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Revision 3

Integration of High Temperature Gas-Cooled Reactors into Industrial Process Applications

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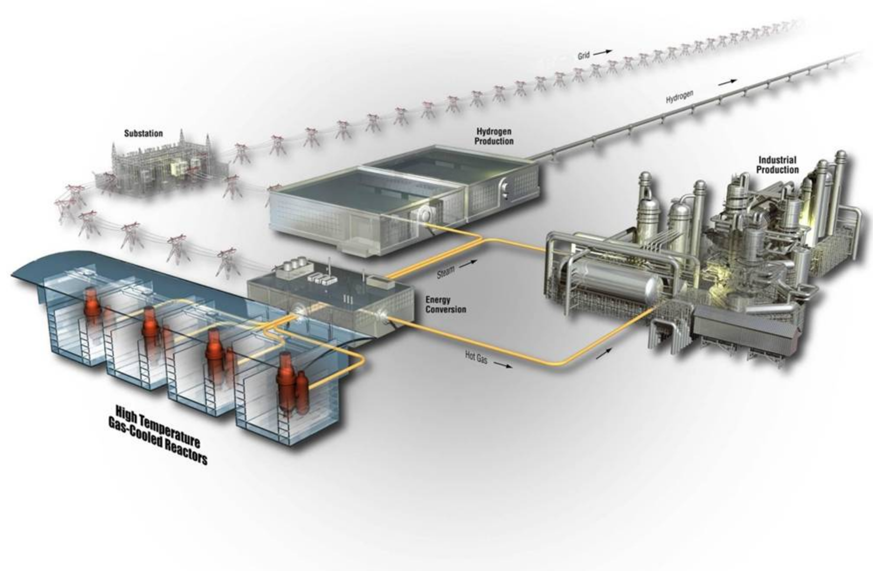

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Integration of High Temperature Gas-Cooled Reactors into Industrial Process Applications

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ABSTRACT

This report is a summary of analyses performed by the NGNP project to determine whether it is technically and economically feasible to integrate high temperature gas-cooled reactor (HTGR) technology into industrial processes. This report summarizes the material and energy requirements for conventional and HTGR-integrated processes that produce synthetic gasoline from natural gas or coal, synthetic diesel from natural gas or coal, ammonia and ammonia derivatives from natural gas, bitumen from oil sands via steam-assisted gravity drainage, and substitute natural gas from coal. The sensitivity analysis shows the impact of economic parameters on the wholesale product selling price. The engineering analyses show that HTGR-integrated processes would sharply reduce carbon dioxide and other GHG emissions, primarily by replacing the heat derived from natural gas and coal with high-temperature process heat from the HTGR.

SUMMARY

The Next Generation Nuclear Plant (NGNP) Project, led by Idaho National Laboratory, is part of a nationwide effort under the direction of the U.S. Department of Energy to address a national strategic need identified in the *Energy Policy Act of 2005*—to promote the use of nuclear energy and establish a technology for hydrogen and electricity production that is free of greenhouse gas (GHG) emissions.

This report is a summary of analyses performed by the NGNP project to determine whether it is technically and economically feasible to integrate high temperature gas-cooled reactor (HTGR) technology into industrial processes. To avoid an overly optimistic environmental and economic baseline for comparing nuclear-integrated and conventional processes, a conservative approach was used for the assumptions and calculations.

The engineering analyses show that HTGR-integrated processes would sharply reduce CO_2 and other GHG emissions, primarily by replacing the heat derived from natural gas and coal with high-temperature process heat from the HTGR. An example is a conventional natural gas power cycle that produces 320 MW(e) (megawatts electrical power). An HTGR-integrated process would produce the same amount of electricity as the conventional process and reduce emissions from 2,843 tons/day CO_2 to 0 tons/day as shown in Figure ES-1. It would also save more than 49 million standard ft^3/day of natural gas for other purposes.

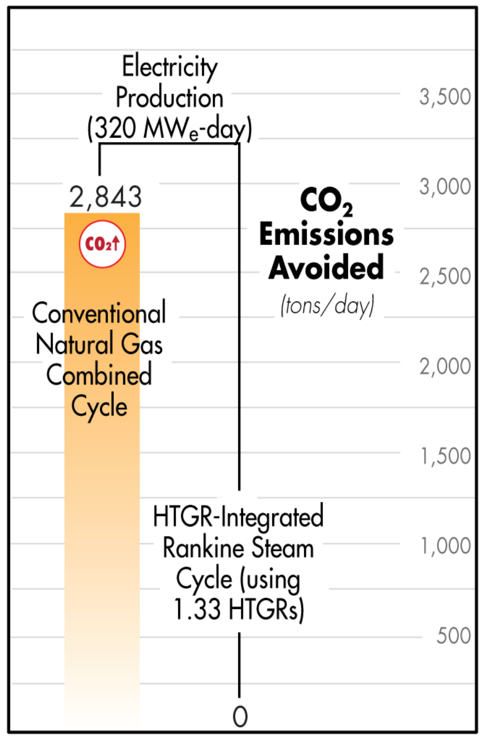

Figure ES-1. A comparison of the potential GHG emissions (tons/day CO_2) avoided if one 600-MW(t) HTGR was used to generate electricity via the Rankine power cycle instead of using a conventional natural gas combined cycle.

Another example: 1,871 tons/day CO_2 emissions would be avoided by using an HTGR-integrated process to produce 38,000 barrels (bbl)/day of synthetic gasoline and liquefied petroleum gas, instead of using the conventional process as shown in Figure ES-2. Besides using less natural gas, the HTGR-integrated synthetic gasoline production process would incorporate more of the carbon in natural gas into the gasoline product.

Economic analyses for the HTGR-integrated cases were completed to identify the major factors that influence the economics of HTGR-integrated processes of interest. The analyses were based on a simplified business model in which a single entity owns and operates the industrial and associated HTGR plants.

In this report, sensitivity charts are used to demonstrate how varying the value of a selected economic parameter, while holding all other parameters at the baseline values, would impact the wholesale product selling price. The baseline wholesale product selling prices were estimated by setting all economic values to the baseline values.

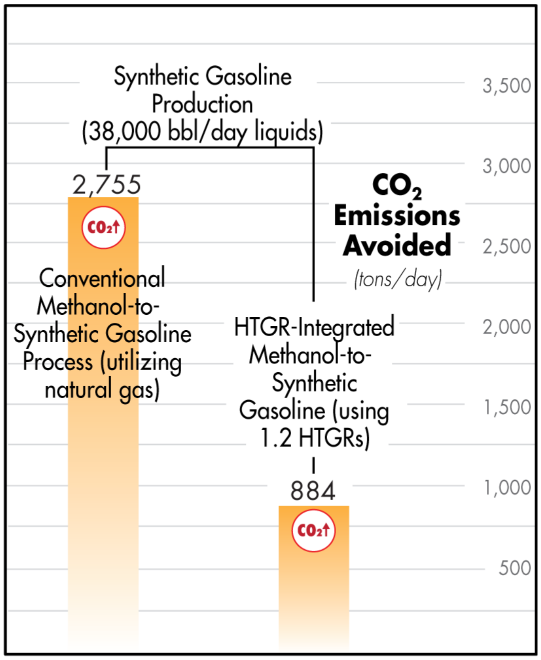

Figure ES-2. A comparison of the potential GHG emissions (tons/day CO_2) avoided if an HTGR-integrated process was used instead of a conventional natural gas-to-methanol-to synthetic gasoline process.

Figure ES-3 shows the sensitivity chart for the HTGR-integrated natural gas to methanol to synthetic gasoline process with a baseline wholesale gasoline selling price of $2.00/gallon. The chart shows that the factors that most influence the wholesale gasoline selling price are the internal rate of return, natural gas price, and total capital investment.

Based on the results of the engineering and economic analyses, the following processes appear suitable for HTGR integration:

- Synthetic gasoline production (Section 5)
- Synthetic diesel production (Section 6)
- Ammonia derivatives production (Section 7)
- Steam-assisted gravity drainage for bitumen recovery from oil sands (Section 8)
- Substitute natural gas production from coal (Section 9).

This HTGR process integration study illustrates potential environmental and economic benefits of providing HTGR heat to conventional industrial processes to reduce the use of fossil fuel resources, reduce CO_2 emissions, and supply products to market at competitive and stable prices. In all process evaluations, HTGR-integrated processes use less natural gas or coal and emit lower quantities of CO_2 than conventional processes. Because of the reduced reliance on fossil fuels, the wholesale selling prices of products generated by HTGR-integrated processes are less affected by fluctuations in fossil energy prices. The economics are not affected significantly by taxes on CO_2 emissions because the HTGR-integrated processes emit less CO_2 than conventional processes.

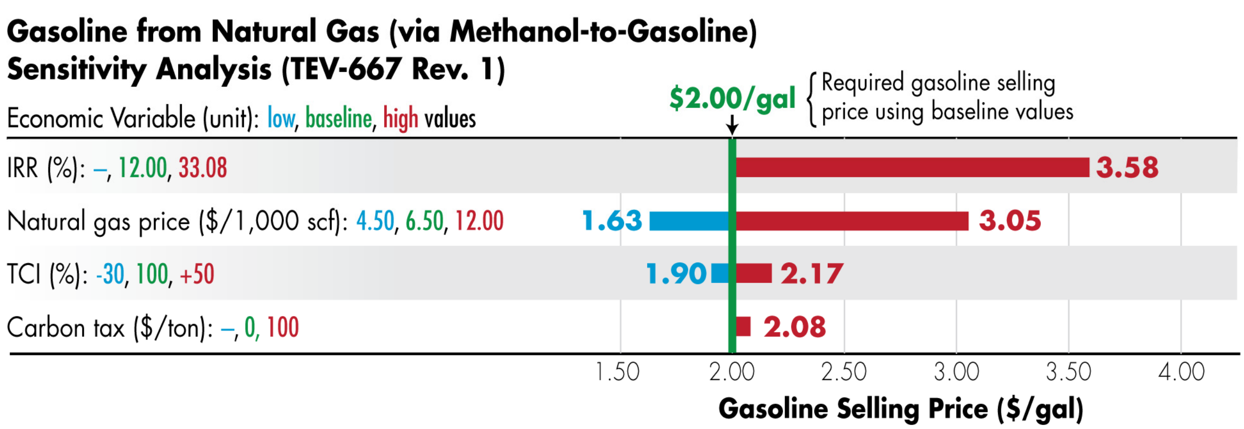

Figure ES-3. Sensitivity chart for production of gasoline via the HTGR-integrated natural gas-to-methanol-to-gasoline process.

CONTENTS

FIGURES

TABLES

ACRONYMS

GHG	greenhouse gas
HTGR	high temperature gas-cooled reactor
HTSE	high temperature steam electrolysis
IRR	internal rate of return
kW(e)	kilowatts electrical power
kW(t)	kilowatts thermal power
kW-hr	kilowatt-hour of electricity
LPG	liquefied petroleum gas
MW(e)	megawatts electrical power
MW(t)	megawatts thermal power
NGNP	Next Generation Nuclear Plant
SAGD	steam-assisted gravity drainage
TCI	total capital investment
TEV	technical evaluation
TRISO	tristructural-isotropic
WTW	well-to-wheel

Integration of High Temperature Gas-Cooled Reactors into Industrial Process Applications

1. INTRODUCTION

Under direction from the U.S. Department of Energy, the mission of the Next Generation Nuclear Plant (NGNP) Project is to develop, design, construct, and operate a prototype plant to generate electricity, produce hydrogen or both. The prototype plant is based on high temperature gas-cooled reactor (HTGR) technology. An HTGR produces and transfers energy in the form of high-temperature process heat. It differs from a third generation light water reactor by using helium instead of water as a coolant, graphite instead of water as the moderator, and tristructural isotropic (TRISO) fuel instead of metal-clad fuel. With these features, an HTGR is capable of operating at higher temperatures, thus offering a broader range of application to industrial processes and higher thermal efficiencies than are achievable with the lower operating temperatures of light water reactors.

Table 1. Projected outputs from a 600-MW(t) HTGR.

Primary Outputs	Temperature Range
High-Temperature Process Heat	
• Helium	700–900°C *(7–9.1 MPa)*
• Steam	540-593°C *(10-24 MPa)*
Secondary Outputs	**Produced/Generated By**
• Electricity	Rankine or Brayton power cycle
• Hydrogen (H_2)	High-temperature steam electrolysis or steam methane reforming
• Oxygen (O_2)	High-temperature steam electrolysis

The capability of the HTGR to produce high-temperature process heat offers such advantages as:

- Reducing CO_2 emissions by replacing the heat derived from burning fossil fuels, as practiced by a wide range of chemical and petrochemical processes, and co-generating electricity, steam, and hydrogen
- Generating electricity at higher efficiencies than are possible with current nuclear power generation technology
- Providing a secure long-term domestic energy supply and reducing reliance on offshore energy sources
- Producing synthetic transportation fuels with lower life cycle, well-to-wheel (WTW) greenhouse gas (GHG) emissions than fuels derived from conventional synthetic fuel production processes and similar or lower WTW GHG emissions than fuels refined from crude oil
- Producing energy at a stable long-term cost that is relatively unaffected by volatile fossil fuel prices and a potential carbon tax (a price set on GHG emissions)
- Extending the availability of natural resources for uses other than a source of heat, such as a petrochemical feedstock
- Providing benefits to the U.S. economy such as more near-term jobs to build multiple plants, more long-term jobs to operate the plants, and a reinvigorated heavy manufacturing sector.

This report summarizes the material and energy requirements for conventional and HTGR-integrated processes that produce synthetic gasoline from natural gas or coal, synthetic diesel from natural gas or coal, ammonia and ammonia derivatives from natural gas, bitumen from oil sands via steam-assisted gravity drainage (SAGD), and substitute natural gas from coal. The sensitivity analysis shows the impact of economic parameters on the wholesale product selling price. References 1 through 7 include more detailed technical analyses of the processes.

2. APPROACH AND ASSUMPTIONS

Engineering analyses were conducted to determine whether it would be technically and economically practical to integrate one or more HTGRs into selected conventional industrial processes. The following processes were evaluated and are described in this report:

- Synthetic gasoline production (Section 5)
- Synthetic diesel production (Section 6)
- Ammonia derivatives production (Section 7)
- SAGD for bitumen recovery from oil sands (Section 8)
- Substitute natural gas production from coal (Section 9).

Process models were developed for all the conventional processes selected for examination, then analyzed to determine where there were opportunities to integrate heat, electricity, and hydrogen from an HTGR. The process models, based on typical plant production capacities, were developed with the Aspen Plus® modeling package. HYSYS® software was also used for modeling hydrogen production and power generation. To evaluate well-to-wheel GHG emissions for synthetic fuels production, the calculated CO_2 emissions included CO_2 equivalents for methane, the principal component of natural gas, and nitrous oxide emissions. Table 2 lists the general assumptions for the process models. The technical evaluations of the HTGR-integrated processes evaluated in this study are included in References 1 through 7.

Table 2. Assumptions used to complete process evaluations.

- No heat loss in piping between HTGRs and process applications
- Natural gas composition based on information published by Northwest Gas Association
- Natural gas standard volume flow: 15.56°C (60°F); 1 atmosphere
- Grade of coal: Illinois No. 6
- Ambient inlet water temperature: 15.56°C (60°F)
- Ambient inlet air temperature: 21.11°C (70°F)
- Ambient pressure: Sea level (1 atmosphere absolute)
- Pump inlets: 2°C minimum sub-cooling to protect against cavitation
- High-efficiency compressors and turbines: 90% efficient
- Process heat exchangers: 10°C minimum temperature approach (except when demonstrated industrial experience indicates differently)

The process models for the HTGR-integrated cases assumed that one or more 600-MW(t) HTGRs were physically located near the conventional plant. An HTGR-integrated Rankine power cycle was used in all cases that required electricity. Water usage was calculated for all processes, excluding water requirements for the HTGR and associated power cycles. Table 3 lists the general assumptions for the HTGR-integrated technology.

The process models were independently reviewed by external reviewers who have significant experience in developing and applying similar models for petrochemical industries. The reviewers participated with the NGNP Project team to resolve comments, concluding that the previous models were acceptable, subject to recommended modifications (see Reference 8). Some of the key modeling parameters, such as operating temperatures, and pressures for ammonia and ammonia derivatives production, were validated during visits to operating plants.

Table 3. General assumptions for the HTGR technology.

- Energy products: electricity, process heat, and/or hydrogen
  - Power generation efficiency: 40–43%
  - Process heat:
    - 700–825°C (high-temperature helium)
    - Up to 593°C (steam)
- Gas inlet temperature: 322°C
- Heat output: 600 MWth
- Primary recirculator: 75% efficient

Economic models were developed for nearly all of the conventional and HTGR-integrated process models to assess the economic viability of integrating HTGR technology into the selected conventional industrial processes. The models reflected all-in costs and revenues, and allowed a discounted cash flow analysis based on the estimated total capital investment (TCI). Manufacturing costs are the sum of: direct production costs for raw materials, utilities, operating labor, and maintenance; and indirect costs, including plant overhead, insurance, and taxes.

The economic analyses, as summarized in this report, are based on a simplified business model in which a single entity owns and operates the industrial and associated HTGR plants.[a] Economic sensitivity analyses were conducted to assess the impact of selected economic parameters on the wholesale product selling price of HTGR-integrated processes. The results are summarized as sensitivity charts. These were created by varying the values of a selected economic parameter, while holding all other economic parameters at their baseline values, then measuring the effect on the final wholesale product selling price. Wholesale product selling prices[b] were calculated based on a 12% internal rate of return (IRR) on the equity investment. To better understand the impact of the wide range of natural gas prices during the past five years, selling prices were calculated based on low, average, and high natural gas prices. The results in this summary report are based on average (\$5.50 thousand standard ft^3) natural gas prices. Table 4 lists the general assumptions for the economic models.

For the HTGR-integrated cases, the estimates of capital costs and operating and maintenance costs assumed the nuclear plant was an "n^{th} of a kind" plant. The economic modeling calculations for HTGR-integrated synthetic gasoline, ammonia, and substitute natural gas production, which included one or more HTGRs, the steam generator, and Rankine power cycle, were based on two capital cost assumptions: (1) a nominal estimate of \$2,000/kW(t) for plants that consist of one or two HTGR modules, and (2) a target estimate of \$1,400/kW(t) for plants that consist of three or more modules. In comparison, current estimates for light water nuclear reactor costs are \$1,333 to \$2,000/kW(t) (\$4,000 to \$6,000/kW(e)) (Nuclear Energy Institute, 2008, *The Cost of New Generating Capacity in Perspective*, White Paper). Based on these capital cost assumptions, the nominal capital cost for a single-module 600-MW(t) HTGR would be \$1.2 billion; the target capital cost for a four-module 2,400-MW(t) plant would be \$3.36 billion.

Table 4. General assumptions used for the economic analyses.

- Plant economic life: 30 years (excludes construction time; models built for 40-year lifespan)
- Construction period
  - Fossil plant: Three years
  - HTGR plant: Five years
- HTGR plant startup year: Immediately following construction, with all HTGRs online simultaneously; one-year startup time
- Start-up assumptions
  - Operating costs: 85% of estimated operating costs
  - Revenues: 60% of estimated revenue
- Plant availability: 92%
- Internal rate of return (IRR): 12%
- Inflation rate: 2.5%
- Interest rate on debt: 8%
- Repayment term: 15 years
- All processes (except SAGD)
  - Effective U.S. income tax rate: 38.9%
  - U.S. state tax: 6%
  - U.S. federal tax: 35%
- SAGD process: Canadian tax rate of 22.1%
- MACRS depreciation: 15-year plant life

The economic modeling calculations for HTGR-integrated synthetic diesel, SAGD, and power production were based on the HTGR cost –estimation tool. The INL HTGR cost estimation tool includes capital, operating, and decommissioning cost estimates based on several inputs, including past cost estimates for similar plants, bottoms-up evaluations, etc. (see

a More complex business models with multiple owner/operators for the nuclear and non-nuclear portions of the HTGR-integrated processes were developed for the cases evaluated. For reasons of brevity and clarity, this report shows only simplified models.

b. Wholesale product selling price, as used in this report, represents the price of products generated by the process of interest. The wholesale product selling price is based on the manufacturing costs, capital costs, and associated product revenues for a given (nominally 12%) internal rate of return on the equity investment. The wholesale product selling prices does not include any adders such as sales tax or retail distribution costs.

Reference 9). The cost-estimation tool may be used to estimate the HTGR cost based on the ROT, power cycle type, and number of reactor modules.

The HTGR-integrated processes evaluated in this report assume a separation between nuclear and non-nuclear parts of the plant, as illustrated in Figure 1. The nuclear part includes the HTGR and the steam generator or intermediate heat exchanger and all associated piping, pumps, valves, and vessels. The non-nuclear part includes the industrial process. The hot steam or helium generated in the steam generator or intermediate heat exchanger leaves the nuclear plant and enters the non-nuclear plant. Cold steam (typically liquid water) and low-temperature helium leave the non-nuclear plant and reenter the nuclear plant.

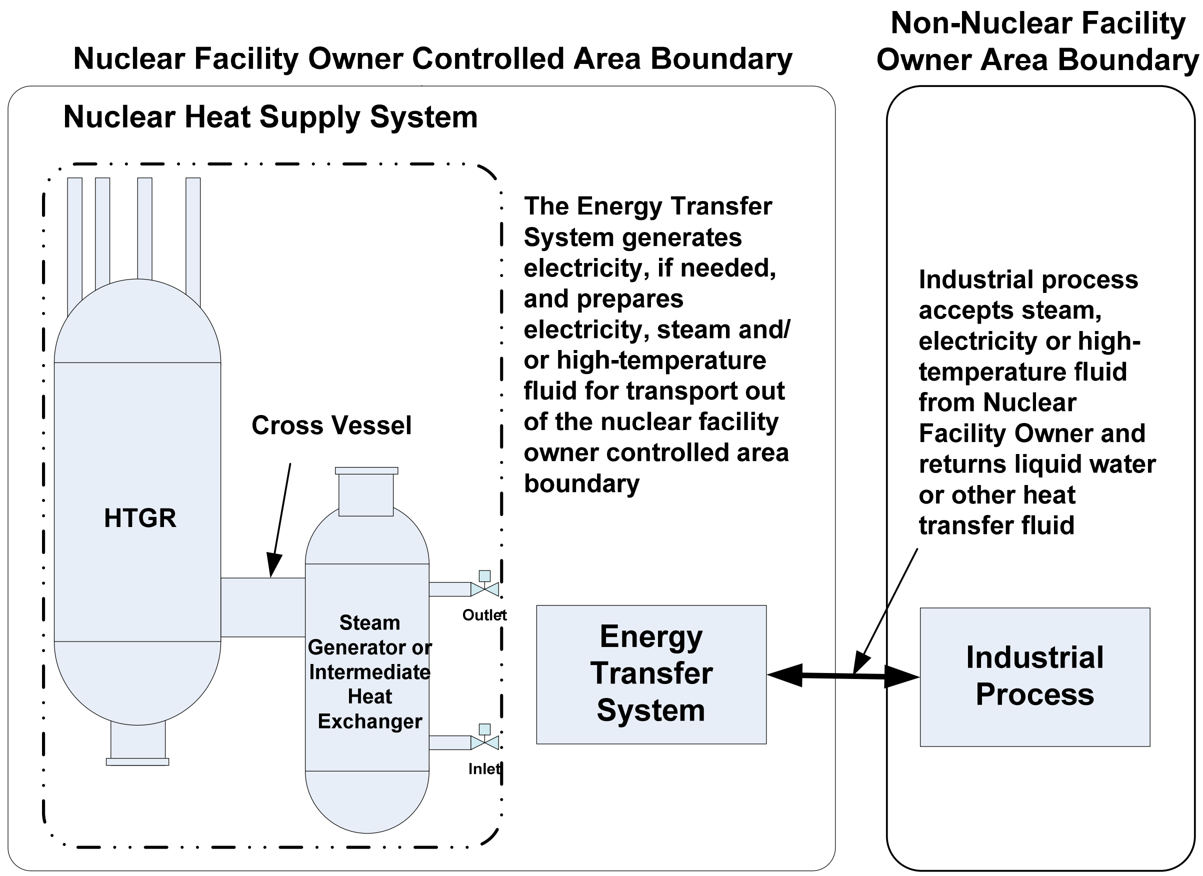

Figure 1. Block flow diagram for a generic HTGR-integrated industrial process.

3. POWER (ELECTRICITY) GENERATION

A conventional method for generating electrical power is the natural gas combined cycle process, which uses natural gas as a source of heat and also generates significant GHG emissions. Three HTGR-integrated power cycle cases were developed as alternatives to the natural gas combined cycle process as shown in Figure 2.[c]

3.1 HTGR-Integrated Rankine Steam Cycle

In this power cycle, water is pumped to a high pressure and then heated by the HTGR to produce 550°C steam, which in turn expands through the turbine to produce power. The reactor heat is separated from the power cycle by the primary helium loop. This power cycle uses 600 MW(t) to produce 239 MW(e), a thermal efficiency of 39.8%. Because this cycle uses 550°C steam, it can be used to generate power from the heat rejected from the HTGR-integrated industrial processes.

3.2 HTGR-Integrated Brayton Helium Gas Cycle with Process Heat

In this power cycle, high-pressure helium, also called working gas, is expanded in a turbine to produce power. The low-pressure warm gas is cooled in an ambient cooler, which reduces the compression power, and the low-pressure cold gas is compressed to the system's high pressure. The reactor heat is separated from the power cycle by two circulation loops: the primary helium loop and the secondary helium loop. This power cycle uses 600 MW(t) to produce 92 MW(e) and 416 MW(t) of high-temperature process heat at temperatures in excess of 600°C, which makes it ideal for applications that require a combination of power and heat. The thermal efficiency of this cycle is 50% for the power generation portion of the process (92 MW(e)/184 MW(t) = 50%).

3.3 HTGR-Integrated Combined Brayton/Rankine Cycle

This power cycle capitalizes on the heat production capabilities of the Brayton helium gas cycle and the 550°C steam requirement of the HTGR-integrated Rankine steam cycle by using the leftover heat from the Brayton cycle to produce steam that is used in a Rankine cycle to generate electricity. An added benefit is that the proportions of heat and electricity produced could be adjusted according to need. This power cycle uses 600 MW(t) to produce 274 MW(e), a thermal efficiency of 45.7%.

An economic sensitivity analysis was conducted to assess the impact of economic variables of interest on the wholesale selling price of electricity generated by the HTGR-integrated Rankine power cycle. The results of the sensitivity analysis are shown in Figure 3. The economic analysis showed that the total capital investment has the largest impact on wholesale electricity selling price, followed by the IRR, debt-to-equity ratio and refueling period. The nominal wholesale selling price of electricity is $98.56/MW(e)-hr. Full results of the process modeling are contained in References 1 and 10.

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c The stated volume of natural gas required to generate 600 MW(t) for conventional natural gas combined cycle is based on a theoretical heating value of methane and does not account for heat losses. Comparison of the HTGR-integrated options is therefore conservative.

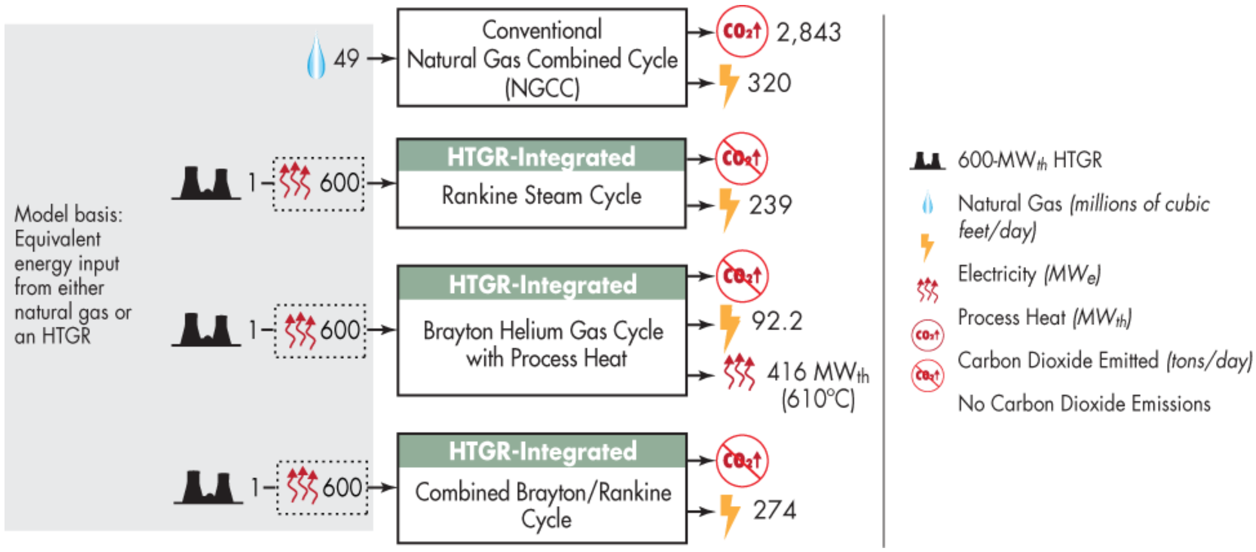

Figure 2. Mass and energy balance calculation results for the conventional and HTGR-integrated cases for power (electricity) generation processes.

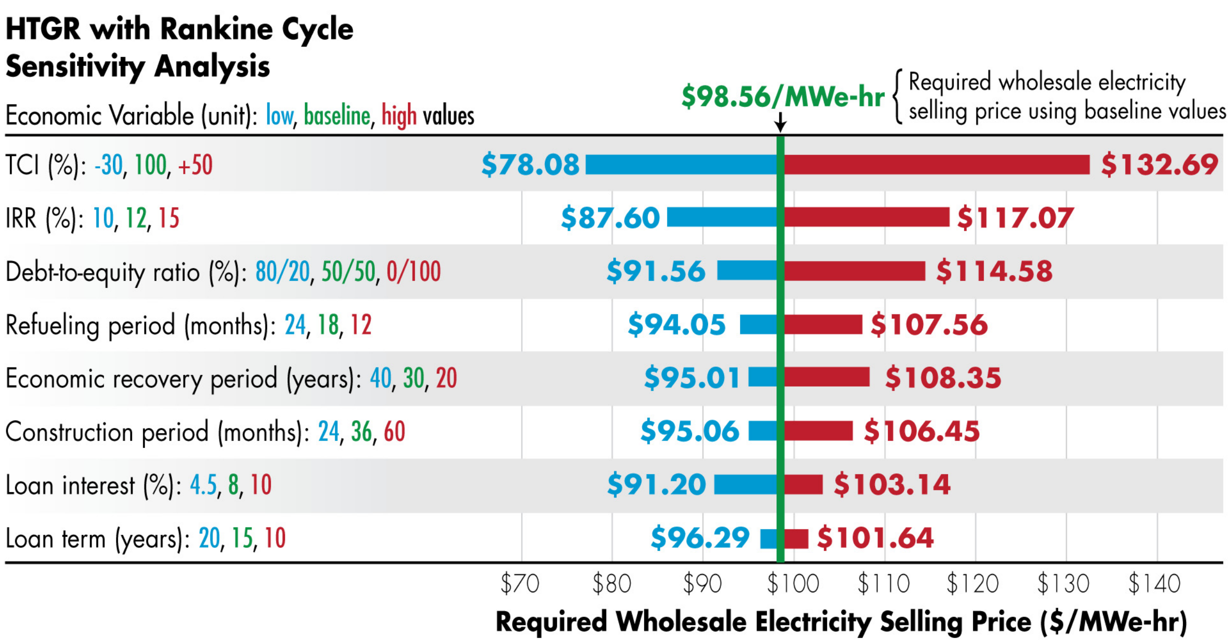

Figure 3. Sensitivity chart for HTGR with Rankine cycle (four 600-MW(t) HTGRs at 700°C) showing the relative impact of each input variable on project economics.

4. HYDROGEN PRODUCTION

Hydrogen is a key element required in the production of many chemical and industrial products, such as ammonia and synthetic hydrocarbon fuels. A conventional method for generating hydrogen is the steam methane reforming process, which converts steam and methane into hydrogen. This method also generates significant GHG emissions.

An HTGR-integrated process model was developed based on a production capacity of 700 tons/day hydrogen. A simplified block flow diagram of the HTGR-integrated process for generation of hydrogen via the HTSE process is shown in Figure 4. The HTGR supplies steam at 540°C and 17 MPa to the Rankine power cycle which operates at an overall thermal efficiency of 40%. Because the HTSE process requires 800°C steam, 15 MW(t) of supplemental topping heat is needed to bring the steam up to the required temperature of 800°C. The topping heat could be obtained from electrical resistance heating or another fuel such as natural gas. A byproduct of the process is nearly pure oxygen, which could be used for other chemical processes such as coal gasification.

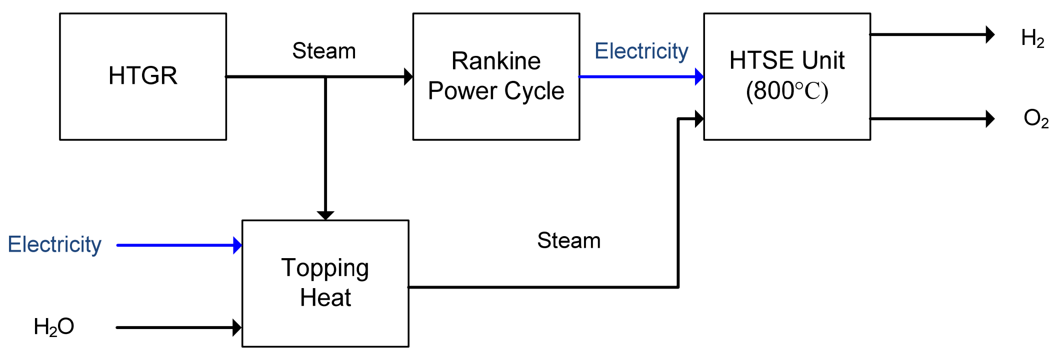

Figure 4. Simplified block flow diagram of the HTGR-integrated process for hydrogen production via the HTSE process.

The results of the process modeling for the conventional and HTGR-integrated hydrogen production process are summarized in Figure 5. The conventional process requires 98 million ft^3 of natural gas/day, 11.5 MW(e), and 1,364 gallons/minute of water. The HTGR-integrated process requires 264 MW(t), 15 MW(t) topping heat, 930 MW(e), and 1,070 gallons/minute of water. Both processes generate 719 tons/day of hydrogen. The HTGR-integrated process generates 5,668 tons/day of oxygen. As indicated in Figure 5, the HTGR-integrated process generates no CO_2, while the conventional process emits 3,393 tons/day of CO_2.

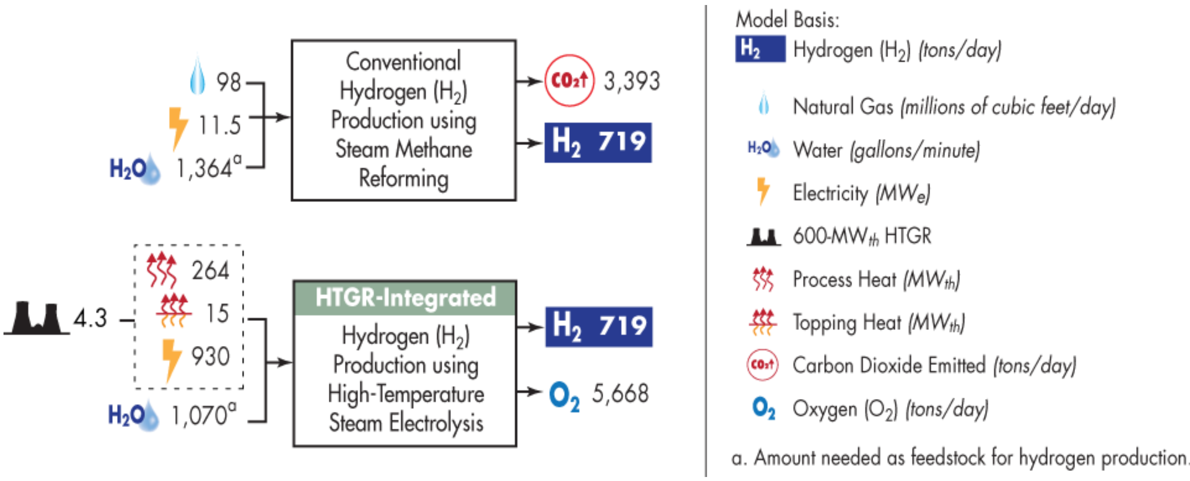

Figure 5. Mass and energy balance calculation results for the HTGR-integrated process for hydrogen production via the HTSE process.

An economic sensitivity analysis was conducted to assess the impact of economic parameters of interest on the wholesale hydrogen selling price for the HTGR-integrated process. The results are summarized as a sensitivity chart as shown in Figure 6. Other economic variables also have an effect on the wholesale selling price of hydrogen. Other input parameters that control and impact the mass and energy balances were also analyzed. While they can also affect project economics, they were not included in the economic sensitivity studies. Reference 2 contains the complete process modeling results and the complete economic sensitivity studies.

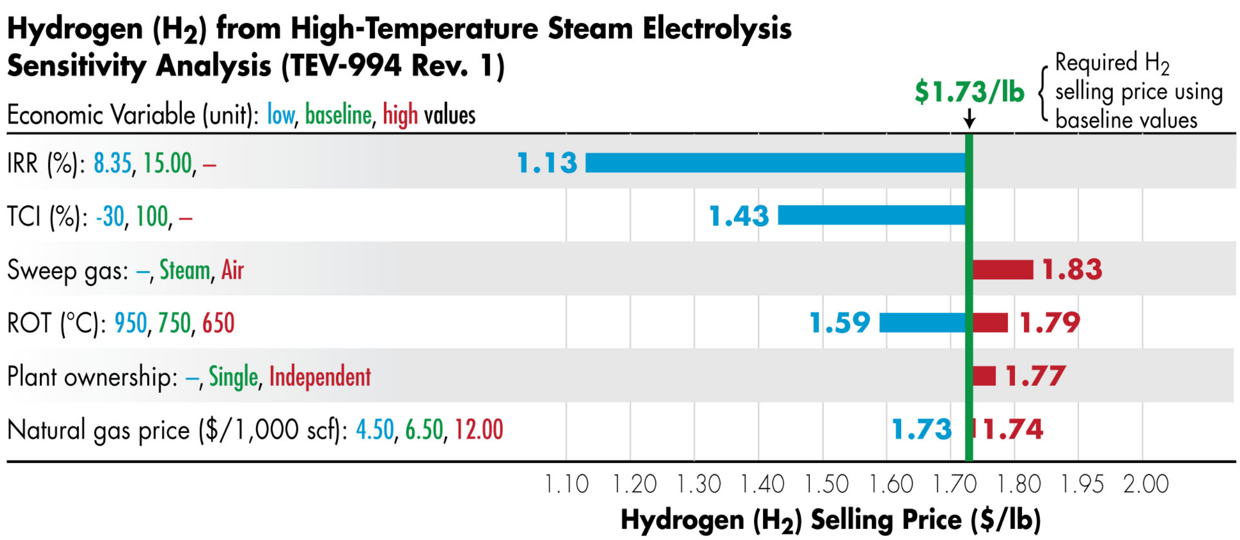

Figure 6. Sensitivity chart for HTGR with HTSE showing the relative impact of each input variable on project economics.

5. METHANOL-TO-SYNTHETIC GASOLINE PRODUCTION UTILIZING NATURAL GAS OR COAL AS INPUTS

Synthetic gasoline may be produced from natural gas or coal via the conventional methanol-to-gasoline process. These processes produce methanol as an intermediate product, synthetic gasoline and liquefied petroleum gas as end products, and significant GHG emissions. A simplified block flow diagram for the conventional cases considered is shown in Figure 7.

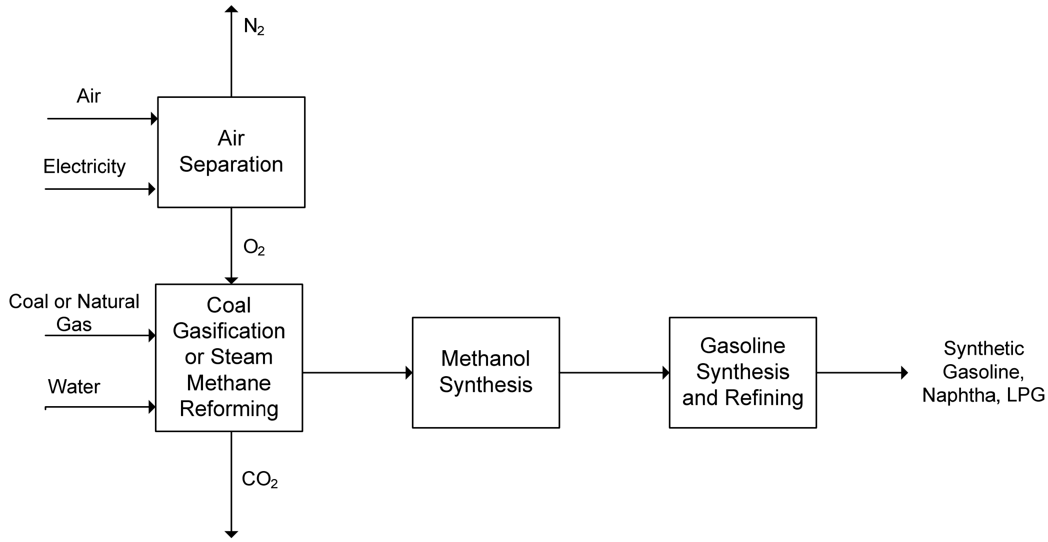

Figure 7. Simplified block flow diagram for the conventional natural-gas- or coal-to-methanol-to-gasoline process.

Two HTGR-integrated process models were developed as alternatives to the two conventional processes that utilize natural gas or coal. The models of the HTGR-integrated processes use nuclear heat as a replacement for some of the heat derived from natural gas or coal combustion but still use natural gas or coal as a source of carbon to produce methanol. The HTGR-integrated natural-gas-to-methanol-to-gasoline process is shown in Figure 8. Heat from the HTGR is used to preheat the feed to the steam methane reformer and initiate the reforming reactions. Electricity from the HTGR is used to supply electricity to the air separation unit. The rest of the HTGR-integrated process is identical to the conventional natural gas process.

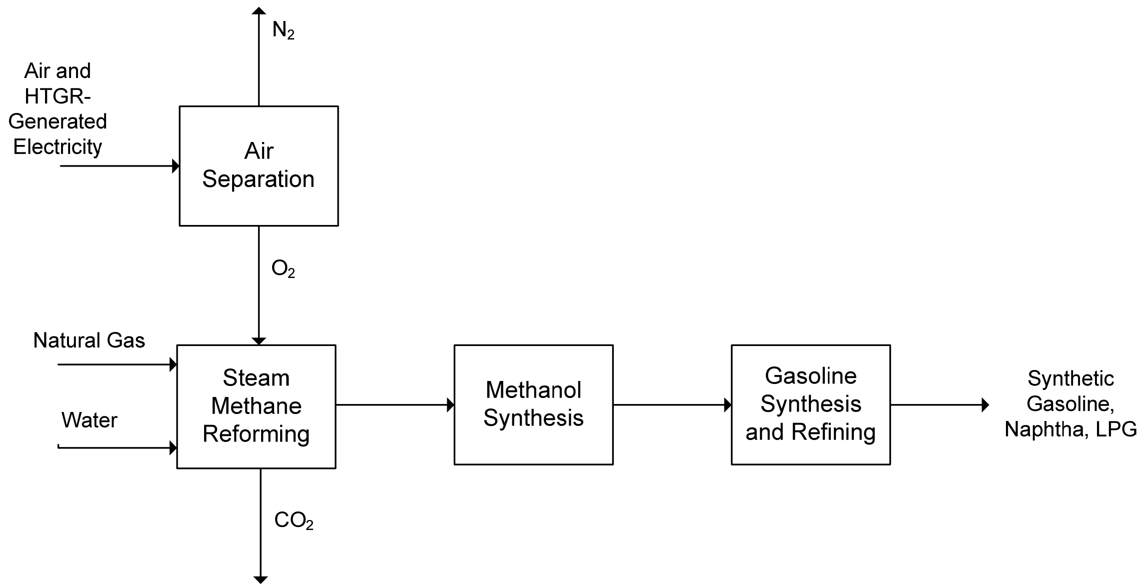

Figure 8. Simplified block flow diagram for the HTGR-integrated natural-gas-to-methanol-to-gasoline process.

The HTGR-integrated coal-to-methanol-to-gasoline process is shown in Figure 9. Oxygen and hydrogen from the HTGR-integrated HTSE process are used to supply the heat requirements of coal gasification. The rest of the HTGR-integrated process is identical to the conventional coal process.

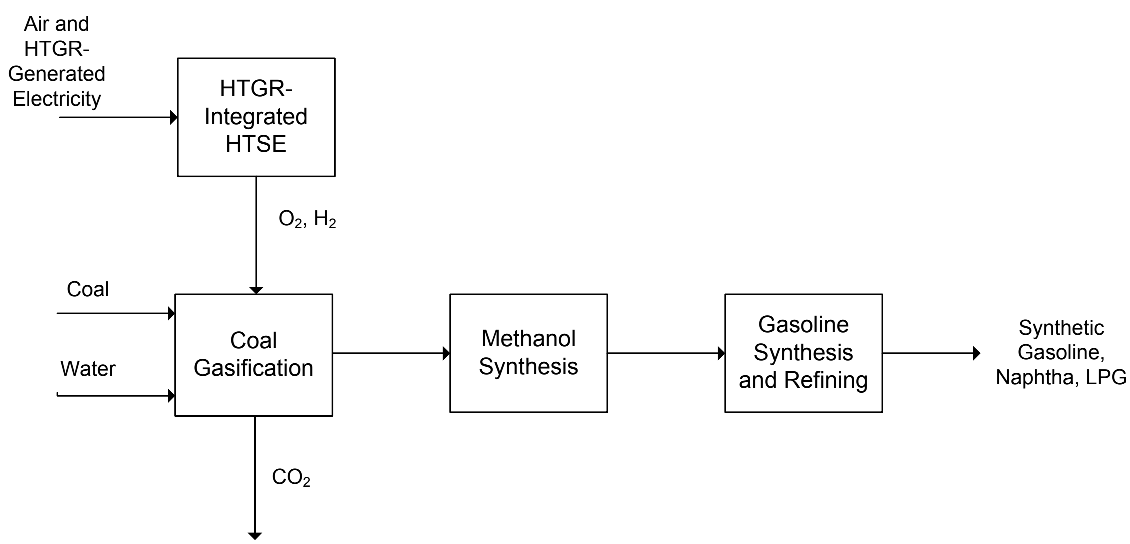

Figure 9. Simplified block flow diagram for the HTGR-integrated coal-to-methanol-to-gasoline process.

The results of the conventional and HTGR-integrated process models are shown in Figures 10 and 11 for the natural gas-based and coal-based processes, respectively. The natural gas-based models were constructed based on a typical plant production capacity of 38,749 bbl/day liquids (gasoline, naphtha, and liquefied petroleum gas [LPG]) and the coal-based processes were constructed based on a typical plant production capacity of 66,804 bbl/day liquids. To produce an output similar to the conventional process, the HTGR-integrated natural-gas-based process would require the energy output of 720 MW(t) and the coal based process would require 6,870 MW(t). In general, the HTGR-integrated processes utilize less coal and natural gas and emit significantly less CO_2 than the conventional cases.

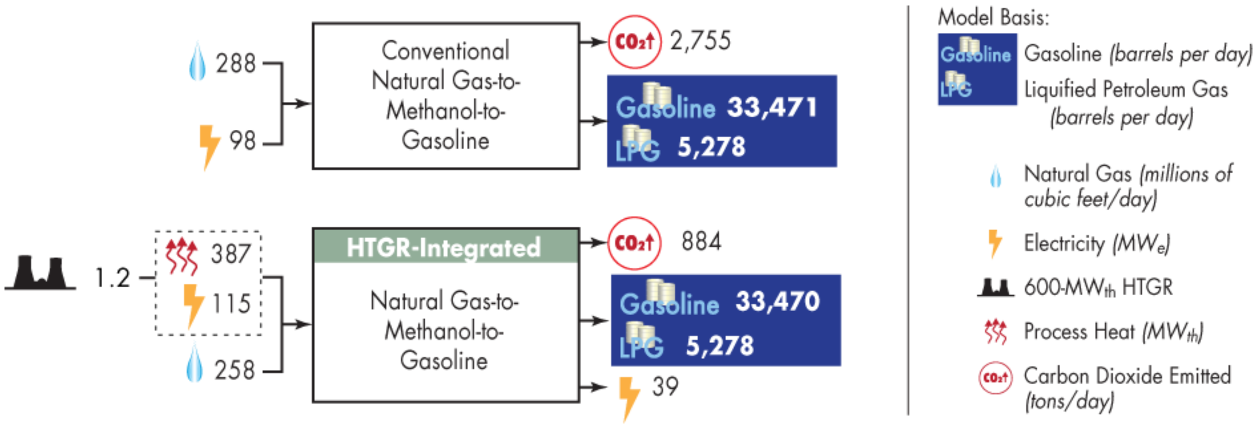

Figure 10. Mass and energy balance calculation results for the conventional and HTGR-integrated cases that were developed to evaluate an alternative for a synthetic gasoline production process utilizing natural gas.

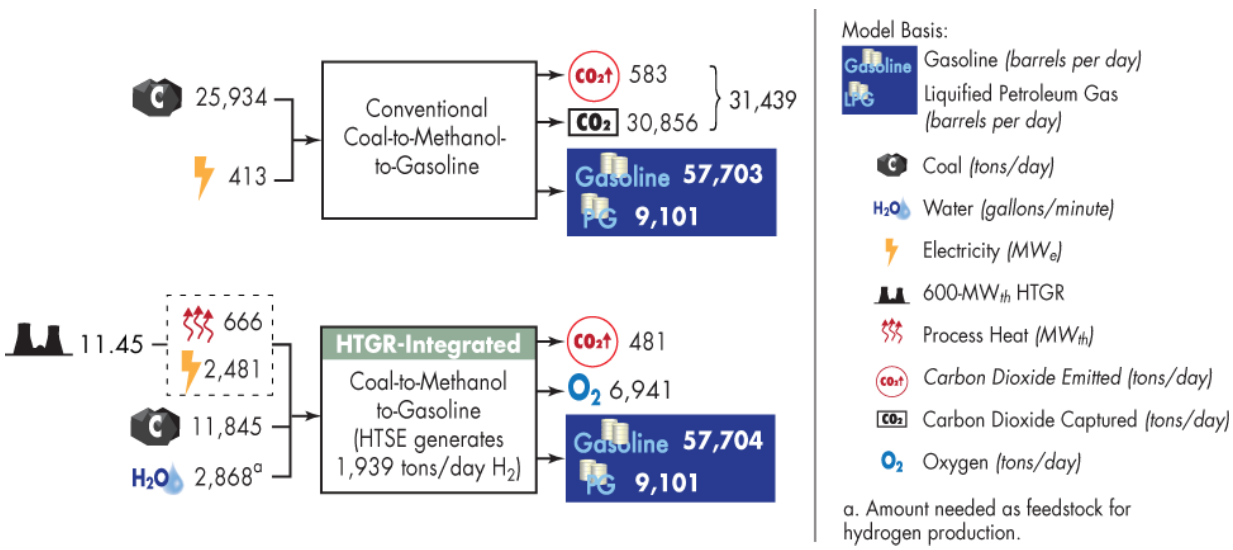

Figure 11. Mass and energy balance calculation results for the conventional and HTGR-integrated cases that were developed to evaluate an alternative for a synthetic gasoline production process utilizing coal.

The engineering models developed for synthetic gasoline production using natural gas and coal made use of published information on commercially available equipment whenever possible. This approach capitalizes on knowledge derived from "standard" sizes, throughputs, energy requirements, efficiencies and costs. Consequently, the basis used for the natural gas and coal process flow sheets are different. If a comparison between the natural gas and coal-based processes were to be made, the output of synthetic gasoline from each flow sheet would need to be adjusted to match the other, proportionally reducing the calculated CO_2 emissions and number of HTGRs required. For example, taking the liquid products from the natural gas flow sheet (38,749 bbl/day) as the norm (1.0), the liquid products from the coal flow sheet (66,804 bbl/d) represent 1.72 times the products from the natural gas flow sheet. Therefore, the CO_2 emissions and the amount of nuclear heat required would need to be proportionally adjusted to compare the processes. This normalization would yield the results shown in Table 5.

Table 5. Normalized output from synthetic gasoline production processes that utilize coal and natural gas.

	HTGR-Integrated Natural Gas Process	HTGR-Integrated Coal Process
Liquid Products (bbl/d)	38,749	38,749 (66,804/1.72)
CO2 Emissions (tons/d)	884	279 (481/1.72)
Amount of nuclear heat required (MW(t))	720	3,994 (6,870/1.72)

An economic sensitivity analysis was conducted to assess the impact of economic parameters of interest on the wholesale synthetic gasoline selling price for the HTGR-integrated processes. The results are summarized as sensitivity charts in Figures 12 and 13 for the natural gas-based and coal-based processes, respectively. Both TCI and IRR have a significant impact on the selling price of gasoline from both the natural-gas- and coal-based processes. Application of a carbon tax does not significantly impact the economics of the HTGR-integrated processes.

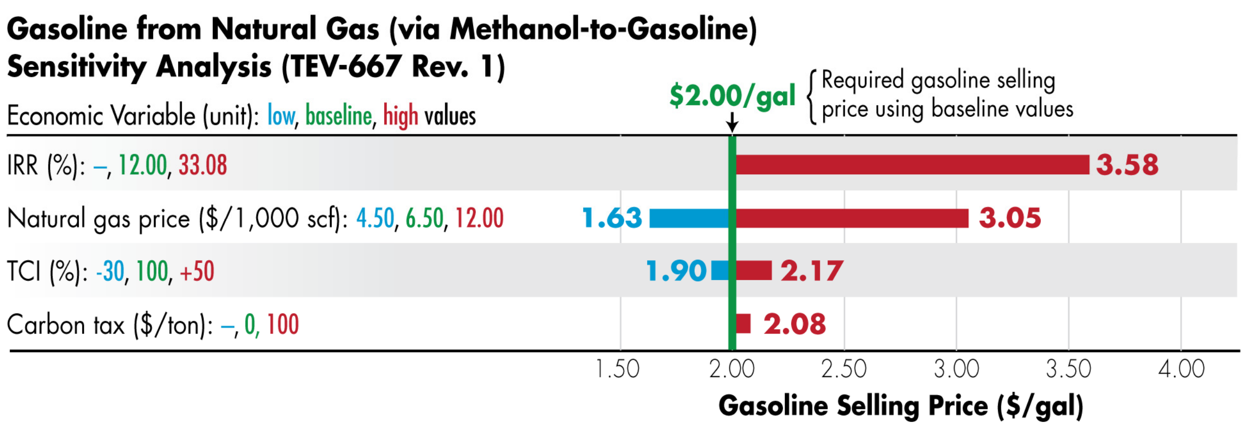

Figure 12. Sensitivity chart for HTGR-integrated production of gasoline from natural gas showing the relative impact of each input variable on project economics.

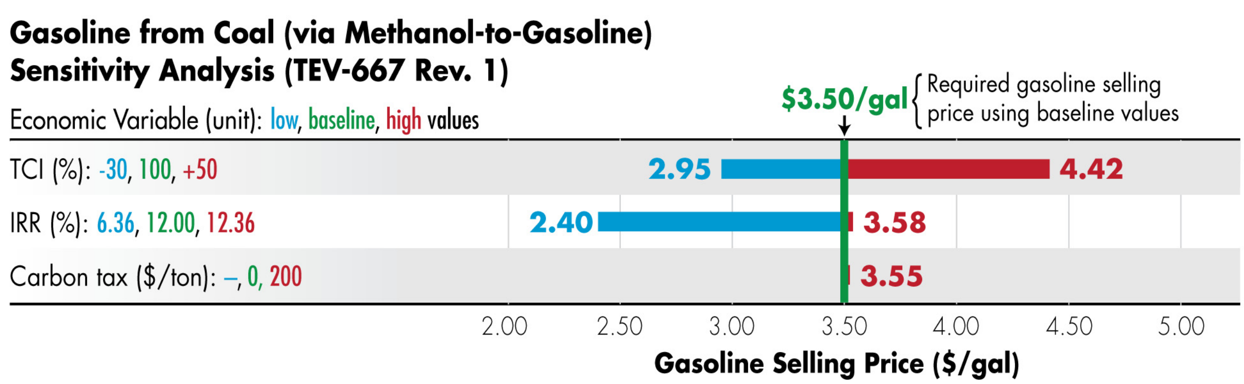

Figure 13. Sensitivity chart for HTGR-integrated production of gasoline from coal showing the relative impact of each input variable on project economics.

6. SYNTHETIC DIESEL (LIQUIDS) PRODUCTION UTILIZING NATURAL GAS OR COAL AS INPUTS

Synthetic diesel may be produced from natural gas or coal via the conventional natural gas- or coal-to-liquids process. A simplified block flow diagram for the conventional cases considered is shown in Figure 14. These processes also produce naphtha and LPG, as well as significant GHG emissions.

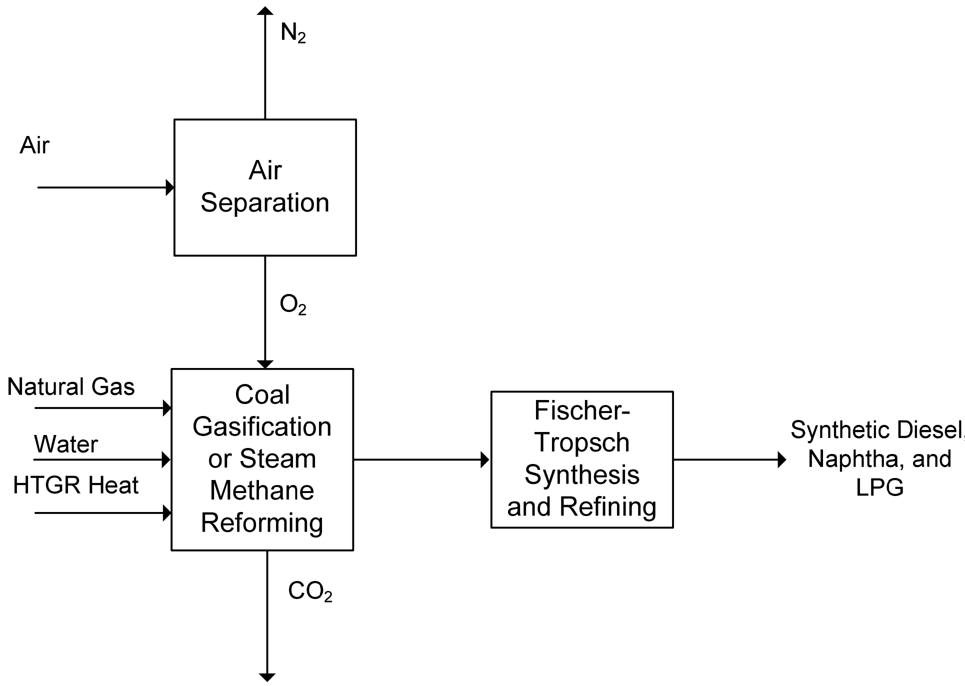

Figure 14. Simplified block flow diagram for the conventional natural-gas- or coal-to-liquids synthetic diesel production process.

Two HTGR-integrated process models were developed as alternatives to the two conventional processes that utilize natural gas or coal. The models of the HTGR-integrated processes use nuclear heat as a replacement for some of the heat derived from natural gas or coal combustion but still use natural gas or coal as a source of carbon to produce synthetic diesel. The HTGR-integrated natural gas-to-liquids (synthetic diesel) process is shown in Figure 15. Heat from the HTGR is used to preheat the feed to the steam methane reformer. The rest of the HTGR-integrated process is identical to the conventional natural gas process.

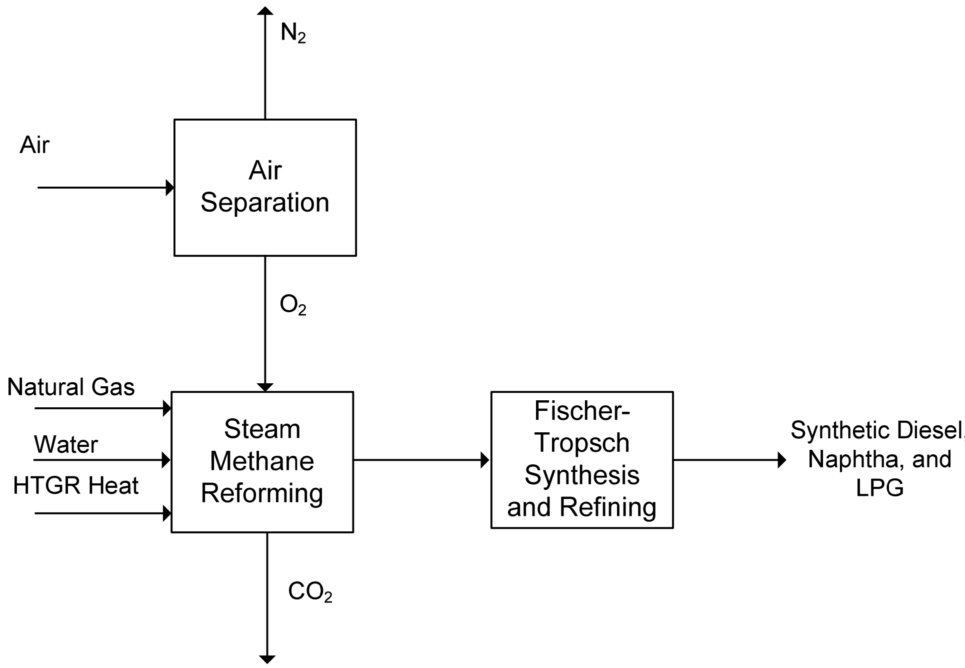

Figure 15. Simplified block flow diagram for the HTGR-integrated natural gas-to-liquids (synthetic diesel) process.

The HTGR-integrated coal-to-liquids (synthetic diesel) process is shown in Figure 16. Oxygen and hydrogen from the HTGR-integrated HTSE process are used to supply the heat requirements of coal gasification. The rest of the HTGR-integrated process is identical to the conventional coal process.

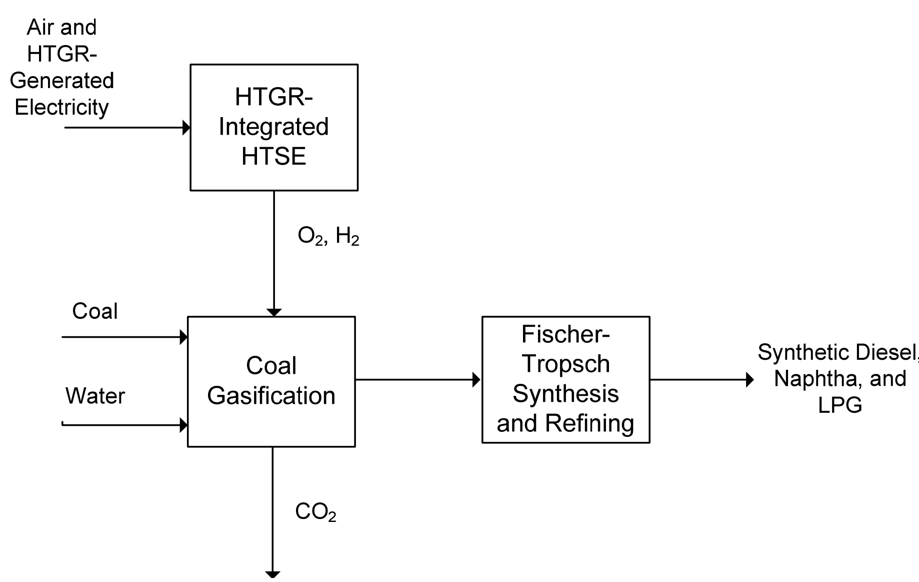

Figure 16. Simplified block flow diagram for the HTGR-integrated coal-to-liquids (synthetic diesel) process.

The analysis of the conventional natural gas-based case indicated that an HTGR could supply the "preheat" for several of the unit operations normally supplied by burning natural gas or light gas from the process. As a result, some of the natural gas combustion requirement would be avoided, reducing GHG emissions. The HTGR case requires the energy output of 479 MW(t) to equal the production of the conventional case. See Figure 17 for a mass and energy balance summary of the conventional process and the HTGR-integrated alternatives.

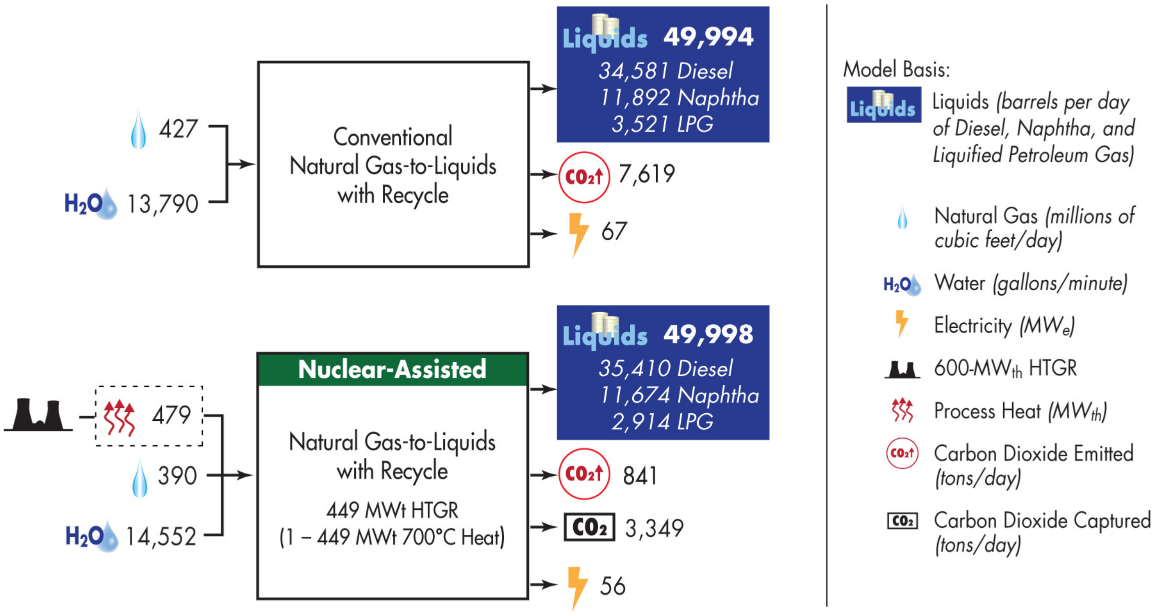

Figure 17. Mass and energy balance calculation results for the conventional and HTGR-integrated cases that were developed to evaluate an alternative for a synthetic diesel production process utilizing natural gas.

The analysis of the conventional coal-based case showed few opportunities for heat integration because the production process generates more than sufficient heat to provide for heat requirements. However, the analysis showed an opportunity for HTSE, which could provide hydrogen and oxygen while reducing coal requirements and subsequent GHG emissions. In the conventional process, only one-third of the carbon in the coal ends up in the final product as compared to over 98% in the HTGR-integrated case. The conventional case also evaluated an option for carbon capture and sequestration to gain a better understanding of the potential reductions in GHG emissions.

The HTGR-integrated process would produce 50,002 bbl/day of product (35,194 bbl/day diesel, 11,810 bbl/day naphtha, and 2,998 bbl/day LPG). This process would also generate less CO_2 emissions than the conventional process. Even if the conventional process includes carbon capture and sequestration, the HTGR-integrated process would produce less CO_2 emissions. Figure 18 shows a mass and energy balance summary for the conventional and HTGR-integrated processes.

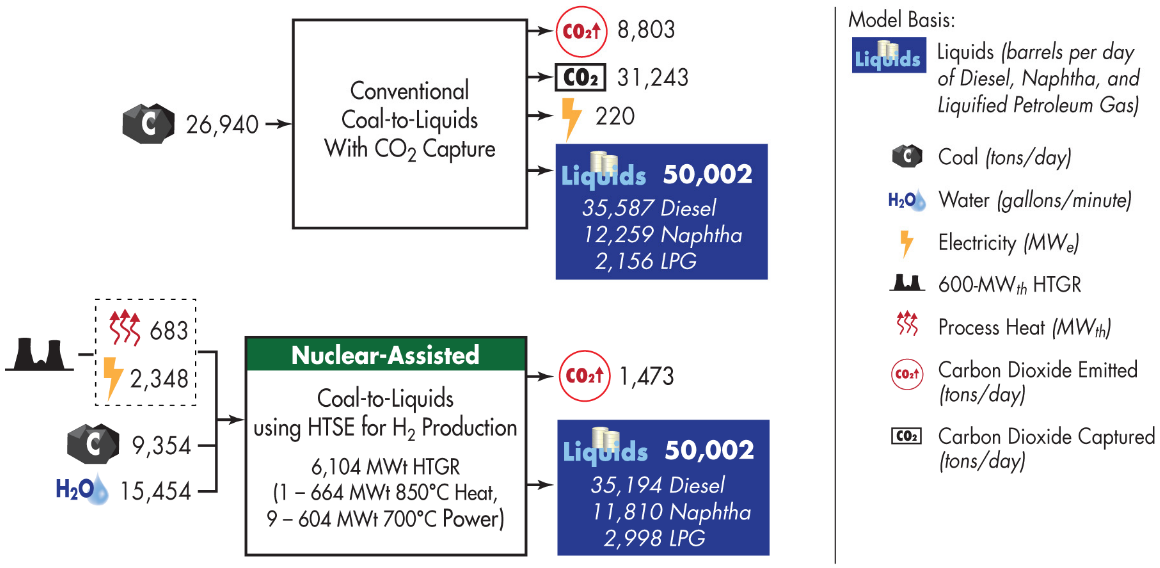

Figure 18. Mass and energy balance calculation results for the conventional and HTGR-integrated cases that were developed to evaluate an alternative for a synthetic diesel production process utilizing coal.

An economic sensitivity analysis was conducted to assess the impact of economic parameters of interest on the wholesale synthetic diesel selling price for the HTGR-integrated processes. The results are summarized in the sensitivity charts in Figures 19 and 20 for the natural-gas-based and coal-based processes, respectively. For the natural-gas-based process, natural gas price has the largest impact on the selling price of diesel followed by IRR, debt-to-equity ratio and TCI. For the coal-based process, TCI, IRR, and debt-to-equity ratio have the largest impact on the diesel selling price. It is important to note that due to the lack of demand, revenue from the sale of oxygen was not included in the economic evaluation. However, the oxygen produced by the coal-based process would be available for sale or use in other processes.

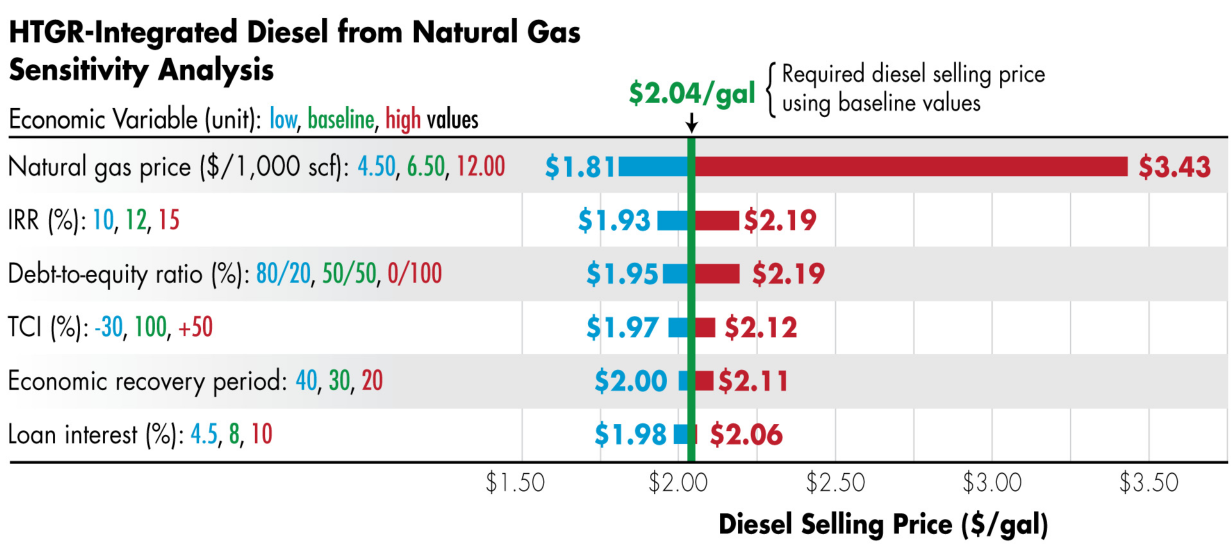

Figure 19. Sensitivity chart for HTGR-integrated production of diesel from natural gas showing the relative impact of each input variable on project economics.

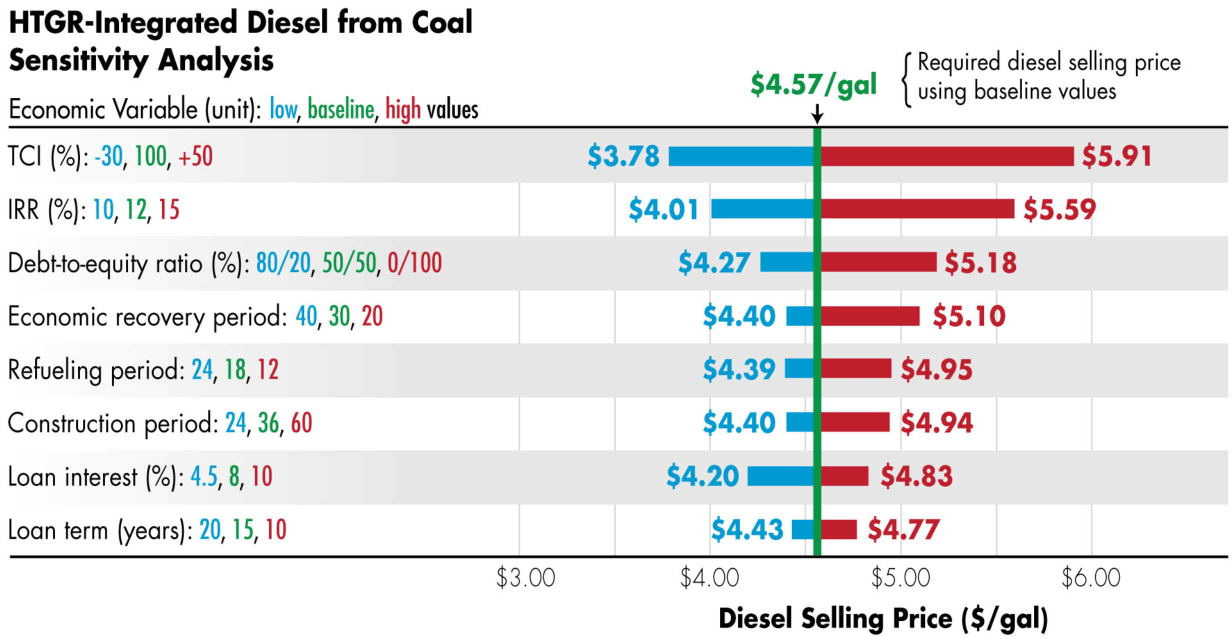

Figure 20. Sensitivity chart for HTGR-integrated production of diesel from coal showing the relative impact of each input variable on project economics.

6.1 Synthetic Diesel (Liquids) Production Utilizing Natural Gas or Coal as Inputs—WTW GHG Emissions Modeling and Results

6.1.1 Natural Gas-based Processes

The results show that WTW emissions from synthetic diesel production were lower for the HTGR-integrated process than the conventional process but would be higher than those for diesel produced by petroleum-derived processes, unless sequestration is included, as shown in Figure 21.

6.1.2 Coal-based Processes

The results show that the WTW emissions from the HTGR-integrated process would not only be lower than WTW emissions from the conventional coal-based process, but also would be lower than those from domestic or imported diesel produced by petroleum-derived processes.

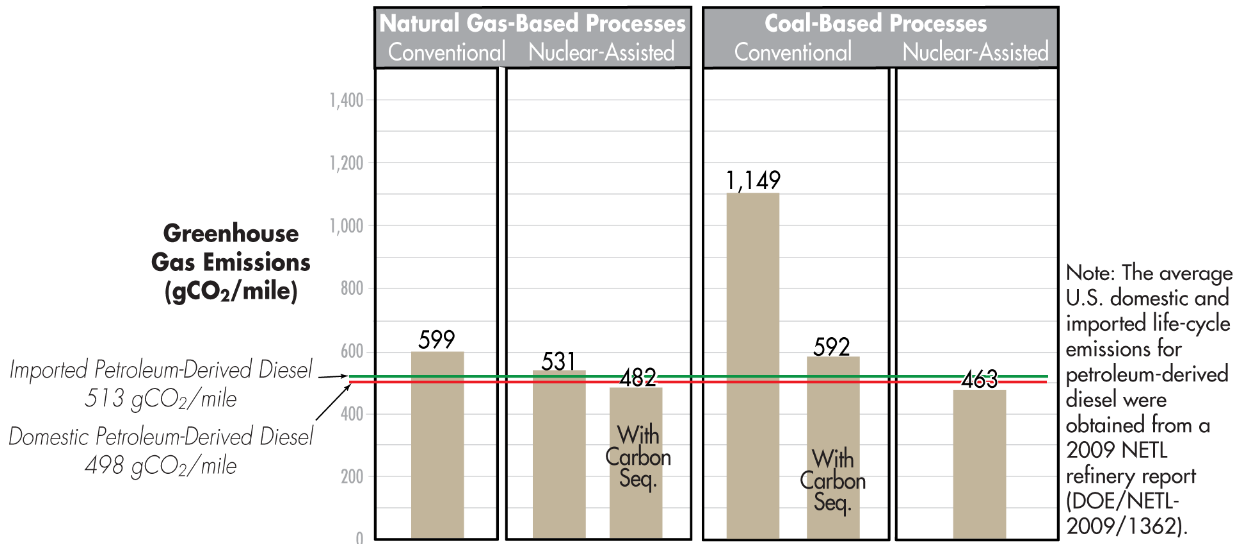

Figure 21. Comparison of calculated WTW GHG emissions from HTGR-integrated synthetic diesel (liquids) production processes with conventional synthetic diesel and imported and domestic petroleum-derived diesel production processes.

7. AMMONIA DERIVATIVES PRODUCTION UTILIZING NATURAL GAS OR COAL AS INPUTS

Ammonia can be produced from natural gas via steam methane reforming or from coal via gasification. Numerous derivative products can be produced from ammonia including nitric acid, ammonium nitrate, and urea as shown in Figure 22. Regardless of whether natural gas or coal is used as the feedstock, CO_2 is produced and significant GHGs are emitted during syngas production.

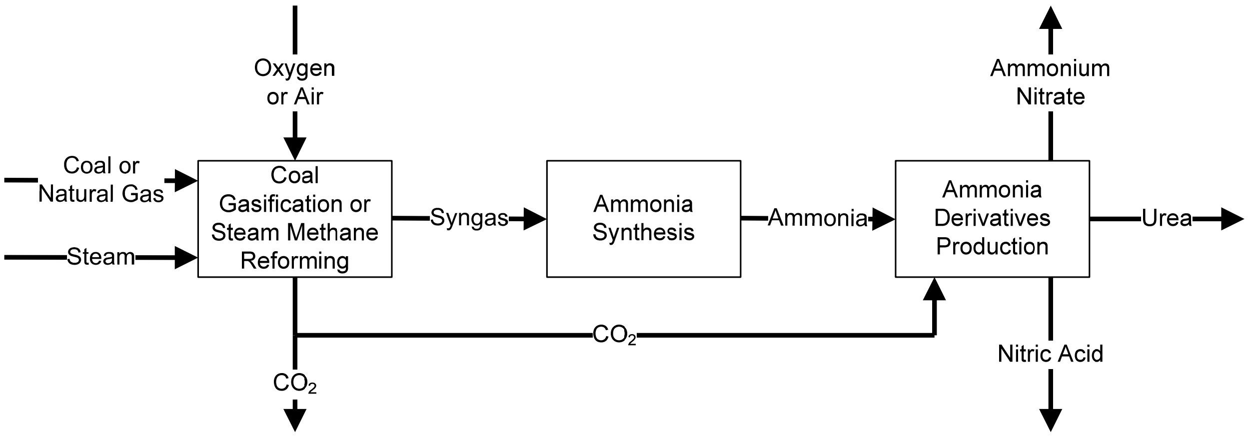

Figure 22. Simplified block flow diagram for conventional production of ammonia derivatives.

Three HTGR-integrated process models were developed as alternatives to conventional ammonia production. Of the three alternatives developed, one case (Figure 23) uses nuclear heat as a replacement for some of the heat derived from the combustion of natural gas and to produce an output equivalent to the conventional process, but utilizes methane to generate hydrogen for the process. The other two cases shown in Figures 24 and 25 further reduce natural gas requirements and subsequent GHG emissions by supplying nuclear heat and electrical power to generate hydrogen from HTSE. All models were constructed based on a plant production capacity of approximately 6,800 tons/day of urea and ammonium nitrate.

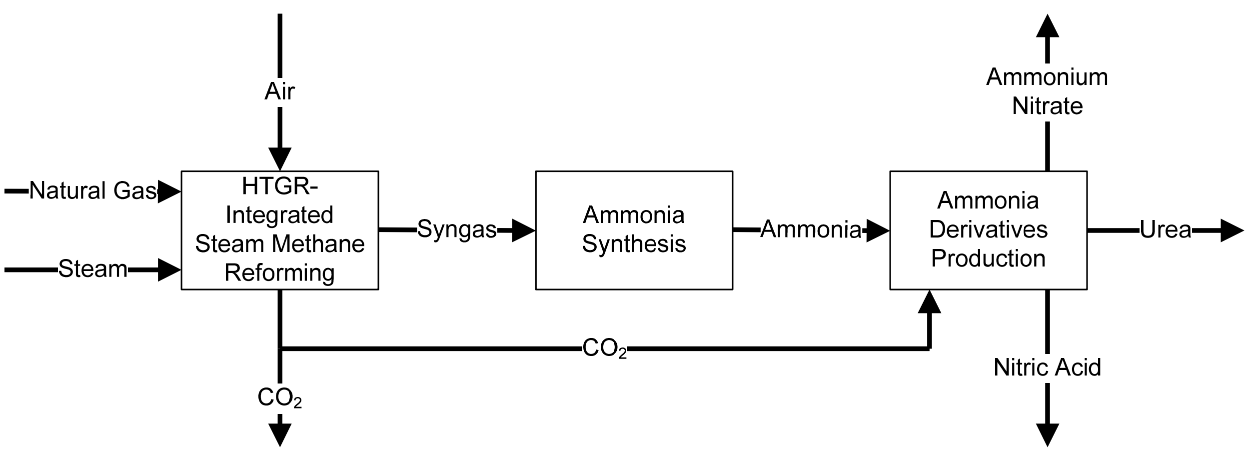

Figure 23. Simplified block flow diagram for HTGR-integrated production of ammonia derivatives using steam methane reforming for hydrogen production.

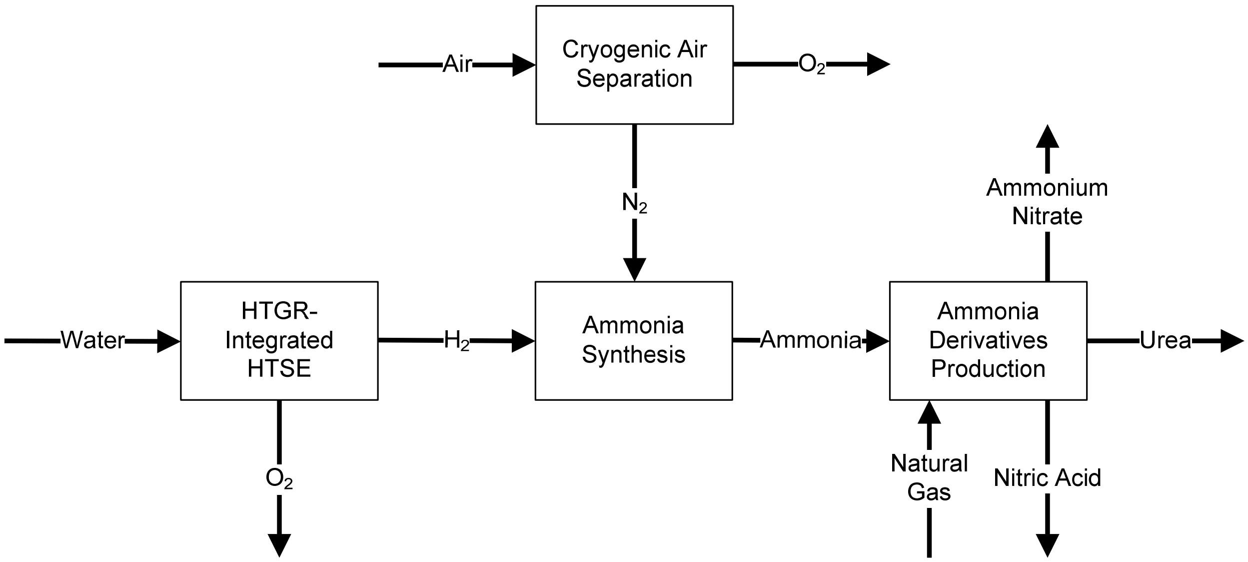

Figure 24. Simplified block flow diagram for HTGR-integrated production of ammonia derivatives using HTSE for hydrogen production and cryogenic air separation for nitrogen production.

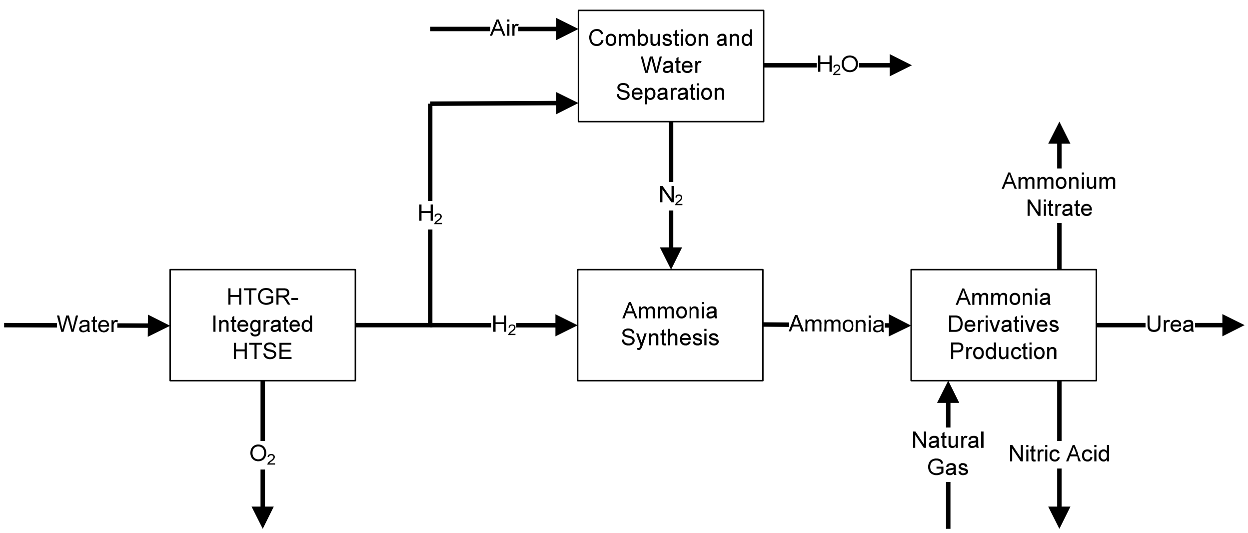

Figure 25. Simplified block flow diagram for HTGR-integrated production of ammonia derivatives using HTSE for hydrogen production and combustion for nitrogen production.

Results of the analysis indicate that HTGR-integration can substantially reduce natural gas consumption and emissions of GHGs. Incorporating HTSE further reduces natural gas consumption while nearly eliminating GHG emissions. Figure 26 summarizes the mass and energy balance results for each alternative.

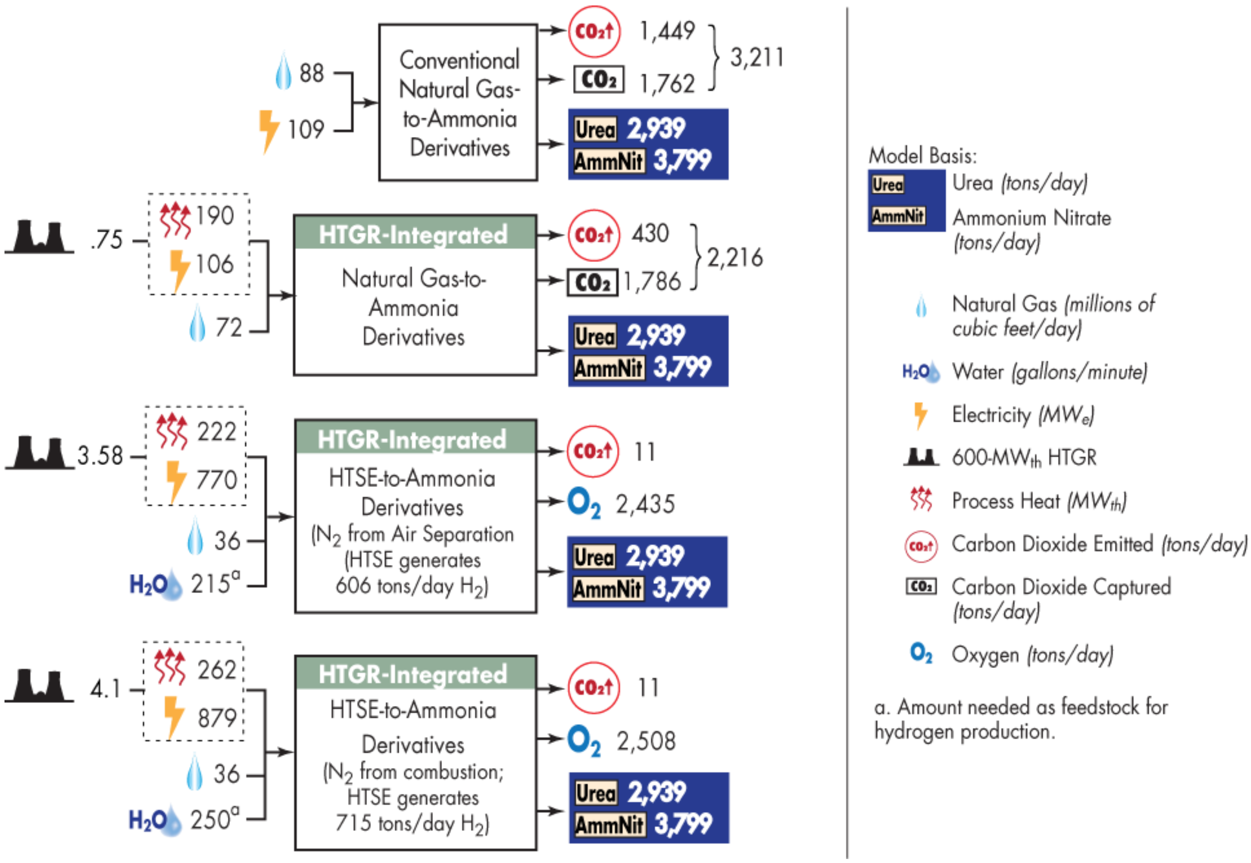

Figure 26. Mass and energy balance calculation results for the conventional and HTGR integrated cases that were developed to evaluate an alternative for an ammonia derivatives production process.

An economic analysis was conducted to assess the viability of the HTGR-integrated alternatives as shown in Figures 27 and 28. This analysis indicated that economics are primarily affected by the: (a) required return on total capital investment, (b) cost of natural gas, and (c) carbon tax imposed on CO_2 emissions. The total capital investment also had a significant impact on project economics for the HTSE scenarios. Detailed process and economic modeling results are included in Reference 5.

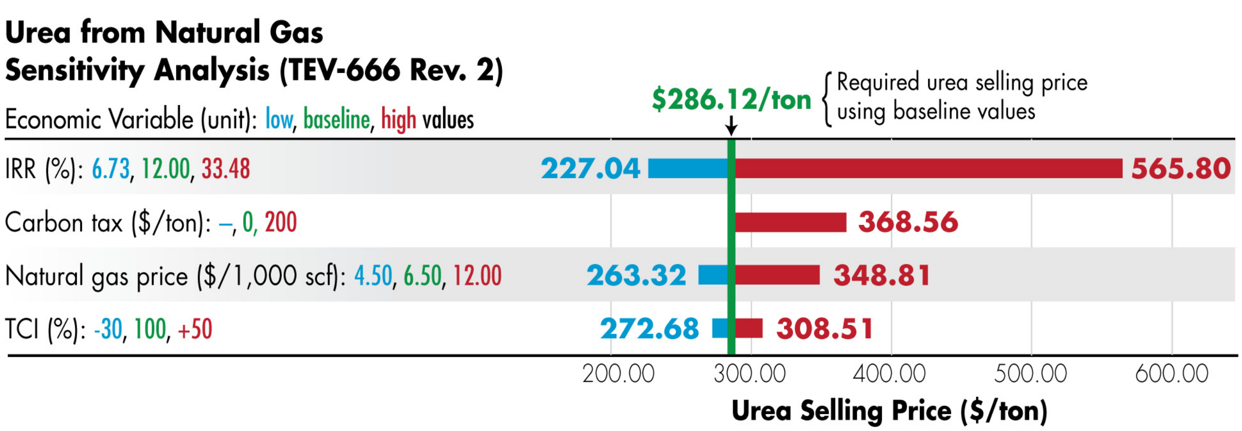

Figure 27. Economic sensitivities for producing ammonia derivatives using HTGR-integrated steam methane reforming.

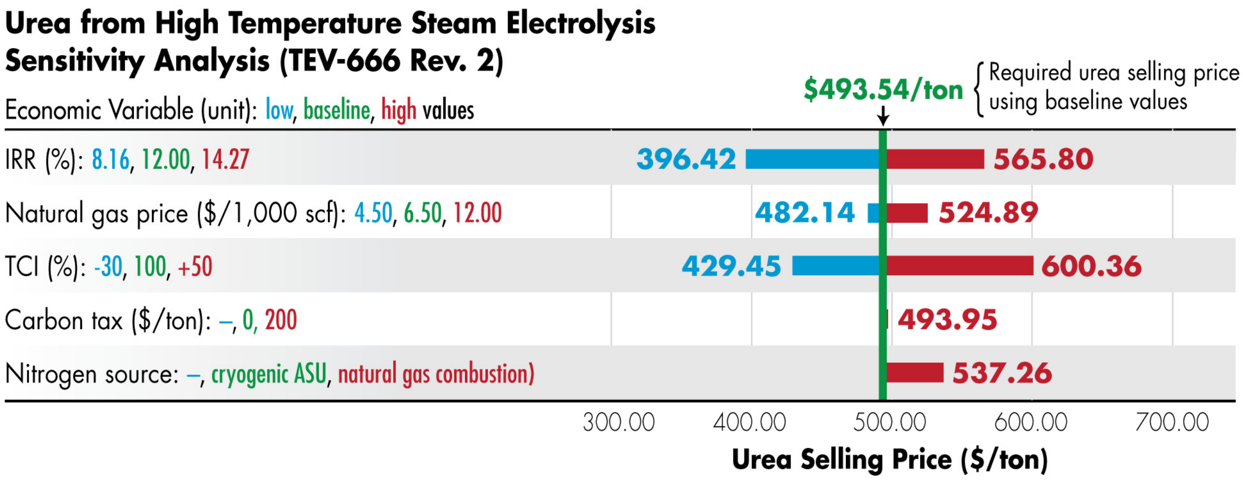

Figure 28. Economic sensitivities for producing ammonia derivatives using HTGR-integrated HTSE.

8. SAGD FOR OIL SANDS RECOVERY UTILIZING NATURAL GAS AS INPUT

The recovery of bitumen from oil sands deposits using steam is called the steam-assisted gravity drainage (SAGD) process. Steam is generated in a boiler fired by natural gas. The steam is injected into the oil sands deposit where it heats the bitumen and allows it to be brought to the surface. Bitumen is blended with naphtha to produce dilbit which is sent to a refinery for upgrading and conversion to transportation fuels and other petroleum products. In addition to dilbit, the conventional process generates significant GHG emissions as shown in Figure 29.

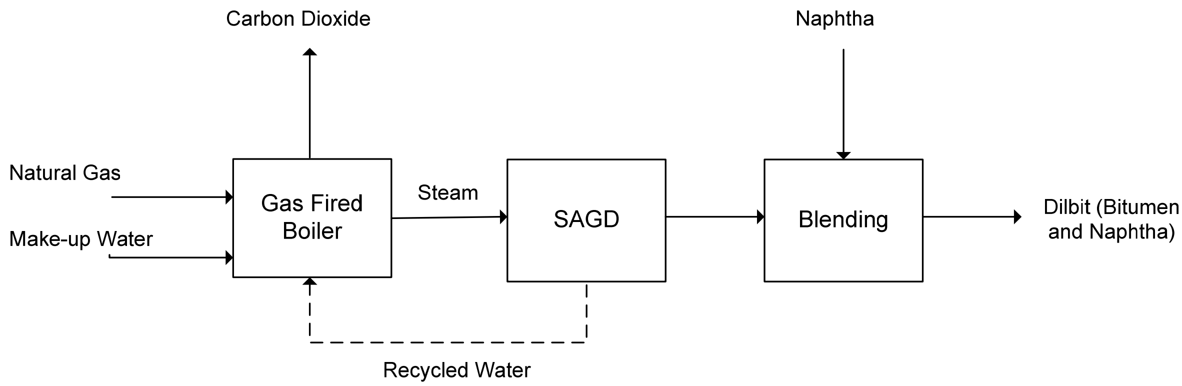

Figure 29. Simplified block flow diagram for the synthetic diesel production methods evaluated in this study.

The HTGR-integrated process is similar to the conventional process. Heat produced in the HTGR is used to generate steam which is then used in the SAGD process to produce dilbit (diluted bitumen), a mixture of naphtha and bitumen. The simplified block flow diagram for the HTGR-integrated process would be identical to the diagram shown in Figure 29 except the HTGR and steam generator replace the gas fired boiler.

The analysis of the conventional and HTGR-integrated SAGD process used parameters drawn from numerous published reports and analyses. Whenever possible, the engineering models used published information on commercially available equipment. This approach capitalized on knowledge derived from standard sizes, throughputs, energy requirements, efficiencies, and costs. A summary of the mass and energy balance results for the conventional and HTGR-integrated cases is shown in Figure 30. Both processes generate 271,429 bbl/day of dilbit (190,000 bbl/day bitumen blended with 81,429 bbl/day naphtha).

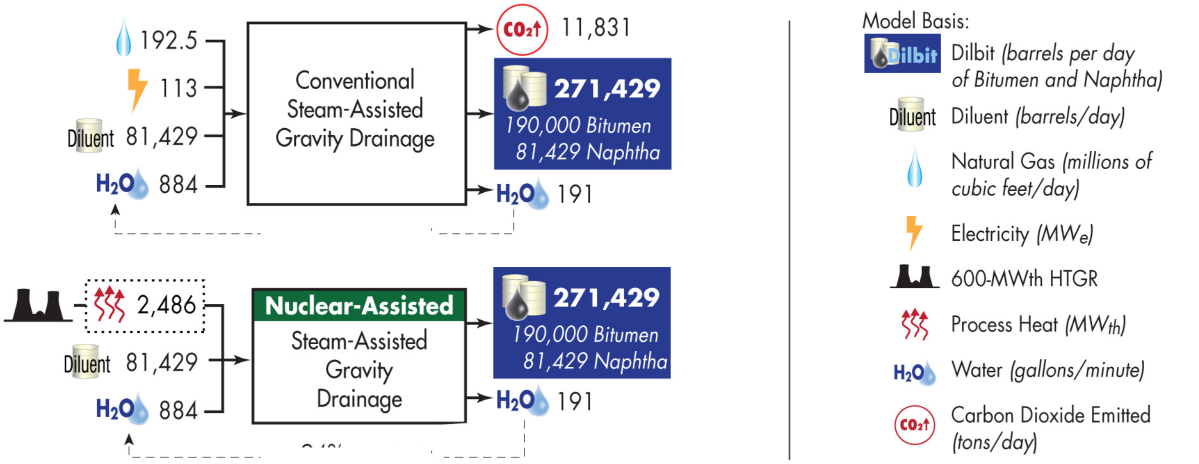

Figure 30. Mass and energy balance calculation results for the conventional and HTGR-integrated cases that were developed to evaluate an alternative for a SAGD process utilizing natural gas.

A sensitivity study was conducted to assess the impact of economic parameters of interest on the wholesale selling price of bitumen for the HTGR-integrated SAGD process. The results are summarized as the sensitivity chart in Figure 31. In the HTGR-integrated process, the total capital investment is the variable with the greatest effect on the selling price. This variable is made more significant by the construction adder of 1.658 for Alberta construction projects. The baseline wholesale selling price of bitumen is $38.72. If the total capital investment drops by 30%, the bitumen selling price decreases to $35.04.

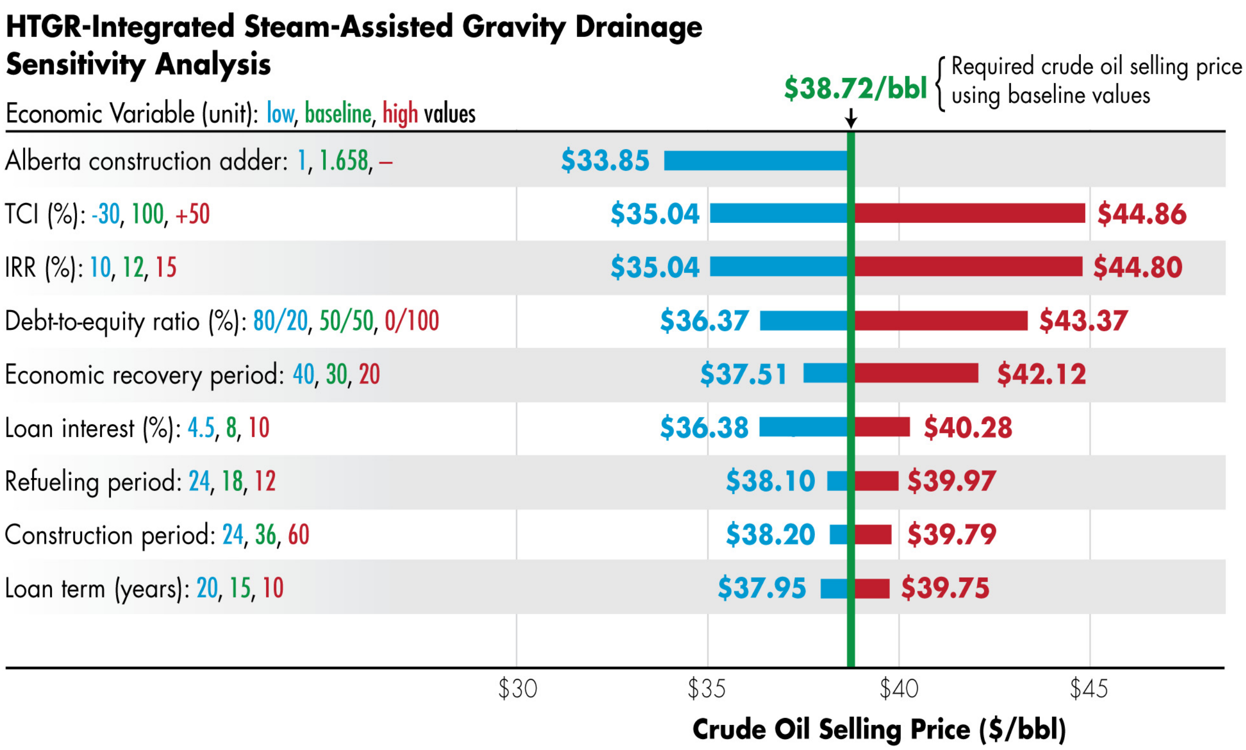

Figure 31. Sensitivity chart for HTGR-integrated production of bitumen from oil sands via the SAGD process showing the relative impact of each input variable on project economics.

9. SUBSTITUTE NATURAL GAS PRODUCTION UTILIZING COAL AS INPUT

A simplified block flow diagram for the production of substitute natural gas from coal is shown in Figure 32. In the conventional process, oxygen is separated from air and fed with coal and water to the coal gasifier. The gaseous product from the gasifier, syngas, is fed to a methanation reactor where the substitute natural gas is formed. The process generates slag and significant CO_2 emissions.

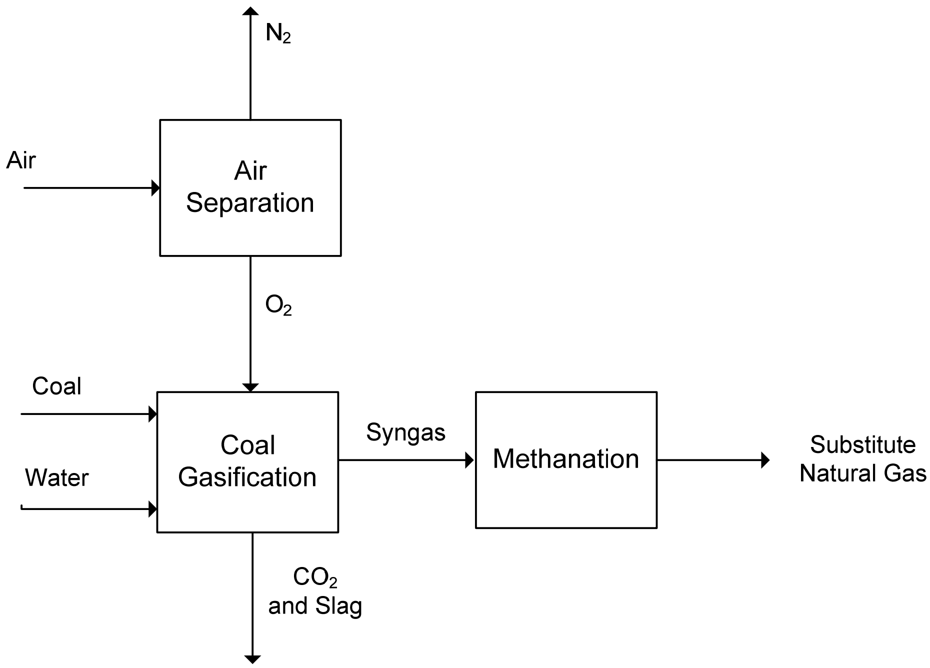

Figure 32. Simplified block flow diagram for the production of substitute natural gas from coal.

An HTGR-integrated process was developed as an alternative for the conventional process. The HTGR-integrated process uses HTSE to provide the hydrogen and oxygen required by coal gasification. The rest of the HTGR-integrated process is identical to the conventional process. A simplified block flow diagram for the HTGR-integrated process is shown in Figure 33.

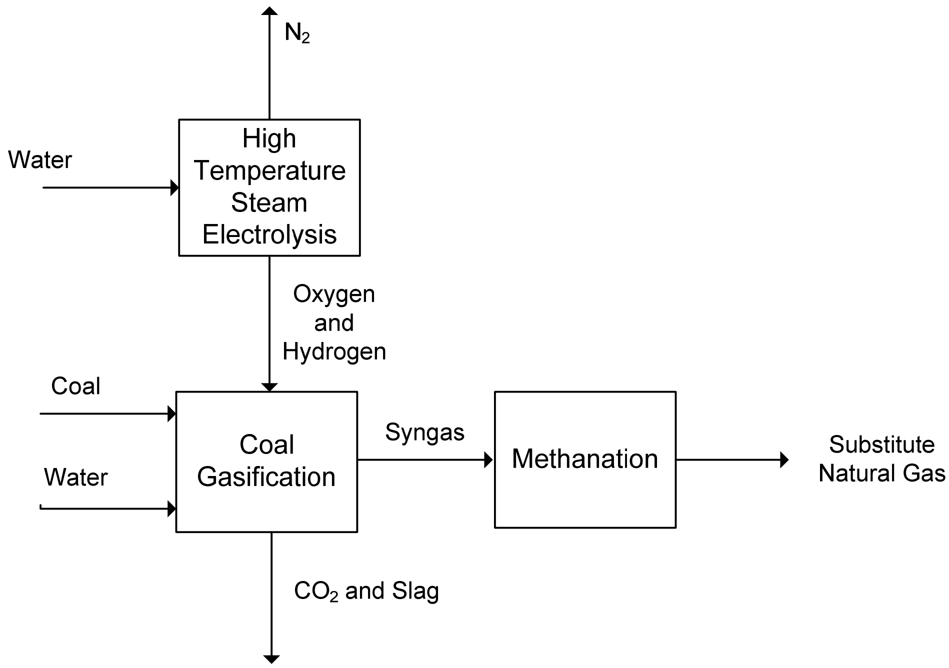

Figure 33. Simplified block flow diagram for the HTGR-integrated process for production of substitute natural gas from coal.

Both the conventional and HTGR-integrated process models were based on a typical plant production capacity of 150 million standard ft^3/day of substitute natural gas. The results of the mass and energy balance calculations for both the conventional and HTGR-integrated processes are shown in Figure 34. The HTGR-integrated case requires significantly less coal, more electricity, and more water. Additionally, the HTGR-integrated process emits significantly less CO_2 than the conventional process.

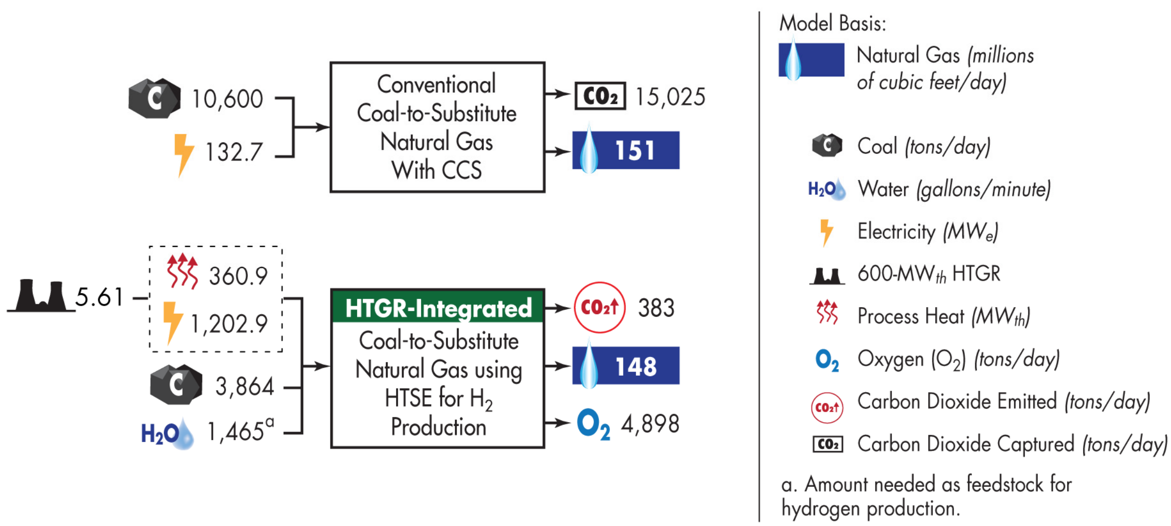

Figure 34. Results of mass and energy balance calculations for the conventional and HTGR-integrated cases that were developed to evaluate substitute natural gas production process utilizing coal.

A sensitivity study was conducted to assess the impact of economic parameters of interest on the wholesale selling price of substitute natural gas for the HTGR-integrated process. The results are summarized as the sensitivity chart in Figure 35. In the HTGR-integrated process, the IRR is the variable with the greatest effect on the selling price. The IRR also has a significant impact on the selling price of substitute natural gas. Application of a carbon tax on CO_2 emissions does not significantly impact the economics of the HTGR-integrated process.

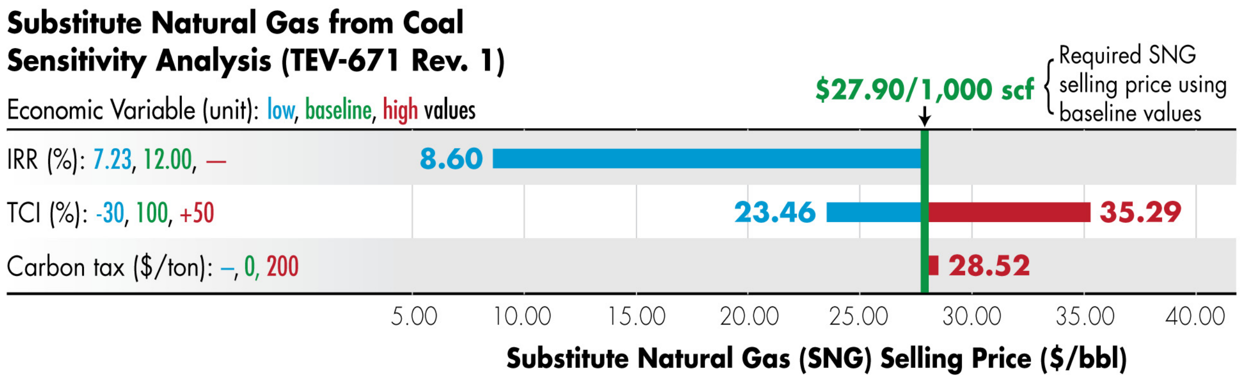

Figure 35. Sensitivity chart for HTGR-integrated production of substitute natural gas from coal showing the relative impact of each input variable on project economics.

10. CONCLUSIONS

This HTGR process integration study illustrates potential environmental and economic benefits of providing HTGR heat to conventional industrial processes to reduce the use of fossil fuel resources, reduce CO_2 emissions, and supply products to market at competitive and stable prices. In all process evaluations presented in this and previous reports, HTGR-integrated processes use less natural gas or coal and emit lower quantities of CO_2 than conventional processes. Because of the reduced reliance on fossil fuels, the costs to produce products generated by HTGR-integrated processes are less affected by fluctuations in fossil energy prices.

There are many variables that influence the economics of integrating HTGR technology into conventional energy and chemical processes. The results of this study indicate that the economic feasibility of these processes is very dependent upon TCI and IRR. However, other variables can also significantly influence the economics of a given project. It is therefore recommended that future work incorporate sensitivity studies similar to those performed as part of this study.

11. RECOMMENDED ACTIONS

The process and economic modeling should be further refined for the HTGR-integrated cases evaluated and summarized in this report with the following actions:

- Update capital, operating, and maintenance costs for the HTGR as new design data become available.
- Develop intermediate heat exchanger equipment in collaboration with industry for exchanging heat between the HTGR and industrial plants to refine model results.
- Develop water treatment and water usage assumptions for the conventional and HTGR-integrated processes with rigorous water treatment models, as this resource will come to play a significant role in siting HTGRs and HTSE operations.
- Update cases as new design data are incorporated into power generation and hydrogen cases.

12. REFERENCES

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