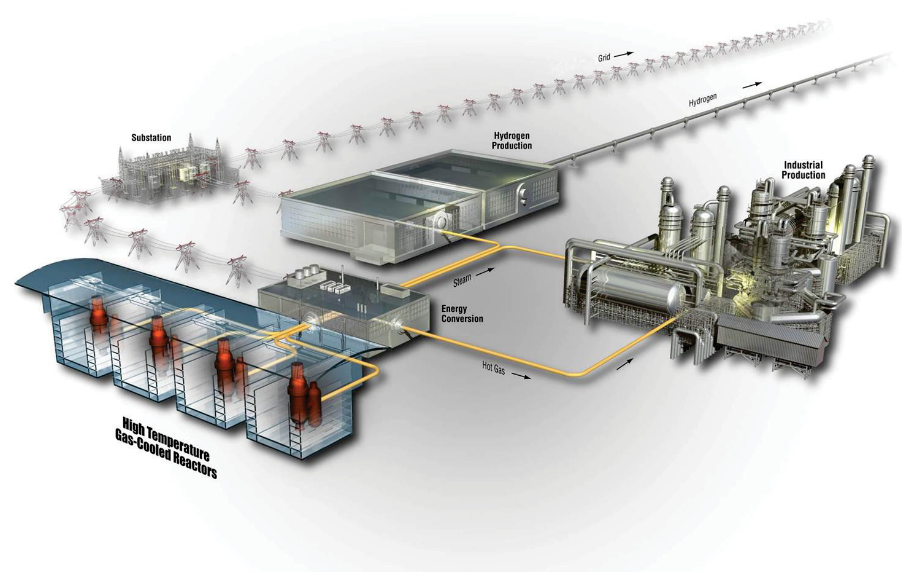
INL/EXT-11-23008

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

August 2011



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

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Next Generation Nuclear Plant Project

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

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ABSTRACT

This report summarizes the material and energy requirements for conventional and high temperature gas-cooled reactor (HTGR)-integrated processes that recover oil from oil shale, desalinate seawater, and upgrade bitumen to synthetic crude oil. An economic sensitivity analysis for HTGR-integrated processes is presented. The sensitivity analysis shows the impact of economic parameters on the wholesale product selling price. Also included is an updated economic sensitivity analysis for power production as a function of the reactor outlet temperature and summaries of other industrial processes that were briefly evaluated, which included processes to produce metallurgical coke and steel. The appendices include more detailed technical analyses for each of the processes. This report broadens a prior similar report (INL 2010a) by summarizing the additional work accomplished in Fiscal Year 2011.

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EXECUTIVE SUMMARY

The Next Generation Nuclear Plant (NGNP) project, led by the 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 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.

The engineering analyses show that HTGR-integrated processes would sharply reduce CO_2 emissions by replacing the heat derived from natural gas and coal with HTGR-supplied high-temperature process heat. An example is a conventional in situ oil shale retort process that produces 50,000 barrels of oil/day and 29.5 billion Btu natural gas/day from oil shale. An HTGR-integrated process would reduce emissions from 6,595 tons/day CO_2 to 533 tons/day as shown in Figure ES-1, while also producing 50,000 barrels of oil and 121 billion Btu/day natural gas.

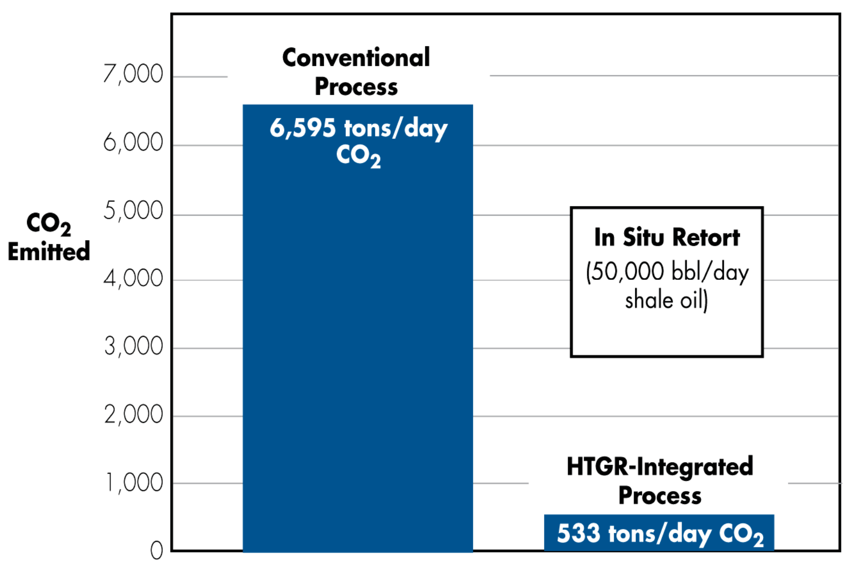

Figure ES-1. A comparison of CO_2 emissions from conventional and HTGR-integrated in situ oil shale retort processes.

During the past year, analyses 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.[a]

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. The results of the complex business models are very similar to the results obtained by the simplified business models. For reasons of brevity and clarity, this report shows only simplified models.

This report summarizes the economic analyses conducted in the past year. 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 final wholesale product selling price. The baseline wholesale product selling prices were estimated by setting all economic values to the baseline values.

Figure ES-2 shows the sensitivity chart for the HTGR-integrated in situ oil shale retort process with a baseline wholesale shale oil selling price of $59.28/bbl. The chart shows that the factors that most influence the wholesale oil selling price are the internal rate of return, natural gas price (the process is a net producer of natural gas), surface facilities capital costs, well drilling and completion costs, debt-to-equity ratio, and the project loan term. If the project internal rate of return is set to 10% for example, the estimated wholesale shale oil selling price is $45.48/bbl.

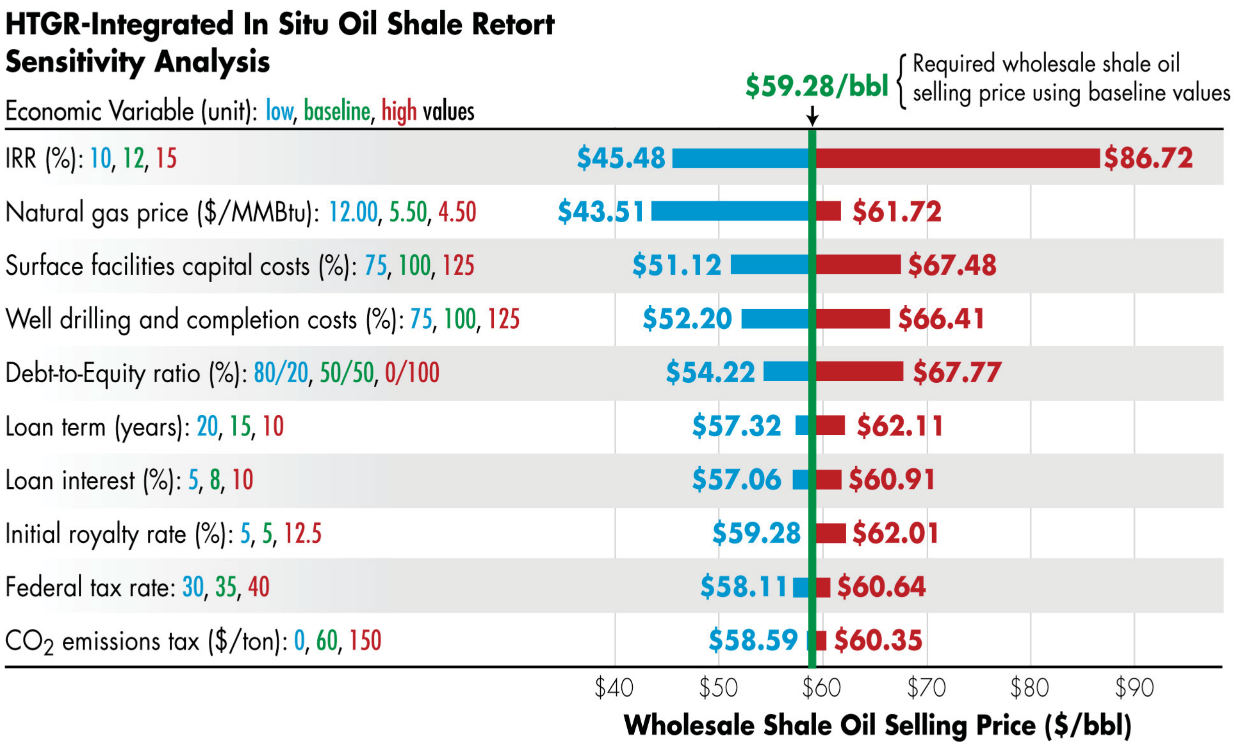

Figure ES-2. Sensitivity chart for HTGR-integrated in situ oil shale retort shows the relative impact of each economic variable on the wholesale shale oil selling price.

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

- Oil recovery from oil shale via in situ retort (Section 3)
- Oil recovery from oil shale via ex situ retort (Section 4)
- Bitumen upgrading (Section 6)
- Seawater desalination (Section 7).

Metallurgical coke and steel production was also evaluated (Section 8), but appears unsuitable for HTGR integration at the current time. In addition to the process evaluations conducted during the last year, the economic evaluation for HTGR heat and power production as a function of HTGR reactor outlet temperature was updated. Results of this update are summarized in Section 5 of this report.

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 the 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. Additionally, because the HTGR-integrated processes emit less CO_2 than the conventional processes, the economics are not affected significantly by taxes on CO_2 emissions.

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CONTENTS

FIGURES

TABLES

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ACRONYMS

GHG	greenhouse gases
HTGR	high temperature gas-cooled reactor
HTSE	high-temperature steam electrolysis
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
IRR	internal rate of return
MED	multi-effect distillation
MSF	multi-stage flash distillation
NGNP	Next Generation Nuclear Plant
RO	reverse osmosis
ROT	reactor outlet temperature
SG	steam generator
SMR	steam methane reforming
TCI	total capital investment
WTW	well-to-wheel

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Integration of High Temperature Gas-Cooled Reactors into Selected 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 differs from a third-generation light water reactor by using helium instead of water as the coolant, graphite instead of water as the moderator, and tristructural-isotropic fuel instead of metal-clad fuel. With these features, an HTGR is capable of operating at higher temperatures, which offers a broader application to industrial processes and higher thermal efficiencies than are achievable with the lower operating temperatures of light water reactors. The projected outputs from an HTGR are shown in Table 1.

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 as fuels that are refined from crude oil (INL 2010a)
- 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 recover oil from oil shale, desalinate seawater, and upgrade bitumen to synthetic crude oil. An economic sensitivity analysis for HTGR-integrated processes is presented. The sensitivity analysis shows the impact of economic parameters on the wholesale product selling price. Also included is an updated economic sensitivity analysis for power production as a function of the reactor outlet temperature and summaries of other industrial processes that were briefly evaluated, which included processes to produce metallurgical coke and steel. The appendices include more detailed technical analyses for each of the processes. This report broadens a prior similar report (INL 2010a) by summarizing the additional work accomplished in FY 2011.

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:

- Oil recovery from oil shale via in situ retort (Section 3)
- Oil recovery from oil shale via ex situ retort (Section 4)
- HTGR heat and power production as a function of HTGR reactor outlet temperature (ROT) (Section 5)
- Bitumen upgrading (Section 6)
- Seawater desalination (Section 7)
- Metallurgical coke and steel production (Section 8).

Process models were developed for all of the conventional processes selected for detailed 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 in Excel®. HYSYS® software was used to model hydrogen production and power generation. The general assumptions for the process models are shown in Table 2.

Table 2. Assumptions in process model 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)
- 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)
- High-efficiency compressors and turbines: 80– 90% efficient
- Steam generators: 25°C minimum temperature approach
- Process heat exchangers: 10°C minimum temperature approach (except when demonstrated industrial experience indicates differently)
- Intermediate heat exchanger: 25°C minimum approach temperature

The technical evaluations for each of the processes evaluated are in Appendices A through I.

The process models for the HTGR-integrated cases assumed that one or more 600-MW(t) HTGRs are located near the conventional plant. The cases that required electricity used an HTGR-integrated Rankine power cycle. The general assumptions for the HTGR-integrated technologies are listed in Table 3.

Table 3. General assumptions for HTGR-integrated technology.

- Energy products: electricity, process heat, and/or H_2
- Power generation efficiency: 41–48%
- Process heat delivered:
  - 700 to 900°C (high-temperature helium)
  - Up to 593°C (steam)
  - Gas inlet temperature: 322°C
- Heat output: 600 MW(t)
- Primary circulator: 80% efficient

Economic models were developed for the conventional and HTGR-integrated process models to assess the economic viability of HTGR integration. The economic models reflect all-in costs and revenues, and perform an after-tax discounted cash flow analysis based on the estimated total capital investment (TCI). Capital cost estimates meet the requirements established by the Association for Advancement of Cost Engineering International for a Class 4 estimate, which has an expected accuracy range of -30% to +50%. Manufacturing costs are the sum of direct costs (raw materials, utilities, operating labor, and maintenance) and indirect costs (plant overhead, insurance, and taxes). Wholesale product selling prices[b] were calculated based on a 12% internal rate of return (IRR) on the equity investment.

The economic results presented in this report illustrate the impact of various economic factors on wholesale producting selling prices for HTGR-integrated processes. To understand the impact of fluctuating natural gas prices, wholesale product selling prices were calculated based on low, average, and high natural gas prices during the past 6 years. This report summarizes the results for average ($5.50 or $6.50/MSCF) natural gas prices. The general assumptions for the economic models are shown in Table 4.

The Idaho National Laboratory (INL) HTGR cost-estimation tool described below was used to conduct the economic modeling calculations for the HTGR-integrated cases, which included one or more HTGRs, a steam generator (SG), and a Rankine power cycle. The estimates of the capital costs, and operating and maintenance costs for the HTGR-integrated cases assumed the nuclear plant was "nth-of-a-kind."

Table 4. General assumptions used for the economic analyses.

- Plant economic life: 30 years (excludes construction time)
- Construction period
  - Fossil plant: Three years
  - HTGR plant: Three years
- Start-up assumptions for "nth-of-a-kind" HTGR
  - Operating costs: 120% of estimated operating costs
  - Revenues: 65% of estimated revenue
- Plant availability: 90%
- Internal rate of return (IRR): 12%
- Inflation rate: 3%
- Interest rate on debt: 8%
- Repayment term: 15 years
- Tax basis assumptions
  - Effective U.S. income tax rate: 38.9%
  - U.S. state tax: 6%
  - U.S. federal tax: 35%
- MACRS depreciation: 15-year plant life

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 Appendix A). Capital costs include pre-construction costs, direct costs, indirect costs, and project contingency. Operating costs include operating and maintenance and fuel costs. Costs were estimated and evaluated for an anticipated ROT of 950°C as well as for lower ROTs of 700, 750, 800, 850, and 900°C. HTGR costs were developed with and without power cycles. The power cycles evaluated included both Brayton and Rankine cycles. Estimates were generated for single and four-pack (four modules) reactor configurations for both 350 and 600 MW(t) power levels and for the NGNP demonstration, first-of-a-kind, and nth-of-a-kind project phases. Cost correlations were developed to enable cost estimates for a spectrum of ROTs and plant configurations.

The cost-estimation tool shows the impact of ROT, power cycle type, and number of reactor modules on total plant costs and economies of scale. For example, the total plant cost per MW(t) increases as the HTGR ROT is increased from 700 to 950°C and when power cycles are added to the HTGR. On the other hand, the total plant cost per MW(t) decreases as the number of HTGR modules in the plant increases because the plant is able to use common systems and infrastructure such as plant utilities and administration buildings (see Appendix A for additional information).

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 SG or intermediate heat exchanger (IHX) and all associated piping, pumps, valves, and vessels. The non-nuclear part includes the industrial process. The hot steam or helium generated in the SG or IHX leaves

b Wholesale product selling price, as used in this report, represent 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. Wholesale product selling prices do not include any adders such as sales tax or retail distribution costs.

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.

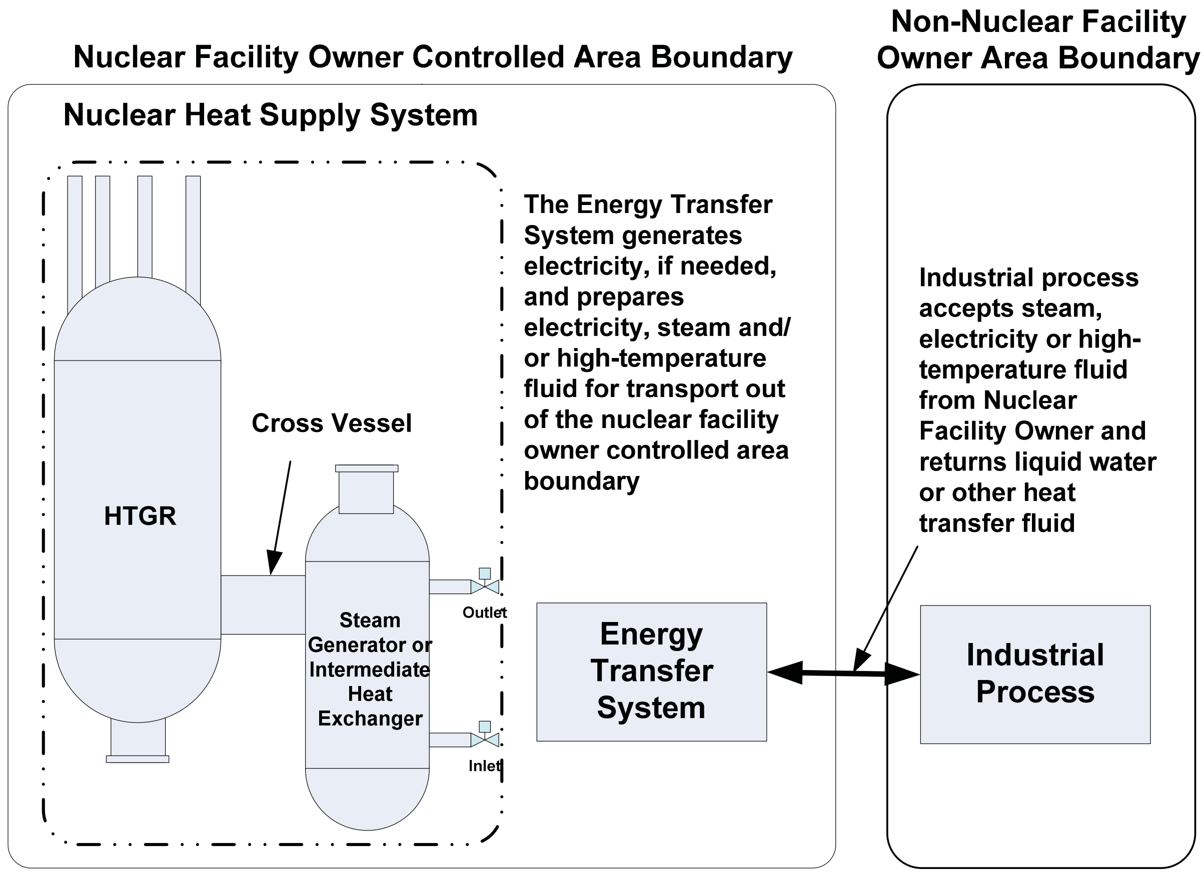

Figure 1. Block flow diagram for a generic HTGR-integrated industrial process.

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.[c] 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.

c 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.

3. PROCESS EVALUATION—OIL RECOVERY FROM OIL SHALE VIA IN SITU RETORT

The high-temperature conversion of kerogen, the organic portion of oil shale, into natural gas and shale oil in the subsurface is called the in situ retort process. A conventional in situ retort process was selected for evaluation, shown as a simplified block flow diagram in Figure 2. Steam is generated in a boiler fired by natural gas. A closed-loop injection-and-return piping system recirculates the steam from the boiler to the subsurface and back. In the subsurface, the heat from the circulating steam is transferred by conduction through the pipe wall into the oil shale. As the shale heats, the kerogen is converted to natural gas and shale oil, which are transported to the surface by the pressure generated during the conversion through production wells. A portion of the produced natural gas is used to generate steam in the gas-fired boiler. The CO_2 that is generated in the process is released to the atmosphere.

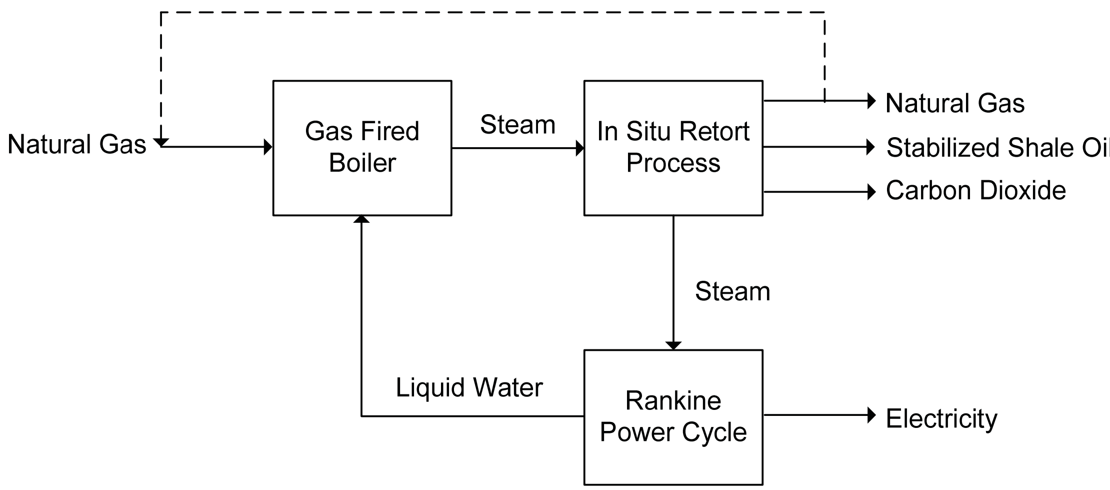

Figure 2. Simplified block flow diagram of the conventional process for recovery of natural gas and oil from oil shale via the in situ retort process.

While there are no commercial in situ oil shale operations worldwide, field-scale research, development, and demonstration projects are currently operating in western Colorado and eastern Utah, and a large-scale, commercial in situ oil shale industry may emerge in the United States within 10 to 15 years.

An alternative process model was developed that uses heat from an HTGR to replace the heat derived from natural gas combustion. In this model, the in situ retort process and the Rankine power cycle are nearly identical to those in the conventional process. The block flow diagram for the HTGR-integrated process is identical to the diagram shown in Figure 2, except the HTGR and SG replace the gas-fired boiler.

The analysis of the hypothetical conventional and HTGR-integrated in situ retort production operations 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 3. Both processes generate 50,000 bbl of oil per day. The conventional process produces less natural gas, but more electricity than the HTGR-integrated process and emits approximately 12.4 times more CO_2.

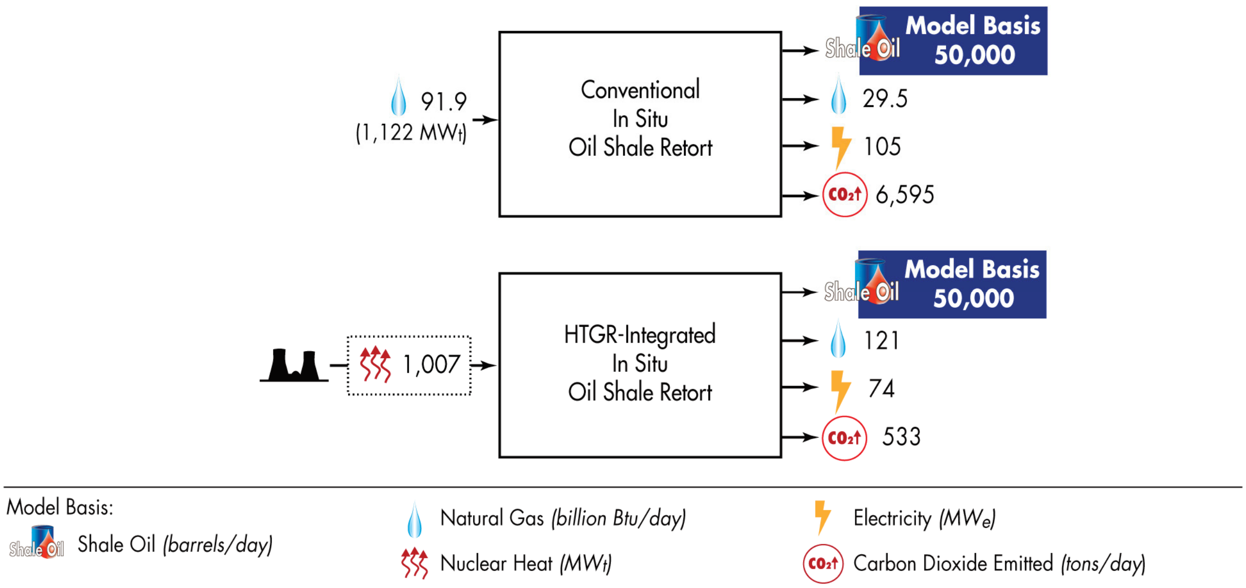

Figure 3. Simplified net mass and energy inputs and outputs for two in situ oil shale retort cases.

An economic sensitivity analysis was conducted to assess the impact of economic parameters of interest on the wholesale shale oil selling price for the HTGR-integrated in situ oil shale retort process. The results are summarized as a sensitivity chart and shown in Figure 4. In the HTGR-integrated process, the IRR is the variable with the greatest effect on wholesale shale oil selling price. For example, assuming an HTGR-integrated process where the wholesale oil selling price for a 12% IRR is $59.28/bbl, varying the IRR from 10% to 15% would cause the wholesale oil selling price to vary from $45.48/bbl to $86.72/bbl. Also, since the HTGR-integrated process is a net producer of natural gas, as natural gas prices increase, the wholesale shale oil selling price decreases. Other economic variables also have an effect on the wholesale selling price of oil.

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. Appendix B contains the complete process modeling results. Appendix C contains the complete economic sensitivity studies.

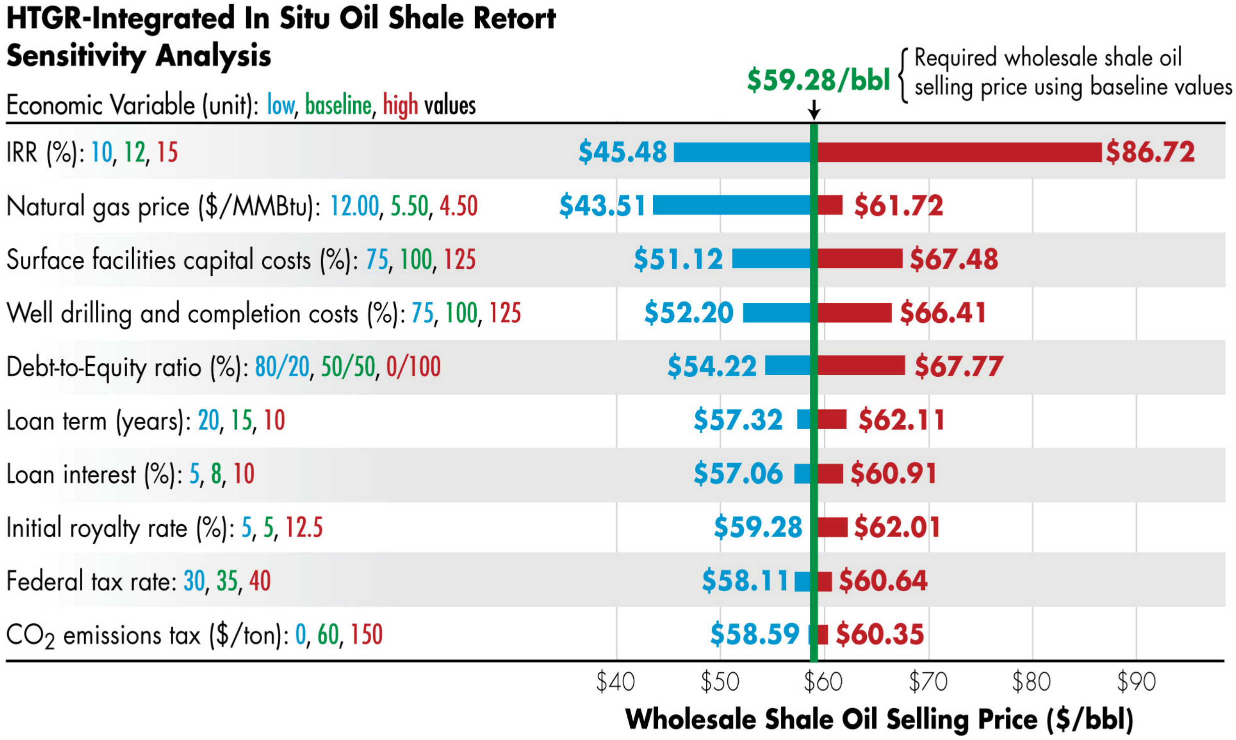

Figure 4. Economic sensitivity chart for the HTGR-integrated process showing the relative impact of each input variable on the wholesale shale oil selling price.[d]

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[d] In this tornado chart and in the other tornado charts presented in this report, the "**low**" economic variable represents the value that results in the lowest wholesale selling price (or IRR in Figure 13) and the "**high**" economic variable represents the value that results in the highest wholesale selling price (or IRR in Figure 13).

4. PROCESS EVALUATION—OIL RECOVERY FROM OIL SHALE VIA EX SITU RETORT

The high-temperature conversion of kerogen, the organic portion of oil shale, into natural gas and shale oil above ground is called the ex situ retort process. The conventional ex situ retort process, shown as a simplified block flow diagram in Figure 5, was selected for evaluation. Oil shale ore is mined from mines located near the retort kiln. All mining equipment and machinery is powered by electricity purchased from the grid. Mined ore is fed into the rotating, horizontally-oriented Alberta Taciuk Processor kiln for retorting. The shale enters the processor and is heated from ambient temperature to about 500°C. During the retort process, the kerogen decomposes into hydrocarbon gases, shale oil, and char. The combustion of the char, which occurs at approximately 750°C, provides the heat necessary for preheating and retorting the shale ore and releases CO_2. At that temperature, the carbonate material in the shale substrate decomposes and releases additional CO_2. The CO_2 generated by the process is released to the atmosphere. Spent shale, which has been retorted and combusted, cools as it transfers its heat to the incoming ore and is further cooled by water spray as it exits the processor. The condensable raw shale oil product leaves the processor kiln with a density of approximately 19°API. To stabilize it for transport via pipeline to a refinery, the oil is upgraded by hydrotreating to approximately 38°API, which lowers its pour point to acceptable pipeline limits as well as reduces the nitrogen and sulfur concentrations.

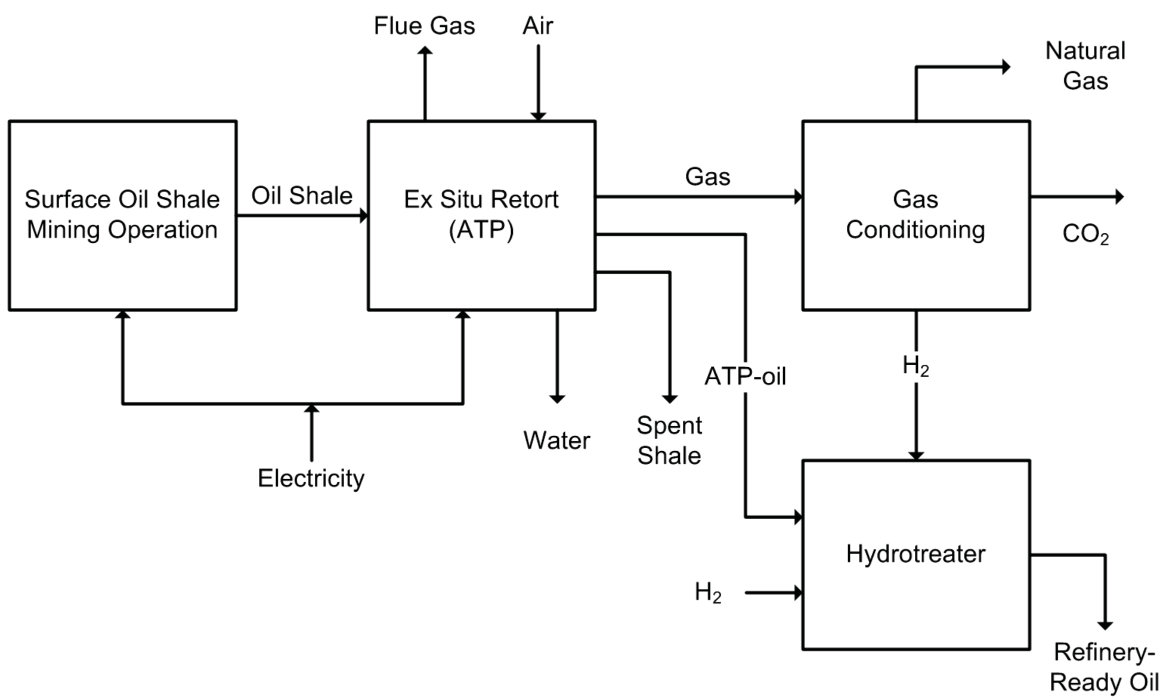

Figure 5. Simplified block-flow diagram for the conventional ex situ oil shale retort process.

An alternative process model was developed that uses high-temperature helium from an HTGR to supply the heat necessary for ex situ retort, replacing the heat provided by the combustion of char. In this model, the spent shale, embedded with char, is ejected from the retort as an output stream at 500°C (the retort temperature). CO_2 emissions resulting from the decomposition of nahcolite mineral are included in the analysis, but CO_2 emissions resulting from the decomposition of the carbonate material in the oil shale ore are not included because the temperature remains below the carbonate decomposition temperature of 600°C. A simplified block flow diagram for the HTGR-integrated ex situ oil shale retort operation is shown in Figure 6.

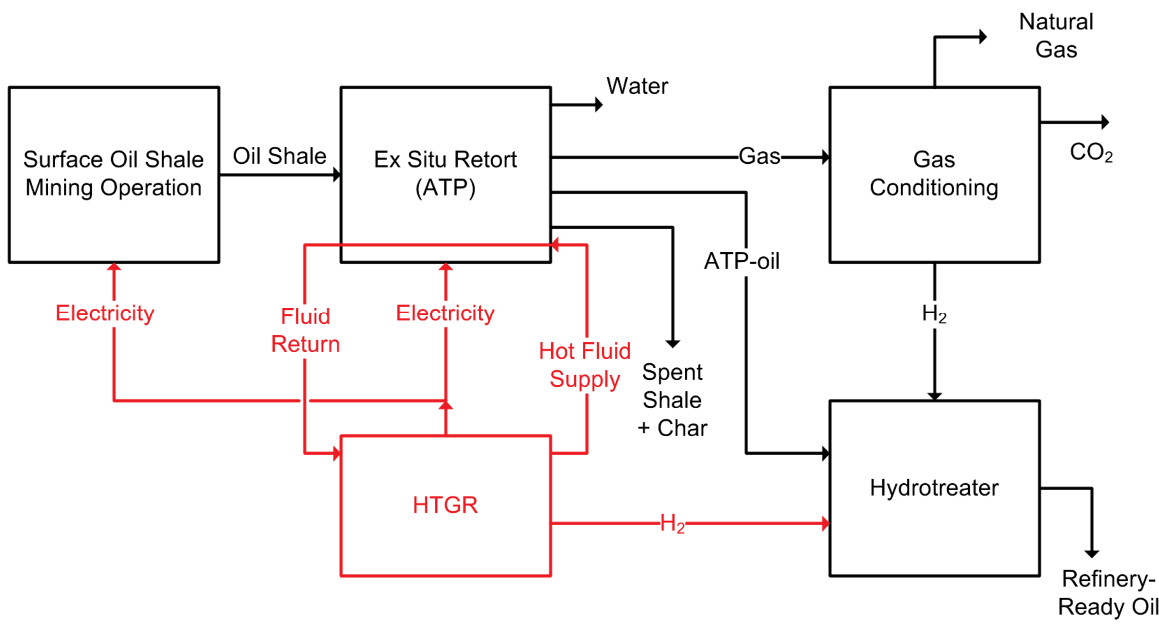

Figure 6. Block-flow diagram for an HTGR-integrated ex situ oil shale retort operation.

The analysis of the hypothetical conventional and HTGR-integrated ex situ retort production operations 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 7. Both processes upgrade 74,444 ton/day of raw oil shale ore to produce 50,000 bbl/day of refinery-ready, 38°API shale oil. The HTGR-integrated case emits 12 times less CO_2 than the conventional case.

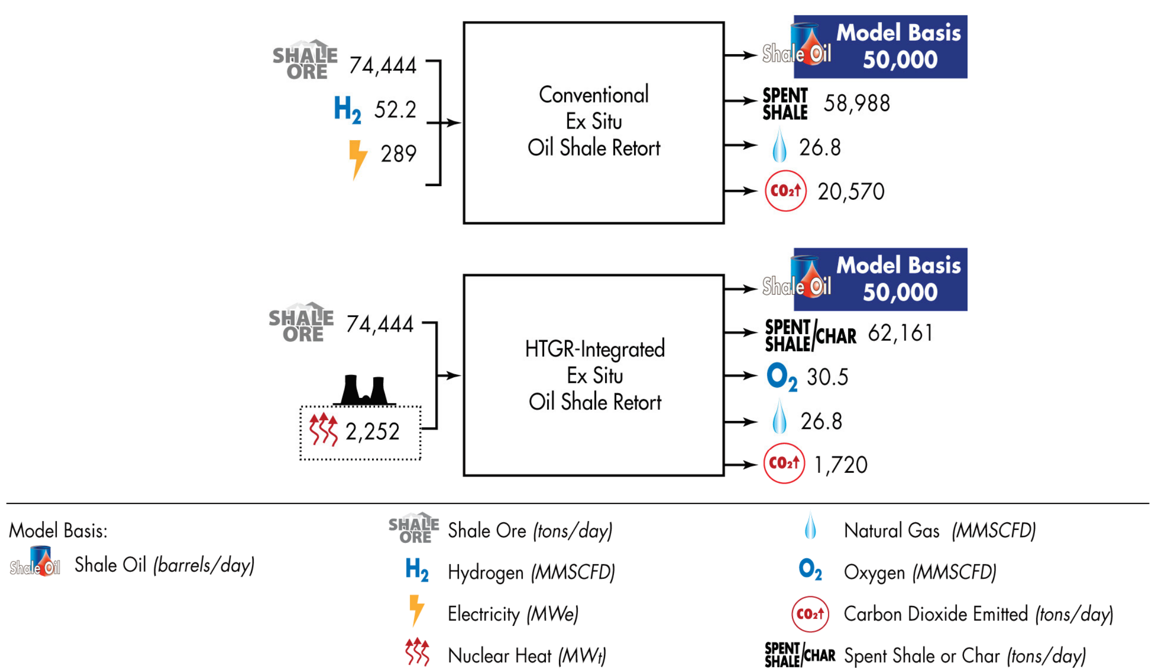

Figure 7. Simplified net mass and energy inputs and outputs for the two ex situ oil shale retort cases.

An economic sensitivity analysis was conducted to assess the comparative viability of the conventional and HTGR-integrated ex situ retort processes. The results for the HTGR-integrated ex situ oil shale retort evaluation are summarized in Figure 8. The economic analysis showed that the IRR has the largest impact on wholesale shale oil selling price, followed by the uncertainty in the HTGR TCI and the debt-to-equity ratio. Full results of the process modeling are contained in Appendix D. Economic modeling results are contained in Appendix E.

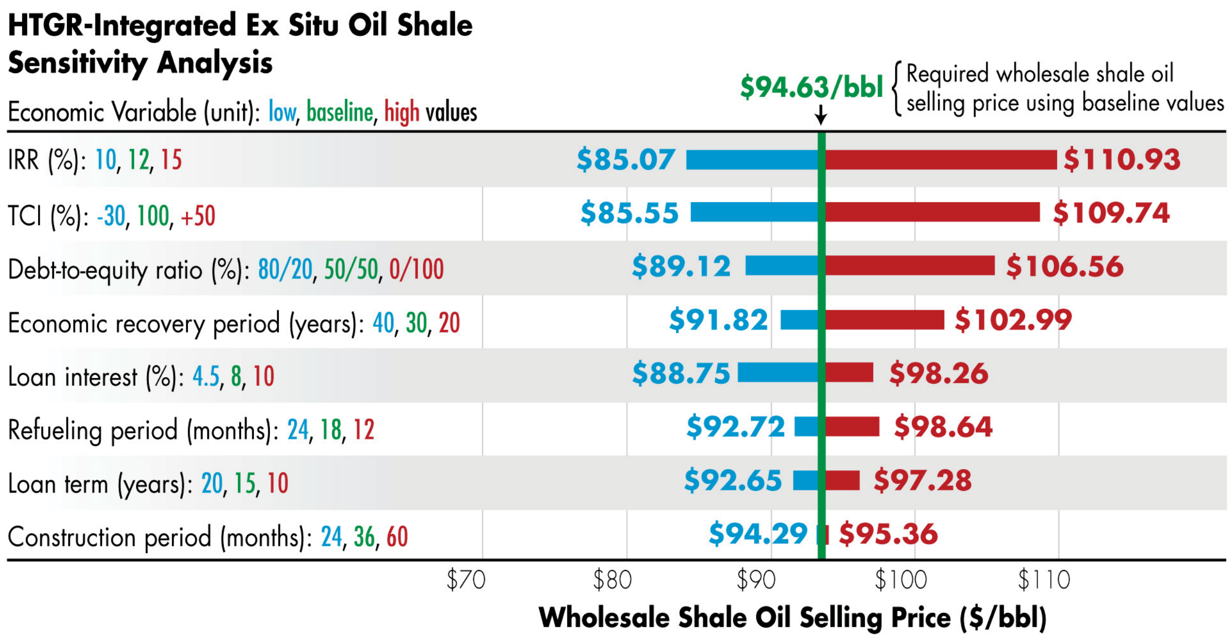

Figure 8. Economic sensitivity chart for the HTGR-integrated ex situ oil shale retort process showing the relative impact of each input variable on the wholesale shale oil selling price.

5. ECONOMIC EVALUATION—HTGR HEAT AND POWER PRODUCTION AS A FUNCTION OF ROT (UPDATED RESULTS)

The economic evaluation for heat and power production as a function of ROT (contained in Appendix F) was updated to include revised HTGR capital and operating cost estimates (contained in Appendix A). In a previous revision of this study, the HTGR capital and operating costs used were not a function of ROT, power cycle type, the number of reactor modules, or reactor power level. Incorporating the updated capital and operating costs allows conclusions to be drawn concerning the effect of ROT on the economic results, as well as gains in economy of scale that can be realized through multiple module installations.

The economics were evaluated for ROTs of 700 to 950°C, in 50°C increments, including configurations with and without power cycles for both Rankine and Brayton cycles. The baseline reactor size evaluated was 600 MW(t) with reactor power levels of 200 and 350 MW(t) also considered. When evaluating the economics of heat and power production using the updated HTGR capital and operating costs from Appendix A, the following conclusions can be drawn:

- The wholesale selling price of heat and power decreases as the number of reactor modules is increased. This is because of gains in economies of scale for the capital costs and the fact that only an incremental increase in staffing is required for each additional module at multiple module sites.
- The economically optimal ROT for heat and power generation is 850°C from a Brayton cycle; 700°C from a Rankine cycle; and 800°C (steam at 540°C and 17 MPa) for steam generation.[e] The Brayton cycle economically outperforms the Rankine cycle at ROTs greater than 900°C. The optimal ROT for heat in the form of hot helium is dependent upon the process heat requirements.
- The economic sensitivity analysis shows that the uncertainty in the TCI has the largest impact on the wholesale selling price, followed by the assumed IRR and the debt-to-equity ratio. A sensitivity diagram in Figure 9 shows the resulting wholesale electricity selling price for a 700°C ROT HTGR with a Rankine power cycle when baseline economic assumptions are varied.
- A sensitivity analysis was also performed on the reactor power level and the number of modules. The results show that as the reactor power level increases, the wholesale selling price of heat and power decreases. Furthermore, as the number of modules increases, the wholesale selling price for heat and power decreases. In both cases, these results are because of gains in economies of scale for capital and operating costs. Figure 10 shows the reactor power level and module number results for an HTGR with a Rankine cycle at an ROT of 700°C. The 700°C ROT was selected because it resulted in the lowest wholesale electricity selling price.

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[e] Based on the material and energy balance, the optimal ROT for steam generation is 770°C (see TEV-981); however, the temperature range of the economic analysis presented in TEV-988 for steam generation was 700 to 900°C in increments of 50°C and the optimal ROT of 800°C was selected for steam generation.

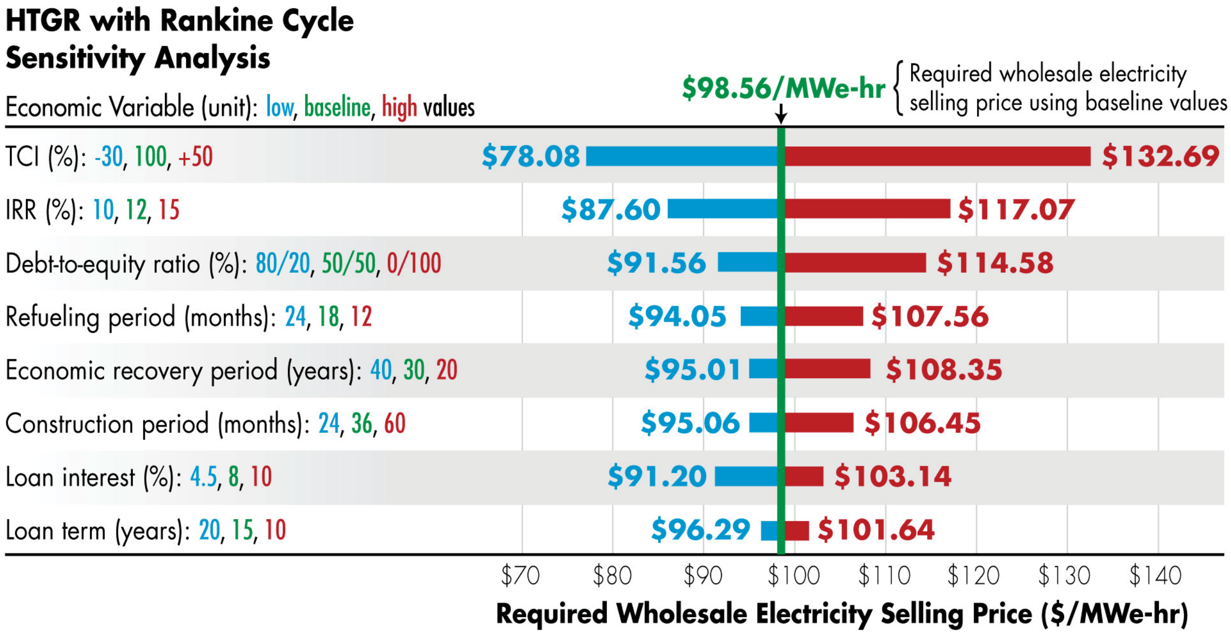

Figure 9. Sensitivity chart for HTGR with Rankine cycle (four 600-MW(t) HTGRs at 700°C ROT) showing the relative impact of each input variable on project economics.

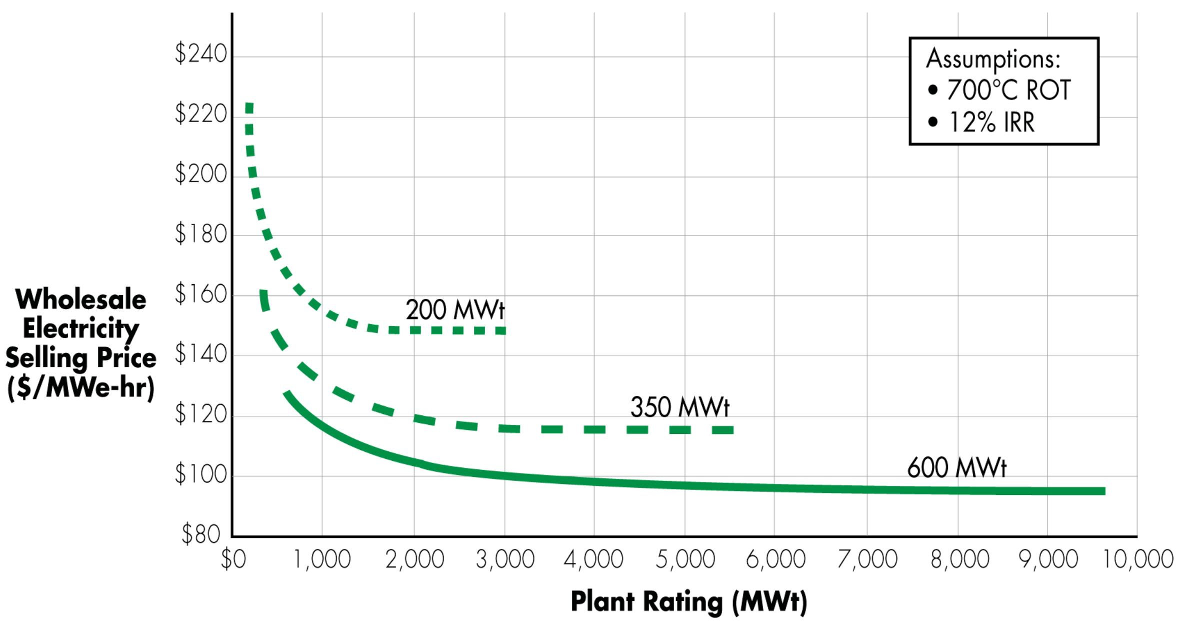

Figure 10. Sensitivity analysis results showing wholesale electricity selling price for HTGRs with Rankine cycles at varying power levels and number of reactor modules.

6. PROCESS EVALUATION—BITUMEN UPGRADING

There are many oil sands deposits around the world, including significant deposits in Canada that have been developed to produce bitumen. Bitumen must be upgraded to synthetic crude oil before it is suitable for further refining to finished products such as gasoline, diesel, and jet fuel.

To upgrade bitumen to synthetic crude oil, a significant amount of heat and hydrogen are required. Typically, much of the heat demand is supplied by combusting fuel gas that is generated from bitumen as a result of the normal upgrading process. Heat requirements above and beyond what can be supplied by fuel gas are typically supplied by combusting natural gas. Hydrogen required for upgrading is produced by steam methane reforming (SMR) of natural gas. Heat from an HTGR can be used to replace heat from natural gas combustion. An HTGR can also be used to produce hydrogen either by heat integration with the SMR directly or by replacing SMR altogether with an HTGR-integrated HTSE system.

A simplified block-flow diagram for conventional bitumen upgrading is shown in Figure 11. HTGR heat could be used for fractionation, primary and secondary upgraders, the steam methane reformer, and the coker. An HTGR-integrated HTSE system could also replace SMR.

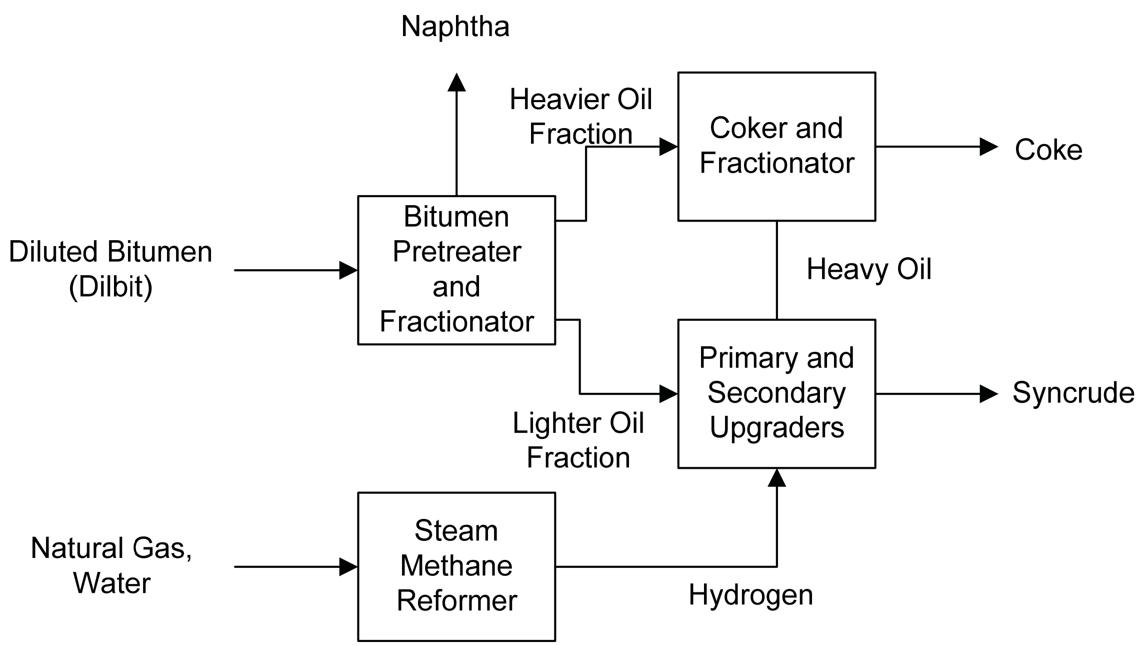

Figure 11. Bitumen upgrading block-flow diagram.

The principal benefits of integrating an HTGR with bitumen upgrading are the conservation of fossil energy resources and reduction of CO_2 emissions. An HTGR/SMR integrated facility for upgrading 56,000[f] bbl/day of bitumen to synthetic crude oil would require 329 MW(t) from the HTGR. Natural gas consumption would be reduced by 46%. CO_2 emissions would be reduced by 38%. An HTGR/HTSE-integrated with the same model basis would require 957 MW(t) from the HTGR, but natural gas consumption would be completely eliminated and overall CO_2 emissions would be reduced by 82%. A summary of mass and energy balance results for each case are shown in Figure 12.

f This size facility was selected to coincide with the INL analysis of SAGD operations (see INL 2010b).

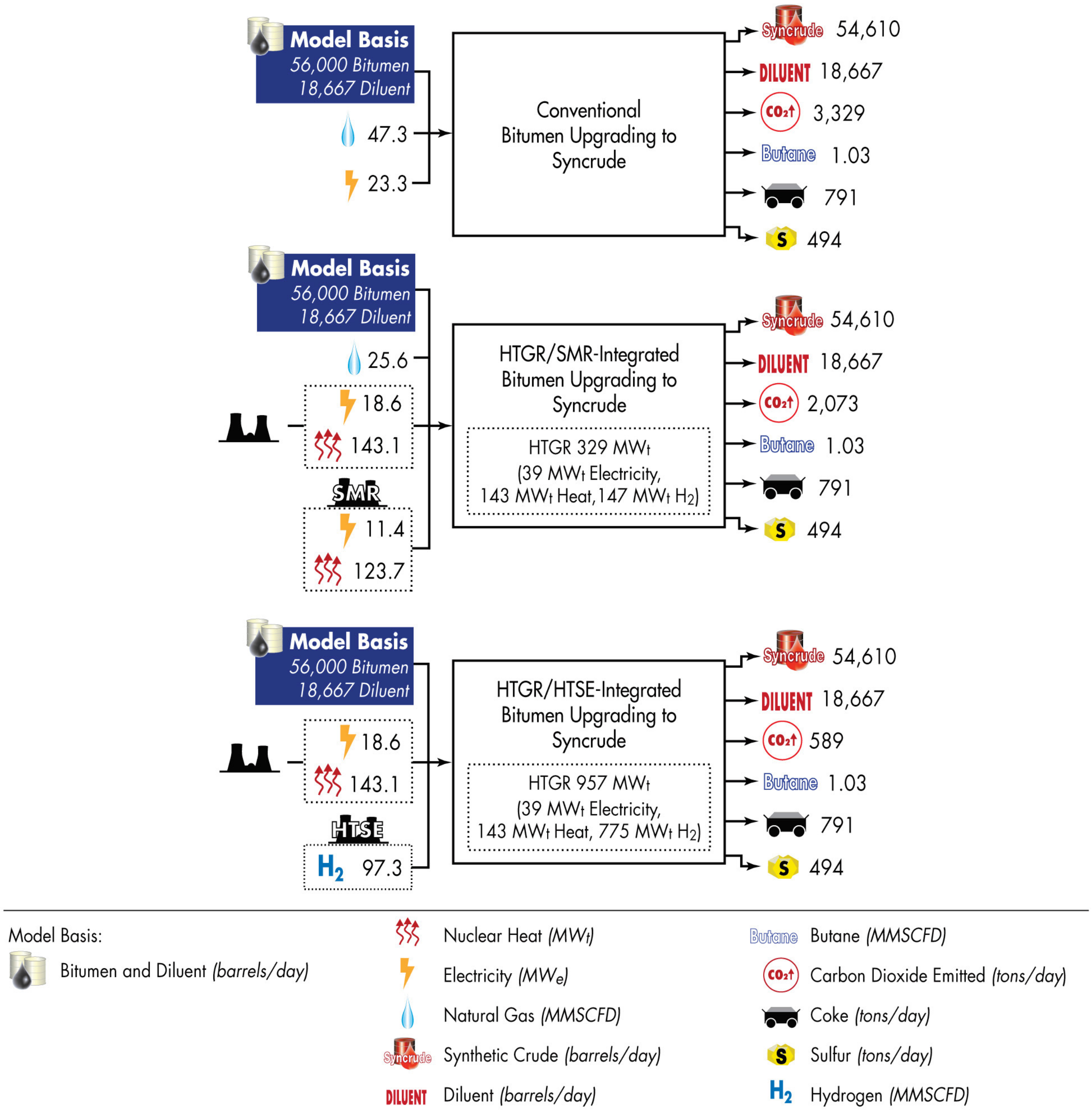

Figure 12. Simplified net mass and energy inputs and outputs for the bitumen upgrading cases.

An economic analysis was performed to determine the impact of incorporating an HTGR into a bitumen upgrading process. The analysis only considered equipment additions and differences in feedstock and product quantities. The objective was to identify the IRR that could be achieved for the HTGR and associated equipment in comparison to the baseline process. The effects of varying CO_2 emissions tax and the price of natural gas were also considered.

Economics were calculated for a scenario in which multiple HTGRs were constructed at a central complex to supply heat and power to a steam-assisted gravity drain operation as well as the upgrader. For this scenario, it was assumed that the capital cost of the HTGRs would be 30% less than for the single-reactor scenario. Economics were also calculated for a scenario that assumed retrofit of an existing upgrader.

The results showed that because the HTGR requirement in the HTGR/HTSE scenario is nearly three times that of the HTGR in the SMR scenario, the HTSE scenario does not become economically viable until gas prices increase to around $12/1,000 scf and/or the tax on CO_2 emissions increases to around $200/ton.

For the HTGR/SMR scenario, the baseline IRR of 5.60% can be achieved with the following assumptions:

- Natural gas price at $6.50/1,000 scf
- CO_2 emissions tax at $50/ton
- TCI assumes a single-reactor scenario
- A new plant construction scenario is considered.

Results for the HTGR/SMR scenario are shown in Figure 13. As can be seen, this scenario becomes economically attractive as natural gas price increases and as more stringent CO_2 emission limits are imposed. More detailed information about the evaluated processes is contained in Appendix G.

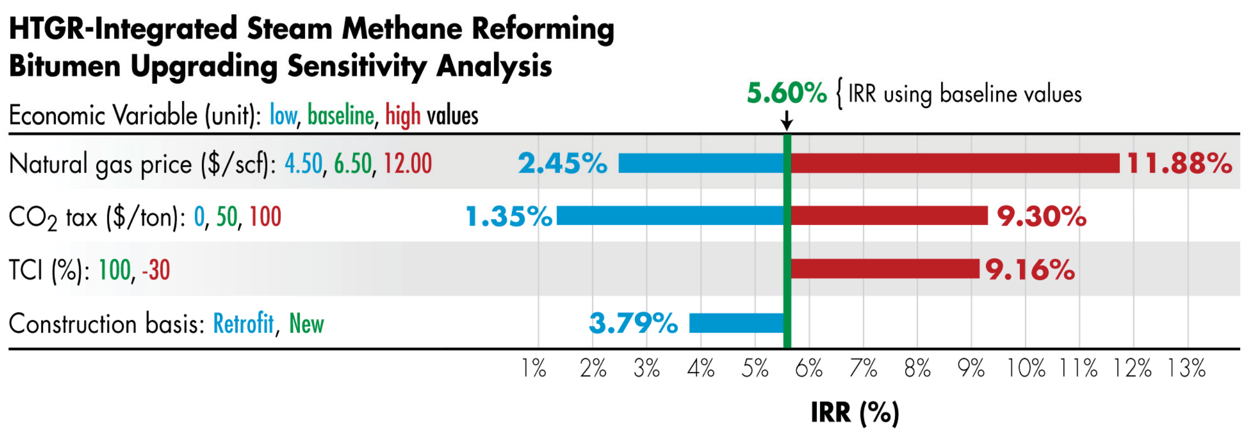

Figure 13. Sensitivity chart for the HTGR-integrated SMR bitumen upgrading case showing the relative impact of each input variable on project economics.

7. PROCESS EVALUATION—SEAWATER DESALINATION

Conventional seawater desalination processes use electricity and/or steam from a conventional electric power station to produce purified water from seawater. Three approaches to seawater desalination were evaluated for HTGR integration: reverse osmosis (RO), multi-stage flash distillation (MSF), and multi-effect distillation (MED). The major differences between the conventional and HTGR-integrated desalination processes are the source of low-pressure steam and electricity. The desalination equipment is the same in both cases. Simplified block-flow diagrams for the conventional and HTGR-integrated RO process and the MSF and MED processes are shown in Figures 14 and 15. More detailed information about the processes evaluated is contained in Appendix H.

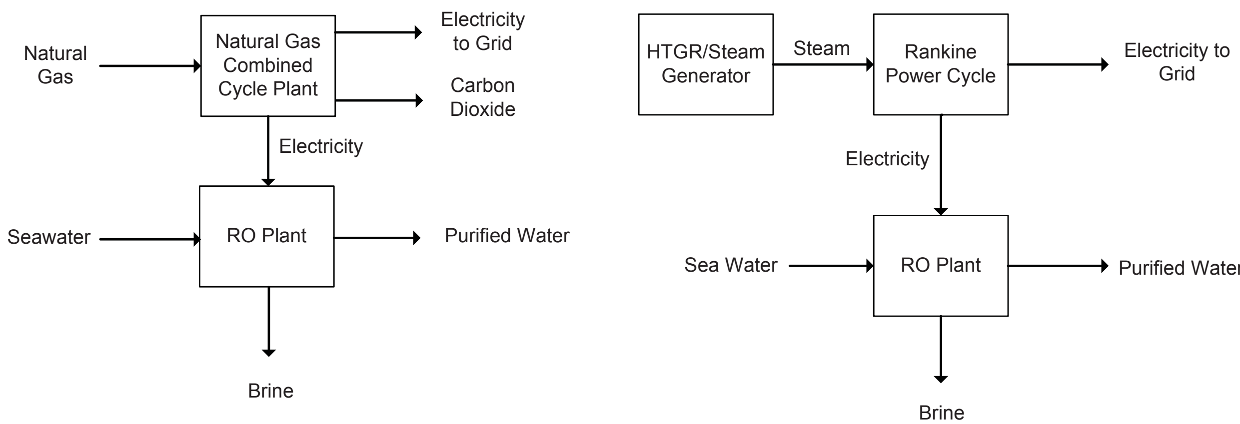

Figure 14. Simplified block flow diagrams for purified water from an RO process, with a conventional natural gas combined cycle process (left) and an HTGR-integrated case with electricity production via the Rankine cycle (right).

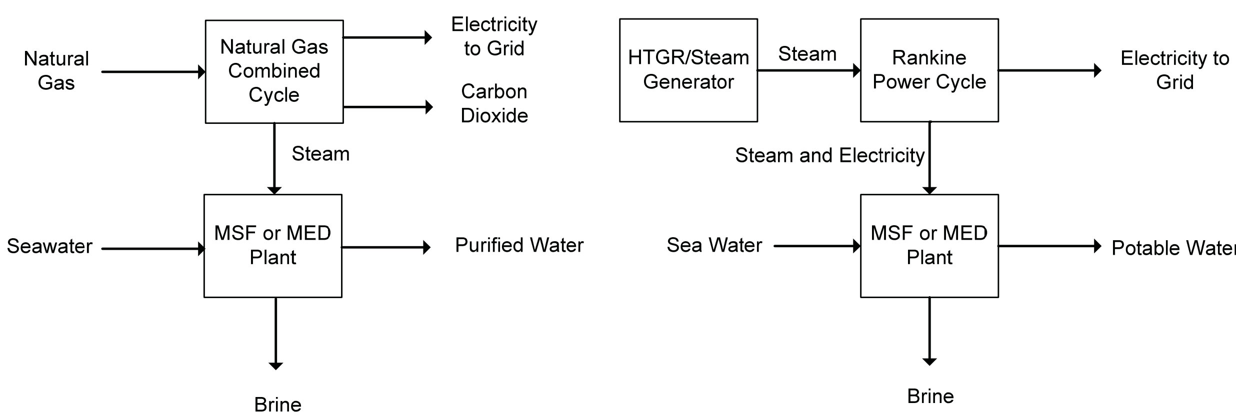

Figure 15. Simplified block flow diagrams for purified water from an MSF or MED process, with a conventional natural gas combined cycle process (left) and an HTGR-integrated case for production of electricity via the Rankine cycle (right).

The economic analysis assumed that the co-generation plant, which generates both steam and electricity, is located adjacent to the desalination plant and is sized to supply adequate steam to support a desalination plant with a capacity of 400,000 m^3/day of purified water from seawater. Process modeling calculations were performed using an Excel spreadsheet. The process modeling results are shown in Figures 16 through 18.

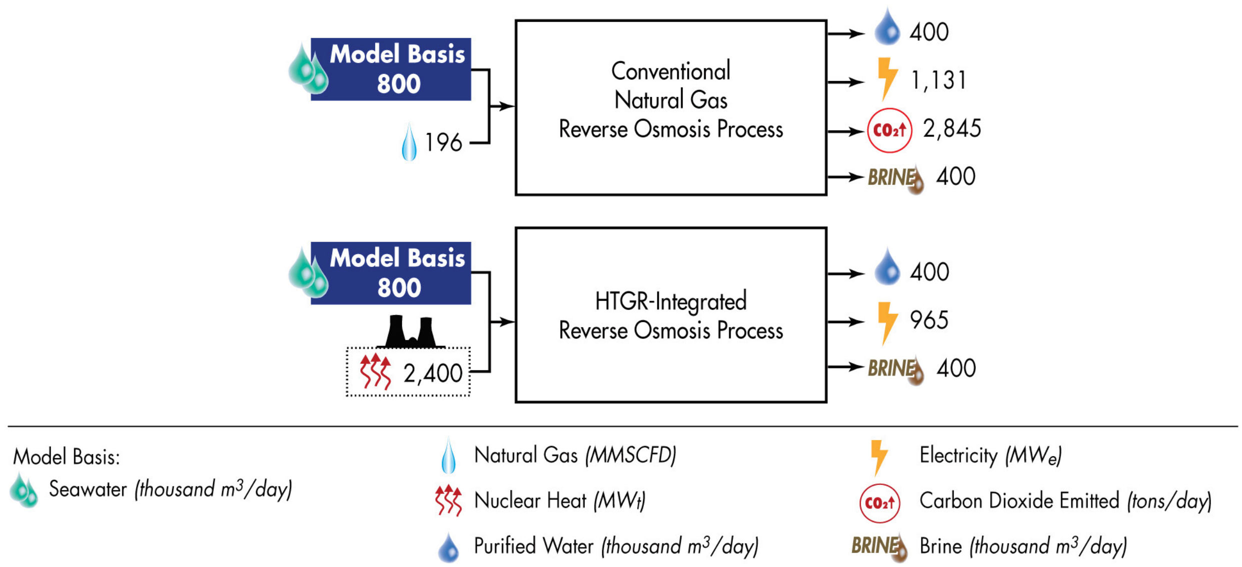

Figure 16. Simplified net mass and energy inputs and outputs for the RO cases.

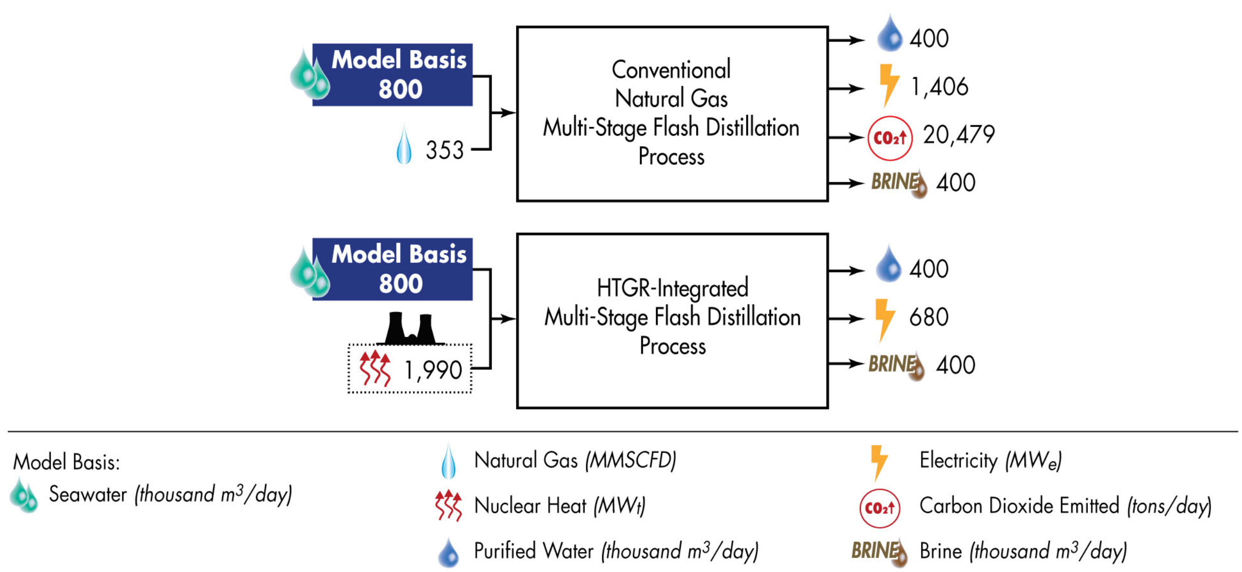

Figure 17. Simplified net mass and energy inputs and outputs for the MSF cases.

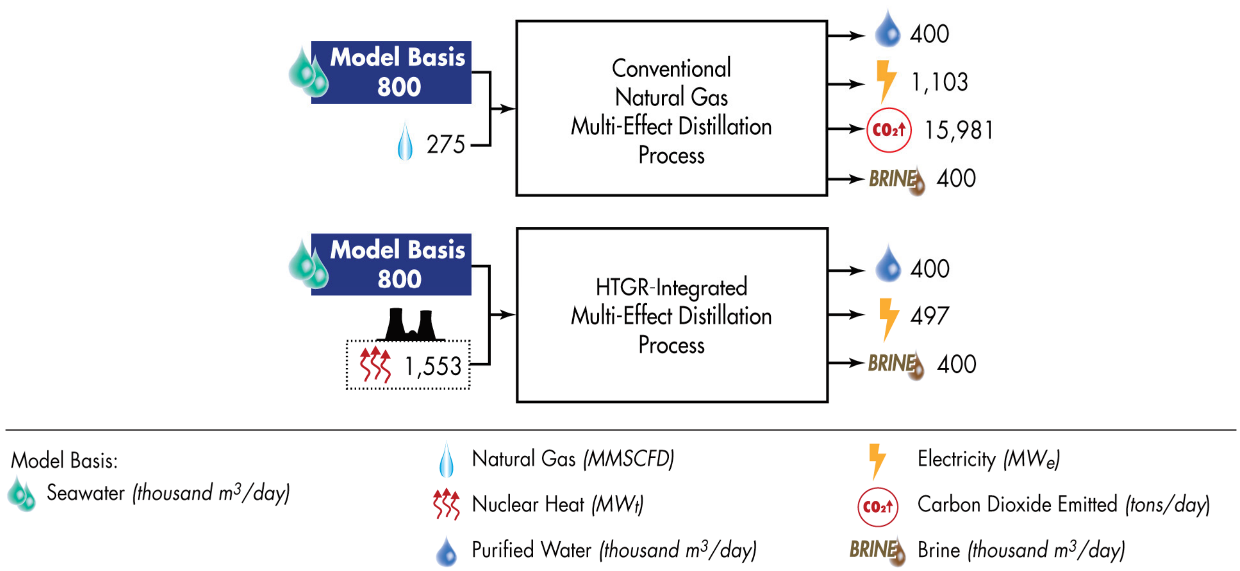

Figure 18. Simplified net mass and energy inputs and outputs for the MED cases.

Economic sensitivity analyses were conducted for each desalination process, shown as sensitivity charts in Figures 19 through 21. With the baseline economic assumptions, the wholesale selling price of purified water from these HTGR-integrated processes are higher than the current market price. In a scenario with higher natural gas prices and/or a moderate CO_2 emissions tax, HTGR-integrated desalination processes could be economically attractive.

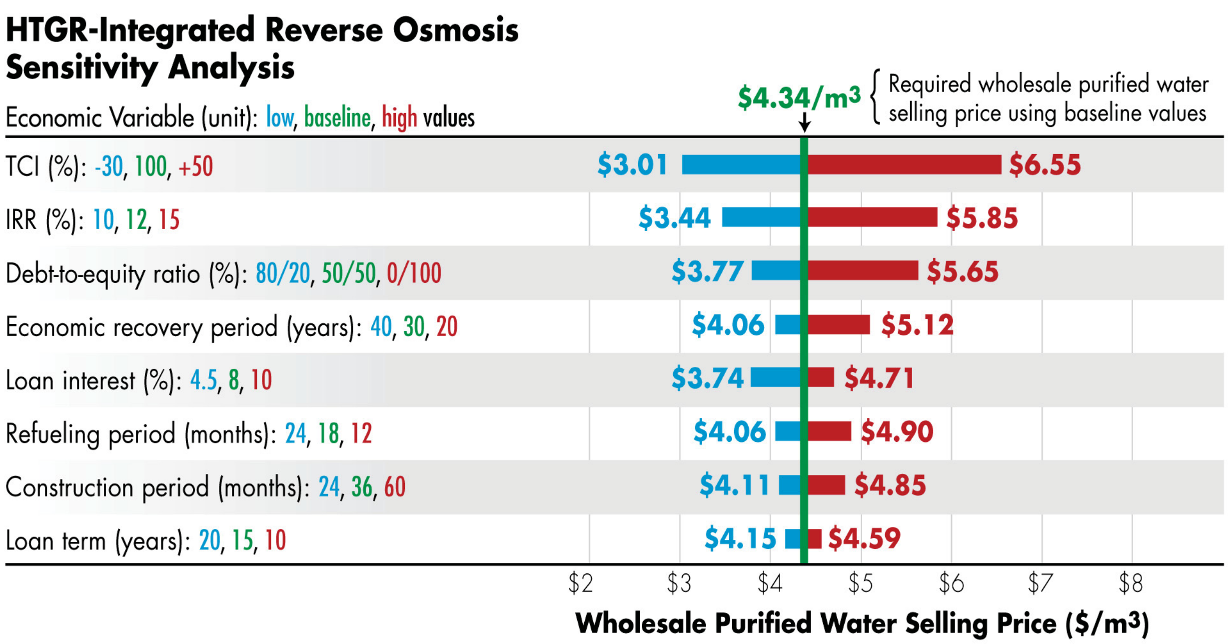

Figure 19. Sensitivity chart for the HTGR-integrated RO desalination case showing the relative impact of each input variable on project economics.

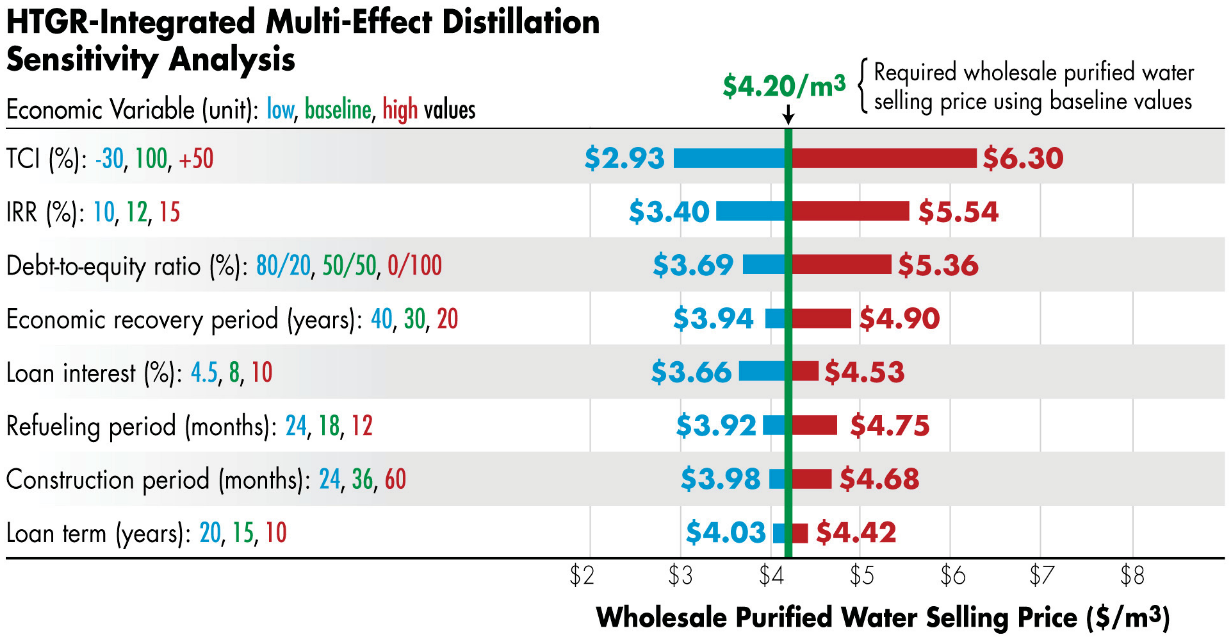

Figure 20. Sensitivity chart for the HTGR-integrated MED desalination case showing the relative impact of each input variable on project economics.

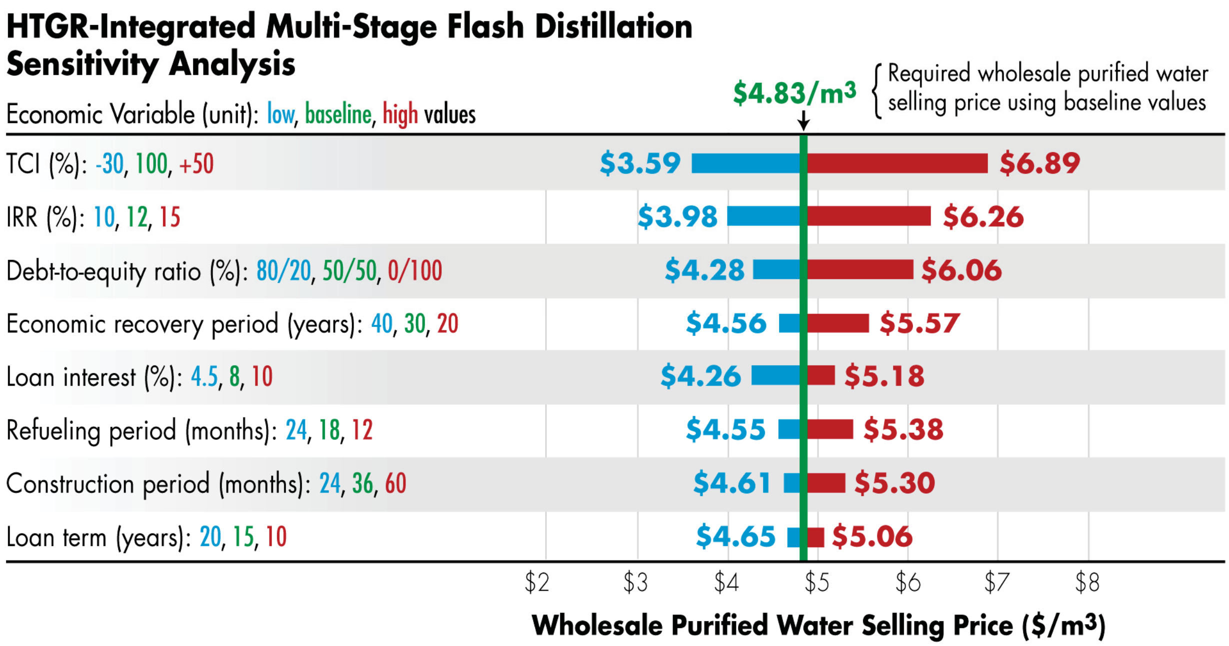

Figure 21. Sensitivity chart for the HTGR-integrated MSF desalination case showing the relative impact of each input variable on project economics.

8. PROCESS EVALUATION—COKE/STEEL PRODUCTION

An evaluation was performed to investigate the potential for integrating HTGR technology into a coke manufacturing process (see Appendix I). Conventional metallurgical coke production requires an operating temperature of 1200°C for the coke oven, which is much higher than the current maximum heat delivery temperature of an HTGR (925°C).[g] However, other commercial coke making technologies could be considered for HTGR-integration, particularly the formcoke process, which may be able to use nuclear heat for coal preheating and devolatilization. Unfortunately, formcoke is not suitable for use in a blast furnace because of excessive degradation at elevated temperatures, so it is questionable whether the formcoke market is large enough to warrant development of an HTGR-integrated process.

An evaluation was also performed to investigate the potential for integrating HTGR technology directly with iron production. As was the case with conventional coke manufacturing, the required operating temperature of a conventional blast furnace (1,500–2,100°C) is much higher than the current maximum heat delivery temperature of the HTGR (925°C). Similarly, direct smelting at 1,300–1,530°C also appears to be out of range for successful integration with an HTGR. Based on process operating temperatures, the best opportunity for integrating HTGR technology with iron production appears to be with direct reduction processes, which use hydrogen as the reducing gas. Hydrogen can be readily produced with assistance from an HTGR. It may also be possible to use heat from an HTGR in the iron reduction step itself; the 925°C operating temperature of the HyL III process matches the current maximum heat delivery temperature of the HTGR. Economics may be the largest hurdle to integrating HTGR technology with direct iron reduction processes. Direct reduction processes are typically viewed as economical only when natural gas is cheap and abundant. Otherwise, conventional coal-based ironmaking processes are preferred. Only 470,000 tons of direct reduced iron was produced in the United States in 2002, compared to 40,200,000 tons of total pig iron produced. In situations favoring direct reduction processes such as cheap and abundant natural gas, it may be hard to justify the additional capital expense associated with integrating an HTGR. Nonetheless, HTGR integration with direct iron reduction processes may be economically viable if high carbon emission taxes are imposed, or under other strong incentives to reduce GHG emissions.

Because of temperature mismatch issues between conventional coke and ironmaking processes and the current maximum heat delivery temperature of the HTGR, detailed studies for integrating an HTGR into iron- or coke-production processes were not pursued. However, as new technologies develop for iron and coke making, more suitable opportunities for HTGR integration may emerge.

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g The current maximum heat delivery temperature of the HTGR is 925°C assuming a reactor outlet temperature of 950°C and a minimum approach temperature in the IHX of 25°C. It is postulated that with advances in fuel and metallics, future HTGRs could reach reactor outlet temperatures in excess of 1000°C.

9. CONCLUSIONS AND RECOMMENDATIONS

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.

The results presented in Section 5 of this report indicate that economies of scale are very important for HTGR-integrated processes. Larger reactors and multiple reactor configurations are key to the economic viability of the processes evaluated.

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.

10. REFERENCES

INL, 2010a, *Integration of High Temperature Gas-Cooled Reactors into Industrial Process Applications*, INL/EXT-09-16942, Rev. 2, Idaho National Laboratory, May 2010.

INL, 2010b, *Nuclear-Integrated Oil Sands Recovery via Steam-Assisted Gravity Drainage*, TEV-704, Rev. 1, Idaho National Laboratory, May, 2010.

Appendix A

TEV-1196, Assessment of High Temperature Gas-Cooled Reactor (HTGR) Capital and Operating Costs

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Appendix B

TEV-1029, Integration of HTGRs with an In Situ Oil Shale Operation

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Appendix C

TEV-1276, Economics of Integrating HTGRs to an In Situ Oil Shale Retort Operation

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Appendix D

TEV-1091, Integration of HTGRs and an Ex Situ Oil Shale Retort Operation

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Appendix E

TEV-1321, Economics of Integrating HTGRs to an Ex Situ Oil Shale Retort Operation

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Appendix F

TEV-988, Sensitivity of HTGR Heat and Power Production to Reactor Outlet Temperature, Economic Analysis

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Appendix G

TEV-1147, HTGR-Integrated Bitumen Upgrading Analysis

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Appendix H

TEV-1302, Integration of HTGRs and Seawater Desalination

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Appendix I

TEV-1174, Evaluation of HTGR Heat Integration for Iron Production and the Manufacture of Metallurgical Coke

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