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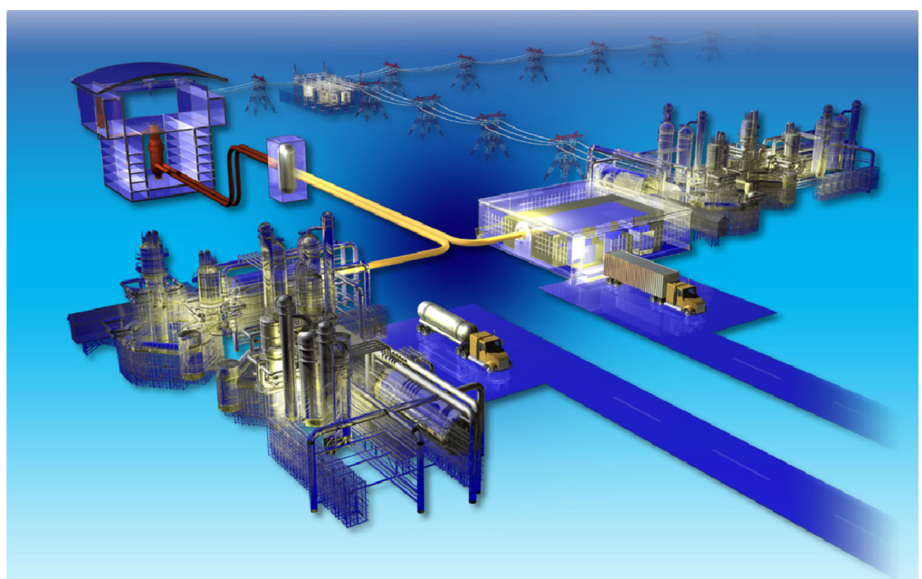
Technical Evaluation Study

Project No. 23843

HTGR-Integrated Hydrogen Production via Steam Methane Reforming (SMR) Economic Analysis



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HTGR-INTEGRATED HYDROGEN PRODUCTION VIA STEAM METHANE REFORMING (SMR) ECONOMIC ANALYSIS	Identifier: TEV-954 Revision: 0 Effective Date: 09/15/2010 Page: 1 of 48

NGNP Project	Technical Evaluation Study (TEV)		eCR Number:	583584

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REVISION LOG

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0	09/15/10	All	Newly issued document.

EXECUTIVE SUMMARY

This technical evaluation (TEV) has been prepared as part of a study for the Next Generation Nuclear Plant (NGNP) Project to evaluate the economics of integrating a High Temperature Gas-cooled Reactor (HTGR) with conventional chemical processes. This TEV addresses the economics of integrating an HTGR for hydrogen production via steam methane reforming (SMR) of natural gas.

The production of hydrogen via SMR has previously been addressed in detail in TEV-953 (Idaho National Laboratory [INL] 2010). In that report, detailed process models for both conventional SMR hydrogen production and HTGR-integrated SMR hydrogen production with a reactor outlet temperature of 750°C (1,382°F) were developed. This report is a follow-up to TEV-953 and evaluates the economics of the four cases modeled. For this analysis, two HTGR cost scenarios were considered: nominal cost refers to the anticipated cost to build a single HTGR, and target cost refers to the HTGR cost for larger installations when three or more HTGRs can be co-located. Significant results from this evaluation are:

- Integrating HTGR heat into a SMR process is economically viable. A 15% internal rate of return (IRR) can be easily achieved in many of the scenarios considered while producing hydrogen for less than $1.13/lb ($2.50/kg).
- For the scenarios without carbon capture:
    - In the absence of a carbon tax, the nominal HTGR-integrated case outperforms the conventional case when natural gas prices rise above $8 per 1,000 scf.
    - Assuming a natural gas price of $6.50 per 1,000 scf, the nominal HTGR-integrated case can produce hydrogen for less than the conventional case when an emissions tax of $20/ton CO_2 or higher is imposed.
    - The target HTGR-integrated case will economically outperform the conventional case across the entire range of natural gas prices considered regardless of whether or not a CO_2 emissions tax is imposed.
- For the scenarios with carbon capture and sequestration:
    - In the absence of a carbon tax, the nominal HTGR-integrated case outperforms the conventional case only when natural gas prices rise above $10.50 per 1,000 scf. The target HTGR-integrated case outperforms the conventional case for natural gas prices above $6.50 per 1,000 scf.
    - Assuming a natural gas price of $6.50 per 1,000 scf, the nominal HTGR-integrated case can produce hydrogen for less than the conventional case

when an emissions tax of \$75/ton CO_2 or higher is imposed. The target HTGR-integrated case will outperform the conventional case regardless of whether or not a CO_2 emissions tax is imposed.

- HTGR integration appears to have more of an advantage over the conventional process for the scenarios that do not capture carbon. However, carbon capture and sequestration is preferable for the HTGR-integrated scenarios when an emissions tax of \$35/ton CO_2 or more is imposed.

Based on the results of this study, several follow-on activities are recommended. The most significant of these recommendations are listed below.

- It is likely that economic results for the HTGR-integrated case would improve if the HTGR temperature could be increased beyond 750°C. Hence, a study to quantify the potential economic improvement is recommended.

- Additional work is warranted to scope out initial equipment design and further assess the feasibility of a HTGR-integrated SMR. Specifically, the economic impact of shifting the mode of heat transfer from radiation in a conventional design to convection in a HTGR-integrated design should be investigated.

- Refined estimates of the HTGR capital cost, annual fuel costs, and annual operation and maintenance costs should be developed, including sensitivity to reactor outlet temperature.

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ACRONYMS AND NOMENCLATURE

AACE	Association for the Advancement of Cost Engineering
ATCF	after tax cash flow
BTCF	before tax cash flow
CEPCI	chemical engineering plant cost index
DOE	Department of Energy
HDS	hydro-desulfurization
HTGR	High Temperature Gas-cooled Reactor
IRR	internal rate of return
MARR	minimum annual rate of return
MSCF	thousand standard cubic feet
MMSCF	million standard cubic feet
NETL	National Energy Technology Laboratory
NGNP	Next Generation Nuclear Plant
NIBT	net income before taxes
O&M	operations and maintenance
PW	present worth
SMR	steam methane reformer
TCI	total capital investment
TEV	technical evaluation

C_1	cost of equipment with capacity q_1
C_2	cost of equipment with capacity q_2
C_k	capital expenditures
d_k	depreciation
E_k	cash outflows
i'	IRR
k	year
n	exponential factor
q_1	equipment capacity

q_2	equipment capacity
R_k	revenues
t	tax rate
T_k	income taxes

1. INTRODUCTION

This technical evaluation (TEV) has been prepared as part of a study for the Next Generation Nuclear Plant (NGNP) Project to evaluate the economics of integrating a High Temperature Gas-cooled Reactor (HTGR) with conventional chemical processes. The NGNP Project is being conducted under U.S. Department of Energy (DOE) direction to meet a national strategic need identified in the *2005 Energy Policy Act* to promote reliance on safe, clean, economic nuclear energy and to establish a greenhouse-gas-free technology for the production of hydrogen. The NGNP represents an integration of high-temperature reactor technology with advanced hydrogen, electricity, and process heat production capabilities, thereby meeting the mission need identified by DOE. The strategic goal of the NGNP Project is to broaden the environmental and economic benefits of nuclear energy in the U.S. economy by demonstrating its applicability to market sectors not being served by light water reactors.

The HTGR produces steam and/or high-temperature helium that can be used for process heat. In addition, the HTGR can produce electricity. A summary of these products and a brief description is shown in Table 1. For this study the HTGR outlet temperature is assumed to be 750°C (1,382°F); this reflects the initial HTGR design and assumes a more conservative outlet temperature. Eventually temperatures of 950°C (1,742°F) are anticipated. Additionally, a 50°C (90°F) temperature approach is assumed between the primary and secondary helium loops, if helium is the delivered working fluid. As a result, the helium stream available for heat exchange is assumed to be at 700°C (1,292°F). In conventional chemical processes these products are generated by the combustion of fossil fuels such as coal and natural gas, resulting in significant emissions of greenhouse gases such as carbon dioxide. Heat or electricity produced in an HTGR could be used to supply process heat or electricity to conventional chemical processes while generating minimal greenhouse gases. The use of an HTGR to supply process heat or electricity to conventional processes is referred to as a HTGR-integrated process. This report provides a preliminary economic analysis of integrating nuclear-generated heat and electricity into conventional processes and compares the economic results with the conventional process.

Table 1. Projected outputs of the NGNP.

HTGR Product	Product Description
Steam	17 MPa and 540°C (1,004°F)
High-Temperature Helium	Delivered at 9.1 MPa and 700°C (1,292°F)
Electricity	Generated by Rankine cycle with 40% thermal efficiency

The production of hydrogen via steam methane reforming (SMR) of natural gas has previously been addressed in detail in TEV-953 (INL 2010). In that report, detailed process models for both conventional SMR hydrogen production and HTGR-integrated SMR hydrogen production were developed. The models documented in TEV-953 are used as the basis for the economic analysis conducted in this report. This TEV assumes familiarity with TEV-953; hence, detailed descriptions of the process models documented in TEV-953 are not presented here.

The economic models used for this analysis have been developed in Microsoft Excel (Excel 2007). This study makes extensive use of these models; this TEV assumes familiarity with Excel. A detailed explanation of the software capabilities is beyond the scope of this study.

This TEV first presents the general process configuration on which the economic models are based. Next, the details of the economic model are discussed. Finally, results of the economic analysis are presented and discussed.

2. CASES CONSIDERED

Four cases were identified for economic modeling based on the process models presented in TEV-953:

- Conventional SMR process without carbon capture
- Conventional SMR process with carbon capture
- HTGR-integrated SMR process without carbon capture
- HTGR-integrated SMR process with carbon capture.

Figure 1 shows the block flow diagram for the conventional SMR cases. The proposed processes include unit operations for steam reforming, syngas shifting and conditioning, steam generation system, cooling towers, and water treatment. Figure 2 and Figure 3 show the block flow diagrams for the HTGR-integrated SMR processes without and with carbon capture. The proposed HTGR-integrated processes include the same unit operations as the conventional SMR processes, but also include the HTGR system. For detailed descriptions of the process models that provide the basis for the configurations considered for the economic analysis, see TEV-953. A high-level material and energy balance summary for these cases is presented in Figure 4.

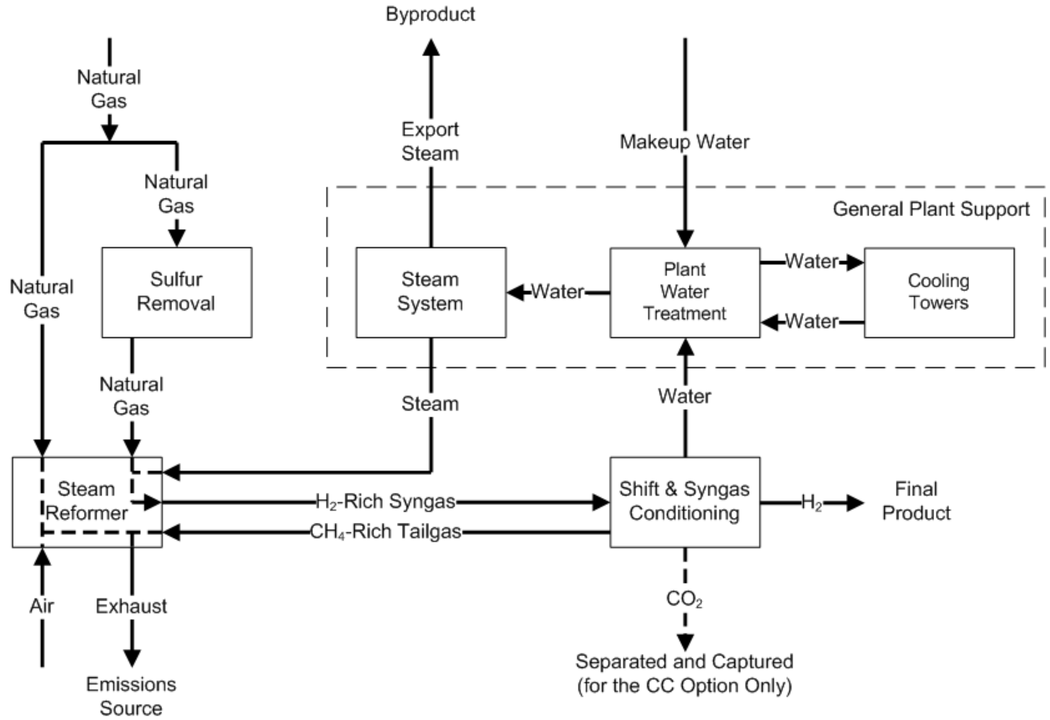

Figure 1. Block flow diagram for the conventional SMR cases.

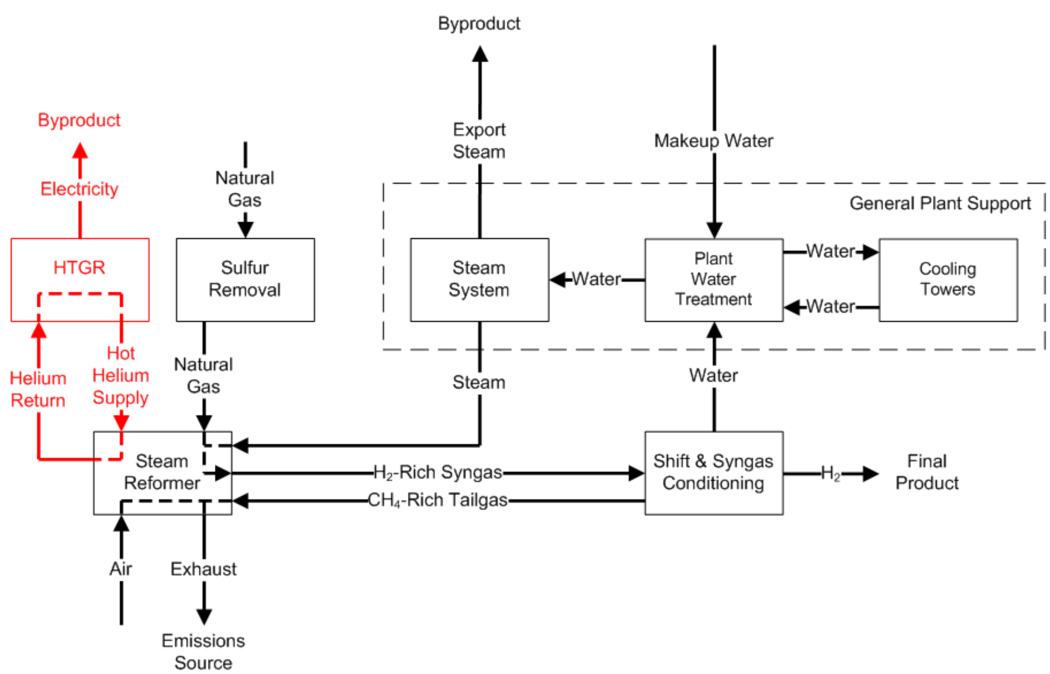

Figure 2. Block flow diagram for the HTGR-integrated SMR case without carbon capture.

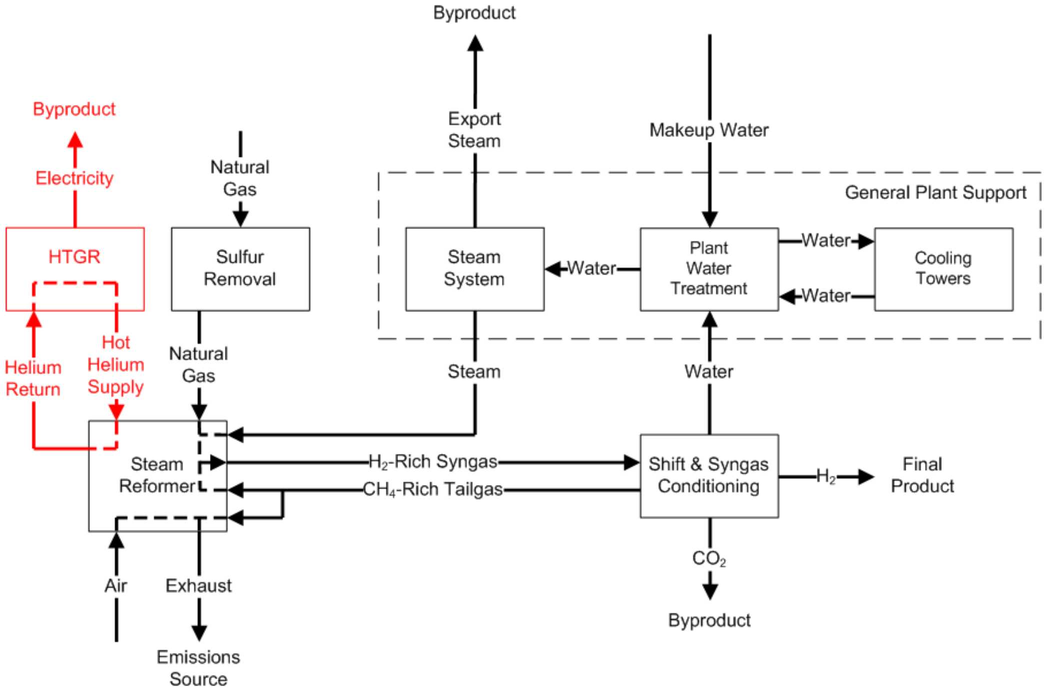

Figure 3. Block flow diagram for the HTGR-integrated SMR case with carbon capture.

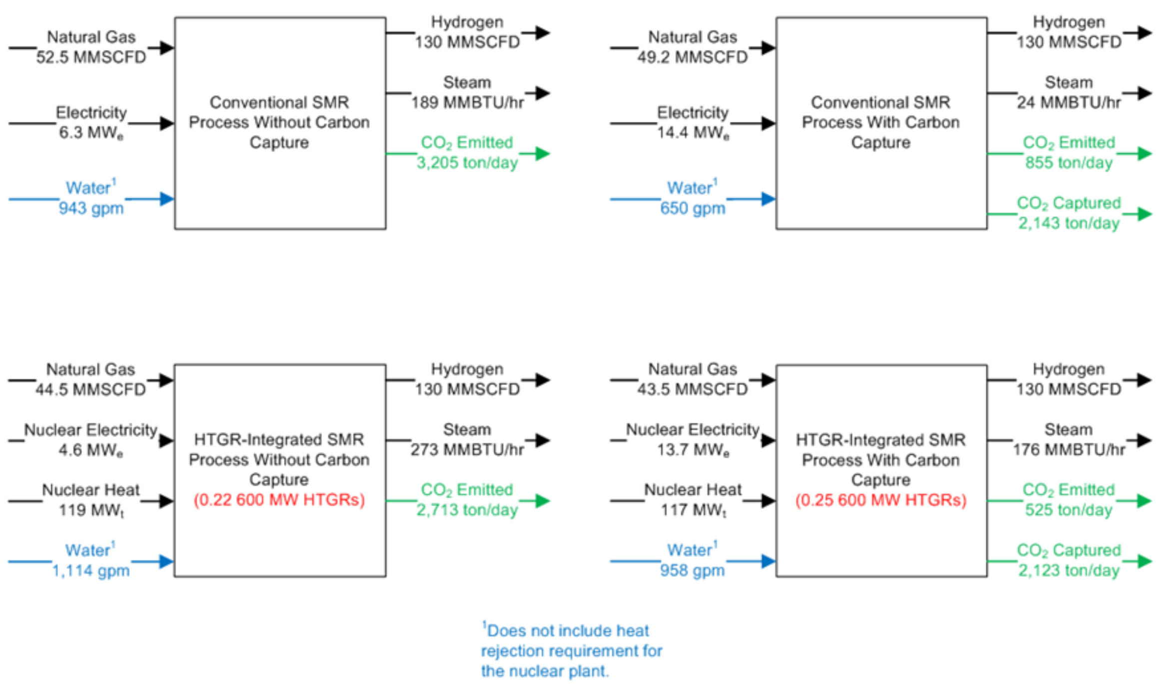

Figure 4. Material and energy balance summary for the cases evaluated.

3. ECONOMIC MODELING OVERVIEW

The economic viability of the SMR processes was assessed using standard economic evaluation methods, specifically the internal rate of return (IRR). The economics were evaluated for the conventional and HTGR-integrated options described in the previous section. The total capital investment (TCI), based on the total equipment costs, annual revenues, and annual manufacturing costs, were first calculated for the cases. The present worth of the annual cash flows (after taxes) was then calculated for the TCI at both the nominal and target HTGR cost. Additionally, the economics were analyzed for multiple owner-operator scenarios, with the HTGR and SMR facilities operated by independent organizations or a single owner-operator. The following sections describe the methods used to calculate the capital costs, annual revenues, annual manufacturing costs, and the ensuing economic results.

3.1 Capital Cost Estimation

Equipment items for this study were not individually priced. Rather, cost estimates were based on scaled costs for major plant processes from published literature. Cost estimates were generated for the SMR, water gas shift reactors, Selexol™, pressure swing absorption, CO_2 removal/compression, cooling towers, and the HTGR. In some instances, several costs were averaged. The estimate presented is a Class 5 estimate and has a probable error of +50% and -30% (AACE 2005).

The installed capital costs presented are for inside the battery limits, and exclude costs for administrative offices, storage areas, utilities, and other essential and nonessential auxiliary facilities. Fixed capital costs were estimated from literature estimates and scaled estimates (capacity, year, and material) from previous quotes. Capacity adjustments were based on the six-tenths factor rule:

$$C_2 = C_1 \left(\frac{q_2}{q_1}\right)^n \tag{1}$$

where C_1 is the cost of the equipment item at capacity q_1, C_2 is the cost of the equipment at capacity q_2, and n is the exponential factor, which typically has a value of 0.6 (Peters 2002). It was assumed that the number of trains did not have an impact on cost scaling. Cost indices were used to adjust equipment prices from previous years to 2009 using the Chemical Engineering Plant Cost Index (CEPCI) as depicted in Table 2. Costs for the HTGR were scaled directly based on capacity; the six-tenths factor rule was not used.

Table 2. CEPCI data.

Year	CEPCI	Year	CEPCI
1990	357.6	2000	394.1
1991	361.3	2001	394.3
1992	358.2	2002	395.6
1993	359.2	2003	402
1994	368.1	2004	444.2
1995	381.1	2005	468.2
1996	381.7	2006	499.6
1997	386.5	2007	525.4
1998	389.5	2008	575.4
1999	390.6	2009	521.9

For the HTGR, the estimates of capital costs and operating and maintenance costs assumed the nuclear plant was an "n^{th} of a kind." In other words, the estimates were based on the costs expected after the HTGR technology is integrated into an industrial application more than ten times. The economic modeling calculations were based on two capital cost scenarios for the HTGR unit, which does not include the power cycle: a nominal estimate of \$1,708/kW_t (Demick 2009) and a target of \$1,196/kW_t (Demick 2009) where kW_t is the thermal rating of the plant.[a] In comparison, light water nuclear reactor costs are approximately \$1,333/kW_t (Nuclear Energy Institute [NEI] 2008). Based on the two capital cost scenarios for HTGR technology, the nominal capital cost for a 600-MW_t HTGR would be \$1.025 billion; the target capital cost would be \$718 million.

After cost estimates were obtained for each of the process areas, the costs for water systems, piping, instrumentation and control, electrical systems, and buildings and structures were added based on scaling factors for the total installed equipment costs, based on information provided in studies performed by the National Energy Technology Laboratory (NETL) (NETL 2000). These factors were not added to the cost of the HTGR, as the cost basis for the HTGR was assumed to represent a complete and operable system. Table 3 presents the factors utilized in this study.

[a] The estimate provided by Demick was \$2,000/kW_t for the nominal case and included the cost of the power generation equipment. \$292/kW_t was subtracted for the power generation equipment to arrive at the listed cost of \$1,708/kW_t. The cost for the target case was obtained by assuming 70% of the nominal case cost: \$1,708/kW_t x 0.70 = \$1,196/kW_t.

Table 3. Capital cost adjustment factors.

Year	Factor
Water Systems	7.1%
Piping	7.1%
Instrumentation and Control	2.6%
Electrical Systems	8.0%
Buildings and Structures	9.2%

Finally, an engineering fee of 10% and a project contingency of 18% were applied to determine the TCI. However, the engineering fee and contingency were not applied to the HTGR cost, as the capital cost provided for the HTGR represents a complete and operable system (i.e., the HTGR estimate received represents all inside battery limits and outside battery limits elements as well as contingency and owner's costs).

The Association for the Advancement of Cost Engineering (AACE) International recognizes five classes of estimates. The level of project definition for this study was determined to be an AACE International Class 5 estimate. Though the baseline case is actually more in line with the AACE International Class 4 estimate, which is associated with equipment factoring, parametric modeling, historical relationship factors, and broad unit cost data, the HTGR project definition falls under an AACE International Class 5 estimate, associated with less than two percent project definition, and based on preliminary design methodology (AACE 2005). Since the HTGR is a larger portion of the TCI, an overall Class 5 estimate was assumed.

Based on the AACE International contingency guidelines as presented in DOE/FETC-99/1100 (DOE 1999) it would appear that the overall project contingency for the non-nuclear portion of the capital should be in the range of 30–50%, 30–40% for Class 4 and 50% for Class 5 (Parsons 1999). However, because the cost estimates were scaled based on estimated, quoted, and actual project costs, the overall non-nuclear project contingency should be more in the range of 15–20%. Eighteen percent was selected based on similar studies conducted by the NETL (NETL 2007). Again, contingency was not applied to the HTGR as project contingency was accounted for in the basis for the capital cost estimate.

Table 4 and Figure 5 present the capital cost estimate breakdown for the conventional SMR case without carbon capture, Table 5 and Figure 6 for the conventional SMR case with carbon capture, Table 6 and Figure 7 for the HTGR-integrated SMR case without carbon capture, and Table 7 and Figure 8 for the HTGR-integrated SMR case with carbon capture. Varying only the cost of the nuclear facility was an adequate assumption, as the cost of the HTGR accounts for over 46% of the capital cost for the HTGR-integrated SMR cases. In addition, there is a greater level of uncertainty in the nuclear plant price given the nascency of HTGR development.

As a check on the capital cost estimates prepared as part of this study, the overall capital cost for a conventional hydrogen plant can be compared to values published in the open literature. One such estimate was published by NETL (NETL 2002). Capacity in the NETL study was only slightly larger than that considered in this study—150 MMSCFD versus 130 MMSCFD of hydrogen product. Based on this comparison, the capital cost values calculated in this study appear to be conservative by as much as 60%.

Table 4. Total capital investment, conventional SMR case without carbon capture ($).

	Installed Cost	Engineering Fee	Contingency	Total Capital Cost
Steam Methane Reformer	109,458,536	10,945,854	21,672,790	142,077,180
Water Gas Shift Reactors	2,922,779	292,278	578,710	3,793,767
PSA System	28,030,028	2,803,003	5,549,946	36,382,976
Cooling Towers	6,557,229	655,723	1,298,331	8,511,283
Water Systems	10,434,769	1,043,477	2,066,084	13,544,330
Piping	10,434,769	1,043,477	2,066,084	13,544,330
I&C	3,821,183	382,118	756,594	4,959,895
Electrical Systems	11,757,486	1,175,749	2,327,982	15,261,217
Buildings and Structures	13,521,109	1,352,111	2,677,180	17,550,399
Total Capital Investment				**255,625,376**

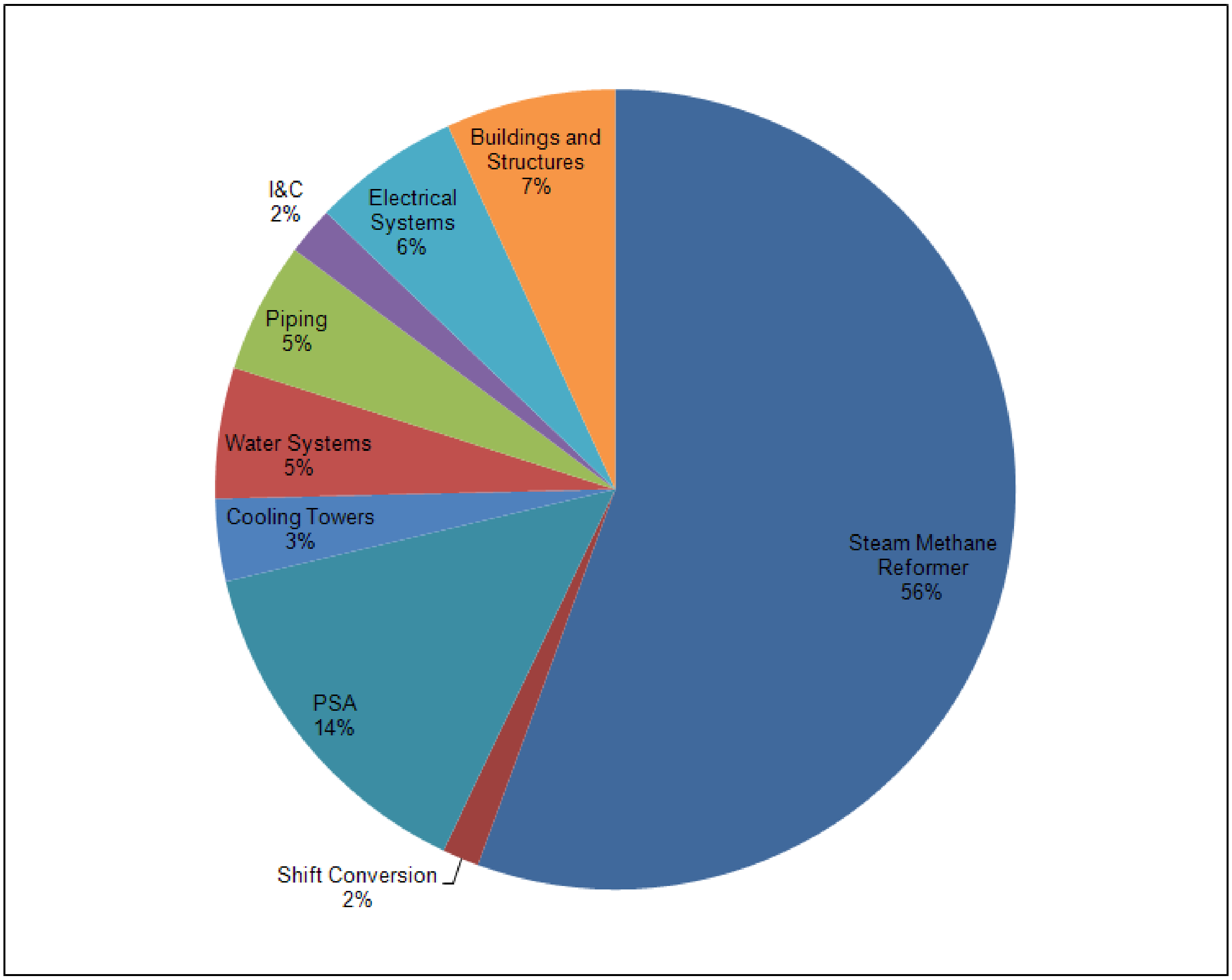

Figure 5. Total capital investment, conventional SMR case without carbon capture.

Table 5. Total capital investment, conventional SMR case with carbon capture ($).

	Installed Cost	Engineering Fee	Contingency	Total Capital Cost
Steam Methane Reformer	105,276,907	10,527,691	20,844,828	136,649,425
Water Gas Shift Reactors	2,932,361	293,236	580,607	3,806,204
Selexol™	21,284,138	2,128,414	4,214,259	27,626,811
CO_2 Compression	6,595,240	659,524	1,305,857	8,560,621
PSA System	24,797,070	2,479,707	4,909,820	32,186,596
Cooling Towers	6,557,229	655,723	1,298,331	8,511,283
Water Systems	11,888,449	1,188,845	2,353,913	15,431,207
Piping	11,888,449	1,188,845	2,353,913	15,431,207
I&C	4,353,517	435,352	861,996	5,650,864
Electrical Systems	13,395,435	1,339,544	2,652,296	17,387,275
Buildings and Structures	15,404,751	1,540,475	3,050,141	19,995,367
Total Capital Investment				**291,236,860**

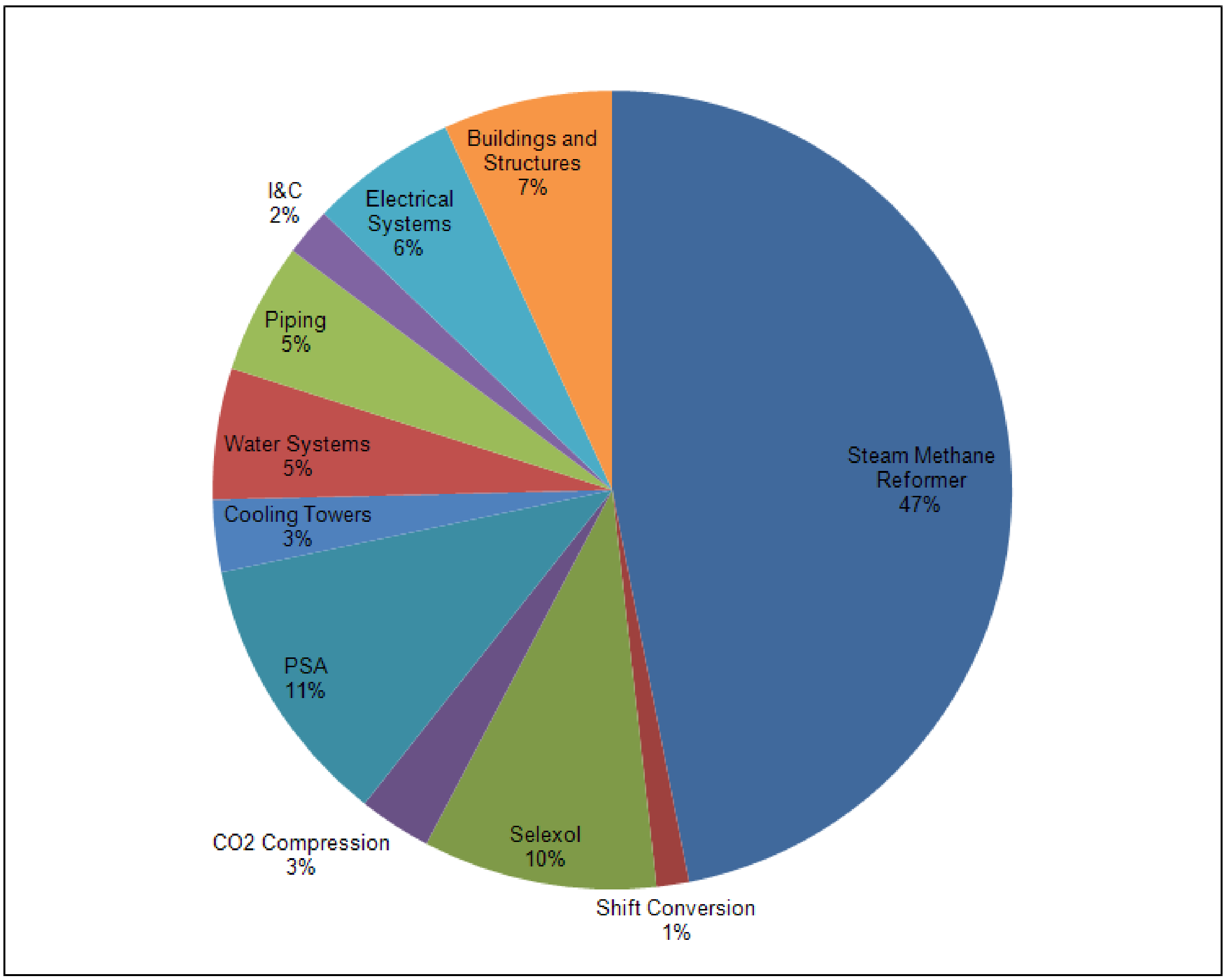

Figure 6. Total capital investment, conventional SMR case with carbon capture.

Table 6. Total capital investment, HTGR-integrated SMR case without carbon capture ($).

	Installed Cost	Engineering Fee	Contingency	Total Capital Cost
HTGR – Nominal Cost	223,279,167			223,279,167
HTGR – Target Cost	156,295,417			156,295,417
HTGR Power Cycle	13,830,930	1,383,093	2,738,524	17,952,547
Steam Methane Reformer	99,122,001	9,912,200	19,626,156	128,660,357
Water Gas Shift Reactors	2,919,820	291,982	578,124	3,789,927
PSA System	28,023,142	2,802,314	5,548,582	36,374,039
Cooling Towers	81,091	8,109	16,056	105,257
Water Systems	9,240,370	924,037	1,829,593	11,994,000
Piping	9,240,370	924,037	1,829,593	11,994,000
I&C	3,383,797	338,380	669,992	4,392,169
Electrical Systems	10,411,684	1,041,168	2,061,514	13,514,366
Buildings and Structures	11,973,437	1,197,344	2,370,741	15,541,521
Buildings and Structures	81,091	8,109	16,056	105,257
Total Capital Investment – Nominal HTGR Cost				**467,597,350**
Fossil Plant				*226,365,637*
HTGR				*241,231,714*
Total Capital Investment – Target HTGR Cost				**400,613,600**
Fossil Plant				*226,365,637*
HTGR				*174,247,964*

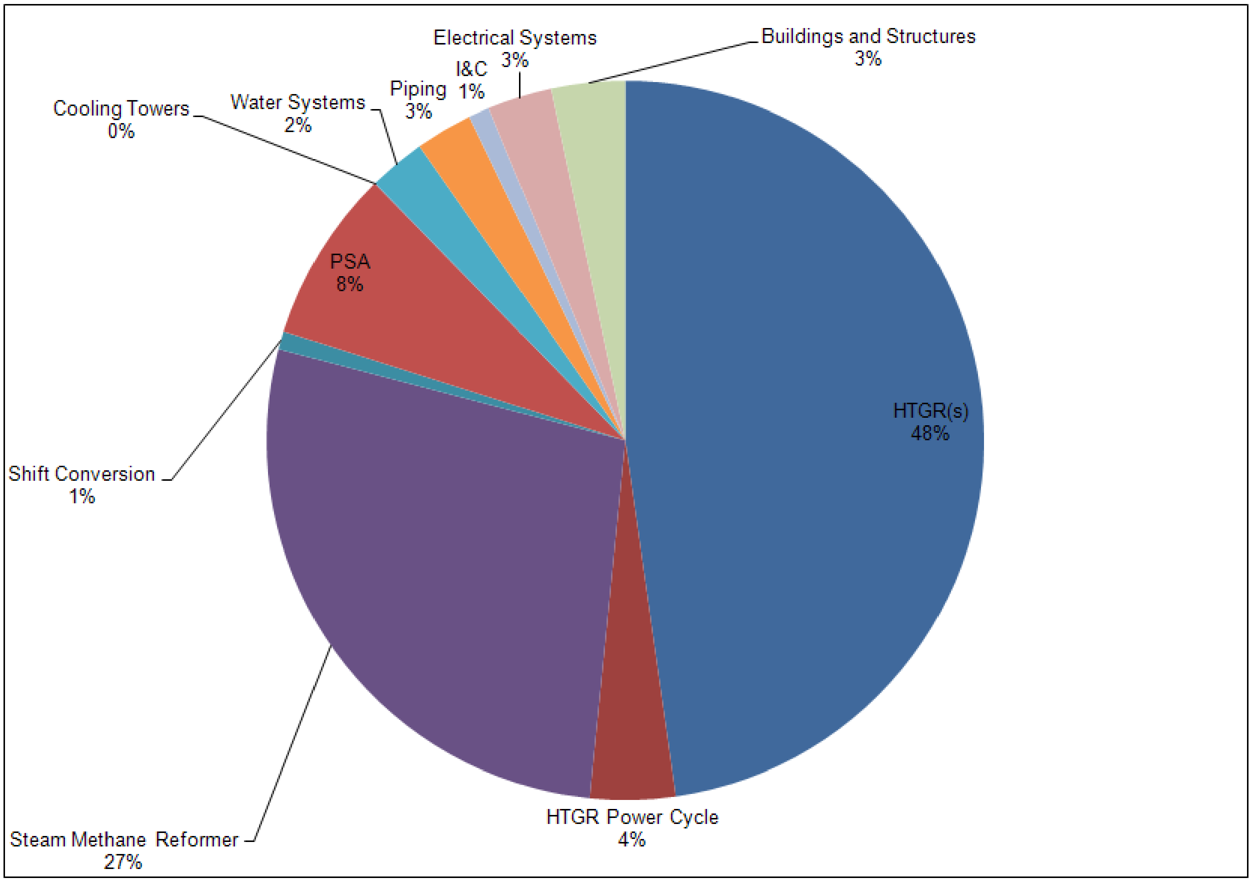

Figure 7. Total capital investment, HTGR-integrated SMR case without carbon capture.

Table 7. Total capital investment, HTGR-integrated SMR case with carbon capture ($).

	Installed Cost	Engineering Fee	Contingency	Total Capital Cost
HTGR – Nominal Cost	258,214,583			258,214,583
HTGR – Target Cost	180750208			180750208
HTGR Power Cycle	26,621,285	2,662,129	5,271,015	34,554,428
Steam Methane Reformer	97,779,454	9,777,945	19,360,332	126,917,731
Water Gas Shift Reactors	2,915,558	291,556	577,281	3,784,394
Selexol™	21,174,957	2,117,496	4,192,641	27,485,094
CO_2 Compression	6,557,229	655,723	1,298,331	8,511,283
PSA System	24,688,943	2,468,894	4,888,411	32,046,248
Cooling Towers	139,617	13,962	27,644	181,223
Water Systems	10,881,159	1,088,116	2,154,469	14,123,744
Piping	10,881,159	1,088,116	2,154,469	14,123,744
I&C	3,984,650	398,465	788,961	5,172,075
Electrical Systems	12,260,461	1,226,046	2,427,571	15,914,078
Buildings and Structures	14,099,530	1,409,953	2,791,707	18,301,190
Total Capital Investment – Nominal HTGR Cost				**559,329,818**
Fossil Plant				*266,560,806*
HTGR				*292,769,012*
Total Capital Investment – Target HTGR Cost				**481,865,443**
Fossil Plant				*266,560,806*
HTGR				*215,304,636*

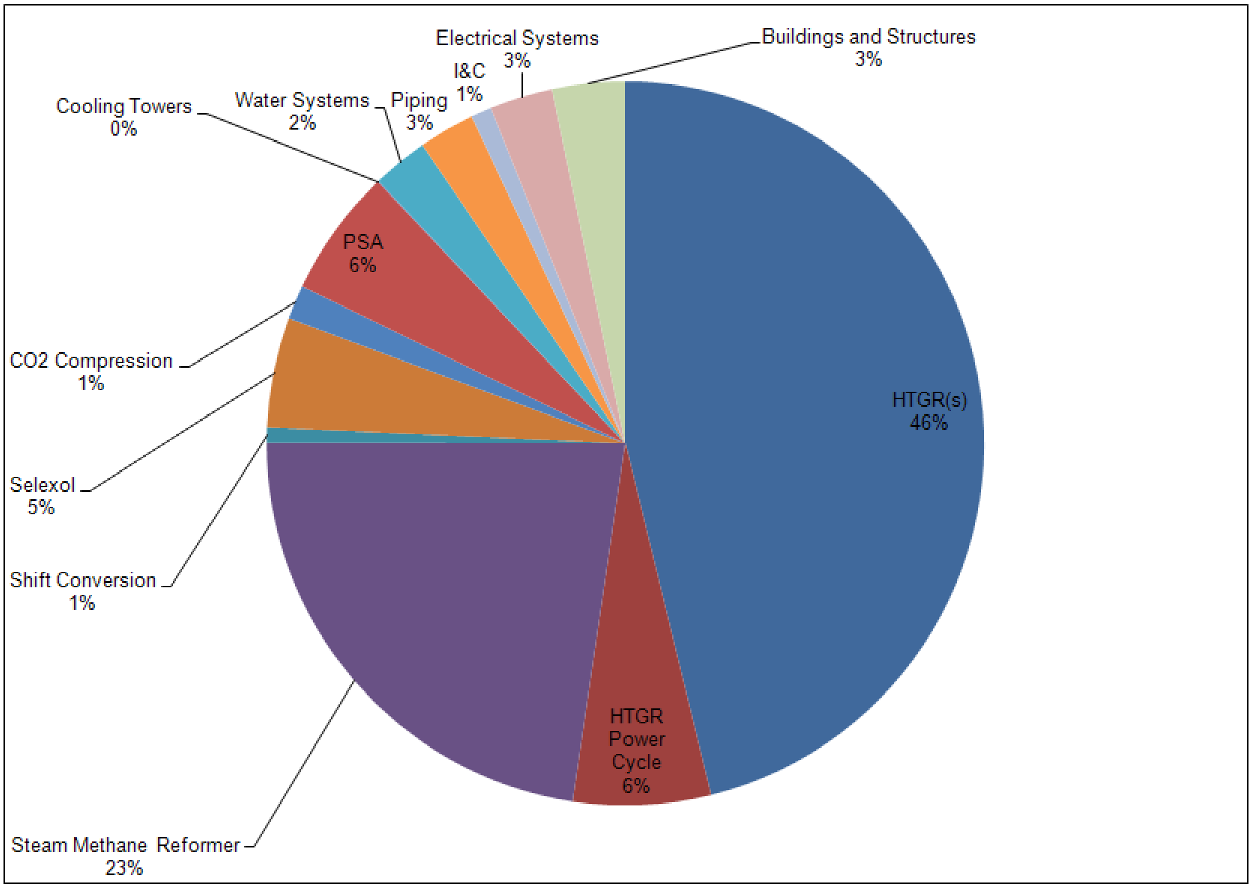

Figure 8. Total capital investment, HTGR-integrated SMR case with carbon capture.

3.1 Estimation of Revenue

Yearly revenues were estimated for all cases based on recent price data for the various products generated, including hydrogen, heat, and/or electricity. When a separate owner-operator configuration is assumed, the HTGR collects revenues from the heat and/or electricity supplied to the fossil process. When heat is exported from the HTGR, the selling price is assumed to be related to electricity price based on the HTGR power generation efficiency based on the following equation:

$$Heat\ Price = Electricity\ Price * Power\ Generation\ Efficiency \quad (2)$$

This relationship provides that when either all heat or all electricity is generated in the HTGR, the annual revenue remains the same for either product.

When heat is exported from the fossil plant, a power generation efficiency of 33% is assumed to relate the price of heat to electricity. Revenues were also calculated to determine the necessary selling prices of hydrogen for the fossil portion of the process along with heat and/or electricity for the HTGR to achieve a specific rate of return.

The revenues presented for the fossil portion are for selling hydrogen, and/or heat at the market price. The market price for hydrogen used in this study is \$1.13/lb (\$2.50/kg) and lies within the range specified in the *NGNP Pre-Conceptual Design Report* (INL 2007). When intermediate revenues for the HTGR are presented for the independent owner-operator scenario, the heat and/or electricity price is presented to achieve the rate of return specified for the project. A stream factor of 92% is assumed for both the fossil and nuclear plants. Table 8 presents the revenues for the conventional SMR case without carbon capture, Table 9 presents the revenues for the conventional SMR case with carbon capture, Table 10 presents the revenues for the HTGR-integrated SMR case without carbon capture, and Table 11 presents the revenues for the HTGR-integrated SMR case with carbon capture.

Table 8. Annual revenue, conventional SMR case without carbon capture.

	Price		Generated		Annual Revenue
Hydrogen	1.13	\$/lb H_2	696,000	lb/day	\$265,030,396
Heat (Steam)	0.55	\$/kWt-day	55,449	kWt	\$10,263,822
Annual Revenue					**\$275,294,217**

Table 9. Annual revenue, conventional SMR case with carbon capture.

	Price		Generated		Annual Revenue
Hydrogen	1.13	\$/lb H_2	696,000	lb/day	\$265,030,396
Heat (Steam)	0.55	\$/kWt-day	6,916	kWt	\$1,280,265
Annual Revenue					**\$266,310,661**

Table 10. Annual revenue, HTGR-integrated SMR case without carbon capture.

	Price		Generated		Annual Revenue
Hydrogen	1.13	\$/lb H_2	696,000	lb/day	\$265,030,396
Heat (Steam)	0.55	\$/kWt-day	80,067	kWt	\$14,820,698
Annual Revenue – Fossil					**\$279,851,094**
Heat (Helium)	0.84	\$/kWt-day	119,200	kWt	\$33,622,982
Electricity	2.10	\$/kWe-day	4,600	kWe	\$3,243,828
Annual Revenue – HTGR (separate owner-operator)					**\$36,866,810**

Table 11. Annual revenue, HTGR-integrated SMR case with carbon capture.

	Price		Generated		Annual Revenue
Hydrogen	1.13	\$/lb H_2	696,000	lb/day	\$265,030,396
Heat (Steam)	0.55	\$/kWt-day	51,639	kWt	\$9,558,591
Annual Revenue – Fossil					**\$274,588,986**
Heat (Helium)	0.87	\$/kWt-day	116,900	kWt	\$34,230,377
Electricity	2.18	\$/kWe-day	13,700	kWe	\$10,029,003
Annual Revenue – HTGR (separate owner-operator)					**\$44,259,379**

3.1 Estimation of Manufacturing Costs

Manufacturing cost is the sum of direct and indirect manufacturing costs. Direct manufacturing costs for this project include the cost of raw materials, utilities, and operating labor and maintenance (O&M). Indirect manufacturing costs include estimates for the cost of overhead, insurance, and taxes (Perry 2008).

Labor costs are assumed to be 1.15% of the TCI for both cases. This percentage is based on staffing requirements for a conventional 50,000 bbl/day coal-to-liquids plant; but is also assumed to adequately represent the labor for the SMR plant and the fossil portion of the HTGR-integrated SMR plant. Maintenance costs were assumed to be 3% of the TCI per the *Handbook of Petroleum Processing*. Taxes and insurance were assumed to be 1.5% of the TCI, excluding the HTGR, an overhead of 65% of the labor and maintenance costs was assumed, and royalties were assumed to be 1% of the natural gas cost; this value was assumed based on information presented in the *Handbook of Petroleum Processing* (Jones 2006). Table 12 and Table 13 provide the manufacturing costs for the conventional SMR case without and with carbon capture, respectively. Table 14 and Table 15 provide the manufacturing costs for the HTGR-integrated SMR case without and with carbon capture, respectively. Availability of both the fossil and nuclear plants was assumed to be 92%. Natural gas prices were varied to account for the large fluctuations seen in the market. Costs were calculated for low (\$4.50/MSCF), average (\$6.50/MSCF), and high (\$12.00/MSCF) industrial natural gas prices. High prices correspond to prices from June 2008, low prices are from September 2009, and the average price was chosen to reflect current natural gas price (Energy Information Administration [EIA] 2010). Only average natural gas prices are presented in the tables below. In addition, the HTGR-integrated cases are presented for the single owner-operator scenario only. When the HTGR is operated independently, the fossil process would purchase heat and/or electricity as specified in the HTGR revenue tables presented previously (Table 10 and Table 11), and the manufacturing costs would be comprised of the nuclear fuel and O&M costs presented below (Table 14 and Table 15).

Table 12. Annual manufacturing costs, conventional SMR case without carbon capture.

	Price		Consumed		Annual Cost
Direct Costs					
Materials					
Average Natural Gas	6.50	\$/MSCF	52,500	MSCFD	\$114,591,750
Makeup H_2O Clarifying	0.02	\$/k-gal	1,358	k-gal/day	\$11,318
Wastewater Treatment	1.33	\$/k-gal	380	k-gal/day	\$170,390
HDS Catalyst	450	\$/ft^3	0.15	ft^3/day	\$22,376
Zinc Oxide	300	\$/ft^3	0.58	ft^3/day	\$58,008
Reforming Catalyst	750	\$/ft^3	0.16	ft^3/day	\$39,650
HTS Catalyst	380	\$/ft^3	0.12	ft^3/day	\$15,282
LTS Catalyst	600	\$/ft^3	0.10	ft^3/day	\$20,710
Utilities					
Electricity	1.67	\$/kW-day	6,300	kW	\$3,533,798
Water	0.05	\$/k-gal	1,358	k-gal/day	\$20,978
Royalties					\$1,145,918
Labor and Maintenance					\$10,608,453
Indirect Costs					
Overhead					\$6,895,495
Insurance and Taxes					\$3,834,381
Manufacturing Costs, Average Natural Gas					**\$140,968,505**

Table 13. Annual manufacturing costs, conventional SMR case with carbon capture.

	Price		Consumed		Annual Cost
Direct Costs					
Materials					
Average Natural Gas	6.50	\$/MSCF	49,200	MSCFD	\$107,388,840
Makeup H_2O Clarifying	0.02	\$/k-gal	936	k-gal/day	\$7,797
Wastewater Treatment	1.33	\$/k-gal	413	k-gal/day	\$184,842
HDS Catalyst	450	\$/ft^3	0.15	ft^3/day	\$22,496
Zinc Oxide	300	\$/ft^3	0.58	ft^3/day	\$58,321
Reforming Catalyst	750	\$/ft^3	0.16	ft^3/day	\$39,866
HTS Catalyst	380	\$/ft^3	0.12	ft^3/day	\$15,365
LTS Catalyst	600	\$/ft^3	0.10	ft^3/day	\$20,823
Selexol™ Solvent	\$2.71	\$/gal	4.91	gal/day	\$4,455
CO_2 Sequestration	14.75	\$/ton	2,143	ton/day	\$10,615,692
Utilities					
Electricity	1.67	\$/kW-day	14,400	kW	\$8,077,253
Water	0.05	\$/k-gal	936	k-gal/day	\$14,452
Royalties					\$1,073,888
Labor and Maintenance					\$12,086,330
Indirect Costs					
Overhead					\$7,856,114
Insurance and Taxes					\$4,368,553
Manufacturing Costs, Average Natural Gas					**\$151,835,088**

O&M costs for the nuclear plant were based on data from General Atomics for the gas-turbine modular high-temperature reactor published in 2002; these costs were inflated to 2009 dollars (GA 2002).

Table 14. Annual manufacturing costs, HTGR-integrated SMR case without carbon capture, single owner-operator.

	Price		Consumed		Annual Cost
Direct Costs					
Materials					
Average Natural Gas	6.50	$/MSCF	44,500	MSCFD	$97,130,150
Makeup H_2O Clarifying	0.02	$/k-gal	1,604	k-gal/day	$13,370
Wastewater Treatment	1.33	$/k-gal	372	k-gal/day	$166,648
HDS Catalyst	450	$/ft^3	0.15	ft^3/day	$22,336
Zinc Oxide	300	$/ft^3	0.57	ft^3/day	$57,907
Reforming Catalyst	750	$/ft^3	0.13	ft^3/day	$32,687
HTS Catalyst	380	$/ft^3	0.12	ft^3/day	$15,369
LTS Catalyst	600	$/ft^3	0.10	ft^3/day	$20,838
Utilities					
Water	0.05	$/k-gal	1,604	k-gal/day	$24,781
Royalties					$971,302
Labor and Maintenance					$9,394,174
Indirect Costs					
Overhead					$6,106,213
Insurance and Taxes					$3,395,485
Nuclear Costs					
Fuel	4.34	$/MWt-h	131	MWt/day	$4,569,562
O&M	1.76	$/MWt-h	131	MWt/day	$1,852,525
Manufacturing Costs, Average Natural Gas					**$123,773,348**

Table 15. Annual manufacturing costs, HTGR-integrated SMR case with carbon capture, single owner-operator.

	Price		Consumed		Annual Cost
Direct Costs					
Materials					
Average Natural Gas	6.50	\$/MSCF	43,500	MSCFD	\$94,947,450
Makeup H_2O Clarifying	0.02	\$/k-gal	1,379	k-gal/day	\$11,493
Wastewater Treatment	1.33	\$/k-gal	396	k-gal/day	\$177,229
HDS Catalyst	450	\$/ft^3	0.15	ft^3/day	\$22,595
Zinc Oxide	300	\$/ft^3	0.58	ft^3/day	\$58,038
Reforming Catalyst	750	\$/ft^3	0.13	ft^3/day	\$32,708
HTS Catalyst	380	\$/ft^3	0.12	ft^3/day	\$15,343
LTS Catalyst	600	\$/ft^3	0.10	ft^3/day	\$20,803
Selexol™ Solvent	\$2.71	\$/gal	4.34	gal/day	\$3,939
CO_2 Sequestration	14.75	\$/ton	2,123	ton/day	\$10,516,619
Utilities					
Water	0.05	\$/k-gal	1,379	k-gal/day	\$21,302
Royalties					\$949,475
Labor and Maintenance					\$11,062,273
Indirect Costs					
Overhead					\$7,190,478
Insurance and Taxes					\$3,998,412
Nuclear Costs					
Fuel	4.34	\$/MWt-h	151	MWt/day	\$5,284,540
O&M	1.76	\$/MWt-h	151	MWt/day	\$2,142,381
Manufacturing Costs, Average Natural Gas					**\$136,455,078**

3.2 Economic Comparison

Several economic indicators were calculated for each case to assess the economic desirability of the SMR cases. For all cases the IRR was calculated for SMR cases at low, average, and high natural gas prices, as well as for multiple owner-operator scenarios for the HTGR-integrated cases. In addition, the hydrogen price necessary for a return of 15% was calculated for all cases. Table 16 lists the economic assumptions made for the analyses.

Table 16. Economic assumptions.

	Fossil Plant	HTGR
Plant Startup Year	2016	2016
Construction Information		
Construction Period	3 years	5 years
Year Construction Begins	2013	2011
Percent Capital Invested Each Year	33%	20%
Plant Startup Information		
Startup Time	1 year	1 year
Percent Operating Costs During Startup	85%	85%
Percent Revenues During Startup	60%	60%
Economic Analysis Period	30 years	30 years
Availability	92%	92%
Inflation Rate	3%	3%
Debt to Equity Ratio	55%/45%	70%/30%
Loan Information		
Interest Rate on Debt	8%	4.5%
Interest on Debt During Construction	8%	4.5%
Loan Repayment Term	15 years	15 years
Tax Information		
Effective Tax Rate	38.9%	38.9%
State Tax Rate	6%	6%
Federal Tax Rate	35%	35%
MACRS Depreciation Term	15 year life	15 year life
IRR	15%	15%
CO_2 Tax	$0 to $100/ton	N/A

3.2.1 Cash Flow

To assess the IRR and present worth (PW) of each scenario, it is necessary to calculate the after tax cash flow (ATCF). To calculate the ATCF it is necessary to first calculate the revenues (R_k); cash outflows (E_k); sum of all noncash, or book, costs such as depreciation (d_k); net income before taxes (NIBT); the effective income tax rate (t); and the income taxes (T_k) for each year (k). The taxable income is revenue minus the sum of all cash outflow and noncash costs. Therefore, the income taxes per year are defined as follows (Sullivan 2003):

$$T_k = t(R_k - E_k - d_k) \tag{3}$$

Depreciation for the economic calculations was calculated using a standard Modified Accelerated Cost Recovery System (MACRS) depreciation method with a property class of 15 years. Depreciation was assumed for the TCI with the first charge occurring the year the plant comes online. Table 17 presents the recovery rates for a 15-year property class (Perry 2008):

Table 17. MACRS depreciation.

Year	Recovery Rate	Year	Recovery Rate
1	0.05	9	0.0591
2	0.095	10	0.059
3	0.0855	11	0.0591
4	0.077	12	0.059
5	0.0693	13	0.0591
6	0.0623	14	0.059
7	0.059	15	0.0591
8	0.059	16	0.0295

The ATCF is then the sum of the before tax cash flow (BTCF) minus the income taxes owed. Note that the expenditures for capital are not taxed but are included in the BTCF each year there is a capital expenditure (C_k), this includes the equity capital and the debt principle. The BTCF is defined as follows (Sullivan 2003):

$$BTCF_k = R_k - E_k - C_k \tag{4}$$

The ATCF can then be defined as:

$$ATCF_k = BTCF_k - T_k \tag{5}$$

When a CO_2 tax credit is included in the economic analysis, the tax would be treated essentially as a manufacturing cost, decreasing the yearly revenue.

3.2.2 Internal Rate of Return

The IRR method is the most widely used rate of return method for performing engineering economic analyses. This method solves for the interest rate that equates the equivalent worth of an alternative's cash inflows to the equivalent worth of cash outflows (after tax cash flow), i.e., the interest rate at which the PW is zero. The resulting interest is the IRR (i'). For the project to be economically viable, the calculated IRR must be greater than the desired minimum annual rate of return (MARR) (Sullivan 2003).

$$PW(i') = \sum_{k=0}^{N} ATCF_k (1 + i')^{-k} = 0 \tag{6}$$

IRR calculations were performed selling hydrogen at its market price for the low, average, and high natural gas purchase prices for the conventional SMR cases, as well as the single owner-operator HTGR-integrated case at the target and nominal HTGR price. In addition, the price of hydrogen necessary for an IRR of 15% and a PW of zero was calculated for all cases. When an independent owner-operator scenario was modeled, the price of heat and/or electricity necessary was calculated to achieve a 15% IRR. The necessary heat and/or electricity selling price was then used for any heat and/or electricity purchased by the fossil plant. The IRR and hydrogen price required (for an IRR of 15%) was solved for using the Goal Seek function in Excel (Excel 2007).

Finally, a CO_2 tax was included into the calculations to determine the price of hydrogen necessary in all cases for a 15% IRR and a CO_2 tax of $0/ton to $100/ton of CO_2 emitted. The tax calculated was added to the existing yearly tax liability.

4. ECONOMIC MODELING RESULTS AND OBSERVATIONS

Economic modeling results for the conventional case without carbon capture and with carbon capture are presented in Table 18 and Table 19, respectively. Results are tabulated for three different natural gas prices. For each natural gas price considered, two results are presented. The first result is the rate of return achievable if the hydrogen product can be sold at the current market price of $1.13/lb ($2.50/kg). The second result is the required selling price for hydrogen to achieve a 15% internal rate of return. As can be seen from these results, a 15% IRR is easily achievable at all but the highest natural gas price considered. Furthermore, as shown in Figure 9, these results show that a price penalty is incurred as a result of including carbon capture in the flowsheet.

Table 18. Conventional SMR case without carbon capture, IRR results.

	TCI	
	IRR	Product Price
Low NG: $4.50/MSCF	*$255,625,376*	
	47.4%	$1.13/lb H_2
	15.0%	$0.58/lb H_2
Average NG: $6.50/MSCF	*$255,625,376*	
	39.6%	$1.13/lb H_2
	15.0%	$0.73/lb H_2
High NG: $12.00/MSCF	*$255,625,376*	
	12.6%	$1.13/lb H_2
	15.0%	$1.17/lb H_2

Table 19. Conventional SMR case with carbon capture, IRR results.

	TCI	
	IRR	Product Price
Low NG: $4.50/MSCF	*$291,236,860*	
	39.2%	$1.13/lb H_2
	15.0%	$0.70/lb H_2
Average NG: $6.50/MSCF	*$291,236,860*	
	31.9%	$1.13/lb H_2
	15.0%	$0.84/lb H_2
High NG: $12.00/MSCF	*$291,236,860*	
	6.4%	$1.13/lb H_2
	15.0%	$1.25/lb H_2

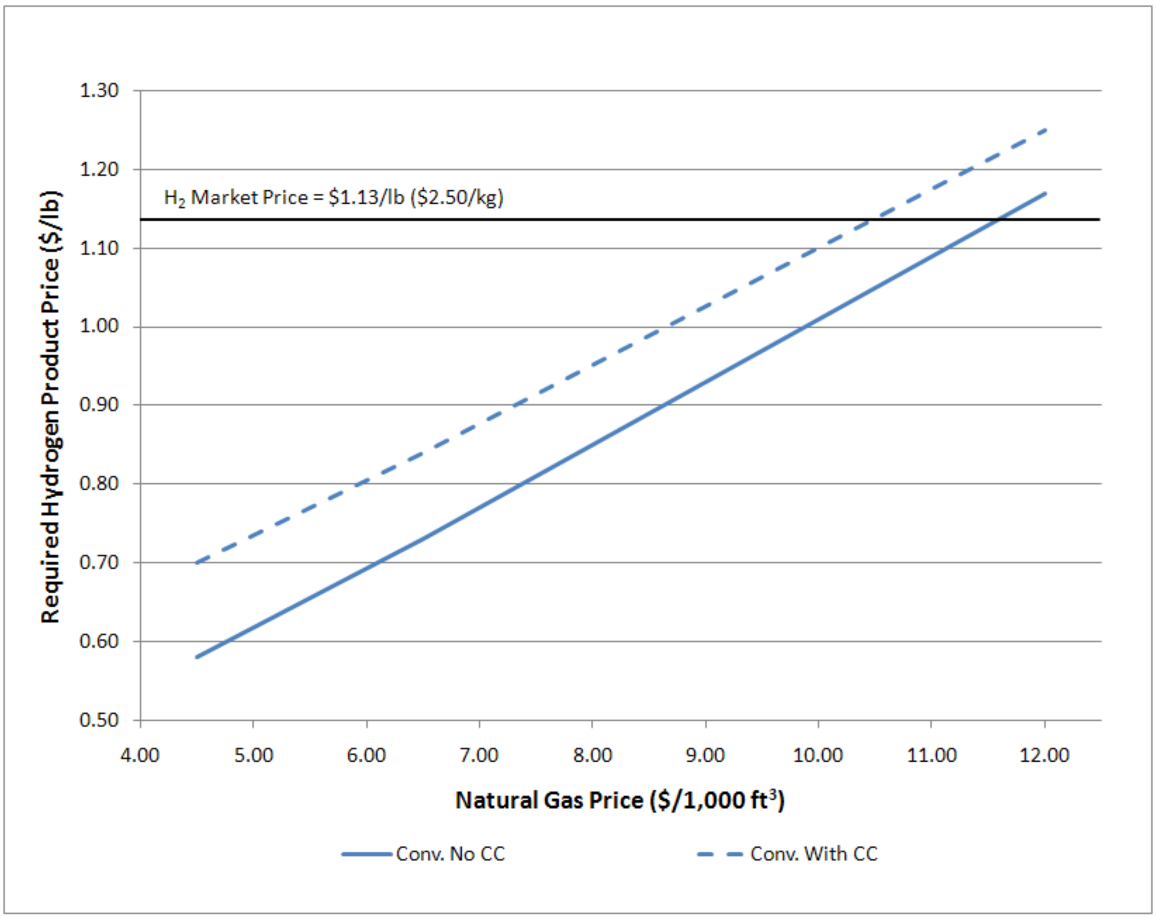

Figure 9. Impact of including carbon capture in the conventional case.

Economic modeling results for the HTGR-integrated case without carbon capture and with carbon capture are presented in Table 20 and Table 21, respectively. These results were obtained for the scenario in which both the fossil and nuclear portions of the plant are owned by a single owner-operator. For the case in which the fossil and nuclear plants are independently owned, results are presented in Table 22 and Table 23 for the scenario without and with carbon capture, respectively. Results are tabulated for three different natural gas prices. For each natural gas price considered, two results are presented. The first result is the rate of return achievable if the hydrogen product can be sold at the current market price of $1.13/lb ($2.50/kg). The second result is the required selling price for hydrogen to achieve a 15% internal rate of return. For the independent owner-operator cases, the prices for electricity, steam, and helium required to achieve a 15% IRR are also tabulated.

Table 20. HTGR-integrated SMR case without carbon capture, IRR results for a single owner-operator.

	TCI – Target HTGR		**TCI – Nominal HTGR**	
	IRR	Product Price	IRR	Product Price
Low NG: $4.50/MSCF	*$400,613,600*		*$467,597,350*	
	37.5%	$1.13/lb H_2	33.9%	$1.13/lb H_2
	15.0%	$0.58/lb H_2	15.0%	$0.62/lb H_2
Average NG: $6.50/MSCF	*$400,613,600*		*$467,597,350*	
	32.9%	$1.13/lb H_2	29.7%	$1.13/lb H_2
	15.0%	$0.71/lb H_2	15.0%	$0.75/lb H_2
High NG: $12.00/MSCF	*$400,613,600*		*$467,597,350*	
	17.7%	$1.13/lb H_2	15.8%	$1.13/lb H_2
	15.0%	$1.08/lb H_2	15.0%	$1.12/lb H_2

Table 21. HTGR-integrated SMR case with carbon capture, IRR results for a single owner-operator.

	TCI – Target HTGR		**TCI – Nominal HTGR**	
	IRR	Product Price	IRR	Product Price
Low NG: $4.50/MSCF	*$481,865,443*		*$559,329,818*	
	30.7%	$1.13/lb H_2	27.8%	$1.13/lb H_2
	15.0%	$0.71/lb H_2	15.0%	$0.75/lb H_2
Average NG: $6.50/MSCF	*$481,865,443*		*$559,329,818*	
	26.4%	$1.13/lb H_2	23.9%	$1.13/lb H_2
	15.0%	$0.84/lb H_2	15.0%	$0.88/lb H_2
High NG: $12.00/MSCF	*$481,865,443*		*$559,329,818*	
	12.1%	$1.13/lb H_2	10.6%	$1.13/lb H_2
	15.0%	$1.20/lb H_2	15.0%	$1.24/lb H_2

Table 22. HTGR-integrated SMR case without carbon capture, IRR results for an independent owner-operator.

	TCI – Target HTGR		TCI – Nominal HTGR	
	IRR	Product Price	IRR	Product Price
HTGR	*$174,247,964*		*$241,231,714*	
Heat and/or Power Production	15.0%	$1.62/kWe-day	15.0%	$2.10/kWe-day
	15.0%	$0.65/kWt-day	15.0%	$0.84/kWt-day
	15.0%	$4.80/1,000 lb-He	15.0%	$6.22/1,000 lb-He
Fossil Process	*$226,365,637*		*$226,365,637*	
Low NG: $4.50/MSCF	49.9%	$1.13/lb H_2	48.0%	$1.13/lb H_2
	15.0%	$0.59/lb H_2	15.0%	$0.62/lb H_2
Fossil Process	*$226,365,637*		*$226,365,637*	
Average NG: $6.50/MSCF	42.8%	$1.13/lb H_2	40.6%	$1.13/lb H_2
	15.0%	$0.72/lb H_2	15.0%	$0.76/lb H_2
Fossil Process	*$226,365,637*		*$226,365,637*	
High NG: $12.00/MSCF	19.0%	$1.13/lb H_2	16.1%	$1.13/lb H_2
	15.0%	$1.08/lb H_2	15.0%	$1.12/lb H_2

Table 23. HTGR-integrated SMR case with carbon capture, IRR results for an independent owner-operator.

	TCI – Target HTGR		TCI – Nominal HTGR	
	IRR	Product Price	IRR	Product Price
HTGR	*$215,304,637*		*$292,769,012*	
Heat and/or Power Production	15.0%	$1.70/kWe-day	15.0%	$2.18/kWe-day
	15.0%	$0.68/kWt-day	15.0%	$0.87/kWt-day
	15.0%	$4.99/1,000 lb-He	15.0%	$6.40/1,000 lb-He
Fossil Process	*$266,560,806*		*$266,560,806*	
Low NG: $4.50/MSCF	39.8%	$1.13/lb H_2	37.6%	$1.13/lb H_2
	15.0%	$0.71/lb H_2	15.0%	$0.76/lb H_2
Fossil Process	*$266,560,806*		*$266,560,806*	
Average NG: $6.50/MSCF	33.0%	$1.13/lb H_2	30.6%	$1.13/lb H_2
	15.0%	$0.84/lb H_2	15.0%	$0.89/lb H_2
Fossil Process	*$266,560,806*		*$266,560,806*	
High NG: $12.00/MSCF	9.8%	$1.13/lb H_2	5.9%	$1.13/lb H_2
	15.0%	$1.20/lb H_2	15.0%	$1.24/lb H_2

Hydrogen selling price results for the single owner-operator HTGR-integrated cases without carbon capture are presented graphically in Figure 10. For comparison, the conventional case without carbon capture is also included. As shown in this figure, the HTGR-integrated case can produce hydrogen for less than the market price of $1.13/lb ($2.50/kg) even if natural gas prices rise to $12 per 1,000 scf. Furthermore, the HTGR-integrated case outperforms the conventional case when natural gas prices rise above $8 per 1,000 scf. If HTGR prices can be reduced by 30% to target levels, then the

HTGR-integrated case will outperform the conventional case across the entire range of natural gas prices considered.

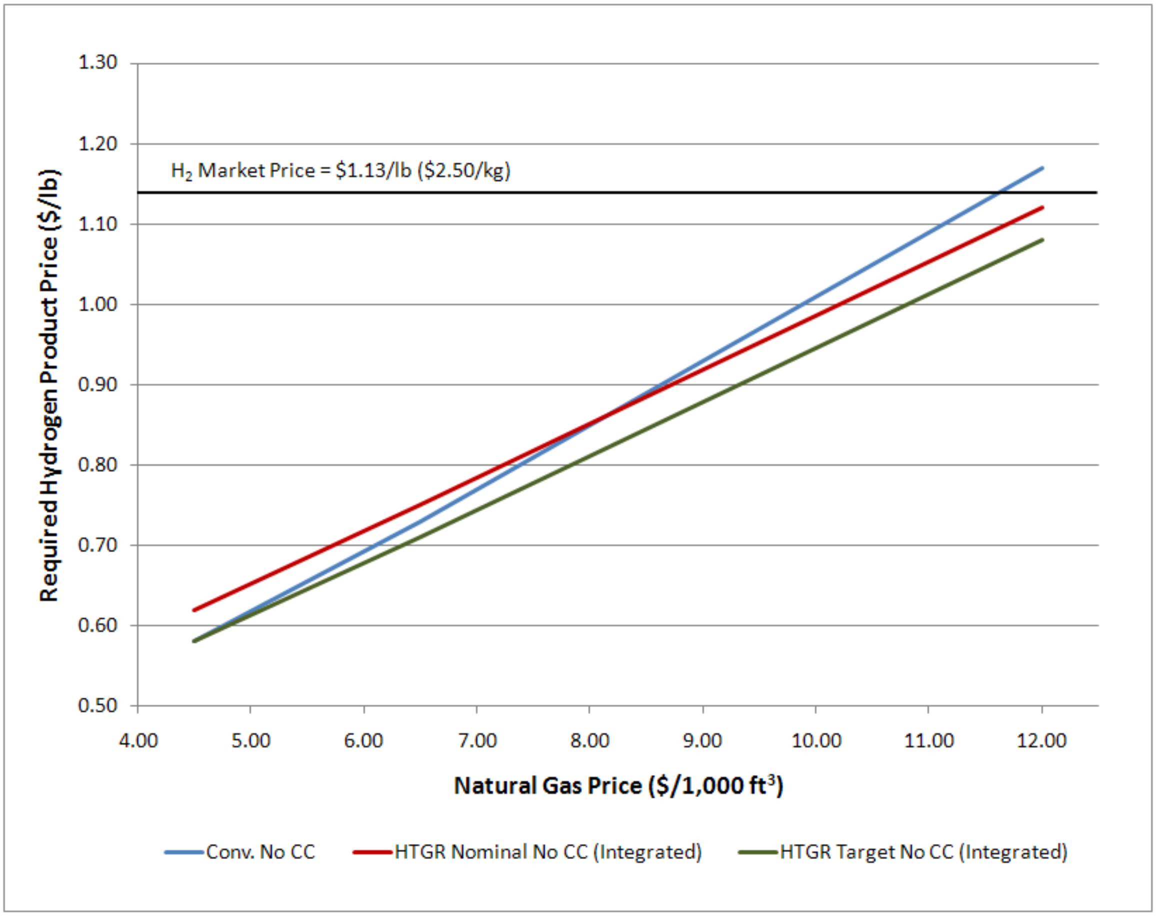

Figure 10. Hydrogen selling price as a function of natural gas price without carbon capture (for a single owner-operator scenario).

Hydrogen selling price results for the single owner-operator HTGR-integrated cases with carbon capture are presented graphically in Figure 11. For comparison, the conventional case with carbon capture is also included. As shown in this figure, the HTGR-integrated case can produce hydrogen for less than the market price of $1.13/lb ($2.50/kg) when natural gas prices are less than $10 per 1,000 scf. The HTGR-integrated case outperforms the conventional case when natural gas prices rise above $10.50 per 1,000 scf. If HTGR prices can be reduced by 30% to target levels, then the HTGR-integrated case will outperform the conventional case when natural gas prices rise above $6.50 per 1,000 scf.

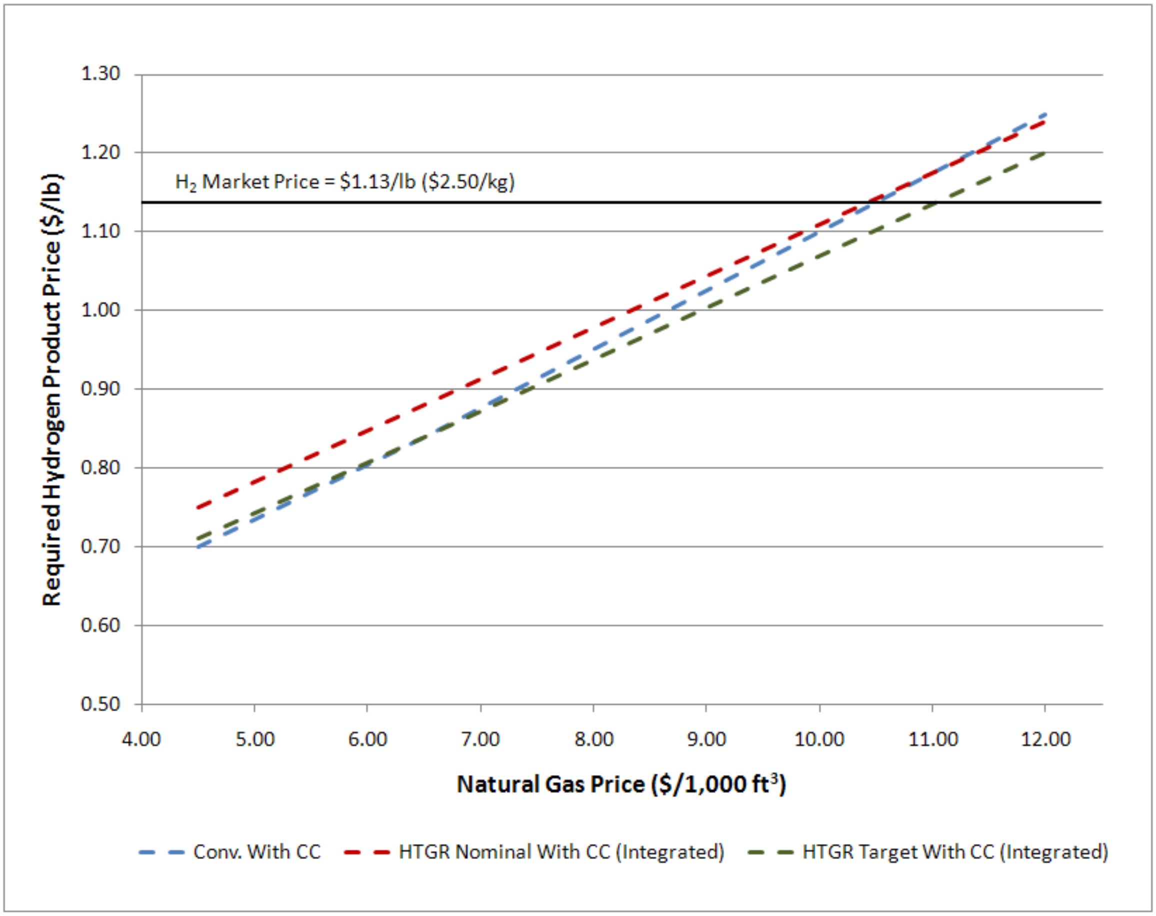

Figure 11. Hydrogen selling price as a function of natural gas price with carbon capture (for a single owner-operator scenario).

The impact of running the economic calculations for a single owner-operator (integrated) scenario versus an independent owner-operator (separate) scenario is shown in Figure 12. For the independent owner-operator scenario in these calculations, the price of heat and electricity were set in order to provide a 15% IRR to the HTGR owner-operator. In the absence of a carbon tax, the economic results are relatively unaffected by the business model selected.

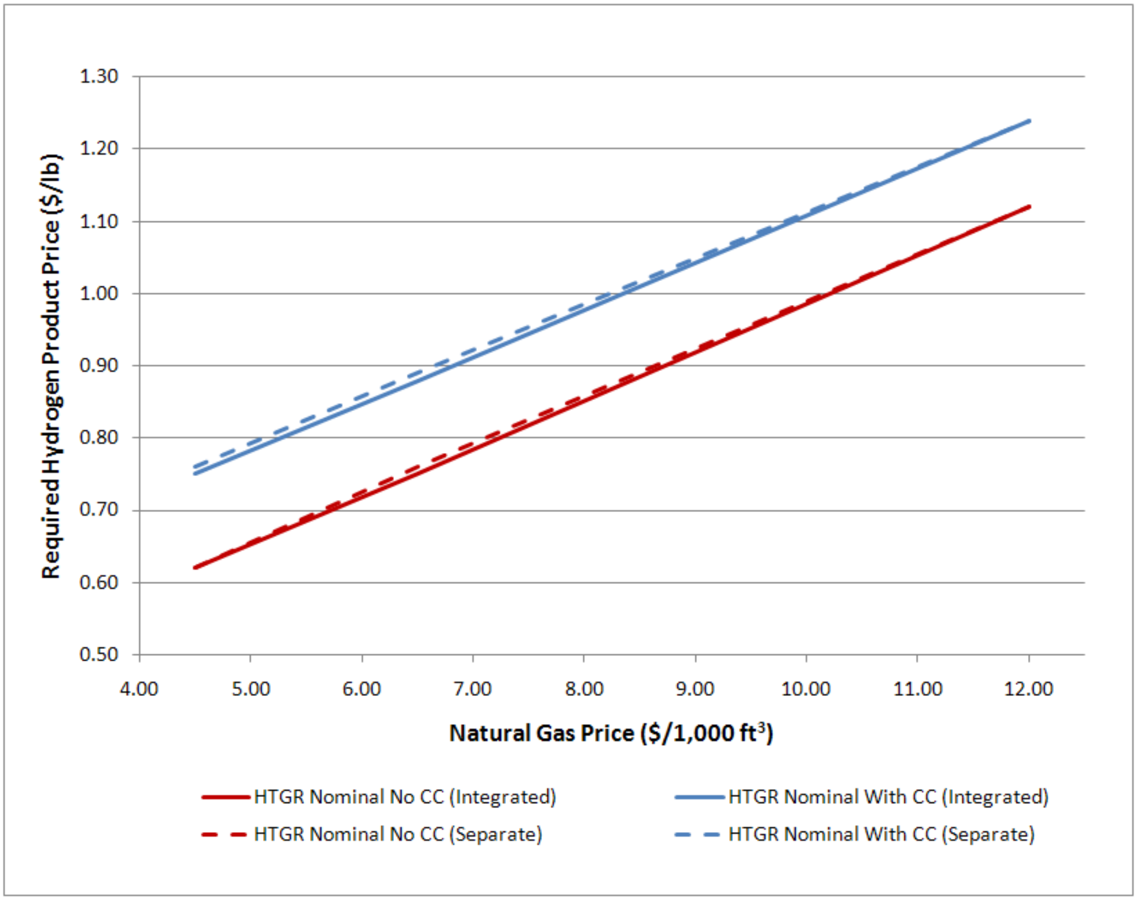

Figure 12. Impact of single owner-operator scenario vs. independent owner-operator scenario on hydrogen selling price in the absence of a carbon tax.

The impact of a CO_2 emissions tax on the hydrogen selling price for the conventional case without carbon capture and with carbon capture are presented in Table 24 and Table 25, respectively. Results are tabulated for three different natural gas prices. As shown in Figure 13, carbon capture and sequestration make economic sense when a carbon tax of $25/ton CO_2 or higher is imposed.

Table 24. Conventional SMR case without carbon capture, carbon tax results.

	Carbon Tax ($/ton)	Product Price ($/lb H_2)
Low NG: $4.50/MSCF	0	0.58
	25	0.71
	50	0.84
	75	0.97
	100	1.11
Average NG: $6.50/MSCF	0	0.73
	25	0.87
	50	1.00
	75	1.13
	100	1.26
High NG: $12.00/MSCF	0	1.17
	25	1.30
	50	1.43
	75	1.56
	100	1.69

Table 25. Conventional SMR case with carbon capture and sequestration, carbon tax results.

	Carbon Tax ($/ton)	Product Price ($/lb H_2)
Low NG: $4.50/MSCF	0	0.70
	25	0.73
	50	0.77
	75	0.80
	100	0.84
Average NG: $6.50/MSCF	0	0.84
	25	0.88
	50	0.91
	75	0.95
	100	0.98
High NG: $12.00/MSCF	0	1.25
	25	1.28
	50	1.32
	75	1.35
	100	1.39

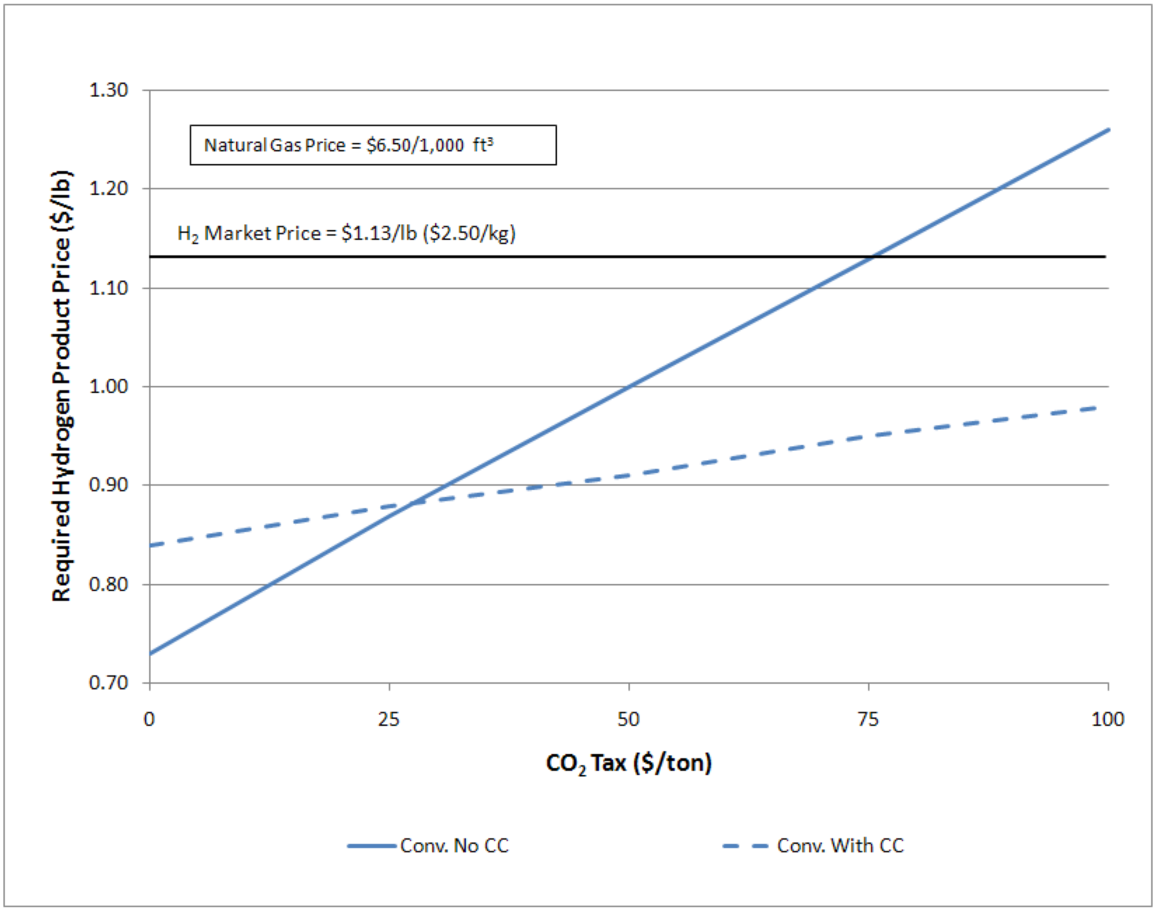

Figure 13. Hydrogen selling price as a function of carbon tax for conventional SMR cases.

The impact of a CO_2 emissions tax on the hydrogen selling price for the HTGR-integrated case without carbon capture and with carbon capture are presented in Table 26 and Table 27, respectively. These results were obtained for the scenario in which both the fossil and nuclear portions of the plant are owned by a single owner-operator. For the case in which the fossil and nuclear plants are independently owned, results are presented in Table 28 and Table 29 for the scenario without and with carbon capture, respectively. Results are tabulated for three different natural gas prices. The results presented for the independent owner-operator cases set the price for electricity and helium to achieve a 15% IRR for the HTGR plant.

For the single owner-operator scenarios without carbon capture, each increase in tax of \$10/ton CO_2 results in a product price increase of about \$0.045/lb H_2. For the single owner-operator scenarios with carbon capture, each increase in tax of \$10/ton CO_2 results in a product price increase of only \$0.009/lb H_2. For the independent owner-operator scenarios, the effect of carbon tax on product price is more pronounced. For the independent owner-operator scenario without carbon capture, each increase in tax of \$10/ton CO_2 results in a product price increase of about \$0.064/lb H_2. For the independent owner-owner operator scenarios with carbon capture, each increase in tax of \$10/ton CO_2 results in a product price increase of about \$0.020/lb H_2.

Table 26. HTGR-integrated SMR case without carbon capture, carbon tax results for a single owner-operator.

	Carbon Tax (\$/ton)	HTGR – Target Price Product Price (\$/lb H_2)	HTGR – Nominal Price Product Price (\$/lb H_2)
Low NG: \$4.50/MSCF	0	0.58	0.62
	25	0.69	0.73
	50	0.81	0.84
	75	0.92	0.95
	100	1.03	1.07
Average NG: \$6.50/MSCF	0	0.71	0.75
	25	0.83	0.86
	50	0.94	0.97
	75	1.05	1.09
	100	1.16	1.20
High NG: \$12.00/MSCF	0	1.08	1.12
	25	1.19	1.23
	50	1.30	1.34
	75	1.42	1.45
	100	1.53	1.56

Table 27. HTGR-integrated SMR case with carbon capture and sequestration, carbon tax results for a single owner-operator.

	Carbon Tax ($/ton)	HTGR – Target Price Product Price ($/lb H_2)	HTGR – Nominal Price Product Price ($/lb H_2)
Low NG: $4.50/MSCF	0	0.71	0.75
	25	0.73	0.77
	50	0.75	0.79
	75	0.78	0.82
	100	0.80	0.84
Average NG: $6.50/MSCF	0	0.84	0.88
	25	0.86	0.90
	50	0.88	0.92
	75	0.90	0.95
	100	0.93	0.97
High NG: $12.00/MSCF	0	1.20	1.24
	25	1.22	1.26
	50	1.24	1.28
	75	1.26	1.30
	100	1.28	1.33

Table 28. HTGR-integrated SMR case without carbon capture, carbon tax results for an independent owner-operator.

	Carbon Tax ($/ton)	HTGR – Target Price Product Price ($/lb H_2)	HTGR – Nominal Price Product Price ($/lb H_2)
Low NG: $4.50/MSCF	0	0.59	0.62
	25	0.81	0.85
	50	0.92	0.96
	75	1.04	1.07
	100	1.15	1.19
Average NG: $6.50/MSCF	0	0.72	0.76
	25	0.95	0.98
	50	1.06	1.09
	75	1.17	1.21
	100	1.28	1.32
High NG: $12.00/MSCF	0	1.08	1.12
	25	1.31	1.35
	50	1.42	1.46
	75	1.53	1.57
	100	1.65	1.68

Table 29. HTGR-integrated SMR case with carbon capture and sequestration, carbon tax results for an independent owner-operator.

	Carbon Tax ($/ton)	HTGR – Target Price Product Price ($/lb H_2)	HTGR – Nominal Price Product Price ($/lb H_2)
Low NG: $4.50/MSCF	0	0.71	0.76
	25	0.76	0.80
	50	0.78	0.82
	75	0.80	0.84
	100	0.82	0.87
Average NG: $6.50/MSCF	0	0.84	0.89
	25	0.89	0.93
	50	0.91	0.95
	75	0.93	0.97
	100	0.95	1.00
High NG: $12.00/MSCF	0	1.20	1.24
	25	1.25	1.29
	50	1.27	1.31
	75	1.29	1.33
	100	1.31	1.35

The impact of a CO_2 tax on hydrogen selling price for the single owner-operator HTGR-integrated cases without carbon capture are presented graphically in Figure 14. For comparison, the conventional case without carbon capture is also included. As shown in this figure, the HTGR-integrated case can produce hydrogen for less than the conventional case when an emissions tax of $20/ton CO_2 or higher is imposed. Furthermore, if the HTGR price can be reduced by 30% to the target level, then the HTGR-integrated case will outperform the conventional case regardless of whether or not a CO_2 emissions tax is imposed.

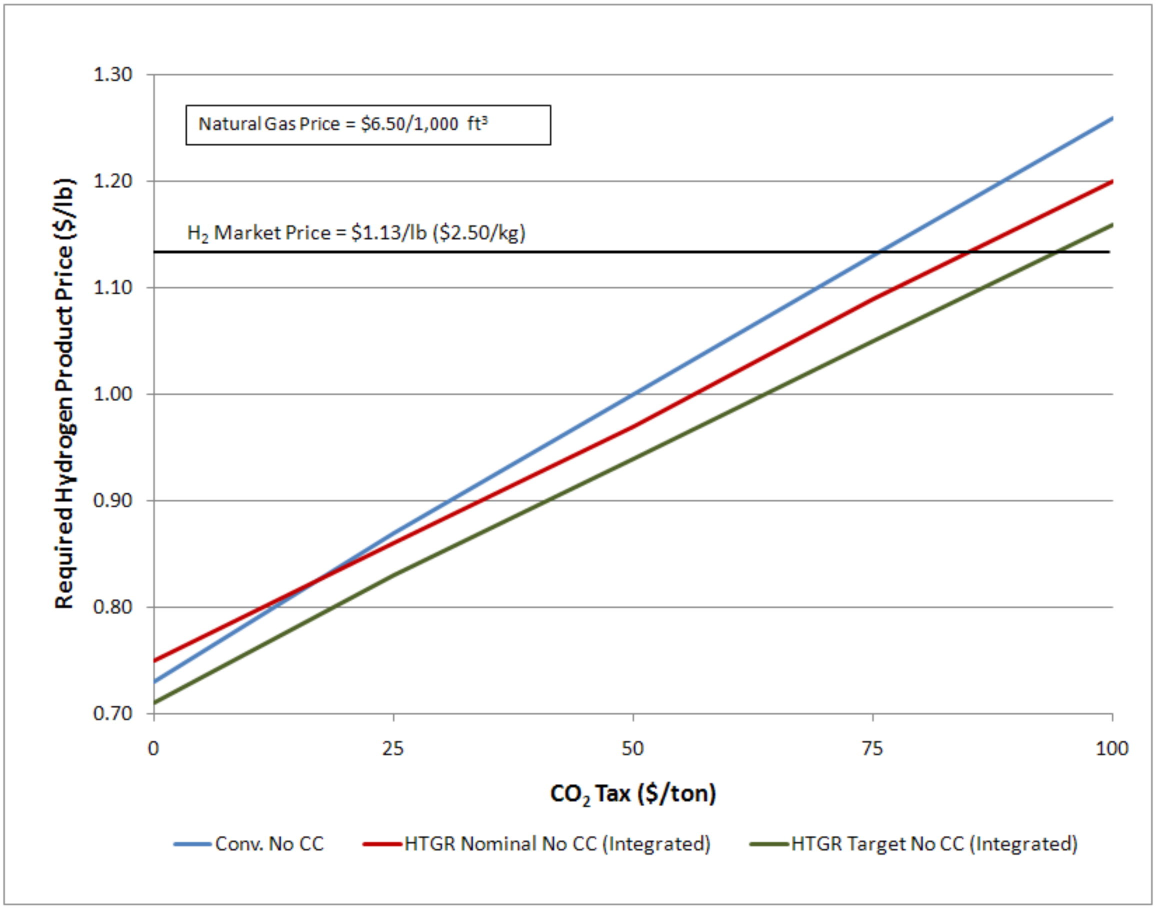

Figure 14. Hydrogen selling price as a function of carbon tax for the HTGR-integrated cases without carbon capture.

The impact of a CO_2 tax on hydrogen selling price for the single owner-operator HTGR-integrated cases with carbon capture are presented graphically in Figure 15. For comparison, the conventional case with carbon capture is also included. As shown in this figure, the HTGR-integrated case can produce hydrogen for less than the conventional case when an emissions tax of $75/ton CO_2 or higher is imposed. Furthermore, if the HTGR price can be reduced by 30% to the target level, then the HTGR-integrated case will outperform the conventional case regardless of whether or not a CO_2 emissions tax is imposed.

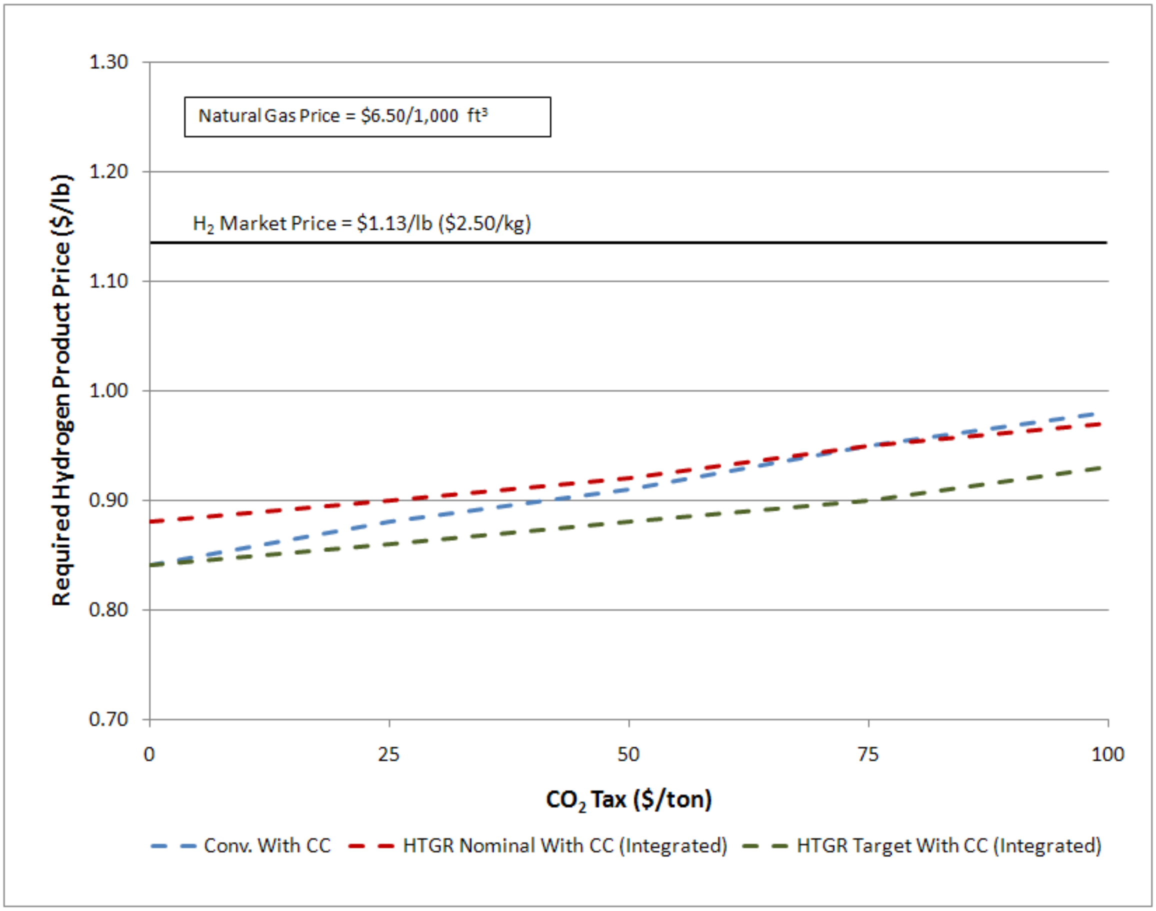

Figure 15. Hydrogen selling price as a function of carbon tax for the HTGR-integrated cases with carbon capture and sequestration.

Figure 16 shows that for the HTGR-integrated cases, carbon capture and sequestration make economic sense when an emissions tax of $35/ton CO_2 or more is imposed.

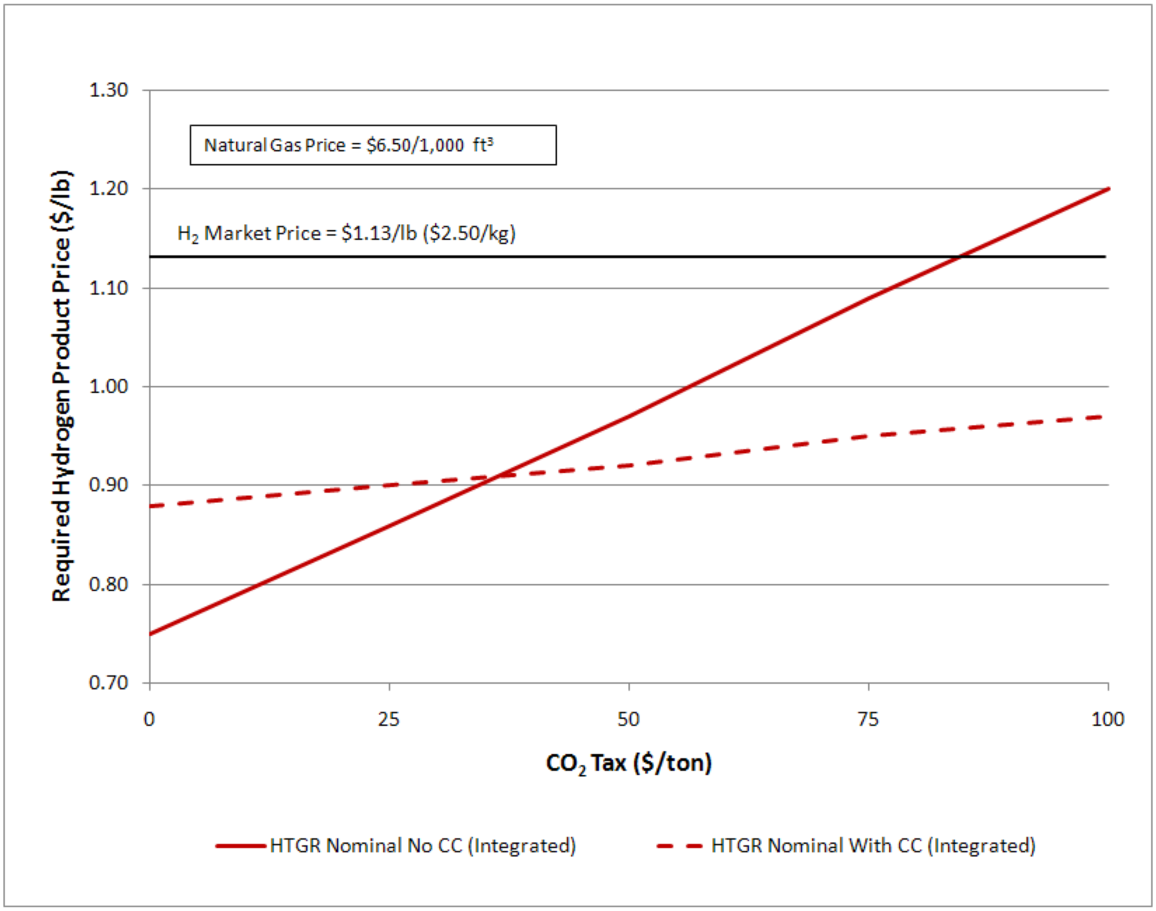

Figure 16. Hydrogen selling price as a function of carbon tax for the HTGR-integrated cases.

It was previously shown in Figure 12 that in the absence of a carbon tax, the economic results are relatively unaffected by the selection of a single owner-operator (integrated) scenario versus an independent owner-operator (separate) scenario. However, this trend does not hold if a carbon tax is imposed. As shown in Figure 17, the single owner-operator scenario produces a more favorable hydrogen selling price when a carbon tax is imposed. This result is likely due to distributing the financial burden of the tax over a wider capital and operating cost base in the single owner-operator scenario rather than shifting the full burden of the tax to the hydrogen plant in the independent owner-operator scenario.

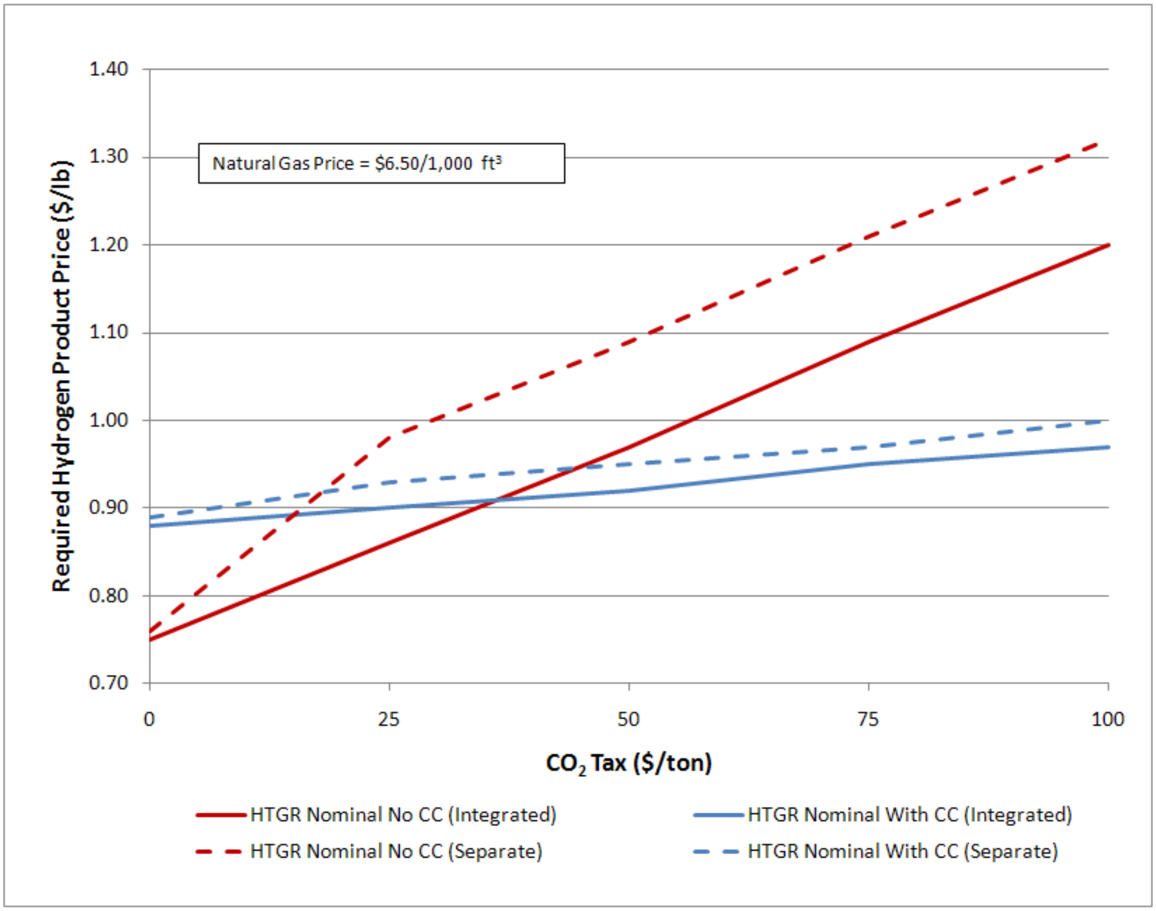

Figure 17. Impact of single owner-operator scenario vs. independent owner-operator scenario on hydrogen selling price when a carbon tax is imposed.

5. CONCLUSIONS AND RECOMMENDATIONS

For this analysis, two HTGR cost scenarios were considered: nominal cost refers to the anticipated cost to build a single HTGR, and target cost refers to the HTGR cost for larger installations when three or more HTGRs can be co-located. The following major conclusions can be drawn from this study:

- Integrating HTGR heat into a SMR process is economically viable. A 15% internal rate of return (IRR) can be easily achieved in many of the scenarios considered while producing hydrogen for less than $1.13/lb ($2.50/kg).

- For the scenarios without carbon capture:

- In the absence of a carbon tax, the nominal HTGR-integrated case outperforms the conventional case when natural gas prices rise above $8 per 1,000 scf.
- Assuming a natural gas price of $6.50 per 1,000 scf, the nominal HTGR-integrated case can produce hydrogen for less than the conventional case when an emissions tax of $20/ton CO_2 or higher is imposed.
- The target HTGR-integrated case will economically outperform the conventional case across the entire range of natural gas prices considered regardless of whether or not a CO_2 emissions tax is imposed.

- For the scenarios with carbon capture and sequestration:
  - In the absence of a carbon tax, the nominal HTGR-integrated case outperforms the conventional case only when natural gas prices rise above $10.50 per 1,000 scf. The target HTGR-integrated case outperforms the conventional case for natural gas prices above $6.50 per 1,000 scf.
  - Assuming a natural gas price of $6.50 per 1,000 scf, the nominal HTGR-integrated case can produce hydrogen for less than the conventional case when an emissions tax of $75/ton CO_2 or higher is imposed. The target HTGR-integrated case will outperform the conventional case regardless of whether or not a CO_2 emissions tax is imposed.
- HTGR integration appears to have more of an advantage over the conventional process for the scenarios that do not capture carbon. However, carbon capture and sequestration is preferable for the HTGR-integrated scenarios when an emissions tax of $35/ton CO_2 or more is imposed.

Based on the results of this study, several follow-on activities are recommended. The most significant of these recommendations are listed below.

- It is likely that economic results for the HTGR-integrated case would improve if the HTGR temperature could be increased beyond 750°C. Hence, a study to quantify the potential economic improvement is recommended.
- Additional work is warranted to scope out initial equipment design and further assess the feasibility of a HTGR-integrated SMR. Specifically, the economic impact of shifting the mode of heat transfer from radiation in a conventional design to convection in a HTGR-integrated design should be investigated.
- Refined estimates of the HTGR capital cost, annual fuel costs, and annual operation and maintenance costs should be developed, including sensitivity to reactor outlet temperature.

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