JOURNAL OF OPTOELECTRONICS LASER ISSN: 1005-0086

Volume 41 Issue 8, 2022

# Study on Solar Hybrid Steam Injection Gas Turbine STIG Cycle Research for Indian Circumstances

**Arvind Kumar Tiwari*[1], Praveen Mishra[2], Arbind Kumar Amar[3], Anupama[4]**

*[1]Assistant Professor, Applied Science Department, Rajkiya Engineering College Sonbhadra, UP, India*

*[2]Assistant Professor, Mechanical Engineering Department, Birla Institute of Technology Mesra Ranchi, India.*

*[3]Associate Professor, Mechanical Engineering Department, BP Mandal College of Engineering, Madhepura, India.*

*[4]Anupama, Associate Professor, Mathematics, Darbhanga College of Engineering, Darbhanga, Bihar, India.*

## ABSTRACT

Solar heat can be utilized to enhance conventional steam injections gas turbine power facilities at moderate temperatures of about 200 °C. For this purpose, Concentrating solar collectors could be less complicated and less expensive to implement in solar power facilities. Thermodynamic analysis of this hybrid cycle is performed. High steam-to-air ratios were researched and found to significantly enhance power when compared to a basic cycle and regular STIG. As of recently, solar thermal power was being widely used to help satisfy global energy demands. Solar thermal systems are expensive and only economically viable in areas with abundant sunlight due to their variable solar power generation. To solve these problems, a reduced hybrid solar heat exchange gas - fired (STIG) cycle was developed. The combustor receives its heat from a combination of gas turbine exhaust or solar heat, which is then used to generate steam and afterwards injected. When compared to a basic cycle, steam injection improves power output & plant efficiency while reducing NOX and CO2 emissions. Without the need for solar components which must operate at high temperature and pressure, it enables very high conversion efficiency. It is advocated that research be conducted on solar radiation conversion technologies that have the potential to attain high converting efficiencies and enhanced competitiveness compared to fossil fuels. In this study, the annual cycle performance for sites in India is shown for two modes of variable and constant power, together with local meteorological data including relative humidity, ambient temperature, and availability direct direct normal irradiance to a solar concentrator. The findings show that the hybrid solar STIG plant's solar to electricity efficiency, with a larger solar contribution, is comparable to that of existing solar thermal technologies. The study found that annual CO2 emissions are lower using gas turbine technology compared to combined cycle plants..

**Keywords**: Solar hybrid steam injection gas turbine (STIG), energy, electricity.

## I. INTRODUCTION

The decrease of conventional fossil fuel usage and greenhouse gases emissions are two important problems for sustainable growth in the 21st century [1]. Energy is a critical component of any country's development. According to the International Energy Agency, effort to make the global energy system more sustainable is still ongoing. Global energy demand is expected to increase by more than one-third between now and 2035. Future clean electricity generation could come from solar power [2].

Photovoltaic (PV) or concentrated solar power systems are the two most common methods of transforming solar energy into usable electricity (CSP). PV offers the advantages of being a simple system with a low cost, however the electricity generation is insufficient and varies depending on the quantity of sunlight [3]. Economic development, industrialization, population increase, and urbanisation all contribute to a dramatic rise in the world's need for energy, particularly in developing countries. Fossil fuels are our primary source of energy and are nonrenewable resources, meaning they cannot be replenished or recreated once consumed. They also have an impact on the environment during their extraction, transportation, and use. When capital costs, time from planning to construction, maintenance expenses, and fuel costs are taken into account, the gas turbine is the best prime mover. Gas turbines, also known as "combustion turbines," are used for base, intermediate, and peak-load electric power generation, as well as marine and aircraft propulsion, cogeneration, and prime movers for automobiles, trains, and tanks, as well as a variety of process applications. The combustor, compressor, and power turbine are the three primary parts of a gas turbine. In the combustor, fuel is introduced, lit, and burned, while in the compressor section, ambient air is pulled in and compressed to a pressure of around 30 times its original volume. The turbine uses the expansion of hot exhaust gases to extract energy, which is then used to generate shaft horsepower. More over half of the energy is utilised to run the compressor, with the rest going to machinery or a generator to produce electricity.

As of March 2013, India's natural gas reserve was 1354.76 billion m3 [26], indicating that there is additional room to increase power output using gas-fired power plants. In November 2014, Gas-fired power plants accounted for almost 9% of India's total installed capacity at 22,971.25 MW [27]. India has a lot of solar energy potential. The average daily solar energy incidence in India is between 4 and 7 kWh/m2, and there are roughly 300 sunny days each year in most sections of the country [4].

The effectiveness of a jet engine plant is greatly affected by the air quality outside. This improved output power is the result of a higher flow rate through turbine as opposed to compressor. Injecting steam into a gas turbine can boost its efficiency and performance (STIG). As a result, it is more effective and produces more power than the basic cycle.

One of the most pressing challenges for energy engineers as well as a major worry for governments, is improving the ecological and economic efficiency of gas turbines. Large "high-technology"advances in turbine blade material, design, and gas turbine manufacture has been developed to meet the demands of a aviation industry, which invests the most in this area of engineering. However, "low technology" cycle improvements available to improve performance (e.g. reheat, intercooling, regeneration, and steam injection) are underutilised because they require a lot of steam or water, or because they have heat exchangers which are too big or too heavy to be useful for aeroplanes. This situation opens up a lot of opportunities for stationary power gas turbines since it indicates that considerable performance enhancements can be obtained with a small amount of R&D.

Solar collector systems with moderate temperatures, A parabolic trough collector is one method of harnessing solar thermal energy for use in a gas turbine [24], improving the cost-effectiveness of solar-generated electrical power without increasing the necessary solar field temperature and concentration [25].

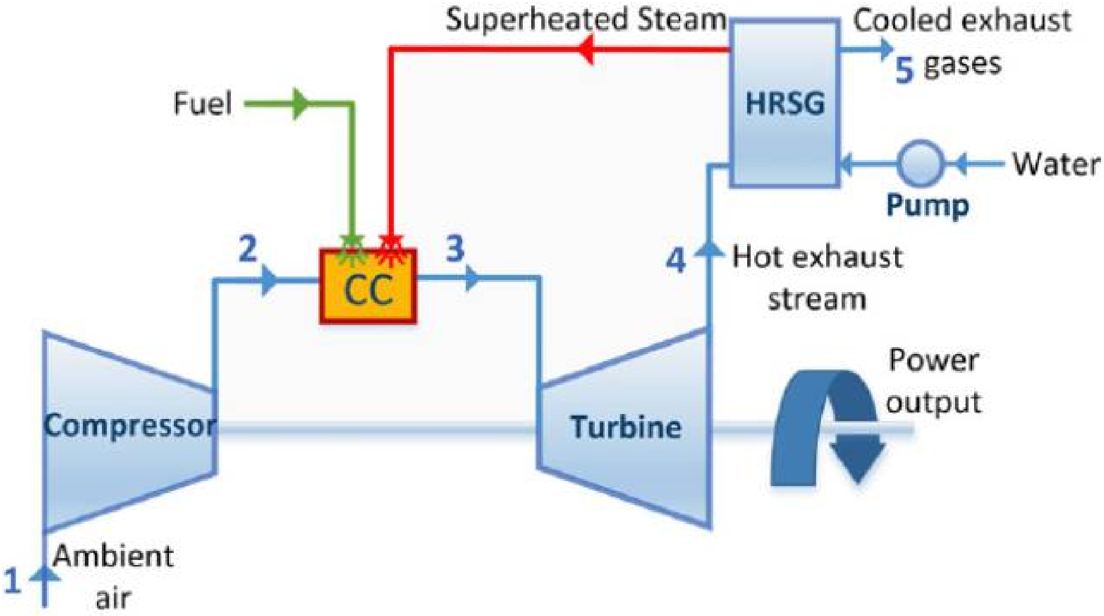


**Fig. 1: Steam injected gas turbine (STIG) cycle**

Inside a Heat Transfer Gas (STIG) cycle, solar vapour under low pressures and temperatures can be utilized to replace substantial quantities of fossil fuel. To use a heat-recovery steam generator (HRSG) to produce steam, the STIG cycle modifies the Brayton cycle by forcing the steam into the combustor of a gas turbine (Fig. 1). To boost power output, it is usual practise to inject steam in a method that increases turbine mass flow relative to compressor mass flow. By lowering the combustion temperature, steam injection also decreases NOx emissions. In a typical STIG cycle, the amount of thermal power available from the HRSG determines the rate of steam injection. The excess heat from solar thermal collectors, however, will make it possible to regulate steam production on a per-boiler basis.

Several variations of a hybrid solar STIG cycle are investigated, including varying the pressure ratio, the temperature at which the turbine is fed steam, and the steam-to-air ratio. Producing solar steam with temperatures of about 200 degrees Celsius using inexpensive concentrators, solar heat can account for as much as half of the energy intake, and conversion efficiency from heat to electricity can reach far beyond 50%. Jet engine exhaust is typically assigned to the severe heat and economizer parts of the vapor production process to reduce the level of irreversibility, whereas solar heat input is ideally suited for evaporation. Saturated steam is produced at a temperature of 180 to 234 degrees Celsius at a pressure of 10 to 30 bars, which is what a normal steam turbine requires. Low-cost linear concentrators, such as the linear Fresnel and the parabolic trough collector, make it simple to reach these pressures and temperatures.

The STIG technology has allowed power plants to perform more flexibly while getting the most out of the steam generated [18,20]. STIG systems are built by integrating a Brayton gases cycle and a steam cycle inside the furnace. The efficiency of the Brayton cycle is increased by using a gas turbine to expand the exhaust as well as the steam produced by the energy recovery process [21,23].

### 1.1 Energy in India

Electric power generation is a critical issue in India today, as it forms the backbone of the country's economic progress. Despite the worldwide economic slowdown, India's energy usage continued to climb. Due to population expansion and economic development, India's energy consumption has increased at a rather rapid rate in recent years.

When it comes to the energy sector, India is a worldwide powerhouse. Since 2000, energy consumption has over doubled as a result of the world's rapidly expanding population and a period of brisk economic growth. In 2019, about 900 million residents acquired access to electricity, marking the first time in more than two decades that everyone in their home had electricity.

India's energy business and politicians will face significant pressures as the country continues to industrialise and urbanise. Compared to the rest of the world, the United States has a far lower per capita energy consumption rate, and there are large discrepancies in energy use as well as service quality among both states as well as between rural and urban areas. India's consumers are worried about the cost of power and its reliability. The Covid19 outbreak has disrupted India's energy use; due to lockdowns and related restrictions, the country's energy demand is expected to fall by around 5% in 2020, with coal and oil use falling the most.

Coal, oil, or solid biomass supply about 85% of India's energy needs. Power plants and factories have grown thanks to coal, and it is still a significant part of the energy mix today. Increases in car ownership and increased demand for transportation as well as imports via roads is largely attributable to the rising costs associated with using oil. Biomass, and fuel wood in particular, fuels fewer homes than it once did, but it's still often the only source of heat in many kitchens. In spite of recent efforts to increase access to LPG in rural areas, not all of India's 660 million people have made the switch to modern, cleaner fuels for cooking and technology.

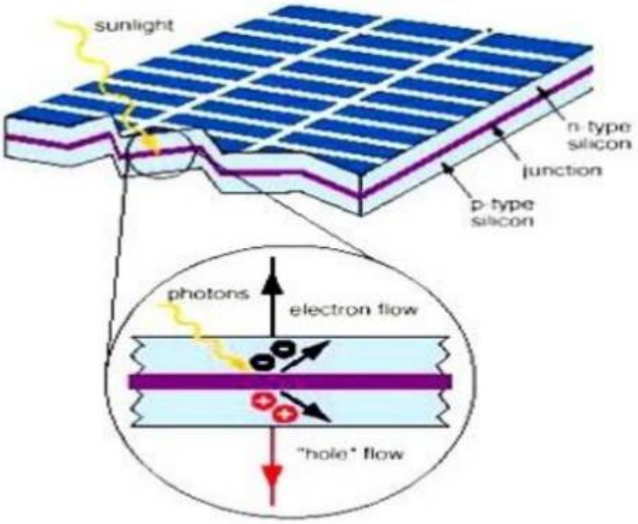
It was in 2020 when the Covid19 pandemic had the least effect, and natural gas and sophisticated renewable energy sources were beginning to gain pace. Progress has been made in solar PV; the resource potential was large, expectations are so high, but legislative supports combined technological cost reductions have swiftly made solar PV the most cost-effective renewable power generating option.

Despite having one of the lowest CO2 emission rates per capita, India ranks third in global CO2 emissions. For example, compared to other countries, its electrical industry has a very high carbon intensity. Over a million individuals in India have lost their lives to premature causes due to ambient or residential air quality in 2019, making air pollution one of the country's most pressing social and environmental challenges [5].

### 1.2 Power Generation From Solar Energy

Solar energy is commonly known as the most abundant and environmentally friendly form of energy, capable of providing electricity and heat in quantities far exceeding all of humanity's needs, but its use is now quite low around the world. The major reason for this obvious contradiction is high price: solar energy is often 2-3 times more expensive to produce than conventional fossil fuels like coal. If the conversion efficiency of solar to electricity is greatly improved, and the energy is made available in a reliable manner that is not dependent on the intermittent availability of sunshine, this cost can be lowered down to competitive levels. This is true for both solar and thermal conversion technologies, which are both confronting similar challenges in the global energy market.

Energy from the sun can be captured and used, and it manifests mostly as heat and radiation. To illustrate, see Fig. Utilizing the sun's light and heat is possible through a wide variety of ever-evolving and cutting-edge technologies, including, but not limited to, molten salt power stations, synthetic photosynthesis, solar thermal, solar thermal, and solar design. Solar energy is an extremely attractive form of energy due to the large amount of energy accessible. The ocean, clouds and land masses absorb the rest of the solar energy, which returns 30 % (about) to space.[6]



**Fig, 2: Internal reaction of solar energy**

### 1.3 Photovoltaic Solar Technology

By directly ability to absorb solar photons—individual units of energy—and either attempting to transform portion of the energy to electricity or solar photovoltaic systems turn sunlight into usable types of energy, with some of that energy being stored inside a chemical reaction (such as the splitting of water into hydrogen and oxygen) [7].

The use of photovoltaics (PV cells) Use solar panels to generate DC power. Batteries and charge controllers manage the power produced by solar panels, avoiding them from being damaged. A battery system is used to preserve electric power when there's not enough sunlight (i.e. night). Figure 3 depicts the connection of this system to an inverter, which transforms Direct Current (DC) to Alternating Current (AC).

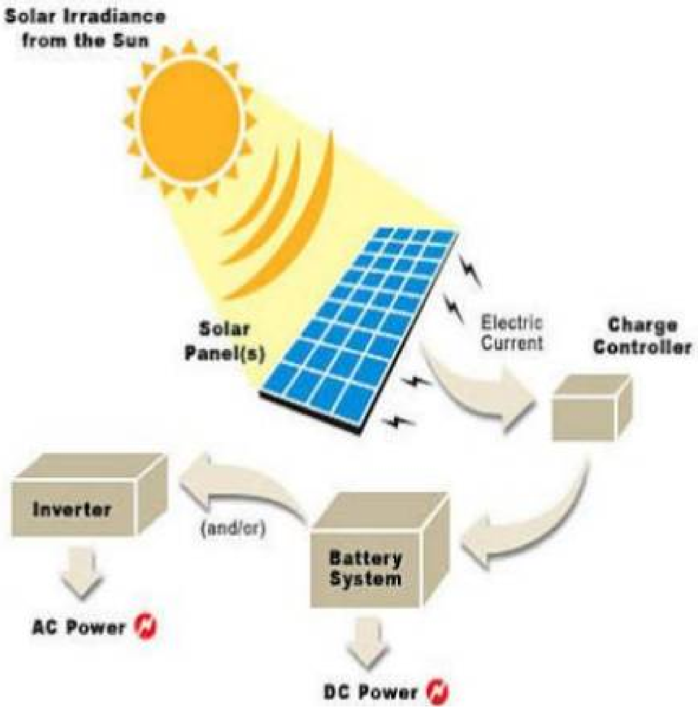


**Fig. 3: Working of solar energy**

## 1.4 Concentrating Solar Power Technology

Solar thermal power, also termed as concentrated solar power, is a type of renewable energy that is underutilised. For energy production in large-scale gird connected power plants, the method utilises focused solar radiation via sun tracking mirrors.

Due to the limited amount of thermal available energy inside the HRSG from of the turbine exhaust stream and other technical problems, the steam flow rate in such a simple STIG system is typically around 5% and 10% of such a compress flow rate. Thermodynamically speaking, if a surplus of heat is available, infusing more steam into to the cycle is indeed a good idea, as well as the steam amount could be optimised separately from the rest of the cycle.

Standard STIGs with duct firing can produce excess steam, which can be used to boost output power or supplied as process steam for cogeneration mode. Instead of using duct firing to supply extra heat during steam generation & injection into the cycle, we investigate the possibility of using solar focusing collectors to do so. When combined with the heat from the combustor's fuels, the STIG cycle produces a solar hybrid. (Illustrated by Figure 4) The rate at which exergy is destroyed in the combustion chamber decreases by 0.21 to 0.35% for every degree Celsius that the ambient temperature rises, while the rate at which exergy is destroyed in the compressor, gas turbine, HRSG, and steam turbine rises by 0.32 to 0.35% for every degree Celsius that the ambient temperature rises [29].

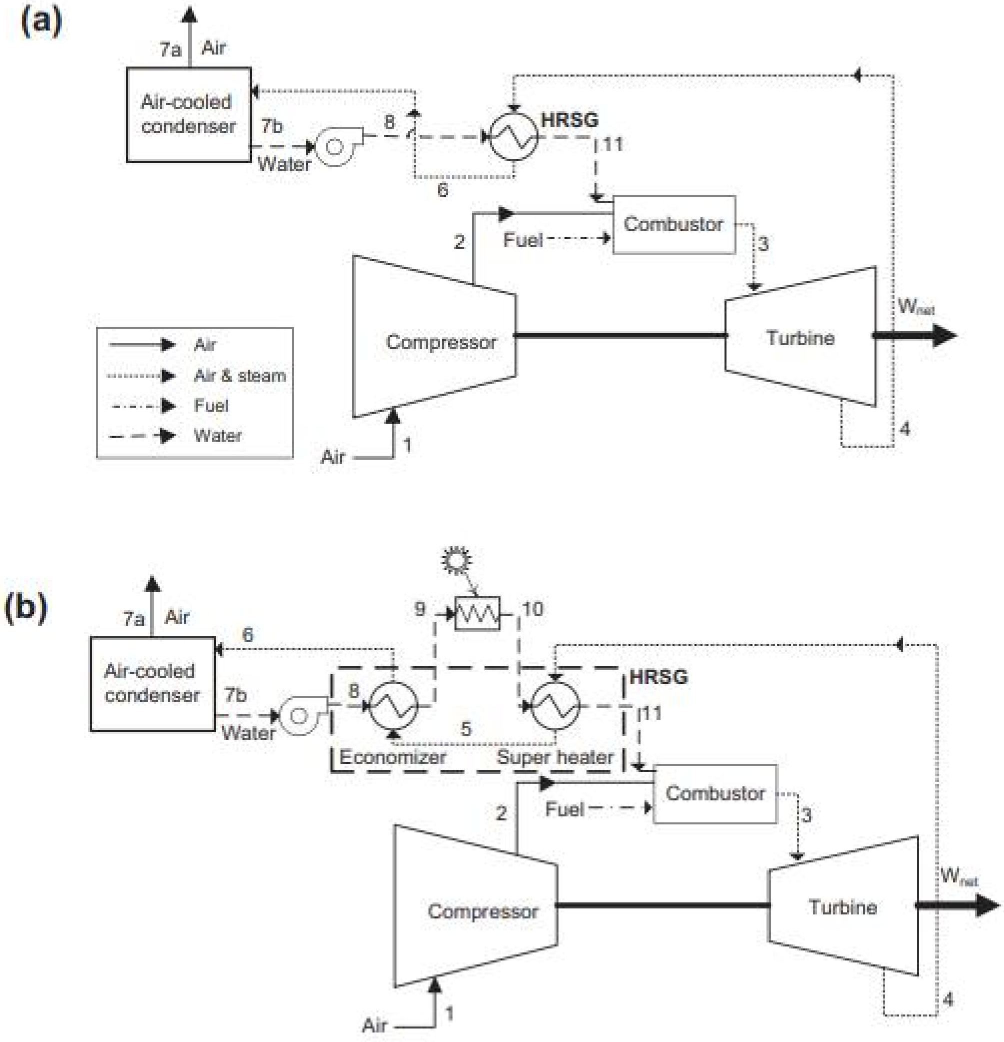


**Fig. 4: Layout of (a) conventional STIG cycle (b) solar STIG cycle.**

Because of the pinch point just at heat exchanger's outlet, which produces considerable temperature changes at the opposite end, the sensible heat from of the turbine exhaust can be utilized for evaporation in a conventional STIG, but this results in thermodynamic irreversibility as well as a loss of work potential. By directing gas turbine exhaust toward the super heat or economizer parts of the proposed solar hybrid STIG, irreversibility can be lowered. Saturated steam temperatures in the range of 180-234 degrees Celsius are optimal again for hybrid STIG cycle's turbine pressure of 10-30 bar. In this case, superheating is unnecessary because the exhaust from the turbines is already very hot. These pressures and temperatures are lower than those utilised in modern solar power plants, but they may be easily achieved by reduced, "downgraded" linear concentrators like parabolic trough and linear Fresnel collectors. For industrial process heat, many types of low-temperature solar collectors have been created, such as a more affordable parabolic trough. Previous research on the use of small linear Fresnel collectors for steam generation at temperatures about 270°C has revealed that these collectors can be highly attractive low-cost alternatives.

## II. LITERATURE REVIEW

M. Bustamante Román (2021) [8] Small-scale solar-biohybrid power generation systems were studied for their potential to use the Rankine (steam turbine) and Brayton (gas turbine) cycles. Thermodynamic models were developed to help select the most efficient solar collection method and ascertain the current state of the working fluid in specialised power generation systems. In order to analyse energy output and select the optimal system architecture, metrics such as the gross generating capacity of energy production and the utilisation effectiveness of solar and biogas energy were used. Overall, the results show that steam turbine systems are more productive over the world (67.7% vs. 55.7%), while gas turbine systems can produce more electricity (27% more than steam turbine systems) (5.6 percent ). To further verify their relevance and practicality, the effects of several climates on selecting appropriate hybrid systems also were investigated. This method can be applied to a number of small-scale hybrid renewable energy producing systems to evaluate and improve them.

N. Yijian He (2020) [9] studied a solar-powered gas turbine that uses steam injection and recovers both heat and moisture. The novel method involves injecting steam into a turbine's intake while also retrieving waste water and heat from the exhaust flow. Thermodynamic models are being developed to investigate the major factors that influence the innovative system's performance and attributes. With a suitable steam injection rate of 0.065, the system efficiency improves by 17%. When waste heat from exhaust gases is retrieved at a high rate, water recovery can reach 98 percent. In comparison to the particular load refrigeration unit, a two-stage unit increases the system's heat recovery rate by 119% and its frozen capacity by 63%. The models are also employed to evaluate the unique system's annual performance and ecological sustainability in Lhasa and Dunhuang, western China. The maximum efficiency & peak power production have been improved by 21.8% and 37.9%, respectively, thanks to the new technology. Its carbon dioxide emissions and fuel consumption are lower than those of conventional gas turbines. These findings suggest that the suggested system has the potential to be very efficient and environmentally sustainable, with water use near zero.

M. R.P Merchán (2017) [10] investigated a thermodynamic model was developed to analyse the performances of solarized gas-turbine power plants on a worldwide scale. Actual meteorological data was used to calculate year averages of efficiency, output power, fuel usage, emissions, and solar share. Plant layouts with or without Brayton cycle recuperation, as well as hybrid and pure combustion operations, were also explored. The yearly average solar share for the power output range tested is minimal due to the size of the heliostats. However, depending on the plant structure, fuel savings (and consequently emissions) ranged from 6% to 8% in annual terms when comparing hybrid operations to pure combustion.

M.J.Santos (2016) [11] Thermodynamic models were used to investigate the operation of a hybrid solar gas turbine plant under conditions of varying irradiance and ambient temperature. When the sun's irradiation is sufficient, the model includes serial solar hybridization. The inlet temperature of the turbine may be kept relatively constant in a combustion chamber, resulting in steady power production. A test plant provided numerical parameters.

D. Olivenza-León (2015) [12] explored a thermodynamic prototype of the a solar turbine engine hybrid power station. From pure combustion at low sun irradiation to the eventual scenario where just solar heat input is adequate to ensure that the operating fluid achieves its turbine intake temperature, analytic formulas for total plant efficiency or power output can be produced in a simple form for any solar share.

Selwynraj A. Immanuel (2014) [13] investigated a system for transforming radiation from the sun that could be more efficient and cost-effective than fossil fuels. Locations in India having local climatic parameters including ambient temperature, humidity levels, or direct normal irradiance to a solar concentrators were used to evaluate annual cycling stability in both variable and constant power modes.

A.K.Tiwar et al. (2013) [28] Exergy analysis of India's NTPC Dadri combination Brayton/Rankine power plant. All the components of a Dadri power plant's combined cycle are subjected to a theoretical exergy analysis. Included in this category are the gas turbine entity, the fuel-free combined heat and power generator, as well as the steam turbine unit. Using an input temperature of 1400 C as well as a pressure ratio of 10, the study found that 35% of all exergy losses happened inside the jet engine combustion chamber, while the remaining 7-21% occurred in various other plant components. When calculating the total exergy losses in the plant, he also factored in the influence of variables such as operating pressure, heat loss inside the combustion process, steam generator inlet temperature, and heat recovery. By altering the pressure ratio and the air temperature that is entering the turbine, one may control the amount of exergy lost.

Mansouri et al. (2012) [14] Heat recovery from of the flue gas increases with increasing HRSG pressure, according to an analysis of the relationship between HRSG pressure and the energy efficiency in gas combined cycle power plants (in HRSG). This improves the efficiency of HRSG or combined cycle power facilities by decreasing the amount of energy lost during heat transfer.

Abam & Moses (2011) [15] performed an energy audit on a 33 MW Brayton cycle power plant using gas turbines. The efficiency of a second law reduces more sharply inside the combustion chamber even as temperature of the environment rises than in the an air compressor or even the gas turbine. The ambient air temperature and the input to the turbine influence the amount of fuel required, the power-to-heat ratios, as well as the efficiency at which energy is utilised.

Kaushik et al (2011) [16] conducted a comparison of the energy and exercise studies of operating coal or gas-fired thermal plants to identify potential areas for improvement. According to the report, expanding the temperature transfer area of heat exchangers can improve their efficiency, but this comes at a price.

Woudstra et al (2010) [17] investigated on the single-pressure, double-pressure and triple-pressure HRSG configurations of the HRSG were put through their paces throughout the combined cycle.They further proved that increasing the number of steam generating levels of pressure not only reduced exergy losses in the stack due to exhaust flue gas but also reduced heat transfer losses in the HRSG.

## III. METHODOLOGY

Honeywell Unisim, process simulation software was used to do thermodynamic simulations of a cycle depicted in Fig. 1 using component models from a standard library. Compressor, water pump, or turbine models' isentropic efficiencys stand in for the actual internal losses and functioning of their respective units. The pressure drop and minimum temperature method selections that were made for the model of the heat exchanger represent friction losses and a finite heat exchange zone. Table 1 presents the results of the investigation into the values of input parameters. The air intake of the compressor was calibrated to operate at 1 bar, 25 ° Celsius, and 30 percent relative humidity when operating in normal ambient circumstances. As a consequence of this, the outcome that was generated here is a nominal outcome that is unaffected by the surrounding environment.

**Table 1: Properties of the components used as inputs to the models of the components during the simulation**

| Parameters | Values |
|---|---|
| Turbine isentropic efficiency | 95% |
| Compressor isentropic efficiency | 90% |
| Water pump isentropic efficiency | 85% |
| Pressure drop in heat exchangers | 6% |
| Minimum approach for the HRSG | $7^{o}$c |
| Minimum approach for the condenser | $18^{o}$c |

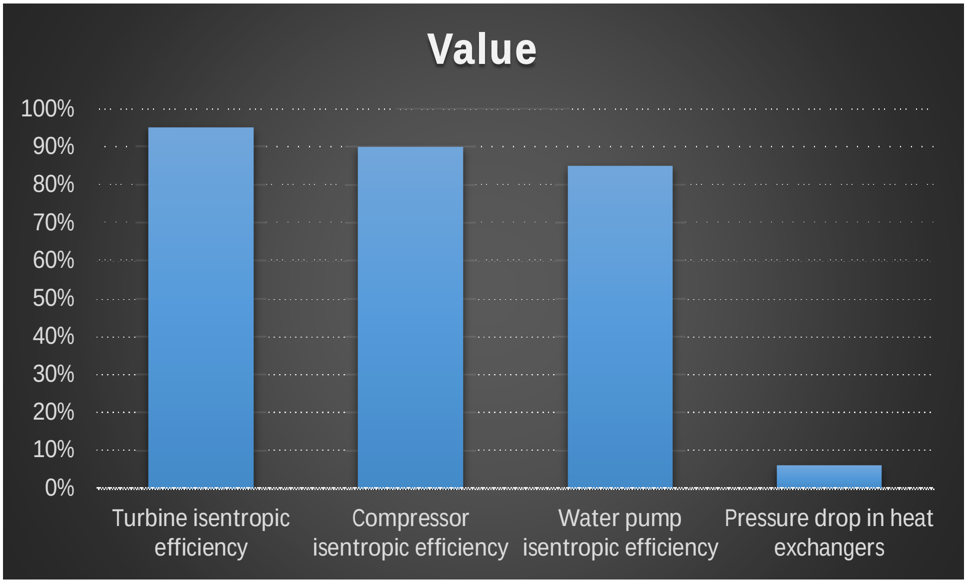


**Fig. 5: Properties of the components used as inputs to the models of the components during the simulation**

Both the compressor pressure ratio and turbine temperature were simulated using several combinations of the major design parameters (TIT). Table 2 provides the actual turbine parameters that were used to develop the four alternative scenarios. The tests varied the percentage of steam added to the cycle across a wide range, while maintaining a constant air mass flow rate. The compressor's size and performance are also unaffected by the changes. However, the turbine and heat exchanger diameters will likely need to be adjusted to account for the increased mass flow rate. The ratio of steam to air is used to determine how much steam a cycle generates (SAR: ratio of steam mass flow rate to air mass flow rate). The simple cycle, shown by SAR = 0, does not involve the injection of steam. Recovery heat via turbine exhaust without augmenting this with solar heat always achieves a maximum SAR value, however that value fluctuates depending on the circumstances. The results of the SAR have been considered to be standard STIG up until this point.In order to get higher SAR values, larger quantities of solar heat must be introduced into the cycle. Table 3 presents all of the instance characteristics for the traditional STIG, which has a high SAR of 0.20, as well as the parameters for the solar STIG, which has a SAR of 1.4. The pressure, temperature, frequency mass flow rate of the fluid are recorded at each phase of the cycle. Not only are the inputs and outputs of power, in addition to efficiency, considered, but also the whole cycle performance.

Data on temperatures, pressures, flows, and composition, and also energy balances for every component, are generated by the models at every point of the process's existence. The system's mass flow rate was set according to the steam flow rate entering the combustor. The air compressors' weight flow rate was therefore set to 1 kg/s, while the turbine's volume flow rate was set to 1 + SAR kg/s. The predicted input and output power is normalised towards this flow rate, making kW per kg-air/s the standard measurement unit for power. This is analogous to the work and heat expressed in kilojoules per kilogramme of air. The results of the simulation are utilized for the development of numerous performance indicators due to their usefulness. The following is a definition of the net specific project as well as the total cycle efficiency (work to heat):

$$W_N = W_T - W_C - W_P \qquad (1)$$

$$\eta = W_N/q_F + q_S \qquad (2)$$

wT represents the amount much specific work performed by the turbine, however, wC and wP stand for the amount of work done specifically by the compressor and the water pump. Fossil fuel combustion (qF) and solar collectors (qs) contribute different amounts of heat to the cycle per unit of air mass. If $SAR_M$ is defined as the largest SAR that can be achieved with normal STIG, then qs for SAR $SAR_M$ is equal to zero (without any additional heat input). The following formula can be used to estimate the additional impact that will result from raising steam production above the STIG limit: Let us refer to the maximum fuel heat input (qF,M) and the maximum work net output (wNM) of a typical STIG as qF,M = qF(SARM) & wNM = wN (SARM), respectively. When we move beyond this threshold, we observe the following increases: qF = qF qF,M, where wN = wN wN,M. SAR > SARM represents the potential improvement in conversion efficiency due to steam additions over excess of the normal STIG limit.:

$$\eta_{inc} = W_N/q_F + q_S \qquad (3)$$

DOI: 10050086.2022.08.68

This increase is accomplished by adding additional fuel while also utilising the heat from the sun in order to raise the air and steam mixture up to the TIT temperature. How much of the total heat input may be credited to the sun is measured by a metric called the Sun Fraction (SF):

$$SF = q_S/q_F+q_S \tag{4}$$

**Table 2: The operational parameters of turbines for the four simulation examples and the actual turbines.**

| Case | Simulation PR | Simulation TIT °C | Real gas turbine | Turbine power (MWe) | Turbine PR | Turbine TIT °C | Simple cycle efficiency (%) LHV |
|---|---|---|---|---|---|---|---|
| A | 15 | 915 | Solar centaur 40-T4700 | 3.51 | 15 | 935 | 29.8 |
| B | 18 | 1100 | GE LM2000 | 17.56 | 18.6 | 1121 | 36.5 |
| C | 35 | 1400 | GE LM6000 PC | 43.57 | 35 | 1460 | 42.5 |
| D | 22 | 1500 | Mitsubishi 701G | 334 | 22 | 1527 | 40.5 |

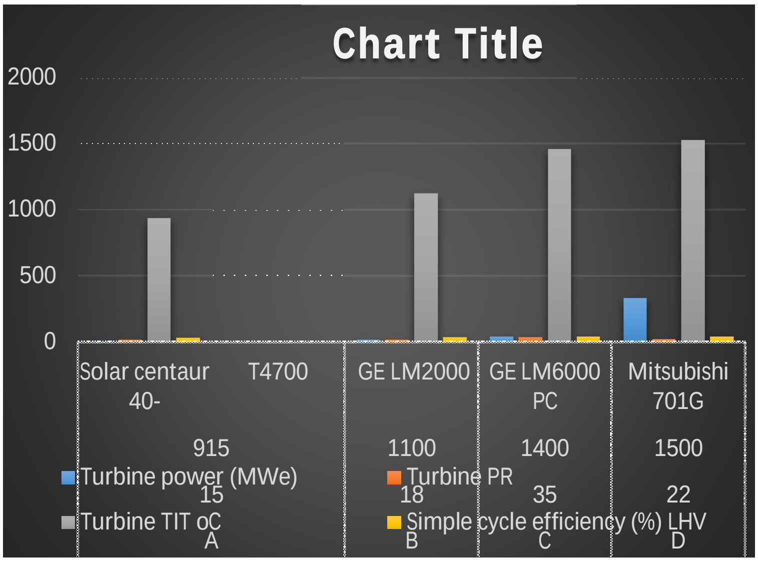


**Fig. 6: The operational parameters of turbines for the four simulation examples and the actual turbines.**

We apply an empirical correlation once more for performances of the a lower thermal parabolic trough collector to calculate the amount of energy gained from the sun.

$\eta_C = 0.7725-6.85.10^{-5}(T_C-T_a) - 0.148\ T_C-T_a/I - 1.683.10^{-3}(T_C-T_a)^2/I$ (5)

The conversion efficiency from solar energy to usable electricity is as follows, based just on progressive cycle efficiency:

$\eta_S = \eta_C.\eta_{Inc}$ (6)

Using T = 50 oC outlet airflow from of the air-cooled condensation (min approaching with in condenser is 20 oC) & = 100% relative humidity, we can calculate the specific consumption of water (SWC) every unit of power. produced. Any lingering water vapour inside the turbine exhaust is condensed and recycled to the evaporator. Compressor intake air is 35 degrees Celsius and has a humidity level of =40%. A net loss of water per unit unit productivity levels (kg/kJ or kg/kW h) is then calculated by using the difference between mass flow rates of vapour, given by the accompanying absolute humidity values (T):

**Table 3: Fluid characteristics at each cycle point, conventional STIG**

| Point | Conventional STIG, at SAR = 0.20 | | |
|---|---|---|---|
| | Temperature °C | Pressure (kPa) | Mass flow rate (kg/s) |
| 1 | 30.0 | 105 | 1.00 |
| 2 | 580.7 | 3155 | 1.00 |
| 3 | 1250.0 | 3040 | 1.15 |
| 4 | 475.0 | 110 | 1.15 |
| 5 | 140.8 | 105 | 1.15 |
| 6 | 50.0 | 105 | 1.00 |
| 7 | 50.0 | 105 | 0.20 |
| 8 | 50.3 | 3282 | 0.20 |
| 9 | 325.1 | 3162 | 0.20 |

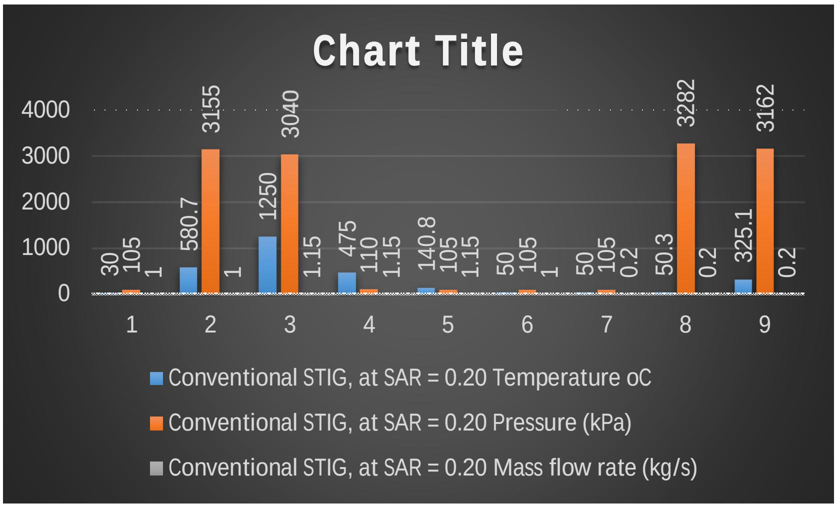


**Fig. 7: Fluid characteristics at each cycle point, conventional STIG**

**Table 4: Fluid properties at each point in the cycle (see Fig. 8)**

| Point | Solar STIG, at SAR = 1.4 | | |
|---|---|---|---|
| | Temperature °C | Pressure (kPa) | Mass flow rate (kg/s) |
| 1 | 30.0 | 105 | 1.00 |
| 2 | 580.7 | 3155 | 1.00 |
| 3 | 1250.0 | 3040 | 2.20 |
| 4 | 529.9 | 109 | 2.20 |
| 5 | 89.4 | 105 | 2.20 |
| 6 | 42.0 | 105 | 1.00 |
| 7 | 42.0 | 105 | 1.20 |
| 8 | 45.0 | 3520 | 1.20 |
| 9 | 460.5 | 3160 | 1.20 |

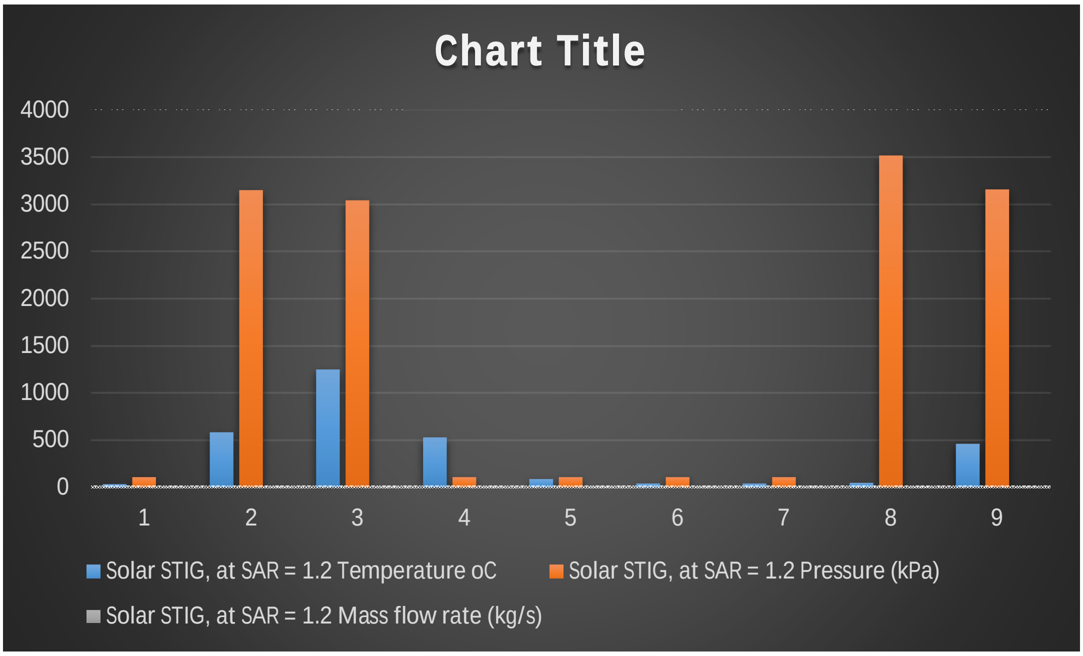


**Fig. 8: Fluid properties at each point in the cycle**

$$S_{WC} = \omega(50^{o}C, 100\%)-\omega(35^{o}c, 40\%)/W_{N} \qquad (7)$$

The following is an estimate of the size of the condenser based on the amount of heat that has to be extracted by the condenser per unit mass flow rate of air:

$$Q_{cond} = (C_{p,a}+SAR.C_{p,st})\ (T_{HSG,O}-50^{o}C) + [SAR+\omega(35\%,40)-\omega(50^{o}C,100\%).h_{fg}] \qquad (8)$$

The maximum quantity of heat that can be provided to the fuel mixture with steam through the process of combustion was calculated based on the amount of oxygen in the air:

$$F_{As} = m\ (fuel)/\ m\ (air) = 0.60\ kg\text{-}fuel/kg\text{-}\ air$$

$$q_{combution,s} = (h^{o}{}_{f\ products}) = (h^{o}{}_{f,\ reactant)}\ ,\ F_{As} \qquad (9)$$

## IV. RESULT

As equation 2 demonstrates, the addition of even a little volume of steam can result in a significant increase in efficiency since it causes a rise in work production owing to recovery even in the absence of any additional heat input. There is a SAR value that is optimal for each scenario that results in the highest efficiency, which is significantly more than the efficiency produced by the fundamental cycle (SAR = 0).For example, in case A, maximal efficiency is reached at SAR = 0.14, whereas it is only 32.8 percent for the same basic cycle with PR = 15 and TIT = 915 degrees Celsius. This is a comparison to the efficiency achieved when PR = 15 and TIT = 915 degrees Celsius. In Case D, the peak efficiency is 55.1 percent when SAR is equal to 0.25, in contrast to the basic cycle's 42.5 percent efficiency when PR is equal to 22 and TIT is equal to 1500 degrees Celsius. The highest efficiency is achieved when the amount of steam produced is equal to SARM without any more heat being added. Maximizing heat collection from the turbine exit stream is key to reaching this level of efficiency. Due to the fact that qS was greater than zero as well as the denominator of equation 2 grows as just a result, the efficiency of a cycle steadily diminishes even as SAR was increased beyond SARM via introducing external heat. However, over a large range of solar radiance (SAR), Even with the addition of solar heat, the overall efficiency is higher than that of a comparable basic cycle. This is the case regardless of the temperature of the sun radiation.

As can be observed, steam injection resulted in a notable increase in power, as was proved in an earlier study. The rise in efficiency is related to the addition of first power due to the recuperation of heat on the internal level. Case B, for example, has an increase in power of 168 percent when operating at its highest level of efficiency, which is equivalent to a SAR value of 0.22. With the addition of external heat, the power increase can be enhanced to up to 538 percent, but the efficiency will drop to that of a basic cycle equivalent. In contrast to traditional STIG, which uses a fixed turbine only with slight power gains within a restricted range of SAR, usually less than 0.1, Over the enormous range to SAR that's been investigated here, a turbine, generator, and heat exchangers must be fitted to the additional weight flow rate & electrical production. This was done to ensure that STIG could function efficiently across the whole spectrum of SAR. This means that employing a commercialized pack with such a matched compressor-turbine set is not viable for achieving a high SAR STIG cycle. Instead, you'll need a bespoke set where the turbine is larger than the compressor and the ratio is adjusted for your desired SAR.

We can view the SF as just a function of a SAR. Until SAR and SARM are equal, the SF is at zero. At present, the HRSG makes full use of the waste heat produced by the turbine's outlet stream. After this point, the $S_F$ begins to increase in proportion to the SAR and continues to do so as the SAR continues to increase. Even with modest SAR levels, it is possible to achieve large SF values; however, the rise in SF happens very quickly. Maximum power enhancement and performance matching the basic cycle are required, the $S_F$ achieves approximately fifty percent in each and every one of the cases that were provided.

The relationship between $S_F$ and the overall cycle efficiency According to the information presented before, efficiency reaches its highest point when $S_F$ equals zero and then begins to decline as SF increases. In spite of this, it is still possible to locate high conversion efficiency values that are satisfactory when the $S_F$ is high. Case D has an efficiency of 50.3 percent and an $S_F$ of 22.1 percent. Additionally, its PR value is 22, its TIT value is 1500 degrees Celsius, and its SAR value is 0.9. Using PR = 15, TIT = 915 C, and SAR = 0.9, the greatest Solar Fraction that may be reported is SF = 48.9 percent, which is at 31.38 percent.

In Equation 1, the incremental performance is denoted by the symbol $g_S$. (3). The increased steam injection over and above $SAR_M$, which is the bare minimum required for regular STIG, is credited with the incremental improvement in efficiency. The progressive efficiency is lower than that of a typical STIG, and it decreases in a linear fashion as the amount of steam that is used increases, reaching an asymptotic value with huge SAR in the end.

The size and expense of a condenser are mostly determined by the amount of water that needs to be condensed and, by extension, the amount of heat that needs to be delivered. The ratio of the condenser heat to the total specific work output (SAR for instance B) and the isentropic efficiency of the a turbine or compressor (qCond) in two different designs are shown below (wN). The first drop in the ratio can be attributed to improvements in efficiency and net power generation from gas turbine exhaust heat exchange. When substantial amounts when solar-generated steam are added to a condenser, the both normalised condenser heat and the condensing thermodynamic efficiency can indeed be up to 1.8 times more than the net output power of a turbine. Therefore, the turbine will extract more work and the condenser will collect less heat if the isentropic performance is good.

## V. DISCUSSION AND CONCLUSION

Under nominal settings, the solar hybrid STIG cycle's annual energy, environmental and exergetic performances were evaluated. Studies have been done on both the basic cycle and the STIG cycle to investigate the implications that inter cooling has on performance, emissions, and economic feasibility. In today's context, when microscopic performance increases and rigorous emission reductions are required, an comprehensive thermodynamics model is being employed to deliver greater precision by utilising in-situ approximate temperature or thermodynamic property values. This model is used to give enhanced precision in today's environment.

Developing a low-cost air-cooled condenser is a key component in making the STIG method commercially viable. On a technological level, the effectiveness of steam with a very high SAR has yet to be established. Common STIG systems have a maximum steam yield of around 10%. One reason for this restriction is that the mass flow rate through the turbine of an available commercially compressor & turbine set is currently limited. Mismatch compressor with oversize turbine, or other innovative combination, such as splitting flow and multiple turbines, are needed for a high-SAR STIG cycle. Alternatively, it is possible to use multiple compressors and multiple turbines. It is also important to think about how the combustor functions when there is a lot of steam present. The effectiveness of the various approaches to dividing, bypassing, and mixing steam flows downstream warrants more study. This study's goal is to analyse the cycle's performance under a consistent, idealised set given nominal conditions. Performance will, of course, alter over time as a direct result of the shifting environmental conditions, and the distribution of those environmental factors will be different depending on where you are. In the future, specific information on the local environment, such as the ambient temperature (conditions at the compressor inlet) and annual performance review of the cycle at multiple places will depend on factors such as the availability of intense sunlight to a solar concentrators. The annual value of a electricity generated is a result of a rate structure, the power demand profiles, and also any regional feed-in limits and special rates, therefore an analysis needs to account for all of these factors in order to present a whole picture. Under the same operating conditions, a thorough annual analysis enables a comparison of the solar STIG's overall performance in terms of energy price to that of comparable solar and conventional power plants.

In order to generate energy that is dispatched to the grid at any time, even during peak demand, solar thermal plants may incorporate heat storage to increase their Capacity Factor (and, in the case of the a hybrid plant, the Solar Fraction). When using a solar STIG, heat storage isn't required because the fuel's heat is already present at the cycle. Even Nevertheless, it may be advantageous to keep a solar STIG facility at the a high Solar Percentage even when sunshine is not present. The need to store solar heat to evaporate water arises from the fact that such an outcome is desirable on regulatory, economic, and environmental reasons. But a wide temperature range is necessary for the successful operation of the heat storage in most solar thermal energy facilities. This range must include superheat. At temperatures as low as 200 ° C, thermal storage that is focused on phase change material looks to be exceptionally well fitted for continually providing heat for evaporation. This is because of the materials' ability to adapt to changing conditions. The incorporation of thermal energy storage into the solar STIG cycle will consequently be an area of focus for future study.Because it generates changes in charge and discharge steam conditions, which in turn impacts cycle efficiency, the fact that charging and discharging are inherently irreversible is one of the most essential aspects of this process. For various site and demand profiles, storage sizing as well as the influence of stored on the plant's dispatchability and energy price be examined.

From a thermodynamic standpoint, STIG technology is being implemented to become a formidable competitor to hybrid solar thermal generation. Hybridization is used to give high conversion efficiency with low cost, but it does not lead to output that is solely powered by the sun.

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