Study of the different Heat Transfer Fluids effect for a Linear Fresnel Power Plant designed in Sebha City, Libya.

Ibrahim Mohamed Ibrahim Eslayem, Mohamed Alamen Sharif

Department of Renewable Energy Engineering, Faculty of Engineering, Sebha University, Libya

Corresponding author: Ibra.eslayem@sebhau.edu.ly, moh.sharif@sebhau.edu.ly

الملخص:

تركزت الدراسات العلمية في الآونة الأخيرة على استخدام أفضل الطرق والتقنيات الحديثة لإنتاج الطاقة الكهربية من المحطات الشمسية التركيزية، وقد تم في هذه الدراسة تصميم محطة شمسية تركيزية بتقنية عاكس فرينل الخطي باستخدام برنامج System Advisor Model (SAM) وقد تم استخدام ثلاثة أنواع من سوائل نقل الحرارة العالية الأداء(Hitec Solar salt – Hitec XL – Hitec) ، واجراء مقارنة بينها من حيث درجة حرارة خروج السائل من الحقل الشمسي وكفاءة الحقل الشمسي، كما تم اجراء مقارنة من حيث تأثيرها على كمية الطاقة المنتجة خلال السنة وعامل القدرة السنوي ومستوى تكلفة الطاقة لكل كيلو وات ساعة، وقد اعتمد هذا الامر على تغيير المضاعف الشمسي (SM) وساعات التخزين (TES)، وقد أظهرت النتائج تشابها كبيرا بين المحاليل الملحية المستخدمة في هذه الدراسة، على الرغم من اختلاف خصائصها الفيزيائية.

Abstract

Scientific studies have recently focused on using the best modern methods and technologies to produce electrical energy from concentrating solar plants. In this study, a concentrating solar plant was designed using the Linear Fresnel Reflector technology using the System Advisor Model (SAM). Three types of high-performance heat transfer fluids were used (Hitec Solar salt - Hitec XL - Hitec). A comparison was made between them in terms of the out solar field's outlet temperature and the solar field's efficiency so, a comparison was made in terms of the effect on the Annual Energy, Capacity Factor and, Levelized Cost of Energy (LCOE), all of this was based on changing the solar multiple (SM) and Thermal Energy Storage (TES). The results showed a significant similarity between the heat transfer fluids used in this study, although their physical properties differed.

Keywords: Linear Fresnel Power Plant, Heat Transfer Fluid, Solar Multiple, Levelized Cost of Energy, Libya.

1. Introduction

Concentrating Solar Power plants are considered the most important future energy in generating energy in the world, where solar radiation is available. Based on previous studies, we can say that the Linear Fresnel Power Plant (LFPP) is considered one of the most promising and future renewable energy technologies in that it can cover the increasing demand for electric energy significantly.

Peterseim et al. [1] focused on evaluating the appropriateness of CSP technologies for operating steam turbines, the study concluded that Fresnel and parabolic trough (thermal oil) are the most significant options for lower temperature steam integration (400°C), and Fresnel systems perform best in the steam integration range of (380 to 450°C). Modi et al. [2] studies focused on research was see if there was any benefit to adopting the Kalina cycle for direct steam generation in a central receiver solar thermal power plant with a high live steam temperature (450°C) and pressure (over 100 bar), The results indicated that that the simple Rankine cycle outperforms the Kalina cycle when a two-tank molten-salt storage system is used as the principal source of heat input. Vignarooban et al. [3] discussed many types of HTF used to transfer thermal energy in concentrating solar energy systems in terms of maintaining their physical properties and thermal equilibrium and the effect of HTF on the parts of the field. Morin et al. [4] the study showed promising results, especially about Molten Salt. They discussed a complete analysis of the use of Molten Salt as HTF liquid in Liner Fresnel Power Plant, as well as a study of corrosion rates in pipes when using Molten Salt and how to treat and avoid its freezing inside the pipes. Therefore, molten salt is a common HTF in modern CSP systems because it may be utilized as an HTF in the solar receiver to store solar energy thermally. Melik et al. [5] discussed the design of a 100 MW Linear Fresnel Power Plant with heat storage for six hours, and the study site was taken in Pakistan, Hitec Solar Salt was used as HTF, the outputs were a capacity factor, and gross to net conversion was found to be 25.2% and 90% respectively. Yakut et al. [6] discussed the study and analysis of the LFR system, where the study concluded that it can reach high temperatures, and also that the ocean temperature has a significant impact on the performance of the LFR system. Khandelwal et al. [7] discussed Water, thermal oils, and molten salts are among the heat transfer fluids addressed. They discussed comparing the effects of various heat transfer fluid properties. Also, investigate the impact of using these heat transfer fluids on the solar cycle's performance. As also, noted through his studies that the water is more convenient than other heat transfer fluids, but because it has a two-phase flow (liquid water + steam), some water evaporates in the receiver during the process, necessitating a more complex solar field control system to keep the steam temperature and pressure at the solar field outlet stable. The most commonly used salt mixtures for CSP plant simulations in Previous and current studies a binary nitrate salt, Hitec Solar Salt (60 % $NaNO_3$, 40 % KNO_3), commonly known as Solar Salt, a ternary nitrite salt, Hitec Heat Transfer Salt (7 % NaO_3, 53 % KNO_3, 40 % $NaNO_2$), commonly known as Hitec, and Hitec XL (7 % NaO_3, 45 % KNO_3, 48 % $Ca(NO_3)_2$), a ternary calcium nitrate salt simply known as Hitec XL, and Table1 show the most important thermal and physical properties

Table 1. The properties of Hitec Solar Salt, Hitec XL and Hitec [8,9].

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)
Molten-salts Solar Salt	$Na\ No_3$ (60)– KNo_3(40)	220	600	0.00326(at 300 °C)	0.55 (at 400 °C)	1.1 (at 600 °C)	0.5
Hitec	$NaNO_3$ (7)– KNO_3 (53)– $NaNO_2$ (40)	142	535	0.00316 (at 300 °C)	~0.2 (at 300 °C)	1.56 (at 300 °C)	0.93
Hitec XL	$NaNO\ _3$(7)– KNO_3 (45)– $Ca(NO_3)_2$ (48)	120	500	0.00637 (at 300 °C)	0.52 (at 300 °C)	1.45 (at 300 °C)	1.1

for these molten salts. Although Hitec and Hitec XL have lower freezing points, they do not offer the same high thermal stability as Solar Salt. [8], [9].

In this study, the Linear Fresnel Power Plant will be designed in southern Libya, and a comparison will be made between the performance of this plant using three types of main heat transfer fluids, which are the best heat transfer fluids used in the CSP plants. Thus, it is possible to obtain the appropriate heat transfer fluid that can be used in the station, which gives the best efficiency and the lowest costs for the designed station.

2. Methodology and Materials

The SAM model was used to simulate the system of the LFPP, which is a model developed by the National Renewable Energy Laboratory (NRCL), through which the system can be simulated to analyze and compare the performance and the work of the plan. The performance of the station's work depends on the basic and important information such as the geographical location information and the nature of the weather, which greatly affects the performance of the LFPP, which also affects the periods of thermal storage for use in periods of less solar radiation [10].

Solar multiple, SM is a term used to describe the solar system's configuration. The SM is defined as the ratio between the solar field thermal power, Q_{solar}, under design conditions and the thermal power required by the power block $Q_{PB,ref}$, under nominal conditions (see Eq. 1) . In solar plants, the solar multiple is always bigger than one in order to meet the nominal conditions on the power block not just instantly [11].

$$SM = \frac{Q_{solar}}{Q_{PB,ref}} \qquad (1)$$

The ratio between the electrical power generated W_{gross} and the efficiency of the power block at full load can be used to calculate the thermal power required by the power block as we see in (Eq. 2) [12].

$$\dot{Q}_{PB,ref} = \frac{W_{gross}}{\dot{\eta}_{T.ref} \times \dot{\eta}_{e,m}} \qquad (2)$$

Where: $\eta_{T.ref}$ is the thermal efficiency of the power block at full load, $\eta_{e,m}$ is the efficiency of the electric generator at partial load.

The steam Rankine cycle is used to construct the power cycle. The power cycle's job is to transform heat energy into electrical energy. The power cycle in the LFPP SAM model consists of a superheated two-stage turbine with several feed water extractions and a reheat extraction between the high and low-pressure turbine stages. The performance of the LFPP is determined by the temperature of the steam inlet, the mass flow rate, and the ambient temperature, and the gross power is defined by (Eq. 3) [12], [13].

$$W_{gross} = \eta_{e,m} \times \eta_T \times Q_{solar} \qquad (3)$$

Where: η_T is the turbine efficiency at part load.

The thermal efficiency of the solar field $\eta_{th.field}$ can be found by (Eq. 4) [14].

$$\eta_{\,th.field} = \frac{Q_u}{Q_s} \qquad (4)$$

Where: Q_u is the useful heat production, and Q_s is the available solar irradiation

The heat transferred from the receiver to the power cycle is conveyed by the heat transfer fluid. The temperature of the heat transfer fluid rises as a result of heat absorption. The useful heat production can be found by (Eq. 5) [7].

$$Q_u = \dot{m}_{htf} \times Cp_{htf} \times (\Delta T_{htf}) \qquad (5)$$

Like any important project, the economic feasibility of the project must be calculated. To calculate this, we will calculate the Levelized Cost of Energy, which is one of the most important indicators for comparing different power plants, where the total costs are calculated on the energy yield and are calculated by the (Eq.4) [11].

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (6)$$

Where: I_t is the investment expenditures in year t (including financing), M_t is the operations and maintenance expenditures in year t, F_t is fuel expenditures in year t, E_t is the electricity generation in year t, r is the discount rate, and n is the life of the system.

The heat in excess of the station's needs is stored in TES stores that are used at night or when there is a shortage of solar radiation. One or more storage tank pairs are integrated with the power cycle in the TES. Each pair includes a hot tank for storing heat from the solar field and a cold tank for storing cold fluid from the power cycle. There are two types of TES, direct and indirect storage systems. The HTF serves as the storage medium in the direct storage system, however in the indirect storage system, a separate heating fluid with heat exchanger is required to heat-up the stored fluid. The number of hours that the TES can contribute thermal energy to the power cycle is expressed as its capacity.

Characteristics of the shortlisted location

The solar irradiation is the main driver of concentrated solar power plants, and although the intensity of solar radiation falling on the planet is not equal in all places, the areas that are exposed to Direct Normal Irradiation (DNI) rates are considered the best for establishing a concentrating solar power.

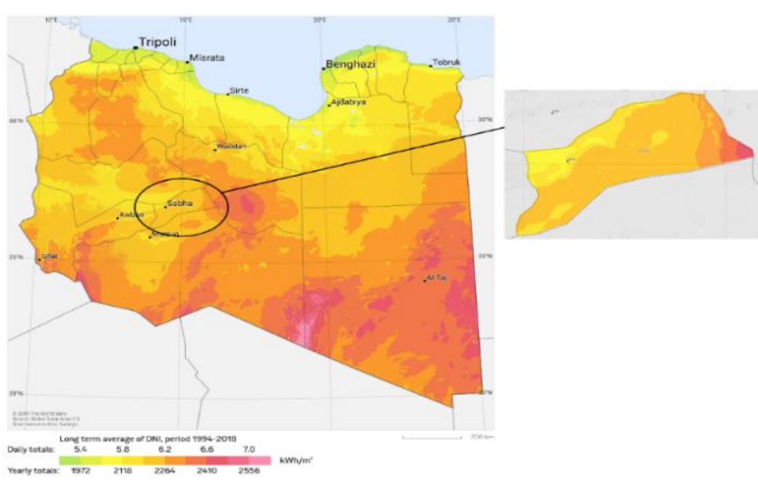


Figure 1. Direct normal irradiation for Libya and Sebha [15]

Libya is one of the countries with high solar radiation, especially in the south, as shown in Fig.1. The study site was chosen in Sebha city ,which is characterized by a large solar radiation intensity ,as shown in Table 2.

Table 2. Sites Geographical Location and Specification

Characteristics of Sebha city	
Latitude	27.038
Longitude	14.428
Elevation	421m
Annual DNI	7.20 $kWh/m^2/day$
Annual average temperature	23.4°C
Annual average wind speed	4.4 m/s
Data Source	ISD-TMY

3. Results and Discussion

Simulations were carried out on the CSP LF system based on the climatic data of the city of Sebha, where the climatic data included the intensity of solar radiation, wind speed, temperature, and sun angle over a whole year.

Therefore, the TES thermal storage system was designed to store heat to benefit from it over a period of 12 hours, and the effect to the Annual Energy, Capacity Factor and LCOE, is shown in Tab.3 , Where the same HTF used in the solar field was relied upon as a storage fluid in TES. Simulations were carried out using the SAM model on the climatic data and the introduction of basic data for the city of Sebha, and the simulation result showed that the best Solar Multiple that can be used in the case of using TES for 12 hours is between six and seven.

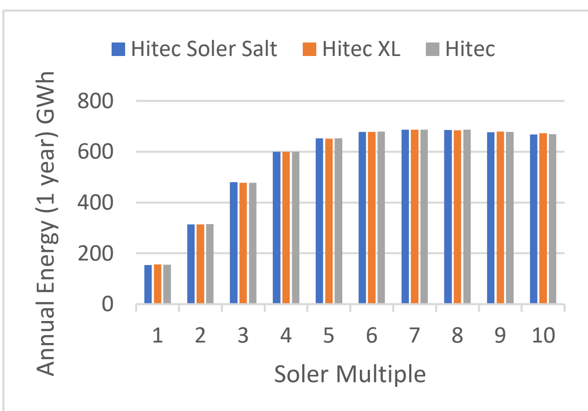
When the results were shown in both the Annual Energy(As shown in figure (2.a)) and Capacity Factor(As shown in the figure (2.b)), starting with (Solar Multiple = 1) low values, it began to rise until it reached the best value when (Solar Multiple =6 to 7). It began to gradually decrease again. This indicates that the best value of SM can be used in this geographical location.

The LCOE chart (As shown in figure 2.c) that showed us the total project lifecycle cost expressed in cents per kilowatt-hour was high when (Solar Multiple = 1). It was gradually declining to (Solar Multiple = 6 to 7). The LCOE started to rise again. The rise in the LCOE value at the beginning of the curve is likely to indicate that the value of SM is low. This leads to not obtaining adequate thermal energy to operate the station throughout the day at the highest capacity.

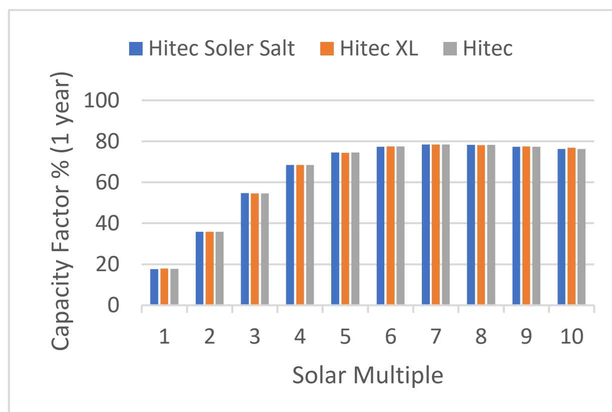
Table 3: The Hitec Solar salt, Hitec XL and Hitec of The Plant

	Hitec Solar salt			Hitec XL			Hitec		
SM	Annual Energy (KWh)	Capacity factor (%)	LCOE (₵/KWh)	Annual Energy (KWh)	Capacity factor (%)	LCOE (₵/KWh)	Annual Energy (KWh)	Capacity factor (%)	LCOE (₵/KWh)
1	153847344	17.6	39.53	157018848	17.9	38.74	154643712	17.7	39.33
2	314773312	35.9	19.55	314560384	35.9	19.54	314846336	35.9	19.52
3	480476256	54.8	12.93	477493248	54.5	13.01	477546496	54.5	13.01
4	600403648	68.5	10.43	599628864	68.5	10.44	600044352	68.5	10.43
5	652775232	74.5	9.62	651814336	74.4	9.64	652443136	74.5	9.63
6	677956672	77.4	9.28	678487680	77.5	9.27	678591360	77.5	9.27
7	686419456	78.4	9.17	687122816	78.4	9.16	686960320	78.4	9.16
8	685281216	78.2	9.19	684282816	78.1	9.20	686246912	78.3	9.17
9	677088256	77.3	9.29	679204736	77.5	9.26	678352832	77.4	9.28
10	667369792	76.3	9.42	672635101	76.8	9.34	668606976	76.3	9.40

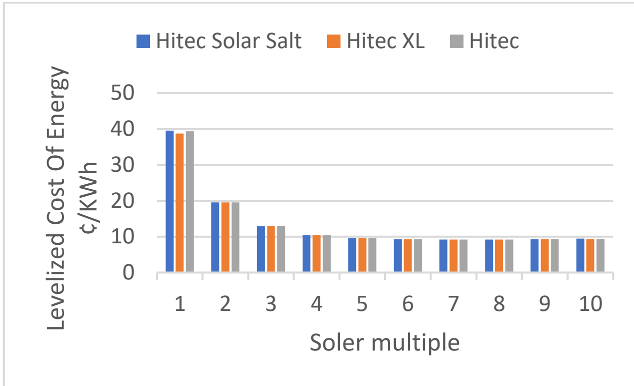
As for the decrease at the end of the curve in the value of LCOE indicates that the value of SM is large, which leads to the use of more resources than required. This increases the construction costs that affect the LCOE directly.



(a)



(b)



(c)

Fig. 2. The effect of solar multiple on: (a) Annual Energy; (b) Capacity Factor; (c) LCOE.

Figure (3) shows Year 1 System Power Generated (kW) For Hitec, as it shows that the largest capacity produced by the station is during the intensity of the sun's brightness and decreases while relying on thermal storage.

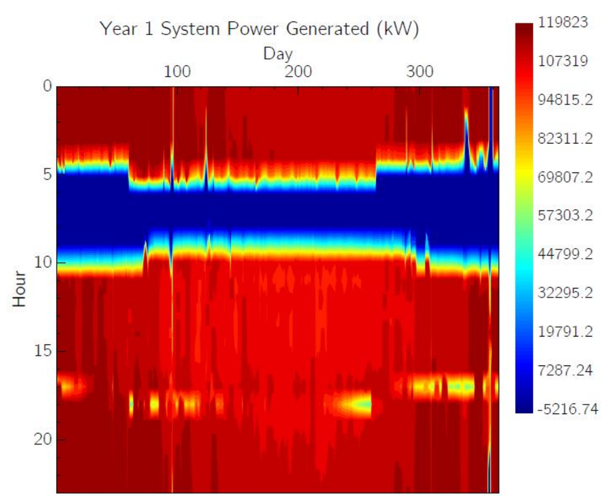


Fig. 3. Year 1 System Power Generated (kW) For Hitec.

The efficiency of the solar field and Field HTF temperature loop outlet differed according to the fluid used (as shown in Tab.4, Fig.4 and Fig.5).

The efficiency of the solar field at (SM = 7), which is shown in figure (4), is stable at the beginning of the day until. It begins to rise with the brightness of the sun until it reaches its maximum value at mid-day, and after that it begins to decline.

The Annual Field HTF temperature loop outlet (C) at (SM = 7), which is shown in the figure (5), is stable at the beginning of the day until it begins to decrease at 5.30 to 7.30 hours. This is due to the loss in the temperature of the fluid passing through the receiving tubes that are exposed to low-temperature atmospheric air. The efficiency of the field begins to rise with the brightness of the sun until it reaches its maximum value at mid-day, and after that, it begins to decline.

The Annual Field HTF mass flow rate loop is shown in Fig.6. Where the flow rate depends on the physical properties of the fluid density, viscosity and evaporation temperature of the fluid (as we see (SM =7). The average flow rate of Hitec fluid is lower than other fluids in the sunshine period and this is due to the physical properties of Hitec that suit the operating conditions.

Table 4: The Annual Thermal efficiency and The Annual Field HTF temperature loop outlet at Solar Multiple equal seven

Time of the Day	Field thermal efficiency			Field HTF temperature loop outlet (C)		
	Hitec solar salt	Hitec XL	Hitec	Hitec solar salt	Hitec XL	Hitec
00:30	0	0	0	281.035	288.9	281.3
01:30	0	0	0	272.723	281.648	273.034
02:30	0	0	0	266.63	274.802	266.991
03:30	0	0	0	262.78	268.574	263.053
04:30	0	0	0	261.436	264.458	261.543
05:30	0	0	0	261.951	261.875	261.972
06:30	0	0	0	263.192	261.274	263.171
07:30	0	0	0	275.937	275.373	275.518
08:30	0	0	0	386.463	381.398	384.744
09:30	0.158995	0.163645	0.158639	492.072	474.88	490.963
10:30	0.336843	0.338245	0.336715	512.873	489.927	512.729
11:30	0.41166	0.408574	0.40888	512.968	489.482	512.933
12:30	0.386085	0.392097	0.385508	511.999	488.807	511.908
13:30	0.401059	0.402381	0.400693	513.759	490.352	513.631
14:30	0.401545	0.403326	0.399325	515.417	492.118	515.538
15:30	0.403444	0.403622	0.401761	511.674	489.155	511.579
16:30	0.371997	0.381025	0.37171	506.762	484.595	506.608
17:30	0.283325	0.281293	0.283573	462.375	448.976	461.375
18:30	0.115885	0.111048	0.114132	374.123	370.398	373.623
19:30	0.0097721	0.00800223	0.00862502	319.525	316.694	320.406
20:30	0	0	0	316.959	316.807	317.415
21:30	0	0	0	308.965	311.532	309.226
22:30	0	0	0	299.447	304.186	299.662
23:30	0	0	0	289.964	296.454	290.192

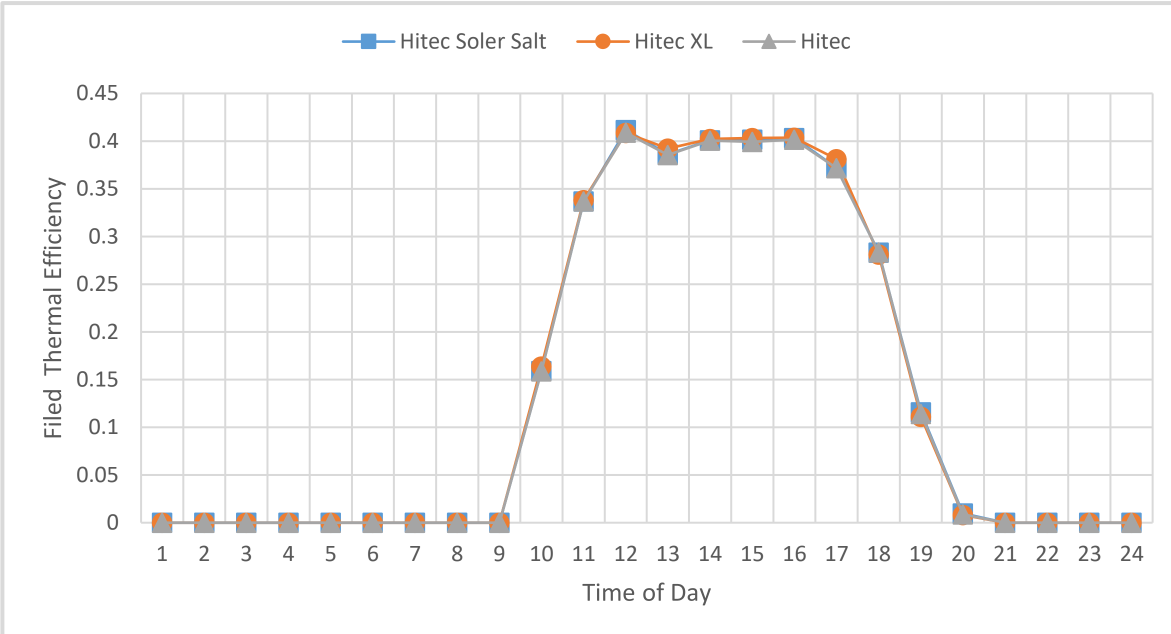


Fig. 4. The Annual Field thermal efficiency

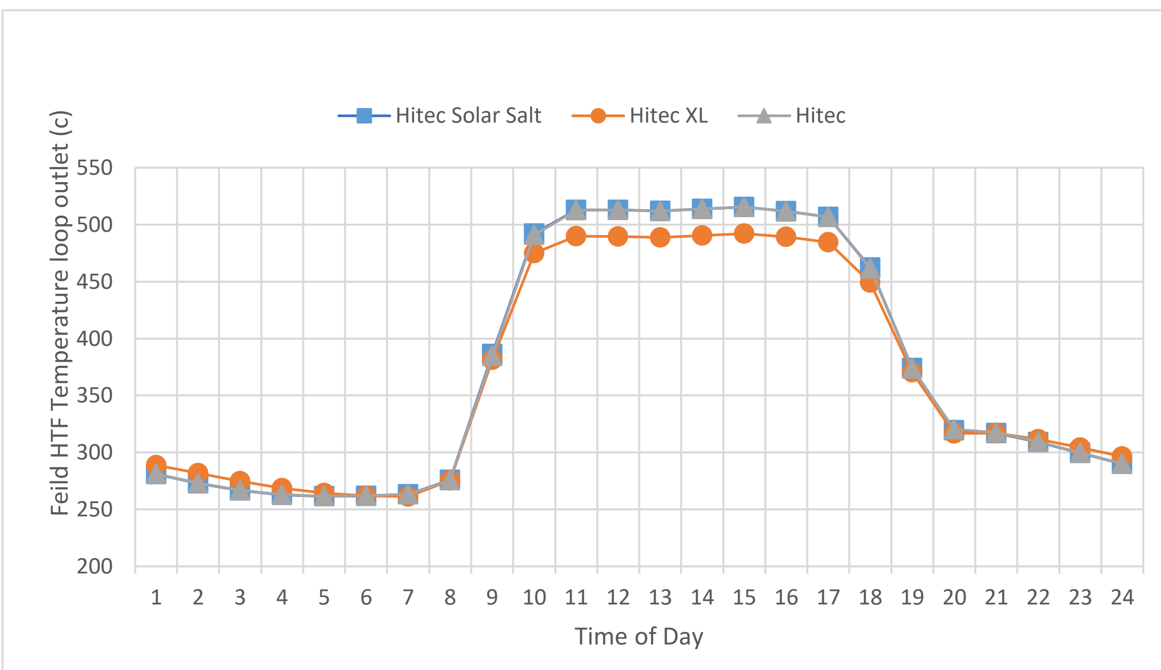


Fig 5.

Fig.5 The Annual Field HTF temperature loop outlet (C)

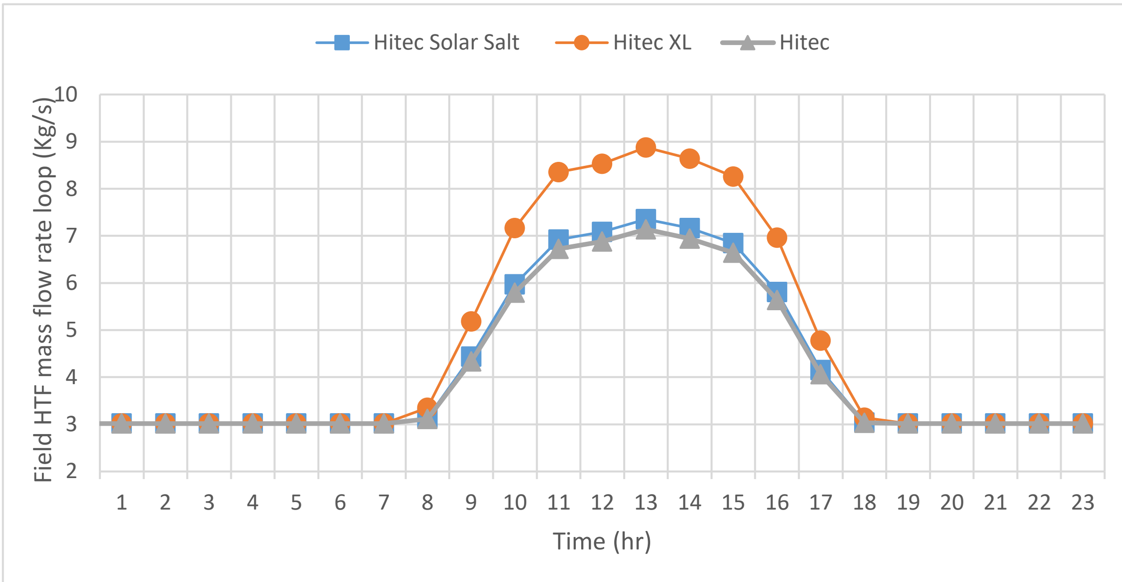


Fig. 6. The Annual Field HTF mass flow rate loop (Kg/s) .

Also from looking at the Hourly System power generated diagram shown in Figure7, the hourly output is almost equal when using any of the types of HTF. This leads the study to choose the best HTF. Likewise, the thermal energy supply has a significant impact on the generation rate, since from the period (3 to 8) in the morning, the rate of energy production decreases due to the absence of solar radiation, as well as the expiration of the heat storage capacity in thermal tanks.

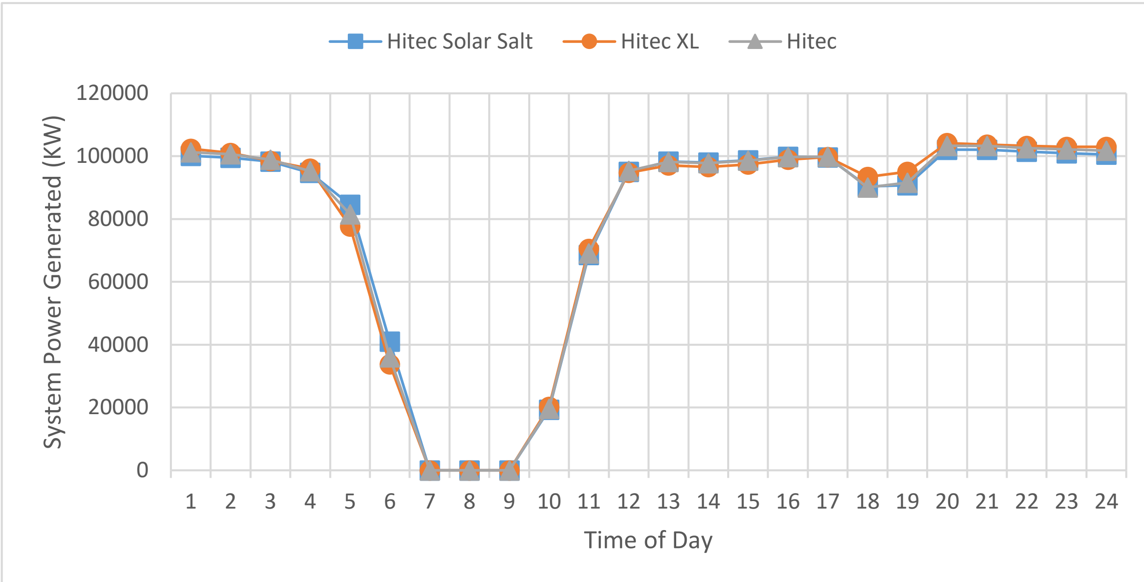


Fig. 7. The Hourly System power generated (kW)

4. Conclusion

By designing and conducting simulations using three types of important heat transfer fluids using the SAM program, we concluded the following:

- The comparison between HTF showed that the best fluid that can be used among these three fluids (Hitec Solar Salt, Hitec XL and Hitec) in these geographical conditions when designing the CSP LF station, with a capacity of 100 MW, is Hitec, which gives the power factor and annual capacity higher than The other HTF, Despite the low characteristics of Hitec and its high price compared to Hitec Solar Salt, it also gave promising results in LCOE.
- Based on previous studies and these results, the geographical location and the surrounding environment influence the choice of the type of heat transfer fluid.
- Choosing the right fluid has a role in increasing the efficiency of the solar field, which is reflected in a large role on the performance and efficiency of the station.

5. References

1. Peterseim, J. H., White, S., Tadros, A., & Hellwig, U. (2013). Concentrated solar power hybrid plants, which technologies are best suited for hybridisation? In Renewable Energy (Vol. 57, pp. 520–532). https://doi.org/10.1016/j.renene.2013.02.014

2. Modi, A., & Haglind, F. (2014). Performance analysis of a Kalina cycle for a central receiver solar thermal power plant with direct steam generation. Applied Thermal Engineering, 65(1–2), 201–208. https://doi.org/10.1016/j.applthermaleng.2014.01.010
3. Vignarooban, K., Xu, X., Arvay, A., Hsu, K., & Kannan, A. M. (2015). Heat transfer fluids for concentrating solar power systems - A review. In Applied Energy (Vol. 146, pp. 383–396). Elsevier Ltd. https://doi.org/10.1016/j.apenergy.2015.01.125
4. Morin, G., Karl, M., Mertins, M., & Selig, M. (2015). Molten Salt as a Heat Transfer Fluid in a Linear Fresnel Collector - Commercial Application Backed by Demonstration. Energy Procedia, 69, 689–698. https://doi.org/10.1016/j.egypro.2015.03.079
5. Institute of Electrical and Electronics Engineers. (n.d.). 2018 International Conference on Computing, Electronic and Electrical Engineering (ICE Cube): 12-13 Nov. 2018.
6. Yakut, M. Z., Karabuğa, A., Kabul, A., & Selbaş, R. (2018). Design, Energy and Exergy Analyses of Linear Fresnel Reflector. In Exergetic, Energetic and Environmental Dimensions (pp. 523–532). Elsevier Inc. https://doi.org/10.1016/B978-0-12-813734-5.00029-9
7. Khandelwal, N., Sharma, M., Singh, O., & Shukla, A. K. (2020). Comparative analysis of the linear Fresnel reflector assisted solar cycle on the basis of heat transfer fluids. Materials Today: Proceedings, 38, 74–79. https://doi.org/10.1016/j.matpr.2020.05.792
8. Pan, C. A., Ferruzza, D., Guédez, R., Dinter, F., Laumert, B., & Haglind, F. (2018). Identification of optimum molten salts for use as heat transfer fluids in parabolic trough CSP plants. A techno-economic comparative optimization. AIP Conference Proceedings, 2033. https://doi.org/10.1063/1.5067028.
9. Vignarooban, K., Xu, X., Arvay, A., Hsu, K., & Kannan, A. M. (2015). Heat transfer fluids for concentrating solar power systems - A review. In Applied Energy (Vol. 146, pp. 383–396). Elsevier Ltd. https://doi.org/10.1016/j.apenergy.2015.01.125.
10. Bishoyi, D., & Sudhakar, K. (2017). Modeling and performance simulation of 100 MW LFR based solar thermal power plant in Udaipur India. Resource-Efficient Technologies, 3(4), 365–377. https://doi.org/10.1016/j.reffit.2017.02.002
11. Marugán-Cruz, C., Serrano, D., Gómez-Hernández, J., & Sánchez-Delgado, S. (2019). Solar multiple optimization of a DSG linear Fresnel power plant. Energy Conversion and Management, 184, 571–580. https://doi.org/10.1016/j.enconman. 2019.01.054
12. Albarqi, A. S., & Boretti, A. (2020). Design of a 100 MW Concentrated Solar Power Linear Fresnel plant with Molten Salt Thermal Energy Storage in Riyadh, Saudi Arabia. Universal Journal of Mechanical Engineering, 8(4), 216–226. https://doi.org/10.13189/ujme.2020.080407
13. Abdelhady, S. (2021). Performance and cost evaluation of solar dish power plant: sensitivity analysis of levelized cost of electricity (LCOE) and net present value (NPV). *Renewable Energy*, *168*, 332–342. https://doi.org/10.1016/j.renene.2020.12.074
14. Bellos, E. (2019). Progress in the design and the applications of linear Fresnel reflectors – A critical review. In *Thermal Science and Engineering Progress* (Vol. 10, pp. 112–137). Elsevier Ltd. https://doi.org/10.1016/j.tsep.2019.01.014

15. World Bank. 2021. Global Solar Atlas. https://globalsolaratlas.info (accessed on 25/4/2022).