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A Study of the Effect of Condenser Type on a Performance of Solar Linear Fresnel Power Plant in Sebha City

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ABSTRACT

This study compares two standard condensers used in electric power plants and examines how they affect a 100 MW solar thermal power plant. The factory uses Fresnel mirrors as a thermal collector and Hitec as a heat transfer fluid in the solar field. Using the System Advisor Model program, the plant performance was designed and modeled, as well as the cycle performance evaluation and energy cost for each type. The results showed a remarkable convergence in the efficiency of the plant as well as the Levelized cost of energy. The study concluded that it is possible to replace the evaporator condensers with air-cooled condensers, with an increase of 6.2% of the Levelized cost of energy, and this percentage is not large compared to the considerable amount of water needed by the water-cooled condensers.

دراسة تأثير نوع المكثف على محطة فرينل الخطية الشمسية لتوليد الطاقة في مدينة سبها

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قسم هندسة الطاقة المتجددة ، كلية الهندسة ، جامعة سبها ، ليبيا

الكلمات المفتاحية:
مكثفات التبريد بالهواء
التكلفة المعيارية للطاقة
محطة توليد الكهرباء فرينل الخطية
ليبيا
مكثفات التبريد بالماء

الملخص

تركز هذه الدراسة على اجراء مقارنة بين نوعين أساسيين من أنواع المكثفات المستخدمة في محطات انتاج الطاقة الكهربائية، حيث تم دراسة تأثير نوع المكثف على محطة طاقة حرارية شمسية بقدرة 100 MW، بالاعتماد على مرايا فرينل كمجمع حراري وHitec كمائع نقل الحرارة مستخدم في الحقل الشمسي، تم تصميم ومحاكاة أداء المحطة في برنامج SAM ودراسة أداء الدورة وكذألك تكلفة الطاقة عند كل نوع، حيث بينت النتائج تقارب كبير في كفاءة المحطة وكذلك التكلفة المعيارية للطاقة. وقد خلصت الدراسة الي إمكانية استبدال المكثفات المبردة بالماء بمكثفات المبردة بالهواء بزيادة 6.2% من التكلفة المعيارية للطاقة، وهذه النسبة غير كبيرة بالمقارنة بكمية الكبير من المياه التي تحتاجها المكثفات المبردة بالماء.

Introduction

The challenges posed by the increase in demand for energy are offset by the rise in the construction and design of stations to accommodate and cover this demand. To obtain the best performance for this station, every part of it must be studied and designed to get the most excellent version. Return the steam to water by lowering the temperature of the steam leaving the turbine.

Libya in general possesses the resources necessary to build concentrating solar stations[1], as the intensity of solar radiation in Libya in general and southern Libya in particular is available in large quantities that could cover the need to establish such stations.

There are several types of condenser used in this field: (1) water-cooled, (2) air-cooled (dry air), (3) air-cooled with water spraying (evaporative) (spraying before the fan, spraying before and after the fan)[2].

Most concentrating solar thermal power plants are built in areas or places where there is a large amount of intensity of solar radiation, but many of these areas suffer from a shortage of water, so it is necessary to study the best types, as well as the impact of the geographical location on its performance. Butler et al.[3] Studied the effect of wind on the optimal design and implementation of a modular air-cooled condenser for a concentrated solar power plant. The study concluded that geographical location dramatically impacts the performance of air condensers. And also another study entitled Achieving near-water-cooled power plant performance with air-cooled condensers by Bustamante et al.[4] In this study, a model of a representative air-cooled condenser unit coupled with a base-load steam power plant was developed to examine the performance of air-cooled condensers under different operating conditions. It has been found that wet cooling systems generate approximately 6% more energy than dry air-cooled condensers.

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Yilmazoglu et al.[2] They studied the effects of the selection of heat transfer fluid and condenser type on the performance of a solar thermal power plant with a techno-economic approach. The study concluded that the water-cooled condenser gives better performance than other types. The air-cooled condensers consume much power, increasing the fans' additional power consumption. As a result, the net capacity is reduced. Lin et al.[5] Also presented was a study on improving air-side heat transfer performance in air-cooled power plant condensers. The optimal geometries for a condenser with smooth, corrugated, and encased fins were determined through parametric analyses. The study found that the most significant boost in cycle efficiency was achieved by lowering the fin distance between conventional and smooth fins (1.14 percent increase for the Rankine cycle, 0.84 percent increase for the combined cycle).

Thermodynamic analysis of the performance of a hybrid solar-geothermal power plant with an air-cooled condenser has been studied by Keshvarparast et al.[6] On some days of the cold and hot months of the year, they did a study and analysis of a parametric study of the critical factors. Examined variables include ambient temperature, working fluid type, working fluid mass flow rate, and engineering fluid mass flow rate. The HTRI program was used to carry out the thermal design for the air-cooled condensers. The results showed that the ambient temperature and climate significantly impacted the hybrid power plant's air-cooled condenser.

As we mentioned earlier, the most prominent types of condensers used in electrical power plants are three types, and we will study here two main types and their impact on the station's efficiency.

Steam enters the tower coil through the upper coil connection and circulates through the waves. The water distribution system distributes the water to the coil tubes, transferring the heat to the water. Air is drawn up and over the coils by the axial fan, agitating the dripping water and increasing heat transfer. A small amount of recycled water evaporates due to latent heat transfer through the tube and fin walls of the cooling tower coil, removing heat from the system. The cooled fluid then returns to the process via the lower coil connection[7], [8]. Figure 1 shows an illustration of a wet cooling tower.

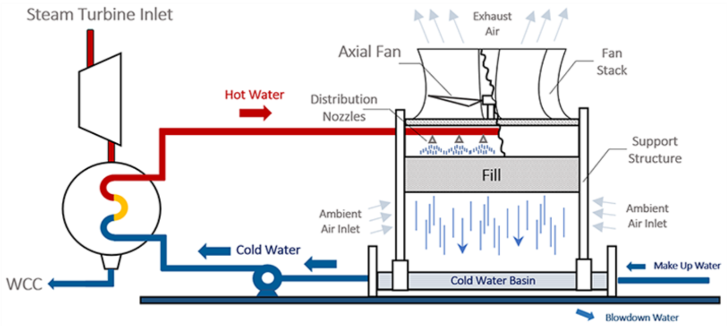

Figure 1: A principle of a wet cooling tower [9].

Dry cooling systems constitute the main alternatives to water-based cooling systems. Such systems are labeled as ‘dry' because there is no need for make-up water. Up to 90-95% of the water can be saved with dry cooling with the sacrifice of cooling efficiency, especially on hot days. In direct dry cooling or air-cooled condensers, fans blow air over the bundles of finned tubes, where heat rejection occurs, and turbine exhaust steam condenses[7], [8].

A schematic of a direct dry cooling unit is shown in Figure2

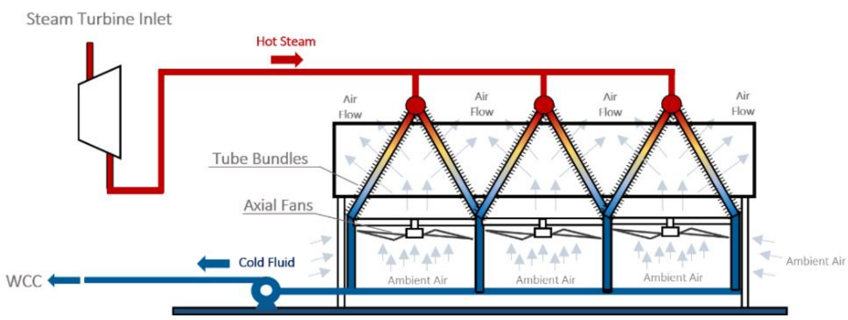

Figure 2: A principle of a dry cooling tower [9].

Methodology

The System Advisor Model (SAM) model was used to simulate the Linear Fresnel power plant (LFPP) system, a model developed by the National Renewable Energy Laboratory (NREL). The system can be manufactured to analyze and compare the plan's performance and work. The performance of the station's work depends on primary and essential information such as geographical location information and the nature of the weather, which significantly affects the performance of the LFPP, which also involves the periods of thermal storage for use in periods of less solar radiation [10].

The steam Rankine cycle serves as the foundation for the power cycle. The power cycle's purpose is to transform heat energy into electrical energy. The superheated two-stage turbine with numerous extractions for feed water heating and a reheat extraction between the high-pressure and low-pressure turbine stages makes up the power cycle in the LFPP SAM model. The LF power cycle's performance depends on ambient temperature, mass flow rate, and steam inlet temperature [11]. The power cycle's ultimate power output calculated by:

$$\dot{W}_{cycle} = \eta_{cycle,ref}\, f_{pb,T}\, f_{pb,load}\, \dot{Q}_{ph} \quad (1)$$

Where: $\eta_{cycle,ref}$ is the Reference efficiency, $f_{pb,T}$ Temperature-based adjustment factor, $f_{pb,load}$ Load-based adjustment factor, $\dot{Q}_{ph}$ Power block thermal energy (MW).

The net power from the cycle can be found by taking into ac- count the electric consumption of the solar field pumps, condenser pump, feed water pump, and cooling water pump [12], given by:

$$\dot{W}_{net} = \dot{W}_{cycle} - \dot{W}_{par,fired} - \dot{W}_{par,var}\left(T_{amb}, \frac{\dot{W}_{cycle}}{\dot{W}_{cycle\ ,des}}\right) \quad (2)$$

The thermal efficiency of the cycle can be calculated from the following eq.3[13].

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \quad (3)$$

Where: W_{net} is the$W_{turbine,out} - W_{pump,in}$, and Q_{in} is the amount of heat gained by the water in the heat exchanger with the heat transfer fluid.

The Levelized Cost Of Energy (LCOE) is the price at which electricity generated from a specific source will break even over the project's life [14], where it can be calculated by

$$LCOE = \frac{\{K_d(1+K_d)^n/[(1+K_d)^n-1]+K_{in}\}\, C_{inv}+C_{O\&M}}{E} \quad (4)$$

Where K_d is the real debt interest (8%), K_{in} is the annual insurance rate (1%), n is the plant lifespan of 30 years. C_{inv} Is the total investment in the plant. $C_{O\&M}$ Is the cost of annual operation and maintenance, and E is the annual electricity production [1].

Characteristics of the selected location

The intensity of solar radiation is significant in choosing the appropriate location for the construction of concentrating solar stations, but on the other hand, in most of the areas where the intensity of solar radiation significantly increases with which, the temperature of the outside air increases, which in turn affects the performance of the condensers.

In this study, the LFPP was designed near the city of Sebha, as shown in Figure 3, which is characterized by high solar radiation intensity, which makes it a suitable location for this type of plant, and Table 2 shows the primary data for the study site.

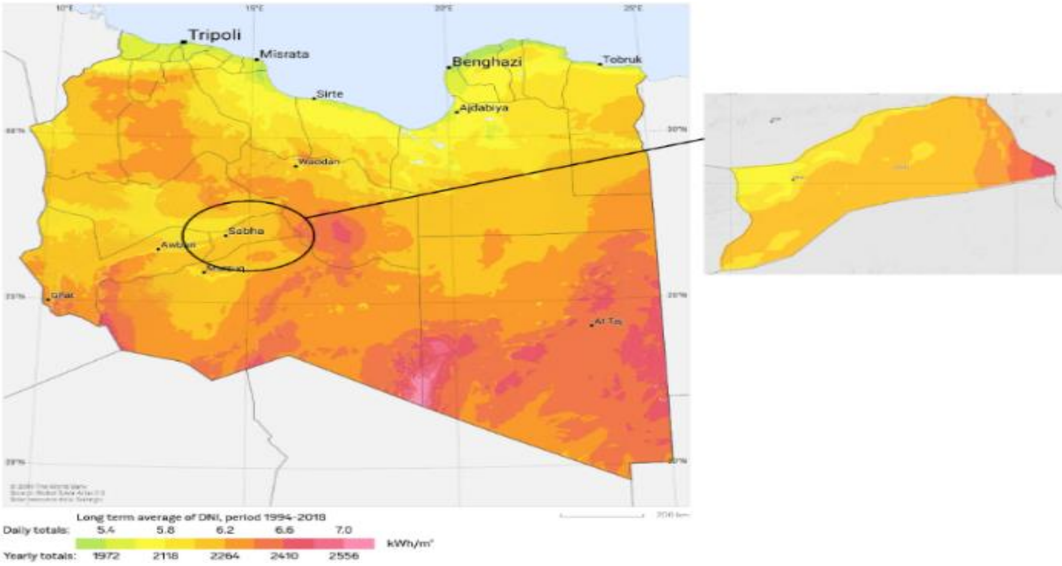

Figure 3: Direct normal irradiation for Libya and Sebha [15].

Table 2: Sites Geographical Location and Specification

Characteristics of Sebha city	
Latitude	27.038°
Longitude	14.428°
Elevation	421m
Annual DNI	7.20 kWh/m2/day
Annual average temperature	23.4°C
Annual average wind speed	4.4 m/s
Data Source	ISD-TMY

Results and Discussion

The simulations were performed on the LFPP based on the climatic data of Sebha city as demonstrated in Table 2.

A solar thermal plant design and simulation were carried out and Hitec was used as a heat transfer fluid used in the solar field, which has properties shown in Table 3.

To obtain the best performance at the lowest costs, a thermal storage capacity of the plant was designed for 12 hours, to cover periods of lack of solar radiation during the night. The simulation was carried out to obtain the best Solar Multiple that can be used

Table 3: The properties of Hitec [16], [17].

Name	**Compositions (wt.%)**	**Melting point (°C)**	**Stability limit (°C)**	**Viscosity (Pas)**	**Thermal conductivity (W m^{-1} K^{-1})**	**Heat capacity (kJ kg^{-1} K^{-1})**	**Cost ($/kg)**
Hitec	$NaNO_3$ (7)– KNO_3 (53)– $NaNO_2$ (40)	142	535	0.00316(at300°C)	~0.2(at 300 °C)	1.56(at 300 °C)	0.93

Table 4 shows the effect of Solar multiple (SM) on the plant performance rates when using Air-cooled, Evaporative, also can be noted is the best performance of the plant when SM is 7.

Table 4: The effect of SM on the plant performance rates when using Air-cooled, Evaporative.

SM	**Air-cooled**				**Evaporative-cooled**			
	Annual AC energy (year 1) KWh	**Capacity factor (year 1) %**	**Annual Water Usage m^3**	**LCOE ₵/kWh**	**Annual AC energy (year 1) KWh**	**Capacity factor (year 1) %**	**Annual Water Usage m^3**	**LCOE ₵/kWh**
1	154643721	17.7	14563	39.33	166995168	19.1	525828	36.45
2	317533344	36.2	28569	19.36	347356672	39.7	988610	17.73
3	482179872	55.0	42359	12.89	531345216	60.7	1475596	11.73
4	603479872	68.9	52673	10.38	652530368	74.5	1792932	9.36
5	654281152	74.7	57663	9.60	703396160	80.3	1926426	8.96
6	679087488	77.5	60723	9.27	724792448	82.7	1983888	8.71
7	687205312	78.4	62618	9.16	732260928	83.6	2007982	8.62
8	685977280	78.3	63853	9.18	730530496	83.4	2010564	8.64
9	677423936	77.3	64498	9.29	721351552	82.3	1993724	8.75
10	667619584	76.2	65110	9.42	711730304	81.2	1977882	8.86

Figure 4 shows the difference between air-cooled condensers and evaporators. It showed that annual alternating current energy, capacity factor, and level cost of energy (LCOE) were pretty close. But the water consumption rate in evaporative was tremendous compared to air condenser.

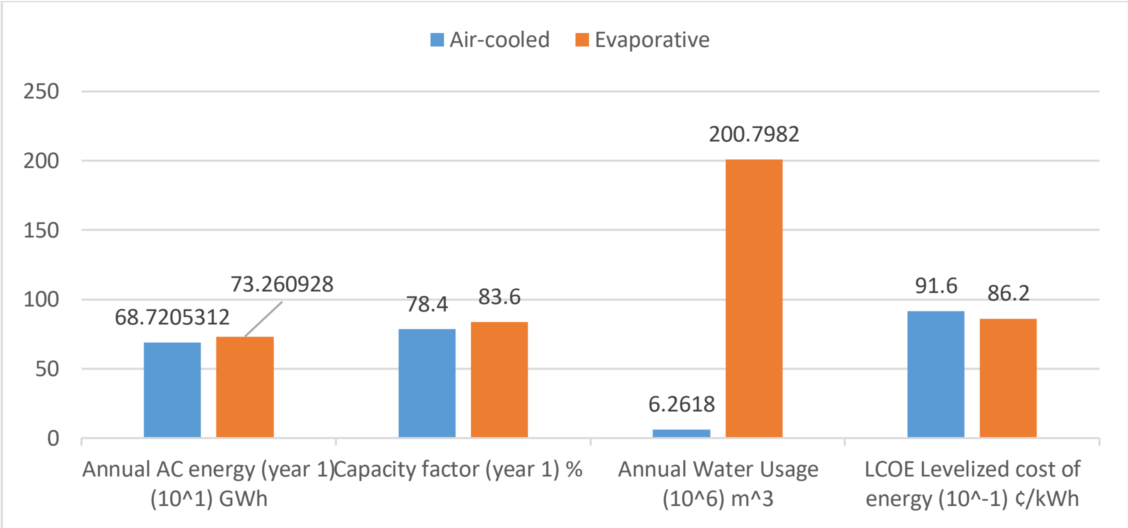

Figure 4: The Annual energy, Capacity factor, Annual Water Usage, and Annual Water Usage for Air-cooled and Evaporative when SM is 7.

Table 5 shows the monthly energy production over a year, it is clear that the rate of energy production when using the evaporator gives the highest energy production in most months of the year, because the water used in the evaporator, helps to increase the absorption of thermal energy.

Table 5: The monthly energy production (kWh) over a year when using Air-cooled, Evaporative.

Month	Air-cooled	Evaporative-cooled
Jan	5.88E+07	6.00E+07
Feb	5.09E+07	5.27E+07
Mar	6.01E+07	6.26E+07
Apr	5.48E+07	5.88E+07
May	5.93E+07	6.38E+07
Jun	6.19E+07	6.77E+07
Jul	6.43E+07	7.02E+07
Aug	6.31E+07	6.93E+07
Sep	6.08E+07	6.60E+07
Oct	5.63E+07	5.99E+07
Nov	5.13E+07	5.38E+07
Dec	4.57E+07	4.75E+07

Figure 5 shows that in January the rate of energy production is almost equal when using any of the two types because of the low average temperatures temperature in that month. Also, the maximum monthly production was in July due to the intensity of solar radiation in this month, which increases the temperature entering the steam turbine.

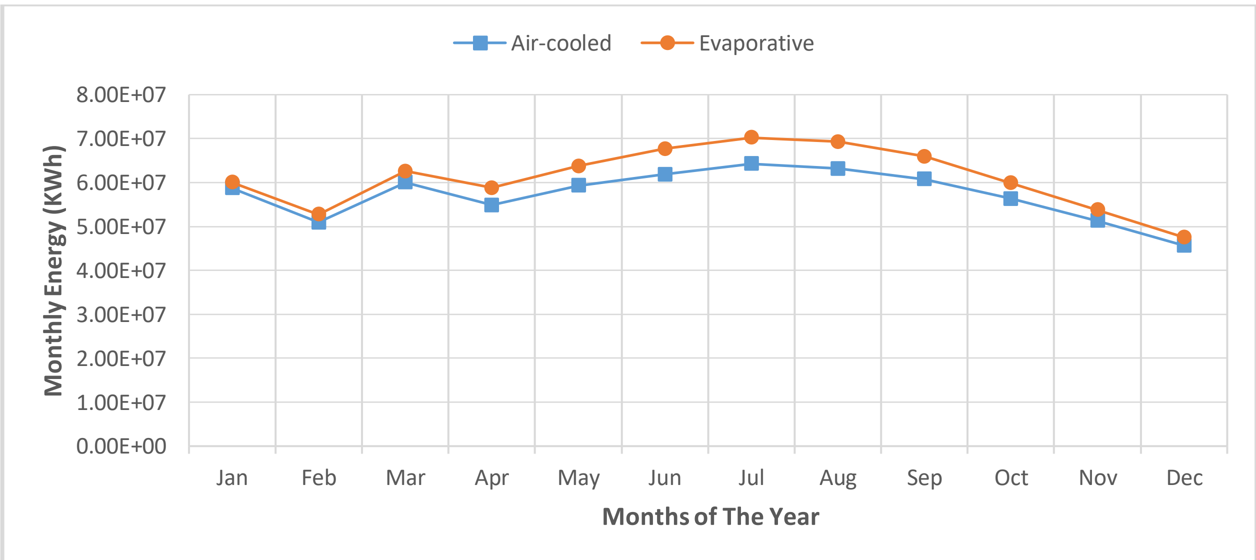

Figure 5: The monthly energy production over a year.

Table 6 and Table 7 show the cycle electrical power output (net) over a whole year, this can be illustrated by Figures 6 and 7, where the electrical power output is almost constant, except for the periods of insufficient heat supply in the boiler, which are often from 4 o'clock to 11 am, as this is the period when the temperature of the stored heat transfer fluid decreases, and it is the beginning of the sun's brightness, during which the intensity of the solar radiation is weak and insufficient. But in general, the (net) cycle electrical power output of the two condensers is closely related, as shown in Figure 8, which shows the annual cycle electrical net power output.

Table 6: Hourly Data of Cycle electrical power output (net) (MWe) when using the Air-cooled.

Time of day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	108.756	109.012	109.286	98.5904	105.755	111.326	110.663	110.257	111.523	102.992	103.737	84.0737	105.498
2	109.489	105.429	109.54	98.9705	104.949	111.854	111.214	110.75	111.965	103.254	100.641	79.6204	104.806
3	106.372	104.793	108.531	99.1937	101.467	112.238	111.691	111.206	112.306	102.4	100.943	64.5399	102.973
4	99.799	101.882	104.78	95.9334	97.3272	112.392	111.865	111.341	112.599	95.2602	94.9662	52.1074	99.1876
5	70.5137	72.6058	98.0586	92.9115	84.95	110.392	112.455	111.878	104.001	74.2096	63.1843	23.4273	84.8822
6	0	0	67.4635	61.6628	50.8895	75.6824	76.9694	73.1286	48.7972	0	0	0	37.5388
7	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	11.157	29.6766	30.1645	40.9384	45.7766	39.7942	39.0744	14.7072	0	0	20.3896
11	37.1107	38.8656	68.832	82.3268	85.5801	96.1763	104.129	100.249	105.01	74.822	44.4513	25.4967	71.9208
12	103.589	101.099	101.211	92.7691	98.888	100.733	101.92	100.145	104.199	104.57	98.9813	83.7758	99.3233
13	110.27	102.621	101.66	93.9326	102.615	105.218	104.547	103.559	105.438	99.909	100.087	97.4316	102.274
14	112.033	102.097	101.787	91.3758	99.4889	104.384	103.638	103.45	105.206	97.8758	99.9146	101.373	101.885
15	110.514	103.321	102.794	95.0529	102.621	105.113	103.767	103.805	106.063	99.3835	100.055	100.284	102.731
16	112.784	101.933	105.934	99.9266	102.719	105.458	104.397	104.176	106.387	101.849	101.473	99.2093	103.854
17	111.267	106.285	106.836	96.444	100.502	106.011	104.759	105.296	107.196	104.26	98.296	100.654	103.984
18	89.4463	101.894	108.681	96.9712	98.9177	107.565	106.568	106.874	108.463	81.6313	57.7508	60.3116	93.7562
19	116.216	108.252	68.5694	75.4481	95.5486	100.729	104.896	87.1557	75.2602	107.135	105.047	100.429	95.3906
20	116.718	107.224	110.531	105.96	109.364	107.23	106.873	107.204	108.95	107.721	104.286	99.1952	107.605
21	116.954	107.681	110.675	103.284	108.412	108.863	108.434	107.972	109.55	108.142	102.994	98.231	107.599
22	117.078	108.119	108.063	100.465	106.621	109.534	109.037	108.606	110.086	108.584	103.302	92.8001	106.858
23	117.261	108.402	108.569	99.7707	104.924	110.238	109.648	109.313	110.69	105.719	103.594	88.5978	106.394
24	113.991	108.621	108.927	98.0126	105.383	110.752	110.16	109.784	111.14	102.768	103.779	88.6412	105.997

Table 7: Hourly Data of Cycle electrical power output (net) (MWe) when using the Evaporative.

Time of day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	109.323	109.112	111.04	102.065	110.109	117.374	116.4	116.044	116.943	106.314	105.598	85.8585	108.848
2	108.362	109.14	111.07	101.975	109.773	117.557	116.539	116.176	117.084	106.357	103.354	81.6472	108.253
3	104.439	104.927	110.742	102.078	106.546	117.658	116.659	116.286	117.354	106.093	101.959	74.7818	106.627
4	102.284	101.32	106.848	100.351	101.274	118.017	117.11	116.604	117.495	101.955	100.249	54.2084	103.143
5	82.4783	86.8793	99.7878	96.937	87.8401	117.054	117.271	116.896	111.448	83.6148	77.9904	43.4281	93.4686
6	0	0	66.1426	74.799	61.0106	95.2954	101.554	101.116	60.7684	0	0	0	46.3798
7	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	12.0978	32.5407	33.429	45.8377	50.9703	44.7955	43.6172	16.2112	0	0	22.7437
11	38.9676	41.2404	73.0704	89.0557	92.9257	105.405	113.536	110.034	114.714	80.891	47.5751	27.0376	77.871
12	107.846	106.459	106.781	100.578	107.098	110.829	111.627	110.309	113.7	111.735	104.652	87.2649	106.573
13	115.1	107.45	107.851	102.417	112.021	117.684	116.703	116.243	116.827	107.236	106.239	101.619	110.616
14	115.702	109.513	108.908	100.565	109.403	117.541	116.602	116.879	117.684	105.908	106.633	106.084	110.952
15	114.953	108.269	110.501	105.042	112.985	118.704	117.224	117.76	118.863	107.942	106.954	105.695	112.074
16	117.496	106.264	114.07	110.57	113.242	119.159	117.872	118.36	119.42	110.555	108.965	105.71	113.474
17	116.031	113.138	114.884	106.436	110.782	119.707	118.567	119.611	120.352	113.019	105.581	102.95	113.422
18	92.6849	107.373	116.003	106.07	110.465	120.914	119.727	120.655	120.908	88.2378	60.9151	60.1377	102.007
19	116.642	111.184	73.7426	81.2951	103.285	111.749	116.133	97.1952	83.9535	112.538	108.251	99.4249	101.283
20	116.543	109.304	114.8	111.973	116.152	115.433	114.753	115.225	116.373	112.727	107.232	99.1869	112.475
21	116.477	109.227	114.579	110.372	115.873	116.536	115.777	115.438	116.484	112.829	105.339	98.3882	112.277
22	116.506	109.215	111.75	105.132	113.021	116.782	115.949	115.632	116.649	112.941	105.371	94.2752	111.102
23	116.538	109.198	111.1	104.778	110.098	117.032	116.128	115.845	116.81	112.056	105.438	87.74	110.23
24	113.906	109.161	110.97	101.77	110.238	117.176	116.2	115.936	116.885	107.05	105.372	87.767	109.369

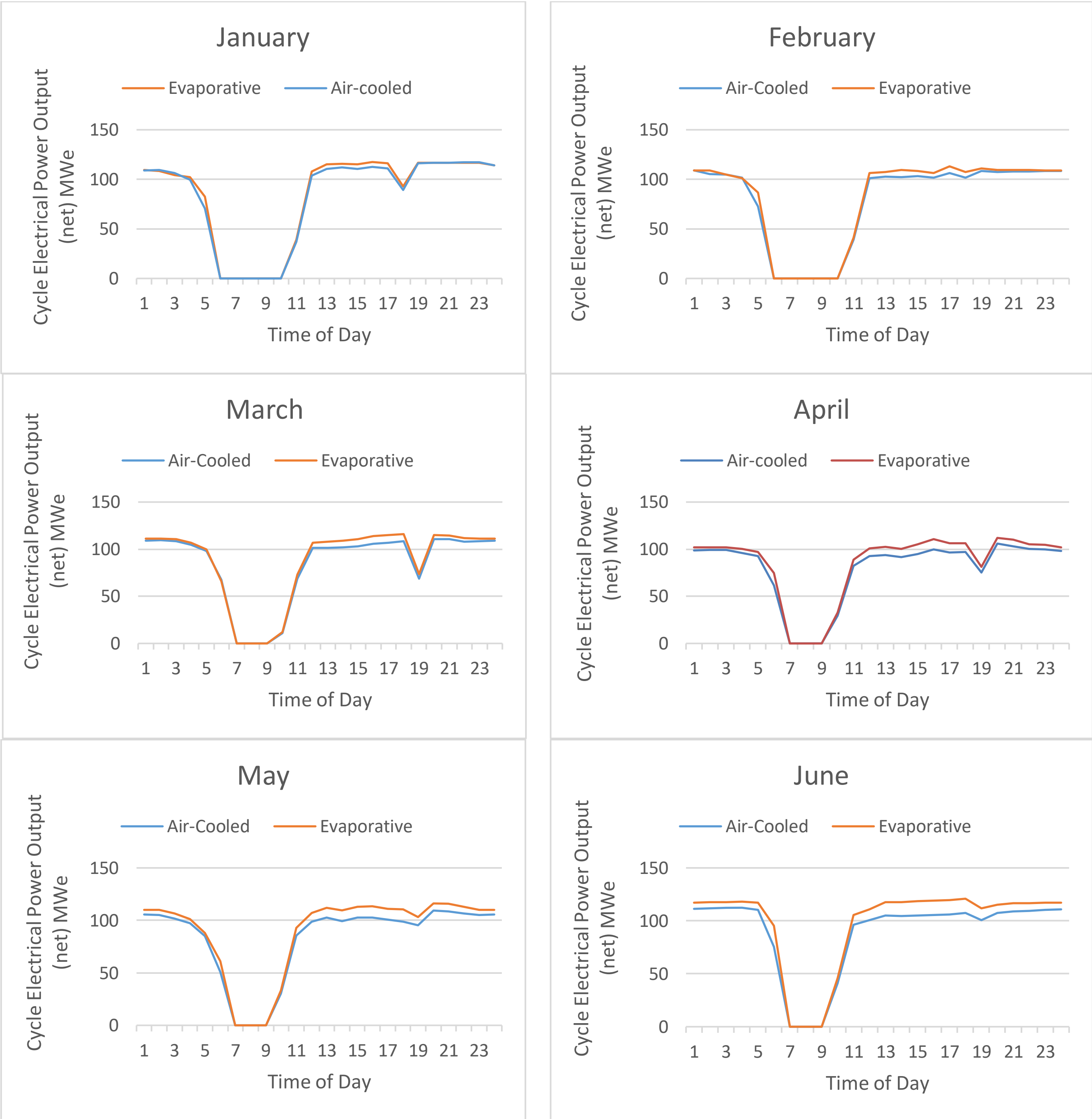

Figure 6: The cycle electrical power output (net) for (Jan, Feb, Mar, Apr, May and June)

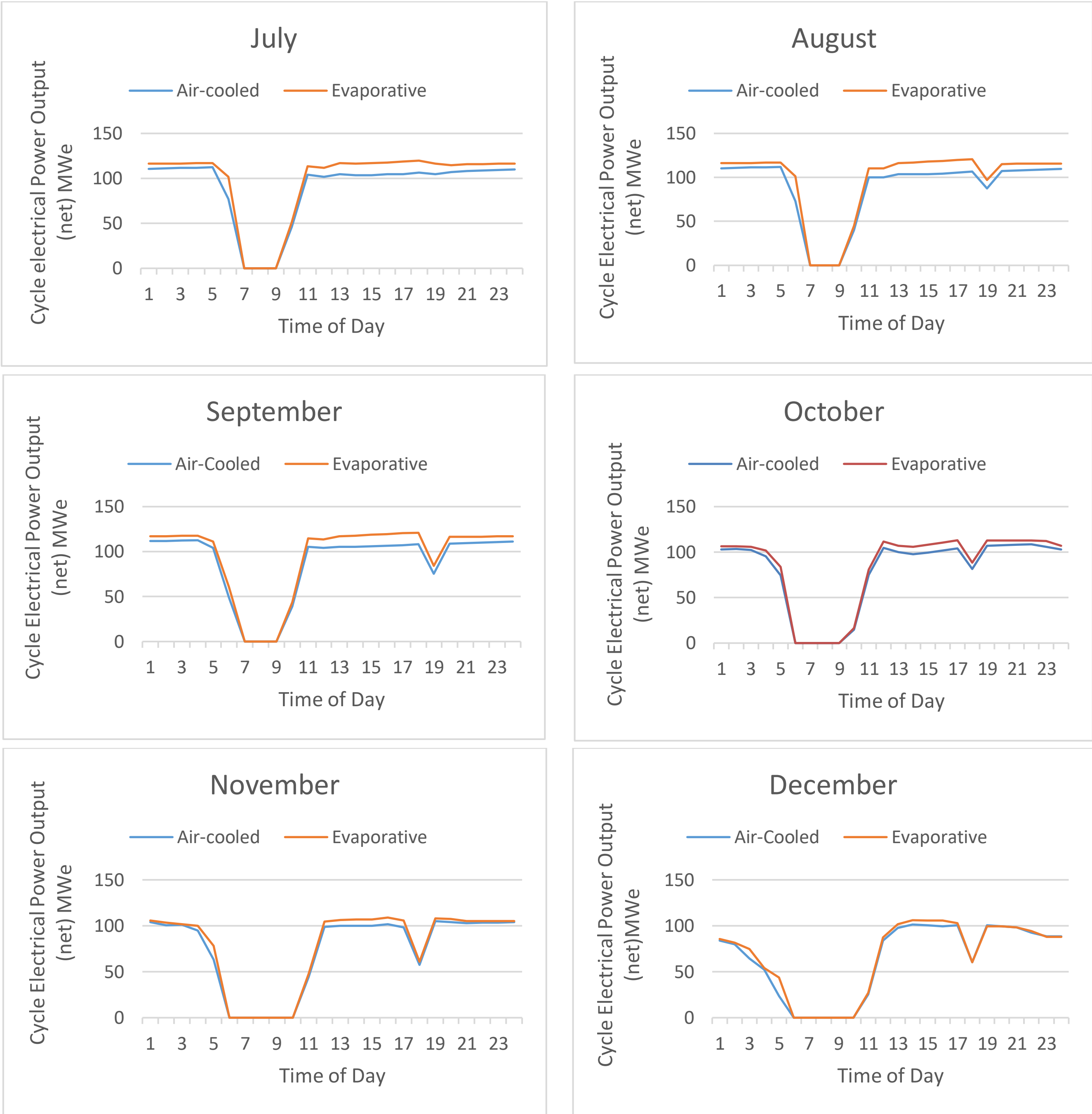

Figure 7: The cycle electrical power output (net) for (July, August, Sep, Oct, Nov and Dec).

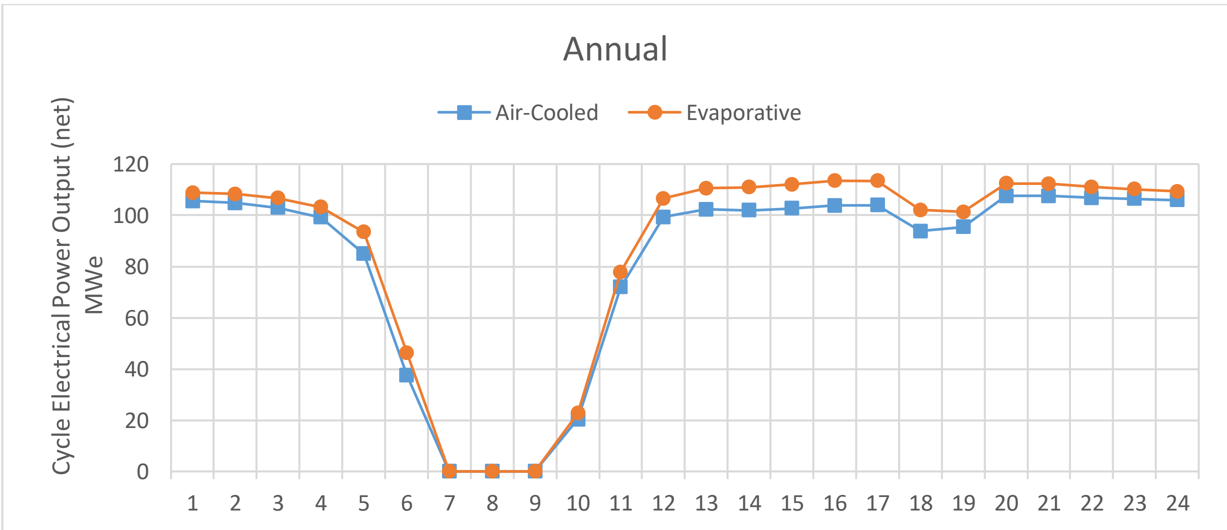

Figure 8: The annual cycle electrical power output (net).

Table 8: The Cycle efficiency (gross) over a Day when using Air-cooled, Evaporative.

Time of day	Air-cooled	Evaporative-cooled
1	0.394686	0.412978
2	0.392223	0.410734
3	0.387413	0.40479
4	0.372951	0.391661
5	0.361533	0.377252
	0.199876	0.204322
7	0	0
8	0	0
9	0	0
10	0.203445	0.203445
11	0.371786	0.386275
12	0.398708	0.420985
13	0.399516	0.423341
14	0.396593	0.422445
15	0.401534	0.427613
16	0.403298	0.430346
17	0.402976	0.429166
18	0.404321	0.426578
19	0.407153	0.428234
20	0.406397	0.42911
21	0.406839	0.428035
22	0.401468	0.423139
23	0.399523	0.41784
24	0.396091	0.415207

Also, in (Table 8 and Figure 9), which shows the cycle efficiency (gross), we note that the cycle efficiency is very close when using the two types of condensers, except the steam generator.

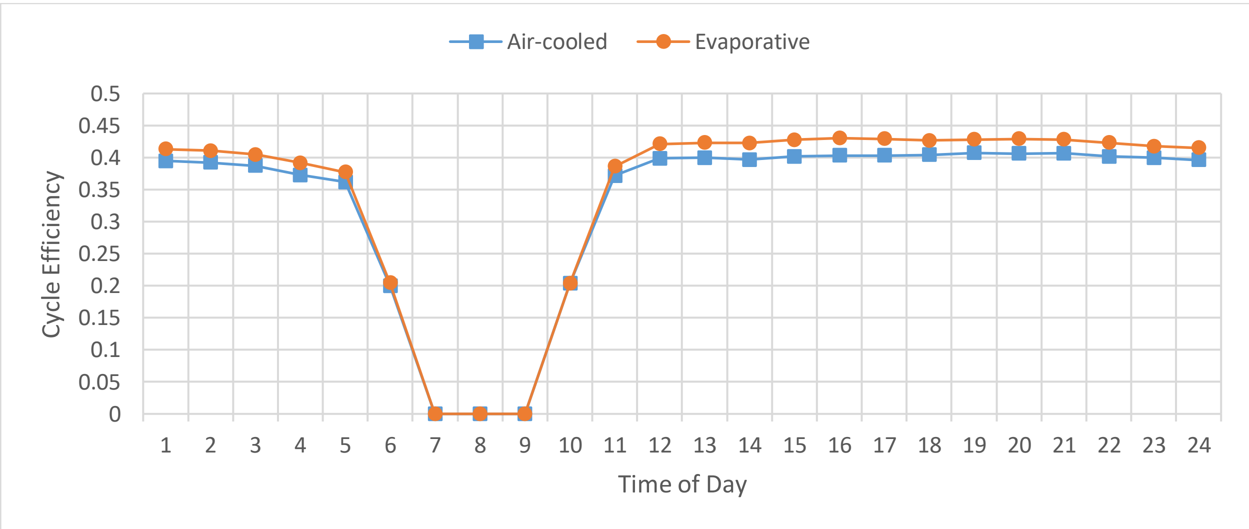

Figure 9: The Cycle efficiency (gross) over a Day.

Conclusion

The study discussed the difference in performance between the use of air-cooled condensers and water-cooled condensers in terms of the effect of geographical location data on their performance, as well as the total energy cost if both are used in the Fresnel linear power plant in Sebha region.
The results of this design of the Fresnel linear power plant showed a high convergence between annual power, capacity factor and LCOE. Where this study showed that the use of water-cooled condensers gives a total energy cost of 0.54 ¢/kWh less than air-cooled condensers, and this difference is not large so the large difference in water use in water-cooled condensers, which is estimated at 2 million cubic meters of water per year, which is a large amount of water for desert places such as the region of Sebha, and therefore gives preference to the use of air coolers for desert areas.
Suppose suitable quantities of water unsuitable for human and agricultural use are available, such as sewage water. In that case, it can be used after treatment in water coolers to increase the total capacity and reduce energy costs.

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