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Simulation Modeling of 140 MW CCGT Quality Indicators Based on DIN-VDI 4661 Standard Using Ebsilon® Professional Software

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ABSTRACT

The operational efficiency of mid-capacity (140 MW) Combined Cycle Gas and Steam Power Plants (CCGT) remains underexplored concerning the DIN-VDI 4661 standard, which defines key quality metrics for energy systems. Addressing this gap is crucial for establishing standardized benchmarks to optimize performance and reduce energy losses. Existing studies mainly focus on Combined Cycle Gas Turbine (CCGT) units outside the 100–180 MW range and often do not explicitly follow DIN-VDI 4661, limiting efficiency comparisons and hindering targeted optimizations. This study simulates a 140 MW CCGT using Ebsilon® Professional software, incorporating DIN-VDI 4661 guidelines to assess eight quality indicators, including thermal efficiency, fuel utilization, and power-to-heat ratio. The model integrates gas and steam turbines, heat recovery, and auxiliary components, with input parameters validated against industry data. Energy balance analysis and sensitivity tests identified loss points. Results show a gas turbine thermal efficiency of 31.39%, steam turbine efficiency of 39.59%, and total system efficiency of 48.42%. However, significant energy losses (52% of input energy) were observed, mainly in gas turbines (87,000 kW) and steam turbines (56,000 kW). These findings highlight the need for design optimizations, such as improving heat recovery and turbine efficiency, to meet DIN-VDI 4661 benchmarks.

INTRODUCTION

Combined-Cycle Gas Turbine (CCGT) power plant simulations have been extensively explored using a variety of software platforms, with Ebsilon Professional, MATLAB/Simulink, and DWSIM emerging as leading tools. The current study demonstrates the platform's ability to evaluate critical performance metrics such as thermal efficiency, power output, start-up time, and fuel consumption. Bany Ata et al. (2021) used Ebsilon Professional to simulate an Integrated Gasification Combined Cycle (IGCC) plant, achieving a thermal efficiency of 91.28% and an increase in steam turbine power of 34.2% in some load cases, with deviations below 5% compared to the measured data. Similarly, a MATLAB/Simulink-based study by Nannarone and Klein (2019) reported significant reductions in start-up time (32.5% for cold start) and fuel consumption (47.0% for cold start), while Hassan and Manji (2023) demonstrated DWSIM's ability to predict power generation with only 0.45% deviation from field data. The study highlights the software's proficiency in optimizing operational parameters, validating models against empirical data, and exploring hybrid configurations, such as solar-integrated CCGT systems.

Some literature emphasizes the role of simulation in overcoming system-level integration challenges. Arakelyan et al. (2022) developed a digital twin of the PGU-450T CCGT unit to analyze both static and dynamic processes, although the validation metrics are not explicitly detailed. Meanwhile, studies such as Talukder and Soori (2015) compare conventional and solar-hybrid CCGT configurations, underscoring the versatility of the software in assessing alternative designs. Despite the results of the existing study, the studies reviewed mostly focused on power plants outside the 100-180 MW range, with only two explicitly mentioning power ratings. In addition, while performance indicators such as thermal efficiency and emissions are widely analyzed, their alignment with standard frameworks such as DIN-VDI 4661 for determining quality metrics for energy systems, is still unexplored (Roy, 2024).

The simulation, which specifically targets the 140 MW CCGT unit under the DIN-VDI 4661 standard, has not yet presented the result data. While studies such as Bany Ata et al. (2021) and Hassan and Manji (2023) validate the accuracy of Ebsilon and DWSIM respectively, the scope does not address the operational criteria and unique design of medium-capacity CCGT plants. The DIN-VDI 4661 standard, which provides guidelines for evaluating the quality of energy conversion systems through metrics such as energy efficiency, reliability, and environmental impact, has not been explicitly referenced or applied in any of the studies reviewed. This leads to limited comparative information of simulation results across platforms and hinders the development of universally accepted benchmarks for CCGT performance.

In addition, inconsistencies in methodology and reporting further complicate cross-study comparisons. For example, validation approaches vary widely: some studies compare results with field data (e.g., 0.45% deviation in Hassan and Manji (2023)), while others do not have explicit validation metrics (e.g., Arakelyan et al. (2022)). Similarly, key simulated conditions, such as ambient temperature, fuel type, and pressure—are often not fully documented, making it difficult to assess generalizations of the findings. The scarcity of power rating data (only 2 out of 10 studies determined capacity) and the focus on different quality indicators (e.g., thermal efficiency, start-up time, combustion stability) further fragmented the knowledge base. Notably, no studies directly compared Ebsilon Professional with alternative platforms such as MATLAB/Simulink or DWSIM for identical performance metrics, leaving uncertainty about its relative strengths and limitations (Arakelyan et al., 2024).

The study proposed to address the gap by conducting the first simulation of a 140 MW CCGT power plant using Ebsilon Professional, explicitly incorporating the DIN-VDI 4661 standard. By aligning simulation objectives with DIN-VDI 4661 quality indicators related to thermal efficiency and power output metrics. The simulation is integrated with system-level analysis, which includes gas and steam turbines, heat recovery systems, and additional components, to reflect the complexity of real-world operations. Limit conditions such as ambient temperature, fuel composition, and load variations will be determined explicitly, following the emphasis of DIN-VDI 4661 on reproducibility.

RESEARCH METHODS

This study employs a quantitative simulation-based approach to evaluate the operational efficiency of a 140 MW Combined Cycle Gas and Steam Power Plant (CCGT) using Ebsilon® Professional software (version unspecified). The research aligns with the DIN-VDI 4661 standard, which provides guidelines for assessing energy conversion system quality through defined performance metrics. The methodology is structured into three primary phases: (1) model development and energy balance distribution, (2) simulation implementation, and (3) quality indicator calculation and analysis. Figure 1 illustrates the workflow, emphasizing iterative validation and optimization steps.

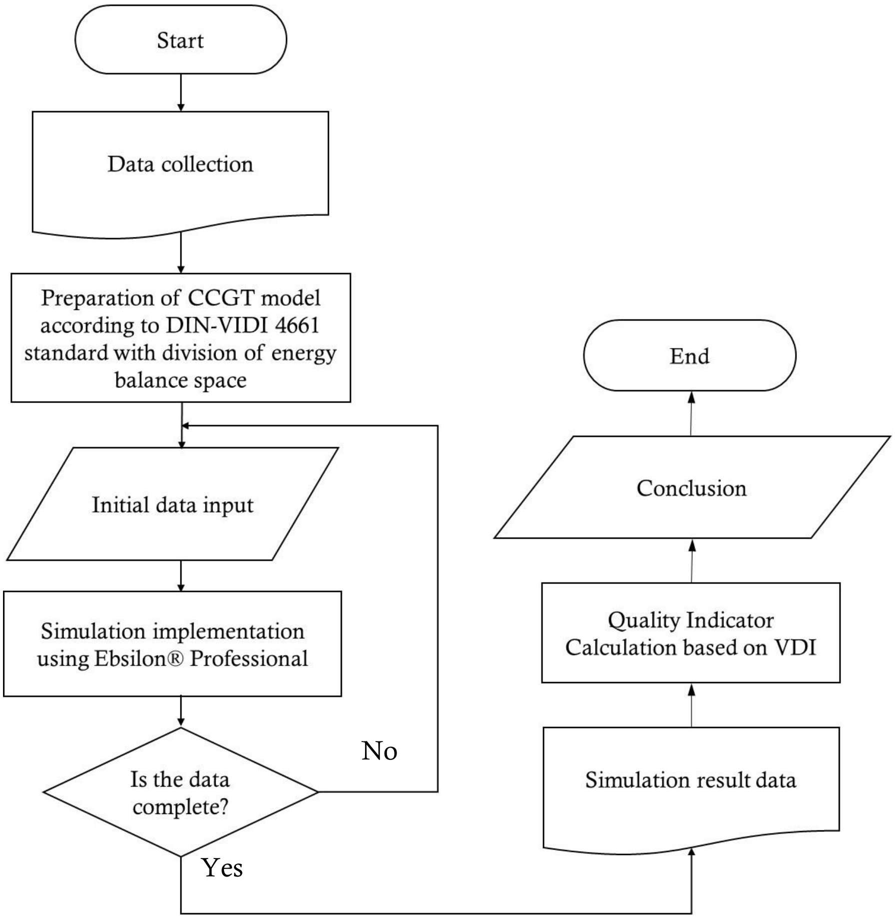

Figure 1. Research Flow Diagram

Data Collection and Input Parameters

After the CCGT model and equilibrium space have been established, the next stage is to enter the initial data, which is presented in Table 1. This data includes technical parameters such as pressure, temperature, fuel flow rate, as well as the efficiency of key components. Data input is carefully carried out to ensure that the simulation can run smoothly without errors that can affect the analysis results. Once all the data has been entered, the simulation is run using the Ebsilon software. This software allows for more accurate calculation and analysis of efficiency by taking into account various thermodynamic and operational variables in the CCGT system. This simulation aims to replicate the operational conditions of the plant and produce data that can be used in the calculation of quality indicators.

Table 1. Simulation input data

Description	Symbol	Value	Unit
Gas Turbine (TG)			
Mass of Airflow	$\dot{m}_u$	300	$\frac{kg}{s}$
Air Temperature	T_u	25	°C
Air Pressure	p_u	1	bar
Air Fuel Ratio (AFR)	λ	1.2	-
Icentropic Efficiency of Gas Turbines	η_{TG}	90	%
Compressor Efficiency	η_K	85	%
Fuel Temperature	T_{bb}	25	°C
Fuel Volume Fraction: Methane (CH_4)	φ_{CH4}	95	%
Fuel Volume Fraction: Methane (CO2)	φ_{CO2}	5	%

Steam Turbine (TU)			
Level 1 Turbine Steam Pressure	p_1	80	Bar
Level 1 Turbine Steam Temperature	T_1	530	°C
Level 2 Turbine Steam Pressure	p_2	60	Bar
Level 3 Turbine Steam Pressure	p_3	30	Bar
Level 4 Turbine Steam Pressure	p_4	12	Bar
Level 5 Turbine Steam Pressure	p_5	3	Bar
Level 6 Turbine Steam Pressure	p_6	0.5	Bar
Condenser Pressure	p_k	0.065	Bar
Pump Efficiency	$\eta_{i,P}$	87	%
Icenttropic Efficiency of Level 1 Steam Turbines	η_1	76	%
Icentropic Efficiency of Level 2 Steam Turbines	η_2	80	%
Icentropic Efficiency of Level 3 Steam Turbines	η_3	83	%
Icenttropic Efficiency of Level 4 Steam Turbines	η_4	85	%
Icentropic Efficiency of Level 5 Steam Turbines	η_5	87	%
Icenttropic Efficiency of Level 6 Steam Turbines	η_6	88	%
Motors & Generators (M)			
Energy Loss Generator		1	%
Motor Energy Loss		1	%
Brutto Electric Power (Mop,b)			
Energy Loss Transformer		1	%
Net Electrical Force ($_{P-el,n}$)			
Brutto Energy Loss		1	%

Model Development

The CCGT system was modeled to replicate real-world operational conditions, incorporating gas turbines, steam turbines, heat recovery steam generators (HRSG), condensers, pumps, and electrical components. Key technical parameters, such as gas turbine capacity (140 MW), steam turbine pressure levels (80–0.065 bar), and component efficiencies (e.g., compressor efficiency: 85%, isentropic turbine efficiencies: 76–88%), were defined based on industry standards. The system was divided into five energy equilibrium spaces (Figure 2) to isolate energy conversion processes (Xu et al., 2024): 1) Fuel combustion and gas turbine operation; 2) Heat recovery and steam generation; 3) Steam turbine power conversion; 4; Electrical power generation; and 5) Auxiliary systems (e.g., pumps, cooling circuits). This segmentation enabled granular analysis of energy flows, losses, and efficiency across subsystems.

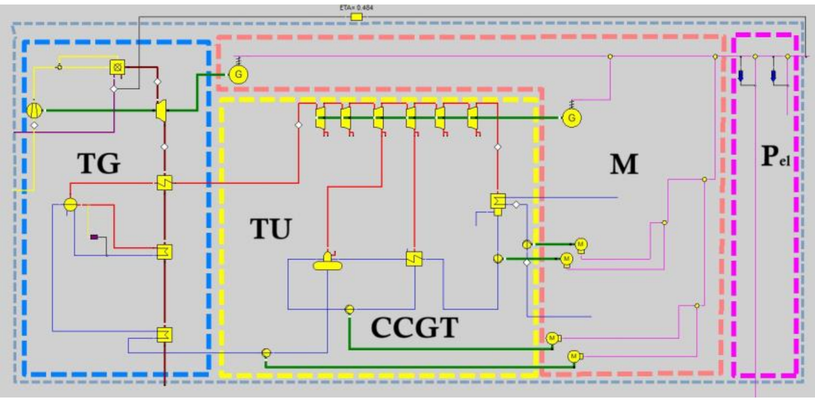

Figure 2. CCGT Simulation Series and Equilibrium Space Distribution

Simulation Implementation

The simulation was executed using Ebsilon® Professional, a thermodynamic modeling tool optimized for power plant analysis. The software's built-in libraries for gas and steam cycles were leveraged to configure the CCGT model. Key steps included: 1) Component configuration: Gas/steam turbines, HRSG, and condensers were interconnected to reflect the CCGT's energy flow; 2) Parameter initialization: Input data from Table 1 were assigned to corresponding components; and 3) Iterative calibration: The model was refined to minimize convergence errors and ensure stable operation across load cases.

Quality Indicators and Metrics

Performance metrics were calculated in accordance with DIN-VDI 4661, focusing on eight quality indicators (VDI, 2024)):

1) Gas turbine thermal efficiency (η): $\frac{\text{Energy output}}{\text{Energy input}}$

2) Power efficiency (β_{TG}): $\frac{P_{TG}}{\dot{m}_{bb}\times H_u}$

3) Heat transfer efficiency (α_{TG}): $\frac{\dot{Q}_{TG}}{\dot{m}_{bb}\times H_u}$

4) Power-to-heat ratio (σ_{TG}): $\frac{P_{TG}}{\dot{Q}_{TG}}$

5) Fuel utilization ratio (ω_{TG}): $\frac{\dot{Q}_{TG}+P_{el.n}}{\dot{m}_{bb}\times H_u}=\alpha_{TG}+\beta_{TG}$

6) Steam turbine efficiency (η_{TU}): $\frac{P_{TU}-(\sum P_{Pump})}{\dot{Q}_{TG}}$

7) Motor/generator efficiency (η_M): $\frac{P_{el.B}}{P_{TG}+P_{TU}-(\sum P_{Pump})}$

8) Electrical power equilibrium efficiency (η_{Pel}): $\frac{P_{el.n}}{P_{el.B}}$

9) Total system efficiency (η_{CCGT}): $(\alpha_{TG}\times\eta_{TU}+\beta_{TG})\times\eta_M\times\eta_{Pel}$

The data from the above calculation is then used in the formula contained in the VDI 4661 standard to calculate the required quality indicators. In general, in the VDI 4661 standard, the energy conversion efficiency (η) can be calculated by the result of the division between the energy input and energy output of a system which can be seen in the formula (1). The first Quality Indicator, namely the power efficiency produced in the equilibrium chamber of a gas turbine (β), can be determined using the formula (2). The second Quality Indicator, namely the heat efficiency that can be transferred to the equilibrium space of the steam turbine (α) can also be calculated by formula (3), in order to evaluate the extent to which thermal energy can be converted into an energy source to produce hot steam required by the steam turbine. Furthermore, the third Quality Indicator, namely the power to heat ratio in the gas turbine equilibrium (σ) can be calculated by formula (4). In addition, the fourth Quality Indicator, namely the fuel utilization ratio in the equilibrium chamber of the gas turbine (ω) which can be calculated by the formula (5) is used to evaluate the extent to which the energy from the fuel is effectively utilized in the equilibrium chamber of the gas turbine. The fifth Quality Indicator is the energy conversion efficiency that occurs in the equilibrium chamber of the steam turbine (η_TU) which can be calculated by the formula (6). The sixth, seventh & eighth Quality Indicator is the energy conversion efficiency in the motor and generator equilibrium (η_M) in the electrical power equilibrium (η_Pel), as well as in the entire CCGT (η_CCGT) which can be calculated by formulas (7), (8) & (9).

RESULTS AND DISCUSSION

Performance Evaluation Based on Quality Indicators

The analysis of the suitability of the results of the *evaluation of quality indicators* in the CCGT system will be explained comprehensively, including a comparison of simulation results and calculations based on the VDI 4661 standard (Swetha et al., 2023). In addition, a study was also carried out on the performance of the power generation system by identifying the main points of energy loss in the CCGT series. The results of the *quality indicator* calculation summarized in Table 2 show that gas turbines have a heat efficiency of 31 percent, while power efficiency reaches almost 39 percent. In addition, the fuel utilization ratio was recorded at 70 percent, with the power-to-heat ratio reaching 123 percent. Meanwhile, steam turbines show efficiencies close to 40 percent. Motors and generators have a fairly high-power conversion efficiency, with efficiency values of 98 percent and 96 percent, respectively, for gross and net electric power. Overall, the total efficiency obtained from the CCGT system reached around 48 percent, indicating that the plant was operating in quite optimal conditions. These results reflect a level of efficiency that is in line with industry standards, although there is still potential for improvement to optimize energy utilization in the system. Further analysis of the source of energy loss and optimization of operational parameters is a strategic step in improving the efficiency of the plant, both through design improvements, technological improvements, and the implementation of a more effective waste heat energy reuse system (Eboh et al., 2019).

Table 2. Quality Indicator Calculation Results

Quality Indicator	α	β	ω	σ	η	η_{CCGT}
			(%)			
Gas Turbine	31.39	38.74	70.13	123.4	70.13	-
Steam Turbine	-	-	-	-	39.59	-
Motor	-	-	-	-	98.53	-
Brutto & Netto Electric Power	-	-	-	-	96.03	-
CCGT						48,42

When compared to prior studies, the results confirm both expected efficiency levels and key areas for improvement. Bany Ata et al. (2021) reported a significantly higher thermal efficiency (91.28%) in an Integrated Gasification Combined Cycle (IGCC) system using Ebsilon Professional, with a steam turbine power increase of 34.2% under optimized conditions. The efficiency gap between IGCC and mid-capacity CCGT systems underscores the potential benefits of advanced gasification techniques and additional waste heat recovery methods (Subramanyam & Gorodetsky, 2017).

Similarly, Hassan and Manji (2023) validated a combined cycle simulation using DWSIM, reporting only a 0.45% deviation from empirical data. However, their study did not incorporate DIN-VDI 4661 quality indicators, limiting direct comparability with the present study. Additionally, Nannarone and Klein (2019) demonstrated a 32.5% reduction in startup time and a 47.0% decrease in fuel consumption in a MATLAB/Simulink-based simulation, emphasizing the potential for operational optimizations beyond steady-state efficiency.

While these studies highlight performance improvements through various modifications, most prior research focused on CCGT systems outside the 100–180 MW range. Furthermore, explicit adherence to DIN-VDI 4661 has been largely absent in existing literature, reducing the comparability of efficiency benchmarks. This study addresses these gaps by systematically integrating quality indicators aligned with standardized evaluation criteria.

Thermal and System Efficiency

The simulation of the 140 MW CCGT plant using Ebsilon®Professional yielded critical performance metrics aligned with DIN-VDI 4661 standards. The gas turbine exhibited a thermal efficiency of 31.39% and power efficiency of 38.74%, with a fuel utilization ratio of 70.13% and a power-to-heat ratio of 123.4%. The steam turbine demonstrated an energy conversion efficiency of 39.59%, while motor and generator efficiencies reached 98.53% and 96.03%, respectively. The total system efficiency stood at 48.42%, consistent with industry benchmarks for combined-cycle plants (Table 2). However, energy losses were substantial, totaling ~150,000 kW (52% of input energy), predominantly from the gas turbine (87,000 kW) and steam turbine (56,000 kW) (Figure 4). Heat transfer analysis in the HRSG (Figure 5) and condenser (Figure 6) revealed efficient thermal exchange but highlighted opportunities to reduce temperature differentials and improve material conductivity.

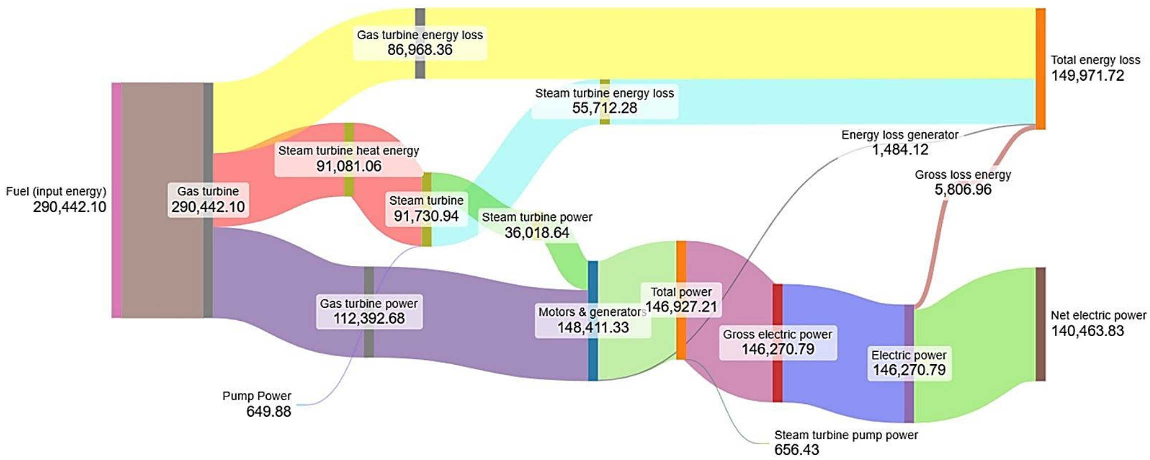

Figure 4. CCGT energy flow

Based on the Sankey diagram shown, the largest point of energy loss occurs in gas turbines, with a total loss of almost 87 thousand kilowatts. This loss contributes significantly to the overall efficiency of the system. Furthermore, the energy loss in steam turbines reaches less than 56 thousand kilowatts, indicating the potential for optimization in thermal energy utilization systems. In addition, there is an energy loss in the generator of less than 2 kilowatts which, although small compared to others, is still important to analyze to improve the efficiency of power conversion. Overall, the total energy loss of the system reached nearly 150 thousand kilowatts, almost reaching 52 percent of the input energy. This loss reduction can be achieved through turbine design optimization, waste heat reuse, and improved conversion efficiency in generators and heat transfer systems.

The gas turbine's thermal efficiency (31.39%) aligns with values reported for mid-capacity CCGT units in operational settings but lags behind studies focusing on advanced configurations. For instance, Bany Ata et al. (2021) achieved 91.28% thermal efficiency in an Integrated Gasification Combined Cycle (IGCC) plant using *Ebsilon® Professional*, though their focus on polygeneration (power and chemicals) and higher-capacity systems limits direct comparability. Similarly, Hassan and Manji (2023) reported a 0.45% deviation in power generation accuracy using DWSIM, underscoring the precision of simulation tools, but their study did not evaluate DIN-VDI 4661 metrics. The total system efficiency here (48.42%) falls within the typical range for CCGT plants (45–55%) cited in industry literature, validating the model's reliability.

1) Heat Transfer in the Steam Generating Heat Exchanger

The diagram shown in Figure 5 illustrates the distribution of heat transfer in a heat exchanger system, which occurs between the exhaust gas after leaving the gas turbine and the feed water which will be converted into water vapor as a steam turbine driving medium. The horizontal axis shows the amount of heat energy transferred in kilowatts, while the vertical axis shows the temperature in degrees Celsius. The two main curves in this diagram show the temperature profile of the exhaust gas on the hot side and the feed water on the cold side of the heat exchanger circuit. The red curve represents the exhaust gas that experiences a decrease in temperature along with the transfer of thermal energy to the feed water. In contrast, the blue curve depicts feed water experiencing an increase in temperature due to heat transfer from exhaust gases. There is a temperature difference between the two curves that reflects the temperature difference in the heat transfer process. This temperature difference value is very important to analyze the effectiveness of heat transfer and determine the log mean temperature difference (LMTD), which is a key parameter in the design of heat transfer systems (Castell & Solé, 2015). In the end, the heat energy that was successfully transferred in the heat exchanger circuit was worth more than 90 thousand kilowatts. This value can certainly be recognized in Figure 4 where the heat energy of the input steam turbine has a value of 91 thousand kilowatts. In energy generation systems, this heat transfer optimization plays a role in improving overall efficiency by reducing thermal energy loss. If the temperature difference is too large or the heat distribution is not optimal, inefficiencies can occur resulting in increased fuel consumption. By analyzing these diagrams, the design and optimization of heat exchanger systems can be carried out to improve the overall thermal efficiency, for example by increasing the heat transfer surface area or using materials with better thermal conductivity.

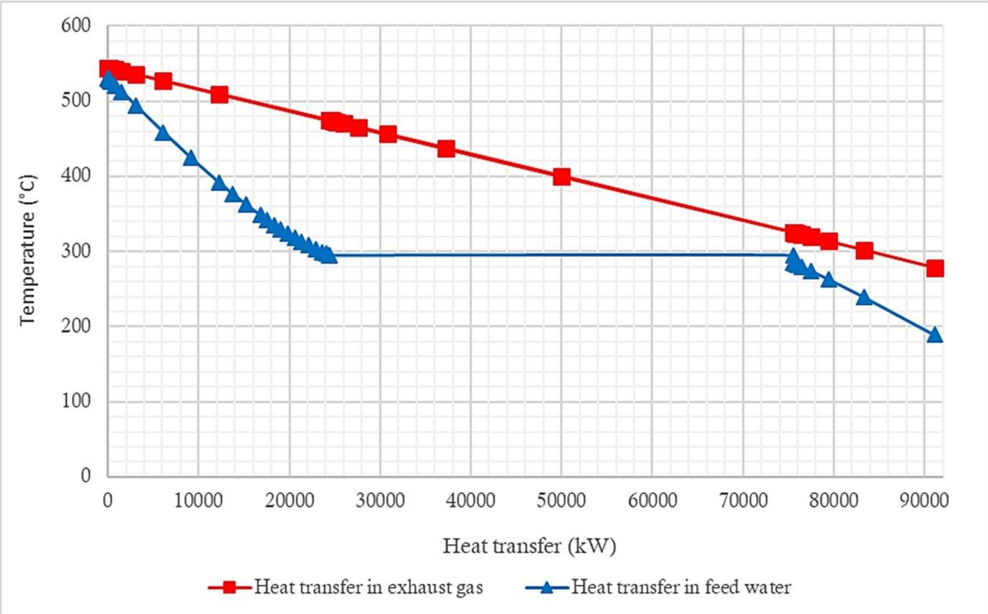

Figure 5. Amount of heat transfer in the steam generating heat exchanger

2) Heat Transfer in Condenser

Figure 6 is a representation of the heat transfer process in the condenser that occurs between the steam leaving the last level steam turbine and the water used as the cooling medium. After the heat transfer occurs, the water vapor that changes into water will be used as feed water which will be redistributed to evaporate. The horizontal axis shows the amount of heat energy transferred in kilowatts, while the vertical axis describes the change in temperature in degrees Celsius (Li et al., 2017). In this diagram, the two main curves depict the temperature profile of water vapor on the hot side and the cooling medium on the cold side of the condenser. A flat red curve indicates that a hot fluid (usually water vapor to be condensed) undergoes a phase change from gas to liquid at a relatively constant temperature. The phase change from gaseous to liquid occurs at a temperature of around 38 degrees Celsius. This is in accordance with the principle of condensation, where phase changes occur at a constant temperature as long as the pressure remains constant (Kato, 2011). Meanwhile, the blue curve shows the water-cooling medium experiencing an increase in temperature from 24 degrees Celsius to 30 degrees Celsius. This signifies that the heat energy from the hot fluid is transferred to the cold fluid to support the condensation process (Chen et al., 2022). In the end, the heat energy that was successfully transferred in the heat exchanger circuit was worth more than 50 thousand kilowatts. This value can certainly be recognized in Figure 4 where the energy loss of the steam turbine has a value of almost 56 thousand kilowatts. From this pattern, it can be concluded that the heat transfer in the condenser takes place efficiently, with a fairly small temperature difference between the hot and cold fluids. However, to further improve efficiency, several optimizations can be made, such as increasing the flow rate of cooling water, using materials with high thermal conductivity, and condenser designs that are able to maximize heat transfer area to reduce energy loss (Jowkar et al., 2019).

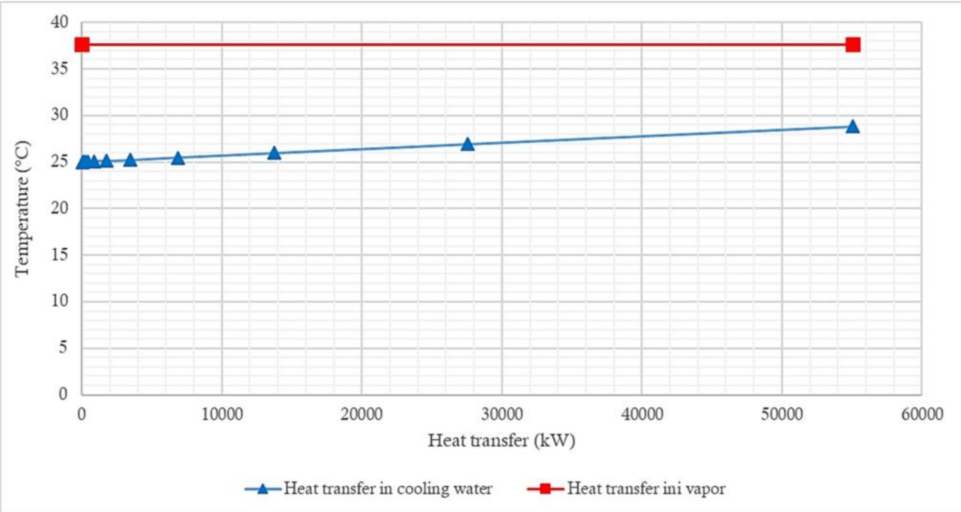

Figure 6. Amount of heat transfer in condenser

To reduce energy loss in the system, several solutions can be implemented (Liu et al., 2023). First, improving the efficiency of gas turbines through optimizing turbine blade design and applying high heat-resistant materials to reduce thermal energy loss. Second, the reuse of waste heat energy by implementing *a heat recovery steam generator* (HRSG) system, which can improve the overall efficiency of the plant. Third, increasing the efficiency of steam turbines through the optimization of steam pressure and temperature so that energy conversion is maximized. Fourth, loss reduction in generators with the use of high conductive materials as well as more effective cooling design. Finally, the optimization of the heat transfer system, such as the improvement of thermal insulation, to minimize unwanted heat dissipation and improve the overall efficiency of the energy generation system (Wu et al., 2021).

Energy Losses and Optimization Potential

The identified energy losses (52% of input energy) exceed those reported in studies prioritizing component-level optimizations. Nannarone and Klein (2019) achieved 32.5% reduction in cold-start time and 47% lower fuel consumption using MATLAB/Simulink, but their focus on transient operations precludes direct efficiency comparisons. Notably, Arakelyan et al. (2022) developed a digital twin for a 450 MW CCGT unit but omitted quantitative loss analysis, whereas this study provides granular insights into loss distribution (e.g., gas turbine losses 58%). The dominance of gas turbine losses mirrors findings by Bassily (2008), who attributed similar inefficiencies to suboptimal combustion and heat recovery, advocating for advanced HRSG designs.

CONCLUSION

This study has evaluated the operational efficiency of a 140 MW CCGT using a simulation approach based on Ebsilon®Professional software and referring to the VDI 4661 standard. From the analysis that has been carried out, it is found that the CCGT system shows a fairly good level of efficiency, although there is still room for optimization to improve the overall system performance (Ibrahim et al., 2017). Based on the results of simulations and quality indicator calculations, the heat efficiency in gas turbines was recorded at 31 percent, while the power efficiency reached almost 39 percent. The fuel utilization ratio shows a figure of 70 percent, with a power-to-heat ratio of 123 percent. On the other hand, steam turbines have an energy conversion efficiency of almost 40 percent, which shows that this system is quite capable of utilizing the thermal energy generated by gas turbines. Motors and generators have a fairly high power conversion efficiency, with efficiency values of 98 percent and 96 percent respectively for gross and net electrical power. Overall, the total efficiency of the CCGT system reaches around 48 percent, which is within the acceptable range for combined cycle-based generation technology. Although these results show relatively high efficiency, an in-depth analysis of the energy distribution in the system reveals that the greatest energy losses occur in gas turbines, with total losses reaching nearly 87,000 kW. Meanwhile, the energy loss in the steam turbine reaches less than 56,000 kW, and the generator experiences a smaller energy loss, which is about 2 kW. With a total energy loss of nearly 150,000 kW, or about 52% of the total energy input, this study indicates the need for further optimization strategies to improve overall system efficiency.

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