Enhancing Efficiency and Sustainability in Solar Thermal Power Plants through Advanced Thermodynamic Cycles

Salam Hasan Ahmed

salam.hasan271183@gmail.com

07706546131

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Abstract

This comprehensive article examines the advancements in thermodynamic cycles employed in solar thermal power plants. With the increasing demand for clean and sustainable energy sources, solar thermal power plants have gained significant attention. The efficient conversion of solar energy into electricity relies on the optimization of thermodynamic cycles. This review provides a detailed analysis of the advancements in various thermodynamic cycles, including Rankine, Brayton, and Stirling cycles, for solar thermal power generation. The working principles, advantages, limitations, and recent technological developments in each cycle are thoroughly discussed. Furthermore, the integration of thermal energy storage systems with these cycles is explored as a means to enhance the dispatchability and overall efficiency of solar thermal power plants. The review also highlights the challenges and future research directions in the field of thermodynamic cycles for solar thermal power plants. This comprehensive analysis serves as a valuable resource for researchers, engineers, and policymakers involved in the design, optimization, and implementation of solar thermal power plants. By understanding the advancements in thermodynamic cycles, stakeholders can make informed decisions to maximize the efficiency and viability of solar thermal power generation systems.

Keywords: **Thermodynamic Cycles; Solar Thermal Power Plants; Rankine Cycle; Brayton Cycle; Stirling Cycle**

1. Introduction

Given the escalating global energy crisis and the persistent increase in greenhouse gas emissions over the last decade, the significance of renewable energy resources has significantly heightened in the context of promoting sustainable development (Maarof et al. 2023; Madadi Avargani, Abdlla Maarof & Zendehboudi 2023). The thermodynamic efficiency of gas turbine power cycles plays a crucial role in determining operating costs. Efforts have been made to enhance the thermodynamic efficiency of gas turbine cycles. A notable achievement in this regard has been the increase in turbine inlet temperature to approximately 1500 °C and even higher, which has resulted in a substantial improvement in thermal efficiency (Mohammadi, McGowan & Saghafifar 2019).

The solar thermal power plant emerges as a highly promising solar energy technology for widespread utilization of solar energy in the future. It has been identified as the most favorable technology among all existing solar energy technologies to date, showcasing immense potential for advancing solar energy utilization (Burke & Stephens 2018; Li et al. 2021; Feng & Zhao 2022). Thermal energy storage systems (TES) are essential components of solar thermal power plants, enabling them to effectively meet both peak and off-peak electrical demand (Halkos &

Gkampoura 2020; Lou et al. 2021; Huang et al. 2022; Takudzwa Muzhanje, Hassan & Hassan 2022; Zhang et al. 2022; Zhao et al. 2022).

Rankine cycles are renowned for their exceptional heat transfer efficiency, primarily attributed to their operation at high temperatures with suitable heat transfer fluids. Nevertheless, the efficiency of the Rankine cycle is constrained by the permissible temperature range of the synthetic oil employed within the cycle (Feng et al. 2020; Mikielewicz & Mikielewicz 2022; Assareh et al. 2023). Low temperatures can be achieved by utilizing gaseous or liquid heat sources. The adoption of Organic Rankine Cycles (ORCs) has led to the widespread implementation of district heating networks, where electricity can be used to locally heat water or heat pumps powered by ORCs can be employed for water heating. The installation cost of ORCs is a crucial factor, as it significantly impacts the efficiency of the system due to expenses associated with the vapor generator and operation. The vapor generator is particularly prone to high exergy losses, making it one of the most energy-intensive components. Therefore, the design of a cogeneration power station should be carefully assessed through a techno-economic analysis. Systems requiring substantial energy extraction at low temperatures necessitate large heat exchange surfaces. Considering these considerations, optimizing the design of the power cycle is essential to maintain cost-effectiveness (Nasir & Kim 2016; Schmidt 2018; Yu, Gundersen & Feng 2018; Ayub et al. 2020).

Concentrating solar power (CSP) plants hold significant potential as a clean and renewable energy source for closed-cycle gas turbine systems, capable of generating thermal energy above 1300 K. Previous studies have focused on solar concentrators incorporating tower and heliostat field configurations, incorporating hybridization mechanisms to regulate system operation in response to changes in solar resource availability. Prototype studies have achieved solar contributions of up to 70%. Ongoing efforts to enhance cycle efficiency have explored various improvements. The author's thermodynamic models have proven effective in analyzing energy consumption, determining net power and efficiency, assessing operating temperatures, and quantifying fuel utilization in hybrid solar thermal plants operating within Brayton cycles (Wang et al. 2020; Moreno-Gamboa, Escudero-Atehortua & Nieto-Londoño 2022).

The Stirling engine, developed by Dr. Robert Stirling in 1816 as an external combustion engine, serves as the central mechanism for converting solar irradiance into mechanical energy at the solar power plant. Regenerative closed-cycle machines utilize their working fluid to undergo compression and expansion cycles. It has been reported that the Stirling engine presents cost advantages over small photovoltaic (PV) units while also exhibiting higher thermal efficiency compared to systems based on the Rankine cycle (Cinar et al. 2005; Batmaz & Üstün 2008; Siddiqui et al. 2015).

Dunham & Iverson et al (Dunham & Iverson 2014) conducted a study and discovered that CO_2 recompression Brayton cycles exhibit a remarkable thermal efficiency above a specific temperature threshold. In fact, they were able to achieve an efficiency of approximately 60% even when employing wet cooling. These cycles can operate at a maximum pressure of 30 MPa and a maximum temperature exceeding 1000 °C. The study includes a comparison of the traditional approach, which optimizes based on Carnot efficiency, in order to determine the operating temperature for the combined receiver and power cycle.

Turchi et al.(Turchi et al. 2012) conducted research on closed-loop Brayton cycles and found that supercritical carbon dioxide (s-CO_2) can achieve equal or even greater cycle efficiencies compared to superheated or supercritical steam cycles when operated at temperatures relevant to Concentrated Solar Power (CSP) applications. In Brayton cycle systems, the use of s-CO_2 results in smaller weight and volume, lower thermal mass, and less complex power blocks compared to Rankine cycles which utilize air. This is due to the higher density of the fluid and simpler cycle design. Additionally, the simplified machinery and compact size of the s-CO2 process may lead to reduced operational, maintenance, and installation costs.

Jamel et al.(Jamel, Abd Rahman & Shamsuddin 2013) conducted a review that focused on hybrid solar–steam cycle power plants as part of their broader examination of hybrid solar conventional power plants. In the study, the researchers also concentrated on hybrid solar-geothermal power plants as the primary focus for hybrid solar non-conventional power plants. They found that there are available options such as Integrated Solar Combined-Cycle Systems (ISCCS) and hybrid solar-gas turbine power plants. Among these options, ISCCS stands out due to its advantages and plans for implementation in various parts of the world, including Tunisia, Egypt, Spain, and Iran. As a result, it is considered the most successful option.

1.1. Solar Thermal Technology Development in the Future

Direct steam generation (DSG) has emerged as a highly promising technology for harnessing solar energy. DSG enables the production of steam directly from solar fields, which can be supplied directly to a power block for electricity generation. This approach offers several advantages, including simplified operation, elimination of environmental risks such as fire and leakage, improved plant efficiency by eliminating fluid toxicity, and reduced plant costs by raising fluid temperatures above 400°C. Compared to synthetic oil systems, DSG systems do not require additional heating systems, resulting in lower operation and maintenance costs. While previous studies have primarily focused on evaluating the performance of parabolic trough (PT) plants integrated with DSG technologies, future research should explore the integration of DSG with other solar thermal technologies such as solar towers (ST), linear Fresnel reflectors (LFR), and solar collectors. Additionally, there is a need to investigate the integration of renewable energy sources with solar thermal power plants and explore hybridization techniques to further enhance plant efficiency. The incorporation of nanoparticles into the base fluid of solar thermal power plants shows promise for improving their thermophysical properties and enhancing thermal conductivity. Research efforts are underway to increase the heat transfer rate and thermal conductivity of commonly used base fluids, such as water, ethylene glycol, and thermion, by incorporating nanoparticle suspensions ranging from 1 to 100 nm. Additionally, future research directions include exploring thermochemical energy storage in solar thermal plants and developing innovative integrated solar combined cycle (ISCC) systems, such as the DSG-ISCC-ET system, which offers better thermoeconomic performance compared to combined cycle gas turbines (CCGTs) or DSG-ISCC plants.

2. Methods Utilized for Concentrating Solar Energy in Solar Thermal Power Facilities

In Concentrated Solar Power (CSP) plants, the transfer of heat between different locations relies on thermo fluids and heat transfer fluids. However, these fluids pose several technical and economic challenges. Their corrosive nature and exposure to high temperatures can lead to significant damage and reduced thermal stability, shortening their lifespan. Managing material compatibility can be difficult due to fluid deterioration, resulting in reduced productivity. Moreover, specialized fluids developed for specific applications can be expensive and not easily accessible, requiring unique handling and shipping methods. Proper disposal and recycling of these fluids can also be environmentally challenging (Chung & Chen 2023). The efficiency of thermal energy storage systems can fluctuate over time, and thermal losses can decrease overall efficiency, resulting in higher operating costs. Addressing corrosion and other issues requires compatible materials, and the complexity of large systems can increase construction and maintenance expenses. Scaling up thermal energy storage systems can be challenging and costly due to the need for specialized equipment and materials. Molten salt systems, for instance, may incur high operation costs due to heat tracing and insulation requirements. These challenges can only be overcome through continuous innovation and investment in new technologies. Operational, material, and design improvements can enhance efficiency and cost savings. Additionally, supportive policy frameworks and regulations can facilitate the development and deployment of CSP technology by addressing market entry barriers. To achieve widespread success, CSP must enhance its cost-effectiveness and competitiveness compared to other renewable energy sources (Guo & Nojavan 2022; Bellos 2023; Díaz-Alonso et al. 2023; 2023).

2.1. A Conventional Power Cycle Configuration is Used in Solar Tower Power Plants

2.1.1 Rankine Solar Plants

A recent article was published that discusses the setups and arrangements of supercritical carbon dioxide (SCO2) cycles in concentrated solar power plants. The article specifically explores how these cycles can operate independently or in conjunction with Rankine cycles (ORCs), as shown in Figure 1.

The studies focus on three main components of a solar power plant: the solar power tower (SPT), the thermal energy storage (TES), and the power block. The SPT subsystem requires heliostats, a solar tower, and molten salt receivers. The TES subsystem consists of two molten salt thermal storage tanks and associated facilities. SCO2 cycle systems can be standalone or combined with an ORC system to form the power block (Xiao et al. 2022).

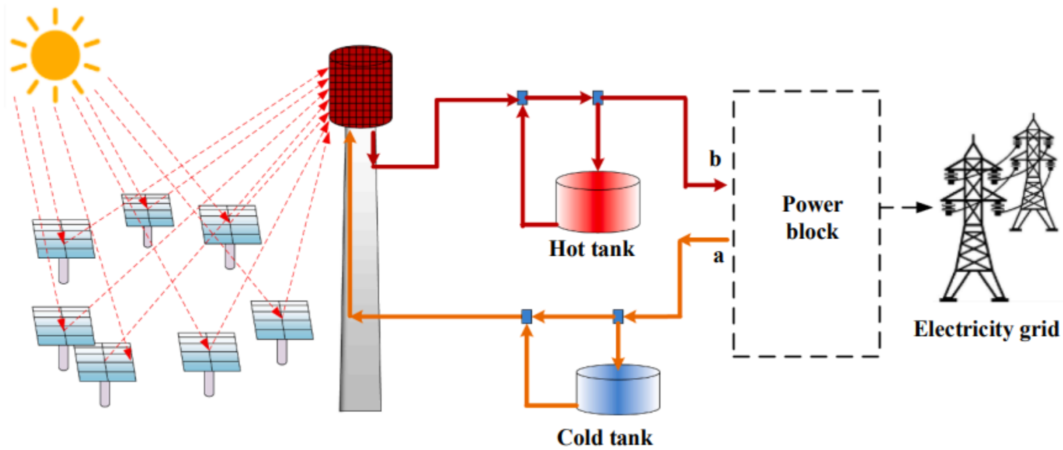

Figure 1: Plant schematic diagram for an SPT (Gupta, Tiwari & Said 2022)

The article examines four different configurations of SCO2 cycle systems: recuperated SCO2 cycles (RE), compressed SCO2 cycles (RC), intercooled SCO2 cycles (IC), and partially cooled SCO2 cycles (PC). Each configuration is described in detail, accompanied by schematic drawings and T-s diagrams (Ahn et al. 2015; White et al. 2021).

In contrast to the simple Brayton cycle system, the RE system incorporates a recuperator to mitigate energy discharge into the environment. However, a challenge arises due to the significant difference in heat capacity between the high-pressure and low-pressure SCO2 streams, resulting in a pinch-point problem. The RE layout addresses this problem by using separate high-temperature (HTR) and low-temperature (LTR) recuperators, along with an additional compressor.

To reduce the compression work of multi-stage compressors, intercooling is introduced in the recompression SCO2 cycle system. Two approaches are discussed: intercooling of the main compressor (IC system) and precooling (PC system). The IC system includes an intercooler, while the PC system incorporates a cooler and pre-compressor before the flow splits into the RC system.

To improve the power block's performance, an organic Rankine cycle (ORC) system is integrated to recover the heat rejected in the SCO2 cooler (Gao & Liu 2017; Wang, Lei & Wu 2023). The SCO2 and ORC subsystems are connected through a shared heat exchanger, and heat recovery occurs in the evaporator (Miller et al. 2017).

The article provides an overview of the SCO2 and ORC subsystems in concentrated solar power plants, with a focus on their layouts and integration. The detailed descriptions and accompanying diagrams offer a comprehensive understanding of the various system configurations, their advantages, and disadvantages. This information is valuable for researchers and professionals involved in solar power plant design and optimization, contributing to the scientific understanding of the subject matter as shown in Figure 2.

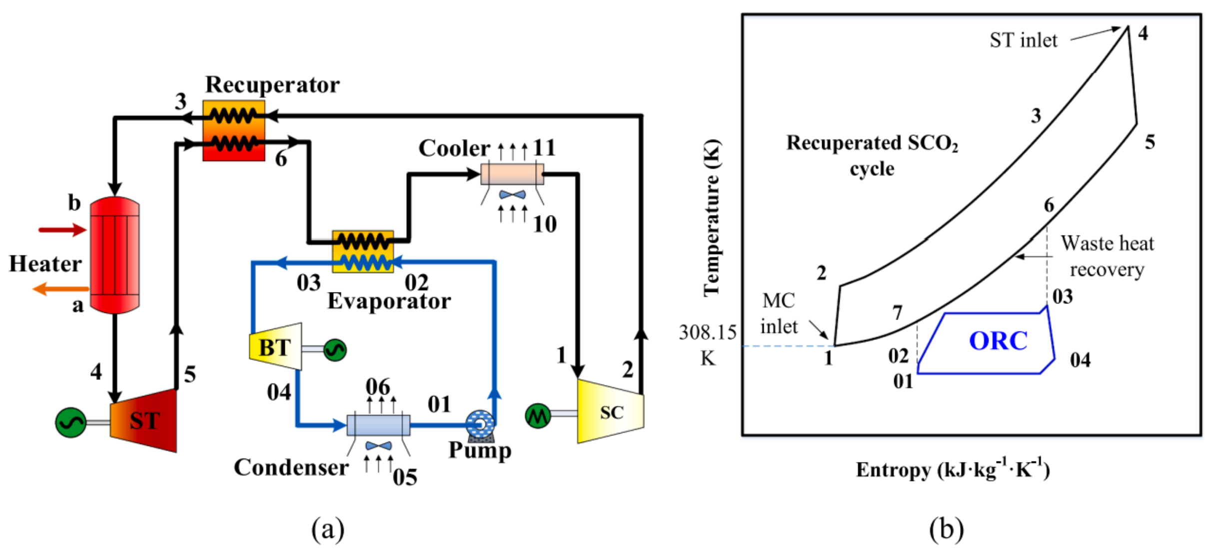

Figure 2: (a) Typical RE-ORC power cycle schematic, and (b) diagram showing the T-S relationship (Ouyang et al. 2023)

2.1.2 Brayton Cycle Solar Plants

Figure 3 show the process that presents a description of off-design calculations and real-time simulation of a solar-powered power plant's operations. The off-design calculation involves obtaining and optimizing the parameters of the heliostat, receiver, and S-CO2 Brayton cycle under design conditions using a GA algorithm. The model utilizes inputs such as direct normal irradiance (DNI), ambient temperature, and wind speed as boundary values and calculates temperatures in tanks and heat exchangers, including molten salt and heat exchanger outlet temperatures. The simulation monitors and adjusts the heating and level of molten salt over a 24-hour period to ensure they remain within acceptable limits. The calculation process is repeated until the rate of difference between molten salt temperature and operation time falls within an allowable range, with adjustments made to the initial temperature and operation time as needed.

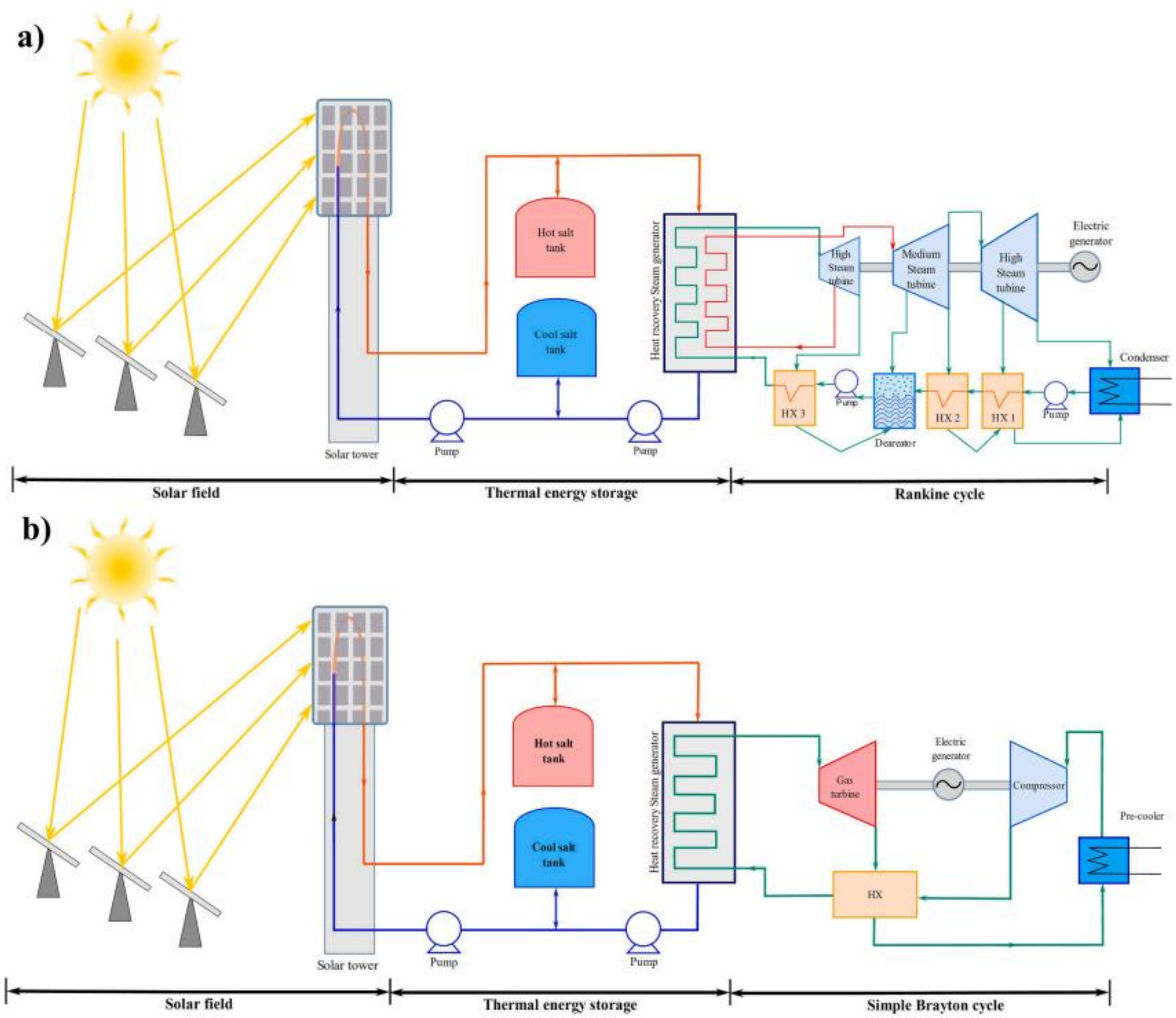

Figure 3: Systems with central towers and molten salt storage systems, a) utilizing steam turbines and b) utilizing gas turbines (He et al. 2020; Yagi, Sioshansi & Denholm 2021)

Figure 3 illustrates the simulation of the power plant's operation in real-time, showing the heliostat field and receiver model used to determine if the solar energy input is sufficient for the power cycle subsystem to reach its rated power. If solar energy input is insufficient, the storage level of the hot tank is checked, and the required quantities of molten salt or fossil fuel are calculated accordingly. The minimum thermal limit is adjusted until the required standard is met (Ma, Meng, et al. 2023).

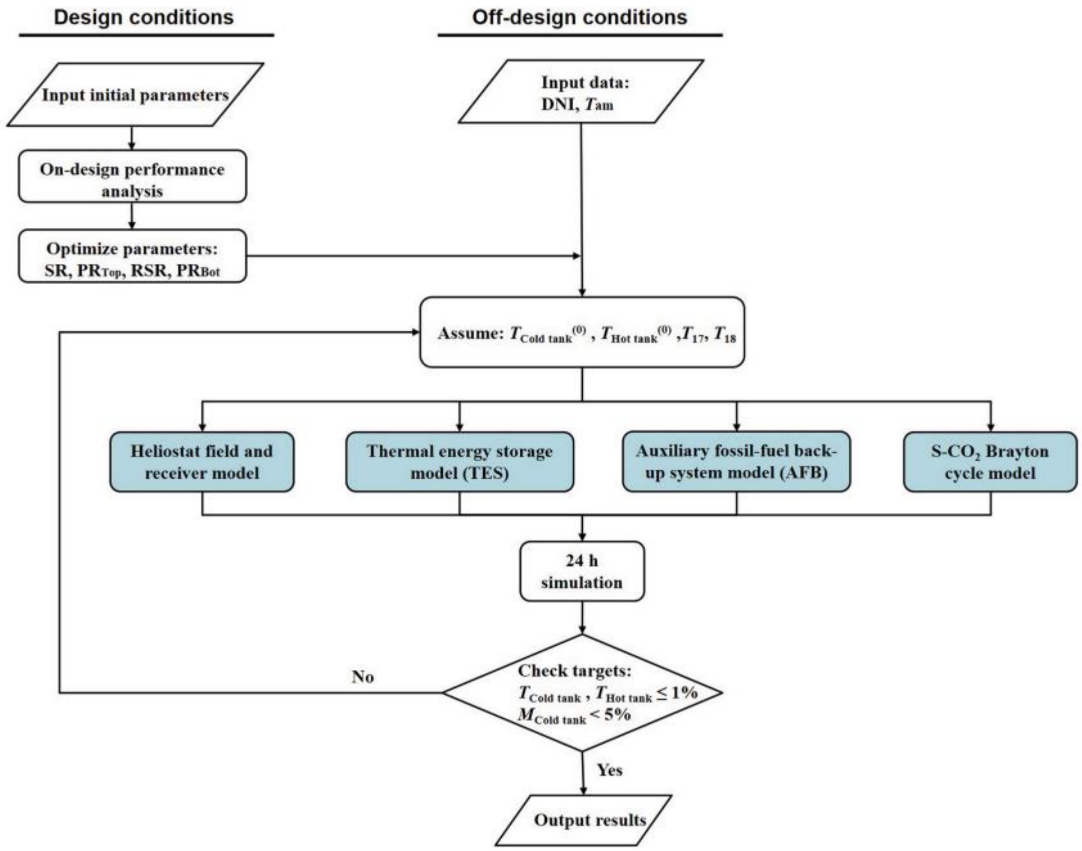

Figure 4: Process flowchart for off-design calculations (Ma, Bu, et al. 2023).

Figure 5 depicts the flow chart of the off-design thermodynamic calculation for the power cycle subsystem, highlighting the use of sliding pressure control to maintain stable and constant heat input to the turbine, while the back pressure remains constant. By utilizing the off-design model and calculation flow chart, it is possible to accurately calculate the performance of the combined cycle under varying external conditions.

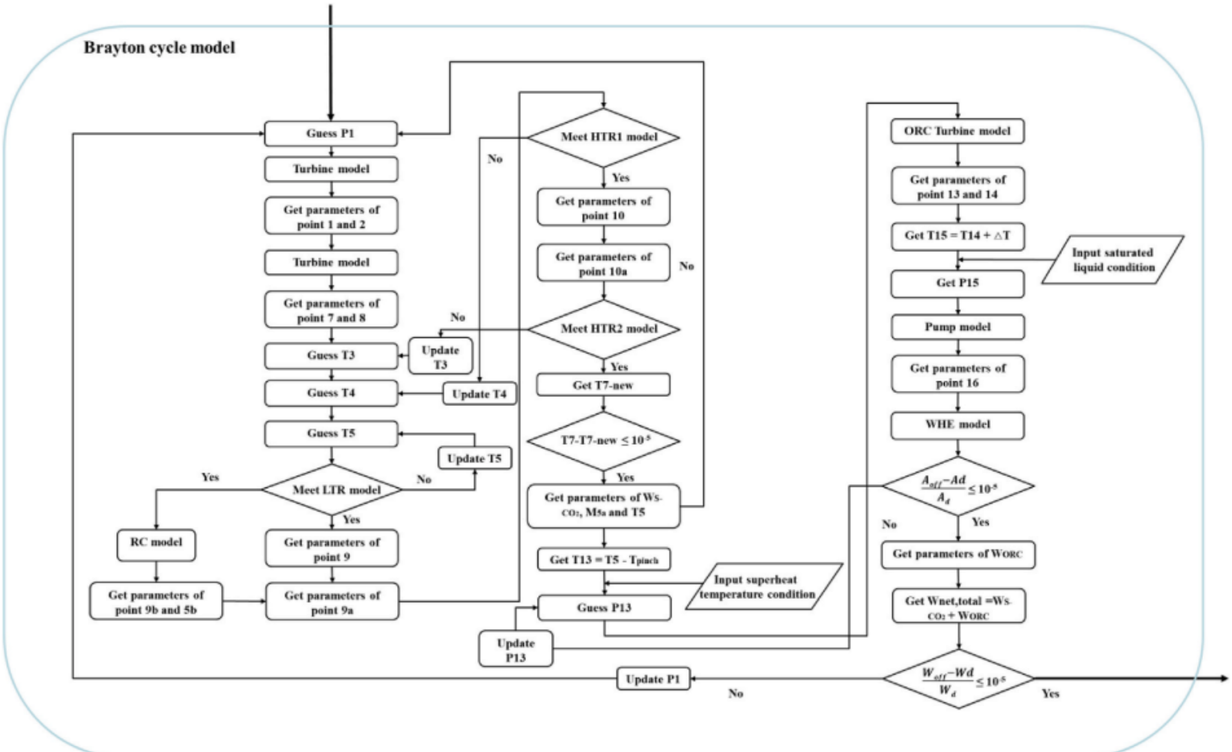

Figure 5: Power cycle subsystem flow chart under off-design conditions (Liu et al. 2023).

2.1.3 Stirling Solar Plants

Stirling system models play a crucial role in the development and optimization processes, encompassing design, simulation, and optimization phases. Numerous studies have been conducted to model the operational behavior of the PDSS (Power Dish Stirling System) using numerical and mathematical techniques. These models have been refined and calibrated using real-world measurements obtained from the Maricopa Solar Electric Generating System (SES) 2013 technical report in Arizona, USA. The Maricopa SDSPP, a 1.5 MW CSP (Concentrated Solar Power) project situated in Peoria, Arizona, has been operational since December 2009 and contributes significantly to the power supply in the Phoenix district. The installation and ownership of the plant are attributed to SES Inc. and Tesserae Solar Partners, which specializes in green energy solutions as shown as Figure 6 a, b.

Figure 6 (c) illustrates the support frame connected to the SE assembly to facilitate mounting and ensure accurate positioning of the PCU relative to the mirror facets. The bracket clearly demonstrates the optimal alignment between the PCU and the mirror facet. The parabolic concentrator is utilized to concentrate sunlight onto the PCU's aperture, resulting in the heating of hydrogen gas within the SE's heater head tubes to temperatures up to 700 degrees Celsius. This heated gas is then directed through a heat exchanger, generating power for the SE. The SE powers an induction generator, producing electricity with a capacity of 3 w/480v/48 amps. The AC power generated by the PCU is fed into the grid via a connector box linked to a power grid connection box. Furthermore, a joint mounting hub is employed in conjunction with the FSS and boom. Provisions for installation were made to accommodate both the elevation drive and azimuth tracking motor drives in the hub and boom of the rig. The dish concentrator structure comprises various components, including the FSS, boom, hub, and mirror facets. To ensure precise sun tracking, a 2-D axis tracking system is utilized, combining a rotating azimuth angle mechanism with the expanding and contracting effects of a screw drive. Additionally, a tubular pedestal assembly is installed to maintain a consistent height above the ground for the dish concentrator. Extensive measurements were conducted at the Maricopa SDSPP between March 2010 and June 2011 to gather operational data. These measurements encompassed significant parameters such as gross electrical output power, direct solar irradiance, wind speed, relative humidity, and ambient temperature. The design of the Maricopa SDSPP aimed to achieve a maximum gross capacity of 1.5 MW at a solar irradiance of 1000 W/m2. The highest monthly energy production, reaching 363 MWh, was observed in June 2010, while the lowest energy production value of 68.2 MWh occurred in March 2011 (Petrescu et al. 2010; Abbas et al. 2011; Hossain et al. 2023).

Figure 6: Fig. 1. (a) Maricopa SDSPP overview in Peoria, Arizona(Coventry & Andraka 2017) (b) Maricopa SDSPP unit-scale sun catchers SDSPP (Carrillo Caballero et al. 2017) *(c) screenshot of Sun Catcher PCU* (Ghodbane et al. 2020).

Figure 7 provides a visual representation of the plant, showcasing the 60 Sun-Catcher TM dish units. Each unit comprises a dish concentrator and a power conversion unit (PCU) responsible for converting solar energy into AC electricity. The dish concentrator, with a diameter of 10.73 m, consists of 44 mirror facets boasting a reflectivity of 94%. These mirror facets are affixed to the facet support structure (FSS), an essential component of the steel framework that ensures the structural integrity of the PDSS.

Figure 7: PDSS schematic (Buscemi et al. 2020)

3. Conclusion

This study focuses on providing an overview of the current state-of-the-art Solar Thermal Power Plants (STPPs), tracing their evolution, and presenting advanced proposals while highlighting their limitations and challenges compared to existing STPP technologies. The research also examines the impact of globalization on STPPs. Among the various steam Rankine cycle power blocks available in the market, one of the most popular options is the steam Rankine cycle coupled with an oil-based Parabolic Trough Collector (PTC) solar field. Hybrid systems offer a dual advantage by effectively managing intermittent energy sources and increasing the working fluid's temperature within the power block, thereby improving the overall efficiency of the STPP. Many projects worldwide have adopted this configuration due to its numerous benefits, with Integrated Solar Combined Cycle (ISCC) plants serving as notable examples. This review presents advanced alternative layouts for solar integrated combined cycle plants, such as ISCC_PR and ISCC-R DRDE, aimed at enhancing the thermal efficiency of the plant by optimizing both solar and fossil heat sources, and emphasizing the annual increase of solar contribution. In recent years, Concentrated Solar Power (CSP) technology has seen increased interest, leading to the emergence of power blocks requiring high maximum fluid temperatures, such as sCO2 Brayton Cycles. Solar-only proposals offer advantages over conventional options, including simplicity of operation and increased efficiency. The study also explores other configurations designed for moderate temperature heat sources, such as Organic Rankine Cycles (ORCs) and Binary Heat Recovery Boilers (B HRBs), which exhibit promising results within specific temperature and power ranges, with comparable cycle efficiency to steam Rankine cycles and notable performance improvements. These alternative configurations offer the advantage of lower complexity and reduced costs. Presently, the solar thermal electricity landscape encompasses multiple alternatives encompassing solar technologies, power conversion systems, and hybrid systems for generating energy from solar thermal power plants. However, despite promising results, the economic evaluation of these alternative options remains uncertain due to high levels of uncertainty. Some of the advanced proposals discussed in this paper require the use of components that are still under development and not yet available in the market. The successful implementation of these technologies would rely on the availability of these components and alternative working fluids under specific operating conditions.

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