

Article

Simulation and Energy Analysis of Integrated Solar Combined Cycle Systems (ISCCS) Using Aspen Plus

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Abstract: The aim of this research is to simulate and analyze a combined power cycle (Steam turbine and gas turbine cycles) by studying the effect of changing the natural gas flow rate on the developed power. Therefore, reducing the amount of used natural gas in the combustion chamber of the gas turbine cycle from 9.2 to 4 kg/s showed a significant drop in the power produced by the gas turbine, i.e., from 123.7 to 57.7 MW. Additionally, this change in the combusted natural gas amount affected the heat recovered in both heat recovery steam generators (HRSGs), i.e., from 219.79 to 100.35 MW, respectively. Consequently, the amount of generated steam in the high pressure HRSGs and the power developed in the steam turbine changed from 60.88 to 27.79 kg/s and from 56.39 to 27.13 MW, respectively. A heat exchanger (HFHX) utilizing a heating fluid was used as an external source of energy to compensate the reduction in the generated heat and to increase the amount of generated steam up to 157.32 kg/s, which keeps the power plant capacity at 180 MW. Existing combined local plant data were used in this study and were simulated in Aspen Plus software V11. A sensitivity analysis was made to optimize the cycle operating conditions that use less natural gas and produce the same amount of power.

Keywords: integrated solar combined cycle; Aspen Plus; sensitivity analysis; simulation; thermodynamics; thermal energy; power plant; concentrated solar power



Citation: Al Mhanna, N.M.; Al Hadidi, I.; Al Maskari, S. Simulation and Energy Analysis of Integrated Solar Combined Cycle Systems (ISCCS) Using Aspen Plus. *Energies* **2024**, *17*, 3986. <https://doi.org/10.3390/en17163986>

Academic Editor: Carlo Renno

Received: 13 March 2024

Revised: 12 July 2024

Accepted: 17 July 2024

Published: 12 August 2024



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1. Introduction

1.1. Energy and Conversion

Fossil fuels are hydrocarbons or carbons, storing chemical energy between their bounds; once they burn, the stored energy is released as heat [1,2]. Petroleum, natural gas, and coal are the three basic types of fossil fuels. Renewable energy sources are vastly available in nature with a constant flow and can be reused; they restore lost energy very fast from other sources, which makes the amount of stored energy consistent. They are also known as infinite energy sources [1,2]. Sunlight is found in most of Earth, and solar radiation can be used as a source of energy [1]; it has the potential to meet a huge portion of the world's future demand for energy with minimum environmental consequences [3]. Solar energy is generated through the nuclear reactions that happen on the surface of the sun as hydrogen molecules change to helium atoms by releasing a single electron, which also release a huge amount of energy [4]. The sun releases this energy in the form of electromagnetic radiation in all directions and a little amount of it reaches the Earth (1.7×10^{14} KW of radiation) [3]. However, if 1% of the Earth's surface were to be used to convert solar energy into sustainable energy, it would satisfy the whole world's need for energy [5]. The natural forms of energy, such as the chemical energy in fossil fuels, nuclear energy from the nuclear reactions, or solar energy which can be found only as photons or thermal energy, cannot be used directly because of their very low efficiency. These forms

need to be converted to other forms, such as electricity, which can be used for lighting and heating [6,7].

1.2. Thermal Power Plants

Thermal power plants use heat energy and convert it into electrical energy; steam power plants and gas turbine power plants are known as the main types of thermal power plants, and combining both cycles results in increasing efficiency; additionally, this reduces carbon emission [5]. In the steam turbine plants, the power cycle is a Rankine cycle, which is widely used due to the superior thermal properties of water and steam. Moreover, the needed equipment and systems to build such a large size power plant can be found easily in the world, and they are well-developed [8–10]. Heat is transferred to the water as it passes through the boiler tubes and drums, which comes from hot gases resulting from the combustion of fossil fuels. The heat source can also control nuclear reactions from nuclear plants, which then transfer the energy to the working fluid through heat exchangers. Furthermore, solar energy using concentrating collectors can also be used to vaporize the working fluid [9,10]. The vapor produced from the boiler expands in the turbine to a lower pressure. Then, it leaves the turbine and passes through the condenser. In the condenser, the vapor condenses on the tube which the cooling water passes through into saturated water, which then passes through the pump to and back to the boiler to repeat the cycle [8–10].

The gas power cycle usually uses only one working fluid which is commonly air mixed with another fuel. Moreover, gas turbine power plants have a higher ratio of power-output-to-weight than vapor power plants [10]. Most gas turbine power plants use air as the working fluid. The basic used power cycle is the Brayton cycle. In an open-loop Brayton cycle, the air is continuously ingested into the compressor where it compresses and reaches a higher pressure. The high-pressure air is then ingested into the combustor where it mixes with the combustion fuel and combustion happens. Combustion produces products at high temperature which expand through the turbine to produce work and then exhaust to the surroundings. Part of the produced work is used to run the compressor, and the rest are available to be used in generating electricity, running a vehicle, or other purposes [8,10].

Combined cycles are a combination of a Brayton cycle and a Rankine cycle using a gas turbine and a steam turbine both producing works instead of one [8,10]. This works by using the gas turbine exhaust to vaporize the water that enters the steam turbine. Recently, new power plants are using a combined cycle and even many other existing plants are converting into combined cycles due to the low initial cost and the high thermal efficiency which is better than each single cycle and can even reach over 50% [8,10].

1.3. Parabolic Trough Technologies and ISCC

The parabolic trough technology of a concentrated solar power (CSP) system uses parabolic-shaped mirrors to focus the sunrays onto a receiver tube. A heat transfer fluid (e.g., oil or molten salt) flows into the receiver. It is heated by concentrated sunlight to generate steam that expands in a turbine, i.e., developing work [11]. Parabolic trough technology is a mature and widely deployed CSP technology, with over 500 MW of installed capacity worldwide [12]. The largest parabolic trough plant in the world is the 580 MW Noor complex in Morocco, which uses a combination of parabolic trough and tower technologies [13]. The efficiency of parabolic trough technology can be improved through several design innovations and improvements in materials. For example, advanced receiver tubes with higher thermal efficiency and improved coatings can reduce heat losses and increase the overall efficiency of the system [14]. In addition, new control systems and tracking algorithms can improve the accuracy of the mirrors and increase the amount of sunlight that is collected [15]. One of the advantages of parabolic trough technology is that it can be integrated with thermal energy storage systems, which allow excess heat to be stored and used later to generate electricity when sunlight is not available [11]. This

makes parabolic trough technology particularly suitable for areas with high levels of solar radiation and a need for reliable and flexible power generation, such as desert regions. Despite its advantages, parabolic trough technology also faces several challenges, including high upfront capital costs, land use requirements, and the need for large amounts of water for cooling [12]. These challenges are being addressed through ongoing research and development efforts to reduce costs and increase the efficiency and sustainability of CSP systems.

Integrated solar combined cycle systems (ISCCSs) are a type of hybrid power generation system that combines parabolic trough technology with a gas-fired power cycle. In an ISCCS, the heat generated by the parabolic troughs is used to supplement the heat generated by natural gas combustion in a combined cycle power plant, which increases the overall efficiency of the system [16]. Studies have shown that ISCCSs can achieve higher levels of efficiency and lower costs compared to standalone CSP or gas-fired power plants. For example, a study conducted in Saudi Arabia found that an ISCCS had a levelized cost of electricity (LCOE) of 12.84 cents/kWh, compared to 18.5 USD/kWh for a standalone CSP plant [17]. ISCCSs also have the advantage of being able to operate continuously, regardless of weather conditions, because the gas-fired power cycle can be used to supplement the heat generated by the parabolic troughs when sunlight is not available. This makes ISCCSs particularly suitable for regions with high levels of solar radiation and a need for reliable and flexible power generation, such as desert regions [16]. However, ISCCSs also face challenges related to the integration of the two technologies, such as the need for specialized control systems and the potential for thermal cycling and fatigue of components. Ongoing research and development efforts are focused on addressing these challenges and improving the overall efficiency and cost-effectiveness of ISCCSs [14,15]. There are two techniques in solar thermal power plants to generate steam. One is by direct steam generation (DSG), and the other is by heat transfer fluid (HTF). According to [17], the DSG technology operates by converting water into superheated steam through three different processes: once-through, injection, and recirculation. In the once-through process, the water is heated and converted into steam as it circulates through the receiver tubes exposed to the heat from the solar collector. In the injection process, a small amount of water is injected into the receiver tubes to enhance heat transfer and prevent overheating. In the recirculation process, the steam and water are separated to maintain the steam quality and avoid corrosion [16,17]. The concept of HTF technology is to generate steam, but indirectly, compared to direct steam generation technology. The collector receives the solar energy directly from the sun as direct normal irradiation (DNI) and reflects it to the receiver which contains a heat transfer fluid (HTF). The HTF could be silicone oil, nonfreezing hydrocarbon, or molten salt. The HTF transfers thermal energy to heat the solar steam generator (HSSG) through the heat exchanger, which generates steam [16].

Kelly et al. reported that adding high-pressure saturated steam from a parabolic trough solar plant to the heat recovery steam generator in the combined cycle power plant is the most efficient way for ISCCs, but its quantity is limited. The authors found that 12 percent of the solar contributions to ISCCs is more economically efficient than a solar-only plant [18]. Li and Yang proposed and studied a novel ISCC consisting of two-stage solar input and work with DSG technology. Results showed that the efficiency and system performance of the ISCC increased by up to 30% compared to a one-stage ISCC power plant [19]. Anwar carried out a mathematical model for the Al-Abdaliya NGCC (Natural Gas Combined Cycle) power plant in Kuwait by integrating a parabolic trough power plant to it using an engineering equations solver to evaluate its performance and sensitivity. The total installed capacity of the plant was 280 MW, while the solar thermal capacity was 60 MW. The mathematical model revealed that the efficiency of the Al-Abdaliya ISCC power plant reached 20% more than an NGCC plant. The annual fuel consumption and carbon emissions decreased by 43,267 boe/year and 64,018 ton/year, respectively. The author claimed that the modeled ISCC will save USD 3000–6000 million over the lifespan of the plants. Molten salt showed one of the best performances due to its high operational

temperature. However, the molten salt temperature must never fall below the freezing temperature 221 °C. The mixture of NaNO₃/40% KNO₃ is the most commercially used in HTF [20].

Alqahtani et al. study the economic and environmental advantage of ISCC power plants versus CSP plants and NGCC plants separately. Results showed that the LOCE of ISCCs is less than stand-alone CSP by 35–40%; however, in the case of NGCCs, the LOCE of ISCCs is lower than that of NGCCs if only the natural gas prices are higher than or equal to 13.5 USD/MMBtu [21].

Mihoub et al. evaluated the technical and economic feasibility of a 50 MW ISCC power plant with a solar field composed of linear Fresnel reflectors in Algeria. Their results showed that the use of a solar field in the ISCC plant achieved an LCOE of 13.94 ¢/kWh, while reducing CO₂ emissions to 95 kg/MWh [22]. Duan et al. proposed a novel configuration of an ISCC power plant that integrates a thermal energy storage system and a concentrating solar power system with parabolic trough collectors. The simulation results showed that the proposed system has a higher annual solar share and a lower levelized cost of electricity compared to a traditional ISCC plant without thermal energy storage [23].

1.4. Using Simulation

A process of chemical or physical transformation is what the simulation represents, as it calculates the mass and energy balances that involve phase equilibrium and other equations by using a mathematical model [24,25]. This is to predict the behavior of a process of known structure, where the data of the process units are available. The simulator uses the process flow diagram, which represents the connections between the unit operations and their specifications, to predict the process failures and evaluate its performance. The specifications and data of the process can be variable, such as temperature, pressure, flows, compositions, geometrical configuration, work, etc. The simulator utilizes these variables in engineering mathematical models to generate the process analysis [24]. Aspen stands for “Advanced System for Process Engineering”, and is a simulator that applies a sequential strategy to predict or evaluate the behavior of a steady-state process or a set of unit operations by their flow diagram [24,25]. It is composed of a group of models which can represent the process units. When these models are provided with the needed information, the mass and energy balances can be calculated [24].

1.5. Local Power Plant in Oman

A local power plant located in Oman that has a total capacity of 678 MW is used in this study. The plant works with fuel oil and natural gas. It is a combined cycle gas turbine (CCGT) power plant. The plant has three gas turbines and two steam turbines that work dependently on the demand for electricity.

1.6. Problem Statement, Objective, and Novelty

An existing conventional combined cycle power plant needs to be improved to reduce CO₂ emissions and fuel consumption without changing the existing plant units. Therefore, the aim of this study is to use commercial software, e.g., Aspen Plus, to model and simulate this actual power plant, i.e., investigating the effect of reducing the amount of combusted natural gas on plant performance. Therefore, an external fluid heat exchanger unit is integrated into this power cycle to achieve the same original total developed power (e.g., 180 MW) by using less amounts of natural gas to solve the mentioned issues without affecting the power produced by integrating a heating fluid heat exchanger as a part of a parabolic trough into the power cycle in the heat recovery steam generator.

To the best of our knowledge, no similar study was made on modifying an existing conventional integrated power plant to improve the heat recovery system by adding only a parabolic trough collector and the heat exchanger of a CSP system. The model and the simulation were achieved by using a commercial software, i.e., Aspen Plus.

2. Materials and Methods

2.1. Process Description

A combined cycle of a local plant site and an Integrated Solar Combined Cycle are depicted in Figures 1a,b and 2a,b. The gas turbine cycle, steam turbine cycle, and heat recovery steam generators were simulated based on the data given by the local plant. The simulation of the integrated solar part depends on engineering models and previous studies. In the main combined cycle, the air compressor (AC) compresses the incoming air. Then, a combustion reaction happens in the combustion chamber (CC), where air is the oxidizer. Consequently, the produced gas expands through the gas turbine (GT), developing work, which is later used to produce electricity through a generator. The high-temperature combustion gas exits the turbine and enters through two different stages of the heat recovery steam generator operating at different pressures, where it uses its heat to produce steam by heating water. Each HRSG contains an economizer (ECO), evaporator (EVA), super heater (SUP), and flash drum (Drum). The two different steam streams coming from each HRSG enter the steam turbine (ST) and expand through each its blades to produce power that are also used to generate electricity through generators. The water exhausting the turbine is then condensed through a condenser into saturated water, enters a pump to increase its pressure, and then goes back and closes the cycle. In the Integrated Solar Combined Cycle, the LP water exits the low-pressure economizer and splits into two streams. One continues as the main cycle, the other goes through a heating fluid heat exchanger (HFHX) where the water is heated through a heating fluid which comes from a parabolic trough. Then, the water continues to the HP drum and mixes with the HRSG cycle, then goes to the steam turbine. This addition helps to increase the power produced by the steam turbine as it helps increase the water flow that expands in the steam turbine.

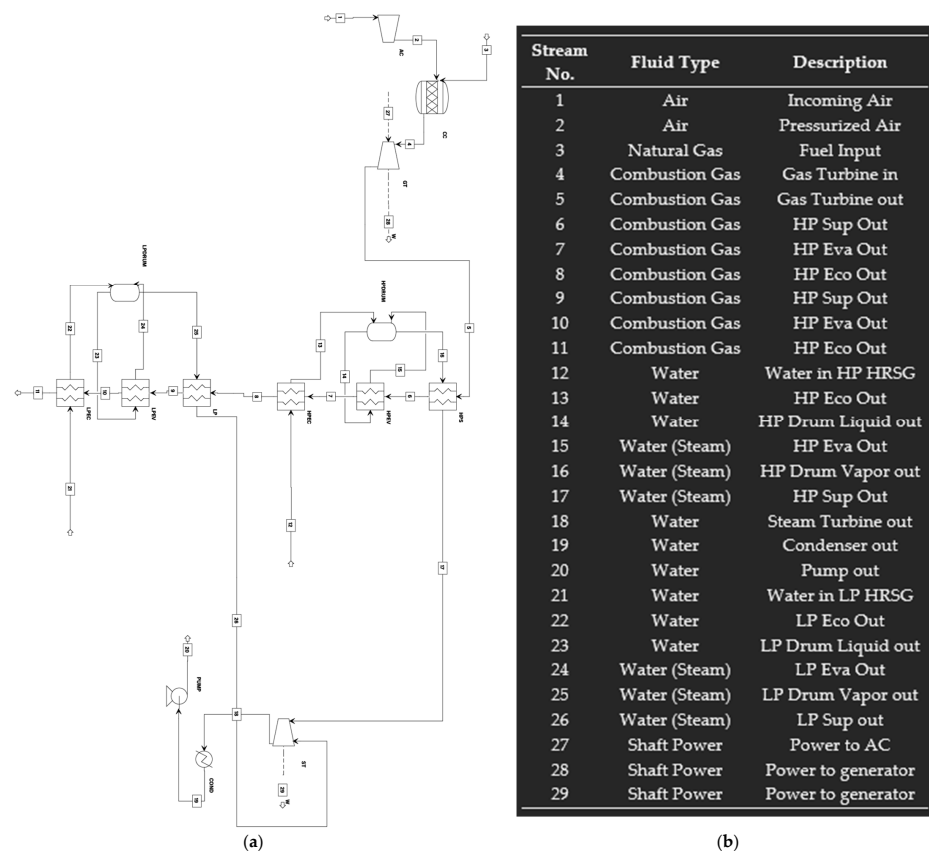


Figure 1. The main cycle. (a) The process flow diagram in Aspen Plus. (b) The streams descriptions.

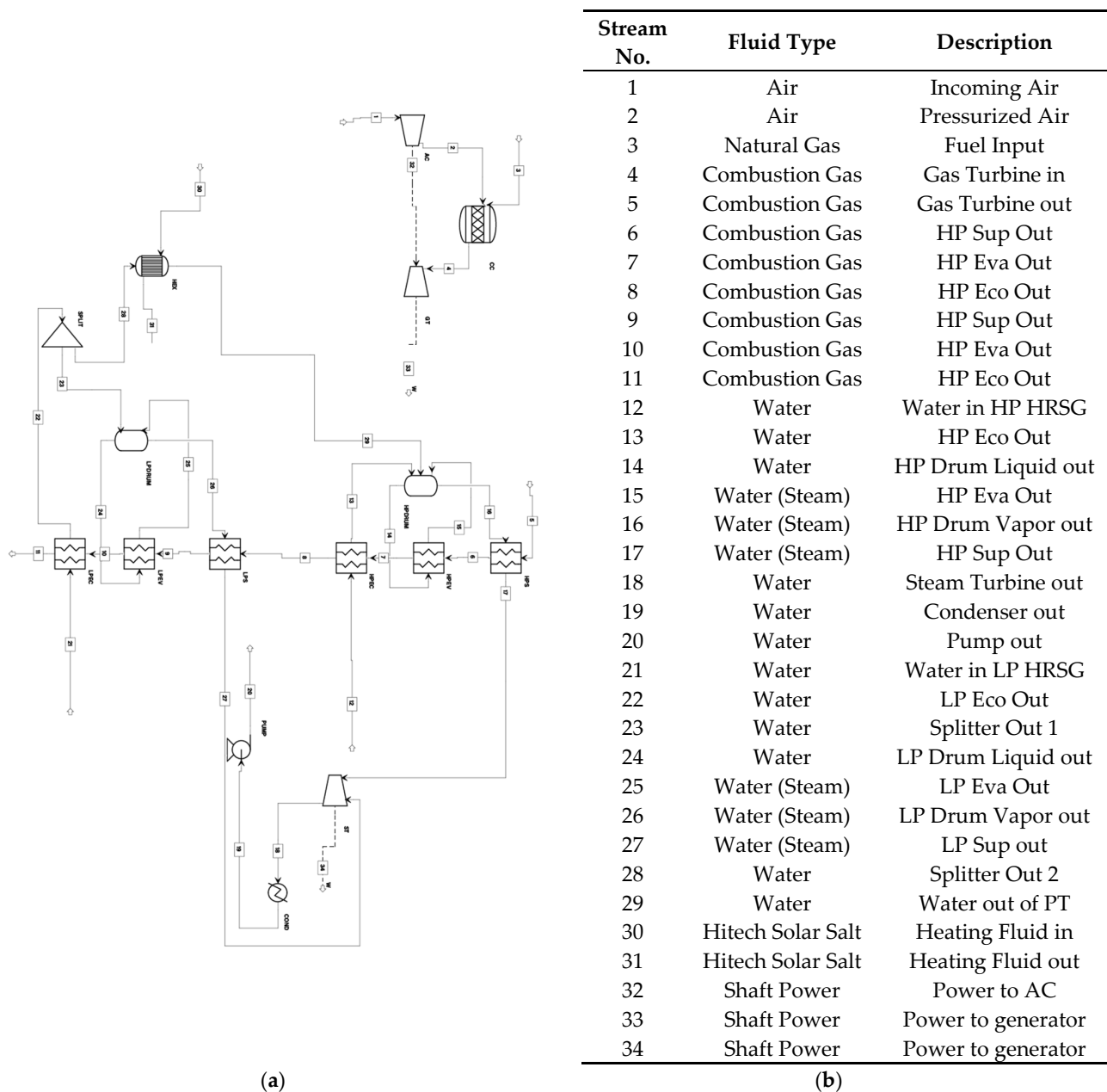


Figure 2. The Integrated Solar Combined Cycle. (a) The process flow diagram in Aspen Plus. (b) The streams descriptions.

2.2. Energy Balance and Simulation

If the heat transfer to the surrounding is neglected, the following equations can be used to calculate the energy balance of the system components using the mass and the specific enthalpy [9,11].

$$\text{Work (ST, GT, AC, pumps)} : \dot{W} = \dot{m} (h_{in} - h_{out}) \quad (1)$$

$$\text{Heat (CC, Condensers)} \dot{Q}_{out} = \dot{m} (h_{in} - h_{out}) \quad (2)$$

$$\text{Heat transfer in Hx } \dot{m}_1 (h_{in} - h_{out}) = \dot{m}_2 (h_{in} - h_{out}) \quad (3)$$

$$\text{Thermal efficiency } \eta = \frac{\text{Net power}}{\text{Generated heat}} \quad (4)$$

$\dot{m}$ = mass flow, h_{in} = specific enthalpy of the inlet stream, h_{out} = specific enthalpy of the outlet stream

In Aspen Plus simulation, the following equations are built in:

$$IHP = Fdh \quad (5)$$

$$\text{Heat duty} = Fdh \quad (6)$$

$$\text{Heat transfer in heat exchanger } F_1dh = F_2dh \quad (7)$$

Indicated horsepower (IHP) and heat duty both are the total enthalpy change in the stream where

F = the molar flow rate

dh = the enthalpy change per mole.

2.3. System Simulation

Aspen Plus

Aspen Plus was used to calculate the mass and energy balances and to run the sensitivity analysis. It was assumed that the process was steady-state, and there was no pressure drop and heat losses in the pipes. The Peng–Robinson thermodynamics method was used for the air and gas side, while the IAPWS-95 thermodynamics method was used for the water side. Table 1 describes the components and the model used in Aspen Plus. Table 2 shows the cycle parameters according to the data of the actual plant.

Table 1. Model description of units in Aspen Plus.

Component	Model in Aspen Plus	Specifications
Air Compressor, Steam Turbine, Gas Turbine	Compressor Model (Compr)	Discharge pressure, Isentropic efficiency
Combustion Chamber	Stoichiometric Reactor (RStoic)	Pressure, Heat Duty
Economizer, Evaporator, Superheater, HFHX	Heat Exchanger (MHeatX)	Outlet Temperature
Flash Drum	Flash (Flash2)	Pressure, Heat Duty
Condenser	Heat Exchanger (Heater)	Pressure, Vapor Fraction
Pump	Pump (Pump)	Discharge Pressure, Isentropic Efficiency
Split	Fraction Splitter (FSplit)	Flow Rate Fraction

Table 2. The cycles parameters.

Parameter	Unit	Value
Air Flow Rate	kg/s	505.3600003
Incoming Air Pressure	bar	0.9981
Incoming Air Temperature	°C	26.6
Compressor Discharge Pressure	bar	9.4
Compressor Efficiency	-	0.883
Fuel Flow Rate	kg/s	9.2
Fuel Pressure	bar	22.8
Fuel Temperature	°C	15.6
Fuel Composition	92.47% Methane, 0.738 CO ₂ 1.68 C ₃ H ₈ 0.20 i-C ₄ H ₁₀ , 0.22 n-C ₄ H ₁₀ , 0.06 i-C ₅ H ₁₂ , 0.05 n-C ₅ H ₁₂ , 3.53 N ₂	
Fuel (LHV)	KJ/kg	43,662.14
Turbine Discharge Pressure	bar	1
Turbine Isentropic Efficiency	-	0.85

Table 2. Cont.

Parameter	Unit	Value
Water Flow Rate entering the HP HRSG	kg/h	235,400
Water Flow Rate entering the LP HRSG	kg/h	40,000
HP Eco Exhaust Temperature	°C	263
HP Eva Exhaust Temperature	Vapor fraction	1
HP Sup Exhaust Temperature	°C	471.48
LP Eco Exhaust Temperature	°C	169
LP Eva Exhaust Temperature	Vapor fraction	1
LP Sup Exhaust Temperature	°C	217
HP Drum Pressure	bar	37.38
LP Drum Pressure	bar	6.72
Steam Turbine Exhaust Pressure	bar	0.08
Condenser Vapor Fraction	-	0
Cooling Water Inlet Temperature	°C	26.6
Cooling Water Outlet Temperature	°C	34.5
Pump Discharge Pressure	bar	21.6
Pump Isentropic Efficiency	-	0.85
Steam Turbine Net Power	MW	61.5
Gas Turbine Net Power	MW	127
Heating Fluid Composition	7%NaNO ₃ , 53% KNO ₃ , 40%NaNO ₂	
Heating Fluid Inlet Temperature	°C	570
Heating Fluid Exhaust Temperature	°C	240
Heating Fluid Pressure	bar	100

2.4. Sensitivity Analysis

2.4.1. Sensitivity Study 1 (Main Cycle)

The aim of this study is to measure the effect of the amount of natural gas used in the combustion chamber on the amount of heat transfer happening in the heat recovery steam generator. In this investigation, the natural gas was lowered from 9.2 kg/s (original value of the operating condition) to 4 kg/s.

The following variables were controlled:

1. The air flow rate was controlled to keep the air-to-fuel ratio constant during the study.
2. The high-pressure water going into the HP HRSG was controlled to keep the exhaust gas stream temperature constant to keep the system from failing.
3. The low-pressure water going into the LP HRSG was controlled to keep the exhaust gas stream temperature constant to keep the system from failing.

The following values were calculated:

- Gas Flow (kg/s).
- Heat in HP HRSG (MW).
- Heat in LP HRSG (MW).
- Steam Turbine Power (MW).
- Gas Turbine Power (MW).
- Total Power (MW).
- Water Flow Rate in HP HRSG (kg/s).
- Water Flow Rate in LP HRSG (kg/s).

2.4.2. Sensitivity Study 2 (ISCC)

The objective of this analysis is to compensate the heat and the power reduced in study 1 using HFHX, and to measure the required heating fluid. In this study, the gas flow rate was lowered from 9.2 kg/s (operating condition) to 4 kg/s. Moreover, the study will find the optimum state between the water feed into HRSG and HFHX, i.e., to use the least amount of heating fluid possible for obtaining the same power production.

The following variables were controlled:

1. The air flow rate was controlled to keep the air to fuel ratio constant during the study.
2. The high-pressure water going into the HP HRSG was controlled to keep the exhaust gas stream from LP HRSG temperature constant to keep the system from failing.
3. The amount of heating fluid was controlled by only using the needed amount.
4. The amount of water coming into the HFHX was controlled to always give a total power of 180 MW from the two turbines.

The following values were calculated:

- Gas Flow (kg/s).
- Heat in HP HRSG (MW).
- Heat in LP HRSG (MW).
- Steam Turbine Power (MW).
- Gas Turbine Power (MW).
- Total Power (MW).
- Water Flow Rate in HP HRSG (kg/s).
- Water Flow Rate in LP HRSG (kg/s).
- Heating Fluid Flow Rate (kg/s).
- Water in HFHX Flow Rate (kg/s).

3. Results and Discussion

3.1. Simulation Validation

Table 3 shows a comparison between the results of the actual data given by the local plant and the results extracted from the simulation run. The simulation results were validated since insignificant error was found, i.e., the error range was 0.443–3.77%.

Table 3. The power cycles parameters.

Parameter	Local Plant Data	Simulation Results	Error %
Gas Turbine Work Output	127 MW	126.45 MW	0.433
Steam Turbine Work Output	61.5 MW	59.47 MW	3.3
Gas Turbine Inlet Temperature	1050 °C	1010.46 °C	3.77
Gas Turbine Exhaust Temperature	540.7 °C	556.93 °C	3.00
Efficiency	46.93%	46.28%	1.39

3.2. Sensitivity Study 1: Study the Effect of Reducing the Natural Gas Flow Rate on the Main Cycle Parameters

The generated results demonstrate that the amount of heat exchange between the flue gas and the water in HP HRSG and in LP HRSG is reduced because of decreasing the gas usage in the combustion chamber. Consequently, significant heat reduction happened in the HP HRSG (i.e., from 177.68 to 81.12 MW) and in the LP HRSG (i.e., from 42.11 to 19.22 MW) when the flue gas flow rate decreased from 9.2 to 4 kg/s, respectively, as shown in Figure 3. It can be explained that the heat duty is proportional linearly with mass flow rate of the working fluid while the used specific enthalpy values were constant, shown in the Equations (2) and (3) [9,11]. This is also demonstrated in Figure 4 as this drop in the

amount of the flue gas caused a reduction in the amount of water in the HP HRSG from 60.89 to 27.80 kg/s and in the LP HRSG from 17.30 to 7.90 kg/s, respectively. Thus, the total heat exchanged is reduced.

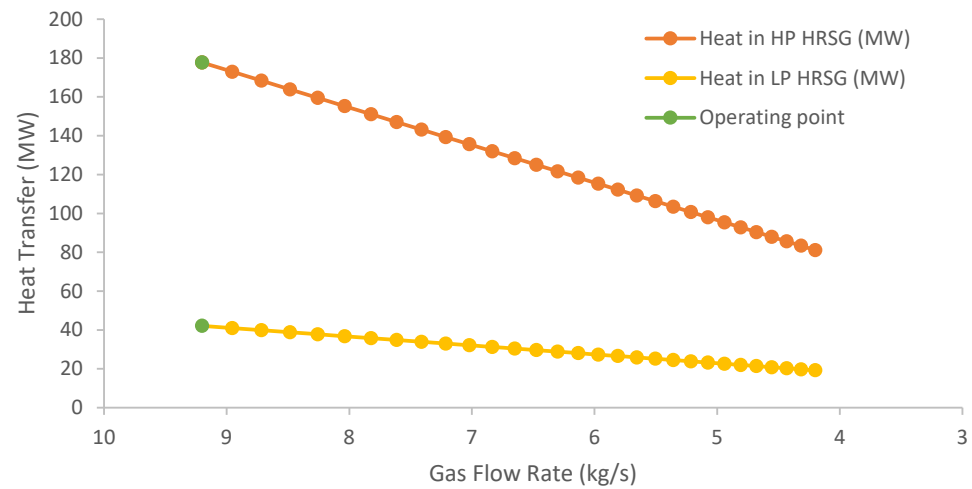


Figure 3. The heat transfer graph in HP HRSG and LP HRSG.

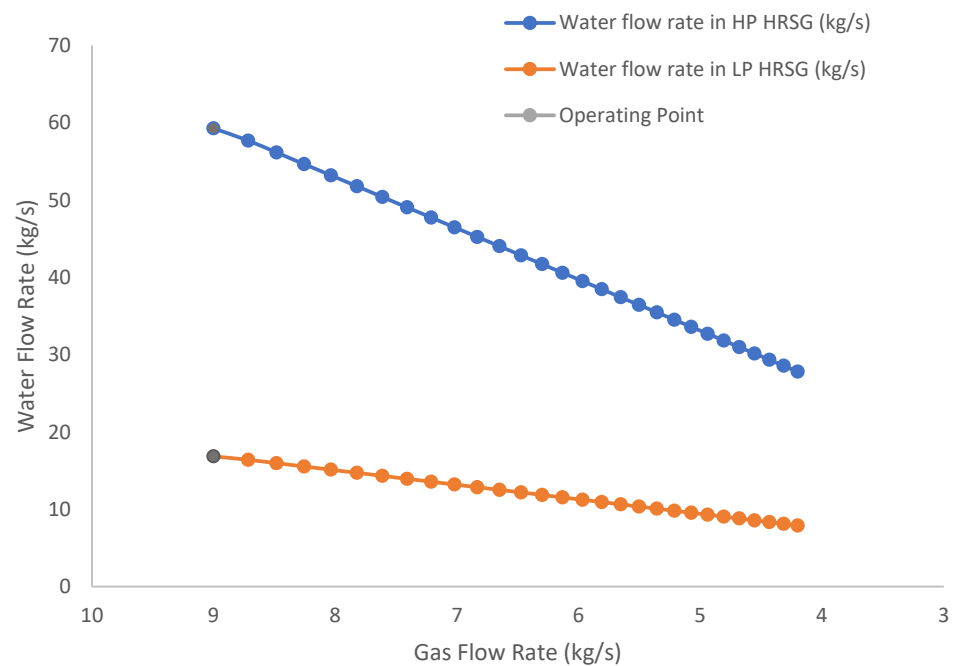


Figure 4. Water flow rate graph in HP HRSG and LP HRSG.

Figure 5 shows that the reduction in natural gas flow rate from 9.2 to 4 kg/s changes significantly with the amount of generated power in the gas turbine, from 123.7 to 57.73 MW, respectively, because the work turbine is proportional directly to the mass flow rate of the combusted natural gas according to Equation (1) [9,11], since the specific enthalpy values across the turbine are kept constant. Moreover, this natural gas flow rate reduction decreases the steam turbine power generation from 56.39 to 27.129 MW due to the decrease in the flue gas flow rate that drops the amount of generated steam in both HRSG systems. Consequently, the total power output is reduced from 180.09 to 84.86 MW accordingly.

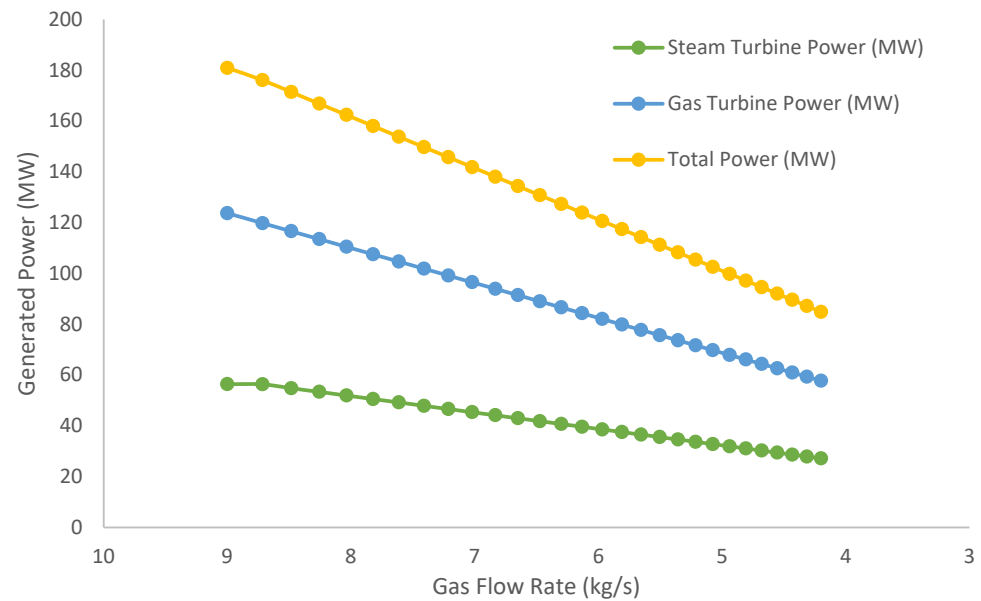


Figure 5. The power generated graph in GT and ST (Study 1).

3.3. Sensitivity Study 2: ISCC Study of the Effect of Dropping the Natural Gas Flow Rate on the ISCC

The results of study 1 confirms that reducing the NG flow rate affects the developed power significantly due to the decrease in the available heat for power generation in both gas turbine and steam turbine cycles. Therefore, the power system was improved (to keep the original total developed power at 180 MW as demonstrated in Figure 6) by integrating it with a solar thermal energy system, i.e., HFHX to increase the total generated steam that is entering the steam turbine from 72.71 to 157.32 kg/s as shown in Figure 7. Consequently, this compensates the amount of reduced energy since the steam turbine power output was increased from 56.4 to 125 MW, respectively, as depicted in Figure 6.

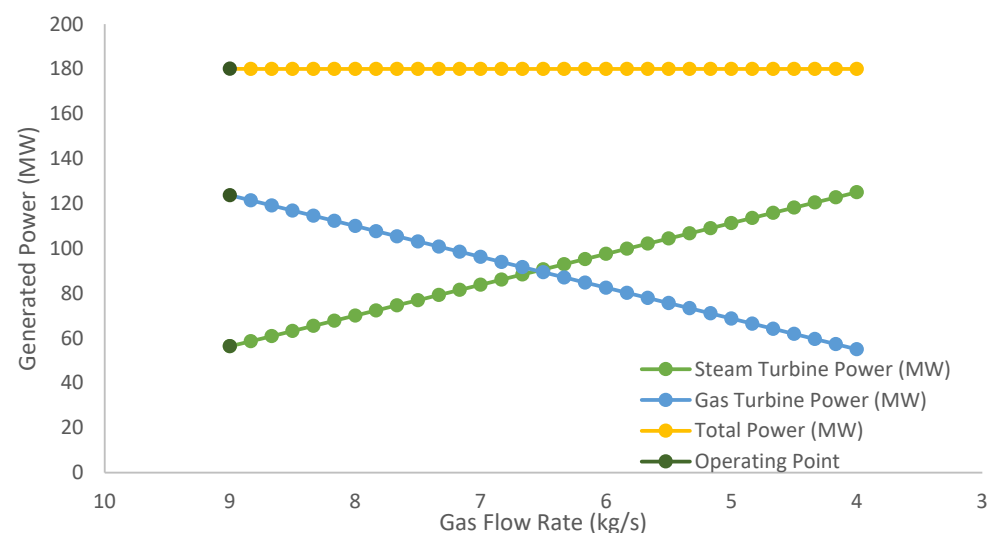


Figure 6. The power generated graph in GT and ST (Study 2).

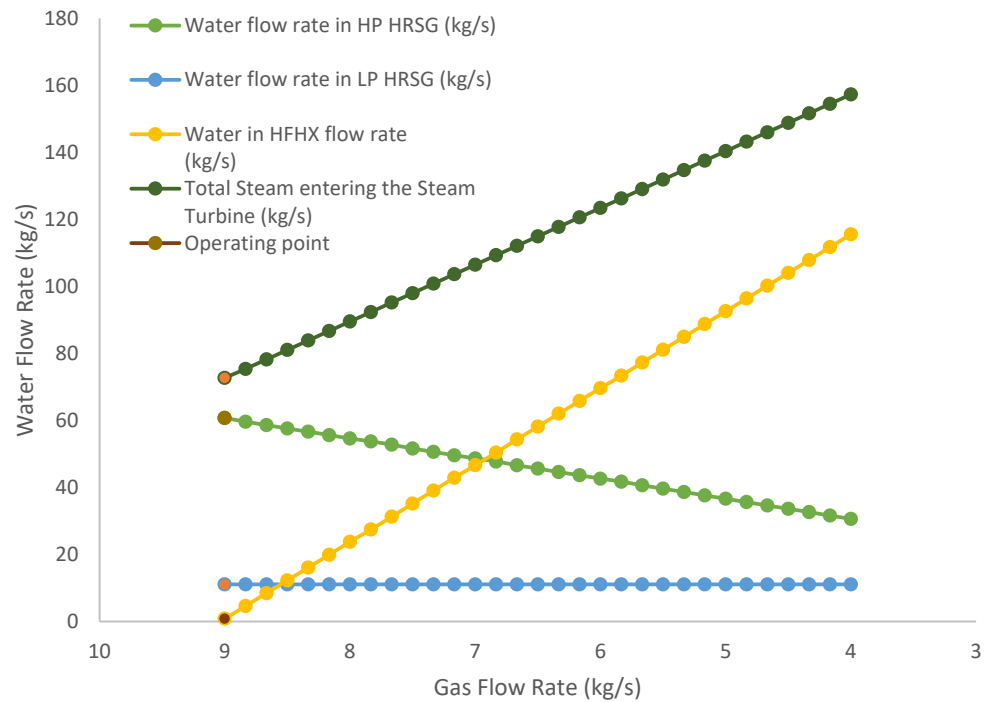


Figure 7. Water flow rate in inlet of HP HRSG, LP HRSG, and in HFHX.

The total power developed decreases from 171.39 MW to 84.86 MW when the NG flow rate decreases from 8.5 to 4.16 kg/s, respectively, as illustrated in Figure 8. However, by adding HFHX, the system gained an extra power in the range of 8.6–95.14 MW to balance the total power to be 180 MW. That was achieved by increasing the amount of heating fluid in HFHX from 2.75 to 425.89 kg/s to generate steam at a flow rate range of 0.84–115 kg/s (as depicted in Figure 9) and at a constant temperature of 566 degrees Celsius. This steam is combined with the other generated vapor in the HP-HRSG drum before they enter the steam turbine.

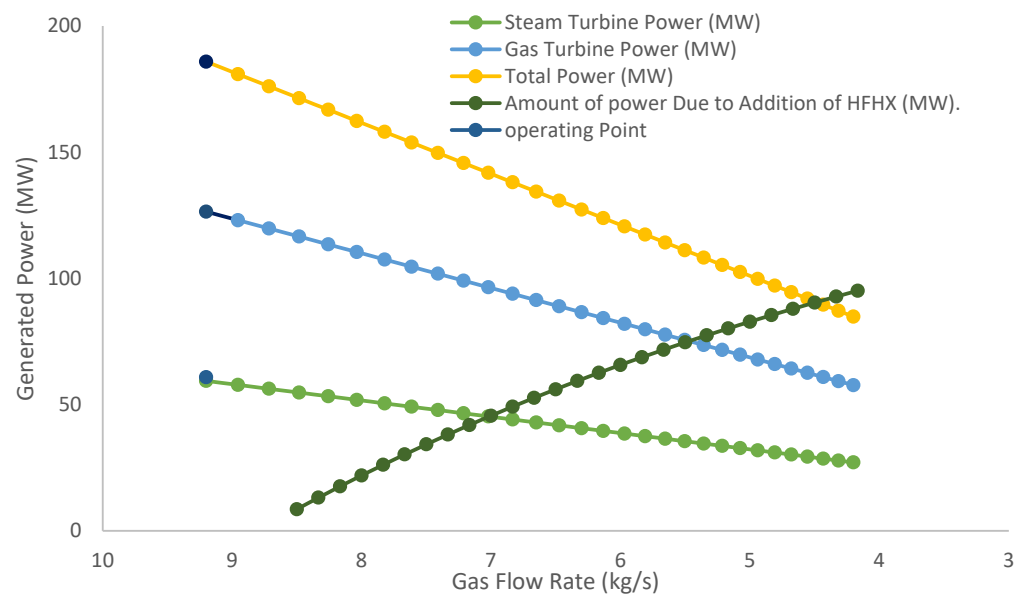


Figure 8. Required power generated by adding the HFHX to keep the total power at 180 MW.

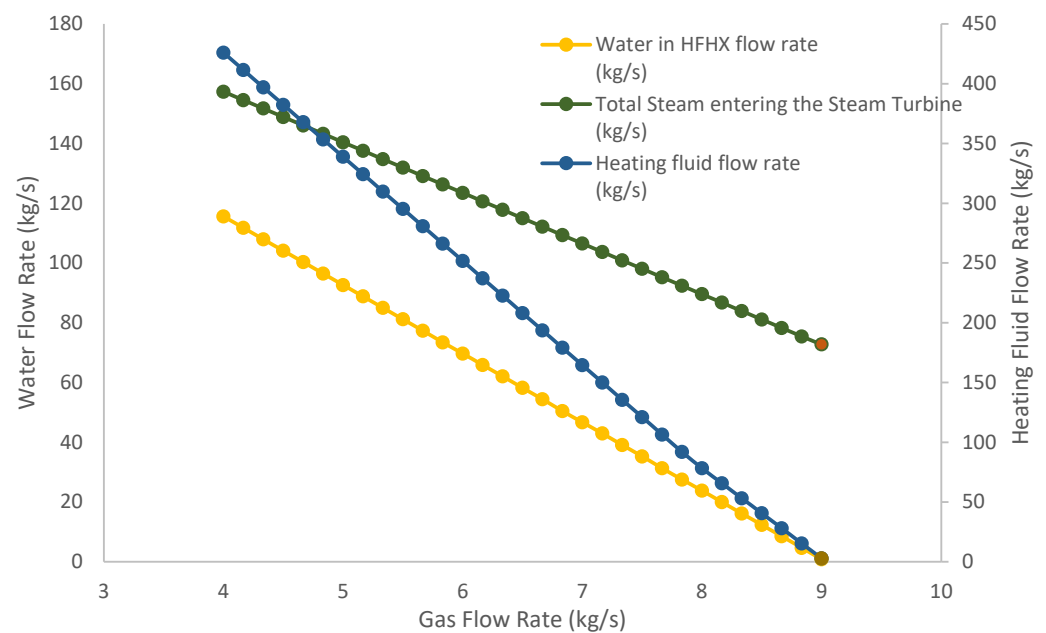


Figure 9. Water flow rate graph in HP HRSG, LP HRSG, and in HFHX.

4. Conclusions

- The research indicates that the development of an integrated cycle is a promising approach to reduce CO₂ emission significantly since the amount of burned NG fuel is reduced.
- It is concluded that the HFHX can be heated up by using an external parabolic trough system. This integration has advanced the power cycle towards using renewable energy sources, i.e., developing an Integrated Solar Combined Cycle (ISCC).
- The results indicate that commercial software can be used in the simulation and analysis of actual power plants, as the data were validated with insignificant errors, i.e., ranging 0.443–3.77%.
- Study 1 shows a direct relationship between the consumed natural gas flow rate and the total developed power, i.e., a reduction in the developed power happens from 180 to 84.86 MW when the natural gas flow rate was decreased from 9 to 4.2 kg/s, respectively.
- The analysis of study 2 proves that the total power output can be kept constant despite the fact that the used NG flow rate is dropped. For instance, 180 MW power was developed when the NG flow rate was reduced from 9 to 4.2 kg/s. This is achieved by adding external heat sources (HFHXs), which increase the generated steam from 72.7 kg/s to 157.31 kg/s. Therefore, the steam turbine power output was increased from 56.4 to 125 MW, respectively.
- Consideration of the turbine size should be taken in defining the natural gas flow rate.

5. Future Work

Further study of an economic analysis and levelized cost of electricity for the new integrated power plant is recommended. Such a study will provide detailed calculation of CAPEX and OPEX costs. Additionally, it will show the feasibility of such a project.

Author Contributions: Conceptualization, N.M.A.M.; methodology, I.A.H.; software, I.A.H.; validation, N.M.A.M. and I.A.H.; formal analysis, N.M.A.M.; investigation, N.M.A.M., I.A.H. and S.A.M.; data curation, S.A.M.; writing—original draft preparation, I.A.H. and S.A.M.; writing—review and editing, N.M.A.M. and I.A.H.; supervision, N.M.A.M.; project administration, N.M.A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: The authors acknowledge the support of German University of technology in Oman for offering the research facilities.

Conflicts of Interest: The authors declare no conflicts of interest.

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