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Review Article

Thermodynamic analysis of solar assisted binary vapour cycle using ammonia-water mixture and transcritical CO_2: A review

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ABSTRACT

The primary focus of this review article is to examine the power cycles employed for generating electricity from steam-dominated resources. It discusses the phenomenon of Transcritical CO_2 (T- CO_2) power cycles and the Rankine Cycle, which have been extensively studied by numerous academics. The article also briefly explores fuel-cell-based power plants using binary cycles, geothermal power plants, and solar-assisted power plants. The article presents information on power generation, thermal efficiency, energy efficiency, and exergy efficiency of these plants. The investigation reveals that geothermal power plants have thermal efficiencies ranging from 6.5% to 16.63% and exergy efficiencies ranging from 7.95% to 82%, producing power in the range of 199.1 kW to 19,448 kW. Solar power plants produce power ranging from 550.9 kW to 4500 kW, with energy efficiency between 21.93% and 57% and exergy efficiency between 50.5% and 64.92%. Fuel cell power plants using NH_3+H_2O as the working fluid generate power from 1015 kW to 20125 kW, with thermal efficiency between 25.4% and 70.3% and exergy efficiency between 12.1% and 36%. The article highlights the use of the Kalina cycle in these scenarios.

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INTRODUCTION

A power cycle Musgrove et al. [1] refers to a set of practices and tools utilized to convert heat or motion into usable power. For example, fuel is considered a heating element, while wind is regarded as a source of motion. The power cycle encompasses the procedures that occur in a power plant or other energy-generating system to convert fuel energy into electrical energy. Depending on the type of power plant or system, the power cycle typically involves multiple stages or processes. This cycle continues to repeat as long as there is a fuel supply and the system is operational. Different variations of this fundamental power cycle are employed in various types of power plants. Geothermal power plants, for instance, utilize steam generated by natural heat sources to drive turbines, whereas combined-cycle power plants generate electricity using both steam and gas

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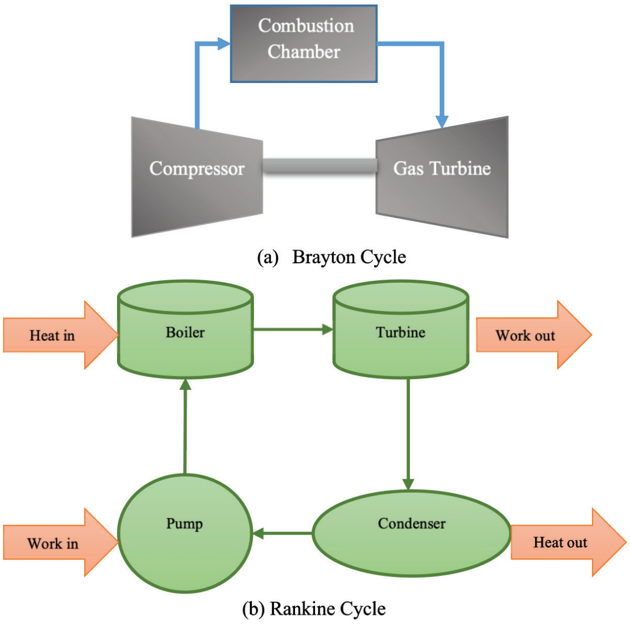

Figure 1. Brayton cycle and Rankine cycle.

turbines. Ultimately, the power cycle plays a vital role in producing the electrical energy that powers homes, businesses, and industries worldwide.

Two thermodynamic cycles frequently employed in power production systems are the Rankine cycle and the Brayton cycle. The Brayton cycle involves a continuous flow of air or gas through the system and finds application in gas turbine engines and certain power plants. In this cycle, fuel is burned in a combustion chamber to heat the air at a constant pressure before it expands through a turbine. The cycle repeats as the expanding gas passes through a heat exchanger, where it cools before undergoing compression once again. The Brayton cycle is effective at generating large amounts of electricity at high pressures and temperatures but is less efficient for power generation at relatively low temperatures.

On the other hand, the Rankine cycle relies on the use of water or another heat transfer fluid in a closed-loop system and is employed in steam power plants. In the Rankine cycle, heat is used to raise the temperature of water in a boiler, achieved through the combustion of fossil fuels, nuclear fission, or other sources, after being pumped to high pressure. The pressurized water then passes through a turbine, expands, and produces power. The water continues to flow, undergoes cooling and condensation back into a liquid state, and is ready to be pumped back to the boiler, completing the cycle. The Rankine cycle is renowned for its reliability and adaptability and is highly efficient for generating power at lower temperatures.

Both the Rankine cycle P. Linke et al. [2] and the Brayton cycle P. Wu et al. [3] follow a similar principle of increasing pressure through a pump or compressor before introducing heat and decreasing pressure through an expansion process using a turbine. Heat addition or removal occurs at a constant pressure during each cycle. Various techniques, such as reheating and recompression, can be employed to enhance the efficiency of these cycles.

Novelty of the Present Work

This comprehensive review article provides an in-depth analysis of power cycles and their applications in power generation systems, with a specific focus on solar-assisted power plants. The study examines the utilization of various cycles, including the transcritical CO_2 cycle and the solar-assisted binary cycle, and emphasizes the importance of the working fluid in power production systems. In particular, the review explores the use of ammonia as a working fluid in binary cycles, highlighting its potential to reduce greenhouse gas emissions. However, it also discusses the environmental issues associated with the manufacture, transportation, and combustion of ammonia, emphasizing the necessity for appropriate handling and disposal practices to mitigate its effects. The paper also reviews and contrasts the utilization of binary cycles in various power plants according to several different criteria. The research under consideration examines the performance enhancements made possible by system designs and working fluid selections for a variety of power generation technologies, including solar, coal-fired, hydrogen liquefaction, and cogeneration systems. The results underline the importance of choosing the right working fluids and system setups to increase net power production, efficiency, power generation, and thermal efficiency while reducing environmental consequences.

Outline of the Present Work

This paper begins with an overview of solar-assisted power generation systems (SPAG), followed by a description of the various cycles employed in these systems. The focus then shifts to binary cycle and binary vapor cycle power plants in Section IV. Section V includes a state-of-the-art review, covering the utilization of an ammonia-water mixture and transcritical CO_2 as potential applications. The literature review on solar-assisted binary cycles is also included. Section VI discusses binary cycles used in different power plants, including geothermal power plants, solar power plants, and fuel cell-based power plants. Finally, the paper concludes with a section on the main findings and implications, addressing the challenges and opportunities for the future use of SPAG technology.

THERMODYNAMIC MODELLING

A hybrid solar power system known as SPAGM. A. Sulaiman et al. [4] substitutes low-grade solar energy for high-grade heat from steam, expressed as a ratio (RRC) power plant extraction in chronological sequence to preheat feedwater. The primary feature of SAPG is that solar heat is not used to generate electricity directly in the turbine; rather, it is simply used to displace the extraction of steam by heating the feedwater entering the boiler. In order to continue using the extraction steam in the turbines to generate energy, it may have been conserved or moved M. A. Sulaiman et al. [4]. Along with the electricity generated by the steam that was either saved or replaced, the energy produced by the solar temperature range is also taken into account M. A. Sulaiman et al. [4].

The SAPG idea delivers substantial advantages of thermodynamics over earlier solar thermal energy generation systems A. Kumar and S. K. Shukla [5]. When the hydraulically sink temperature is fixed, the maximum temperature that the planet's thermal generator can sustain limits or caps the thermodynamic efficiency of any solar thermal power system A. Kumar and S. K. Shukla [5]. The hottest setting of solar thermal input places unique restrictions on a conventional solar thermal power system's maximum efficiency. The SAPG systems' solar-to-battery effectiveness is instead limited or capped by the plant's greatest temperature reading, the consume temperatures, which are often much warmer than the environment of the solar heat input A. Kumar and S. K. Shukla [5].

Different Types of Cycles Used in Power Generation Systems and Their Impact on Environment

Electricity-producing systems are often referred to as heat engines since they continuously convert heat into work. Incomplete combustion of fossil fuels (coal, oil, and natural gas), nuclear fuel preparation, or harnessing mechanical energy from renewable resources are all methods of generating heat. For example, in a conventional coal-fired power plant, the energy from coal is ultimately converted into electricity (often referred to as a "power station") M. S. Jamel et al. [6]. Conventional power sources S. R. Paital et al. [7], such as steam Rankine power plants, organic Rankine power plants, combustion turbine power plants, combined cycle energy stations, nuclear power plants, and hydroelectric energy plants, are well-known power-generating technologies. These conventional power generation systems (CPGSs) produce mechanical work as their primary output, which is then transmitted to subsequent components through rotating shafts. In vehicle drive systems, the energy from the engine shaft is used for propulsion. In stationary power plants or generators, the shaft power from the prime mover is used to drive an electricity generator, which converts the mechanical energy into electric energy. Geothermal power plants can also generate electricity by utilizing steam from geothermal reservoirs. There are three methods J. Phillips et al. [8] used in geothermal power plants to convert hydrothermal fluids into energy: dry steaming, flash steaming, and binary cycling. The specific conversion method employed depends on the temperature and state (steam or water) of the fluid.

The environmental impact of binary cycle power generation depends on several factors, including the energy source used, the efficiency of the system, and the specific environmental context. Some key points regarding the environmental impact of binary cycle power plants are shown in figure 2. It is important to note that the environmental impact of binary cycle power plants can vary significantly depending on the specific implementation and the energy source being utilized. To ensure sustainable and environmentally friendly operation, it is crucial to adhere to rigorous environmental regulations, employ effective pollution control technologies, and consider the specific environmental context of each project.

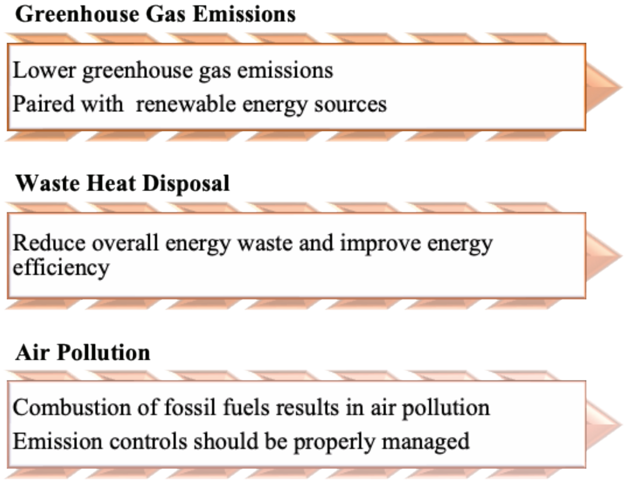

Figure 2. Environmental impact of binary cycles.

Binary Cycle and Binary Vapour Cycle Power Plants

A geothermal power plant, also known as a binary cycle power plant, employs two fluids to generate energy. The first fluid is hot geothermal water or steam, which is used to heat a second fluid with a lower boiling point, such as isobutane or pentane. The lower boiling point of the second fluid causes it to vaporize and drive a turbine, producing electricity. After the vapor is cooled and condensed back into a liquid state (as shown in Figure 3), the heating process is repeated. Binary cycle power plants are an effective way to utilize low-temperature geothermal energy that would otherwise not be suitable for power generation M. Karadas et al. [9].

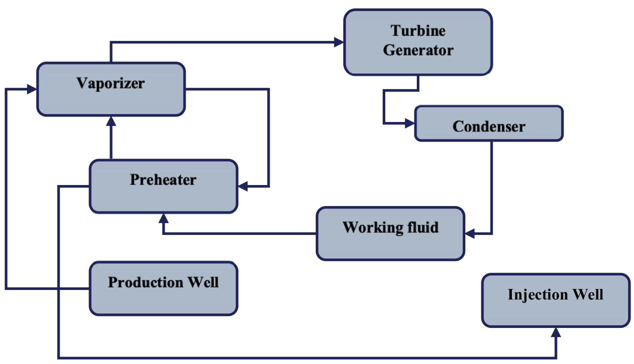

Figure 3. Binary cycle power plant.

On the other hand, a binary vapor cycle is a type of power cycle that utilizes two vapor streams with different compositions. Typically, one vapor stream consists of a hydrocarbon, while the other consists of water or another non-condensable gas. These two streams are combined, heated, and expanded through a turbine to generate energy X. Zhang et al. [10] F. A. Al-Sulaiman et al. [14]. The spent vapor is then separated into its constituent streams, with the working fluid being compressed and returned to the heating process, and the non-condensable gas being recycled back into the mixture. Binary vapor cycles are commonly used in combined-cycle power plants and have the potential to be more efficient than other cycle types, especially at high pressures and temperatures. Both binary cycle and binary vapor cycle power plants offer specific advantages and are suitable for particular power generation applications.

To operate at lower temperatures, binary cycle power plants utilize water with temperatures ranging from 74 to 177°C. A "working fluid," which is typically a chemical substance with a low boiling point, such as isobutene, is heated in these facilities using the heat from the hot water. Examples of working fluids include isopentane, propane, freon, or ammonia. The hot water transfers its heat energy to the working fluid through a heat exchanger in either a conventional Rankine cycle or a Kalina cycle X. Zhang et al. [10]. The working fluid vaporizes in the heat exchanger and is then used to drive a turbine. The geothermal water and the working fluid are kept in separate closed systems. The expanding vapor of the working fluid powers the turbine, which in turn drives a generator. In binary power plants that employ air cooling, the geothermal fluid is returned to the underground geothermal reservoir without being exposed to the atmosphere, effectively minimizing emissions. In a closed loop configuration, when the fluid in a binary plant is reinjected into the heat exchanger, only water is effectively released into the atmosphere. Small-scale power plants offer numerous possibilities, particularly in rural areas A. Giovannelli et al. [11]. Various small, modular power generation technologies fall under the category of "distributed energy resources" M. F. Akorede et al. [12], and together, they aim to improve the efficiency of power generation systems A. Chauhan and R. P. Saini et al. [13]. Recent approaches involve evaluating changes in boiling points based on density.

The binary vapor cycle is a thermodynamic cycle that converts thermal energy into mechanical energy. It consists of two separate sub-cycles, each using a different working fluid. Although a parallel arrangement is also possible, the most commonly used configuration is serial coupling of the sub-cycles. Binary sets have gained widespread recognition since the turn of the 20th century. The mercury-steam cycle was developed to enhance the efficiency of the steam cycle without increasing pressure F. A. Al-Sulaiman et al. [14], in line with the principles of the Carnot heat engine L. Chenet al. [15]. Advances in industrial technology and materials science have allowed complex and expensive binary sets to be replaced by steam sets with live steam conditions of 550°C and pressures of 15 MPa or higher.

Governing Equations for Thermodynamic Analysis of Solar Assisted Binary Vapour Cycle

The governing equations related to the thermodynamic analysis of a binary vapor cycle provide a mathematical representation of the fundamental principles and relationships within the cycle. These equations allow for the calculation and analysis of various thermodynamic properties and performance parameters:

Mass balance equation

The mass balance equation ensures that the total mass entering the cycle is equal to the total mass exiting the cycle. It accounts for the conservation of mass in the system. The equation states that the sum of the mass flow rates of the two working fluids at the inlet ($M_1 + M_2$) is equal to the sum of the mass flow rates at the outlet ($M_3 + M_4$). This equation helps in determining the mass flow rates and their distribution within the cycle. It can be expressed as:

$M_1 + M_2 = M_3 + M_4$

where M_1 and M_2 are the mass flow rates of the working fluid at the inlet, and M_3 and M_4 are the mass flow rates at the outlet of the cycle. It can be simplified as Keshvarparast et al. [16]:

$$\sum \mathrm{M_{in}} = \sum \mathrm{M_{out}}$$

Energy balance equation

Considering a binary vapor cycle with n stages, the energy balance equation for a binary vapor cycle can be expressed as:

$$\sum \left(\mathrm{M} * (\mathrm{H_{in}} - \mathrm{H_{out}})\right) = \sum (\mathrm{Q_{in}} - \mathrm{W_{out}})$$

Where, M represents the mass flow rate of the fluid at each stage. H_{in} and H_{out} represent the enthalpy of the fluid at the input and output of each stage, respectively. Q_{in} represents the heat input to each stage. W_{out} represents the work output from each stage. This energy balance equation ensures the conservation of energy within the binary vapor cycle, accounting for the heat input and work output at each stage Keshvarparast et al. [16].

Thermodynamic Equations for Each Component of Binary Cycle Keshvarparast et al. [16]

For Pump, $W_{pump} = \dot{M}_{wf} \cdot (H_{out} - H_{in})$

Recuperator: $Q_{Recuperator} = \dot{M}_{wf} \cdot (H_{out} - H_{in})$

Evaporator: $Q_{Evaporator} = \dot{M}_{wf} \cdot (H_{out} - H_{in})$

Turbine (4-5): $W_{Turbine} = \dot{M}_{wf} \cdot (H_{out} - H_{in})$

These governing equations are fundamental in analyzing the thermodynamic performance of binary vapor cycles, providing insights into the mass and energy balance, as well as the principles of energy conservation and entropy generation within the system.

State of the Art Review

Due to the massive energy waste generated by open cycle gas power stations, engineers and scientists began to investigate other energy sources, including

- Closed cycle gas turbine
- Binary vapor power cycle
- Solar assisted power cycle
- Renewable energies
- Power cycle using working fluids other than water

Olumayegun et al. [17] provided a summary of global closed-cycle gas turbine research initiatives and studies conducted to date. The authors described crucial components, including heat sources, working substances, heat exchangers, and cycle designs/configurations, and presented a chronological account of historical development. They evaluated significant research projects, experimental and pilot facilities, as well as commercially operational units. Rahbar et al. [18] concluded that waste heat recovery and the utilization of renewable energy sources can effectively address low-grade energy. The Rankine Cycle (ORC) has been demonstrated as a reliable method for converting low- to medium-temperature heat systems into usable power. Pethurajan et al. [19] emphasized a review of various thermodynamic power cycles and the selection of the best turbine, focusing on the use of ORC as a topping or bottoming cycle in primary heating or energy cycles, along with its applications. Bamorovat Abadi & Kim [20] favored zeotropic refrigerant blends composed of two or three refrigeration systems instead of a single working fluid. The main advantages of this approach are increased energy efficiency and reduced irreversibility in the evaporator and condenser, where the temperature profile of the heat source and heat sink does not align with the cyclical phase shift of pure refrigerant. Sarkar & Bhattacharyya [21] analyzed several working fluids and concluded that ammonia excels in terms of net energy generation, while n-Pentane is the optimal fluid for thermal efficiency and heat transfer compactness, considering turbomachinery compactness.

Analysis of the Utilization of an Ammonia-Water Mixture as a Working Fluid

Calculating the thermodynamic characteristics of an ammonia-water mixture at various key stages is the initial and most crucial step in its utilization as a working fluid. Different authors have employed different equations of state. M. Wang et al. [22] used water and ammonia as the working fluid and discussed the development of an ammonia-water mixture Property Code (AWProC) based on Gibbs free energy. The authors validated these property codes using a nuclear power plant and also explored its use in energy storage and transportation due to the ammonia-water mixture's temperature glide properties, increased energy density, and carbon-free nature, as indicated by the Kalina cycle [23], Kim et al. [25]. Consequently, over the past two decades, there has been significant research interest in the use of an ammonia-water mixture as a fluid flow instead of a single liquid. It has been established that ammonia-water mixtures have the potential to extract more energy from low-grade heat sources, thus increasing energy conversion and generation processes in various applications. In Regulation et al. [26], the author provides experimental data on the heat capacity and fluid viscosity of ammonia-water mixes used in ORC applications, considering five different ammonia-to-liquid ratios.

Yuan et al. [27] investigated a new power cycle that utilizes low-temperature heat sources such as biomass, oceanic heat, and industrial waste heat. In this ammonia-based cycle, both a liquid-gas ejector and a reheater are employed. The theoretical performance is evaluated through energy analysis and functional analysis, and experimental investigation is conducted to validate the theoretical findings. The results demonstrate that turbine outlet pressure, generator pressure, heating source temperature, and cycle performance can all influence the performance, particularly the depressurization of the turbine outlet carried out by the ejector. Junye et al. [28] aimed to simulate a modified Kalina cycle by incorporating preheaters and water-cooling solution coolers into the first loops of a triple-pressure ammonia-water steam generator. The authors concluded that by implementing appropriate internal recuperation and suitable surface temperature in phase transition techniques to match the heat source and coolant, the cycles achieve a higher power output recovery of 15.87%. Chen et al. [29] compared two Organic Rankine Cycles (ORC) and two Kalina cycles under two heat source temperature scenarios: medium (346 °C) and low (146 °C). They also suggested the use of an iodine-powered cycle with a distillation phase.

Many researchers have also theoretically and experimentally investigated the inclusion of various thermodynamic components in the fundamental Kalina cycle. Bozorgian et al. [30] examined the impact of the environment on the thermodynamic performance of the combined ammonia-water cycle through simulation. Yuan et al. [31] inserted an ejector between the turbines and absorbers, following the recommendation to utilize low-temperature heat sources such as biomass, oceanic thermal energy, and industrial effluents heating in a novel ammonia-water power cycle. Higa et al. [32] discussed the utilization of binary component combinations used in absorption refrigeration, such as ammonia-water, as a working mixture in a Kalina cycle, presenting an intriguing opportunity for harnessing energy sources at low temperatures. In small-scale ammonia-water steam generators, the liquid is typically transferred from the absorbers to the evaporator using diaphragmatic pumps.

Heat recovery steam generators (HRSG) are heat exchangers that utilize waste heat to convert water into steam. Heat recovery vapor generators (HRVG), on the other hand, are heat exchangers that convert binary mixtures like ammonia and water into their vapor phase. Kim et al. [33] describe the first and second law assessments in terms of sensible heat for an ammonia-water mixed heat recovery vapor generator (HRVG) with a low-temperature energy source. They conducted an evaluation of essential factors such as ammonia mass percentages and ambient mixed pressures to determine their impact on the system's effectiveness in terms of heat transfer, entropy generation, and exergetic production.

A power generation cycle without appropriate thermo-economic calculations is inefficient. Altamirano et al. [34] focus on comparing cycle performance across various refrigerant families and working pairs. They provide a comprehensive analysis of the theory, experiments, and business aspects of narrow (50 kW) continuous line absorbing vented devices using symmetric plasmas (NH_3-H_2O, NH_3LiNO_3, H_2O-LiCl). Sun et al. [35] propose a device for ammonia-water power/cooling co-generation with configurable composition.

In recent years, there has been significant interest in a combination coolant and power system (CCPS) using an NH_3-H_2O absorption system. C. Wang et al. [36] examine previous works on CCPS to describe the characteristics of the working pair, as well as the experimental setup and demonstrative equipment. Totla et al. [37] explain the creation and use of absorption refrigeration, which is considered a better alternative to compressor refrigerators. They also provide important information and a methodology for implementing absorption refrigeration.

The unique connection of water and ammonia as a working fluid in steam cycle models has been compared with other configurations. The saturation characteristics of the mixtures under various pressures and temperatures have been examined. Thorin et al. [38] and Luo et al. [39] evaluate the performance of a nuclear ammonia-water energy and chilled co-generation plant (NAPR) and assess the performance of a modified acetic acid-water power/refrigeration mixed bottoming cycle (APR).

Exergy analysis, derived from the first and second laws of thermodynamics, is a technique for energy conservation. Raju & Kanidarapu et al. [40] assert that exergy analysis can reveal the work done within the network, the level of unsustainability, and potential solutions to increase system efficiency. Their discussion mainly focuses on various methods and potential strategies to enhance the effectiveness of the organic Rankine cycle (ORC), offering guidance on selecting optimal parameters and reducing system degradation rates. Mohtaram et al. [41] analyze how the engine compression ratio (RP) affects the performance of the ammonia-water combined cycle in terms of yield, flow velocity, enthalpy temperatures, and energy and exergy destruction. Shokati & Khanahmadzadeh et al. [42] investigate different combinations of the iodine Rankine power cycle and the iodine refrigerating cycle, as well as the exergetic performances of co-generation cycles. Roy et al. [43] study NH_3-H_2O-based Rankine cycles with fixed supplier and sink inlet values, comparing cycles with and without a steam generator.

Sharma et al. [44] explore advancements in thermal power cycles (CSP) in relation to concentrated solar power applications. They highlight that supercritical steam turbines are a preferred option for larger-scale implementations using multiple solar towers and heat transfer fluid (HTF).

Wang et al. [45] emphasize that in the limited ammonia-water power cycle, the typical method of transferring the liquid from the absorber to the evaporator is through the use of a diaphragm pump. They highlight that the efficiency and reliability of the system are significantly influenced by the energy consumption and potential losses associated with this pump. Kim et al. [25] conduct a systematic exergy analysis based on the second law of thermodynamics for Rankine (AWR) and regenerative (AWRR) ammonia-water power generating cycles. The purpose of their work is to evaluate the exergetic performance and identify areas of improvement for these cycles. By analyzing the exergy losses and efficiencies, they provide insights into optimizing the design and operation of Rankine and regenerative ammonia-water power generating systems.

Effect of Ammonia on Environment

The utilization of ammonia as a working fluid in binary cycles for power generation offers the potential to decrease greenhouse gas emissions when compared to conventional fossil fuel-based power plants. However, the environmental consequences associated with ammonia usage are influenced by several factors, including the production, transportation, and handling processes involved. Ammonia production can contribute to air and water pollution, and the transportation of ammonia requires energy, which can result in additional emissions Sanchis et al. [46]. Moreover, large-scale release of ammonia into the environment can be toxic and have adverse effects on aquatic life and ecosystems. Additionally, the combustion of ammonia can produce nitrogen oxides, which contribute to air pollution and pose health risks Sutton et al. [47]. It is crucial to implement proper storage, handling, and disposal procedures, as well as appropriate safety measures, to minimize the environmental impact of ammonia usage in binary cycle power plants. While ammonia shows promise in reducing greenhouse gas emissions, careful management of its environmental impact is essential to ensure its long-term sustainability Bicer et al. [48].

Exploring the Use of Transcritical CO_2 as a Potential Application

Song et al., [49] In some applications, T -CO_2 cycle systems have shown promise as power-generation technology. The turbine efficiency, which has a substantial impact on the overall system performance, is typically assumed to be constant in traditional T- CO_2-cycle system studies published in the literature. However, this can lead to subpar designs and optimization outcomes. Huang et al., [50] concluded that the CTPC system is an excellent engine waste heat recovery (E-WHR) technology due to its compactness and improved temperature matching benefits, as well as its good thermodynamic features and natural property of CO_2. Investigation is being done into the relationship between the turbine expander's electric current, voltage generation, and rotating speed. Test data revealed that the low power generation of the turbine expander was caused by leakage resulting from the failure of the dynamic seal. L. Li et al., [52] investigated and compared Organic Rankine cycles (ORC) and CO_2subcritical power cycles (T- CO_2) for low-grade thermal power generation through experimental studies on two separate test rigs.

Ge et al., [51] discovered that CO_2 combustors power cycles (T- CO_2) were more suitable for low-grade heat-to-power conversion and system flatness due to the carbon footprint of the working fluid and the temperature matching of the cycle heat reactions. However, the thermal efficiency of a T- CO_2 system still needs to be enhanced. A test rig for a small-scale power production system using T- CO_2 power cycles was developed, allowing subsequent system and component design and optimization guided by the simulation results.

M. J. Li et al., [53] provided a detailed analysis of the most recent trends in the development of the S- CO_2 power cycle and its numerous applications across the energy spectrum, especially in the nuclear and solar industries. The essay includes a summary of theoretical research, experimental analysis, and classifications of various strategies. Operating fluids and component designs are also compared.

Sarkar & Bhattacharyya, [21] explored the effects of liquid mass flow rates and water inlet temperatures of the gas chiller and evaporator on the water outlet temperatures, scheme COP, and water cooling and heating capacities of transcritical CO_2 heat pumps. Bamisile et al., [54] thermodynamically studied the combination of a CO_2 cascade refrigeration system, a CO_2 parabolic solar trough collector system, a supercritical CO_2 power cycle, a transcritical CO_2 power cycle, and a CO_2-based power cycle for the production of hydrogen and multiple generations. Chai et al. [55] aimed to provide an in-depth understanding of PCHEs' capabilities based on currently available literature and a survey of the heat exchangers currently on the market Li et al. [56] examined low-grade power production systems using CO_2 combustors power cycles (T-CO_2) and R245fa steam Rankine cycles using dynamic experimental methods (ORC).

Mehrpooya et al. [57] presents the representation and analysis of a combination process involving LNG regasification, transcritical CO_2 cycle combined-cycle power plants, and cryogenic air separation. Mosaffa et al. [58] discusses the carbon dioxide recapture unit of a coal-fired steam power plant with combustion CO_2 gas power generation. The study simulates three S- CO_2 Brayton cycles: a straightforward one, one with recompression, and one with partial cooling, and compares them with the available literature. Besarati & Yogi Goswami [59] provides information on the applications of supercritical CO_2 power generation processes, including oxygen/methane-fueled rockets and hyper water-cooled nuclear reactors. Pizzarelli et al. [60] and Wang et al. [61] introduce the primary designs and performance aspects of CO_2 power plants in their research. Liao et al. [62] cover the research and development of turbomachinery and heat exchangers in the context of S- CO_2 power cycles. They also discuss various applications of the S- CO_2 power cycle in nuclear companies, solar energy, coal-fired nuclear reactors, fuel cells, and waste heat recovery. This overview provides insights into the state-of-the-art of S- CO_2 power cycles.

Literature Review on Solar Assisted Binary Cycle

A solar-assisted binary cycle is a power production system that utilizes solar energy to enhance the efficiency of a binary cycle system. It involves integrating a large-scale solar collector into the heat exchanger of the binary cycle system, where solar energy is used to evaporate the working fluid. This integration allows the system to generate a significant amount of heat with reduced dependence on the primary heat source, resulting in improved efficiency. The working fluid in a solar-assisted binary cycle system is typically a refrigerant or hydrocarbon, such as isobutane or R245fa. This system is environmentally favorable as it utilizes renewable energy and emits fewer greenhouse gases compared to conventional power generation systems. Zhang et al. [63] propose a novel solar-powered power cycle system called "self-production and self-sale," which combines a cooling-power cycle with ammonia and water and a recompression supersonic carbon dioxide cycle ($RSCO_2$) (ACPC). The refrigeration capability of the ACPC is utilized to cool the $RSCO_2$'s main compressor inlet fluid. Milani et al. [64] present a unique model for a decentralized small-scale supercritical CO_2 shut Brayton cycle (s CO_2-CBC). The model focuses on three key performance indicators (KPIs), including cooling water demand, compatibility with concentrated solar power (CSP), and thermal efficiency. Luu et al. [65] provide control methods for a solar-assisted direct-heating hyperbaric Brayton cycle that uses supercritical CO_2 (sCO_2). They also conduct dynamic analysis and propose two control techniques to manage fluctuating net solar power (NSP) levels. Luu et al. [66] describe the cold start to full functioning of a solar-assisted recompression sCO_2 Brayton cycle, including an analysis and recommendation of a start-up method. They develop a comprehensive dynamic model of the complete solar integrated process. Besarati & Yogi Goswami [59] simulate various configurations of S-CO_2 Brayton cycles, including straightforward, under recompression, and with partial cooling. They compare the results to literature data and investigate the integration of organic Rankine cycles (ORCs) to utilize waste heat. Kizilkan & Yamaguchi [67] examine the viability of an innovative transcritical carbon dioxide Rankine cycle (RC) with an absorbent cooling system (ARS). They conduct experimental research on a test rig with solar assistance.

Tchanche et al. [68] utilize an exergy-topological method to examine three modified engines based on a simple Rankine engine with regeneration. The investigations consider three working fluids: R600, R245fa, and R134a. Khankari & Karmakar [69] propose utilizing the flue gas waste heat from a low-pressure 500MW (SubC) coal-fired power plant to power a solar-assisted Allam Cycle Scheme 11 (KCS 11).

Facão et al. [70] examine three solar-aided thermodynamic cycles for a 5 kW micro-cogeneration system. The cycles are based on the Rankine Cycle in Organisms (ORC), and the working temperatures for Solar thermal collectors in cycles 1, 2, and 3 range between 80°C and 250°C, respectively. Noriega-Sánchez et al. [71] provides a summary of important studies published in the field of power cycles, with a focus on working fluid mixtures. Colonna et al. [72] describe the development and current state of power converters, aiming to provide accurate information on their progress. Ahn et al. [73] introduce the current state of evolution of S- CO_2 cycles and offer a brief comparison of cycle efficiency for various S- CO_2 topologies. Delgado-Torres et al. [74] highlights the advantages of using solar power cycles in desalination applications, such as the ability to incorporate thermal energy storage systems or implement a multi-generation plan involving electricity, water, cooling, and hydrogen. Calderón et al. [75] reviews solid particles as candidates for use as heat transfer fluids (HTFs) and thermal energy storage (TES) in CSP facilities with open receivers. The paper also discusses the interaction between solid particles and key system components. Khandelwal et al. [76] presents a study that may be useful for specialists working on power plants aiming to modify solar-based Multifunction Cycle Power Plants (CCPP) or retrofit existing Oil Shale Coupled Cycle (NGCC) plants with enhanced solar cycles. Mondejar et al. [77] discusses several newly developed working fluids for thermal energy production. Ho et al. [79] examines solar receiver designs in central concentrators for high-temperature power cycles.

Walther et al. [78] covers the technological challenges associated with micro-scale combustion and the development of thermochemical power production devices. Riffat et al. [80] notes the rapid development of power generation systems using water or air as working fluids. Heat transfer fluid for concentrated solar power systems is identified as a crucial element. Vignarooban et al. [81] provides an in-depth analysis of gathering and transporting thermal energy in concentrated solar power systems, including the topic of heat transfer fluid. Babatunde et al. [82] conducts a study on working fluid selection for various applications, assisting in determining the potential best organic fluids for different ORC applications based on operating parameters. Alrebei et al. [83] presents an analysis of alternate working fluids used in the energy sector, focusing on gas turbines and combustion systems. Ziółkowski et al. [84] conducts a thorough examination of the development of a binary power plant in connection with low-temperature petro-geothermal resources. Igobo et al. [85] examines quasi-isothermal expansion sub-atmospheric power cycle heat engines and the techniques used to achieve heat transfer. W. Su et al. [86] discusses the accuracy of the excess free energy mixing rule model, particularly UNIFAC cultural lines, in the context of VLE (vapor-liquid equilibrium) data and its impact on the accuracy of the model. Table 1 presents different energy sources and binary cycles utilizing ammonia, water, and CO_2, along with key findings.

The binary cycle is an approach to power generation that can utilize a variety of energy sources. It entails transferring heat from the original heat source employing a secondary fluid with a lower boiling point than water. Here are few examples of how the binary cycle can be used to various energy sources:

- Geothermal Energy: High-temperature geothermal fluids are used to heat a secondary fluid, often an organic Rankine cycle (ORC) fluid, that drives a turbine to create electricity.
- The binary cycle can be employed with fossil fuel sources such as natural gas or coal. The combustion of the fuel generates high-temperature gases, which heat the secondary fluid and power the turbine.
- Waste Heat Recovery: Binary cycle systems may recuperate and transform waste heat from industrial activities including steel mills or cement plants.
- Concentrated Solar Power (CSP): By utilizing the heat generated by concentrated sunlight to produce electricity, binary cycle systems can improve the efficiency of CSP plants.
- Biomass power plants can generate electricity by using the heat generated by biomass burning in a binary cycle.

A solar-assisted binary cycle system operates at lower temperatures compared to conventional steam-based power plants due to the utilization of a binary mixture as the working fluid. This binary mixture consists of two fluids with different boiling points. Typical working fluids in such systems include isobutane, pentane, and propane. These fluids have low boiling points, which make them efficient in converting solar thermal energy into mechanical or electrical energy. Additionally, they possess eco-friendly characteristics and have a low potential for contributing to global warming. As a result, they are considered a preferred option for sustainable energy generation.

Binary Cycles Used in Different Power Plants

A binary fluid, which is often a combination of two fluids with differing boiling points, is used in binary cycles, a form of power production technique, to generate energy. The investigated cycles include binary cycles, SOFC-PTC (Solid Oxide Fuel Cell and Parabolic Trough Collector) integration, ejector-compression refrigeration, multi-component refrigerant systems, Kalina cycles, and temperature-swing adsorption. The findings highlight improvements in net power output, efficiency, power generation, and thermal efficiency achieved through various system configurations and working fluid choices. In

Table 1. Work done by different researchers on different working fluids

Authors / Reference	Energy Sources	Working Fluid/ Power Cycles	Key Findings
(Roy et al., 2010)	Industrial waste gas	NH_3-H_2O	Thermal and energetic efficiency are 11% and 73%, respectively.
(Vignarooban et al., 2015)	Solar thermal energy	There are numerous new molten-salts being offered.	We discuss in depth a number of different kinds of heat transfer fluids, such as air, water/steam, thermal oils, organic fluids, molten salts, and liquid metals.
			The system efficiency rises by 2.4%, and the effective operating time is marginally reduced by 0.14 h.
(Altamirano et al., 2019)	Geothermal	NH_3 -H_2O as well as NH_3 -$LiNO_3$	The primary binary working fluids analysed for single answer cooling are compared.
			Pressurizer
(Noriega-Sánchez, 2021)	Waste heat	Organic and CO_2 mixtures	desired thermodynamic characteristics
(Bamorovat Abadi & Kim, 2017)	Waste heat	Zeotropic refrigerant mixtures	Zeotropic mixes have benefits and drawbacks when used in orc power plants.
(M. J. Li et al., 2017)	Solar energy	S- CO_2	extremely efficient cycles
(Song et al., 2020)	Heat recovery from ICE	T- CO_2	improved, more dependable turbine operation
(Sun et al., 2013)	Waste heat	NH_3-H_2O	The suggested system's power generation and exergy efficiency are 40.6% and 36.4%, respectively.
(Igobo & Davies, 2014)	Waste heat	Condensable vapour	Achieve a noticeable enhancement in performance (over 40% and a 20% increase in productivity and efficiency for a specific task).
(Z. X. Wang et al., 2020)	Biomass energy	Water/ CO_2	Future CO2-EGS implementing should receive technical support.
(Olumayegun et al., 2016)	Fossil fuel, concentrated solar power, nuclear, biomass and waste heat	Nitrogen, air, CO_2, Helium,S-CO_2 ,etc	Summarises the flowing fluid's relative benefits and drawbacks
(Sarkar & Bhattacharyya, 2015)	Waste heat	Comparison between n-Pentane, and ammonia	The best fluid for net power generation and turbomachinery compactness is ammonia, while the best fluid for thermal efficiency and heat exchanger compactness is n-Pentane.
(Delgado-Torres & García-Rodríguez, 2022)	Solar	ORC, S- CO_2	Design proposals are examined and evaluated to identify design suggestions.
(Liao et al., 2019)	Nuclear industries, solar energy, coal-fired power plant, fuel cell	S- CO_2	The S-CO2 power cycle can achieve a high thermal efficiency at the moderate turbine inlet air temp (450–600 °C).
(Mondejar & Thern, 2014)	Concentrating solar thermal plants	R1233zd(E), R1234yf or R1234zeE	Examines a number of working fluid groups that are now utilised in thermal power conversion systems or have a great deal of promise for usage in the near future.
(Junye et al., 2014)	Waste heat	NH_3-H_2O	The power system efficiency is 15.87%, or roughly 16.6% better than the steam Rankine cycle's.

a binary cycle system, a turbine vaporizes and expands the working fluid, which then powers a generator to produce energy. Subsequently, the working fluid is returned to the heat source to complete the cycle once the turbine's exhaust has been condensed. Compared to conventional steam-based power plants, binary cycle systems have fewer adverse environmental implications and can produce electricity at room temperature.

Table 2. Binary cycle using NH_3+H_2O as the working fluid in geothermal power plants

Power Plant Location	Temperature (°C)	Cycle	Generated Power	Exergy Efficiency	Energy Efficiency	References
Ampallas area, West Sulawesi, Indonesia	168°C- - 175°C	Kalina Cycle	12 MWe	82.12%	-	N. Nasruddin [105]
Husawik, Iceland	124°C	Kalina Cycle	2030 kW	-	-	A. Setel [106]
Bruchal, Germany	120°C	Kalina Cycle	610 kW	-	-	G. V Tomarov [107]
Indonesia Power UPJP Komosang	160°C	Kalina Cycle	7811 kW	36.98%	10.49%	Santos et al. [108]
-	162°C	Binary Cycle	3942 kW	5.3%	18.66%	Sadiq J. Zarrouk [109]
Velika Ciglena	108.83°C	Kalina Cycle	3949kW	44%	-	Guzovic et al. [111]

Geothermal Power Plants

To generate electricity, hydroelectric generators are used in geothermal power plants N. Chagnon-Lessard et al. [87], W. Tasnin et al. [88]. The main distinction that sets them apart from coal or nuclear power facilities is the heat source. Geothermal energy replaces the need for a boiler in a coal plant or a reactor in a nuclear plant A. N. Shulyupin and I. I. Chernev [89], A. Basaran [90], D. Moya et al. [91]. In order to supply the nuclear plant, hot water or steam is extracted from the Earth through a network of wells. Most geothermal systems draw in groundwater and then return it Q. Liu et al. [92], M. C. Bassetti et al. [93], G. Cui et al. [94]. Since the rate of water consumption is generally higher than the amount of water returned, make-up water supplies are typically required. Among the three main types of power stations, the flash cycle is the most common Z. Lei et al. [95]. The type of plant to be used is determined by the quantity and temperature of the geothermal resource. Various geothermal plants located in different locations have demonstrated power and exergy efficiency using ammonia and water, as well as transcritical CO_2, as shown in Table 2 and Table 3.

- Dry steam plants: These plants utilize naturally occurring underground dry steam L. A. Prananto et al. [96]. The steam rises from the production well, transferring its energy to the turbine, and then condenses and is released into the atmosphere Venkatalaxmi et al. [97].
- Flash cycle steam plants: This type of plant is the most common due to the scarcity of naturally occurring high-quality steam. The groundwater enters the well at its own pressure and needs to be hotter than 180°C. As the pressure drops, some of the freshwater "flashes" into steam, which is then directed through the turbine (Jason Phillips [98], Bruscoli et al. [99], Assad et al. [100], S. Akar et al. [101]). The remaining water that didn't vaporize can be recirculated and used for other heating purposes. Despite the complexity of their components, these systems are competitive with traditional power sources despite higher costs (A. Darmawan Pasek et al. [102]).
- Cycle plants: With the utilization of geothermal heat expanding beyond identified hot spots, binary power plants are expected to become the dominant type of geothermal power generation technology X. Liu et al. [103]. These plants can use lower temperature water compared to other types of geothermal plants. The term "binary" refers to the use of a second loop containing a substance with a low boiling point, such as butane or pentane B. M. Grassiani [104]. The well water is heated by the fluid in the secondary loop, causing it to evaporate due to its low boiling point. The resulting vapor then passes through a turbine, serving the same purpose as steam.

Table 2 provides details on various power plants that generate electricity using binary cycles, particularly the Kalina Cycle and Binary Cycle. These power plants are located globally, including Germany, Iceland, and Indonesia. The heat source temperature ranges from 108.83°C to 175°C, and the power output ranges from 610 kW to 12 MWe. Exergy efficiency figures are provided for some power facilities, ranging from 5.3% to 82.12%. Additionally, several power plants have published their energy efficiency,

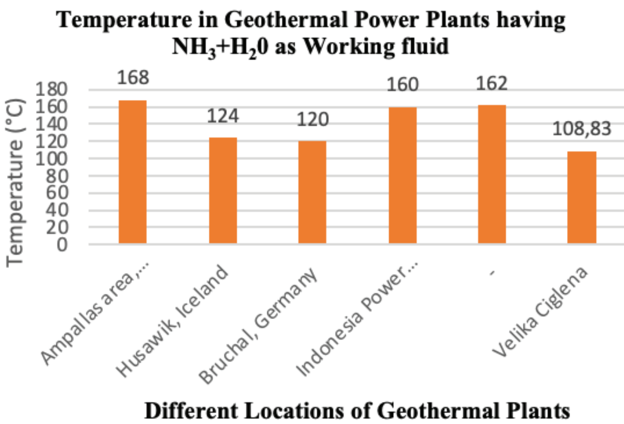

Figure 4. Temperature in geothermal power plants with NH_3+H_2O as the working fluid at different locations.

Table 3. Binary cycle in geothermal power plants having CO_2 as working fluid.

Power Plant Location	Temperature (°C)	Cycle	Generated Power kW	Exergy Efficiency	Thermal Efficiency	References
-	120°C	Transcritical CO_2 Cycle	534.21	7.95%	-	J. Wang et al. [112]
Sabalan geothermal wells energy,	-	Transcritical Rankine Cycle	19448	63.78%	16.63%	M. Abdolalipouradl et al. [113]
Sidirokastron, Greece	73.33°C	CO_2 Supercritical Binary Cycle	300	-	8.2%	D. Chasapis et al. [114]
-	130°C	CO_2 transcritical power cycle	1911.78	82%	8.48%	C. Wu et al. [115]
Yangbajain, China	126.75°C	CO_2 transcritical power cycle	199.1	56.8%	6.5%	S. Li and Y. Dai [116]

with coefficients ranging from 10.49% to 44%. The table includes other references for the data presented.

Geothermal power plants often utilize binary cycles with a mixture of NH_3 and H_2O as the working fluid. Figure 3 illustrates the temperature variations in Geothermal Power Plants at different locations using NH_3+H_2O as the working fluid. In this system, the geothermal source heats the NH3 and H_2O mixture, which vaporizes and drives a turbine to generate electricity. One of the advantages of binary cycles using NH_3/H_2O is their ability to operate at lower temperatures compared to conventional steam-based power plants. Additionally, NH_3/H_2O is non-toxic and non-flammable, making it environmentally preferable to other working fluids. The exergy and thermal efficiencies of NH_3/H_2O binary cycles can vary depending on the system's design and the temperature of the heat source.

Geothermal power plants are increasingly adopting binary cycles using CO_2 as the working fluid to produce energy. In this power generation technique, the geothermal heat source heats the CO_2, producing steam that powers a turbine to generate electricity. Binary cycle systems with CO_2 can operate at lower temperatures and have a smaller environmental impact compared to conventional steam-based power plants. CO_2 is a non-toxic and non-flammable gas, making it advantageous as a working fluid from an environmental standpoint. The energy and thermal efficiency of CO_2 binary cycle systems can be influenced by the temperature of the heat source and the specific design of the system.

Table 3 presents details of various geothermal power stations that generate energy using binary cycles with CO_2 as the working fluid. These power plants are located worldwide, including China, Greece, and an unidentified site. The heat source temperature ranges from 73.33°C to 130°C, and the power output ranges from 199.1 kW to 19,448 kW. Several power plants report exergy efficiency figures ranging from 7.95% to 82%. Additionally, thermal efficiency values are provided for several power facilities, ranging from 6.5% to 16.63%. The table includes references for further information.

The studies mentioned in this section offer valuable insights and advancements in the field of geothermal power plants, opening up potential future scopes. These include optimizing Organic Rankine Cycles (ORCs) to maximize specific power output, integrating geothermal plants with other renewable sources, reducing steam deficit through improved methods, enhancing geothermal-solar hybrid systems with thermal storage, utilizing depleted reservoirs and CO_2 recycling, optimizing specific geothermal fields, utilizing excess steam, optimizing the design and configuration of binary cycle plants, addressing scaling and operational challenges, exploring exergy and environmental optimization, and considering average temperature geothermal resources. These future directions collectively contribute to the potential development and advancement of the geothermal power sector.

Solar Power Plants

The solar field and the power block are two main systems utilized in photovoltaic arrays for energy generation H. Michels et al. [119], M. R. Shahnazari et al. [120], G. A. Barron-Gafford et al. [121]. The choice of working fluid and specific thermodynamic cycle arrangement significantly impact the functionality of the power plant R. Chacartegui et al. [122]. The selection also depends on the type of renewable technology employed. Currently, the steam Rankine cycle paired with a parabolic trough solar field is the most popular and commercially viable solution. However, alternative setups have been implemented in solar stations worldwide I. Gašparovic et al. [123]. In a study conducted by Hossain et al. [124], a solar power plant utilizing a binary cycle with isobutane as the working fluid was examined. The power plant achieved a thermal efficiency of 12.5% with a power generation capacity of 250 kW. The operating temperature ranged from 120 to 200°C. The findings demonstrated that the proposed system

Table 4. Binary cycle in solar power plants having NH_3+H_2O as working fluid

Cycle	Power generated kw	Energy efficiency	Exergy efficiency	System efficiency	Temperature (°C)	References
S CO_2 cycle	2750	-	-	-	360	M. Emre and I. Dincer [126]
T CO_2	1413.08	-	-	66.39%	104.85	Hossain et al [127]
Organic Rankine cycle	550.9	21.93%	64.92%	-	176	Tukenmez et al. [128]
S CO_2	582.8	-	-	50.5%	106	B. Ghorbani [129]
T CO_2	4500	-	-	57%	155	A. M. Delgado-torres and L. García-rodríguez [130]

exhibited higher energy conversion efficiency compared to conventional solar power plants, highlighting its potential for solar energy harnessing in Malaysia. While installed power combined cycles have seen significant implementation, the majority of them are based on other solar technologies that are also connected to a steam Rankine cycle. Initially, Rankine, Brayton, and combined Brayton-Rankine power block topologies, utilizing traditional thermoelectric materials, were introduced R. Chacartegui et al. [122], I. Gašparovic et al. [123], Hossain et al. [124], E. Oró et al. [125]. In Table 4 and 5, we provide information on power generation in solar power plants employing binary cycles with ammonia and water as the working fluid, as well as carbon dioxide as a working fluid.

Table 4 presents various binary cycles utilized in solar power plants that employ NH_3+H_2O as the working fluid. These cycles encompass the Organic Rankine cycle, T CO_2cycle, S CO_2cycle, and others. The power output ranges from 550.9 kW to 4500 kW, while the energy efficiency ranges from 21.93% to 57% and from 50.5% to 64.92%. The temperature of the systems spans from 104.85°C to 360°C. The efficiency and power generation of each cycle are influenced by multiple factors, including the system's configuration and the temperature of the heat source. Overall, the utilization of binary cycles with NH_3+H_2O as the working fluid in renewable energy production holds great promise.

The binary cycles utilized in solar power plants that employ CO_2 as their operating fluid are displayed in Table 5. At a temperature of 746°C, the supercritical CO_2(SCO_2) cycle produces 2280 kW with an energy efficiency of 22.3% and an exergy efficiency of 11.9%. At a temperature of 549°C, the S-transcritical CO_2 cycle generates 2100 kW with a high energy efficiency of 26.9% and an exergy efficiency of 41.9%. At a high temperature of 620°C, the CO_2-Brayton cycle achieves a thermal efficiency of 33%. The Brayton cycle has a heat transfer rate of 49% and produces 50,000 kW. Finally, at a temperature of 650°C, the SCO_2 power cycle generates 10,000 kW with a 44% energy conservation.

Binary vapor cycles in solar power plants offer significant potential for future advancements and research. Key areas of focus include the utilization of CO_2-based cycles with ground-cooled condensers, enhancing geothermal energy extraction through CO_2 utilization, investigating cascaded latent heat storage systems, optimizing plant locations using remote sensing and GIS methods, assessing the life cycle sustainability of thermal energy storage systems, integrating solar power plants with trigeneration systems, exploring advanced cycle technologies, and incorporating

Table 5. Binary cycle in solar power plants having CO_2 as working fluid

Cycle	Power generated kw	Energy efficiency	Exergy efficiency	Thermal efficiency	Temperature (°C)	References
S CO_2	2280	22.3%	11.9%	-	746	O. K. Singh and S. C. Kaushik [131]
S- transcritical CO_2	2100	41.9%	26.9%	-	549	H. Ishaq and I. Dincer [132]
CO_2 –Brayton cycle		-	-	33%	620	K. H. M. Al-Hamed and I. Dincer [133]
Brayton cycle	50000	-	-	49%	-	R. Valencia-Chapi et al. [134]
S CO_2 power cycle	10000	-	-	44%	650	O. Bamisile et al. [135]

biomass, cryogenic energy, and carbon capturing systems. These endeavors aim to improve the efficiency, sustainability, and overall performance of binary vapor cycles in solar power plants.

Fuel Cell Based Power Plants

A conventional fuel cell power plant consists of a fuel processor that converts the fuel, such as natural gas or methanol, into hydrogen, a multi-cell fuel cell stack, a power conditioner that converts the fuel cell's output from direct current to alternating current, and heat exchangers. The design of a fuel cell power plant depends on the application and type of fuel cell being used. In Table 6 and 7, we provide the power generated in fuel cell-based plants using binary cycles with ammonia and water as the working fluid, as well as carbon dioxide. The thermal performance of using firewood for electricity generation is weak A. Choudhury et al. [137], K. Rajashekara et al. [138], Spinelli et al. [139]. Rankine cycle reactors with electric power outputs of approximately 10-20 MW have efficiencies ranging from 25% to 28% K. Rajashekara et al. [138]. For lower demands, ORC (Organic Rankine Cycle) and Stirling generators (5-1000 kW) can be used, but their effectiveness may be reduced Spinelli et al. [139]. The development of low-emission, efficient energy generation systems has recently received significant attention. Fuel cells are considered the most promising technology among advanced power conversion systems due to their environmental, sustainability, and safety benefits Spinelli et al. [139]. Fuel cells come in various types, with the Solid Oxide Fuel Cell (SOFC) A. Massardo et al. [140] emerging as a device suitable for both small and large power plants. The Kalina cycle is another environmentally beneficial method that can be used to recover heat from systems operating at different temperatures M. D. Lukas et al. [141]. In a study conducted by Ma et al. [142] on a coal-fired power plant integrated with a solid oxide fuel cell (SOFC) and a solar collector, air and CO_2 were used as working fluids. The integrated system achieved a thermal efficiency of 50.2% and had a power generation capacity of 350 kW. The results demonstrated that the incorporation of the SOFC and solar collector enhanced the overall efficiency of the coal-fired power plant and decreased its carbon emissions. This research emphasized the potential of this hybrid system in improving the sustainability of coal-based power generation. In another study discussed in Skjervold et al. [144], the authors investigated the enhanced flexibility of a coal-fired power plant through the integration of a moving bed temperature-swing adsorption (MBTSA) CO_2 capture system with thermal energy storage (TES). The researchers examined the integration of TES with the MBTSA process and analyzed its impact on the power plant's flexibility and efficiency. The study revealed that the use of TES enabled the power plant to respond more effectively to varying power demands and reduced the energy penalty associated with the CO_2 capture process.

The productivity of binary cycles in fuel cell power plants utilizing the working fluid NH_3+H_2O is shown in Table 6. The Rankine cycle generated the highest power output, reaching 20,125 kW at an unspecified temperature, with a thermal efficiency of 39% and an exergy efficiency of 36%. At 124°C, the Kalina cycle produced 1,015 kW of power with a thermal efficiency of 42%, while the exergy efficiency was not reported. Another Kalina cycle generated 2,109.6 kW of power at an unspecified temperature, achieving a thermal efficiency of 41% and an exergy efficiency of 28.9%. The Refrigeration system, operating at 180°C, generated 17,900 kW with a thermal efficiency of 70.3% and an exergy efficiency of 12.1%. At 350°C, it produced 5,664.8 kW with a thermal efficiency of 25.4% and an exergy efficiency of 28.6%.

The binary cycle in fuel cell-based power plants using CO_2 as a working fluid is shown in the table. These cycles generate power ranging from 1000 kW to 2186.1 kW. The exergy efficiencies of these cycles range from approximately 62.35% to 80.79%, while their thermal efficiencies range from 20.03% to 80.79%. The operating temperatures of these cycles fall within the range of 85°C to 127°C. In all cases, the Kalina cycle is employed.

The future prospects for binary vapor cycles in fuel cell-based power plants encompass various significant areas of development. These areas include the pursuit of

Table 6. Binary cycle in fuel cell power plants having NH_3+H_2O as working fluid

Cycle	Power generated	Energy efficiency	Exergy efficiency	Temperature (°C)	References
Rankine cycle	17900kw	70.3%	12.1%	180°C	G. Fan and Y. Dai [144]
Kalina cycle	1015kw	-	42%	124°C	M. Zeeshan [145]
Rankine cycle	20125kw	39%	36%	-	L. Pierobon and M. Rokni [146]
Kalina cycle	2753kw	-	28.9%	120°C	P. Bombarda et al. [147]
Kalina cycle	2109.6kw	-	41%	-	E. Gholamian and V. Zare [148]
Rankine cycle	5664.8kw	25.4%	28.6%	350°C	J. Ryu et al. [149]

Table 7. Binary cycle in fuel cell based power plants having CO_2 as working fluid

Cycle	Power generated	Exergy efficiency	Thermal efficiency	Temperature (°C)	References
Kalina cycle	1101kw	-	80.79%	85°C	M. H. Ahmadi et al. [150]
Kalina cycle	1000kw	-	20.03%	126°C	M. H. Ahmadi et al. [151]
Kalina cycle	1615kw	-	21.5%	127°C	S. J. Bae [152]
Kalina cycle	2186.1kw	62.35%	64.22%	-	H. Hemmatabady et al. [153]

Table 8. Comparative analysis of geothermal power plants, fuel cell based power plants, and solar power plants

Parameter	Geothermal Power Plants	Fuel Cell Based Power Plants	Solar Power Plants
Fuel source	Heat from the earth	Hydrogen	Sunlight
Availability	Requires specific geology	Dependent on availability of hydrogen	Depends on location and climate
Efficiency	High efficiency	High efficiency	Moderate efficiency
Operating cost	Low cost	High cost	Moderate cost
Environmental impact	Low emissions	Low emissions	Low emissions
Energy storage	Limited storage options	Can store energy as hydrogen	Can store energy with batteries
Power output	Can generate large amounts of power	Can generate moderate amounts of power	Can generate moderate amounts of power
Reliability	Reliable	Reliable	Moderately reliable

high-efficiency thermodynamic power cycles, advancements in solid oxide fuel cell (SOFC) technology, exploration of hybrid fuel cell strategies, evaluation of molten carbonate fuel cell-based approaches for carbon capture, and optimization of the integration of microturbines with fuel cells. The primary objective is to enhance the overall efficiency of the system, improve the performance and reliability of fuel cells, maximize power generation from different fuel cell technologies, and seamlessly integrate them with complementary energy conversion cycles. These advancements are aimed at optimizing power plant performance, mitigating environmental impact, and facilitating sustainable and environmentally-friendly power generation in fuel cell-based power plants.

A facility that produces electricity comprises several intricate open and closed systems. However, if the entire facility is considered as the system with appropriately defined boundaries, it can be described as a closed system. These systems are commonly referred to as power plants, and a quick thermodynamic assessment can provide crucial insights into their operation. In comparison to flash power systems, binary cycle plants exhibit higher efficiency and can utilize reservoirs with lower temperatures. Moreover, they eliminate concerns related to corrosion and environmental hazards. However, these systems require large pumps, which incur higher costs and consume a significant portion of the plant's output.

DISCUSSION AND COMPARATIVE STUDY

In Jouybari et al. [154], a study evaluated an innovative structure for hydrogen liquefaction through thermodynamic and exergy analysis. The system incorporated an ejector-compression refrigeration unit, a cascade multi-component refrigerant system, and a Kalina power plant. The researchers concluded that the structure demonstrated feasibility and advantages for efficient energy conversion and utilization in hydrogen liquefaction. A comparative study conducted in Aksar et al. [155] assessed the Kalina (Ammonia-Water) cycle, steam Rankine cycle, and pure ammonia cycle for cogeneration systems. The study revealed that the Kalina cycle exhibited higher energy conversion efficiency and economic viability, indicating its potential as an efficient option for cogeneration systems. Geothermal, solar thermal, and waste heat recovery systems are among the power plants that utilize this technology, which are compared in Table 8 based on different parameters.

Geothermal power plants have high efficiency and low environmental impact; however, they require specific geology to be effective. Fuel cell-based power plants are dependent on the availability of hydrogen, which can be expensive, but they exhibit high efficiency and the capability to store energy as hydrogen. Solar power plants, on the other hand, rely on location and climate, but they offer moderate efficiency and the ability to store energy using batteries.

CONCLUSION

For producing electricity from steam-dominated resources, the power cycle, which comprises a generator, condensation, and waste heat rejecting equipment, is relatively simple. Conceptually, these components are similar to those found in traditional thermal power plants. This review article examines power cycles, solar-assisted energy generation methods, and the research conducted by various researchers in relation to the Rankine Cycle. It also reviews power cycles that use Transcritical CO_2 (T- CO_2) as a working fluid. We have presented power generation plants such as geothermal power plants, solar-assisted power plants, and fuel-cell based power plants that utilize binary cycles in the process. Additionally, we have provided the thermal efficiency, energy efficiency, and exergy efficiency of all the aforementioned power plants consisting of binary cycles. Moreover, we have discussed the power generated by each plant. The study highlights several binary cycles with CO_2 and NH_3+H_2O as the working fluids used in geothermal and solar power plants, respectively. The power production and efficiency of each cycle depend on various variables, including the system's layout and the heat source's temperature. Below are the key points of the different power cycles considered in the literature:

- Geothermal Power Plants:
- Power Generation Range: Geothermal power plants using CO_2 as the working fluid can generate power ranging from 199.1 kW to 19,448 kW.
- Efficiency Range: The thermal efficiency of geothermal power plants varies from 6.5% to 16.63%, while the exergy efficiency ranges from 7.95% to 82%.
- Solar Power Plants:
- Power Generation Range: Solar power plants utilizing NH_3+H_2O as the working fluid can generate power ranging from 550.9 kW to 4500 kW.
- Efficiency Range: The energy efficiency of solar power plants spans from 21.93% to 57%, and the exergy efficiency ranges from 50.5% to 64.92%.
- Fuel Cell-Based Power Plants:
- Power Generation Range: Fuel cell-based power plants employing NH_3+H_2O as the working fluid can generate power ranging from 1015 kW to 20125 kW.
- Efficiency Range: The thermal efficiency of these power plants ranges from 25.4% to 70.3%, while the exergy efficiency falls between 12.1% and 36%.
  Fuel Cell-Based Power Plants with CO_2:
- Power Generation Range: Fuel cell-based power plants using CO_2 as the working fluid can generate power ranging from 1000 kW to 2186.1 kW.
- Efficiency Range: The thermal efficiency ranges from 20.03% to 80.79%, and the exergy efficiency is approximately 62.35%.
- The choice of working fluid and cycle design play a crucial role in determining the efficiency and power production of geothermal, solar, and fuel cell-based power plants. The Kalina cycle shows high exergy efficiency, while the CO_2 transcritical power cycle and SCO_2 cycle exhibit notable efficiency values in their respective power plant applications.

NOMENCLATURE

Abbreviations

ORC-	Organic Rankine Cycle
HRSG/HRVG	Heat recovery steam generators/Heat recovery vapor generators Combination
CCPS	Coolant and Powering System
HTF	heat transfer fluid
COP	Coefficient of Performance

Symbol

$\sum M_{in}$	Working fluids at the inlet, kg/s
$\sum M_{out}$	Working fluids at the outlet, kg/s
W_{pump}	Work consumed by the pump, kJ
$Q_{Recuperator}$	Heat transfer in the recuperator, kJ
$Q_{Evaporator}$	Heat transfer in the evaporator, kJ
$W_{Turbine}$	Work output of the turbine, kJ/kg
M/M_{wf}	Mass flow rate, kg/s
H	Specific enthalpy, kJ/kg

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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