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ENERGY SYSTEMS

COMPARATIVE STUDY OF A CONCEPTUAL DIRECT STEAM GENERATION SOLAR
POWER PLANT USING PARABOLIC TROUGH COLLECTORS AND OPTIMIZED
LINEAR FRESNEL REFLECTORS

THESIS

Submitted in partial fulfilment of the requirements for the degree of
DOCTOR OF ENGINEERING SCIENCES

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Articles

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- González-Mora, E., Poudel, R., & Durán-García, M.D. (2023). *A practical upper-bound efficiency model for solar power plants.* Journal of Non-Equilibrium Thermodynamics. 48(1). DOI: 10.1515/jnet-2022-0080
- González-Mora, E., & Durán-García, M.D. (2021). *Energy and exergy (2E) analysis of an optimized solar field of linear Fresnel reflectors for a conceptual direct steam generation power plant.* Energies. 14(4234). DOI: 10.3390/en14144234

Book chapters

- González-Mora, E., & Durán-García, M.D. (2023). *Aplicación de “La nueva ingeniería” en el modelado de un reflector Fresnel para la generación directa de vapor.* UAEM. Accepted.
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- González-Mora, E., & Durán-García, M. D. (2023). *Alternative methodology for modeling direct steam generation in parabolic collectors: A study case in Northeast Mexico.* In ECOS 2023, Gran Canaria, Spain. DOI: 10.52202/069564-0136

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- González-Mora, E., & Durán-García, M. D. (2022). *Propuesta de eliminación del coeficiente convectivo h para el modelado de flujo bifásico en concentradores parabólicos.* XVIII Congreso Ibérico y XIV Congreso Iberoamericano de Energía Solar (pp. 105-112). Universitat de les Illes Balears, Palma, España.
- González-Mora, E., Poudel, R., & Durán-García, M.D. (2022). *Maximum work rate extractable from the sun.* In International Conference on Thermodynamics 2.0 (pp. 57). Appalachian State University, North Carolina, USA.
- González-Mora, E., & Durán-García, M. D. (2020). *Comparativa del rendimiento teórico máximo y estimado de una planta solar de generación directa de vapor.* In CIES 2020 - XVII Congreso Ibérico e XIII Congreso Ibero-americano de Energia Solar (pp. 137-144). LNEG-Laboratório Nacional de Energia e Geologia, Lisboa, Portugal. DOI: 10.34637/cies2020.1.2014

Other research merits

During the course of the research leading to this present work, the author of this thesis has participated in several other publications related to solar energy, thermodynamics, and renewable energy topics. These publications are listed below. While not extensively discussed in this thesis, these publications significantly contributed to project development.

Articles

- Duran García, M. D., Jiménez García, J., González-Mora, E., Weber, B., & García-Vallejo, M. (2022). *Impact of Cost of Solid Biofuels on the Viability of their Application to Generate Process Heat in Mexico: A case of study*. Biofuels Bioproducts and Biorefining. X(X). DOI: 10.1002/bbb.2500
- González-Mora, E. (2021). *Evolution and further improvement opportunities of a non-imaging optics solar cooker design*. Academia Letters. DOI: 10.20935/AL3184
- Durán-García, M.D., Weber, B., Jiménez, J., & González-Mora, E.. (2021). *The application of solid biofuels as a source of process energy in Mexico: case studies using agave and coffee waste*. Biofuels Bioproducts and Biorefining. 15(2). DOI: 10.1002/bbb.2230

Book chapters

- González-Mora, E., Poudel, R., & Durán-García, M.D. (2023). *Solar radiation exergy model to study photosynthesis*. In Albert Reimer (Ed.), *Horizons in World Physics* (pp. 231-255). Nova Science Publishers.
- Rincón-Mejía, E.A., Islas, M. & González-Mora, E. (2023). *Potencial y límites de la energía solar*. In *Transición energética justa y sustentable*. CONACyT. Accepted.

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- González-Mora, E., & Rincón-Mejía, E. A. (2022). *Aplicaciones potenciales de un novedoso concentrador de óptica anidólica.* XVIII Congreso Ibérico y XIV Congreso Iberoamericano de Energía Solar (pp. 133-139). Universitat de les Illes Balears, Palma, España.
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- González-Mora, E., & Rincón-Mejía, E. A. (2021) *Optical Evaluation of the Tolokatsin-2020 High-Efficiency Solar Cooker.* In ISES Solar World Congress 2021. On-line. DOI: 10.18086/swc.2021.31.03
- González-Mora, E., Rincón-Mejía, E. A., & Morillón, D. G. (2020). *Diseño constructal de CPCs y la evolución de los diseños Tolokatsin.* In CIES 2020 - XVII Congreso Ibérico e XIII Congreso Ibero-americano de Energia Solar (pp. 131-136). LNEG-Laboratório Nacional de Energia e Geologia, Lisboa, Portugal. DOI: 10.34 637/cies2020.1.2013

These publications showcase the author's expertise in the field and highlight the diverse applications of solar energy, thermodynamics, and renewable energy technologies. The contribution of the different partners to the project development is acknowledged and appreciated.

Declaration of Authorship

I hereby declare that the contents of this thesis are my original work and have not been submitted in whole or in part for consideration for any other degree or grade at this or any other University, with the exception of explicit references to the work of others. This thesis was developed without any collaboration unless explicitly stated in the text.

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Abstract

Concentrating solar power systems provide a promising option for generating energy from the Sun using thermodynamic cycles. The most commonly used solar power systems are parabolic trough collectors, which use thermal oils as the working fluid. However, the direct steam generation concept provides an alternative approach that generates superheated steam directly in the solar field without using thermal oil. Additionally, one can implement linear Fresnel reflectors instead of parabolic trough collectors. While some analyses of direct steam generation in both concentration geometries exist, there need to be more impartial comparisons of the operating conditions, specifically in Mexico. Therefore, we carried out an unbiased evaluation of several solar fields operating under identical conditions to determine the best option. The analysis considers two 10 MW power blocks employing a Rankine cycle with two and three steam extractions. Sixteen solar fields capable of delivering superheated steam at 400°C and 100 bar, with the mass flow restrictions in the absorbers taken into account, are analyzed. The comparison accounts for the effective concentration area, the nominal pressure at the inlet of each loop, the energy and exergy efficiency, and the hypothetical thermal storage size. Our findings suggest using parabolic trough collector solar fields with ten loops for superior overall performance in both power blocks. However, if pressure reduction is the primary concern, we can use three linear Fresnel reflector loops. For compact solar fields, we recommend using 2-loop of linear Fresnel reflector fields to minimize land use. Furthermore, we suggest using ten parabolic trough collectors loops to prioritize thermal energy storage and enable year-round solar plant operation, even though eight parabolic trough collectors loops would maximize thermal energy storage if that is the sole consideration. The analysis indicates that, under specific criteria, using Fresnel reflectors is advantageous compared to parabolic troughs, thereby providing an opportunity for further studies in this area and a foundation for studies of these technologies for Mexican operating conditions.

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1

Introduction

1.1 Presentation

The consumption of fossil fuels in the socio-economic model has caused such dramatic consequences in recent years that people widely acknowledge that the current energy model is in crisis and, therefore, under a fast and unstoppable transformation. It is urgent to shift from the current centralized system based on fossil fuels toward a distributed system based on renewable energies. Solar energy is an energy source that ought to form a significant portion of the global energy mix due to its cleanliness, environmental friendliness, and widespread availability. One can use solar energy to produce both thermal and electrical power.

Thanks to recent developments in solar energy applications over the past few decades, some of the technologies have already reached a level of maturity that provides a certain degree of confidence for their deployment. In this regard, it is essential to establish the behavior of concentrating solar power plants to facilitate the integration of this technology into the energy matrix. Hence, simulating the installation is mandatory to comprehend the system's operation.

At present, numerous scholars are engaged in research across various disciplines within the realm of harnessing solar energy. Nevertheless, delving into the fundamental constraints set forth by the principles of thermodynamics provides a solid foundation for evaluating solar technologies, including concentrated solar power. This understanding serves as a valuable framework for informed decision-making concerning the deployment and advancement of these technologies. Concentrated solar systems operate by absorbing incident solar radiation, subsequently transforming it into thermal energy, which is then transferred to a fluid circulating within the collector. These systems are typically analyzed using the first law of thermodynamics; however, this does not account for the degrada-

tion of energy during conversion or exchange between streams through heat transfer and pressure drop.

In most cases, engineers design solar power plants with the intention of converting thermal energy into electricity. This conversion is achieved through power cycles employing solar fields equipped with parabolic trough collectors and utilizing thermal oil as the heat transfer medium. The thermal oil, circulating within the collector, passes through heat exchangers within the feed block. Here, it fulfills the roles of preheating, inducing water to boil, and superheating steam, all essential for driving a turbine. It is worth noting that this process operates through two distinct and separate circuits, each employing a different fluid - one in the solar field using thermal oil and the other in the power block utilizing water/steam [16]. In addition, Fresnel reflectors have gained growing interest as a lower-cost alternative to parabolic trough collectors recently.

Furthermore, it is possible to eliminate the necessity for thermal oil in the solar field by obtaining superheated steam directly from it, known as direct steam generation. The direct steam generation systems in linear concentrators appear to have a clear advantage over those using thermal oils. As a result, researchers have compared the two technologies for different thermal powers and diverse locations. However, an objective comparison of the two systems is necessary to establish trends in their future implementation in México.

Establishing the thermal behavior of concentrating solar power plants is crucial if the aim is to include this technology into the energy matrix, both globally and nationally. Although there are already analyses for some case studies, researchers have conducted limited research on direct steam generation in a plant of this type in México. To compare these systems, we need to analyze the alternative of direct steam generation in linear concentrating systems. Therefore, we propose a methodology for designing a parabolic trough plant that can be extended to Fresnel reflectors.

The proposed comparison requires the thermohydraulic characterization of the solar field. For this purpose, we developed flexible thermal-hydraulic models that allow an adequate description of the temperature evolution along each loop using single- and two-phase fluids to characterize the behavior of the solar fields. These models adjust the heat transfer equations and fluid pressure drop correlations by *The New Engineering* methodology. This methodology allows transforming the convection equation in two-phase flow and the friction factor that allows estimating the pressure drop, as described in Appendix A. We validated the thermohydraulic models with experimental data from the Plataforma Solar de Almería (Spain) to ensure they are fully applicable.

The rationale behind this choice lies in the fact that exergy efficiency serves as a metric that takes into account the distinct attributes and limitations inherent to each process within these systems. Nonetheless, the inherent nature of solar energy, manifesting as a flux of thermal radiation, compels a reevaluation of the conventional notion of exergy concerning heat transfer. In the course of calculating the exergy of solar radiation, we discerned that existing models developed over the past six decades overlook certain irreversibilities that manifest within concentrating solar systems. Thus, in tandem with the core research, we embarked on crafting a more comprehensive model that delineates the maximum work rate attainable from the Sun. This model serves as a pragmatic upper-

bound indicator for assessing the efficiency of solar radiation conversion.

The analysis of the conceptual direct steam generation involves two Rankine cycle configurations. The two configurations differ in the number of steam extractions in the turbine, namely two and three steam extractions. These two configurations of the Rankine cycle allow one to identify the water input conditions in the solar field loops. Consequently, we can postulate that the configuration of solar fields can be tailored according to the requisite mass flow rate demanded by the power blocks.

Within the diverse solar field configurations, we systematically adjusted the number of loops to satisfy two critical criteria: firstly, ensuring a turbulent flow regime to facilitate efficient heat transfer from the receiver to the water/steam; secondly, promoting the existence of an annular flow pattern, a preference validated by experimental findings at the Plataforma Solar de Almería. Under the consideration of the three days of analysis (maximum insolation, minimum insolation, and summer solstice), we performed 24 simulations.

Based on the results obtained, we compared the most relevant parameters of the installation. These parameters are the nominal pressure at the loop inlet, total length (and area) of each loop, thermal energy storage, and energy and exergy efficiencies. Special attention must be paid to thermal energy storage since there is not yet a technically mature and commercial system for direct steam generation; thus, we consider only a generic thermal energy storage; so that, in future works, it will be possible to establish its size according to the available thermal capacity and the energy density of the chosen thermal energy storage.

The expected outcomes of this study include identifying the optimal design parameters for solar concentration plants utilizing direct steam generation under different operation conditions, providing valuable insights into the potential for direct steam generation in parabolic trough collectors and linear Fresnel reflectors, contributing to the development of more efficient and sustainable renewable energy technologies. Overall, this study is a significant contribution to the field of renewable energy and has practical implications for the development of solar concentration plants.

1.2 Thesis structure

This Ph.D. thesis was conducted in fulfillment of the requirements for the degree of Engineering Sciences through the specialized post-graduate option as stipulated in articles 57, 59, and 60 of the *Reglamento de Estudios Avanzados* of the Universidad Autónoma del Estado de México. The research project titled “Thermal and Comparative Analysis of a Conceptual Plant for Direct Steam Generation Using Parabolic Trough and Optimized Fresnel Reflectors” was registered under the Secretariat of Advanced Studies with the registration number DCISEN-0222 and is described in this thesis.

The description of this research project begins by stating the problem, followed by presenting the hypothesis, objectives, scope, and limitations. Then, it discusses the methodology used to propose the solar concentrator plant, including the geometries of linear

concentrators and the power block. After that, it summarizes the research conducted by various scholars on direct steam generation. Followed by a summary of the factors that enabled the analysis is shown. Finally, the Research project roadmap provides an overview of the publications derived from our research project, assessing how each publication contributes to fulfilling the project objectives.

2

Research proposal

2.1 Problem statement

The commercial implementation of concentrated solar steam generation power plants utilizing parabolic trough collectors and linear Fresnel reflectors has shown great promise in recent years. However, a significant limitation within this field of research lies in the scarcity of readily applicable models for direct steam generation in solar plants. Existing models often cater to specific study cases, rendering them less effective for broader applications.

Designing a generalized model for direct steam generation analysis of solar concentrators presents a substantial challenge, primarily due to the inherent variations in design features among linear concentrator models. These variations encompass critical factors, including tube diameter, concentrated radiation profile, and receiver inclination. Addressing these discrepancies and incorporating them into a unified framework is essential for achieving comprehensive and reliable results.

Moreover, the prevailing criteria employed in previous studies may not be directly applicable to the unique irradiance conditions encountered in the context of solar steam generation in Mexico. This calls for a thorough reassessment and customization of the evaluation criteria to ensure their suitability for the specific environmental parameters of the region.

By undertaking a comprehensive comparative analysis of parabolic trough collectors and linear Fresnel reflectors, this research aims to develop an enhanced and versatile model that can be applied to a wider range of solar concentrators. The proposed model will account for the varying design features and optimize the direct steam generation process, thereby bridging the gap between existing case-specific models and the need for a more universally applicable solution.

The successful development of this generalized model will significantly contribute to advancing the field of solar steam generation by enabling more accurate predictions and evaluations of system performance. Furthermore, it will facilitate the adoption of solar concentrator technologies in diverse geographical locations, including Mexico, and lay the foundation for the commercial viability of such systems on a larger scale.

Through this study, the research community can gain valuable insights into the design considerations and operational characteristics of parabolic trough collectors and linear Fresnel reflectors, leading to improved decision-making in the selection and optimization of solar concentrators for direct steam generation. Ultimately, this work aims to pave the way for increased sustainability and reduced reliance on conventional energy sources, thereby fostering a greener and more environmentally conscious future.

2.2 Hypothesis

The 2E (energy and exergy) analysis will allow the establishment of thermal performance indicators between an optimized Fresnel reflector system and parabolic troughs, allowing the selection of the most suitable concentration geometry under different operating conditions.

2.3 Objectives

2.3.1 General objective

Use energy and exergy analysis to evaluate concentration systems and formulate indicators for thermal efficiency, solar multiple, and effective concentration area. These will enable the identification of design trends for solar concentration plants in direct steam generation.

2.3.2 Particular objectives

- Define the thermal analysis conditions for the proposed solar plants based on analyses conducted by other researchers;
- Identify and select the type of parabolic trough to be used in the solar field;
- Propose a 2E thermal analysis model for the concentrating system;
- Perform a 2E analysis of each configuration to obtain system performance, solar multiple, and effective concentration area;
- Benchmark the performance and size of the analyzed solar plants to identify design trends.

Through achieving these objectives, this study aims to contribute to the successful development of more efficient and sustainable solar concentration plants in direct steam generation. By identifying design trends and evaluating the performance of different configurations, this study provides valuable insights into the potential for direct steam generation in parabolic trough collectors and linear Fresnel reflectors in México. The findings may serve as a basis for future research in this field and may have practical implications for including this renewable energy technology in the national energy mix.

2.4 Scope and limitations

This study's primary objective is to perform a comprehensive energy and exergy analysis of concentrating solar power plants implementing direct steam generation within both parabolic trough collectors and linear Fresnel reflectors, all under various operational scenarios. The study aims to couple the solar field to two Rankine cycles to deliver a nominal power of 10 MW. The two Rankine cycle configurations differ based on the number of steam extractions. Thus, the fluid temperature at the solar field inlet varies. The analysis will consider the optical errors and imperfections of the concentrating systems but not the tracking errors. For this purpose, it is imperative to define and validate a thermohydraulic model using experimental data gathered from the open literature to get certainty about the results.

The study has some limitations, however. Firstly, the analysis excludes a thermal storage evaluation, as there is no commercial system with direct steam generation for the selected power range. Secondly, due to a lack of analyses to establish an objective and unbiased comparison, the study does not include the thermoeconomic and environmental analysis of the plants. Finally, the study evaluates the thermal process by utilizing relationships reported in the literature rather than conducting a detailed computational fluid dynamics characterization of the two-phase flow in the boiling zone.

Despite these limitations, the study will provide valuable insights into the performance of direct steam generation in parabolic trough collectors and linear Fresnel reflectors under different operating conditions and the coupling of the solar field to a Rankine cycle. The results of this study can provide valuable insights for future research in this field and potentially contribute to the development of efficient and sustainable solar power plants in the Northwest region of Mexico.

2.5 Proposed methodology

The current research project intends to evaluate and compare two linear concentration systems in the context of direct steam generation (DSG). We will extend the methodology proposed by Wang [17] for parabolic troughs collectors to linear Fresnel reflectors, justified by the optical similarity widely reported in the literature [4, 7, 18–21]. We have

opted for this methodology because it incorporates experiences acquired over 30 years of parabolic trough power plant implementation [4].

As stated by Wang [17], design of the concentrating solar power plant, regardless of the chosen concentrating system, should adhere to the fundamental principles of solar energy utilization:

- Adapt to local circumstances, incorporate technological advancements, ensure economic feasibility, and maintain safe and dependable operations.
- Realize economic and societal advantages, conserve energy, optimize engineering investments and raw material usage, and reduce construction timelines.
- Align with prevailing national laws and regulations to protect land, conserve water resources, promote environmental preservation, and adhere to occupational safety and industrial hygiene standards.

When initiating the design proposal for a concentrated solar power (CSP) plant, it is essential to determine the concentration system, working fluid, and nominal power output. The research project objective is to conduct a comparative analysis of two linear concentration systems, both operating at a nominal power output of 10 MW, with a specific emphasis on direct steam generation performance. The aim is to identify design trends and explore the potential integration of these systems into the national energy grid.

The first step is to define the plant's location, typical days of the year to be analyzed, and possible types of tracking. With this information, it will be possible to calculate the solar angles, cosine efficiency, and daily and annual radiation entering the concentrators. This information will aid in selecting the type of tracking and opto-geometric parameters to characterize the concentrating systems. Subsequently, the thermal model will be programmed and validated to ensure convergence and calculate the thermal process. Once we achieve the thermal characterization of the plants, we will determine the thermal performance and the field layout to allow for a comparison of the analyzed systems. Figure 2.1 illustrates this methodology.

2.5.1 Plant location

The location of the plant will be in Agua Prieta, Sonora ($31^{\circ}19' N$, $109^{\circ}32' W$, 1219 m.a.s.l., see Figure 2.2). We selected this specific location due to the presence of a previously constructed integrated solar combined cycle (ISCC) power plant by Abengoa in 2014. This facility utilized parabolic trough collectors and had a nominal power capacity of 12 MW [22, 23]. This is the only CSP plant in México.

2.5.2 Typical days

Wang's methodology [17] establishes the days of solstices and equinoxes as the typical days to be analyzed. The solstices and equinoxes hold paramount importance in the realm

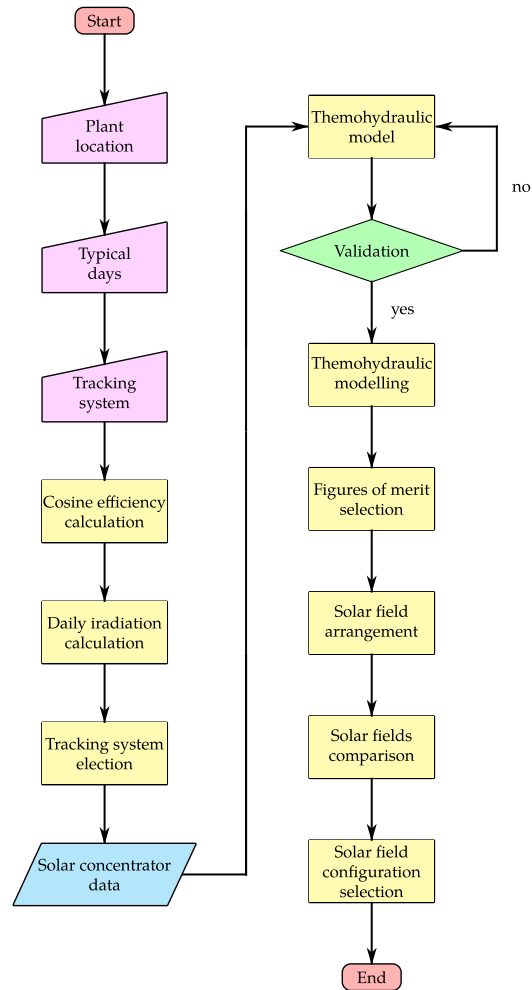


Figure 2.1: Design methodology for concentrating solar power plants with linear systems.

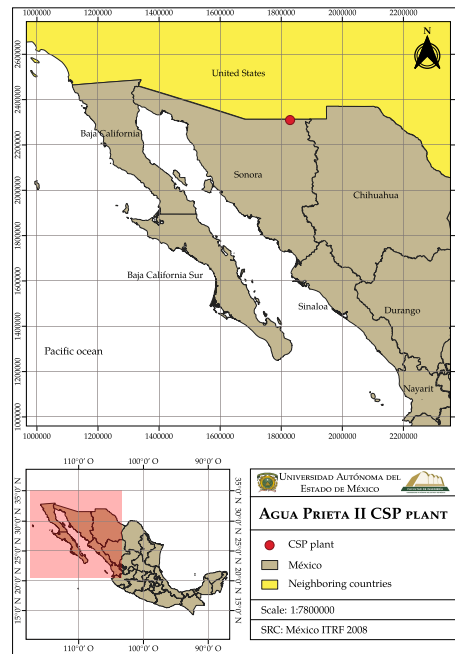


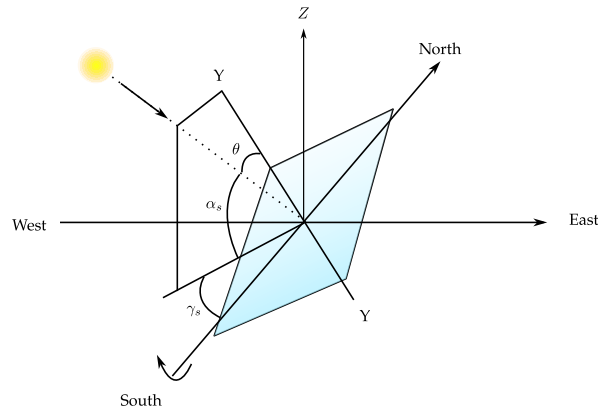
Figure 2.2: Location of Agua Prieta II.

of solar radiation research, as they signify profound shifts in the Earth's position relative to the Sun. These celestial phenomena wield a substantial influence on the quantity and intensity of solar radiation that graces diverse corners of our planet. Consequently, it becomes imperative to embrace these exact moments when delving into the calculations of cosine efficiency and average solar irradiation. This selection follows the same criteria set in other references [14, 24]. Thus, the analyzed selected days are:

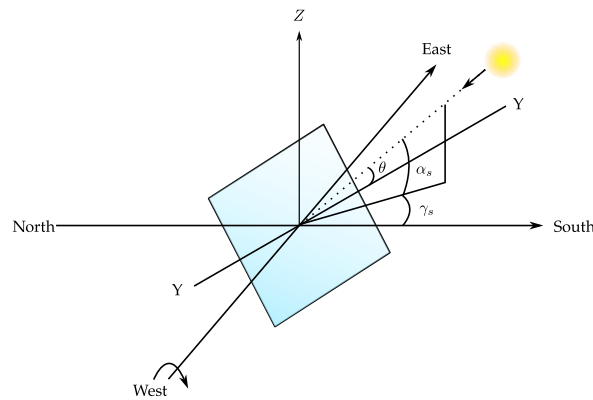
- Spring equinox: March 21st;
- Summer solstice: June 21st;
- Autumnal equinox: September 21st;
- Winter solstice: December 21st.

2.5.3 Tracking system

Concentrating systems are oriented with a tracking system to minimize the angle of incidence of radiation and thereby maximize direct incident radiation [14, 24]. These systems achieve this through the rotation of mirrors around one or two axes. The single-axis rotation may have various orientations, but it is commonly oriented horizontally East-West, horizontally North-South, vertically, or parallel to the Earth's axis.



(a) E-W tracking of the horizontal North-South axis.



(b) N-S tracking of the East-West horizontal axis.

Figure 2.3: Different tracking modes of linear concentrators.

For linearly focused systems such as parabolic trough collectors and linear Fresnel reflectors, there are two ways to track the apparent motion of the Sun on the celestial sphere:

- North-South tracking;
- East-West tracking.

Figure 2.3 exemplifies both systems with a generalized surface.

2.5.3.1 Calculation of solar angles, cosine efficiency and irradiance

It is necessary to define the solar angles involved to evaluate the incidence angle to calculate the cosine efficiency, which depends on the type of tracking. In the case of East-West tracking:

$$\cos \theta = \sqrt{1 - \cos^2 \delta \sin^2 \omega} \quad (2.1)$$

$$\cos \theta = \sqrt{\cos^2 \theta_z + \cos^2 \delta \sin^2 \omega} \quad (2.2)$$

where θ is the incidence angle, δ the solar declination, ω the solar hour angle and θ_z solar zenith angle. These angles, in degrees, are determined by:

$$\delta = 23.45 \sin \left(360 \frac{284 + n}{365} \right) \quad (2.3)$$

$$\omega = 15 (lst - 12) \quad (2.4)$$

$$\cos \theta_z = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta \quad (2.5)$$

with n as a counter for the day of the year, lst the local standard time and ϕ the latitude.

Hottel's model [25] is utilized for calculating irradiance on typical days under specific atmospheric conditions, namely, when the visibility is limited to 5 km, and the altitude is below 2.5 km through:

$$G_{b,n} = 1367 \left[1 + 0.033 \cos \left(\frac{360n}{365} \right) \right] \tau_b \quad (2.6)$$

where $\tau_b = a_0 + a_1 \exp(-k/\cos \theta_z)$ is a parameter indicating the atmospheric transparency of the radiation. The coefficients of this expression, as a function of the altitude A , are determined with:

$$\begin{aligned} a_0 &= 0.97a_0^* \\ a_1 &= 0.99a_1^* \\ k &= 1,02k^* \\ a_0^* &= 0.4237 - 0.00821(6 - A)^2 \\ a_1^* &= 0.5055 - 0.00595(6.5 - A)^2 \\ k^* &= 0.2711 + 0.018580(2.5 - A)^2 \end{aligned} \quad (2.7)$$

When choosing the type of tracking system, a critical parameter to consider is the calculation of daily radiation for typical days (as defined in Eq. 2.8) and the annual radiation (as defined in Eq. 2.9). These calculations play a significant role in determining the suitability and efficiency of the tracking system for a given location.

$$H_{b,n,\text{day}} = \int_{\omega_1}^{\omega_2} G_{b,n} \cos \theta \, d\omega \quad (2.8)$$

$$H_{b,n,\text{annual}} = \int_1^{365} \int_{\omega_1}^{\omega_2} G_{b,n} \cos \theta \, d\omega \, dn \quad (2.9)$$

Table 2.1: Comparison of daily radiation received by concentrators in different tracking modes.

Tracking	Daily radiation [kJ/m ²]		Percentage of daily radiation [%]	
	East-West	North-South	East-West	North-South
Spring equinox	30511	23864	91.44	71.5
Summer solstice	38487	28720	98.51	73.51
Autumal equinox	29866	23544	90.99	71.73
Winter solstice	16991	20935	68.11	83.92

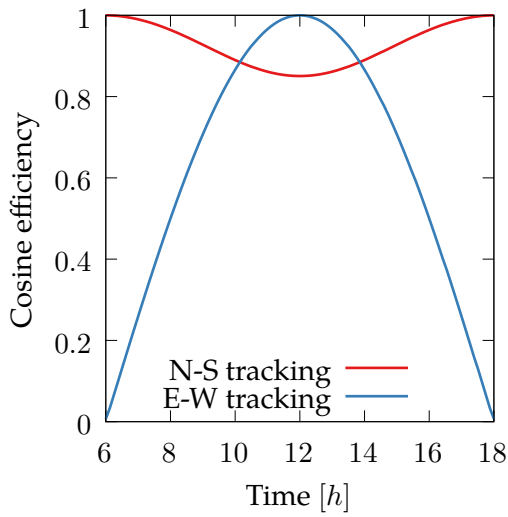
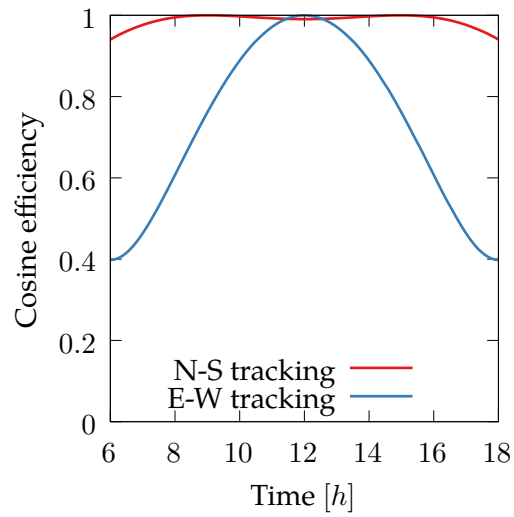
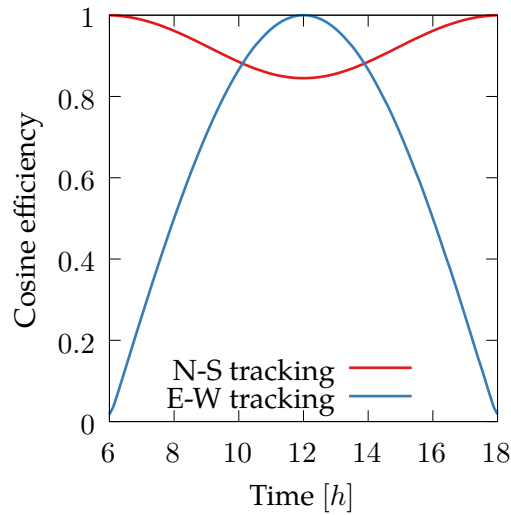
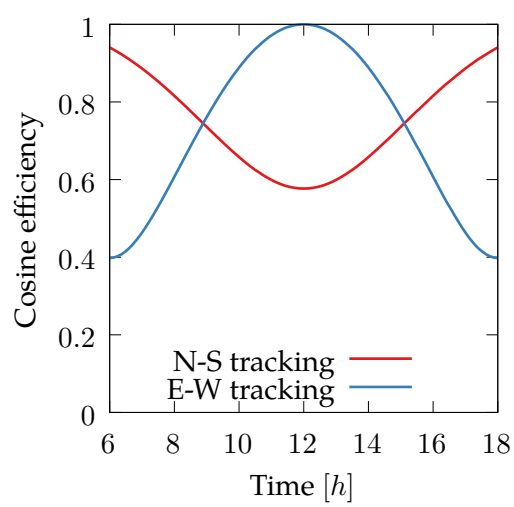
Discussion according to the type of tracking system

The above-described mathematical models can calculate daily and annual radiation values in various axial directions projected onto the concentrator at different times. These values vary in proportion to the cosine of the incidence angle of the Sun's rays. The plots in Figure 2.4 show the cosine efficiency of the N-S and E-W tracking systems as a function of two-axis tracking ($\cos \theta = 1$) for the four typical days of the year.

As a result of the characteristics of solar radiation, the irradiances per unit area of the concentrator exhibit lower values during the morning and afternoon, peaking around noon for both tracking modes. Nonetheless, it is worth noting that in the East-West horizontal axis tracking mode, within the primary operational timeframe of 8:00 - 16:00, the irradiance at the collector exhibits more significant fluctuations compared to the North-South horizontal axis tracking mode. In the latter, the irradiance remains more uniform with less variation. Additionally, the East-West horizontal axis tracking mode features a single peak in all-day instantaneous irradiance, occurring at noon. Conversely, the North-South horizontal axis tracking mode displays two distinct peaks in all-day instantaneous irradiance, each appearing approximately 3 hours before and after noon ($\omega = 0$).

Table 2.1 shows the daily radiation percentage $H_{b,n,day}$ for the two types of tracking analyzed in comparison with two-axis tracking¹, while Figure 2.5 shows the daily radiation values throughout the year. Table 2.2 displays the annual radiation values for the different types of monitoring. The results in both tables were obtained by numerically integrating Eqs. 2.8 and 2.9, with a time step of 36 seconds, as a function of the daily insolation hours.

¹This is because adjusting the angle of incidence to the position of the Sun at all times in two-axis tracking allows capturing the greatest amount of radiation.

(a) *Spring equinox.*(b) *Summer solstice.*(c) *Autumnal equinox.*(d) *Winter solstice.***Figure 2.4:** Cosine efficiency for the different tracking modes.

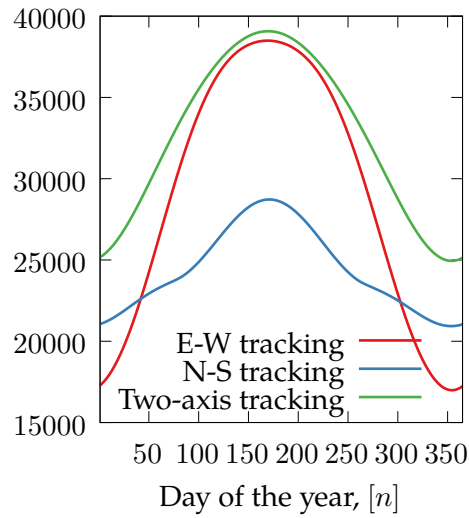


Figure 2.5: Daily solar radiation for different tracking modes throughout the year.

Table 2.2: Annual radiation received by concentrators in different tracking modes.

Tracking	Annual radiation [GJ/m ²]	Average annual radiation [MJ/m ²]	Standard deviation [MJ/m ²]
East-West	10.61	29.12	7.77
North-South	8.88	24.39	2.54

Daily radiation

As shown in Table 2.1, the daily radiation per unit area of the concentrator consistently attains its peak value when employing the two-axis tracking mode. This tracking mode defines the daily radiation received as 100%.

The daily irradiances received by the concentrator play a substantial role, constituting over 90% of the total radiation in the case of the North-South horizontal axis tracking mode. This is due to the relatively small angles of incidence of solar rays during the spring equinox, summer solstice, and autumnal equinox. However, during the winter solstice, the angle of incidence of the solar ray becomes notably larger, resulting in a lower instantaneous radiation per unit area. Consequently, only 68% of the total radiation is attributed to the daily radiation in this mode.

Conversely, in the East-West horizontal axis tracking mode, the daily irradiances during the spring equinox, summer solstice, and autumnal equinox are relatively modest, accounting for approximately 75% of the total radiation. However, during the winter solstice, the radiation per unit area is proportionally higher, allowing the daily radiation to account for up to 84% of the total radiation in this mode.

Annual radiation

Figure 2.5 illustrates the variations in daily radiation across the seasons in the three monitoring modes employed throughout the year. Notably, the daily radiation levels peak during the summer months and dip to their lowest values in winter. Monthly radiation patterns reveal that the highest levels occur in May and July, while the lowest values are observed in January and December, with the former being nearly twice as high as the latter. Consequently, it is evident that the prime period for harnessing solar energy effectively falls between April and September.

The examination of the annual radiation calculation, as presented in Table 2.2, indicates that the North-South horizontal axis tracking mode boasts the highest annual radiation levels. Linear concentrator systems, such as parabolic troughs and Fresnel reflectors, usually employ a single-axis tracking mode due to their simple structure and lower tracking accuracy requirements.

In contrast to the East-West horizontal axis tracking mode, the North-South horizontal axis tracking mode receives greater radiation into the concentrator. Nonetheless, it is essential to note that the variation between summer and winter output is substantial ($\sigma = 7.77 \text{ MJ/m}^2$). Therefore, if the objective is to attain maximum energy output from the collector during the winter months, the East-West horizontal axis tracking method is preferable. Conversely, if the primary focus is on summer utilization, then the North-South horizontal axis tracking mode should be adopted.

One parameter to consider in concentrating solar power plants is the amount of total precipitation throughout the year. Figure 2.6 shows the average precipitation in each month, which shows the low amount of precipitation, so this will not be a variable that significantly affects the solar radiation profiles shown in Figure 2.5.

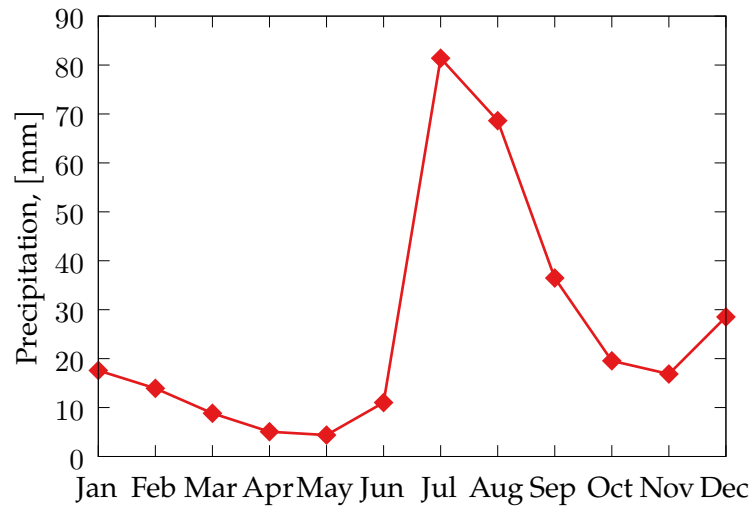


Figure 2.6: Average precipitation of Agua Prieta, Sonora (1961-2016) [1].

Apart from the factors discussed earlier, linear concentrators are often connected in series and parallel configurations to achieve the necessary temperature levels and generate electricity using thermodynamic cycles. Consequently, it is crucial to account for potential shading effects caused by nearby collectors. In the North-South horizontal axis tracking mode, shading is minimal and primarily occurs during mornings and evenings. Conversely, in the East-West horizontal axis tracking mode, the shading impact is negligible, with the concentrator mainly casting shadows on collectors situated to the north during the winter solstice when its tilt angle reaches its maximum value.

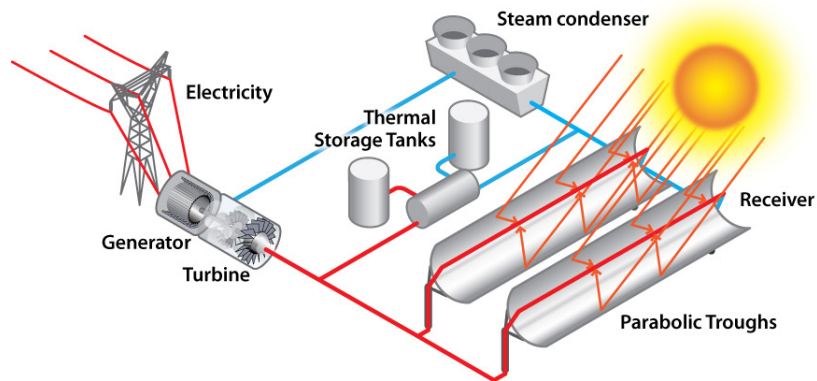
2.5.4 Linear solar concentrator geometries

Linear solar concentrators utilize parabolic troughs or linear Fresnel reflectors to concentrate solar radiation onto a linear receiver. A linear Fresnel concentrator represents a distinct concentrator type characterized by individual reflectors rather than a continuous reflecting surface. While this design choice might entail a slight optical efficiency loss, it could potentially bring about other advantages that enhance the overall efficiency or cost-effectiveness of the concentrator. To better understand and quantify these potential benefits, further research is warranted, as indicated in Figures 2.7(a) and 2.7(b).

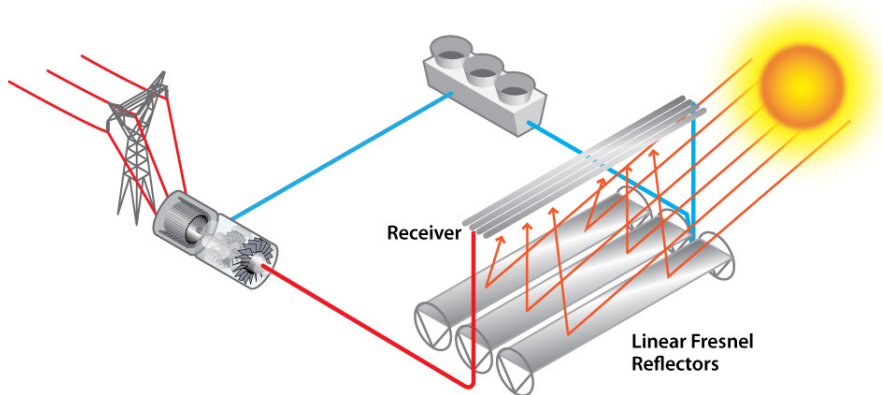
2.5.4.1 Parabolic trough collector

A traditional parabolic trough solar concentrator consists of a parabolic reflector [3], which includes:

- Support structure for the reflector;



(a) *Parabolic trough collector with mobile receiver and thermal energy storage tanks.*



(b) *Linear Fresnel reflector with fixed receiver and no thermal energy storage.*

Figure 2.7: Linear solar concentrator geometries [2].

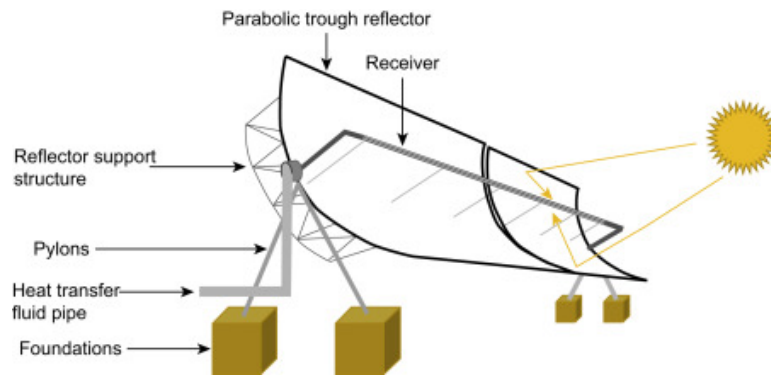


Figure 2.8: Schematic of a parabolic trough collector [3].

- Pylons equipped with joints for single-axis tracking;
- Foundation piers for stability;
- Receiver fixed to the reflector support structure;
- Piping system for transferring the heat transfer fluid to the receiver and directing it to the storage or utilization location.

Parabolic trough concentrators (PTC) are organized in parallel rows within a solar field. These rows are spaced apart strategically to prevent excessive shading of the reflectors, ensure ease of maintenance access, and minimize the energy needed for pumping the heat transfer fluid (HTF). Normally, the HTF enters at one end of the trough and exits at the opposite end. However, some configurations may feature a pipe-in-pipe arrangement, allowing both entry and exit at a single end [4, 21, 26], see Figure 2.8.

Typically, one installs parabolic troughs to optimize annual energy production by aligning the concentrator with the north-south axis for horizontal tracking. During winter, it is possible to install PTC aligned in the east-west direction to optimize solar midday power production. Commercially available solar trough concentrators achieve optical concentration ratios of 50 to 80, depending on the HTF [4, 21, 26].

Opto-geometric description of the parabolic trough collectors

Concentrating solar devices PTCs rely on solar tracking systems to adjust their orientation according to the Sun's apparent path in the sky, which changes from sunrise to sunset. These solar collectors move with a single degree of freedom, typically involving a single-axis rotation. This rotation is crucial to ensure that the concentrator consistently reflects and focuses the solar radiation beam onto the receiver tube. Precise concentration wouldn't be achievable without maintaining the correct rotational angle throughout the day.

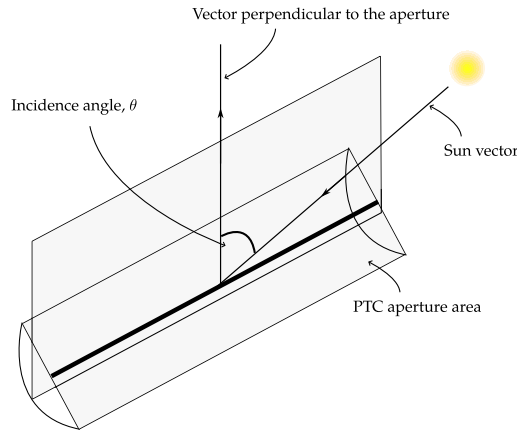


Figure 2.9: Positioning of a PTC.

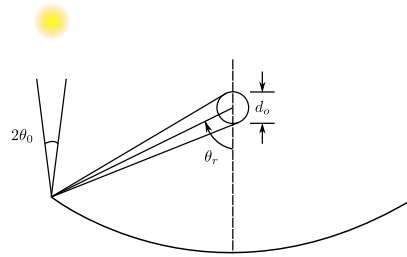


Figure 2.10: Schematic diagram of the cross section of a PTC. Adapted from [4].

Figure 2.9 visually represents the necessity for direct solar radiation to reach the collector's aperture plane for efficient reflection by the receiver tube. To achieve this, it is essential that the parabolic trough collector is positioned in a specific manner. Specifically, the solar vector (indicating the direction of sunlight), the focal line of the collector, and the vector perpendicular to the collector's aperture plane should all lie within the same plane. This alignment ensures that the angle of incidence remains minimized, allowing for optimal collection of solar energy.

Figure 2.10 represents the cross-section of a PTC geometry. The optimal concentrator using this geometry should reflect the extreme rays incident at an angle θ_0 over the entire circumference avoiding optical losses. The geometric concentration ratio, C_g , denoted as the aperture-to-absorber area ratio, quantifies the relationship between the collector's aperture area and the total absorber area (assuming that the PTC has a length equal to that of the absorber), allows relating the parameters of the rim angle (θ_r) and the acceptance angle ($2\theta_0$) by:

$$C_g = \frac{Wl}{\pi d_o l} = \frac{\sin \theta_r}{\pi \sin \theta_0} \quad (2.10)$$

The wider the acceptance angle of the PTC, the lower the precision required for the

solar tracking system. This is because a wider acceptance angle allows the concentrator to maintain effective concentration even with slight deviations in its orientation, reducing the need for frequent adjustments. The acceptance angle cannot exceed the size of the Sun ($2\theta_0 = 2\theta_s \approx 32'$), which is the limiting factor for the acceptance angle. Commercial parabolic trough collectors are typically designed with recommended acceptance angles falling within the range of 1 to 2 degrees. Additionally, the rim angles are usually set between 70 and 100 degrees. These specifications result in geometric concentrations ranging from 20 to 30, depending on the heat transfer fluid used [4, 21, 26]. With $\theta_0 = 16'$ and $\theta_r = 90^\circ$, one obtains the maximum geometric concentration ratio of 68.39.

Parabolic trough collector receivers

In large-scale PTCs, the conventional receiver tube comprises two concentric tubes: an inner steel tube that contains the working fluid and an outer glass tube that surrounds the steel tube. To enhance the transmittance of solar radiation, manufacturers typically employ borosilicate glass with low iron content for the outer glass tube. The outer surface of the steel pipe is equipped with an optically selective coating, which exhibits high solar absorptance and low infrared radiation emission. Additionally, the glass tube is often coated with an anti-reflective material to boost solar transmittance and enhance overall annual performance [4, 14, 24].

Parabolic trough collector receivers can be categorized into two main types: evacuated and non-evacuated. Evacuated receivers, as shown in Figure 2.11, are typically employed when operating temperatures exceed 300°C . They feature a high vacuum, often around 10^{-5} mbar, located between the steel tubing and the glass cover. This vacuum significantly diminishes convective heat losses, leading to improved overall efficiency of the parabolic trough collector, particularly at elevated operating temperatures [4].

The diameter of the receivers in a PTC is contingent on the opening width of the parabolic trough. For parabolas up to 6 meters, the standard outside diameter of the steel absorber tube measures 70 mm. However, for larger parabolas, it becomes feasible to employ steel tubes with diameters of 80 mm or 90 mm. For more detailed information, please refer to Table 2.3, which outlines specific receiver parameters.

2.5.4.2 Linear Fresnel reflector

A conventional linear Fresnel solar concentrator consists of reflectors, which can either be flat or slightly parabolic [3], these components typically include::

- A support structure for the reflectors;
- A framework with joint attachments to enable single-axis solar tracking;
- Foundations in the form of piers;
- A receiver positioned above the support structure, but separate from it;

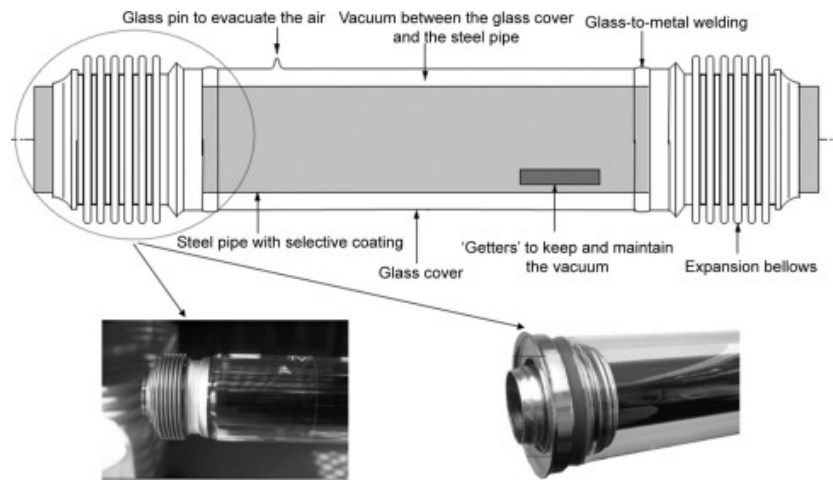


Figure 2.11: Scheme of typical evacuated receiver for parabolic-trough collectors and details of two different expansion bellows [4].

Table 2.3: Technical parameters of the 70 mm and 90 mm PTC receivers offered by Rioglass in 2019 [4].

	70 mm PTC Receivers	90 mm PTC Receivers
Steel absorber solar absorptance	0.94	0.95
Glass cover solar transmittance	0.96 – 0.97	0.96 – 0.97
Steel absorber thermal emittance	0.095 at 400°C	0.095 at 400°C
Length	4060 mm ± 2 mm	4060 mm ± 2 mm
Steel pipe inner/outer diameters	66/70 mm	85/90 mm
Steel absorber	Stainless steel	Stainless steel
Glass cover outer diameters	125 mm ± 2.5 mm	142 mm ± 2.5 mm
Glass cover	Borosilicate	Borosilicate
Active length ratio at 350°C	96% – 97%	96% – 97%
Maximum fluid temperature	400 – 450°C	400 – 450°C

More information at: <https://www.rioglass.com/our-products/hce-tubes>

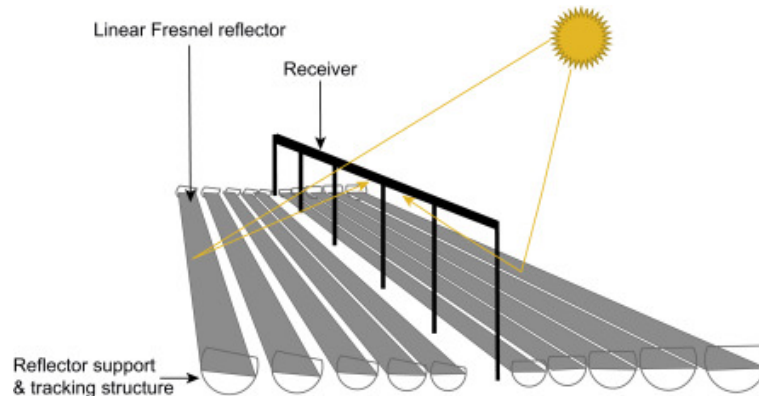


Figure 2.12: Schematic of a linear Fresnel reflector [3].

- A network of pipes for transporting the heat transfer fluid to the receiver and from there to the storage or utilization location.

In a linear Fresnel reflector (LFR), one places the primary mirrors above the ground, resulting in each mirror having a distinct focal length in relation to its respective receiver. The designer minimizes the reflector spacing to reduce discontinuity in the reflecting area or aperture. The primary mirror width is optimized to allow easy access maintenance without adding complexity to the support structure or tracking mechanism [7, 21, 26], see Figure 2.12.

While one can position a reflector to serve more than one receiver, one must also consider providing access to the receiver for maintenance. The alignment procedure for Linear Fresnel systems is akin to that of PTCs. Commercially available LFR can attain optical concentration ratios ranging from 30 to 70, contingent upon the choice of heat transfer fluid employed [7, 21, 26].

Opto-geometric description of the linear Fresnel Reflectors

It is possible to approximate the optical properties of parabolic troughs using small reflector elements distributed over a suitable flat surface. This design makes it possible to construct large concentrating systems from small mirrors. Figure 2.13 outlines the fundamental geometry of a LFR. In this representation, we denote w as the width of each mirror, g as the spacing between adjacent mirrors, W as the overall width of the LFR, and H as the receiver height.

Typically, the receiver of linear Fresnel reflectors includes a secondary concentrator to ensure that it redirects rays not directly incident on the absorber tube, avoiding any optical losses. Generally, this second concentrator stage employs non-imaging optics, mainly modified compound parabolic collector (CPC) geometries [5, 6].

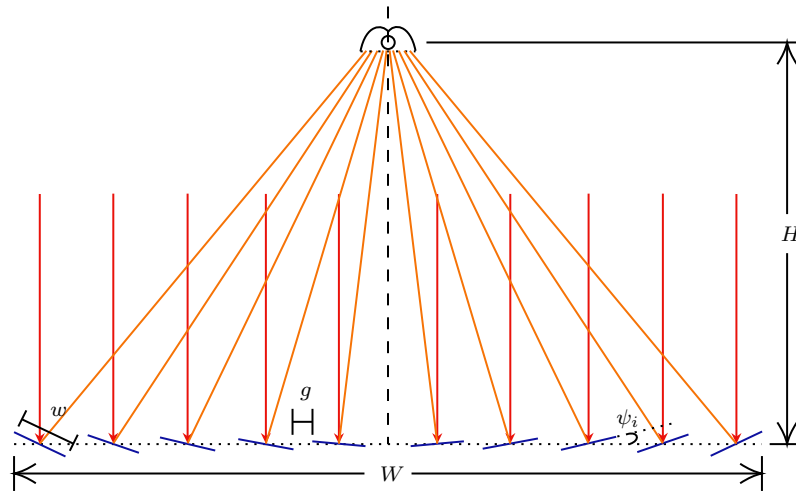


Figure 2.13: Geometric cross section of a LFR system. Adapted from [5–7].

2.5.4.3 Characteristics of commercial linear concentrators

Companies have developed several parabolic trough collectors and Fresnel reflectors for different applications [4, 7]. Nevertheless, few companies have generated data on power production in commercial systems. A comparison between the FRESDEMO prototype system and a previously analyzed optimized system is in Table 2.4. Table 2.5 summarizes the most relevant opto-geometric parameters of the different parabolic trough collectors.

Table 2.4: Comparison of the description of the Fresnel reflector with the optimized solar field for Agua Prieta, Sonora [6, 12].

Concentrator	FRESEMO	Optimized
Number of primary mirrors	25	
Field width, [m]	21	
Primary mirrors total length, [m]	100	
Primary mirrors width, [m]	0.6	
Fill factor	0.7143	
Receiver length, [m]	100	
Receiver height, [m]	8	15
Receiver aperture area, [m]	0.5	
Absorber diameter, [m]	0.14	
CPC half-acceptance angle, [deg]	56	66.30
Intercept factor	0.5753	0.7231
Average optical concentration ratio	74	80

Table 2.5: Characteristics of commercial parabolic troughs [4, 13–15].

Concentrator	Acurex 3001	M.A.N. M480	Luz LS-1	Luz LS-2	Luz LS-3	Eurotrough	SL4600	
Year	1981	1984	1984	1985	1988	1989	2004	2011
Area, [m ²]	34	80	128		235	545	545/817.5	550
Aperture, [m]	1.8	2.4	2.5		5	5.7	5.77	4.6
Length, [m]	20	38	50		48	99	99.5/148.5	120
Absorber diameter, [m]	0.051	0.058	0.042		0.07	0.07	0.07	0.07
Average optical concentration ratio	36	41	61		71	82	82	66
Optical efficiency	0.77	0.77	0.734	0.737	0.764	0.8	0.78	0.75
Receiver absorptivity	0.96	0.96	0.94	0.94	0.99	0.96	0.95	-
Mirror reflectivity	0.93	0.93	0.94	0.94	0.94	0.94	0.94	0.95
Absorber emittance [at °C]	0.27	0.17	0.3 (300)	0.2 (300)	0.1 (350)	0.1 (350)	0.14 (400)	-
Operating temperature [°C]	295	307	307	349	390	390	390	500

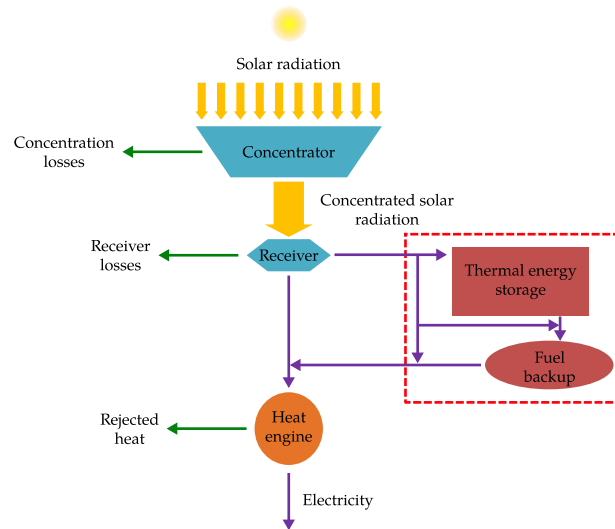


Figure 2.14: Schematic diagram of a typical solar thermal power plant. Adapted from [8].

2.6 Solar power plant description

2.6.1 Power block proposal

Concentrated solar power plants convert solar radiation into electricity using lenses or mirrors with their respective solar tracking systems. Thus, CSP uses different geometries to capture the energy in one area and redirect it to a small one to increase the energy density, increasing the temperature of a heat transfer fluid. A thermodynamic cycle can use this fluid at high temperatures and pressure, generally, a Rankine cycle [3, 27].

Concentrated solar power is an indirect method of power generation; Figure 2.14 schematically depicts the typical configuration of this technology. Large-scale solar thermal to electric power conversion is not only technically viable but also economically sound, particularly in grid-connected applications. Such installations can range from several megawatts (MW) in capacity to smaller facilities like Puerto Errado (1 MW) and Tai Solar One (5 MW), as well as larger projects like the Ivanpah Solar facility with 377 MW capacity [8].

Concentrating solar technologies can be broadly classified into two groups, namely linear focus concentrators and point focus concentrators [3, 26, 27]. Of all the existing ones, the ones used for solar plants are the solar tower, parabolic dish, parabolic troughs, and linear Fresnel reflectors [3, 9]. Linear focus concentrators can reach temperatures of up to 550°C, while point focus concentrators between 800-1000°C [28, 29]. Thus, as shown in Figure 2.14, it is possible to supply this thermal power to a heat engine, generally Rankine cycles.

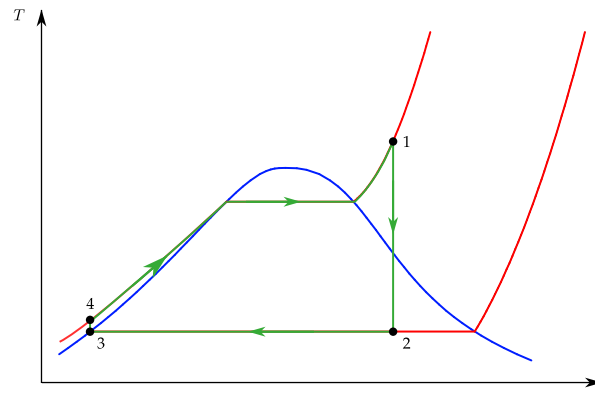


Figure 2.15: $T - s$ diagram of an ideal Rankine cycle.

Rankine cycle description

The Rankine cycle is, in essence, a modified Carnot cycle¹ to overcome and eliminate many of the difficulties that arise with the Carnot cycle when the working fluid is steam [30]. The ideal superheating Rankine cycle, depicted in Figure 2.15 with a $T - s$ diagram, is composed of four basic processes:

- 1→2: Isentropic expansion in a turbine;
- 2→3: Isobaric cooling in a condenser;
- 3→4: Isentropic compression in a pump;
- 4→1: Isobaric heating in a steam generator.

Integration of linear concentrators with a steam Rankine cycle

A heat engine, such as a Rankine cycle, allows certain flexibility in the high-temperature source that supplies heat to generate steam at high temperatures and pressure. In the case of concentrating solar power plants, using different concentrating geometries allows the supply of heat demands.

At present, there are two alternatives for the integration of linear concentrators in power cycles, as shown in Figure 2.16. The first option, Figure 2.16(a), corresponds to a traditional system in which the solar field works with a heat transfer fluid, generally thermal oil, which is redirected to a series of heat exchangers to transfer heat and generate steam. The limitation of this configuration is that the heat transfer fluid usually degrades at 400°C [4, 9], limiting the maximum operating temperature of the thermodynamic power cycle.

An alternative approach, referred to as direct steam generation (DSG), presents an innovative solution by bypassing the use of thermal oil altogether. Instead, DSG systems produce the necessary superheated steam directly within the receiver tubes, effectively

¹The Carnot cycle is a theoretical cycle that obtains the highest possible thermal efficiency.

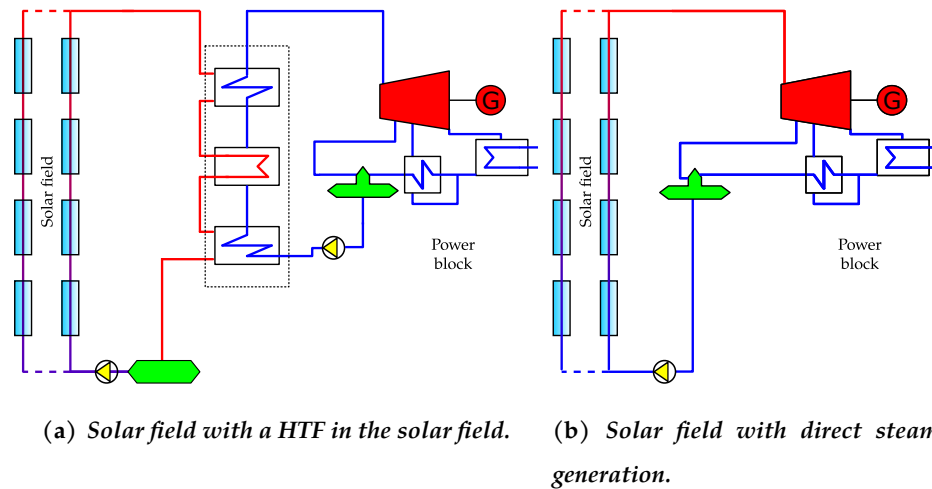


Figure 2.16: Schematics of solar plants with linear concentrators. Adapted from [9].

streamlining the process and eliminating the need for an intermediate heat transfer fluid like thermal oil [9], as shown in Figure 2.16(a). DSG has some technical advantages that should be considered [9, 31, 32]:

- It eliminates the risk of contamination or fire associated with thermal oil usage;
- It enables the potential to elevate the maximum temperature of the Rankine cycle beyond the current limit of 400°C imposed by conventional thermal oil systems;
- It allows for a reduction in the size of the solar field, leading to decreased investment costs;
- It results in lower operational and maintenance expenses compared to thermal oil-based systems, which necessitate annual oil replacement and antifreeze measures in temperatures below 14°C.

Historically, direct steam generation was the first technology employed in solar thermal concentrating systems. John Ericsson’s heat engines (1870-1883) delivering 0.3 kW output were essentially the first DSG concentrators, while Frank Shumman’s plant (1912) in Egypt is considered the first commercial direct steam generation solar plant [33]. The concept of direct steam generation obtains more than 522 MW of the total installed [22]. Power towers are the most common direct steam generation technology, accounting for 90.9% of the total installed capacity. The largest power tower plant worldwide is the Ivanpah Solar plant, with a capacity of 377 MW. Linear Fresnel reflectors account for 7.7%. The only commercial parabolic trough collector plant is Thai Solar Energy 1, with a capacity of 5 MW.

Direct steam generation is considered a potential method for improving the current technology of parabolic solar power plants. Nevertheless, adopting this approach introduces specific challenges attributed to the two-phase flow (comprising liquid water and steam) within the absorber tubes of the solar field's boiling section. Prior to widespread commercial adoption of this technology, it is imperative to confront the uncertainties stemming from the existence of two-phase flow. These uncertainties encompass [4, 9]:

- Effective control of the solar field's operations;
- Maintaining process stability throughout operation;
- Mitigating thermal stresses experienced by the receiver tubes;
- Managing potentially higher steam losses (leakage) compared to oil-based systems.

2.7 Direct steam generation research

The DISS (DIrect Solar Steam) project aimed to address the concerns surrounding DSG technology. It involved the creation of a testing facility at the Plataforma Solar de Almería in Spain, as documented in [34]. This facility boasted a 100-meter-long array of parabolic trough concentrators with a 2 MW capacity. Researchers at this facility conducted tests under various operating conditions and pressures, aiming to determine the optimal control parameters, as detailed in [31]. Researchers also utilized the facility to thoroughly examine startup and shutdown procedures and assess the rate of absorber tube deformation. The facility was operational for more than 3500 hours during the period from 1999 and 2001 [35]. The results obtained from these experiments have significantly contributed to the growing interest in DSG research, as evidenced by the bibliometric network depicted in Figure 2.17, which illustrates the evolving trends in direct steam generation for power production.

As can be seen, establishing the thermal behavior of a CSP is of great relevance since a better understanding of this technology will lead to an increase in its deployment in the global energy mix. Regarding DSG is concerned, there is already a variety of research on this topic, some focus on operability, while others focus on modeling. For example, Almanza et al. [36, 37] operated a PTC plant to power a low-power steam engine, emphasizing the deflection problems that low-temperature systems present.

Eck et al. [34], Zarza [35] and Giglio et al. [32] describe the DSG process and some technology trends, emphasizing the problems associated with two-phase flow. These works establish that PTC technology will allow for a considerable reduction in energy costs. Bernhard et al. [12] describe the Plataforma Solar de Almería FRESDEMO field and emphasize that DSG with LFR is still under development, but a good starting point is the analysis already done with PTC. Chiarappa [38] performs a comparison between a DSG system in the laboratory with an actual plant with more than 500 hours of operation, detailing that current models allow for an error of less than 5%.

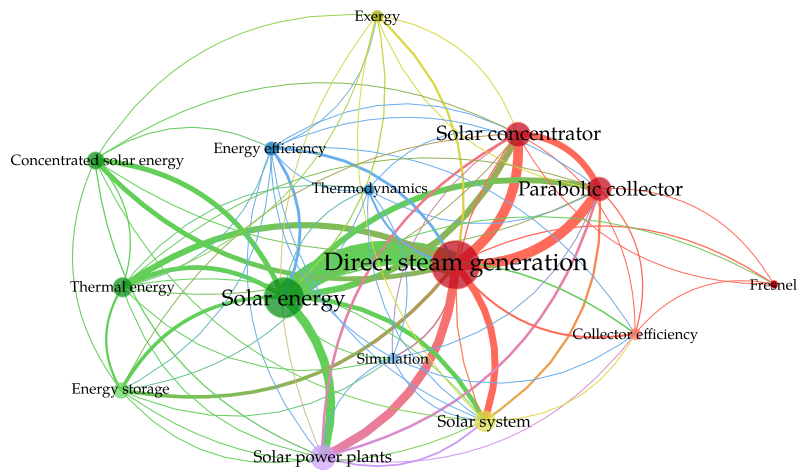


Figure 2.17: Bibliometric network of the study of direct steam generation of articles indexed in Scopus.

In their study Sun et al. [39] review some numerical models developed for PTC with DSG and note the need for proprietary codes since most models are not readily available for general use. Meanwhile, Hachicha et al. [40], Sandá et al. [41], and Gharbi et al. [18] conduct comparative studies of LFR and PTC for DSG. They conclude that while LFR and PTC systems have similar optical properties, LFR systems tend to have lower overall performance due to the inherent characteristics of the reflectors. Additionally, Morin et al. [19] compare LFR and PTC for CSP and highlight that while solar plants using LFR generally achieve lower optical efficiency, compensating for the thermal losses results in the final efficiency.

Montes et al. [42] analyze different LFR configurations in DSG and define a new variable, "useful energy efficiency" as a function of the blocking between shadows of the mirrors. They highlight that although the optical performance increases, the thermal performance does not show much difference. However, the complexity of the system will become higher. In a study conducted by González-Mora et al. [43] one can find an in-depth energy and exergy (2E) analysis. This analysis encompassed various configurations of a hypothetical direct steam generation solar power plant featuring optimized LFR in Agua Prieta, Sonora. As a result of the DSG research, it is possible to identify some operating parameters that will allow establishing the initial values for the thermal model and the analyses to be developed in the next stage of the project. These parameters are shown in Table 2.6.

Table 2.6: Plant operation parameters in DSG with linear concentrators.

Project	Technology	Power [MW _t]	Pressure [bar]	Temperature [°C]	Operation mode
					Recirculation (Preferred)
DISS [31, 34, 35]	PTC	2	100	400	Injection Once-through
REAL-DISS (Carboneras) [44]	PTC	–	120	500	Recirculation
INDITEP [45]	PTC	19	70	410	Recirculation
DUKE [46]	PTC	244	110	500	Recirculation
TSE-1 ¹ [47–49]	PTC	5	30	330	Recirculation
Puerto Errado 1 [22]	LFR	11.5	55	550	Once-through
Puerto Errado 2 [22]	LFR	150	55	270	Once-through
eLLo Solar [22]	LFR	–	70	285	Once-through
FRESEMO [12]	LFR	10	110	400	Once-through
Optimized ² [8, 43]	LFR	35	100	400	Once-through

¹ Only commercial plant in operation.² Corresponds to a conceptual plant in northwestern Mexico.

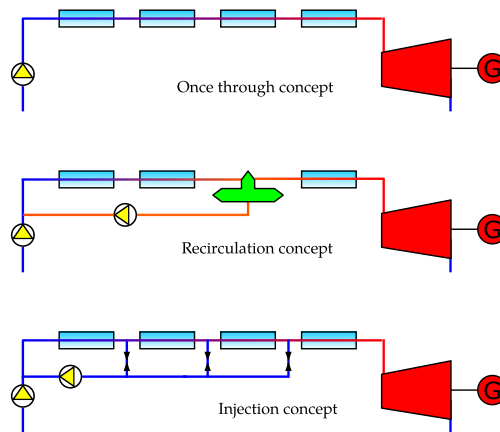


Figure 2.18: Operation concepts for direct steam generation in linear concentrators.

From Table 2.6, one can note that the solar field can adopt different arrangements for the DSG concept. Those arrangements can be seen in Figure 2.18. Findings from the DISS loop experimentation [31, 34, 35], indicate that the most favorable operational approach for PTC plants engaged in DSG involves a recirculation mode. This method incorporates an intermediate water/steam separator positioned between the boiling and superheating zones. This condition ensures an annular flow pattern in the boiling zone. Figure 2.19 shows the flow patterns in horizontal tubes.

2.8 Considerations for the analysis

Although there is considerable research on direct steam generation in linear concentrating systems, researchers have conducted few analyses for Mexico. To implement the DSG concept in the region and make informed decisions, researchers have to perform a study focused on the irradiance conditions of the country to establish a trend between PTC and LFR in DSG. It is necessary to compare the technologies using consistent criteria and operating conditions to identify a design trend, such as the same power block and locality.

The research proposal suggests two conceptual solar-only regenerative Rankine cycles that integrate the direct steam generation concept with hypothetical thermal energy storage. These cycles utilize either parabolic trough collectors or linear Fresnel reflectors. Since the power block is a calculation basis that allows scaling the solar plant to large power ranges by affecting the results by a scaling factor, the design is to produce 10 MW of net power output. Figure 2.20 illustrates the two configurations of the proposed Rankine cycles.

The solar field with PTC uses EuroTrough [50] collectors, while the LFR case uses an optimized version of the FRESDEMO field [6]. From the operating parameters described in Table 2.6, we propose to fix the conditions at the turbine inlet to 100 bar and 673.15 K (400°C), and 0.08 bar at the turbine outlet, using an SST-200 turbine [51]. However,

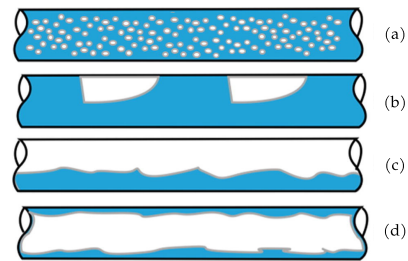


Figure 2.19: Horizontal tube flow patterns. (a) Bubbly flow. (b) Slug flow. (d) Stratified flow. (e) Annular flow. Adapted from [10].

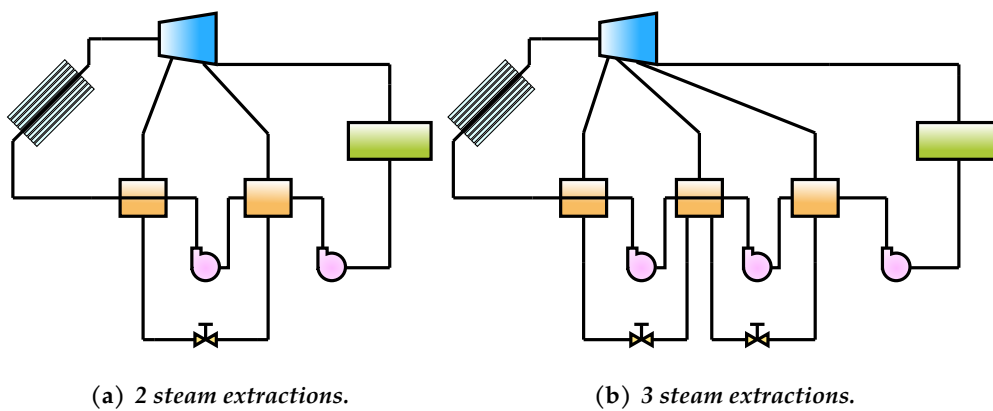


Figure 2.20: Rankine power cycle configuration diagrams. Adapted from [11].

the conditions at the inlet of the loop cannot be predetermined, as the temperature is dependent on the pressure extractions, as shown in Figure 2.20. Reference [11] explains how the extraction pressures are determined using the entropy generation minimization methodology using the theory of endoreversible thermodynamics to optimize the power block and operate at maximum efficiency.

We aimed to create flexible thermohydraulic models for both solar fields that enable the characterization of temperature evolution along each loop using single- and two-phase fluids. The model differs from the rest developed by other authors since we use the methodology proposed by Adiutori [52], called *The New Engineering*. In this methodology, the aim is to provide a more agile solution to heat transfer problems. Appendix A gives a comprehensive overview of this methodology. The model is Finally, the present study assumes the once-through operation mode. This mode is selected because the objective is limited to determining the system's thermal behavior rather than establishing control and stability techniques.

3

Research project roadmap

In this chapter, one can find an overview of the publications resulting from our research project and their connection to aim the comparison of solar steam generation plants that use parabolic troughs and linear Fresnel reflectors to identify design trends for solar concentration plants in direct steam generation (section 2.1), and how each one contributes to fulfilling the project objectives (section 2.3). As engineering researchers, we understand the importance of publishing our findings in peer-reviewed publications to communicate our results and advancements to a broad research community. Thus, this chapter aims to highlight the related publications' order and the research's project significance.

3.1 Publications order

Please note that the subsequent project development order is presented in a sequential manner to facilitate a clear and organized path for your convenience¹. Additionally, Figure 3.1 provides a comprehensive diagram illustrating the connection between the submitted and published publications, highlighting the respective sections within the chapter where each work is presented. In Table 3.1, you will find the titles of the submitted works that are further described in the subsequent section. However, it is important to acknowledge that publication dates may not always align chronologically due to the rigorous reviewing process. In the event of any potential confusion, I sincerely apologize and strongly encourage you to refer to this project roadmap as a reliable and accurate representation of the research progress.

¹You can access each of the works mentioned above without leaving this document. To access the PDF documents, simply click on the title of each subsection, and a new window will open displaying the document

Table 3.1: Titles of the works shown in Figure 3.1.

Section	Title
3.1.1	Energy and exergy (2E) analysis of an optimized solar field of linear Fresnel reflectors for a conceptual direct steam generation power plant
3.1.2	Comparison of theoretical maximum and estimated maximum efficiency of a direct steam generation solar plant
3.1.3	Approaching a LFR direct steam generation power plant towards an endoreversible heat engine
3.1.4	Proposal for the elimination of the convective coefficient h for the modelling of two-phase flow in parabolic concentrators
3.1.5	Validation of an alternative methodology for direct steam generation modelling in parabolic collectors
3.1.6	Maximum work rate extractable from the sun
3.1.7	A practical upper-bound efficiency model for solar power plants
3.1.8	Alternative approach for the thermodynamic modeling of direct steam generation in parabolic trough solar collectors
3.1.9	Alternative methodology for modeling direct steam generation in parabolic collectors: A study case in Northwest Mexico
3.1.10	Comparison of a conceptual linear CSP plant with DSG using PTC and optimized LFR. A study case for the northwest region in México

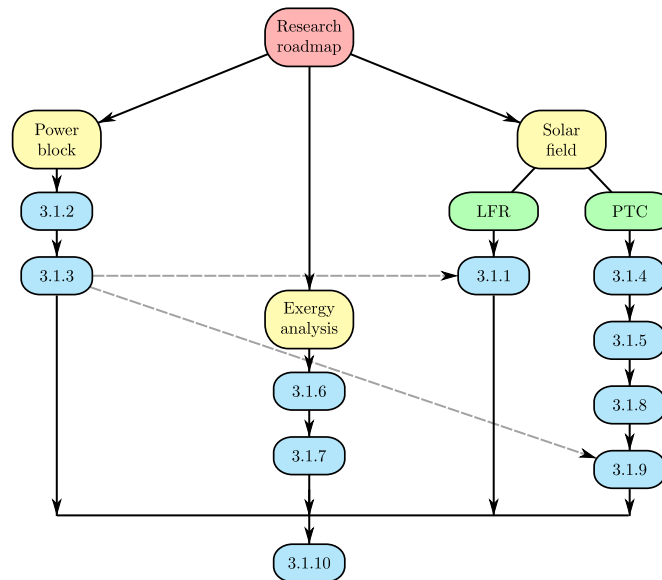


Figure 3.1: Connection between submitted and published works described in the following sections.

3.1.1 Energies journal

Title: Energy and exergy (2E) analysis of an optimized solar field of linear Fresnel reflectors for a conceptual direct steam generation power plant.

Abstract: Direct steam generation is a promising alternative to conventional heat transfer fluids for solar thermal power plants using linear concentrators because water and steam do not have thermal and chemical stability problems. The novelty of this study, an energy and exergy (2E) analysis, was that it was performed on several configurations of a conceptual direct steam generation solar power plant with optimized Fresnel reflectors in Agua Prieta, Mexico coupled with a regenerative steam Rankine power cycle to quantify their efficiency and establish a reference for future implementation of this technology in concentrated solar power plants in Mexico. The thermal model was assumed to be a 1D steady-state flow and validated against results in the literature. It was then applied directly to a case study to determine the size of the solar field. The design point was the lowest solar irradiance day, and evaluating the solar multiple with the highest solar irradiance, taking care not to oversize the solar field, as suggested for solar plants without energy storage. Comparing the performance of the optimized Fresnel field against the FRESDEMO field of Plataforma Solar de Almería, a considerable decrease in the length of the loop has been demonstrated with a low reduction in thermal efficiency.

Status: Published.

Fulfillment of the project proposal

The article discusses the potential of direct steam generation in solar thermal power plants as an alternative to conventional heat transfer fluids. The study conducted an energy and exergy analysis on several configurations of a direct steam generation solar power plant in Mexico using optimized Fresnel reflectors with a developed model validated with the results from FRESDEMO. This analysis was the starting point for research on parabolic troughs.

3.1.2 CIES 2020 Conference (online)

Title: Comparison of theoretical maximum and estimated maximum efficiency of a direct steam generation solar plant. (Original in spanish as “Comparativa del rendimiento teórico máximo y estimado de una planta solar de generación directa de vapor”).

Abstract: In the present work, the maximum theoretical limit of a direct steam generation solar plant is discussed under the theory of endoreversible thermodynamics and classical thermodynamics, comparing it with the estimated efficiency in operating conditions. The solar plant uses Fresnel reflectors for direct steam generation in order to feed two Rankine cycle configurations, with two and three steam extractions respectively. The pressures of the steam extractions were determined by stipulating a minimum generation of entropy in the cycle in order to maximize the thermal performance. As a result of optimizing the generation of entropy, the analyzed plant has a thermal efficiency very close to that of endoreversible thermodynamics, so it can be established that the Rankine cycles discussed will be operating at practically the maximum power output under the physical limits of the plant itself system.

Status: Published.

Fulfillment of the project proposal

The paper discusses the theoretical limit of a direct steam generation solar plant by employing endoreversible and classical thermodynamics. An initial elucidation of the process for determining steam extraction pressures, aimed at optimizing entropy generation, leads to a significantly high thermal efficiency that approaches the uppermost theoretical threshold. The results show that the proposed Rankine cycles can operate at the maximum power output under the physical limits of the plant system. The study emphasized an initial approach to ascertain the suitability of endoreversible thermodynamics analysis for direct steam generation.

3.1.3 “Advanced Energy Technologies and Systems” book chapter

Title: Approaching a LFR direct steam generation power plant towards an endoreversible heat engine

Abstract: Concentrated solar power, or solar thermal energy, has proven to be a renewable alternative for the production of power, using different technologies that allow the use of thermal energy from the Sun to reach temperatures high enough to drive a thermal engine, mainly steam Rankine cycles and thus be able to convert thermal energy into electrical energy that can be supplied into the electricity grid. However, like any engineering development, it is sought to optimize some processes to increase the overall performance of the system and reach the highest possible efficiency. In the present Chapter, the proposed design and optimization of a direct steam generation linear Fresnel reflector power plant leads to an efficiency close to the endoreversible model efficiency, so the analyzed configurations will be working at near maximum power condition with high possible efficiency.

Status: Published.

Fulfillment of the project proposal

The chapter provides a comprehensive account of the endoreversible model of a Rankine cycle, which finds application in direct steam generation solar power plants. Furthermore, it elucidates the power block optimization procedure concerning the steam extraction pressures required to achieve the lowest total exergy destruction possible. The results indicate that the computed efficiency closely approximates the endoreversible model, thereby leading to the inference that the power block can operate under near-maximum power conditions without compromising its high efficiency.

3.1.4 CIES 2022 Conference

Title: Proposal for the elimination of the convective coefficient h for the modelling of two-phase flow in parabolic concentrators. (Original in spanish as “Propuesta de eliminación del coeficiente convectivo h para el modelado de flujo bifásico en concentradores parabólicos”).

Abstract: The analysis of the two-phase flow in linear concentrators remains a fundamental part of the implementation of direct steam generation in solar thermal plants. In the present work, the thermo-hydraulic model of a parabolic trough in direct steam generation is described by means of a methodology in which the use of the convective coefficient and the friction factor is eliminated. This allows to solve in a direct way, and without the need of iterative processes, the model to predict the temperature rise and pressure drop along the receiver, especially in the two-phase flow zone. The results are comparable to those reported by other researchers using the traditional methodology. This ensures the usefulness of the model for further analysis.

Status: Published.

Fulfillment of the project proposal

The article discusses the development of a thermo-hydraulic model for a parabolic trough in direct steam generation that eliminates the need for convective coefficients and friction factors. With this, it is possible to predict the temperature rise and pressure drop along the receiver, particularly in the two-phase flow zone. The results show that the model is comparable to those using traditional methods, making it useful for further analysis.

3.1.5 EUROSUN 2022 Conference

Title: Validation of an alternative methodology for direct steam generation modelling in parabolic collectors.

Abstract: The analysis of the two-phase flow in linear concentrators remains a fundamental part of implementing the concept known as direct steam generation in concentrated solar thermal plants. The models developed to date require, on the one hand, an iterative analysis to estimate the coefficient h , and, on the other hand, high demand for computational fluid dynamics calculations. In the present work, with the help of Adiutori's methodology, a one dimensional thermo-hydraulic model of a parabolic trough collector in the direct steam generation is described. The difference between the present model, which stands out from the rest, is that for the analysis of convective heat transfer, a functional of the temperature is evaluated, instead of dimensionless groups to estimate the h coefficient, a similar approach is used for the pressure drop instead of the fluid friction factor. This allows to solve directly, and without the need for iterative processes, the model to predict the temperature rise and the pressure drop along the receiver, especially in the two-phase flow zone. The results obtained are similar to the experimental data published by different researchers, which validates the developed model, and will allow simulations to be carried out in a more agile way and reduce calculation errors. This ensures the usefulness of the model for further analysis.

Status: Accepted to be published.

Fulfillment of the project proposal

The article examines the validation of the established thermo-hydraulic model for a direct steam generation parabolic trough collector, eliminating the necessity for iterative analysis and computationally intensive fluid dynamics calculations. By comparing the attained results with experimental data reported by various researchers, the developed model is confirmed and enables expedited simulations with diminished calculation errors. This substantiates the applicability of the model for subsequent analyses.

3.1.6 International Conference on Thermodynamics 2.0 2022 Conference (Hybrid)

Title: Maximum work rate extractable from the sun.

Abstract: The socio-economic model based on the fossil fuels is unsustainable, resulting into various crisis related to the supply and demand, therefore, it is in the process of a conscious transition. It is urgent to shift from the current centralized system based on fossil fuels toward a system that is distributed and based on local renewable energy. Solar energy is an important part of the world's energy mix. Solar energy is clean, environmentally friendly, and freely available over the planet. Over the last 60 years, several researchers such as Jeter, Spanner, Petela, Press, Badescu, had proposed different models to define the physical limit of solar radiation conversion. These models overestimate the real maximum work rate extractable from solar radiation. The exergy of solar radiation is a useful index in the preliminary assessment of the performance of solar technologies, since the model provides upper limit of the efficiency of the system. A practical engineering model, however, should consider physical constraints associated with this useful index. In the present work, a generalized expression of a work extraction from solar radiation is presented as a function of the high-temperature radiation reservoir and a low-temperature heat sink that take into account a physical limit of the energy conversion.

Status: Published.

Fulfillment of the project proposal

The study investigates the theoretical limit of solar radiation conversion proposed by multiple researchers, which overestimates the maximum attainable work rate obtained from solar radiation. At first, we introduce a comprehensive formulation that incorporates the genuine physical limitations associated with the effective exergy index of solar radiation to extract work from solar radiation.

3.1.7 Journal of Non-Equilibrium Thermodynamics

Title: A practical upper-bound efficiency model for solar power plants.

Abstract: A generalized model for the maximum work rate extractable from the Sun is developed considering a reversible and an endoreversible system to define a more practical upper-bound efficiency for the conversion of solar radiation into work and power. This model is based on a photo-thermal work extractor in communication with a high-temperature radiation reservoir and a low-temperature heat sink. Following the model, a parametric analysis of the concentration acceptance product (ξ) and thermal conductance is performed to identify the interdependence of variables for the solar exergy. The results are compared with existing models to provide a practical baseline of work and power extractable from concentrated solar power plants (CSP) technologies. Therefore, it is possible to quantify the irreversibilities of an idealized thermodynamic system oper-

ating between the Sun and the absorber (via radiative transfer) and the environment (via convective transfer).

Status: Published.

Fulfillment of the project proposal

The article outlines a generalized model that establishes a practical upper-bound efficiency for converting solar radiation into work, considering the physical limitations of a solar power plant. To identify the interdependence of variables for solar exergy, we conduct a parametric analysis and compare the findings with existing models. This comparison establishes a practical baseline for the extractable work and power from technologies used in concentrated solar power plants.

3.1.8 Journal of Thermal Science and Engineering Applications

Title: Alternative approach for the thermohydraulic modeling of direct steam generation in parabolic trough solar collectors.

Abstract: This work presents an alternative methodology for thermohydraulic characterization of the direct steam generation (DSG) process in parabolic trough solar collectors, emphasizing two-phase flow phenomena. The proposed methodology has yielded a generalized function for heat transfer in the two-phase flow region, which matches boiling curves reported in the literature. This function does not require the use of the convective coefficient h and also predicts the flow pattern inside the receiver. We applied the developed model to a case study of meteorological conditions in Agua Prieta, Sonora (North West Mexico). We compared the model to experimental results reported in the literature, and the comparison yielded RSEs of less than 3% for calculating temperatures and pressure drops.

Status: Submitted.

Fulfillment of the project proposal

The article provides a detailed presentation of an alternative methodology for thermohydraulic characterization of the direct steam generation process in parabolic trough solar collectors. It also includes a validation procedure to ensure the methodology's applicability. The proposed methodology emphasizes a generalized function use for heat transfer in the two-phase flow region. This function accurately predicts the flow pattern within the receiver, aligning with the boiling curves documented in the literature. We applied the developed model to a case study in Agua Prieta, Sonora, and compared it with experimental results. The comparison demonstrated a high level of agreement and confidence, supporting its use for subsequent analyses.

3.1.9 ECOS 2023 Conference

Title: Alternative methodology for modeling direct steam generation in parabolic collectors: A study case in Northwest Mexico.

Abstract: The possible implementation of direct steam generation (DSG) in parabolic troughs in the Northwest region of Mexico is very limited, since there are no analyses of this type to try to define a first proposal for a solar plant. Recently, a methodology has been implemented to eliminate the convective coefficient h in order to model the DSG process in a simpler way. This methodology has been validated with experimental data from the DISS results from PSA. This methodology allows to evaluate the temperature evolution along the loop, the pressure drop and the flow pattern in a short time and with low computational resources. This allows generating the first evaluation of a solar field with parabolic troughs. Additionally, by applying a new practical efficiency limit for the conversion of solar radiation into work, the exergetic efficiency of the installation is evaluated. The results show that this first evaluation, seems to be adequate according to the results suggested in the open literature.

Status: Published.

Fulfillment of the project proposal

This article discusses the implementation and evaluation of the validated model to analyze the direct steam generation in parabolic troughs in the Northwest region of Mexico. Furthermore, the upper-bound efficiency for converting solar radiation into work is employed to assess the exergetic efficiency of the installation. This evaluation reveals significant figures of merit, indicating the potential feasibility of implementing the technology in this region.

3.1.10 Renewable Energy journal

Title: Assessing Parabolic Trough Collectors and Linear Fresnel Reflectors Direct Steam Generation Solar Power Plants in Northwest México.

Abstract: Concentrating solar power (CSP) systems offer promising solutions for harnessing solar energy. Parabolic trough collectors (PTC) are prevalent in CSP, but direct steam generation (DSG) in solar fields is an innovative alternative that eliminates the need for thermal oils. This study compares PTC and linear Fresnel reflector (LFR) geometries for DSG for Mexican operating conditions. Two 10 MW Rankine cycles with two and three steam extractions are considered. The study evaluates 16 solar field configurations capable of delivering 400°C superheated steam at 100 bar. Assessment parameters include effective concentration area, nominal loop inlet pressure, energy and exergy efficiency, and hypothetical thermal storage size. The findings strongly favor PTC solar fields with 14 loops, exhibiting superior performance. However, three-loop LFR configurations are suggested where pressure reduction prevails. For spatially constrained installations,

three-loop LFR arrays minimize land utilization, while larger five-loop configurations optimize efficiency. Employing 14 PTC loops prioritizes thermal energy storage. In contrast, 8 PTC loops maximize storage capacity. The study underscores the advantages of Fresnel reflectors over parabolic troughs in specific scenarios, presenting avenues for future exploration. This analysis lays the groundwork for assessing these technologies in the distinctive context of Mexican operations, offering valuable insights for sustainable energy applications.

Status: Submitted.

Fulfillment of the project proposal

The article compares parabolic trough collectors and linear Fresnel reflectors solar fields for direct steam generation under Mexican operating conditions. The analysis includes several criteria, such as effective concentration area, energy and exergy efficiency, and thermal storage size, to identify the most appropriate solar field. In both scenarios, we utilize the previously validated thermo-hydraulic models in conjunction with the proposed solar exergy radiation model. The analysis shows that using Fresnel reflectors has advantages over parabolic troughs based on specific criteria. This outcome hand out prospects for further investigation into this area and serves as an initial foundation for examining these technologies under operating conditions specific to Mexico.

4

Discussion

The analysis in this section aims to provide a comprehensive comparison between two distinct Rankine cycle power block configurations: one featuring two steam extractions and the other incorporating three. These configurations are specifically designed for direct steam generation, utilizing either parabolic trough collectors or linear Fresnel reflectors within the solar field.

The purpose of this comparative analysis is to establish a solid foundation for conducting an impartial assessment of direct steam generation solar fields employing both PTC and LFR technologies in a once-through operational mode. It is crucial to emphasize that this evaluation is conducted under uniform conditions, including identical power block specifications, geographical location, and meteorological conditions. This approach ensures a fair and unbiased selection of the optimal configuration based on rigorous performance criteria.

4.1 Evaluation framework for solar field comparison

Figure 4.1 serves as an illustrative guide to elucidate the comprehensive process employed in the evaluation of LFR and PTC solar fields. This process is undertaken within the context of defining a power block configuration, particularly focusing on Rankine cycles featuring 2 and 3 steam extractions. This strategic choice of power block configurations serves as the foundational step in establishing the operative parameters for subsequent analyses.

The subsequent phase of this research encompasses the meticulous thermohydraulic characterization of the solar fields. Specifically, this entails a detailed examination of both PTC and LFR solar field configurations. It is essential to highlight that this characterization phase is underpinned by a rigorous analytical framework that incorporates validated

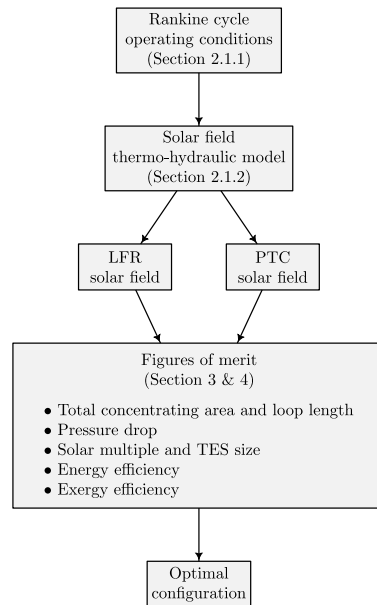


Figure 4.1: Evaluation and comparison procedure.

models based on data from previous studies.

Upon the completion of the thermohydraulic characterization, the obtained results are synthesized and organized into a set of five distinct figures of merit. These figures of merit are meticulously curated to facilitate a rigorous comparison among various solar field configurations, thereby enabling the identification of the optimal choice. Importantly, the selection of these five figures of merit is a purposeful decision, intended to provide a clear and unbiased assessment of the solar field options. Each of these parameters is intricately interlinked, underscoring their collective significance.

The five selected figures of merit encompass:

- **Solar Field Length and Area:** This parameter assesses the spatial requirements of each solar field, a critical consideration for land utilization and overall system footprint.
- **Pressure Drop:** An evaluation of the pressure drop within the solar field, a key determinant of energy efficiency and system performance.
- **Thermal Storage Size:** This parameter investigates the capacity of the thermal storage system, a crucial aspect for continuous energy supply and system reliability.
- **Energy Efficiency:** An assessment of the efficiency of energy conversion within the solar field, a pivotal factor in maximizing energy output.
- **Exergy Efficiency:** This parameter offers a comprehensive measure of the solar field's effectiveness in converting energy into useful work, taking into account both quantity and quality of energy.

These carefully selected parameters collectively serve as a comprehensive framework for objectively assessing and contrasting solar field configurations. Their interconnectedness underscores their critical role in guiding decision-makers, even those less acquainted with CSP systems, toward a well-informed and impartial selection of the most advantageous solar field configuration.

4.2 Solar field design parameters guidelines

To ensure the technical feasibility of the solar field, it is imperative to adhere rigorously to the specified conditions, as outlined in the work by Wang et al. [17]. These conditions, meticulously designed to optimize the solar field's performance, are as follows:

- **Pressure Control for Efficiency:** The reduction of pressure at the loop inlet is paramount for minimizing the power requirements associated with fluid circulation. This reduction enables the deployment of smaller, more energy-efficient pumps. To strike an optimal balance, it is recommended to limit the pressure drop to less than 10 bar. Consequently, the maximum permissible pressure at the solar field's inlet is set at 110 bar.
- **Land Utilization Efficiency:** In pursuit of environmental sustainability and effective space utilization, it is imperative to consider the minimization of land use. A primary strategy to achieve this objective involves employing solar field configurations featuring loops with dimensions of less than 1000 meters of linear concentrators.
- **Emphasis on Energy Efficiency:** To harness the full potential of solar radiation and convert it efficiently into usable solar energy, a paramount focus is placed on achieving high energy and exergy efficiency values. This approach ensures that a substantial proportion of the incident solar radiation is effectively channeled toward the conversion of solar energy into useful work.
- **Optimizing Thermal Energy Storage:** An essential facet of solar power plant operation revolves around the effective utilization of thermal energy storage (TES) systems. Large-scale TES systems are integral to extending the operating hours of the solar power plant, thereby enhancing its overall reliability and energy output.

These four guiding conditions collectively serve as a foundational framework for the technical evaluation and design of the solar field, ensuring that it aligns with established efficiency and sustainability goals within the concentrated solar power domain.

Within the framework of our prescribed conditions, it is pivotal to adopt a pragmatic perspective when considering the initial two criteria, characterized by numerical values. Rather than interpreting these values as rigid constraints, it is imperative to view them as flexible guidelines. To facilitate a comprehensive analysis and accommodate the inherent variability associated with real-world conditions, measurement and instrumentation errors, and prudent risk management, we have established a maximum tolerance threshold

of 10%. This allowance serves as a practical buffer, providing the decision-making process with resilience and adaptability.

It is noteworthy that both pressure and length parameters are subject to this 10% tolerance margin, underscoring their mutual interdependence. As we delve into the intricacies of these conditions, it becomes evident that smaller field areas are intrinsically linked to the attainment of higher energy and exergy efficiencies. Conversely, the pursuit of larger field areas necessitates a commensurate increase in thermal energy storage capacity. This expansion, however, comes at the cost of elevated pressure drops within the system.

This nuanced interpretation of the criteria not only enhances the robustness of our analysis but also fosters a decision-making framework that embraces variability and optimally balances the interconnected facets of solar field design, efficiency, and technical applicability.

5

Conclusions

Performing an impartial comparison between parabolic trough collectors (PTC) and Fresnel reflectors (LFR) within the context of direct steam generation (DSG) power plants, particularly those integrating thermal energy storage, emerges as a compelling imperative. Such a comprehensive evaluation plays a pivotal role in advancing the broader acceptance and utilization of concentrating solar power technologies for the efficient and sustainable generation of electricity.

In the course of this extensive study, we have conducted a meticulous analysis, focusing on two 10 MW steam Rankine power blocks, each equipped with an optimized FRESDEMO field for LFR and EuroTrough collectors for PTC. The central objective was to identify the optimal solar field configuration for direct steam generation power plants that share identical operational conditions and geographical locations. The complexity of this task stems from the inherent challenge of conducting an unbiased comparison between PTC and LFR, as they function within the same contextual framework. This research addresses this critical gap and serves as a driving force, offering insights into the selection of the most suitable solar field configuration to enhance the performance of DSG power plants.

The power blocks examined in this study have undergone a comprehensive optimization process rooted in the principles of endoreversible thermodynamics theory. This optimization approach was meticulously executed with the goal of maximizing the operational efficiency of the Rankine cycle, ensuring it closely aligns with its theoretical maximum efficiency. Our extensive efforts included precise adjustments to the conditions at the turbine's inlet and outlet. Through the careful manipulation of the number of steam extractions in the turbine, we were able to define the precise solar field inlet conditions for two distinct scenarios: one involving two extractions and another with three extractions. Following this rigorous optimization process, our analysis yielded specific requirements, highlighting that the case with two extractions necessitates a flow rate of 12.8058 kg/s of

water/steam at a temperature of 496.121 K. Conversely, for the case with three extractions, a flow rate of 13.2629 kg/s and a temperature of 518.358 K were determined as optimal. These findings lay the foundation for the subsequent stages of our study, guiding our exploration of solar field configurations and their implications.

In the pursuit of technical viability and performance optimization, we undertook a meticulous examination of the number of loops in both PTC and LFR solar fields. Our paramount objective was to establish and maintain a comparable flow velocity between these two configurations, facilitating a more straightforward and equitable comparison. To achieve this goal, we systematically partitioned the PTC solar field into four distinct loop configurations, encompassing 8, 10, 12, and 14 loops. Simultaneously, we subjected the LFR solar field to a parallel division, resulting in four loop configurations comprising 2, 3, 4, and 5 loops. This strategic partitioning served as the basis for our subsequent analysis of these configurations' thermohydraulic characteristics, enabling a comprehensive evaluation of their performance in the context of DSG power plants.

In the quest for a rigorous assessment of the solar fields, we embarked on the thermohydraulic characterization phase, leveraging two well-validated models that drew upon data compiled by previous researchers. Our unique approach distinguished these models from those developed by other authors by obviating the need for convective coefficient calculations. Instead, we employed generalized heat transfer functions, simplifying the heat transfer model while rendering it more amenable to solution. This methodological choice allowed us to delve deeper into the intricacies of the solar fields' thermal performance, elucidating their behavior under various conditions. Consequently, we obtained a comprehensive understanding of how changes in loop configuration, mass flow rates, and inlet temperatures influenced the overall performance, efficiency, and effectiveness of the solar fields.

Our study has revolved around five fundamental operating parameters, meticulously chosen for their relevance during the design phase of concentrated solar power systems. These parameters encompassed solar field length, linked to the land area, pressure drop, thermal storage size, and energy and exergy efficiencies. The exhaustive analysis of these parameters laid the foundation for establishing five distinct criteria to identify the most suitable solar field configuration, all while considering the consistent thermal processes executed by each loop within these fields. This structured framework not only facilitated the evaluation of individual performance aspects but also enabled a comprehensive comparison of solar fields under various conditions and configurations. Consequently, our research contributes to the creation of a comprehensive decision-making tool that provides stakeholders with valuable insights into the selection of optimal solar field configurations for specific operational contexts.

The primary criterion we focused on was the overall performance across these five crucial parameters. Our extensive analysis unequivocally demonstrates that solar fields featuring 14 loops with parabolic trough collectors outshine their counterparts employing linear Fresnel reflectors with only 3 loops. This superiority stems from their optical similarity and superior performance across the board. As such, we confidently advocate for the implementation of parabolic trough collector fields in both power blocks. How-

ever, recognizing that operational contexts can differ significantly, we have also provided nuanced recommendations to accommodate diverse priorities. Our study underscores the importance of careful consideration of performance metrics, emphasizing that a well-informed selection process is essential to realize the full potential of concentrated solar power technologies.

Compact solar fields present an array of advantages, primarily in the optimization of land utilization and area allocation. When the paramount concern is minimizing land use, our research endorses the 3-loop linear Fresnel reflector field as the most prudent choice for both power blocks. This configuration offers a reduced physical footprint while still delivering commendable performance metrics, aligning with objectives of sustainable land use. Conversely, when the objective is to minimize the total area while simultaneously maximizing efficiency and ensuring adaptability through fuel backup options, the 5-loop linear Fresnel reflector field emerges as the preferred choice. This selection guarantees higher system efficiency values without compromising overall compactness. In addressing these considerations, our study accentuates the importance of recognizing the multifaceted nature of decision-making in concentrated solar power system design.

In conclusion, this comprehensive study provides invaluable insights into the design and configuration of concentrated solar power systems, particularly in the context of direct steam generation with thermal energy storage. Through a meticulous and unprejudiced examination of parabolic trough collectors and linear Fresnel reflectors, we have established a robust framework for decision-makers. The importance of considering multiple factors, such as land use, area optimization, pressure reduction, and efficiency enhancement, is evident in the versatility and adaptability of our recommended configurations. By prioritizing specific parameters, such as thermal energy storage (TES) or efficiency, our research offers clear and well-founded guidance for enhancing the performance, efficiency, and sustainability of concentrated solar power plants. This thesis serves as a cornerstone for future advancements in the field, paving the way for the broader adoption of concentrated solar power technologies in the pursuit of clean and efficient electricity generation.

Appendix

A

The New Engineering: Transformation of heat transfer equations

“One of the principal objects of theoretical research is to find the point of view from which the subject appears in the greatest simplicity.”

Josiah Willard Gibbs (1833 – 1903).
From Gibbs's letter accepting the Rumford Medal (1881).

The traditional approach to solving heat transfer problems involving unknown temperatures and heat fluxes requires iterative processes. However, when coupling the three transfer phenomena, the equations become highly nonlinear, making the analysis more complex. This complexity is particularly evident in convection, where determining the convective coefficient h through Nusselt relations generates significant interest in fluids with phase change.

To overcome the limitations of the traditional approach, Adiutori [52] has proposed a methodology that provides a more efficient solution to heat transfer problems, eliminating the need for iterative processes. This method promises to simplify the solution process and accelerate progress in the heat transfer field.

A.1 Basic approach

In this methodology, which Adiutori has called *The New Engineering*, the aim is to obtain functionals of separable variables that allow the solution of any heat transfer problem.

Consider the equation of convective heat transfer by convection per unit area described by:

$$q = h\Delta T \quad (\text{A.1})$$

The definition given for the convective coefficient is $h = q/\Delta T$, so that:

$$q = \left(\frac{q}{\Delta T}\right) \Delta T \quad (\text{A.2})$$

which works well with proportionality problems, because $q/\Delta T$ (or h) are constants. Both Eqs. A.1 and A.2 are not suitable for nonlinear problems because $q/\Delta T$ (or h) are variables that greatly complicate the solution, specifically in cases where phase change phenomena are present.

Any problem that is traditionally solved by using q , h , and ΔT , can be solved much more simply by eliminating the h parameter, which is *The New Engineering*. In Eq. A.3 is the convective heat transfer law, and always has two variables that can be easily identified, while Eq. A.1 has three variables.

$$q = f(\Delta T) \quad (\text{A.3})$$

Equation A.3 can be conveniently rewritten in such a way that it is possible to obtain ΔT directly, as follows:

$$\Delta T = f(q) \quad (\text{A.4})$$

In this sense, q and ΔT are always separate, i.e., they are never combined as a h coefficient (in the case of using thermal resistances, the h coefficient becomes U). Conventional heat transfer coefficient correlations are easily transformed in *The New Engineering* by replacing h with $q/\Delta T$, then separating q and ΔT resulting in correlations in the form described by Eqs. A.3 or A.4.

A.1.1 Parametric correlations preferred form

In *The New Engineering*, the recommended form of parametric correlations is outlined as follows:

- Dimensionless group parameters are substituted with individual parameters.
- Temperature-dependent parameters are simplified to temperature.
- Correlations are tailored to specific fluids rather than being generalized for multiple fluids.

In summary, parametric correlations are user-friendly due to their straightforward nature, as they:

- Can be assessed without substituting dimensionless group parameters.

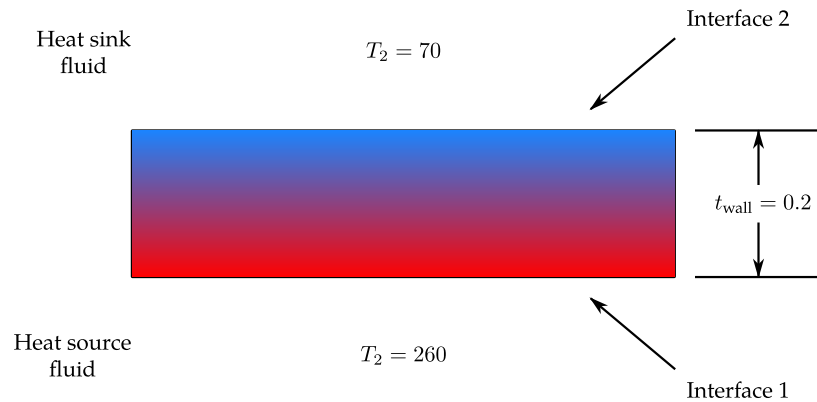


Figure A.1: Heat transfer problem setup.

- Uncover the relationships among individual parameters.

Please note that when temperature replaces temperature-dependent parameters, the correlations exclusively consist of the parameters measured in the underlying experiment. In contrast, traditional engineering correlations incorporate temperature-dependent parameters that were not measured during the original experiment.

A numerical example

Graphs describing heat transfer by natural convection¹ generally have the form Nusselt number versus Rayleigh number [57, 58]. Graphs of this form can be read directly if ΔT is given and q is desired, because Ra is independent of q . However, if q is given and ΔT is desired, the graph cannot be read directly, because Nu and Ra depend directly on ΔT .

Note that the Nusselt number is proportional to $q/\Delta T$ (proportional to h) and the Rayleigh number is proportional to ΔT . Therefore, the product of Nu and Ra eliminates h because ΔT in the denominator of the Nu number cancels ΔT in the numerator of the Ra number. When this product is plotted against the Ra number, the elimination of h makes it possible to read the graph directly if ΔT is given and q is desired, or if q is given and ΔT is desired.

To exemplify this methodology, consider the configuration in Figure A.1; which corresponds to a typical heat transfer problem. In this case, it is desired to know the heat flux and wall temperature on both faces that are in contact with a fluid.

In the schematic in Figure A.1, all the data needed to solve the problem are known. From the conventional heat transfer literature, the conductivity value $k = 8.6$ and the

¹For the case of forced convection, the Nusselt number is reported with respect to the Reynolds number [53–56], and although Re does not directly involve ΔT , the thermal properties have to be evaluated generally at the film temperature.

following equations can be obtained, with the dimensions of each parameter in J, s, m and °C, as appropriate.

$$\text{Nu}_1 = 0.15 (\text{Gr}_1 \text{Pr}_1)^{0.33} \quad (\text{A.5})$$

$$\text{Nu}_2 = 0.47 (\text{Gr}_2 \text{Pr}_2)^{0.20} \quad (\text{A.6})$$

To convert Eqs. A.5 and A.6 from heat transfer coefficient correlations to heat transfer behavior correlations, we substitute $(qL/\Delta T k)$ with Nu, and by calculating with the provided values, we separate q and ΔT :

$$q_1 = 0.15 \left(\frac{k}{L} \right) \left(\frac{g\beta L^3}{\nu^2} \right)^{0.33} \text{Pr}^{0.33} \Delta T_1^{1.33} = 2.80 \Delta T_1^{1.33} \quad (\text{A.7})$$

$$q_2 = 0.37 \left(\frac{k}{L} \right) \left(\frac{g\beta L^3}{\nu^2} \right)^{0.20} \text{Pr}^{0.20} \Delta T_2^{1.20} = 1.64 \Delta T_2^{1.20} \quad (\text{A.8})$$

With the help of Figure A.1, the equations of q and ΔT_{total} can be established, using:

$$q_1 = q_{\text{wall}} = q_2 = q \quad (\text{A.9})$$

$$\Delta T_{\text{total}} = \Delta T_1 + \Delta T_{\text{wall}} + \Delta T_2 = T_2 - T_1 \quad (\text{A.10})$$

With Eqs. A.6 to A.8, to substitute ΔT_1 , ΔT_2 and ΔT_{wall} in Eq. A.10, we obtain:

$$\Delta T_{\text{total}} = 260 - 70 = \left(\frac{q}{2.80} \right)^{0.75} + \left(\frac{q}{1.64} \right)^{0.833} + \left(\frac{q}{430} \right) \quad (\text{A.11})$$

By solving the system, it is obtained that $q = 585 \text{ W/m}$, $T_{\text{wall},1} = 205 \text{ °C}$, $T_{\text{wall},2} = 204 \text{ °C}$. Thus, QED that the coefficient h is unnecessary. ■

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