THE STUDY ON THE POTENTIAL OF SOLAR POWER TOWER AND SUPERCRITICAL CARBON DIOXIDE BRAYTON CYCLE TO REDUCE CARBON EMISSION IN AZERBAIJAN

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Abstract

The environmental challenges posed by conventional energy production necessitate a shift towards sustainable alternatives. This study explores the potential of solar power, particularly focusing on Solar Power Tower (SPT) systems utilizing the supercritical carbon dioxide (sCO_2) Brayton cycle, as a viable solution to reduce carbon emission in Azerbaijan. Through data collection and analysis, the study evaluates the efficiency and feasibility of SPT systems. Results indicate that the sCO_2 Brayton cycle offers a net cycle efficiency of 50.8%, surpassing traditional power generation methods. The Direct Normal Irradiance (DNI) analysis identifies the Nakhchivan Autonomous Republic as an optimal location for deploying SPT technology due to its high DNI levels. This transition to advanced solar technologies promises to meet rising energy demands, reduce carbon emissions, and mitigate environmental degradation, aligning with global efforts to address climate change and secure a sustainable future.

Keywords: solar energy, concentrated solar power, solar power tower, supercritical CO_2, photovoltaic, power cycles, sustainable energy

I. Introduction

Most current types of energy production and utilization cause environmental issues at local, regional, and global scales, reducing the quality of life and endangering human health. Fossil-fueled power plants produce large amounts of environmentally harmful emissions of gases such as carbon dioxide (CO_2). In 2023, the total CO_2 emissions from energy-related activities increased by 1.1% compared to the previous year. This rise pushed total CO_2 emissions to a record high of 37.4 billion tones [1]. Furthermore, worldwide energy demand is expected to rise approximately 1.5–3 times by 2050 [2]. By 2025, it is projected that the CO_2 intensity of global power generation will attain a level of 417 grams of CO_2 emitted per kilowatt-hour (g CO_2/kWh) [3]. This record-high level of emissions highlights the need for action to reduce carbon emissions, as these high levels significantly worsen global climate change. Thus, there is a pressing need to use renewable energy resources, such as solar, wind, hydropower, and biomass, instead of fossil fuels for energy generation. 26.49% of the world's electricity production comes from renewable energy sources [4], but for Azerbaijan, this figure is 20.3% [5].

The most developed form of renewable energy in Azerbaijan is hydropower, but in 2022, severe droughts recorded in several countries led to a decrease in confidence in hydropower [6]. On the other hand, solar energy has the highest economic potential among renewable energy sources. On average, each square meter of Earth receives roughly 342 watts of solar energy in a year [7]. This amounts to an enormous total energy input of 44 quadrillion (4.4×10^{16}) watts [7]. In Azerbaijan, the economic potential of solar energy sources is 23,000 MW [5], exceeding the economic potential of other renewable sources. Therefore, it is essential to develop solar energy, considering its vast potential globally and in Azerbaijan.

Solar energy stands out as an affordable renewable energy source with significant potential to generate clean and environmentally friendly energy. Solar radiation can be transformed into either heat or electricity through diverse solar conversion technologies. Solar energy conversion technologies can be classified into solar photovoltaic (PV) and concentrated solar power (CSP) systems. Solar photovoltaic systems directly transform solar radiation into electricity, whereas concentrated solar power systems convert solar radiation into heat energy. Solar power plants installed in Azerbaijan are all based on PV technology. However, CSP offers several advantages over PV systems. Thus, this study will focus on the potential installation of CSP technology in Azerbaijan.

Concentrated Solar Power (CSP) is a technology capable of large-scale electricity generation, providing reliable energy and the ability to deliver power on demand through thermal energy storage. CSP plants offer advantages such as high efficiency and the capability to accumulate heat, enabling operation nearly around the clock. Accumulating heat in CSP technology helps generate electricity when desired and stabilizes and controls power generation. CSP plants produce 33.3% more electrical energy compared to PV plants. [8]. Many positive aspects of CSP-type power plants make the installation and operation of this technology more appropriate. There are four distinct types of concentrated solar power systems: parabolic dish, parabolic trough, solar power tower, and Linear Fresnel reflector. They differ in how the sun's rays are concentrated in the receiver.

Solar Power Tower (SPT) technology is a promising option due to its wide temperature range, comparable cost per kilowatt, and longer storage durations [9]. SPT power plants work with the Rankine cycle. Rankin is pretty advanced, so there's little room for improvement. The simple Rankine cycle can achieve an efficiency of up to 29.6% [10], and specific studies indicate that this can potentially be improved to as much as 41% [11]. On the other hand, when supercritical carbon dioxide (SCO_2) is used as the working fluid in the Brayton cycle, the work efficiency appears to exceed 50% [12]. Supercritical CO_2 Brayton cycles can increase power plant capacity and efficiency, which will play a role in improving SPT technology [9].

In this paper, we investigate the potential of SPT power plants in reducing CO_2 emissions in Azerbaijan. We analyze the sCO_2 Brayton recompression cycle, develop a numerical model of an SPT plant, and propose a suitable region for its installation in the country. The results highlight the environmental benefits and feasibility of using SPT technology in Azerbaijan's shift towards renewable energy.

II. sCO_2 Brayton Recompression Cycle

Our study examines the sCO_2 (supercritical carbon dioxide) Brayton recompression cycle [13]. The recompression cycle reduces inefficiencies in the internal heat recovery process by using two recuperators and adding a secondary compressor. The cycle starts by compressing sCO_2 from low to high pressure with a compressor. As the sCO_2 is compressed, its temperature increases significantly due to its high heat capacity. Under these conditions, the sCO_2 enters the heat exchanger from the compressor, where it receives heat from an external source. In the heat exchanger, thermal energy from the Solar Power Tower heats the sCO_2, further increasing its temperature and pressure. The high-temperature, high-pressure sCO_2 then expands through a turbine, converting thermal energy into mechanical work. This turbine drives a generator to produce electrical power. After expansion, the sCO_2 enters the heat exchanger at a lower temperature and pressure to release the absorbed heat, reducing its temperature and preparing it for the next cycle. At reduced pressure and temperature, the sCO_2 is recompressed by the compressor to initiate the subsequent cycle.

Fig. 1 demonstrates a schematic representation of this cycle, which serves as the foundational framework for modeling an SPT power plant.

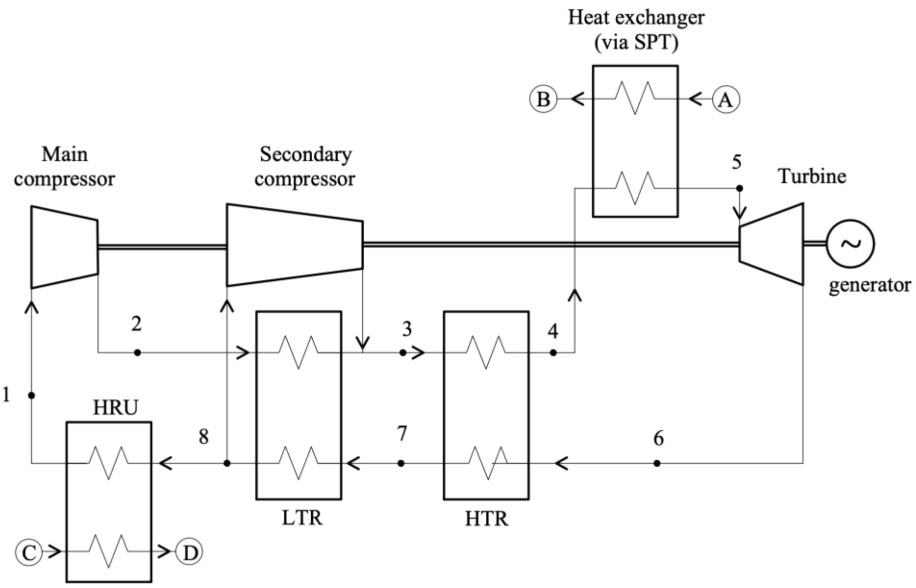

Figure 1: *Schematic of the sCO_2 Brayton recompression cycle [13]*

III. Methods

The numerical model of the sCO_2 cycle for the SPT power plant was constructed using Mathcad software. The numerical model uses primary assumptions outlined in Table 1.

Table 1: *Main assumptions for the sCO_2 cycle*

Parameter	Value	Parameter	Value
Heliostat field, F_H, m²	67	Maximum cycle temperature, t_0, °C	650
Heliostat reflectance, R_H	0,82	Maximum cycle pressure, P_{max}, MPa	25
Maximum irradiance of the heliostat mirror E_H, W/m².	610	Minimum cycle pressure, P_{min}, MPa	10,5
Maximum receiver irradiance, E_i, MW/m²	1,94	Relative internal turbine efficiency, η	0,84
Receiver absorption coefficient, A_{absorp}	0,95	Receiver emissivity ε_{em}	0,94

Direct Normal Irradiance (DNI) rates were analyzed to determine the optimal area for SPT implementation in Azerbaijan. This analysis was facilitated by utilizing geographic data provided by Solargis [14].

Additionally, we employed a comparative analysis approach to examine CO_2 emissions and technical parameters of the six most powerful non-renewable power plants in Azerbaijan: Shimal, Janub, Sumgayit, Gobu, Sangachal, and Azerbaijan. The parameters selected for this analysis are Capacity (MW), Cycle type, Cycle efficiency, and CO_2 emissions per kWh. Technical parameters were obtained through direct correspondence with the relevant power plant. This analysis was employed to evaluate the reduction in CO_2 emissions by replacing non-renewable power plants with SPT systems.

IV. Result and Discussion

I. Performance of power cycle

Our study began with an examination of the operational mechanisms of the sCO_2 Brayton recompression cycle. We based our calculations on the assumptions outlined in Table 1. We demonstrate the T-s diagram of the sCO_2 Brayton recompression cycle based on our results in Figure 2.

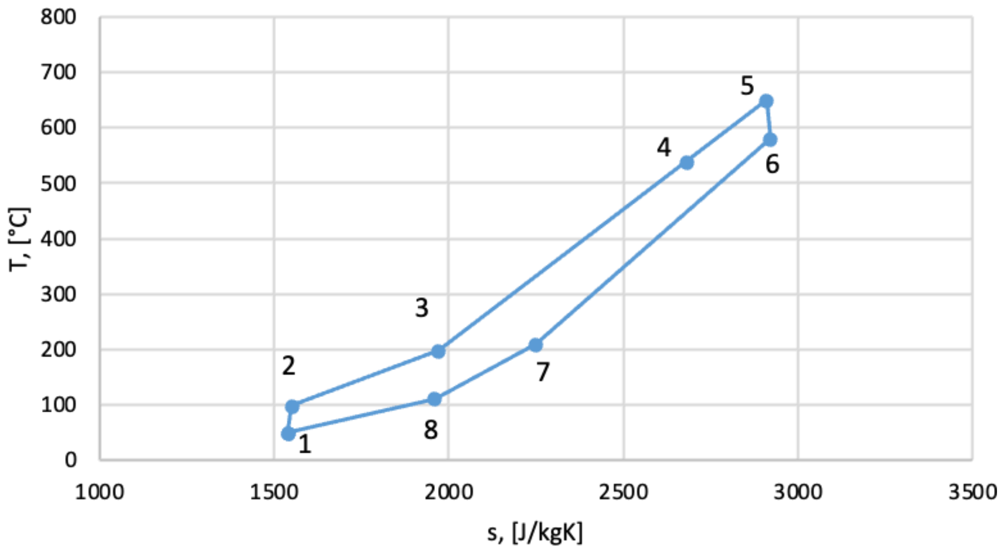

Figure 2: *T-s diagram of sCO_2 Brayton recompression cycle*

Additionally, we documented the outcomes of our calculations in Table 2. This table includes key performance metrics and design specifications such as sCO_2 mass flow, number of heliostats, heat exchanger characteristics, and operational parameters. These results provide a comprehensive overview of the system's performance under the specified conditions, demonstrating the feasibility and efficiency of using sCO_2 in SPT technology. The data in Table 2 are critical for validating the model and comparing the projected performance against conventional power generation systems. The efficiency of the cycle was determined to be 50.8%, indicating that the sCO_2 Brayton cycle is more appropriate for use in SPT plants than the Rankine cycle.

Table 2: *Main results for the sCO_2 cycle*

Parameter	Value	Parameter	Value
CO_2 mass flow at turbine inlet, D_0, kg/s	364	Turbine electric power, **MW**	72.8
Net heat input, Q_{ty} *KW*	107714	Main and secondary compressor electric power, **MW**	10/8
Receiver area, **m²**	57.5	Number of heliostats	3512
Capacity of Solar power tower, N_e, MW	54,8	Net Cycle efficiency, %	50.8

II. Identifying promising regions for Solar Power Tower deployment

Direct Normal Irradiance (DNI) is critical in analyzing a suitable area in Azerbaijan for an SPT. CSP systems, including SPT, concentrate sunlight on a small area to generate high temperatures. This concentration process is effective only with direct sunlight, making DNI an essential parameter for assessing the potential efficiency and viability of the system. High DNI values indicate a greater availability of direct sunlight, which is necessary for optimizing the performance of CSP technologies. The analysis of DNI levels in Azerbaijan, conducted using data from the Solargis [14], reveals several regions with significant potential for the deployment of SPTs. Upon analyzing the DNI maps, the Nakhchivan Autonomous Republic in Azerbaijan emerges as a particularly suitable location for the installation of an SPT power plant. The high DNI levels in this region indicate optimal conditions for the efficient operation of CSP systems, making it a promising site for harnessing solar energy effectively.

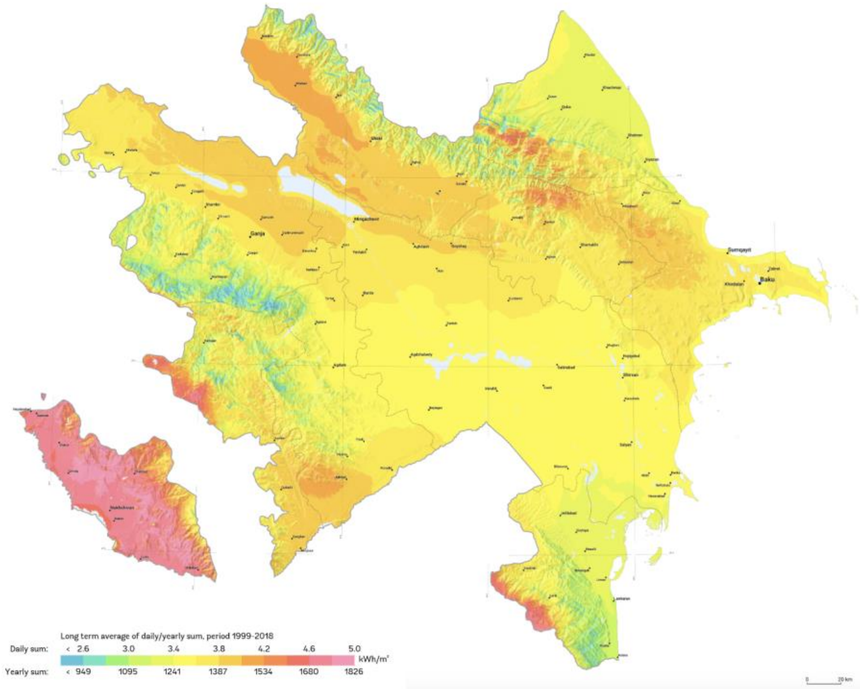

Figure 3: *Direct Normal Irradiation map of Azerbaijan [14]*

III. Potential for emissions reduction through Solar Power Tower

As previously discussed, energy production is a major contributor to environmental pollution. Therefore, it is essential to evaluate the carbon dioxide (CO_2) emissions produced by the operational non-renewable power plants in Azerbaijan. Table 3 provides the technical parameters of operational non-renewable power plants in Azerbaijan, including capacity, cycle type, cycle efficiency, and CO_2 emissions per kWh of electricity generated. The data highlights significant disparities in both capacity and efficiency among the power plants, with capacities ranging from 2400 MW for Azerbaijan TPP to 300 MW for the Sangachal Power Plant. Furthermore, variations in CO_2 emissions per kWh range from 0.414 kg for Shimal Power Plant to 0.538 kg for Azerbaijan TPP, underscoring the importance of technological efficiency in mitigating environmental impact in the energy sector.

Table 3: *Technical parameters of non-renewable power plants in Azerbaijan*

Name of the power plants	Capacity (MW)	Cycle	Efficiency of cycle (%)	CO_2 emitted per kWh (kg)
Azerbaijan TPP	2400	Rankine	37	0.538
Shimal Power Plant	800	Combined	55	0.414
Janub Power Plant	780	Combined	51	0.446

Sumgayit Power Plant	525	Combined	52	0.438
Gobu Power Plant	380	Otto	48	0.464
Sangachal Power Plant	300	Diesel	46	0.495

The data in Table 3 highlights that the Shimal Power Plant, with the highest efficiency, emits 0.414 kg of carbon per kWh of energy production. Replacing this plant with a SPT power plant would reduce CO_2 emissions by 331,200 kilograms per hour.

V. Conclusion

In conclusion, the urgent need to address environmental challenges stemming from conventional energy sources necessitates a transition towards sustainable alternatives. The exploration of solar energy, particularly through advanced technologies like the sCO_2 Brayton cycle, presents a promising pathway toward achieving this transition. By leveraging the efficiency and lower emissions offered by such innovative approaches, Azerbaijan can not only meet rising energy demands but also prevent environmental damage.

The comprehensive analysis conducted in this study underscores the viability and potential of solar power towers (SPT) utilizing the sCO_2 Brayton cycle in Azerbaijan's energy landscape. Through data collection, modeling, and analysis, we have demonstrated the feasibility of integrating advanced technologies into the energy infrastructure, thus opening avenues for a more sustainable future. With a net cycle efficiency of 50.8%, these systems offer a substantial improvement over traditional power generation methods.

Furthermore, the examination of Direct Normal Irradiance (DNI) levels in Azerbaijan reveals promising locations for the deployment of solar power towers, with the Nakhchivan Autonomous Republic emerging as particularly suitable. These regions boast high DNI levels, indicating optimal conditions for harnessing solar energy efficiently and effectively.

By adopting Solar Power Tower technologies with supercritical CO_2 cycles, Azerbaijan and other countries can fulfill their energy requirements while substantially contributing to global efforts to address climate change and safeguard the planet for future generations.

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