

# Modeling and Performance Analysis of Combined Cycles with Trans-Critical and Kalina Bottoming at High TIT Levels

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**Abstract:** The current work examines the effect of turbine inlet temperature (TIT) on the first law efficiency of different combined power cycle configurations at a constant ambient temperature of 20°C. Analysis is done for three TIT levels of 1600K, 1800K, and 2000K and assesses performance for a variety of cycle pressure ratios (CPR) of 20, 30, and 40. Each system configuration consists of a topping gas turbine cycle combined with bottoming cycles based on trans-critical CO<sub>2</sub> and ammonia water mixtures. Thermodynamic modeling is used to calculate network output and energy input, from which first law efficiencies are derived. The results show that the rise in TIT considerably improves first law efficiency and net power output because of the improved temperature differential between the heat supply and the ambient sink. Yet at 2000K, the efficiency improvement rate slows, indicating the impact of thermodynamic limitations and rising irreversibility's at high temperatures. Among the configurations that were evaluated, the Simple Ammonia Absorption Cycle (SAAC) always produced the highest efficiency at all levels of TIT, but the trans-critical CO<sub>2</sub> cycle had relatively poorer performance with higher internal losses. The research highlights that the choice of an optimal TIT is key to balancing thermal efficiency, material constraints, and operational reliability in designing advanced combined cycle power plants.

**Keywords:** Turbine inlet temperature (TIT), first law efficiency, ambient temperature, gas turbine cycle, Simple Ammonia Absorption Cycle (SAAC).

## I. INTRODUCTION

The demand for power has grown with the world's population. The more the population of the world, the greater the need for energy [1]. Earlier research estimated that the demand for energy would grow by 6% each year. Numerous In the future, combined cycle power plants, or CCPPs, are

expected to be constructed throughout the globe to meet the demand for electricity. The inclusion of combined cycle power plants is one of the most effective means of curbing the problems introduced by CO<sub>2</sub> emissions. Moreover, the plant has greater thermal efficiency compared to a simple gas turbine or steam turbine cycle. Bryton and Rankine cycles are the two cycles composing a CCPP [2]. The idea that the open and closed cycles are the basic elements of a power plant with a gas turbine was patented by John Barter in 1791. With this, the concept of the gas power cycle emerged [3]. Franz Stolze came up with the first contemporary gas turbine design, which utilized internal combustion and an open circuit. You can simulate any power plant that uses the gas turbine cycle using the Joule/Brayton cycle based on the thermodynamic concept. In order to propel the gas turbine engine, air and burned gases are pressurized through its units. The generator produces the required power output by utilizing the mechanical power produced by the expanding gases. Gases are created in the combustion chamber when compressed air and fuel are burned. A schematic diagram of the main elements of an open system gas turbine is shown in Figure 1.

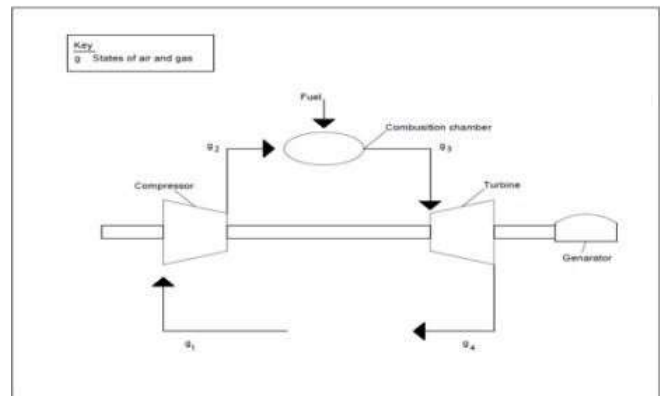


Figure 1. Open Circuit Gas Turbine

Environmental parameters and thermodynamic

conditions—especially Turbine Inlet Temperature (TIT)—are crucial in determining the overall performance of combined power systems [4]. TIT is one of the most significant factors on the efficiency of energy conversion and thermal performance in the topping and bottoming cycles in a combined cycle power plant. This research specifically investigates differences in first law efficiency for various combined cycle configurations such as those that combine trans-critical CO<sub>2</sub> and ammonia–water bottoming cycles [5]. The performance is calculated for TIT values of 1600K, 1800K, and 2000K at a constant ambient temperature of 20°C (293K). Results indicate that a substantial increase in TIT greatly improves first law efficiency from the enhanced temperature gradient between the heat source and sink, which yields more work output and less specific fuel consumption [6]. The gain in efficiency does start to fall off around 2000K, which reflects thermodynamic and mechanical limits. This emphasizes the need for optimal TIT choice to balance performance with material limitations and operational reliability in cycle design [7].

Today, some 50% of power in most parts of the world comes from natural gas, 28% from crude and fuel oils, and some 15% from diesel. These fossil fuels continue to remain the prominent portion of the energy mix, with the rest coming from renewable energy sources (RES). But increasing worry regarding fossil fuel exhaustion and global warming has prompted the world to look towards renewable technologies. Among these, Integrated Solar Combined Cycle (ISCC) power plants have become popular for their better thermal performance when compared with traditional direct steam generation (DSG) approaches. ISCC systems usually involve parabolic trough collectors (PTCs), which have proved to be cost-effective and reliable in high-temperature solar thermal power uses [8]. In order to increase system flexibility and mitigate solar intermittency effects, most ISCC schemes currently feature Thermal Energy Storage (TES) systems.

With the increasing difference between demand and supply of energy, the growth of new energy sources and optimization of available power generation technologies are in greater demand. CCHPs are a more efficient means to address future power requirements, with the potential for high output energy and enhanced fuel use. For optimal performance, performance analysis of such systems—particularly via energy and exergy analysis—stands paramount. A number of researches have centered on CCHPs running on natural gas and have used operational information to carry out detailed thermodynamic analyses. Specifically, it has been observed that the largest exergy losses take place in the combustion chamber. In one of the research projects, the

energy and exergy efficiencies of an air compressor were 92% and 94.9%, and for the gas turbine were 82% and 92%. The combustion chamber proved to have much lower efficiencies at 61.8% (energy) and 67.5% (exergy), as for the overall system energy and exergy efficiencies of 32.4% and 34.3%.

More studies have evaluated the influence of TIT, CIT, and PR on system performance. Optimum total power generation occurred at TIT = 1600K, CIT = 288.15K, and PR = 22. Other studies have also resulted in empirical models providing an estimation of the power generation potential of gas turbines during non-standard ambient conditions, with maximum performance occurring at CIT = 273.15K, TIT = 1423.15K, and PR = 18 [9].

Gas turbine engines are extensively used not only for land-based power generation but even for aerospace propulsion because of their excellent power density, high thermal efficiency, and overall performance. Increasing gas turbine efficiency while decreasing CO<sub>2</sub> emissions and fuel burn is a prime focus, as these are the major contributors to climate change. As such, significant research and development have focused on enhancing the performance of gas turbines. Over the last five decades, increasing the TIT has been the most effective strategy for enhancing both the power output and thermal efficiency of gas turbines [10]. Operating temperatures have steadily risen, with fourth-generation aviation engines now achieving TITs in the range of 1800–2000K. Combined cycle plants operating at 2000K can reach thermal efficiencies of up to 65%. Fifth-generation aero-engines are projected to reach TITs of 2100–2250K. For instance, Japan's Mitsubishi Heavy Industries has already created the M701J heavy-duty gas turbine, which runs at about 1900K. Future innovations will advance TIT values in modern gas turbines to 2000K and more, establishing new records for efficiency in power generation [11].

## II. LITERATURE REVIEW

Razmi et al. (2019) discussed a novel Combined Cooling, Heating, and Power (CCHP) system that combines an Organic Rankine Cycle (ORC), Compressed Air Energy Storage (CAES), and a hybrid compression–absorption refrigeration cycle. Identified with its robust techno-economic and environmental sustainability in building uses, this new cogeneration setup accomplishes the simultaneous generation of 2,280 kW of electricity and 416.7 kW of cooling capacity during peak load operation. In comparison to an isolated CAES setup, the upgraded configuration attained a round-trip efficiency (RTE) of 65.15%, an increase of 13.15% attributable to the system improvements.

Musharavati and Khanmohammadi (2021) considered a

high-temperature Solid Oxide Fuel Cell (SOFC)-based hybrid power and desalination system. In the configuration, fuel and pressurized steam are fed into the SOFC anode, while air is fed to the cathode. The system directs surplus energy from internal reactions of the SOFC to a combustion chamber that, in turn, drives a gas turbine and a Multi-Effect Distillation (MED) system. The combined system has the potential to produce 54.8 MW of electricity, 7.43 kg/h of hydrogen, and 53.46 kg/s of desalinated water. By exergo-economic multi-objective optimization, the energy efficiency of the system—originally at 36.45%—can be optimized to a level between 50.8% and 61.17% and fuel and equipment costs lowered.

Okati et al. (2023) explored integrating an Ejector Refrigeration Cycle (ERC) within a Brayton–Rankine combined cycle in order to maximize intercooling by recovering waste heat. The hybrid configuration was analyzed through energy, exergy, economic, and environmental criteria, and compared with traditional Brayton–Rankine cycle design. In comparison with conventional air-based intercoolers, the ERC-based intercooling lowered the LCOE, fuel consumption, and CO<sub>2</sub> emissions. With the reheat Brayton–Rankine–ERC optimum, the highest thermal and exergy efficiencies were 62.79% and 60.11%, respectively. The lowest reported fuel consumption (114.7 kg/MWh), LCOE (\$27.61/MWh), and CO<sub>2</sub> emissions (316.83 kg/MWh) were also reported.

Javaherian et al. (2023) presented a dual-source hybrid system that can generate constant and sustainable electricity while at the same time minimizing reliance on fossil fuels. Redundancy in the system allows it to function uninterrupted even when one subsystem has been compromised. The system produces around 243.6 MW of electricity, 9.3 MW of heat output, 0.9 MW of cooling, and 149.7 kg/s of drinking water under baseline conditions. The system has an energy efficiency of 53.97% and an exergy efficiency of 45.03%, a unit exergy cost of 0.1122 kg/kWh, and an energy cost of \$15.31/GJ. The economic analysis resulted in a net present value (NPV) of \$771.8 million and a payback period of 7.24 years. The supercritical CO<sub>2</sub> (SCO<sub>2</sub>) reactor had the largest irreversibility among all components and accounted for 31.88% of the total exergy destruction.

Yeranee et al. (2023) showed a thermal-fluid-structural performance comparison of the new Diamond Triply Periodic Minimal Surface (TPMS) structure with conventional pin fin arrays in application to gas turbine blade trailing edge cooling channels. Simulations under typical turbine conditions at a Reynolds number of 30,000 showed that Diamond- TPMS architecture enhanced significantly flow distribution and heat

transfer behavior. The Diamond structure, as compared to the baseline design, registered enhancements of 145.3% in thermal transfer, 200.9% in friction factor, and 32.5% in the overall thermal performance. These findings underscore the capability of TPMS-based designs in the improvement of cooling efficiency and the minimization of thermal stress in gas turbine applications.

### III. METHODOLOGY

This research assesses the effect of fluctuating Turbine Inlet Temperatures (TIT) on the first law efficiency of several combined power cycle configurations via a thorough thermodynamic performance analysis. All the cycle evaluations are made for a constant ambient (sink) temperature of 20°C (293 K) to maintain boundary condition consistency across all simulations. The main aim is to examine how an increment of TIT from 1600 K to 1800 K and 2000 K affects thermal efficiency and network output. The combined systems here involve a simple gas turbine topping cycle in association with various bottoming cycle technologies, such as supercritical Rankine cycles, ammonia–water mixture Rankine cycles, and trans-critical CO cycles.

#### A. Thermodynamic Framework

The first law of thermodynamics, which links a system's network output to the heat input from fuel burning, serves as the foundation for the analysis. The following formula is used to determine the first law efficiency ( $\eta_1$ ):

$$\eta_1 = \frac{W_{net}}{Q_{in}} \quad (1)$$

$W_{net}$  = Total network output of the combined cycle (topping + bottoming)

$Q_{in}$  = Total heat added to the system (from fuel energy input to the gas turbine combustor)

The work output and thermal efficiency for each cycle configuration are calculated by taking into account the energy contributions and bottoming cycle units of the compressor, turbine, combustion chamber, and heat recovery steam generator (HRSG).

#### B. Simulation Parameters and Assumptions

For maintaining uniform sink thermal conditions, the present simulations are performed for three different Turbine Inlet Temperature (TIT) levels: 1600 K, 1800 K, and 2000 K, while keeping the ambient temperature at 293 K (20°C). Varying the Cycle Pressure Ratio (CPR) across three different values—20, 30, and 40—is done for each level of TIT to study its influence on system performance as a whole. The combined power system configurations examined include a topping Brayton cycle combined with a range of

bottoming cycles, such as a trans-critical CO<sub>2</sub> cycle (using supercritical CO<sub>2</sub> in a Rankine-like setup), an ammonia–water mixture cycle (Kalina-type), and a traditional steam Rankine cycle as the reference case.

Both air and combustion gases in simulating the Brayton cycle are modeled as ideal gases, and isentropic efficiencies of the compressor and turbine are set to be constant through all the simulations in order to ensure consistency and comparability. In further separating the influences of TIT and CPR, heat exchanger effectiveness remains constant, while pressure losses in heat exchangers and in the combustion chamber are excluded for base case analysis. Further, specific heat variations with temperature are also considered, especially at higher TIT levels, to maintain thermodynamic integrity. All the simulations are carried out under steady-state conditions, thus eliminating transient dynamics and concentrating on thermal efficiency and network output for various cycle configurations.

### C. Modeling Approach

A component-based thermodynamic model is utilized for simulating the combined cycle system. The exhaust gas temperature and flow rate obtained by initially duplicating the topping cycle (gas turbine) are utilized in the bottoming cycle. In bottoming cycle, thermal energy is transferred from the exhaust by the HRSG unit to the working fluid for driving an additional turbine.

Each case's overall configuration is performed in MATLAB, EES (Engineering Equation Solver), or an equivalent tool, where thermodynamic property libraries are employed in order to determine enthalpy, entropy, temperature, and pressure at all major thermodynamic states. To keep everything uniform, each subsystem's energy balance is closed.

## IV. OBJECTIVE OF METHODOLOGY

The main aim of this approach is to develop a controlled and systematic framework for analyzing the thermodynamic performance of different combined cycle power systems [18]. Through the accurate control of Turbine Inlet Temperature (TIT) and Cycle Pressure Ratio (CPR) and keeping the ambient temperature constant at 293 K (20°C), the approach separates the sole effect of TIT on performance metrics. This method allows for proper comparison of first law efficiencies of various cycle configurations, thus facilitating greater insight into the influence of thermal input variations on network output. In addition, it offers insights into the efficacy of bottoming cycles in extracting remaining thermal energy from the exhaust stream of gas turbines [19].

The methodology also facilitates ranking and

benchmarking of various configurations of the system under well-defined operating conditions, such as the ammonia–water mixture cycle, trans-critical CO<sub>2</sub> cycle, and the Simple Ammonia Absorption Cycle (SAAC). The systematic assessment helps to determine the most thermodynamically efficient and practically effective configurations for high-performance combined cycle power generation applications [20].

## V. Results and Discussion

### A. First Law Efficiency Variation with Different Cycles in Combined Power Systems at 1600K and 20°C

First law efficiency of several configurations studied as a function of cycle pressure ratio, turbine inlet temperature, and ambient temperature

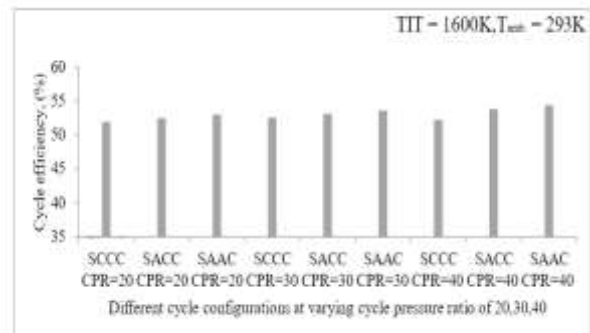


Figure 2 Variation in efficiency of different combined power cycles based on simple gas turbine for CPR of 20, 30 and 40 at TIT of 1600K and atmospheric temperature of 293K.

### B. First Law Efficiency Variation with Different Cycles in Combined Power Systems at 1800K and 20°C

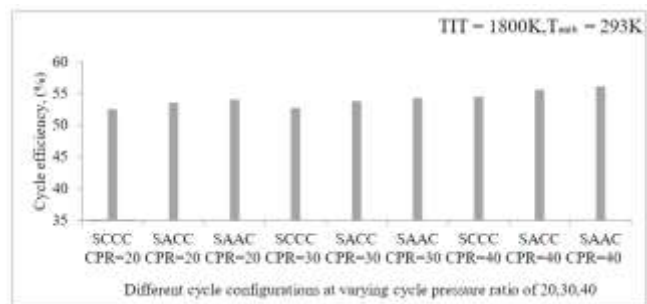


Figure 3 Variation in efficiency of different combined power cycles based on simple gas turbine for CPR of 20, 30 and 40 at TIT of 1800K and atmospheric temperature of 293K.

### C. First Law Efficiency Variation with Different Cycles in Combined Power Systems at 2000K and 20°C

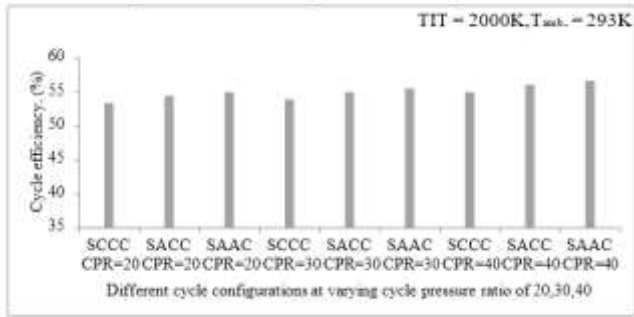


Figure 4 Variation in efficiency of different combined power cycles based on simple gas turbine for CPR of 20, 30 and 40 at TIT of 2000K and atmospheric temperature of 293K.

Figures 5.1 to 5.3 illustrate the effect of different cycle pressure ratios (CPR) on performance at different configurations. By increasing the CPR from 20 to 40 in steps of 10, the graphs show an increase in cycle efficiency at any given configuration. This is mostly due to increased work output and lower fuel energy input. Nonetheless, at extremely high-pressure ratios (around CPR = 40), there is an efficiency drop. The drop can be explained due to a higher back work ratio in the topping cycle or due to the effect of temperature-

dependent changes in specific heat values.

Among the configurations considered, the Simple Ammonia Absorption Cycle (SAAC) always has the highest efficiency for a specified turbine inlet temperature and pressure ratio. Such higher performance is probably a result of reduced internal work losses in SAAC as compared to the trans-critical CO cycle, which could have higher irreversibilities. Also, as the turbine inlet temperature is higher, all configurations have improved work output, leading to overall thermal efficiency gains across the board [21].

*D. Work Output Variation with Different Cycles in Combined Power Systems at 2000K and 20°C*

This section examines the effects of incorporating a trans-critical carbon dioxide cycle as a bottoming cycle into a basic gas turbine-based combined power system. The effect on work output at 1800K and 20°C of changing the cycle pressure ratio from 20 to 40 is shown in Figures 4.7, 4.8, and 4.9.

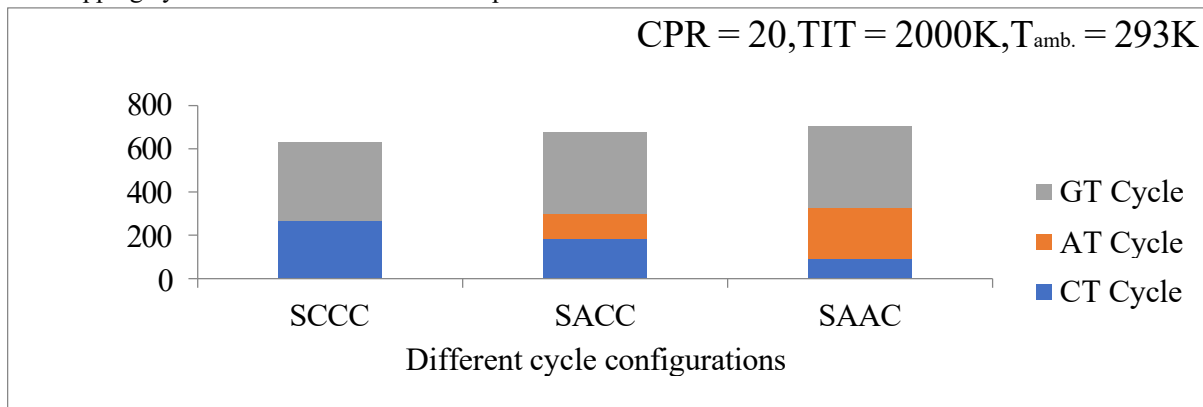


Figure 5 Variation of work produced in topping and bottoming cycle of different combined power cycles based on simple gas turbine for a CPR of 20, TIT of 2000K and atmospheric temperature of 293K.

*E. Work Output Variation with Different Cycles in Combined Power Systems at 1800K and 20°C*

This section examines the effects of incorporating a trans-critical carbon dioxide cycle as a bottoming cycle into a basic

gas turbine-based combined power system. Work output at 1800K and 20°C is shown in Figures 5.4, 5.5, and 5.6 when the cycle pressure ratio is changed from 20 to 40[22].

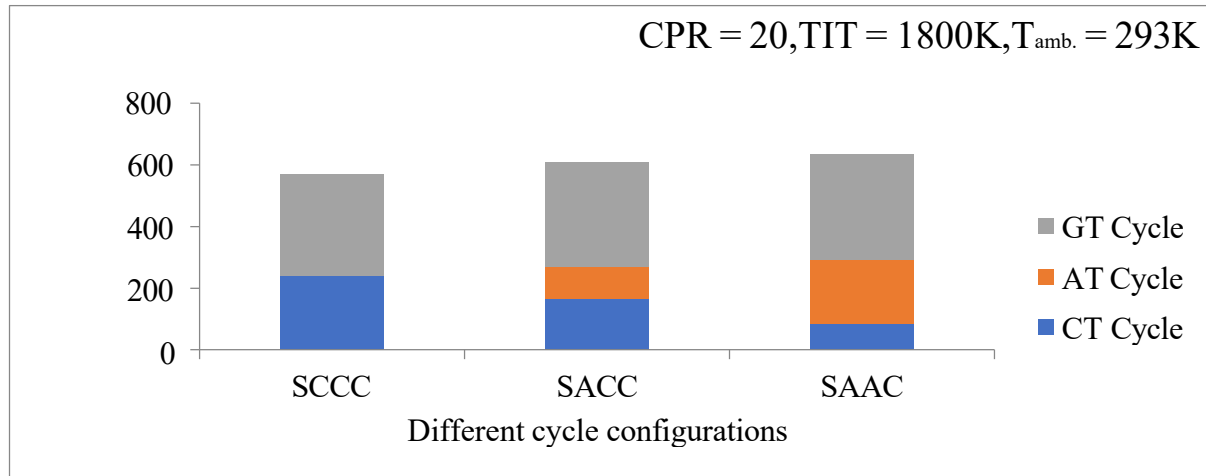


Figure 6 Variation of work produced in topping and bottoming cycle of different combined power cycles based on simple gas turbine for a CPR of 20, TIT of 1800K and atmospheric temperature of 293K.

*F. Work Output Variation with Different Cycles in Combined Power Systems at 1600K and 20°C*

The effects of including a trans-critical carbon dioxide cycle as a bottoming cycle in a basic gas turbine-based

integrated power system are examined in this section. The effect of changing the cycle pressure ratio from 20 to 40 on work productivity at 1600K and 20°C is shown in Figures 5.4, 5.5, and 5.6.

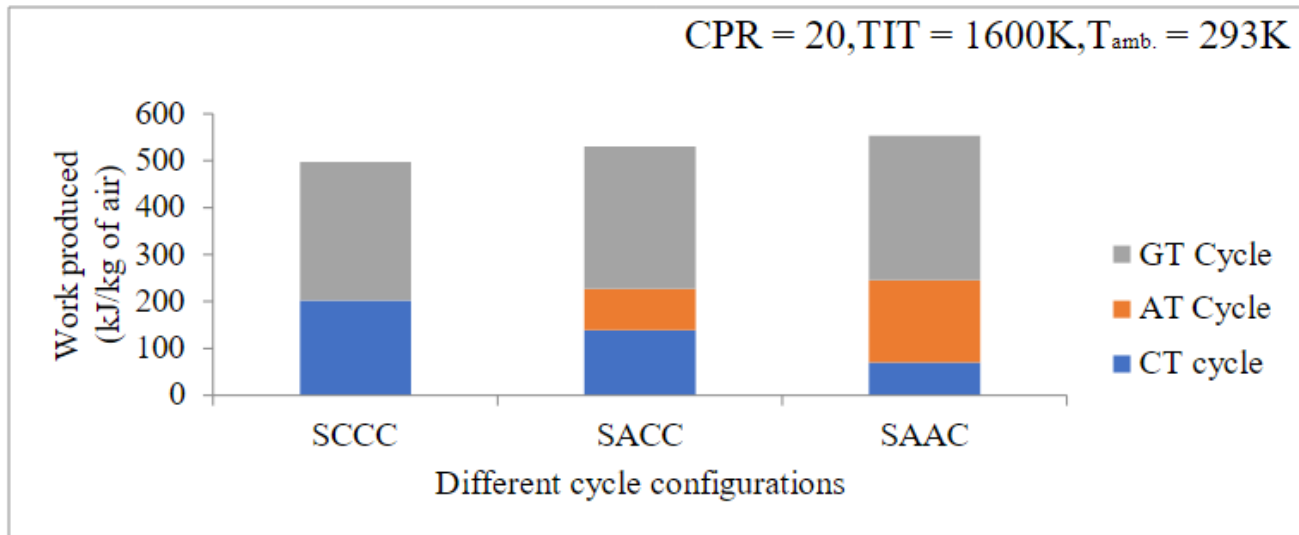


Figure 7 Variation of work produced in topping and bottoming cycle of different combined power cycles based on simple gas turbine for a CPR of 20, TIT of 1600K and atmospheric temperature of 293K.

*G. Effect on Work Output and First Law Efficiency at TIT 1800K, 1900K, 2000K and Ambient 20°C*

When the turbine inlet temperature (TIT) is raised from 1800K to 1900K and further to 2000K and the ambient temperature is maintained at a constant 20°C, first law efficiency and work output in combined power cycles improve slowly. Particularly, when the TIT is at 1800K, the

efficiency of the system is low (~41–43%), being bound by the relatively smaller temperature difference between the heat source and sink [23]. As a result of increased enthalpy drop through the turbine, enhancing shaft work, efficiency typically rises by 2–3% to about 44–46% when TIT is increased to 1900K. Maximum efficiency values (~47–49%) are achieved by the cycle at 2000K, though the rate of rise decreases significantly, indicating diminishing returns. The

reason for this plateauing effect is higher back work ratios, thermal stresses on turbine components, and increased cooling requirements. Even though the net gain is reduced due to internal energy losses, total effort (both from topping and bottoming cycle) increases significantly from 1800K to 1900K (approximately 8–12%) and continues to increase at 2000K. Generally, increasing TIT enhances performance at 20°C; however, the optimal TIT should find a balance between the cost of the system, life, and thermal efficiency [24, 25].

## VI. CONCLUSION

This paper offers an extensive thermodynamic analysis of first law efficiency for different power cycle combined configurations at turbine inlet temperatures (TIT) of 1600 K, 1800 K, and 2000 K, with a constant ambient temperature of 20°C. The findings evidently show that higher TIT increases thermal efficiency as well as network output owing to higher energy availability and efficient turbine expansion processes. Significantly, the power output and efficiency show a marked rise by increasing TIT from 1600 K to 1800 K, but there is limited incremental gain by raising it further to 2000 K, reflecting the impact of diminishing returns due to increased back work ratios and losses.

It is also possible to see the effect of cycle pressure ratio (CPR), with best performance at CPR = 30. From this value, efficiency starts to drop because of increased compression work and the effect of variable specific heat. Of the cycles considered in this analysis, the trans-critical CO<sub>2</sub> cycle shows lower efficiency owing to higher internal irreversibilities and restricted potential for heat recovery. For the Simple Ammonia Absorption Cycle (SAAC), on the other hand, there is consistently better performance, especially at higher TITs. In general, the results highlight the central role of TIT in increasing the performance of combined cycle power systems and place emphasis on the importance of optimizing cycle parameters and design options with care in order to attain high-efficiency and eco-friendly generation of power.

**Conflict of Interest:** The corresponding author, on behalf of second author, confirms that there are no conflicts of interest to disclose.

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