



# Modelling Study of Utilizing Dry and Wet Cooling in Solar Tower Power Plant in Jordan

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*Received: 25.01.2024 Accepted:28.02.2024*

**Abstract-** This study investigates the use of dry and wet cooling systems in a solar tower power plant in Jordan, with a focus on optimizing energy efficiency. The study simulates the Gamesolar power plant in the southern region of Jordan and compares the performance of three different cooling systems. By analyzing the efficiency of the solar tower power plant and energy efficiency in Jordan, the study aims to identify the most suitable cooling system for the country's hot climate. The findings demonstrate that the implementation of the Gamesolar plant in Jordan leads to an 8.1% increase in energy production compared to the average in Spain. This highlights the success of the program in the local context and emphasizes the potential for sustainable energy generation. The study reveals that utilizing a collective energy system (CSP) with efficient energy storage can significantly contribute to meeting Jordan's energy demand and reducing reliance on fossil fuels. The methods employed in this study involve modelling and simulation techniques to evaluate the performance of different cooling systems. The results indicate that the hybrid cooling system proves to be the most effective in Jordan's climate conditions, offering optimal energy efficiency for the solar tower power plant. Overall, this study contributes to the understanding of the optimal cooling system design for solar tower power plants in Jordan. It supports the feasibility and effectiveness of implementing CSP technology in the country, paving the way for sustainable energy generation and reducing reliance on fossil fuels.

**Keywords:** Solar tower power plant, concentrated solar power (CSP), dry cooling, wet cooling, hybrid cooling, thermal energy storage, power plant efficiency.

## 1. Introduction

Energy is essential for a nation's economic development but utilizing fossil fuels to produce it contributes to climate change and global warming due to dwindling oil reserves and damaging emissions. Instead, it should focus on long-term renewable energy sources. The variety of technology and resources distinguishes renewable energy. Despite the size of the potential, renewable energy sources now make a small contribution the world's energy resources [1,2]. Jordan does not produce oil as other Middle Eastern nations do. The country's domestically recoverable energy resources are constrained and unable to meet the demands of an expanding population and economy. As a result, the nation currently and for the foreseeable future will entirely rely on burning imported fossil fuels to meet its domestic energy needs. Power stations that burn fossil fuels produce almost all of the electricity used in Jordan. Heavy fuel oil and diesel fuels are

the most widely used fuels. This choice, meanwhile, is not particularly appealing [3-6].

Beyoud et al. [7] study a combination of a double supercritical CO<sub>2</sub> Brayton cycle with a concentrated solar tower plant, hydrogen combustion chamber, and solid oxide electrolyzer cell (SOEC) device to ensure a continuous energy supply. Excess solar energy is used to produce and store hydrogen for nighttime or low-solar periods, enabling uninterrupted power generation. The study introduces a new parameter, large solar multiple (L.S.M), which determines plant size based on different Moroccan regions and rainfall patterns. Results show that clear and dry conditions yield higher hydrogen production with a smaller heliostat area, while turbid conditions lead to lower hydrogen production and a larger heliostat area.

Atak et al. [8] identify suitable sites for solar power plant installation in Sivrihisar, Turkey, using weighted overlay analysis in GIS. Factors such as solar potential, topography,

and infrastructure were considered. Results show that a small percentage of the area has high suitability, while a larger portion has secondary suitability. By installing polycrystalline solar power plants in a specific area, the district's annual electricity demand can be fully met. The methodology and findings offer guidance for future solar installations in similar regions.

Mohamed Adel et al. [9] study introduces a methodology to evaluate the optical performance of central tower concentrated solar power plants by analyzing the reflected solar flux from heliostats. By utilizing high dynamic range images, a solar flux map is constructed at the target receiver. This approach provides a simple, automatic, and effective tool for accurate analysis, surpassing the limitations of previous methods. Experimental tests conducted indoors and outdoors confirm the methodology's ability to achieve precise results. Beyoud et al. [10] analyze Aerosol Optical Depth (AOD) data concerning turbidity Linke factor and heliostat atmospheric attenuation for solar tower technology. The study utilizes a Weibull distribution of AOD and statistical tests to accurately describe solar beam attenuation under different rainfall conditions. Using a decade-long dataset from multiple climate zones in Morocco, distinct climate zones and fluctuations in turbidity factors are identified, offering insights for optimal management and sizing of solar energy systems. The study has implications for similar environmental conditions and discusses potential applications.

### 1.1. Renewable Energy

Renewable energy sources (RES) account for 14% of total global energy demand [1]. Biomass, hydropower, geothermal, solar, wind, and marine energies are all included in RES. Renewable energy sources are the main, pure, and limitless sources of energy [11-14]. The 20% of the world's electricity is generated by large-scale hydropower. A promising energy source is wind power in windy areas like the seashore [15,16]. Table 1 lists the major renewable energy sources and the various ways they can be used [17]. Alternative energy sources are another name for RESs. In 2100, a very significant increase in the proportion of RESs is anticipated [15]. Table 2 provides the global renewable energy situation by 2040. Measurement and comparison of the environmental effects of human activity on various products are necessary for sustainable development [18,19].

**Table 1.** Main renewable energy sources and their usage form [17]

Energy source	Energy conversion and usage options
Hydropower	Power generation
Modem biomass	Heat and power generation. pyrolysis. gasification, digestion
Geothermal	Urban heating, power generation, hydrothermal, hot, dry rock
Solar	The solar home system, solar dryers, solar cookers
Direct solar	Photovoltaic, thermal power generation, water heaters
Wind	Power generation, wind generators, windmills, water pumps
Wave	Numerous designs
Tidal	Barrage, tidal stream

Recently, renewables have become increasingly significant. Three categories of energy sources have been established: nuclear, renewable, and fossil [20]. Renewable energy sources, also known as alternative sources of energy, are those resources that can be utilized repeatedly to produce energy, such as solar energy, wind energy, biomass energy, and geothermal energy [21]. Renewable energy sources that satisfy domestic energy needs have the ability to produce energy with zero or almost zero emissions of both air pollutants and greenhouse gases.

**Table 2.** Global renewable energy scenario by 2040 [18].

	2001	2010	2020	2030	2040
Total consumption (million tons oil equivalent)	10,038	10,549	11,425	12,352	13,310
Biomass	1080	1313	1791	2483	3271
Large hydro	22.7	266	309	341	358
Geothermal	43.2	86	186	333	493
Small hydro	9.5	19	49	106	189
Wind	4.7	44	266	542	688
Solar thermal	4.1	15	66	244	480
Photovoltaic	0.1	2	24	221	784
Solar thermal electricity	0.1	0.4	3	16	68
Marine (tidal/wave/ocean)	0.05	0.1	0.4	3	20
Total RES	1,365.5	1,745.5	2,964.4	4289	6351
Renewable energy source contribution (%)	13.6	16.6	23.6	34.7	47.7
Biomass	2001	2010	2020	2030	2040

### 1.2. Motivation

The act of storing energy is vital to adjust for differences in the sun, and this is what distinguishes CSP from other systems, as it enhances energy storage, allowing energy production towards the end of the day when there is no solar field. There is no doubt that the high solar radiation present in Jordan, the city of Ma'an, is an important incentive for the installation and establishment of this system, due to the increase in efficiency. There are many countries in the world that use the CSP system, and the stations in the world will be discussed, and then the mention will be devoted to the stations in the Middle East. The countries that use CSP systems, including the United States, Australia, Canada, Chile, China, Denmark, France, Germany, India, Italia, Mexico, the Kingdom of Saudi Arabia, South Africa, Spain, Thailand, Egypt, Kuwait, Turkey, Morocco, Sudan, The United Arab Emirates and Algeria.

**Table 3.** Concentrated solar power in Morocco and this is the largest station [22]

Power Station	Location	Owners (%)	Technology	Nominal Capacity	Status	Start Year
Airlight Energy Ait-Baha Pilot Plant	Ait Baha Sous-Massa Morocco	Cymer, Interlacement Group	Parabolic Trough	3 MW	Operational	2014
ISCC Ain Beni Mathar	Ain Beni Mathar Oriental Morocco	Abengoa, ONE	Hybrid, Parabolic Trough	20 MW	Operational	2011
NOOR I	Ouarzazate Draa-Tafilalet Morocco	ACWA	Parabolic Trough	160 MW	Operational	2015
NOOR II	Ouarzazate Draa-Tafilalet Morocco	NOMAC	Parabolic Trough	200 MW	Operational	2018
NOOR III	Ouarzazate Draa-Tafilalet	NOMAC	Power Tower	150 MW	Operational	2018

### 1.3. Study Plan

The study presents a study of the work of the CSP tower station in Jordan and explains it in four sections. The first section of the study provides a general description of renewable energy with an emphasis on solar energy. Solar energy in general and solar energy in Jordan discusses how Jordan has benefited from renewable energy in general.

The second section of the study reviews the sources of solar energy with an indication of each type and the statement of equations and calculations for solar radiation. It also discusses the types of combined solar stations. It discusses the cycle used in the concentrated solar power tower station and what are the parts of this cycle and the methods used to increase efficiency. It also discusses the importance of storage in these systems.

## 2. Theoretical Work

### 2.1. Global Energy Resource

The energy produced when two atoms of hydrogen fuse with each other ends with a helium atom. The energy produced by this reaction is  $3.85 \times 10^{26}$  W and around the temperature of 6000k. Due to electromagnetic waves, radiation travels from space to the Earth at the speed of light [23].

To calculate the intensity of the solar radiation that hits the earth, this formula can be used [24]:

$$I(r) = I_{sun}/4\pi r \quad (1)$$

where:  $r$  is the distance between the sun and the earth,  $I_{sun}$ : is the power at the sun's surface, and  $I(r)$ : is the intensity that reaches the earth.

#### 2.1.1 Energy balance on a receiver

The net of the total useful energy can be determined by this equation:

$$Q_{useful} = Q_{sun} - Q_{loss} \quad (2)$$

The incoming radiation on the receiver is divided into three parts:

1. Absorbed.
2. Transmitted.
3. Reflected.

Four numbers define the radiation received by the body which are Absorbance, Transmittance, Reflectance, and Emissivity [25]:

1. Absorbance ( $\alpha$ ): the ratio between the absorbed light by the body and the amount of light incoming to the body.
2. Transmittance ( $\tau$ ): the light that is transmitted by the body to the light falls off on the body.
3. Reflectance ( $\rho$ ): the amount of light that is reflected by the body to the light incoming to the body.
4. Emissivity ( $\varepsilon$ ) is the light emitted by the body to the light that would be emitted if the body was black at the same temperature.

$$\rho + \tau + \alpha = 1 \quad (3)$$

The power received from the reflected radiation:

$$I_{reflected} = I_{incident} \rho_m A_a = I_a \rho_m A_a \quad (4)$$

where:  $\rho_m$  is the reflectance of the mirrors,  $A_a$ : is the aperture area ( $m^2$ ), and  $I_a$ : is the insulation ( $W/m^2$ ).

From the transmitted radiation [25]:

$$I_{transmitted} = I_{incident} \tau = I_a A_a \rho_m \tau \quad (5)$$

where  $\tau$  is the transmittance of the glass.

From the absorbed radiation:

$$I_{absorbed} = I_{incident} \alpha_r = I_a \rho_m A_a \tau \alpha_r \quad (6)$$

where  $\alpha_r$ : the absorbance of the receiver.

So, the energy from the sun is [25]:

$$Q_{received} = I_a \rho_m A_a \tau \alpha_r \quad (7)$$

#### 2.1.2 Optical losses

The instantaneous efficiency of the heliostat can be obtained by multiplying the loss factors together [25];

$$\eta = \eta_{cos} \times \eta_{atm} \times \eta_{ref} \times \eta_{sb} \times \eta_{spillage} \quad (8)$$

where:  $\eta_{cos}$ : the cosine effect efficiency,  $\eta_{atm}$ : atmospheric attenuation,  $\eta_{ref}$ : mirror reflectivity,  $\eta_{sb}$ : shadowing and blocking losses, and  $\eta_{spillage}$ : spillage loss. Some losses affect radiation that falls off on the collector [26]:

1. Shadowing, due to the closing of the mirrors between each other.
2. Blocking, is also because of the closing of the mirrors so that the incident rays cannot hit the receiver because of the front mirror.
3. Spillage, some of the radiations miss their path.
4. Cosine loss.
5. Mirror reflectivity, the standard value is 0.88, which means 88% of the energy is reflected.
6. Atmospheric attenuation, depends on the distance between the mirror and the receiver:

$$0.99321 - 0.0001176 \text{ dis} + 1.97 \cdot 10^{-8} \text{ dis}^2, \text{ dis} \leq 1000\text{m} \quad (9)$$

$$\exp(-0.0001106 \text{ dis}), \text{ dis} > 1000\text{m} \quad (10)$$

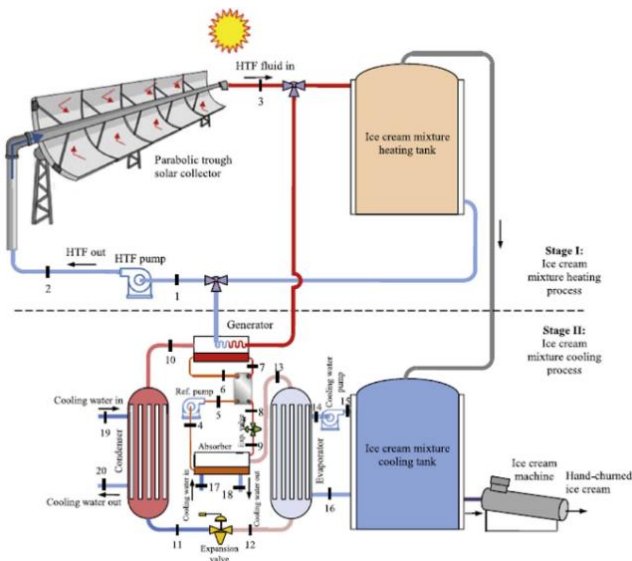
### 2.2. Concentration Technology

It is time to move towards renewable energy sources after the economic crises that countries are suffering from, and the end of non-renewable energy sources is feared. One form of this renewable energy is solar energy, as it is easy to harvest and does not affect the environment in any way. This energy is obtained through solar photovoltaic and solar thermal

energy. Among the types of solar thermal energy are Parabolic troughs, Linear Fresnel collectors, Solar towers, and Dish Stirling which will be discussed as the following [27].

### 2.3. Parabolic Trough (PTC)

The PTC system uses mirrored surfaces of a linear parabolic concentrator/reflector to focus direct solar radiation to a tubular absorber tube located along the focal line of the parabola. Then the concentrated solar radiation is absorbed and converted into thermal energy by the heat transfer fluid (HTF) flowing through the tube. The thermal efficiency of this type reaches up to 80% and, overall, up to 15%. Figure 1. We'll see what this type looks like and its components [27-29]. The receiver is made of steel with a black coating and surrounded with protective glass, Synthetic oil or molten salt can be used as a heat transfer fluid, and the parabolic surface is coated with glass mirrors or polished aluminum.



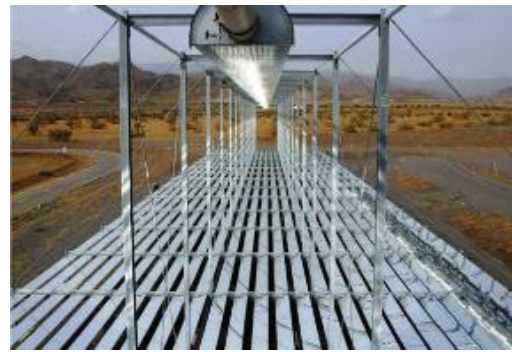
**Fig. 1.** Parabolic trough component.

The Applications of PTC are power generation, heat pumps, solar heat to industrial processes, and water supply in a building.

The tracking system of PTC: this system has a tracking system in most cases whose axis is from north to south to follow the sun from east to west. It is installed by supports made of steel, aluminum, or other strong materials [30].

### 2.4. Linear Fresnel Collector (LFC)

A linear Fresnel collector is made of several flat or slightly curved mirrors that can be oriented independently to track the sun; the temperature of this system ranges between 150-550 C by station in China, and efficiency is less than the parabolic trough. Figure 2 represents the system shape and components. Molten salt, synthetic oil, or pressurized water can be used as heat transfer fluid. The absorbers can be single-tubule or multi-tube, and they can be evacuated to minimize heat loss [31, 32]. Application of LFC are industrial heat processing, Electricity generation, and space heating and cooling at a small scale.



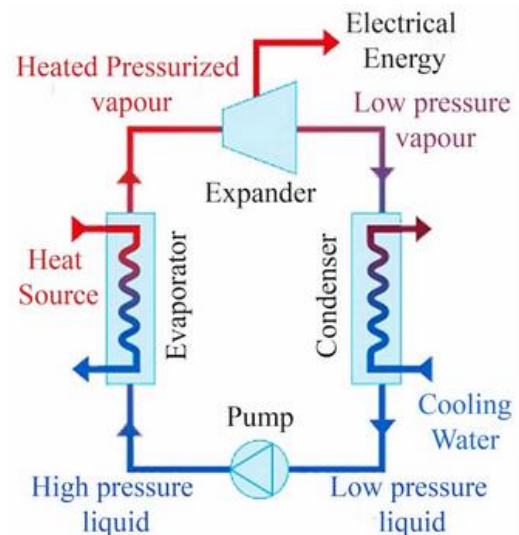
**Fig. 2.** Linear fresnel collector.

### 2.5. Dish Stirling

It's designed to reflect the sun's rays towards a small receiver, as the concentration of radiation in one small area increases the temperature and efficiency. Therefore, this system is considered to have the highest efficiency among the systems.

### 2.6. Rankine Cycle

Like the Rankine steam cycle, the organic Rankine cycle substitutes water with an organic fluid such as refrigerants or hydrocarbons as the working fluid [33].



**Fig. 3.** The organic rankine cycle [34].

As shown in Figure 3, an Organic Rankine Cycle power plant produces electricity on a small scale, typically between 10 and 250 kW. The principal variations between big thermal power facilities that use ORC and the traditional steam-based Rankine cycle operative fluid.

### 2.7. Solutions to Increase the Efficiency of a Rankine Cycle

It is now known that the cycle utilized in steam power plants is the Rankine cycle. Increasing the Rankine cycle results in increased efficiency of the power station, and several methods will be presented through which the efficiency of the Rankine cycle can be enhanced.

The efficiency of the Rankine cycle is calculated as follows:

$$\eta = \frac{W_{net}}{Q_{in}} \quad (11)$$

This means that increasing the  $W_{net}$  means increasing the efficiency so that the network represents the area under the most extensive stress line in the T-s diagram. After knowing the efficiency relationship, let's learn about ways to increase the efficiency of the Rankine cycle, which can be summarized as follows [35, 36]:

- Raise the boiler pressure.
- Reducing the condenser pressure.
- Superheating to a higher temperature.

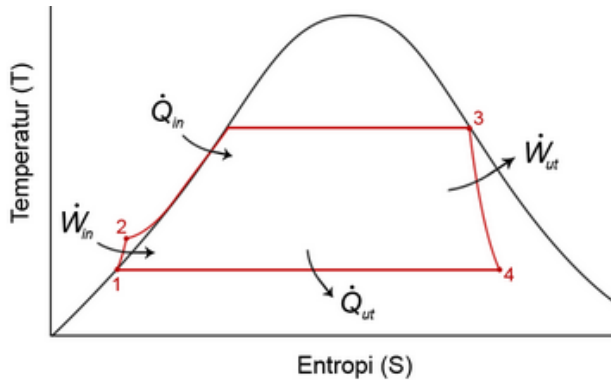


Fig. 4. Actual rankine cycle.

Note that from Figure 4, the area between 1234 represents the network, while the area between the entropy line and the 1.4 pressure line represents the energy added or paid to the system.

### 2.8. Solutions to Increase the Efficiency of a Solar Power Plant

In power production plants, in general, many options can be made to increase the efficiency of this station or its operational capacity, and this is due to the station's work. It has been mentioned that using a preheater after the turbine increases efficiency by increasing the boiler's thermal efficiency. Even if what is required is to increase the station's operating capacity, and that is by providing the fuel necessary for it to operate during the hours when the sun sets. CSP systems capture solar heat and can either be transformed directly into electricity or stored for later conversion when there is a greater electricity demand. Among renewable energy systems, the flexibility offered by the capacity to store thermal energy as heat is exceptional [35].

Also, the heat transfer fluid used has a vital role in efficiency. Using a fluid with a high ability to store heat increases thermal efficiency. To date, water has been the working fluid in steam turbine power cycles, whereas nitrate ( $\text{NO}_3^-$ ) and nitrate/nitrite ( $\text{NO}_3^-/\text{NO}_2^-$ ) molten salts have been employed primarily in GEN2 CSP tower plants as the HTF and for thermal storage.

However, nitrates only function up to a temperature of  $550^\circ\text{C}$  before they break down, while the maximum temperature for CSP steam cycles is  $600^\circ\text{C}$ . Finding the best materials for HTF and thermal storage is difficult [37].

## 2.9. Energy Storage in CSP

### 2.9.1 The significance of energy storage

The process of storing energy is essential to compensate for the differences in the sun, and this is what distinguishes CSP from the rest of the other systems, and that is through molten salt that increases energy storage, which allows energy production at the end of the day when there is no solar field [38].

### 2.9.2 Steam accumulator

Steam Accumulator is a shell-type pressure vessel that is used to store steam generated by a boiler and use it for varying load demands. The accumulator itself consists of a cylindrical vessel partially filled with water. The water level would typically be between 50 and 100%. Steam is charged into the vessel during the charging stage using steam injectors below the water's surface. The water in the vessel takes up the latent heat from the steam, thus condensing it back into the water. There is a corresponding rise in temperature and pressure within the accumulator and an increase in water volume [39].

When the accumulator is required to discharge steam at a lower process pressure, steam is flashed off from the high-pressure, high-temperature water, thus reducing the total heat of the water content. The key here is the difference in pressure between the steam-generating plant (and accumulator) and the final process: the more significant this differential, the smaller the size of the accumulator required. In most manufacturing processes, steam is typically generated at a higher pressure than the process requires anyway. With the above in mind, and for the accumulator to function, a pressure-maintaining valve would be mounted between the steam boiler plant and the vessel, and a pressure-reducing valve on the exit from the vessel to the plant or process [40].

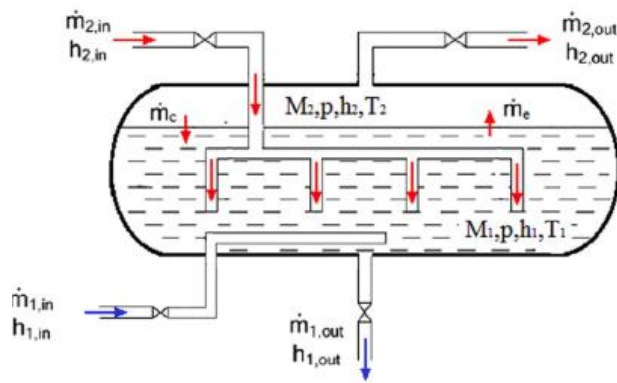


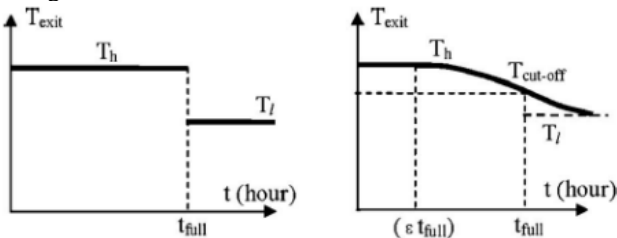
Fig. 5. Steam accumulator diagram.

### 2.9.3 Thermocline storage system

Creating the perfect thermocline tank design involves a careful calculation of its dimensions (length and diameter) to fulfill the required energy storage capacity for the solar plant. Various factors, such as electrical power, thermal efficiency, heat discharge period, and the highest and lowest temperatures of the heat transfer fluid (HTF), play a crucial role in determining the size of the storage tank. Additionally, the properties of the HTF, filler material, and packing porosity also heavily influence the tank's dimensions. At first, the tank was deemed to be a perfect thermocline tank, and the initial

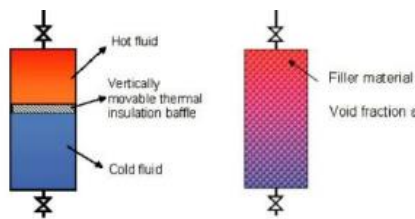
volume was determined using this assumption. However, upon further examination, it became evident that the filler material within the tank disrupted the temperature distribution and resulted in stratification. As a result, the key distinguishing factor between an ideal thermocline tank and an actual one is the inclusion of the filler material and its influence on temperature distribution [41], as can be seen in Figure 6.

When it comes to preventing temperature degradation shown in Figure 7, there are two possible solutions. One option is to utilize an ideal thermocline tank, while the other is to design a system with a larger thermal energy storage capacity than what is actually needed. By implementing either of these strategies, the potential for temperature decline during discharge can be greatly reduced. However, it's important to note that in a practical thermal energy storage system, introducing cold fluid into the tank results in the filler material absorbing heat. As a result, both the heat transfer fluid (HTF) and the filler material experience a decrease in temperature over time. This can ultimately lead to temperature degradation, even if the storage material was initially fully charged.



**Fig. 6.** Distribution temperature during the discharge process when the hot fluid goes out from the top of the tank [42].

Hence, in developing a thermal storage system, the main goal is to minimize the degree of temperature decline. This will ensure that during the necessary operating period, such as when the system is being discharged, the heat transfer fluid (HTF) maintains a minimal level of temperature decrease [42].



**Fig. 7.** Illustration of a single tank thermal storage system.

### 2.10. Cooling System in CSP Technology

Concentrating solar power is one of thermoelectric power generation that has the highest uses of water than other industries in the world. It uses around 201 billion gallons per day to cool the water and runs the turbines to produce electricity. The cooling systems in all power plants could play a huge role in increasing or decreasing the annual output as well as efficiency and this affects on the revenues of these plants [43]. Research and conducted studies have demonstrated that the wet cooling system exhibits higher efficiency compared to the dry cooling system. However,

these two systems can be combined to form a hybrid cooling system that utilizes both air and water to cool the HTF and power block components, it's known that there are three types of cooling technologies to cool down the components and reject heat out to the atmosphere.

### 3. System and Modelling Description

This section presents the working principle of one of the solar power tower types CSPs called Gemasolar power station. This station used molten salt as its heat transfer fluid and energy storage medium. Then, numerically a similar CSP system was built to the characteristics of the Gemasolar power station based on the weather conditions of southern Jordan. Gemasolar is the world's first commercial-scale solar power plant with a central tower receiver located in Fu.

The Gemasolar power plant is located in Fuentes de Andalucía, Spain, approximately 40 miles east of Sevilla. It is the world's first commercial-scale plant to utilize a central tower receiver and molten salt heat storage technology. With a capacity of 19.9 MWe (gross) and spanning an area of nearly 2000 dunams, as depicted in Figure 8, the plant is owned and operated by Torresol Energy. Torresol Energy is a joint venture between SENER and Masdar. Although specific performance data from the plant is not publicly available, even with limited weather information, the SAM model predicts an annual energy output that is proportional to the values reported in the media [44].

#### 3.1. System Description

The impressive Gemasolar power plant boasts a network of 2,650 heliostats that encircle a towering structure. Together, these heliostats cover an expansive reflective area of 304,750 m<sup>2</sup>, spanning across a circular expanse of 185 hectares. Innovatively created by SENER, these heliostats incorporate cutting-edge technology to precisely follow the sun's trajectory, ensuring an optimal collection of thermal energy. The placement of these state-of-the-art heliostats was determined using the highly advanced ASANSOL software. [44, 45].

The main purpose of the heliostats is to direct and intensify sunlight onto a powerful solar receiver, capable of storing up to 120 MWh. This receiver is perched atop a towering 140 m structure. Cold molten salt is continuously circulated from a storage tank, passed through the receiver where it is heated, and then transferred to a hot tank for storage. Subsequently, the heated salt is then pumped into a steam generation system. This system utilizes superheated steam to drive a Siemens SST-600 two-cylinder reheat steam turbine, boasting a gross capacity of 19.9 MWe. This turbine is linked to a generator that produces electricity [45].

SAM simulation software was utilized to carry out this simulation, which comes equipped with a range of analytical capabilities such as scenario comparison, input parameter optimization, and advanced parametric and statistical analyses. Its reliability is supported by the multitude of projects successfully implemented on this software [46].



**Fig. 8.** Aerial view of Gemasolar.

**3.2. Location and Resources**

The site of the land was chosen in the city of Ma'an because the price of the land on which the project will be applied is very low compared to other regions. It has excellent solar power potential due to extended daylight hours and a few cloudy days, the high DNI average is 2922 kWh/m<sup>2</sup>/year. It contains vast lands that are not suitable for agriculture. It has an average annual wind speed of 15 m/s. The place was also chosen for its proximity to the Wadi Al-Jordan Dam which has a capacity of (2000000) m<sup>3</sup>, for the grid is close. This reduces the cost of the station due to the transmission line cost to the grid.

**3.3. Heliostat Field**

The Heliostat Field page displays the variables that specify the position of the heliostats in the solar field, along with the heliostat geometry and optical properties. Unlike parabolic trough and dish system designs, which can be based on modular designs of individual components, power tower system designs typically require optimizing tower height, receiver geometry, and distribution of heliostats around the receiver as a complete system.

The Heliostats used in the Gemasolar power plant are square-shaped with a height and width of 10.9 meters each of 2,650 heliostats. The plant consists of a total Collectively, these heliostats contribute to a total reflective area of 304,750 square meters and the ratio of reflective area to profile is 0.97.

**3.4. The Cost**

The system cost is categorized into four primary sections, which include Direct Capital Costs, Indirect Capital Costs, Total Installed Costs, and Operation and Maintenance Costs. Each section focuses on the cost breakdown of specific components within the system. For the Gemasolar power plant, the construction cost of the plant amounts to \$209,003,198.

**4. Results and Discussions**

**4.1. SAM Verification**

The SAM simulator was used first to verify the simulator results by using the real characteristics of Gemasolar station data. Table 4 presents a comparison between the actual values of the Gemasolar station and the values obtained from the SAM software simulation [44]. The discussed metrics include annual energy production, capacity factor (CF), power purchase agreement (PPA) price, total land area, and total installed cost.

**Table 4.** SAM software reliability (comparison of station reality with simulation)

Metric	Gemasolar Sam value	Reported value	Difference (%)
Annual Energy (GWh)	107.35	110	2.4
CF (%)	70.4	74	3.6
PPA price (USD/kWh)	0.17	----	----
Total Land Area (acres)	438.18	457.00	4.1
Total Installed Cost (USD)	209,003,198	----	-----

In terms of annual energy production, the simulation result from SAM software shows a slight difference of 2.4% compared to the reported value of the Gemasolar station. This indicates that the simulation was relatively accurate in estimating the energy output of the station. The capacity factor, which represents the ratio of actual energy production to the maximum possible energy production, is reported to be 70.4% for the Gemasolar station, while the simulation result from SAM software shows a slightly higher value of 74%. This suggests that the simulation predicted a slightly more efficient utilization of the solar resources compared to the actual station. The power purchase agreement (PPA) price is not reported for the Gemasolar station, but it is worth noting that the SAM software does not provide a value for this metric. Therefore, no comparison can be made between the simulation and reported values in this regard. Regarding the total land area, the simulation result from SAM software indicates a 4.1% difference compared to the reported value of the Gemasolar station. This could be attributed to variations in the simulation inputs or assumptions regarding the land area required for the station. The total installed cost of the Gemasolar station is reported as 209,003,198 USD, while no value is provided for the simulation result in the table. Therefore, no comparison can be made regarding the total installed cost.

**4.2. Wet Cooling Techniques**

This technique is employed due to its advantages, as mentioned in section 2.5. By using this type of cooling technique, the SAM has been run according to the two prices for the selling of kWh the first price is 0.085 JOD and the second price is 0.045 JOD.

**Table 5.** Wet cooling in Ma'an at two prices

Metric	Price (0.085JOD/0.119\$)	Price (0.045JOD/0.063\$)
Annual Energy	116,079,488 kWh	116,079,488 kWh
PPA price	12.00 ¢/kWh	6.30 ¢/kWh
LCOE Real	10.43 ¢/kWh	5.48 ¢/kWh
Internal rate of return (%)	10.63 %	0.00 %
Minimum DSCR	1.03	0.42
Calculated ppa escalation (%)	1.00 %	1.00 %

Calculated debt fraction (%)	50.00 %	50.00 %
Capacity factor	76.1 %	76.1 %
Gross to Net Conv. Factor	0.89	0.89
Annual Water Usage	379,438 m <sup>3</sup>	379,438 m <sup>3</sup>
Total Land Area	438.18 acres	438.18 acres

In Table 5 for the price (0.085 JOD/0.0119 USD), the annual electricity production of the station is presented for the scenario of using wet cooling, which requires an annual water consumption of 379,438 cubic meters. The station's annual electricity production using wet cooling amounts to 116,079,488 kWh. Assuming a selling price of \$0.119 per kWh, it was observed that the project would generate an annual financial return of \$13,813,460. The table also provides the actual levelized cost of electricity (LCOE) value for the station, which represents the average cost of producing one kilowatt-hour of electricity over the project's lifetime, considering all expenses. The LCOE value is measured in cents per kilowatt-hour (¢/kWh), and in this case, the cost of producing one kilowatt-hour at the station is 10.43 ¢/kWh.

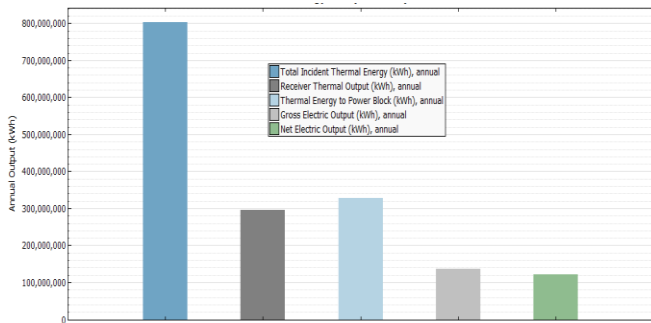


Fig. 9. Annual energy flow.

In the graphical analysis of Figure 9, it was observed that the system's energy production significantly differs when wet cooling is employed. The analysis reveals that the station generates approximately 810 MWh of thermal energy annually, which is then converted into electrical energy, resulting in an annual production of approximately 116 MWh.

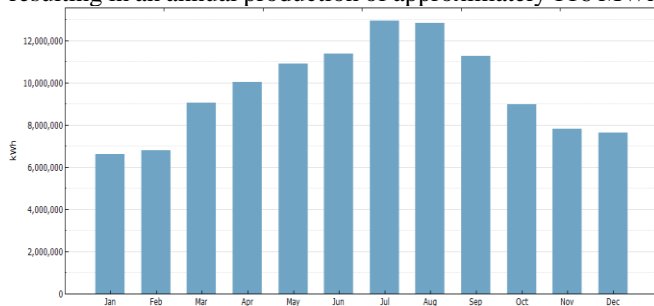


Fig. 10. Monthly power production of CSP plant (wet cooling).

### 4.3. Dry Cooling Techniques

This technique is employed due to its advantages, as mentioned in section 2.5. By using this type of cooling technique, the SAM has been run according to the two prices for the selling of kWh the first price is 0.085 JOD and the second price is 0.045 JOD.

Table 6. Dry cooling in Ma'an, Jordan

Metric	Price (0.085JOD/0.119 \$)	Price (0.045JOD/0.063 \$)
Annual Energy	109,998,224 kWh	109,998,224 kWh
PPA price	12.00 ¢/kWh	6.30 ¢/kWh
LCOE Real	10.43 ¢/kWh	5.48 ¢/kWh
Internal rate of return (%)	8.13 %	0.00 %
Minimum DSCR	0.96	0.38
Calculated PPA escalation (%)	1.00 %	1.00 %
Calculated debt fraction (%)	50.00 %	50.00 %
Capacity factor	72.1 %	72.1 %
Gross to Net Conv. Factor	0.88	0.88
Annual Water Usage	22,672 m <sup>3</sup>	22,672 m <sup>3</sup>
Total Land Area	438.18 acres	438.18 acres

Table 6 illustrates the annual electricity production of the station for the price (0.085 JOD/0.119 \$) under the condition of utilizing dry cooling, which consumes 22,672 cubic meters of water per year. The station's annual production using dry cooling amounts to 109,998,224 kWh. It is essential to mention that the output is lower than wet cooling, as wet cooling is more efficient in energy output. If this annual production is sold for \$0.119 per kilowatt-hour, the project's yearly financial return will reach \$13,089,788. The table also presents the actual levelized cost of electricity (LCOE) for the station, which represents the average cost of generating one kilowatt-hour of electricity over the project's lifetime, accounting for all expenses. The LCOE value is expressed in cents per kilowatt-hour (¢/kWh), and in this case, the cost of producing one kilowatt-hour at the station is 10.43 ¢/kWh. It is worth noting that the production cost remains consistent between the dry and wet cooling methods; the difference lies in the annual electricity productivity of the station.

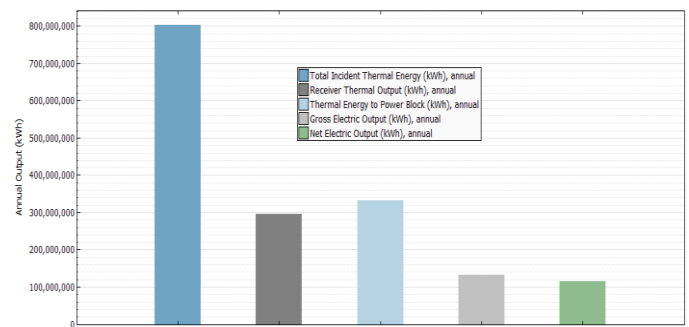


Fig. 11. Annual energy flow.

In this graphical analysis (Figure 11), the energy production of the system is observed in the case of using wet cooling. It is noticed that the thermal energy generated by the

station in the case of using dry cooling amounts to 800 MWh annually, which is then converted into electrical energy resulting in an annual production of 109.99 MWh.

#### 4.4. The CSP Power Output Using Different Cooling Technologies

Three cooling systems were implemented in SAM software to simulate the operation of the CSP power station. Table 7 provides a summary of the differences between these three systems.

**Table 7.** Comparison of cooling properties

Type of cooling	Wet cooling	Dry cooling	Hybrid cooling
Annual Energy	116,079,488 kWh	109,998,224 kWh	110,380,104 kWh
Annual Water Usage	379,438 m <sup>3</sup>	22,672 m <sup>3</sup>	202,908 m <sup>3</sup>
The Saved money (\$)	\$ 51,086,876.00	\$ 36,952,780.00	\$ 38,569,458.00

Table 7 presents the wet cooling system has a higher electricity production compared to both the dry cooling and hybrid cooling systems, with a 5.5% increase over the dry cooling system and a 5.2% increase over the hybrid cooling system. However, it also requires significantly more water than both the dry cooling and hybrid cooling systems, making it less water efficient. On the other hand, the dry cooling system has lower electricity production but significantly lower water usage, making it a more water-efficient option. The hybrid cooling system strikes a balance between electricity production and water usage, offering moderate values for both parameters. The choice of a cooling system depends on considerations such as resource availability, environmental impact, and overall efficiency goals.

### 5. Conclusion

In conclusion, this modelling study focused on the utilization of dry and wet cooling systems in a solar tower power plant in Jordan. The findings emphasize the feasibility and effectiveness of implementing concentrated solar power (CSP) technology in Jordan, which can contribute to sustainable energy generation and reduce reliance on fossil fuels.

The study highlighted the success of the Gamesolar power plant implementation in Jordan, showcasing an 8.1% increase in energy production compared to the average in Spain. This demonstrates the potential for utilizing CSP systems in Jordan, particularly in the region of Ma'an, which benefits from abundant sunlight and can maximize the efficiency of solar energy generation. By examining the efficiency and energy efficiency of solar tower power plants in Jordan, the study aimed to understand the optimal cooling system design to enhance overall plant efficiency. The results support the use of CSP technology and provide valuable insights for future power plant designs. Renewable energy sources play a crucial role in addressing the energy demands of nations while mitigating climate change and reducing greenhouse gas emissions. Jordan, with its limited domestically recoverable

energy resources, heavily relies on imported fossil fuels. Therefore, the adoption of renewable energy, such as CSP, is vital for the country's sustainable development.

The study also highlighted the global significance of renewable energy sources and their potential contribution to the world's energy resources. The utilization of biomass, hydropower, geothermal, solar, wind, and marine energies can diversify the energy mix and promote a sustainable future. In summary, this modelling study underscores the importance of exploring and implementing renewable energy solutions, particularly CSP technology, in Jordan's energy sector. The findings contribute to the understanding of efficient cooling system designs for solar tower power plants and pave the way for sustainable energy generation, reducing Jordan's dependence on fossil fuels for power generation and promoting a greener and more sustainable future. Based on the findings of our study, several potential areas for future research and development can be identified. These areas aim to further explore and expand upon the insights gained from our investigation. Here are some suggestions for future directions:

1. Investigation of Other Renewable Energy Technologies: While our study focused on solar tower power plants utilizing dry and wet cooling systems, various other renewable energy technologies warrant exploration. Future research could delve into the analysis of different technologies such as photovoltaic systems, wind farms, geothermal energy, or biomass, to assess their feasibility, efficiency, and potential for implementation in Jordan.
2. Expansion to Other Locations in Jordan: Our study specifically examined the implementation of solar tower power plants in the southern region of Jordan. However, it would be valuable to extend the research to other geographical locations within the country. Different regions may have varying solar resources, environmental conditions, and energy demands, which could impact the performance and viability of solar tower power plants. By expanding the study to other locations, a more comprehensive understanding of the potential for renewable energy generation in Jordan can be attained.
3. Addressing Limitations Encountered: During our study, we may have encountered certain limitations that could be addressed in future research. For example, the impact of intermittency in solar radiation and its effects on energy generation and storage could be further investigated. Additionally, the economic feasibility and cost-effectiveness of implementing solar tower power plants in Jordan could be examined in greater detail, considering factors such as capital investment, operation, and maintenance costs, and potential revenue streams.
4. Integration of Hybrid Systems: Hybrid systems that combine multiple renewable energy technologies, such as solar and wind, or solar and biomass, have the potential to provide more reliable and consistent power generation. Future research could explore the design, optimization, and performance evaluation of hybrid systems, considering the specific energy demands and available resources in Jordan.
5. Environmental Impact Assessment: Conducting a comprehensive environmental impact assessment of solar tower power plants in Jordan would be a valuable area for



future research. This assessment could evaluate the potential environmental effects, such as land use, water consumption, and emissions, associated with the construction and operation of these power plants. It would help in ensuring sustainable and environmentally friendly energy development in the region.

## Acknowledgments

Authors may acknowledge the reviewers and the Editors-in-Chief for spending their valuable time on the article. We also appreciate our undergraduate project group (R. k. Al-Saaideh, Y. T. Al-Bazlamet, A. G. Al-Njadat, A. H. Al-Maameed, M. Z. Al-Bsharat, M. A. Awad) for completing this study.

## Author Contributions

Mohsen Ahmed: Conceptualization, methodology, software, simulation, data curation, formal analysis, writing – original draft preparation, and project administration.

Mohammad Shalby: Validation, investigation, technical review, writing – review & editing, and supervision.

Mohamed R. Gomaa: Methodology support, resources, visualization, critical revision of the manuscript, and supervision.

All authors have read and approved the final published version of the manuscript.

## Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper. The authors confirm that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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