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Operational and Thermodynamic Methodology for Integrating a Gas–Steam Cycle Into a Legacy Coal-Fired Power Block

Original Scientific Article

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Abstract This paper investigates the thermodynamic integration of a gas–steam combined cycle into an existing coal-fired power block with the objective of reducing coal utilisation and associated emissions. In the baseline configuration, the legacy unit relies entirely on pulverised coal combustion, whereas the retrofit concept introduces a natural gas-fired gas turbine with heat recovery steam generation. The recovered exhaust heat is used to supplement steam production for the existing steam turbine train, thereby increasing the overall cycle efficiency and enabling partial fuel substitution. From an ecological perspective, natural gas presents a significantly lower carbon emission factor compared to coal, resulting in a proportional reduction of CO_2 and other greenhouse gas emissions at the system level. Additional benefits include lower NO_x formation due to cleaner combustion and improved operational flexibility, enabling more efficient load following under variable renewable penetration. The results suggest that such hybridisation offers a viable decarbonisation pathway for thermal assets by leveraging the existing infrastructure while achieving meaningful reductions in specific emissions.

Keywords
natural gas, power, recovery, steam, turbine

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The integration of a gas–steam combined cycle into a legacy coal-fired power block represents a transitional decarbonisation approach that combines thermodynamic efficiency gains with significant ecological benefits. In the retrofit concept, the existing coal boiler is removed fully and replaced by a gas turbine (GT), heat recovery steam generator (HRSG) that utilises the high-temperature GT exhaust gases from two independent gas–steam blocks. The original steam turbine and district heating (DH) station are retained to preserve both power production and cogeneration functionality. Each HRSG generates high-pressure (HP) steam at approximately 95 bar and 520 °C, and intermediate-pressure (IP) steam at approximately 9.5 bar and 250 °C, as well as heat for district heating [1]. The HP and IP steam streams are supplied to the existing extraction-condensing steam turbine (ST), while the turbine extractions provide IP and low-pressure steam for industrial uses and district heating. Figure 1 shows the principle of operation of the existing coal-fired boiler and the gas–steam combined cycle.

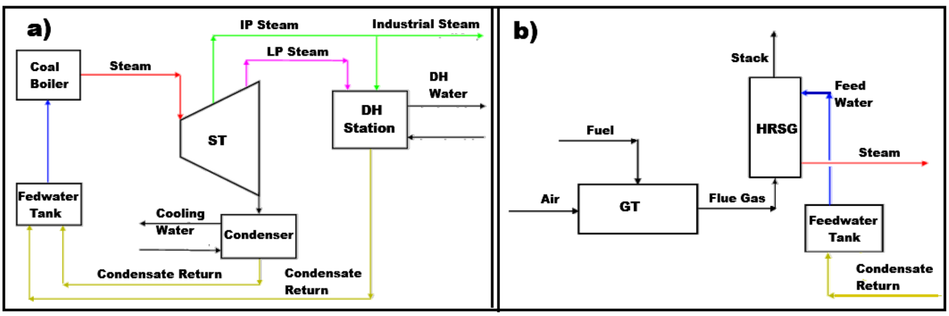

Figure 1: a) Principle of operation of: (a) the existing coal-fired boiler, and (b) the gas–steam combined cycle.

In the existing coal-fired boiler pulverised coal is combusted with air in the furnace to generate thermal energy. The released heat is transferred to the boiler heat-exchange surfaces, where the feedwater is converted into high-pressure steam. The HP steam is supplied to an ST, where a portion of the steam is extracted for DH station and industrial steam supply. The remaining steam expands further through the ST to the condenser, where it is condensed. The resulting condensate is then returned to the feedwater system. The flue gases pass through superheaters, economisers, and air preheaters before being discharged through the stack, while the ash and particulate matter are removed by appropriate gas-cleaning systems [2].

In the gas–steam combined cycle, natural gas is combusted in a GT, producing mechanical power and high-temperature exhaust gases. The exhaust heat is recovered in an HRSG, which generates HP and IP steam, as well as thermal energy for DH. The HP and IP steam are supplied to the existing steam turbine, where they expand to produce additional power. After expansion the steam is condensed, and the resulting condensate is returned to the feedwater tank via the condensate return line. By utilising the GT exhaust heat, the combined cycle increases overall plant efficiency and reduces specific fuel consumption significantly.

From an ecological perspective, the substitution of coal combustion with natural gas reduces specific CO_2 emissions and associated pollutants such as SO_2, particulates, and heavy metals significantly. Thermodynamically, the combined cycle configuration enhances exergy utilisation through heat recovery and multi-pressure steam generation, leading to increased overall efficiency and improved seasonal operation tied to the district heating demand. Collectively, the proposed hybridisation offers a viable pathway for reducing coal dependency, while extending the lifetime and functional value of the existing thermal assets. The operating principle of integrating two gas–steam combined-cycle units into the existing ST and DH system is shown in Fig. 2

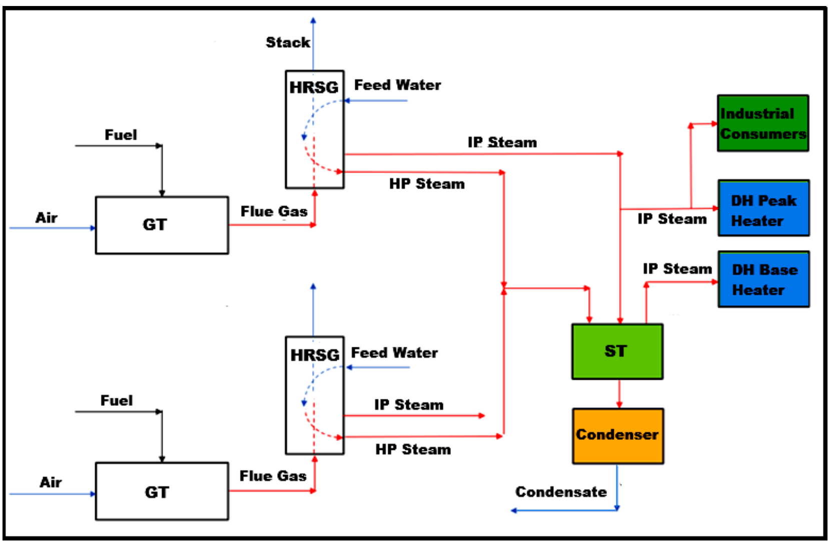

Figure 2: Operating principle of integrating two gas–steam combined-cycle units into the existing ST and DH system.

The proposed configuration consists of two independent gas–steam combined-cycle units connected to a single existing ST, which enables efficient utilisation of the existing infrastructure and reduces the overall investment costs. Each combined-cycle unit comprises a GT and an HRSG, Fig. 3. Natural gas is combusted in the GTs to generate electrical power, while the high-temperature exhaust gases are recovered in the HRSGs. The HP and IP steam generated in the HRSGs are supplied to the existing ST. The steam expands through the ST to produce additional electrical power, while controlled steam extractions are used for the DH and industrial steam supply, allowing a combined heat and power operation with high overall efficiency. The remaining steam expands to the condenser, where it is condensed, and the condensate is returned to the feedwater system.

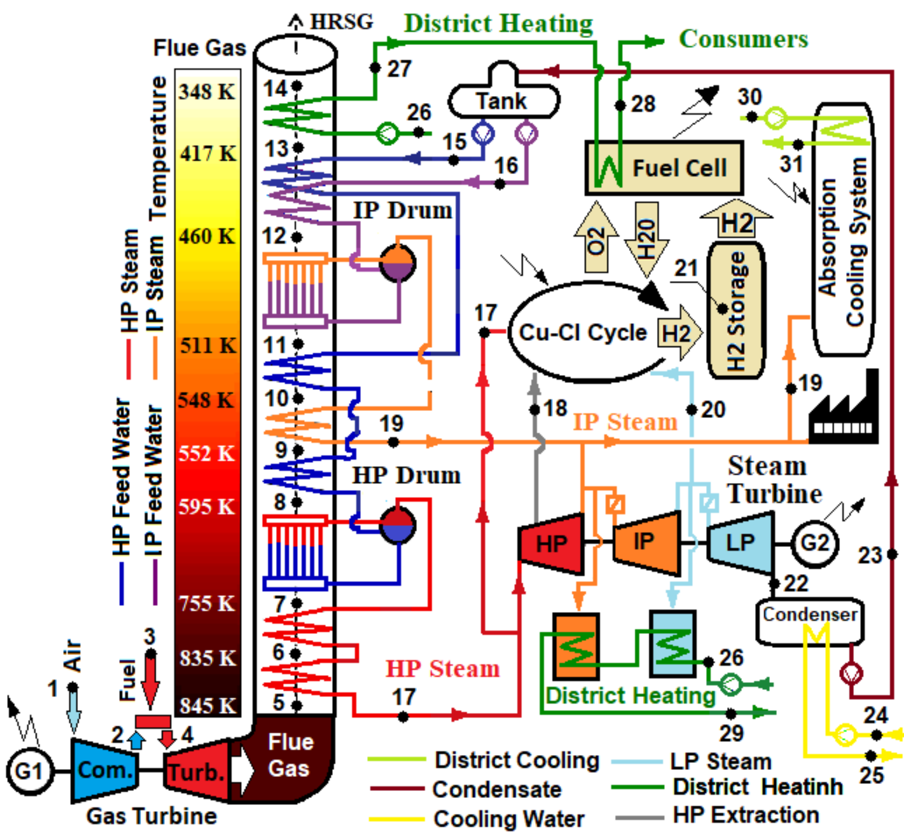

Figure 3: Configuration of independent gas–steam combined-cycle units connected to a existing ST [2]**.**

The independent operation of the two combined-cycle units provides high operational flexibility and availability, enabling stable electricity and heat supply under varying load conditions and during maintenance or partial outages. The integration of gas–steam cycles improves fuel utilisation, reduces specific CO_2 emissions, and enhances the overall efficiency of the energy system significantly. Despite its advantages, the proposed configuration introduces increased system complexity, particularly in steam system control and coordination between multiple HRSGs and the existing ST. Variations in the steam parameters may impose operational constraints on the turbine, while the use of natural gas increases the exposure to fuel price volatility and supply risks. In addition, the capital and maintenance costs are higher compared to a single combined-cycle configuration.

Fig. 4 illustrates an existing condensing ST configuration operated within a closed Rankine cycle and equipped with a surface condenser and four steam extraction points. During steady-state operation, high-pressure superheated steam expands through the turbine's high-, intermediate-, and low-pressure stages, thereby converting the steam enthalpy into mechanical shaft work. The exhausted wet steam is directed to the surface condenser, where condensation occurs under sub-atmospheric pressure conditions [3]. By maintaining a deep vacuum, the condenser increases the overall expansion ratio and enhances the cycle's thermodynamic efficiency. Simultaneously, the condenser provides the heat sink for phase change, and enables the recovery of condensate for subsequent pressurisation by the condensate and feedwater pump train, thus ensuring closed-loop mass continuity within the water–steam circuit.

The four-turbine extraction, Fig. 4, serves distinct thermal and process functions. The first two extractions supply steam for regenerative heating of the condensate and feedwater. The regenerative preheating reduces the temperature differential across the HRSG heat exchangers, thereby decreasing the exogenous heat input requirements and improving the overall thermal efficiency of the Rankine cycle. The third extraction originates from the IP section and supports primarily process-level heat integration within the plant's balance of system. The fourth extraction originates from the LP turbine section and is utilised for district heating of the adjacent urban network, supplying low- to medium-grade thermal energy suitable for space-heating applications. The integration of district heating increases the overall plant exergy utilisation otherwise rejected thermal energy and contributes to improved seasonal utilisation factors.

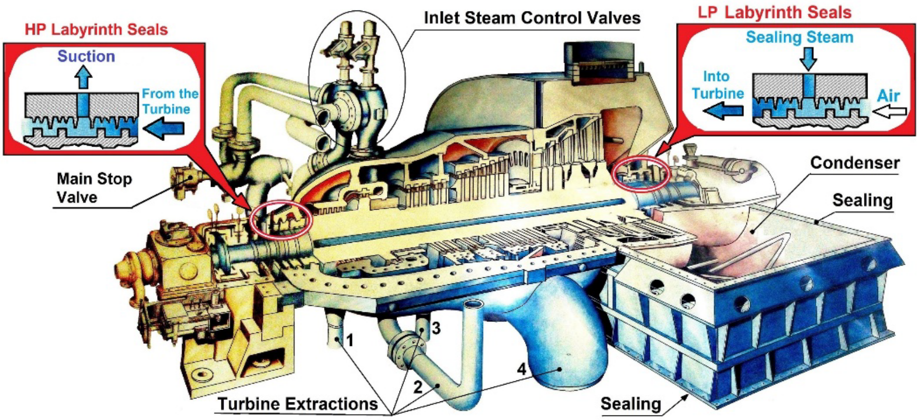

Figure 4: Existing condensing ST with condenser and four turbine extractions [4]**.**

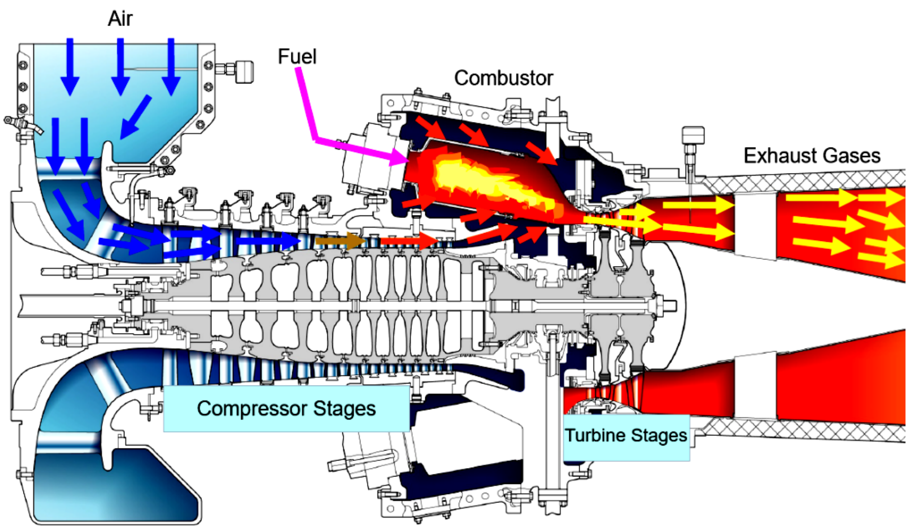

Figure 5: 5. Cross-section of the Siemens SGT-800 gas turbine [5]**.**

Fig. 5 illustrates the main components and operating principle of the Siemens SGT-800 industrial gas turbine, which is a single-shaft, high-efficiency Brayton-cycle unit intended for combined-cycle power generation, industrial cogeneration and district heating applications. The turbine integrates an axial compressor, combustor and multi-stage power turbine on a common shaft, enabling efficient conversion of chemical fuel energy into mechanical and electrical power while providing high-grade exhaust heat for downstream heat recovery in the HRSG.

Fig. 6 shows an HRSG cross-section of the layout of the HP and IP evaporator heat exchangers, the corresponding HP and IP steam drums, and the superheater bundles. Hot exhaust gases from the gas turbine pass sequentially through the heat-transfer surfaces, thereby enabling multi-pressure steam generation and superheating in the HRSG.

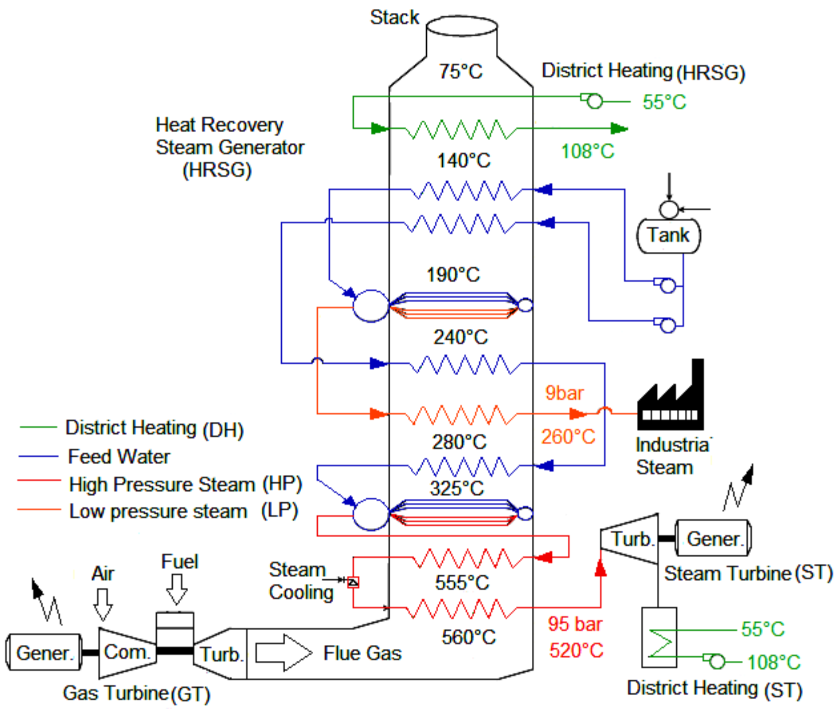

Figure 6: Cross-section of the HRSG and the flow direction of the hot GT exhaust gases [6]**.**

In the steam generation process, feedwater enters the HRSG at a pressure slightly above the final HP and IP steam pressures. Within the HP and IP evaporator sections, the water undergoes a phase change, forming a water–steam mixture which, subsequently, enters the respective HP and IP drums. In each drum, the water and steam are separated via natural circulation. The water is recirculated back to the evaporator tubes, while the dry saturated steam is directed to the HP and IP superheaters, where it is heated to the final fresh-steam temperature. The superheated HP and IP steam streams are then supplied from the HRSG to the existing ST for further expansion and power generation.

2 The thermodynamic methodology for integrating a gas–steam cycle into a legacy coal-fired power block

The proposed thermodynamic methodology for retrofitting a legacy coal-fired power block with a gas–steam combined arrangement is based on the integration of a Brayton cycle gas turbine subsystem with the existing Rankine cycle steam turbine. Such integration enables the utilisation of high-temperature heat from the gas turbine exhaust to augment the steam production and improve the overall thermal efficiency of the plant without extensive modification of the installed steam cycle infrastructure. This approach is particularly suitable for coal-fired units with a sufficient steam path margin and appropriate mechanical design allowances for elevated steam mass flows and temperatures.

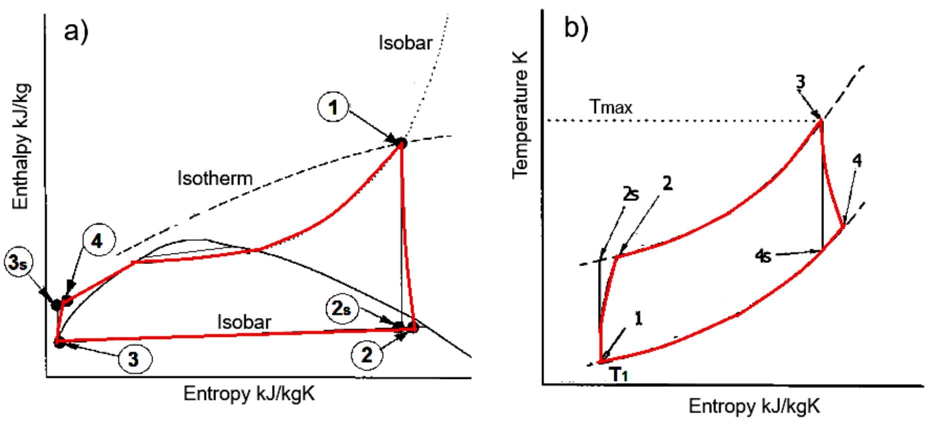

Figure 7: Thermodynamic diagrams of a) the Rankine cycle, and b) the Brayton cycle.

From a thermodynamic perspective, the combined configuration exploits the complementary characteristics of the Brayton and Rankine cycles. The Brayton cycle consists of the compression of ambient air in a gas compressor, followed by constant-pressure fuel combustion within a combustor, and subsequent expansion of the high-temperature gases in a GT. The relatively high turbine outlet temperature (typically exceeding 773–873 K) provides a viable source of thermal energy for an HRSG. A schematic representation of the thermodynamic diagrams for both the Brayton and Rankine cycles, including their principal processes and state points, is provided in Fig. 7.

The thermodynamic assessment of replacing a conventional coal-fired boiler–ST system with a gas–steam combined cycle requires explicit consideration of the energy and exergy balances, combustion thermochemistry, heat recovery and steam cycle integration. The formulations of the energy, First Law, and exergy, Second Law, balances serve as the fundamental thermodynamic framework for evaluating system performance and assessing the irreversibilities within the integrated gas–steam retrofit configuration. For the energy balance, the First Law, the steady-state formulation is [7]:

$$\dot{Q} - \dot{w} = \sum \dot{m}_i \cdot \left(h_i + \frac{v_i^2}{2} + g \cdot z_i\right)_{in} - \sum \dot{m}_e \cdot \left(h_e + \frac{v_e^2}{2} + g \cdot z_e\right)_{out} \quad (1)$$

where $\dot{Q}_{cv}$ is the heat transfer rate, $\dot{w}$ is the work transfer rate, $\dot{m}_i$ is the inlet mass flow rate, h_i is the inlet specific enthalpy, v_i is the inlet specific velocity, g is the gravitational acceleration, z_i is the inlet elevation (potential term), $\dot{m}_e$ is the outlet mass flow rate, h_e is the outlet specific enthalpy, v_e is the outlet specific velocity, and z_e is the outlet elevation, potential term. For HRSG comparison, the kinetic and potential terms are negligible, yielding [8]:

$$\dot{Q}_{fuel} - \dot{w} = \dot{m}_{steam} \cdot (h_{out} - h_{in}) \quad (2)$$

where $\dot{Q}_{fuel}$ is the fuel heat input, $\dot{m}_{steam}$ is the steam mass flow, h_{out} is the steam specific enthalpy from the HRSG, and h_{in} is the HRSG feedwater specific enthalpy. The Brayton cycle performance is calculated as [9]:

- Compressor work: $w_c = c_a \cdot (T_2 - T_1)$, (3)
- Turbine work: $w_t = c_f \cdot (T_3 - T_4)$ and (4)
- Net specific work: $w_{GT} = w_t - w_c$ (5)

where w_c is the specific work input to the compressor, c_a is the specific heat of air, T_2 is the compressor outlet temperature, T_1 is the compressor inlet temperature, w_t is the specific work produced by the GT, c_f is the specific heat of the flue gases, T_3 is the turbine inlet temperature, T_4 is the turbine exit temperature and w_{GT} is the net specific work of the GT.

The Steam Cycle (Rankine) and Multi-Pressure Integration. Steam generated in the HRSG replace the coal boiler output. For the HP and IP steam stages, the ST work output is calculated as [10]:

$$\dot{w}_{ST} = \sum\left(\dot{m}_{HP} \cdot (h_{HP} - h_{IP}) + \dot{m}_{IP} \cdot (h_{IP} - h_{ex})\right) \cdot \eta_{ST} \tag{6}$$

where $\dot{w}_{ST}$ is the ST work produced, $\dot{m}_{HP}$ is the HP steam mass flow, h_{HP} is the HP steam specific enthalpy, h_{IP} is the IP steam specific enthalpy, $\dot{m}_{IP}$ is the IP steam nass flow, h_{ex} is the exhaust steam specific enthalpy and η_{ST} is the ST efficiency. The heat removed from ST extractions for DH and industrial steam is calculated as [11]:

$$\dot{Q}_{DH} = (h_{IP} - h_{conden}) + (h_{LP} - h_{conden}) \tag{7}$$

$$\dot{Q}_{IS} = (h_{IP} - h_{conden}) \tag{8}$$

where $\dot{Q}_{DH}$ is the heat supplied to the DH system, h_{conden} is the condensate specific enthalpy, h_{LP} is the LP steam specific enthalpy and $\dot{Q}_{IS}$ is the heat supplied for industrial purposes. The HRSG Energy balance is calculated as [12]:

$$\dot{m}_{GT} \cdot c_f = \left(T_{ex,GT} - T_{stack}\right) = \sum \dot{m}_{steam} \cdot (h_{out} - h_{in}) \tag{9}$$

where $\dot{m}_{GT}$ is the mass flow rate of the GT exhaust gases, $T_{ex,GT}$ is the temperature of the GT exhaust entering the HRSG, T_{stack} is the temperature of the flue gas leaving the HRSG. The Exergy (Second Law) Considerations, the exergy destruction, which quantifies the irreversibilities in the system, is calculated as follows [13]:

$$\dot{E}_D = T_0 \cdot \dot{S}_{gen} \tag{10}$$

where $\dot{E}_D$ is the rate of exergy destruction, T_0 is the ambient or reference temperature and $\dot{S}_{gen}$ is the rate of entropy generation. The overall combined-cycle efficiency, accounting for both gas and steam contributions, is calculated as follows [13]:

$$\eta_{cc} = \frac{\dot{w}_{GT}+\dot{w}_{ST}}{\dot{m}_{fuel} \cdot LHV_{NG}} \tag{11}$$

where η_{cc} is the overall efficiency of the combined cycle and LHV_{NG} is the lower heating value of the fuel.

3 Results

The results are presented in the Figures below and are derived from the high-resolution operational data obtained from the plant's Supervisory Control and Data Acquisition (SCADA) system [14]. SCADA is an industrial control system used for real-time monitoring, control and data collection from processes and equipment. It acquires operational signals such as temperature, pressure, flow rates, and electrical power continuously, enabling process supervision, automated or remote control, data archiving and visualisation through Human-Machine Interfaces (HMIs). SCADA also provides alarms and notifications for abnormal conditions, supporting safe and efficient plant operation.

The SCADA infrastructure acquires and archives real-time process variables continuously (24/7/365), including the electrical power output, thermal loads, turbine control parameters and auxiliary system signals. This continuous data acquisition enables detailed performance assessment, transient analysis, and reliable validation of both thermodynamic and operational models.

The presentation of the results is based on the operation period of November 2025 and is organised sequentially. Under nominal conditions, the two GTs units exhibit similar load-following behaviour and operate in parallel within a comparable dispatch band. Deviations from parallel operation are associated primarily with abnormal or fault-induced conditions. In such cases, manual operator interventions are often required to reduce the GT load to maintain system integrity, prevent protection trips and preserve the turbine component lifetime. These deviations are clearly observable in the SCADA data as abrupt changes in electrical output, modified control setpoints and altered GT–ST interaction dynamics.

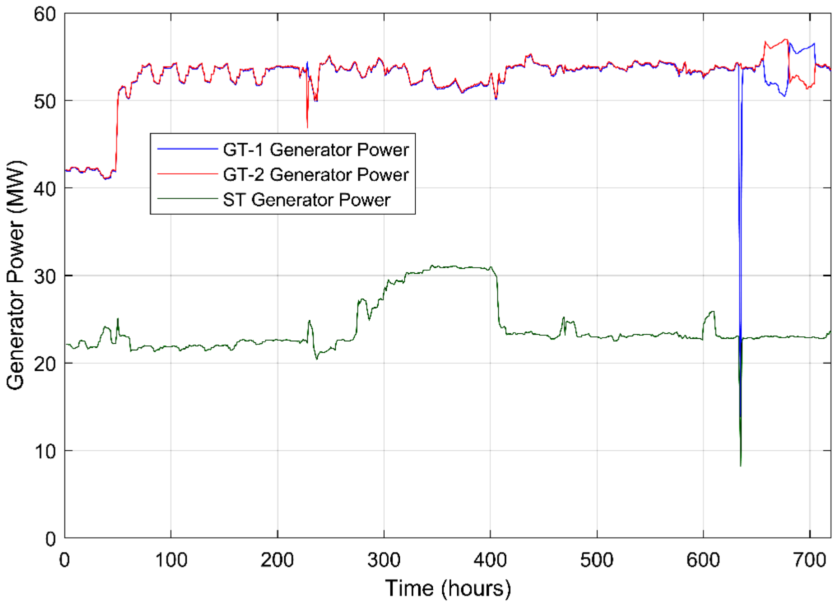

Figure 8: Electric power output of combined-cycle generators.

Fig. 8 shows the electric power generated by the GT-1, GT-2 and ST generators. During the analysed period the average power output of each gas turbine generator was approximately 54 MW, while the steam turbine generator produced around 22 MW. The Figure highlights the correlation between the ST power output and the combined output of both GTs, as all the steam generated in the HRSGs is directed to the ST. A minor temporal deviation in the response of the ST relative to the GTs can be observed, reflecting the slight delay between the changes in GT power and the resulting adjustment in the ST output.

Figure 9 shows the natural gas consumption of the combined-cycle generators, which serves as the primary fuel for plant operation. As an alternative, fuel oil may be used, or a dedicated system can inject up to 45% hydrogen into the natural gas supply. The gas consumption is expressed in normal cubic metres per hour (Nm^3/h). During the analysed period, a single GT consumed on average approximately 12500

Nm^3/h, resulting in a total average consumption of around 25000 Nm^3/h for both GTs. The natural gas is delivered through the pipeline network at a pressure of 33 bar.

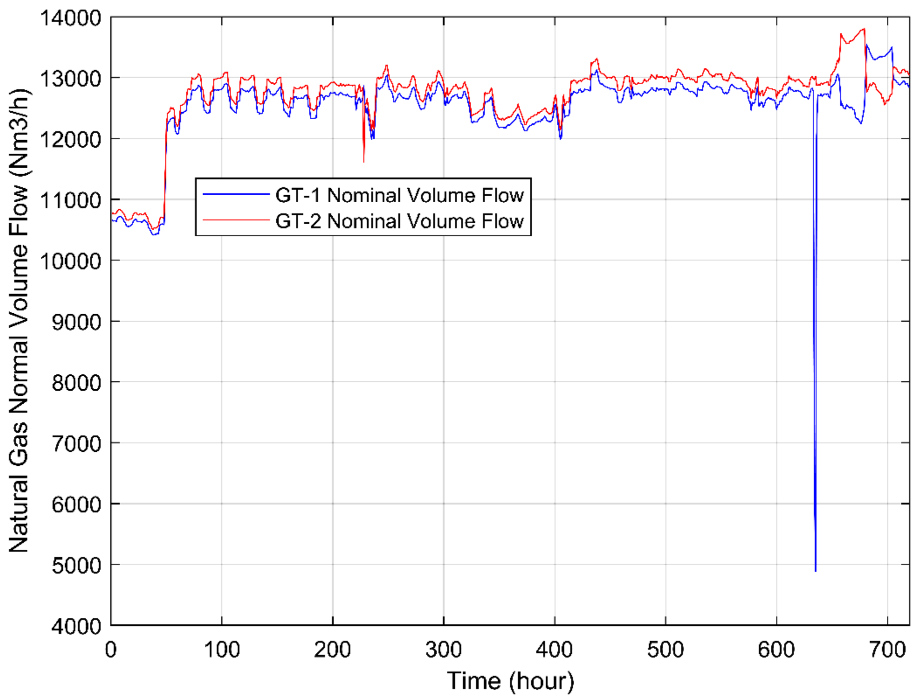

Figure 9: Natural gas consumption of combined-cycle generators.

The hot exhaust gases entering the HRSGs transfer thermal energy to the water. The mass flow rate of steam from the heat HRSGs represents the water that is evaporated and superheated within the HRSG heat exchangers, leaving the HRSGs as superheated steam. During the operation of a single GT, as shown in Fig. 8, one HRSG generates on average approximately 17 kg/s of HP steam at 90 bar and 520 °C, and about 3 kg/s of IP steam at 8,5 bar and 250 °C. The combined output from both HRSGs amounts to roughly 34 kg/s of HP steam and 6 kg/s of IP steam. The mass flow rates of steam from the HRSGs are shown in Fig. 10.

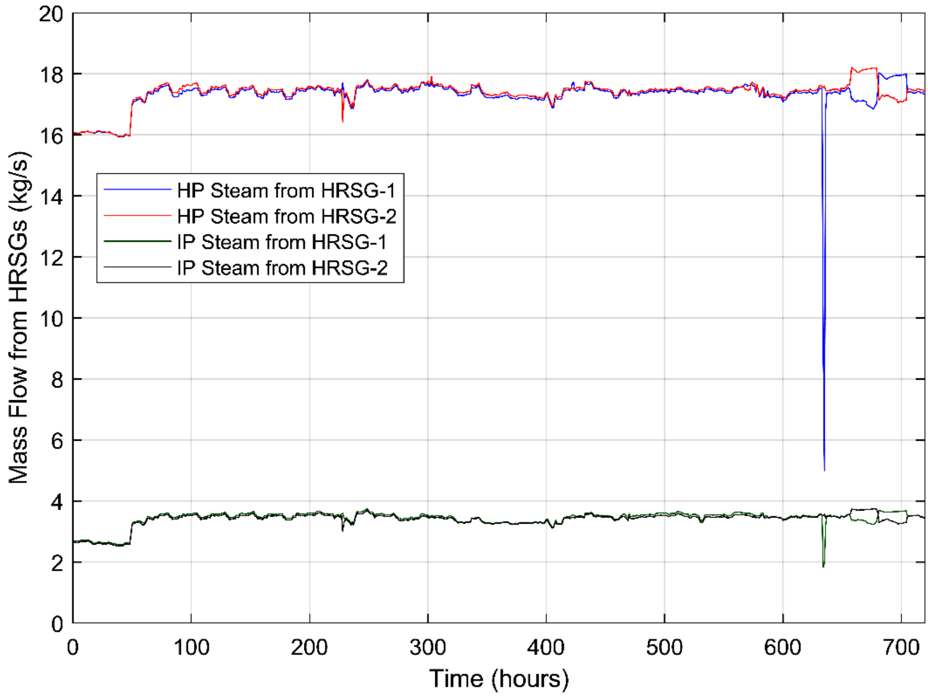

Figure 10: Mass flow rates of steam from the HRSGs.

This steam is directed to the ST, where it is converted into electrical energy at the generator, thermal energy for the district heating system and steam for industrial processes. Variations in the GT load influence the steam mass flow from the HRSGs directly, with a minor temporal delay due to the dynamics of water evaporation and superheating. These interactions are consistent with the Rankine cycle operation of the ST, highlighting the coupling between GT operation, HRSG steam generation and ST performance.

Fig. 11 presents the thermal energy supplied for a DH system and industrial purposes from the combined-cycle plant. During the analysed period, the average heat delivered to the DH network was approximately 85 MW, while the heat supplied for industrial applications averaged around 16 MW. These values reflect the distribution of steam extracted from the ST, and illustrate the combined-cycle plant's capability to provide both electrical and thermal energy, highlighting its role in the cogeneration and efficient utilisation of fuel energy.

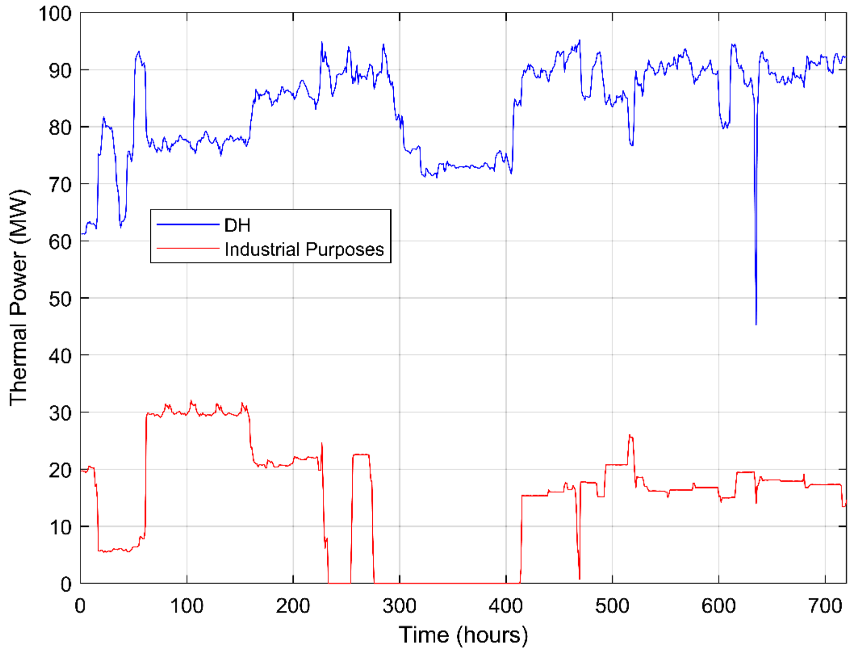

Figure 11: Heat supplied for district heating and industrial purposes from the combined-cycle plant.

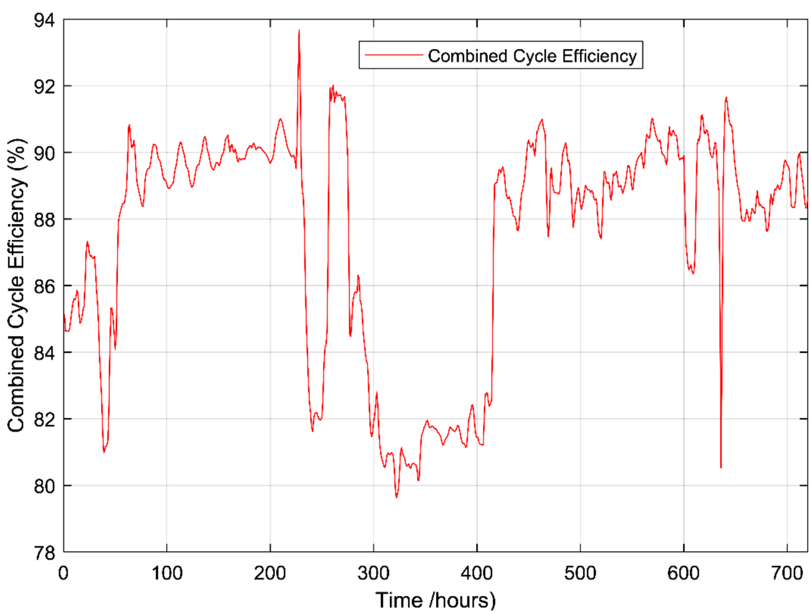

Figure 12: Combined-cycle plant efficiency.

Fig. 12 illustrates the thermodynamic efficiency of the combined-cycle plant, which ranged from 80% to 93% during the analysed period. The average efficiency over this period was approximately 87%.

The calculated results demonstrate that the combined-cycle plant operating in cogeneration mode achieves high thermodynamic efficiency, while, simultaneously, contributing to the reduction of greenhouse gas emissions. This represents a key advantage of such processes, highlighting both their energy and environmental benefits.

3 Conclusion

This study analysed the operational performance of a combined-cycle cogeneration plant retrofitted into an existing coal-fired power block, using high-resolution SCADA data collected during November 2025. The retrofit introduces a natural gas-fired GTs coupled with heat recovery steam generators HRSGs, while leveraging the existing steam turbine ST. The investigation focused on power generation, fuel consumption, steam mass flows, thermal energy delivery for district heating and industrial purposes, and overall thermodynamic efficiency.

The results indicate that both GTs units operated in parallel with similar load-following behaviour, producing on average 54 MW per unit, while the ST generated around 22 MW. The ST output followed the combined GT output closely, with minor temporal deviations due to the steam production dynamics. The natural gas consumption aligned directly with the GT load variations, averaging 12500 Nm^3/h per GT and 25000 Nm^3/h for both, delivered at a pipeline pressure of 33 bar.

The HRSGs convert exhausted heat into HP and IP steam efficiently, with combined mass flow rates of 34 kg/s of HP steam and 6 kg/s of IP steam. This steam supports electricity generation, approximately 22 MW, district heating, approximately 85 MW on average, and industrial applications, approximately 16 MW on average, demonstrating the plant's cogeneration performance and effective utilisation of recovered energy.

The thermodynamic efficiency of the combined-cycle system ranged from 80% to 93%, averaging 87%. These high efficiencies underscore the benefits of cogeneration, including optimised fuel utilisation and reduced greenhouse gas emissions. By substituting coal partially with natural gas, the retrofit achieved a meaningful reduction in CO_2 and NO_x emissions, while maintaining the operational flexibility and reliable load-following capability.

Overall, the study confirms that retrofitting a coal-fired block with a gas–steam combined cycle represents a feasible decarbonisation strategy. It leverages the existing infrastructure to achieve high energy efficiency, reduce fuel consumption and minimise the environmental impact, while maintaining a reliable power and heat supply. Future work may focus on advanced operational optimisation, predictive maintenance, and integration with variable renewable energy sources to enhance the performance, flexibility and sustainability of hybrid thermal assets further.

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[14] SCADA system-TE-TOL Ljubljana.

Povzetek v slovenskem jeziku

Operativna in termodinamična integracija kombiniranega plinsko-parnega cikla v obstoječi premogovni blok. Ta prispevek preučuje termodinamsko integracijo kombiniranega plinsko-parnega cikla v obstoječi blok na premog z namenom zmanjšanja porabe premoga in povezanih emisij. V osnovni konfiguraciji obstoječa enota popolnoma temelji na zgorevanju mletega premoga, medtem ko retrofitna zasnova uvaja plinsko turbino na zrmrljski plin z rekuperatorjem pare. Izpušna toplota iz plinske turbine se uporablja za proizvodnjo pare za obstoječo parno turbinno, s čimer se poveča skupna učinkovitost cikla. Z ekološkega vidika zemeljski plin predstavlja bistveno nižji dejavnik emisij ogljika v primerjavi s premogom, kar povzroča sorazmeren upad emisij CO_2 in drugih toplogrednih plinov na ravni sistema. Dodatne prednosti vključujejo manjšo tvorbo NO_x zaradi čistejšega zgorevanja in izboljšano operativno fleksibilnost, kar omogoča učinkovitejše prilagajanje obremenitve ob spremenljivi integraciji obnovljivih virov. Rezultati nakazujejo, da takšna hibridizacija ponuja izvedljivo pot do dekarbonizacije termalnih virov z izkoriščanjem obstoječe infrastrukture, hkrati pa dosega pomembno zmanjšanje specifičnih emisij.