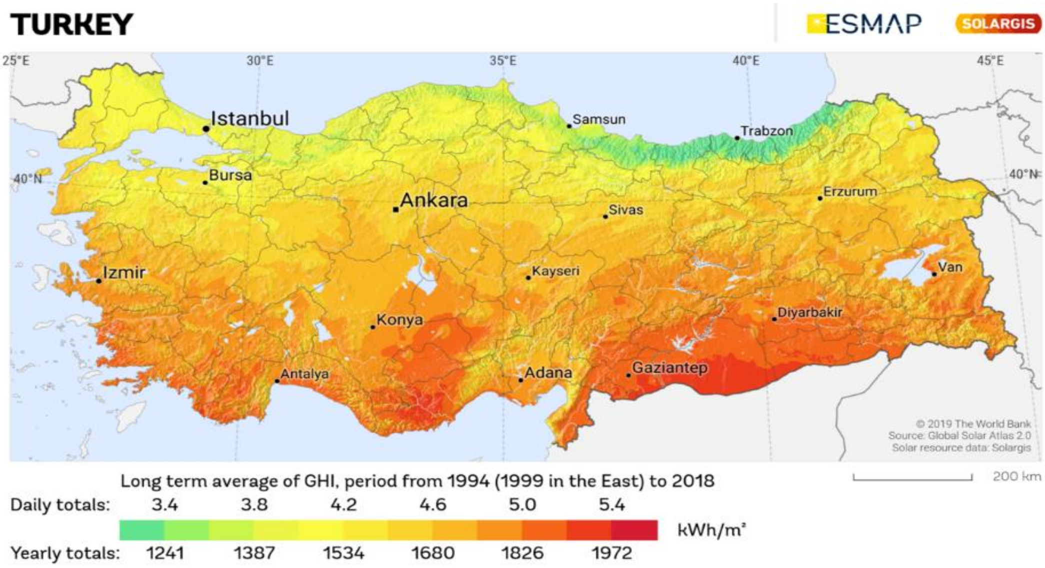

Figure.5 Turkey Sunlight Projection

According to the statistics of TEİAŞ, Turkey increased its energy capacity by 672 MW in the first quarter of 2021 and increased its total solar energy capacity to 6,700 GW, but the vast majority is achieved with PV systems. Most solar energy systems in Turkey are rooftop PV systems.

Figure.6 Mersin CSP Facility

The first CSP system in Turkey was established in Mersin. It is the only example of its kind in Turkey. It was constructed using the Solar tower model as shown in *Figure.6 Mersin CSP Facility*. The business was founded by Greenway and in 2013 the business became operational.

Greenway invested 50 million dollars in the project, which was supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK) and the Technology Development Foundation of Turkey (TTGV).[2] The capacity of the facility is 5 MW. Considering the capacities of the enterprises in the world, this facility is very small.

3.Journal Paper "Progress in Research and Development of Molten Chloride Salt Technology for Next Generation Concentrated Solar Power Plants"

States want to switch to renewable energy, but they cannot obtain energy at low cost and producing energy with fossil fuels is still in the first place. CSP systems that have been developing in recent years to obtain energy at low cost are examined in this article. The fact that CSP systems have thermal energy storage (TES) systems gives hope that low-cost systems can be formed. Many existing CSP facilities today use TES systems. The availability of TES systems to generate distributed electricity is one of the most important factors. It is aimed to improve the performance of the TES system to make CSP systems more cost-effective. The heat transfer fluid (HTF) maintained by the TES system is aimed to reach high performance values. Many R&D studies are carried out for New Generation Concentrated Solar Power Plants. There are three topics examined in TES/HTF technology. Energy transport with solid particles, energy transport with molten salts and energy transport with gases.

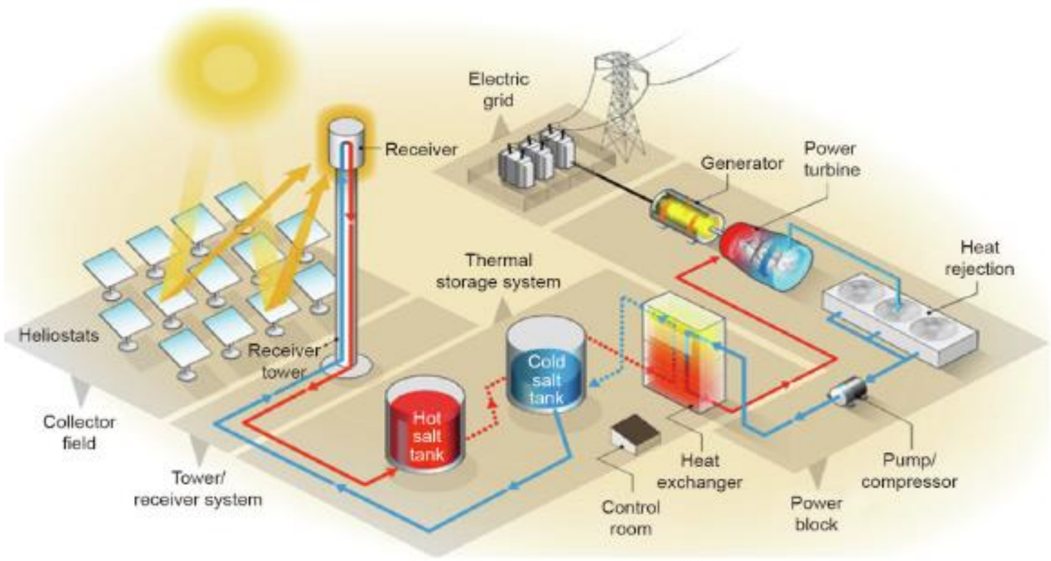

Figure.7 Classic CSP System

Today, it has a thermal-electrical energy efficiency of about 40% using the traditional CSP system, as shown in *Figure.7 Classic CSP System*. The system seen in *Figure.8 NREL CSP System* is a concept proposed by NREL and is a TES/HTF system with molten salt combined with sCO2. With the realization of this system, it is aimed to have more than 50% thermal-electrical energy efficiency and the R&D process continues.

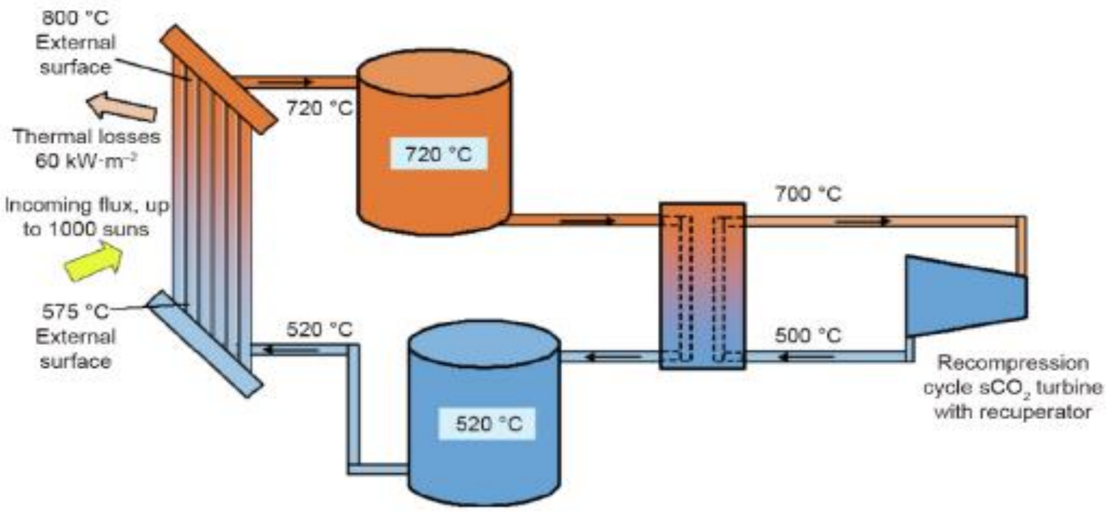

Figure.8 NREL CSP System

Many different concepts, as in *Figure.8 NREL CSP System*, are maintained in America, Australia, Europe and Asia. Preferred research systems are Parabolic trough and Solar tower systems.

The United States In 2011, DOE launched the ten-year SunShot Initiative to support the R&D of solar energy technologies (i.e., CSP and photovoltaic).[3] The DOE then released new targets to run through 2030 and gave $72 million in funding to the Gen3 CSP program in 2018.

Australia has a very suitable geography in terms of solar energy collection and attaches importance to CSP technologies. Australia is helping the US's Gen3 CSP program to support next-generation CSP systems.

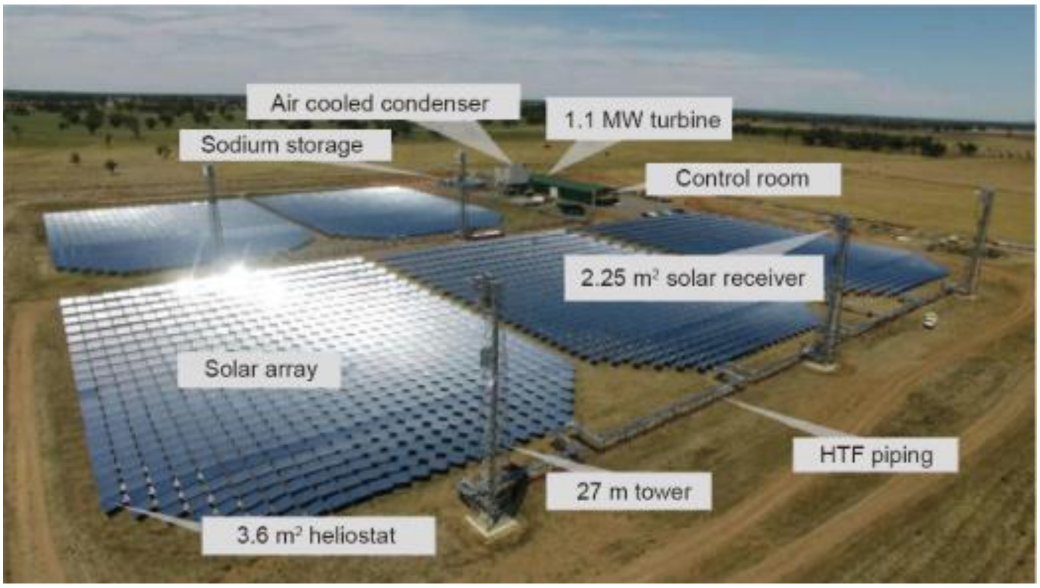

Figure.9 CSP Test Station in South Wales

The area shown in *Figure.9 CSP Test Station in South Wales* is the CSP test station in South Wales, whose construction was completed in 2019. Liquid sodium metal was used as HTF in the tests and successful results were obtained in the tests. However, the heat transfer fluid used causes corrosion in TES systems due to high temperatures. Necessary R&D work is carried out to reduce corrosion.

Among EU countries, Spain undertakes general projects as the pioneer of CSP systems. Support is given to Spain's R&D programs from countries such as Germany, Italy and France. There are also several experimental facilities in Europe. Molten carbonate salt tests are carried out for TES/HTF technology. In addition, some European states also support the Gen3 CSP program.

In Asian countries, China and India lead the CSP systems. Although China seems to lag behind other world states, there are many CSP systems (> 1.1 GW) under construction. Since there is no domestic production required for CSP systems in India, R&D studies are more concerned with production. Other countries such as Japan and Korea have focused on different energy sources apart from CSP systems.

HTF/TES technology	Advantages	Main challenges	Demonstration
Alternative molten salts	• Similar thermo-physical properties as commercial molten nitrate salts • High thermal stability, maximum operation temperature up to 800 °C • Chloride salts: abundant and inexpensive	• Corrosion of construction materials • Adaption of receiver, TES, valves and pumps, and steam generator components for higher operation temperatures including up-scaling • Operation with no freezing and overheating	• FASTR, the United States • Avanza-2, Spain
Solid particles	• Maximum operation temperature up to 1000 °C • Simple handling in air from low to high temperature • Inexpensive storage materials	• Low thermal conductivity • Particle transport (e.g., erosion) • Adaption of receiver, TES, particle transport, and steam generator as new components with the requirement for up-scaling	• G3P3, the United States • CentRec, Germany
Salt-based PCMs	• High energy density • Maximum operation temperature 600–1000 °C • Abundant and inexpensive storage materials	• Corrosion of construction materials • Cost-effective heat transfer enhancement concepts to overcome low thermal conductivity • Improvement of material cycling stability • System integration of PCMs	Not available
Gases as HTF with indirect TES	• Combinability with a variety of TES technologies • Low-cost and mature gas HTF technologies	• Indirect TES system (additional cost) • System complexity • High power consumption for fluid circulation	• Helium loop for very high temperature reactor (VHTR), the United States
Liquid metals with indirect TES	• High thermal conductivity • High thermal stability • Experience from the nuclear power field	• Hazards (e.g., sodium fire) • Corrosion control • High costs of materials, operation, and maintenance • Expensive as TES material	• Vast Solar, Australia • SOMMER CSP pilot plant, Germany

Table.1 TES/HTF Technologies Assumptions

Significant advances have been made in TES/HTF technologies in the last decade. Certain assumptions have been reached with many experimental installations. As seen in the *Table.1 TES/HTF Technologies Assumptions*, the data were obtained. According to R&D studies, the formula $MgCl2/KCl/NaCl$ is shown as the best chloride salt mixture. The necessary preventive technologies for corrosion have been found, but they are still not cheap. The needs of the molten chloride technology have been found, but the optimum values have not yet been achieved. Therefore, necessary R&D studies should be carried out and more experimental facilities should be opened in order to increase heat transfer, prevent corrosion and ensure high thermal stability.

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