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HTGR-Based Industrial Heat Retrofit: Feasibility Assessment for Steam Cracking and RWGS

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1. Introduction

Achieving a carbon-neutral economy presents an unavoidable challenge in the industrial sector, which accounts for ~23% of global energy-related carbon dioxide (CO_2) emissions [1]. This sector is widely recognized as "hard-to-abate" due to its requirement for large-scale, high-temperature heat, which is currently provided predominantly by the combustion of fossil fuels. While low-carbon alternatives are being explored, they often struggle with technology readiness and cost competitiveness. In this context, the high-temperature gas-cooled reactor (HTGR) emerges as a practical solution, capable of providing a stable, high-temperature supply of heat [2].

The HTGR is a helium-cooled, graphite-moderated reactor concept using ceramic fuels, such as TRISO-coated fuel particles. These reactors typically produce outlet temperatures of 750–950°C, expanding the range of low-carbon nuclear heat applications beyond conventional power generation. Compared with light water reactors, HTGR offers distinct advantages for industrial decarbonization through inherent safety characteristics, enabled by TRISO fuel and a high-capacity graphite core. These features enable the passive removal of decay heat without operator intervention or an external power supply. Such enhanced safety allows for the collocation of reactors near industrial sites to minimize heat transport losses. HTGRs are thus ideal for retrofit "plug-in applications," replacing fossil-fired boilers by utilizing existing steam networks with relatively small engineering modifications [2].

Despite this potential, HTGR has not yet been demonstrated in large-scale industrial process heat applications, and uncertainties remain in process compatibility and techno-economic for deployment. This study aims to bridge this gap by providing a thermodynamic and energy analyses of HTGR-based retrofitting for two key processes: Reverse Water Gas Shift (RWGS) and Steam Cracking. By evaluating these processes in terms of required temperature levels and heat quantity, this paper quantifies the sensitivity to HTGR heat-supply conditions and assesses their potential to contribute to decarbonization in the industrial sector.

2. Methodology

This study evaluates HTGR-based heat integration for two representative high-temperature processes; steam cracking and reverse water gas shift (RWGS). For each process, (1) the baseline process configuration is summarized and the heat-integration point is identified using a schematic from the literature, (2) HTGR coupling is justified by documenting temperature/operability sensitivity reported in prior studies, (3) a required temperature level is estimated using a first-order calculation with literature cross checks, and (4) a plant-relevant total heat duty is quantified using literature-reported specific heat requirements and reference plant capacities. The resulting temperature and heat-duty benchmarks are then used to discuss feasible staged heat supply from HTGR.

3. Thermal Requirements of Steam Cracking for HTGR Coupling

3.1. Steam Cracking Process Overview

Steam cracking is the most widely used technology for producing light olefins (e.g., ethylene and propylene), which are key building blocks for polymers and related petrochemical products [3]. In a steam-cracking furnace, hydrocarbon feed is mixed with diluted steam and preheated in the convection section (typically 500–680°C) and then sent to the radiant section (firebox), where highly endothermic gas-phase pyrolysis proceeds in radiant coils, heating the stream to ~850°C within short residence time. To suppress secondary reactions, the effluent is quenched in a transfer line exchanger (TLE), cooling rapidly to 400–500°C. The configuration is illustrated in Figure 1.

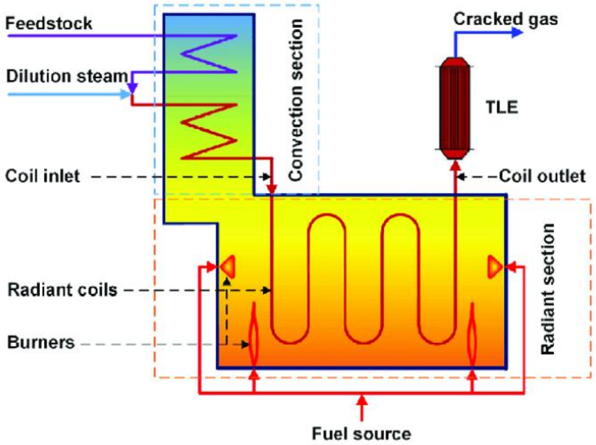

Figure 1. Schematic diagram of steam cracking furnace [4]

3.2. Temperature sensitivity and HTGR coupling Rationale

Steam cracking is highly sensitive to temperature level, particularly the coil outlet temperature (COT). Increasing COT from 830 to 845°C raises the ethylene yield (30 →35%) but also accelerates coke formation (7→23%), indicating a trade-off between yield improvement and run-length deterioration [3]. Modern short-residence-time (SRT) coils operate with residence times of 0.08–0.25s, and reported designs (τ ≈ 0.22s, q>100kW/m²) require intense heat transfer to achieve the target temperature within a short contact time [5]. Together, these features indicate that an HTGR-based heat supply, which can deliver steady high-temperature heat, is well suited to support high temperature steam cracking under short-residence conditions while limiting performance penalties caused by temperature fluctuations.

3.3. Calculation of Required Temperature

Steam cracking is commonly described as a free-radical chain process, where initial radicals generated during pyrolysis repeatedly drive propagation reactions and are ultimately removed via termination. Since the initial step is largely associated with C-C bond scission, representative bond dissociation energies (345kJ/mol) provide an approximate energy metric for high-severity operation.

As an intuitive thermodynamic lower bound, a representative dehydrogenation/cracking reaction ($C_2H_6 \rightarrow C_2H_4 + H_2$) can be considered with $\Delta G(T) = \Delta H - T\Delta S$. Setting $\Delta G = 0$ yields $T = \Delta H/\Delta S$, giving $T \approx 1136$ K (≈863°C) under standard-state assumptions. This temperature is interpreted only as a lower-bound indicator rather than a design setpoint. The bond energies should not be directly converted into the process heat duty. Instead, as industrial steam cracking must reach meaningful conversion within a short residence time, the required temperature is more appropriately obtained from kinetics by back-calculating the rate constant needed to achieve a target conversion over the available residence time.

Following the Rice–Herzfeld treatment, ethane decomposition can be modeled using first-order kinetics with an activation energy of 73 kcal/mol (Marek and McClure) [6]. The rate constant is correlated as:

$$(1)\ \log k = 13.7 - \frac{73{,}000}{2.303RT} \qquad (2)\ \log k = 15.12 - \frac{73{,}000}{2.303RT}$$

Based on this first-order model, a target conversion X over a residence time τ implies a required rate constant k, which increases as τ decreases for fixed X.

$$(3)\ \frac{dC}{dt} = -kC \qquad (4)\ k_{req} = \frac{-\ln(1-X)}{\tau}$$

Substituting k into the empirical correlation and solving for T yields Eq. (5).

$$(5)\ T = \frac{73{,}000}{2.303R\left(15.12 - log_{10}\left(k_{req}\right)\right)}$$

As summarized in Table 1, for X=0.6 the calculated Temperature increases from ~802°C to ~855°C as τ decreases from 0.50s to 0.10s, quantitatively illustrating why high-temperature operation is required under short-residence steam cracking.

Table 1: Required Operating Temperature for X = 0.6 [7]

τ (s)	k_{req} (s^{-})	T (°**C**)
0.50	1.83	≈ 802
0.22	4.17	≈ 828
0.10	9.16	≈ 855

3.4. Total Heat-Demand Scaling

The total thermal input was estimated based on the reported specific heat demand of 60 GJ per ton of high-value chemicals (HVCs) [3]. The specific heat demand of 60 GJ/t is converted to 16.7 MW per 1t/h of HVC. Utilizing a representative plant-scale case with a naphtha feed rate (36.0 t/h) and defining HVC as the sum of ethylene, propylene, and 1,3-butadiene, a total thermal requirement of approximately 307 MW is calculated [8]. The process is as follows:

$$Q_{req} = 16.7MW/(t/h) \times 36.0t/h \times d \\ \times (0.2796 + 0.1751 + 0.057).$$

Table 2: Scoping inputs for convection/radiant sensible duties (per 1kg-feed) [10]

Item	Symbol	Value	Unit
Steam-to-feed ratio	*S/F*	0.30	Kg/kg
Feed specific heat	$C_{p,f}$	2.8	kJ/kg·K
Steam specific heat	$C_{p,s}$	2.3	kJ/kg·K
Cracked-gas specific heat	$C_{p,cg}$	2.5	kJ/kg·K
Convection inlet	T_{in}	150	°C
Radiant inlet	T_{XOT}	540	°C
Coil outlet	T_{COT}	855	°C

Realistic HTGR integration requires resolving where this total thermal requirement occurs across the furnace. Accordingly, the steam-cracking furnace is decomposed into: (1) feed sensible heating, (2) the endothermic heat of cracking, and (3) gas-phase sensible heating from the radiant-coil inlet temperature (XOT) to COT. Component (1) is supplied in the convection section, whereas (2)–(3) are supplied in the radiant section. Using the scoping inputs in Table 2 and setting, the convection preheating duty (150→540 °C) is:1

$$q_1 = (C_{p,f} + (\mathrm{S/F})\, C_{p,s})\,(T_{XOT} - T_{in}) = 1{,}361\ \mathrm{kJ/kg - feed}$$

And the radiant sensible increment (540→855 °C) is:

$$q_2 = (C_{p,cg} + (\mathrm{S/F})\, C_{p,s})\,(T_{COT} - T_{XOT}) = 1{,}005\ \mathrm{kJ/kg - feed}$$

As shown by the results, *q1* itself is substantial, even though *q2* represents only the radiant-section sensible heating and does not include the endothermic heat of cracking. This supports a feasible near-term retrofit strategy in which HTGR is prioritized for stable, continuous preheating, while the remaining heat requirement to reach the target COT is provided by an additional topping heat source.

Beyond this near-term integration, long-term options may enable the direct supply of high-grade industrial heat. The HTTR provides a credible basis, as it is designed to transfer 10 MWth to secondary helium at 905 °C and 4.1 MPa through an intermediate heat exchanger (IHX) [11]. Building on this foundation, a matured VHTGR concept–targeting core outlet temperatures above 950 °C and delivering >900 °C helium for industrial processes–could feasibly meet the high-temperature heat demand of steam cracking. The same high-temperature heat-supply pathway also extends to other endothermic processes considered in this study, including RWGS.

4. Thermal Requirements of RWGS for HTGR Coupling

4.1. RWGS Process Overview

Reverse Water Gas Shift (RWGS) is an upstream process that converts CO_2 to CO to secure and tune the carbon form in syngas, thereby supplying a tailored feedstock for downstream synthesis routes [11]. This process is exemplified by Power-to-Fuel pathways with downstream synthesis units such as methanol production and methanation, highlighting the versatility of RWGS.

The operational sequence of the RWGS process can be summarized into three integrated stages: (1) feedstock preparation, where captured CO_2 and electrolytic H_2 are mixed to a specific target H_2/CO_2 ratio; (2) thermal conversion, in which the mixture is preheated using heat exchangers and processed through a high-temperature RWGS reactor to drive the endothermic conversion of CO_2 into CO; and (3) purification and routing, where the effluent is cooled for heat recovery, water is condensed and removed (knock-out), and the refined syngas is sent to downstream synthesis units, according to the desired product composition. The integrated operational sequence of the RWGS process described above is illustrated in Figure 2.

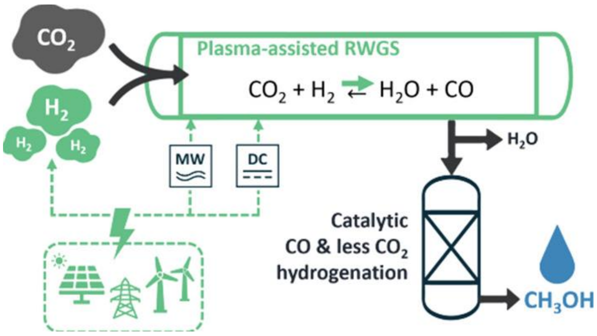

Figure 2. Schematic of the RWGS process [12]

4.2. Heat-Demand sensitivity and HTGR coupling Rationale

The RWGS process faces a counterintuitive heat demand; while it requires high temperatures, any reduction in operating temperature can penalize the system by promoting methane formation and increasing recycle throughput, ultimately elevating the net reheating duty [13]. This behavior favors coupling RWGS with a continuous, stable high-temperature heat source to improve operational robustness.

4.3. Thermodynamic benchmark temperature(ΔG=0)

RWGS can be represented by the equilibrium reaction $CO_2 + H_2 \rightleftharpoons CO + H_2O$. The CAMERE study reports that this reaction is endothermic with $\Delta H^{\circ} \approx +41.12$ kJ/mol [14]. To quantify, at a back-of-the-envelope level, the qualitative trend that higher temperature favors CO formation, a standard-state approximation is adopted:

$$(6) \quad \Delta G^{\circ}(T) \approx \Delta H^{\circ} - T\Delta S^{\circ}$$

A benchmark boundary temperature is defined by $\Delta G^{\circ} = 0, T_{bench} = \Delta\dot{H}/\Delta\dot{S}$. Using Standard molar entropies at 1 bar suggested in Table 3:

$$\Delta S^{\circ} = (197.660 + 188.835) - (213.785 + 130.680)$$
$$= 42.03\ J/mol \cdot K. \qquad \text{With } \Delta H^{\circ} \approx +41.12 \text{ kJ/mol,}$$

The benchmark temperature becomes T = 41.12 x 10^3 / 42.03 ≈ 979 K (≈ 706°C).

Table 3: Standard molar entropies at 1 bar for estimation [7]

Species	S° (J/mol· K)
CO_2	213.785 J/mol K
H_2	130.680 J/mol K
CO	197.660 J/mol K
H_2O	188.835 J/mol K

Temperature obtained from ΔG=0 under standard-state assumptions, should be interpreted as an indicative thermodynamic threshold. Adelung et al. further showed that CO selectivity (S_{co}) and yield in RWGS vary strongly with operating temperature, pressure, and composition, with particularly high temperature sensitivity in regimes where methanation occurs (S_{co}<1) [15]. Accordingly, practical RWGS operation typically adopts higher temperatures than calculated temperature to secure CO selectivity and suppress competing methanation.

4.4. RWGS Heat-Demand Scaling

Using the INL methanol pathway as a reference case, the RWGS heat demand can be calculated from the reported specific requirement. INL reports a methanol production rate of 10,299 t/d and an RWGS heat requirement of 1.20 GJ per tonne of methanol at 600°C [16]. Accordingly, the daily thermal energy demand for the RWGS section (preheater + RWGS reactor) is estimated as $10{,}299\ \mathrm{t/d} \times 1.20\mathrm{GJ/t} = 12{,}358.8\mathrm{GJ/d}$, which corresponds to 143MW.

INL-based scaling indicates that the RWGS heat demand is at a plant-relevant level, comparable to the thermal output of near-term HTGR-based SMRs. This makes RWGS a practical benchmark for nuclear–process integration. In deployment, consistent with the approach used for steam cracking, an HTGR-SMR can either (1) supply the full RWGS heat demand for a single large train or (2) provide staged heat–covering most of the ~600 °C duty for feed preheating and reactor heating–while reserving only the final temperature lift, if required, for a compact topping heater.

4. Conclusions and Further works

This work establishes simple, literature-based benchmarks for integrating HTGR heat with steam cracking and RWGS, indicating that both high-temperature operation and selectivity control benefit from a steady supply of non-carbon based heat. Overall, the results suggest that HTGR SMRs are a strong candidate for industrial retrofits, and that plant-relevant heat duties can be addressed through staged heat delivery. Future work will broaden the same framework to additional high-temperature processes and integration options, and will refine practical design inputs (temperature levels, heat-duty splits, and interface assumptions) to support comparative assessments and deployment-oriented studies for industrial and district heat application.

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