**REPORT**

GTI PROJECT NUMBER: 22481
DOE AWARD NUMBER: DE-EE0008637

# Techno-Economic Analysis for GTI's Compact Hydrogen Generator

**Reporting Period:**
January 01, 2020 through July 20, 2020

**Report Issued:**
July 20, 2020

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## Executive Summary

A technoeconomic analysis of the compact hydrogen generator compared to a traditional steam methane reformer (SMR) was performed for both processes with and without carbon capture. The project goal for the technoeconomic analysis was to demonstrate a minimum of 20% lower CAPEX and 15% lower levelized cost of hydrogen compared to SMR with and without carbon capture. GTI obtained baseline capital and costs for the SMR with and without and methodology to calculate the levelized cost of hydrogen from an IEAGHG Technical Report: 2017-02 Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS. This methodology was then applied to GTI's compact hydrogen generator using direct material costs previously obtained from a reputable engineering procurement and construction company, CB&I Howe-Baker. The analysis was performed for plants producing 90MMSCFD (million standard cubic feed per day) of hydrogen. Direct material costs were converted to total installed costs and total capital requirements using the same multiplying factors for both processes. We have found that the direct materials cost of the compact hydrogen generator is less than half the direct materials cost required for SMR without capture, and about one quarter the direct materials cost of SMR with carbon capture. This low materials cost translates into a significant CAPEX savings and lower levelized cost of hydrogen that exceed the goals of the techno-economic assessment. We have found that the CHG has a 43% lower installed cost and capital requirement compared to SMR without capture, that results in a levelized cost of hydrogen that is 19% lower than SMR. When 90% $CO_2$ capture is added to the plants, the advantages is even better. The CHG has a 51% lower installed and capital requirement compared to SMR with capture, resulting in a 28% lower levelized cost of hydrogen. A sensitivity analysis was performed and showed natural gas feedstock cost and discount rate to be the main contributors to hydrogen price sensitivity. Given these significant cost advantages, GTI is encouraged to continue to develop the technology and market the economic advantages as well as the efficiency gains and ability to inherently capture $CO_2$.

## Introduction

The overall approach to the technoeconomic analysis is presented in the steps outlined in Figure 1. GTI sized the compact hydrogen generator plant for 90MMSCFD in order to match the size of an SMR with published economics found in an IEAGHG report 2017-2 ("Techno-Economic Evaluation of SMR based Standalone (Merchant) Hydrogen Plant with CCS." more detail on that report below).

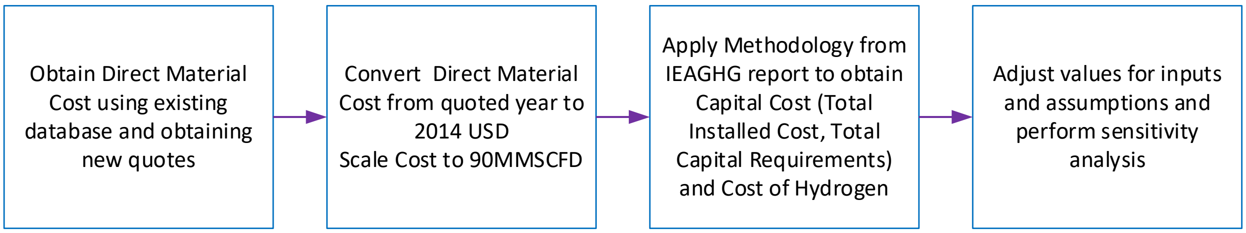


*Figure 1. Overall Approach to the Technoeconomic Analysis*

The foundation of the direct materials cost for the compact hydrogen generator is a detailed equipment cost list for a 60MMSCFD hydrogen plant developed by CB&I Howe-Baker International during an assessment performed in June 2005. GTI has scaled these costs to 2014 dollars using the Chemical Engineering Plant Cost Index (CEPCI). Costs were adjusted to 2014 since that is the same year basis for the costs in the IEAGHG report 2017-2. Additionally, GTI scaled the costs of the CHG technology to 90MMSCFD capacity using a scaling factor of n=0.65 for the equation:

$$\text{Cost of Size 2} = \text{Cost of Size 1}\ (\text{size 2} / \text{size 1})^n$$

A summary of the equipment list with cost scaled for size and adjusted for 2014 costs is provided in Table 1 below. The most expensive equipment is the pressure swing absorber (PSA) required for purification of the hydrogen. The IEAGHG report we used for comparison to SMR does not provide a detailed equipment lists with costs, rather it contains the total direct materials cost. The report does contain fine details of how that direct material cost was translated to a installed cost, total capital requirement and levelized cost of hydrogen.

*Table 1 Summary of equipment costs for a 90MMSCFD Compact Hydrogen Generator*

| Equipment | Required | Total Cost |
|---|---|---|
| Pressure Vessels | 11* | $842,558 |
| Heat Exchange Equipment | 12* | $3,849,108 |
| Air Cooled Exchangers | 1 | $561,200 |
| Pumps | 1 | $358,285 |
| Fired Equipment & Aux components | 7 | $2,834,971 |
| PSA Units | 1 | $5,094,919 |
| Filters & Specialties | 3 | $103,815 |
| Instrumentation | 4 | $1,781,127 |
| Electrical Equipment | 5 | $432,686 |
| Total Valves and Specialties | 3 | $732,966 |
| | Total | $16,591,635 |

*four pressure vessels and four heat exchangers are not required for no $CO_2$ capture case

In addition to the CHG equipment costs listed in Table 1, other required equipment for the compact hydrogen generator includes lockhoppers, solids handling equipment, and a hydrogen compressor (the latter required for capture case only).

The lockhoppper equipment cost is $3,350,491 including instrumentation and electrical costs, This is based on a GTI's quoted equipment database using lockhopper equipment costs from Jacobs. The solids handling equipment cost is $3,992,884 scaled from the original CBI, Howe-Baker estimate for a 60MMSCFD hydrogen plant.

GTI obtained numerous quotes from vendors for a Hydrogen Compressor. The cost of $3,900,000 was obtained using the exact stream composition and flowrate expected for the 90MMSCFD plant. We added 5% contingency to account for any added safety requirements such as explosion proof containment. The package includes a model 2TVL500 compressor, 2 stage, non-lubricated four throw, horizontal reciprocating compressor with four water-cooled cylinder per API 618 5$^{th}$ Edition. This compressor is only required for the compact hydrogen generator with $CO_2$ capture. It is used to increase the reactor product gas pressure from 120psig to 360psig delivery to the PSA unit. The non-$CO_2$ capture case reactor operates at 360psig and the compressor is not necessary.

The total direct materials costs for the CHG with and without capture is summarized and compared to SMR (reported in the IEAGHG 2017-2 report) with and without capture in Table 2. Without capture, the materials cost of the CHG is less than half that of a steam methane reformer. While the addition of an amine system doubles the material cost of a steam methane reformer to achieve 90% $CO_2$ capture, the cost of the compact hydrogen generator increases by just 22% to achieve 90% $CO_2$ capture. The total direct materials cost of the compact hydrogen generator with capture is just 27% the cost of the SMR with capture (prior to inclusion of utilities, balance of plant, and $CO_2$ compression).

*Table 2. Total direct materials cost of the CHG and SMR with and without capture, considering just the cost of the hydrogen plant and the $CO_2$ capture plant, excluding $CO_2$ compression ($CO_2$ Compression direct materials is $15.6-16.7MM)*

| | CHG without Capture | CHG with 90% Capture |
|---|---|---|
| Major Equipment | $15,635,876 | $16,591,635 |
| Lockhoppers | $3,350,491 | $3,350,491 |
| Solids Handling | $3,992,884 | $3,992,884 |
| Hydrogen Compressor | | $4,095,000 |
| Total Direct Materials Cost | $22,979,251 | $28,030,010 |
| | Excludes Utilities and balance of plant | Excludes Utilities Balance of Plant and $CO_2$ Compression |
| | SMR without Capture | SMR with 90% Capture |
| Direct Materials Cost | $50,810,658 | $104,439,342 |
| | Excludes Power Island and Utilities and Balance of Plant | Excludes Power Island and Utilities and Balance of Plant, and $CO_2$ Compression |

To translate the materials cost into a Total Plant Cost and Total Capital Requirement, and to calculate the levelized cost of hydrogen (LCOH) GTI used the methodology outlined in a publicly available IEAGHG Technical Report 2017-2. The report was prepared by researchers from AMEC Foster Wheeler, a company that designs and licenses steam methane reformers. Therefore, GTI views the capital costs and technoeconomic analysis methodology to be highly reliable. GTI searched the literature for other publicly available reports for advertised SMR capital costs and levelized cost of hydrogen and found this IEAGHG report to be the most complete. GTI used the costs for IEAGHG Base case: SMR Plant equipped with Feedstock Pre-treatment, Pre-reforming, High Temperature shift and PSA as our base case for capital costs and levelized cost of hydrogen without $CO_2$ capture. GTI used the costs for IEAGHG Case 03: SMR with 90% capture of $CO_2$ from the flue gas using MEA as the baseline case for hydrogen generation with 90% $CO_2$ capture. The methodology used in the IEAGHG report to translate the direct materials cost into installed costs, total capital requirements, and calculate the levelized cost of hydrogen was applied to the direct materials costs of the compact hydrogen generator to prepare a rational comparison of the economics between the processes. GTI did not take into account any advantage the CHG may have with respect to modular construction. Therefore, the factors use to convert materials cost to installed costs are the same for SMR and the CHG.

The IEAGHG report provided costs in fourth quarter 2014 basis euros. GTI used an exchange rate of $1.249 per euro to convert to 2014 dollars, which was the average for the fourth quarter 2014.

Block flow diagrams for the four different cases (SMR without and with $CO_2$ capture, and CHG without and with $CO_2$ capture) are provided in Figure 2, Figure 3, Figure 4, and Figure 5 respectively. Detailed descriptions of the SMR cases can be found in the IEAGHG report. Some of the key details of this very standard process are reported here. Preheated natural gas is mixed with a slipstream of the purified produced hydrogen and fed to a pretreatment section for preheat to 370°C and desulfurization, this gas is then mixed with steam to achieve a steam to carbon ratio of about 2.7-2.8 on a molar basis. This feed is sent to a pre-reformer to convert heavy hydrocarbons into syngas leaving the C2+ concentration in the remaining feed to less than 500ppmv. Steam is added to this stream to fine tune the steam to carbon ratio before entering the reformer. The product gas leaving the reformer contains 3.3-4% methane (dry molar basis). The reformer is air fired using a fuel blend of natural gas and pressure swing absorber (PSA) tail gas. The furnace exit gas temperature is as high as 900°C, and this hot gas stream is used to generate high pressure saturated steam. The syngas exiting the reformer is cooled to 320°C and fed into the High temperature shift convert where the excess steam reacts with CO to form $H_2$ and $CO_2$ over a fixed bed of supported nickel catalyst. The PSA then purifies the dried product gas from 75.6% to 99.5% hydrogen, recovering about 85-92% hydrogen from the PSA feed. Hydrogen is delivered to the battery limits at 363psig for all cases evaluated.

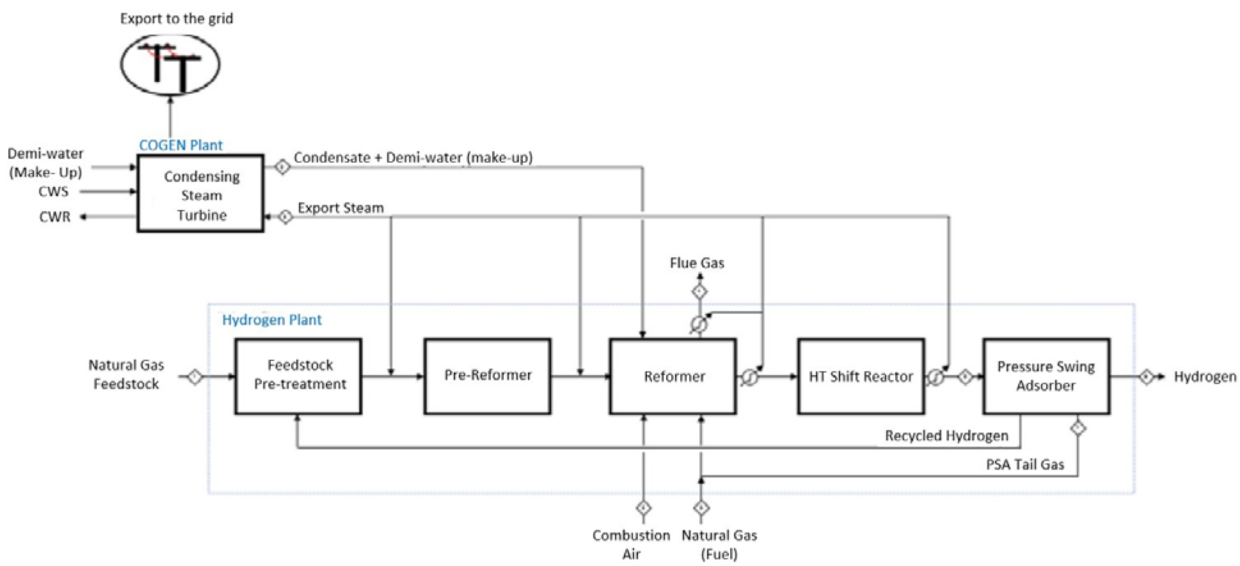


*Figure 2. Block Flow Diagram of Steam Methane Reforming without CO2 Capture*

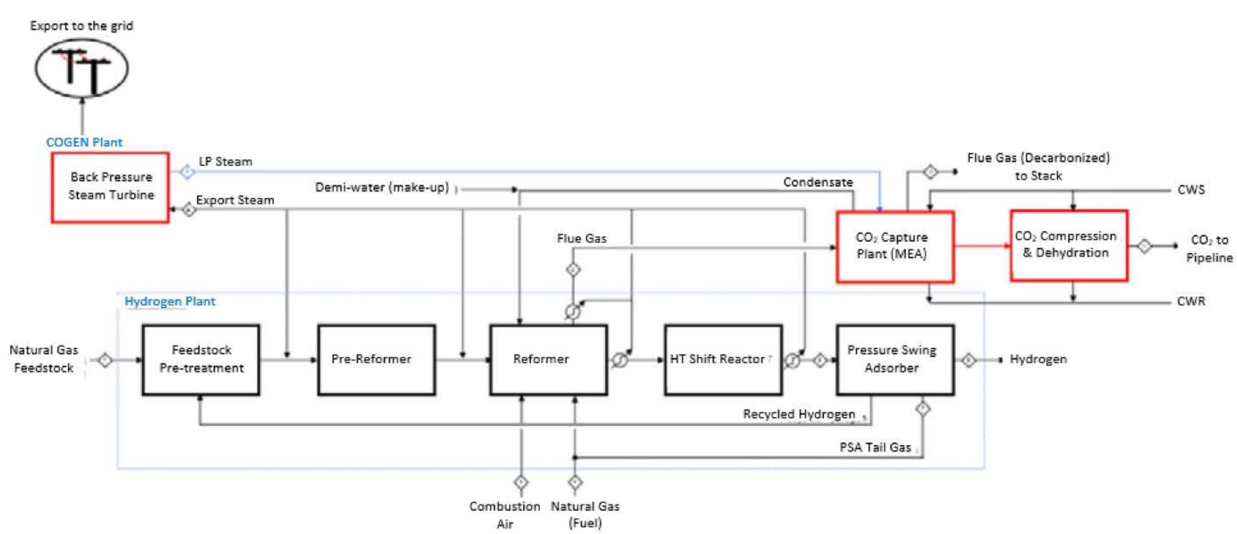


*Figure 3. Block Flow Diagram of Steam Methane Reforming with 90% carbon capture*

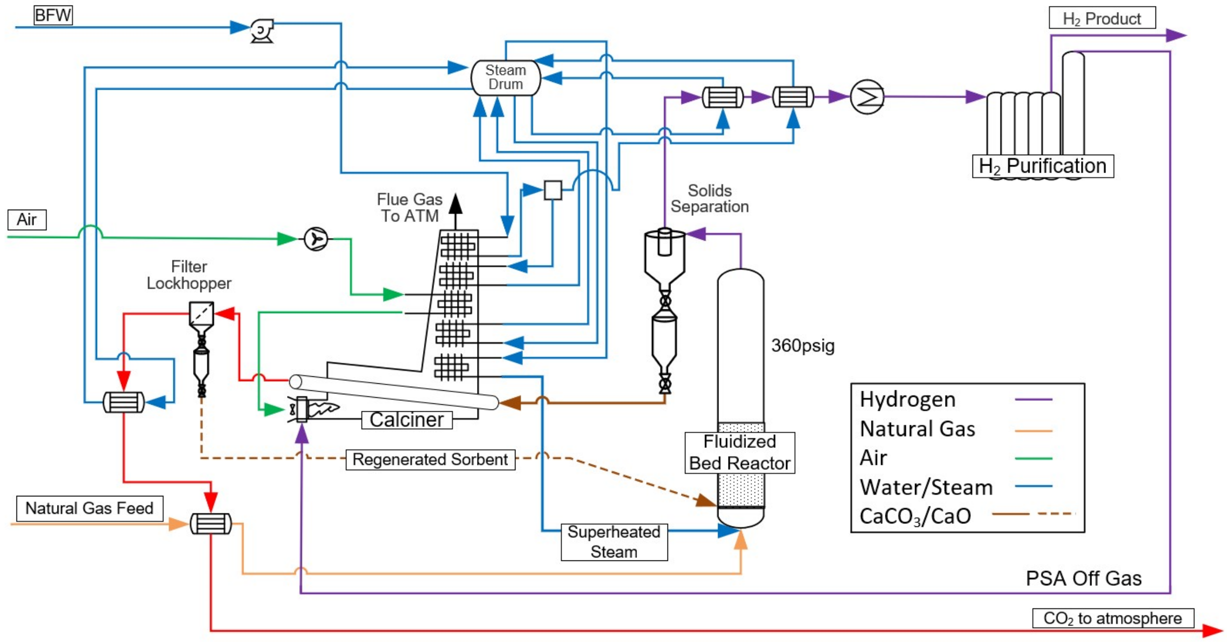


*Figure 4. Block Flow Diagram of GTI's compact hydrogen generator without $CO_2$ capture and compression*

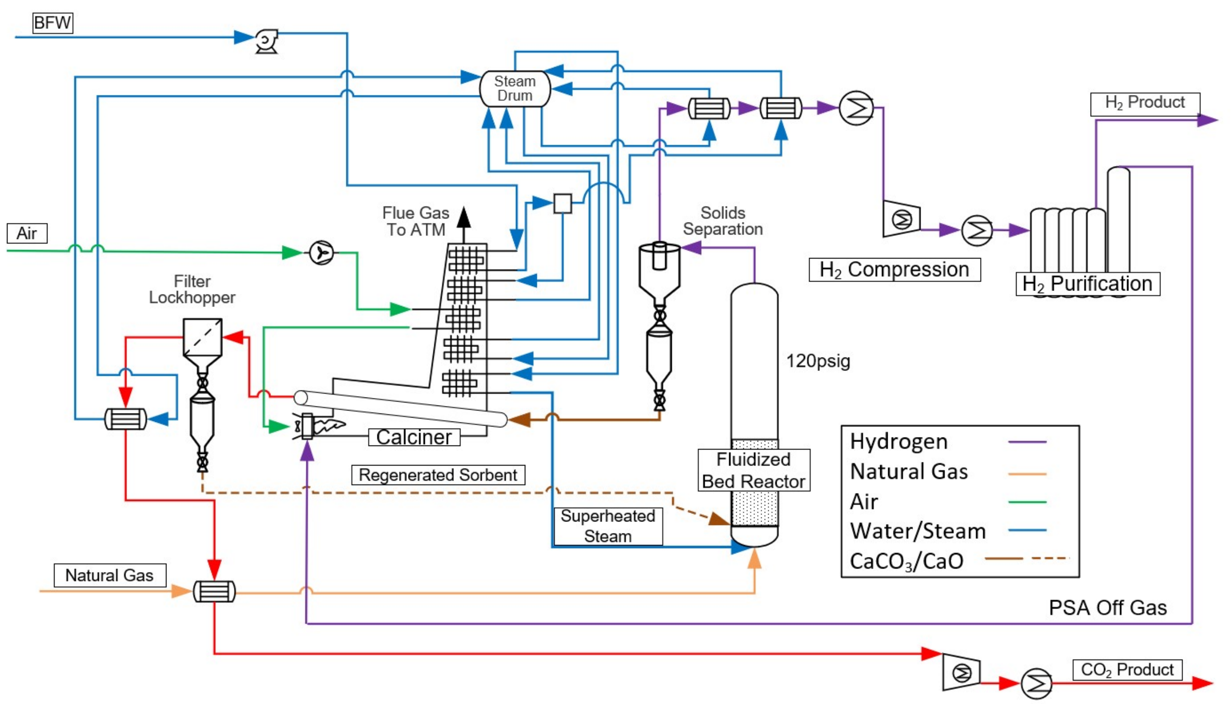


*Figure 5. Block Flow Diagram of GTI's Compact Hydrogen Generator with 90% $CO_2$ capture and compression*

There are two unique features of the SMR cases described by AMEC Foster Wheeler. The first is that a high firing temperature of the reformer results in the product gas leaving the reformer at 900-950°C, this results in high efficiency, and special metals must be used to achieve these temperatures, GTI is not aware of the metallurgy used by AMEC Foster Wheeler to achieve these temperatures. The second is that cooling hot flue gas contributes to steam generation within the plant. A typical SMR at a refinery exports this steam for sale to the refinery. As the IEAGHG cases are standalone hydrogen plants the steam does not have a customer to export to. In order to monetize the steam, the IEAGHG cases include steam turbines used to generate electricity that is available for export and the credit for electricity sale is applied in the calculation for levelized cost of hydrogen. The direct material cost of the power island is $10.6MM while the cost of the SMR hydrogen island is $50.8MM. Without addition of the power island there would not be a way to credit the export steam.

The difference in the flow sheets for SMR without $CO_2$ capture (Figure 2) and with capture (Figure 3) are the addition of a solvent based $CO_2$ capture system using monoethyleamine (MEA) and the required $CO_2$ dehydration and compression. The differences are highlighted in red. This configuration captures 90% of the plant's $CO_2$ emissions by removal of $CO_2$ from the flue gas exiting the reformer furnace. The low-pressure steam exiting the steam turbine has sufficient energy to regenerate the MEA solvent in the $CO_2$ capture plant. The cooled, dried $CO_2$ is delivered to the battery limits at 1595 psig.

The compact hydrogen generator is steam neutral, it does not export steam and therefore a power island is not included in the economic assessment of the CHG. The SMR systems are net power exporters while the CHG systems are net power importers.

The CHG requires sulfur removal from the feed, however a pre-reformer is not necessary nor is a water gas shift reactor. Natural gas is mixed with superheated steam and fed to the fluidized bed reactor where the product (~94.1% $H_2$) is then purified to 99.5% $H_2$ using a PSA. The main differences in the configuration for the compact hydrogen generator with and without capture lie in the operating pressure of the reactor. High pressure operation results in lower conversion of natural gas. The CHG without $CO_2$ capture operates at 360psig to achieve optimal operating costs associated with taking advantage of feed natural gas pipeline pressure and the inlet pressure requirements of the PSA (and to match the $H_2$ delivery pressure of the IEAGHG baseline cases).

To achieve 90% $CO_2$ capture, higher conversion of natural gas is necessary which requires operating the reactor at lower pressure, specifically 120 psig. This requires a $3.9MM hydrogen compressor and associated water knock out vessels, oil coalescers, and the addition of heat exchange equipment as mentioned in Table 1. Additionally, the capture case requires a $CO_2$ compressor, GTI used the AMEC Foster Wheeler provided centrifugal $CO_2$ compressor cost for consistency.

As stated above, detailed descriptions of the SMR and the methodology to calculate the capital costs are available in the IEAGHG report. The key details and results are presented here in the Table 3 through Table 20. Table 3 contains a list the key use inputs for utilities and other factors. These factors are converted from Euros to USD using a conversion rate of 1.239 USD per euro (for quarter 4, 2014) and modified somewhat from the IEAGHG report, specifically we used lower natural gas and electricity prices than those assumed for the European placement of the plants in the IEAGHG report. Additionally, we assumed that the purchase cost of electricity for the CHG was higher than the sales price of electricity for the SMR cases. The calculations for capital cost and levelized cost of hydrogen of the baseline SMR cases were re-run by GTI using these inputs.

*Table 3. List of user inputs and key variables used for the technoeconomic analysis.*

| | | |
|---|---|---|
| Natural Gas | 3 | $/MMBTU (LHV) |
| Raw Process water | 0.000946 | $/gallon |
| Electricity sales price | 40 | $/MWh |
| Electricity purchase price | 67 | $/MWh |
| CO2 Transport and Storage | 12.49 | $/tonne |
| CO2 emission cost | 0 | $/tonne emitted |
| CHG Direct Materials Cost | 22,979,251 | $ without capture |
| | 42,907,382 | $ with 90% CO2 capture |
| Discount Rate | 11% | |
| Labor Rate | 74948 | $/year/person |
| Capacity Factor Y1 | 70% | |
| Capacity Factor Rest of Life | 95% | |

The basis for design of the SMR plants was the northeast coast of the Netherlands (Table 4). This location affects factors such as labor rates, installation costs, and taxes. GTI decided for simplicity to keep these factors constant, and while they ultimately affect the levelized cost of hydrogen, keeping them constant for both the SMR and CHG allows for a comparison of the percent decrease in total capital requirements and levelized cost of hydrogen regardless of the factor used (i.e. the % cost advantage should be mostly independent of the exact factors used, as long as they are consistently applied for all cases). The major assumptions used in this study are listed in Table 4 and show that the plant has a 3 year expected build time with investments costs spread across this time period. 20% continency is added to the total installed cost, and the accuracy of the cost estimations for the IEAGHG report are +35%/15%. Factors for startup costs, and definitions of working capital and the description of how the interest during construction is calculated are described in Table 5.

*Table 4. Design basis of the hydrogen plants and major assumptions*

| | | |
|---|---|---|
| <u>Design Basis</u> | | |
| Greenfield, northeast coast of the Netherlands, no major site preparation required | | |
| Excess High Pressure steam is converted to electricity | | |
| <u>Major Assumptions</u> | | |
| Capacity Factor | | |
| 0.7 | For first year of operation | |
| 0.95 | For rest of the life of the plant | |
| 25 | year plant life | |
| 0.11 | discount rate | interest during construction is assumed same as discount rate<br>Inflation rate, depreciation, decommissioning cost not considered in the discounted cash flow analysis |
| 3 | year design and construction period | |
| Year | Investment cost | |
| 1 | 20% | |
| 2 | 45% | Expenditure is assumed to take place at the end of each year and interest during construction payable in a year is calculated based on money owed at the end of the previous year. |
| 3 | 35% | |
| +35%/-15% | accuracy, AACE Class 4 estimate | |
| 20% | Contingency is added to the capital cost to give a 50% probability of a cost overrun or underrun | |
| Scaling Factor | 0.65 | |

*Table 5. Factors for determining startup costs, and explanations of working capital and interest during constructions.*

| | |
|---|---|
| Startup costs | |
| 2% | of the TPC to cover modifications to the plant |
| 25% | of monthly feedstock and fuel cost to cover any inefficient operation during the startup period |
| 3 | months of operating labor and maintenance labor cost to cover manpower and personnel training costs |
| 1 | month of chemical, catalyst, and waste disposal cost and maintenance materials costs |
| | start-up costs are charged to 3rd year of the project |
| Working Capital | Working capital includes inventories of fuel and chemicals (materials held in storage outside the process plants). Storage for 30 days at full load is considered for chemicals and consumables. It is assumed that the cost of these materials are recovered at the end of the plant life |
| Interest during construction: | calculated from the plant construction schedule and the rate is assumed to be equal to discount rate. Expenditure is assumed to take place at the end of each year and interest during construction payable in a year is calculated based on money owed at the end of the previous year. |

Table 6 contains a summary of the multiplication and percentage factors used to determine total plant cost, total capital requirements, fixed and variable operating costs. All factors used were exactly as they were reported in the IEAGHG report and have been applied to the compact hydrogen generator. It can be seen IEAGHG assumed 38 employees for the SMR without capture and 43 employees total for the CO2 capture case. GTI assumed a constant 38 employees for the compact hydrogen generator both with and without CO2 capture. The basis for this was that for the CHG to enable carbon capture the only major equipment to be added are the H2 and CO2 compressors, a complicated amine system is not necessary, and therefore we don't expect a need for additional staffing. Another advantage given to the compact hydrogen generator is the lower catalyst cost due to the smaller reactor size. The CHG does have the added expense of sorbent replacement cost.

*Table 6. Factors for determining Total Plant Cost, Total Capital Requirement, Fixed Operating Costs, and Variable Operating Costs*

| | | |
|---|---|---|
| <u>Total Plant Cost (TPC)</u> | | |
| Direct Materials | | |
| Construction | 0.632 | x Direct Materials |
| EPC Services | 0.313 | x Direct Materials |
| Other Costs | 0.046 | x Direct Materials |
| Contingency | 0.2 | x total installed cost (Direct material + construction + other + EPC services) |
| <u>Total Capital Requirement</u> | | |
| Total Plant Cost | | |
| Interest during Construction | | |
| Owners Costs | 7% | of TPC, charged on first year of project |
| Spare parts costs | 0.50% | of TPC |
| Working capital | 0.35% | of annual fuel, chemicals, and catalyst cost, see assumptions |
| Start-up costs | 2.00% | of TPC, charged on 3rd year of the project |

| | | |
|---|---|---|
| <u>Fixed Operating Cost</u> | | |
| Direct labor cost | $74,948 | per employee per year |
| Administrative and general overhead cost | 43.5% | of the direct labor |
| Annual operating and maintenance cost | 1.50% | of TPC |
| Insurance | 0.50% | of TPC |
| Local taxes and fees | 0.50% | of TPC |
| Maintenance labor | 40% | of the overall maintenance costs |
| Indirect Labors Costs (Overhead, administrative and support labor) | | |
| | 30% of the direct labor costs and the maintenance labor cost. | |

| | No Capture | 90% CO2 Capture |
|---|---|---|
| Employees | 38 | 43 |

| | | |
|---|---|---|
| <u>Variable Operating Cost</u> | | |
| Feedstock (natural gas) | | Based on consumption |
| Raw water make-up | | Based on consumption |
| Catalysts | 25% | of SMR Catalyst cost is the CHG Catalyst, basis: 1/2 the life but 1/7 of the volume |
| CHG Chemicals includes $150 per ton and 1864 tons of sorbent replacement required per year. | | |

The plant performance summary, Table 7, contains the critical heat and material balance of the plants, the SMR data is obtained from the IEAGHG report while the CHG data is derived from Aspen Plus models. From this table some of the key advantages of the compact hydrogen generator can been seen. The total feedstock and fuel for the compact hydrogen generator is lower than SMR for both cases, additionally this figure is lower for the compact hydrogen generator with capture than for the SMR case without capture. With less natural gas fed to the system this results in the total emissions of the CHG for the 90% capture case being 14% lower than they are for SMR with capture. Accordingly, the specific $CO_2$ emissions of the compact hydrogen generator are lower than the SMR case. The steam methane reforming plants gain an advantage of being able to export power to the grid, as seen below this results in a revenue stream, this revenue stream is not significant enough to have a large effect on the cost of electricity, more on this below.

*Table 7 Plant Performance Summary for the four cases evaluated.*

| | units | Base case SMR | SMR with 90% $CO_2$ Capture | CHG without Capture | CHG with $CO_2$ Capture |
|---|---|---|---|---|---|
| Inlet Stream | | | | | |
| NG to Feedstock | t/h | 26.23 | 26.23 | 30.01 | 30.01 |
| NG to fuel | t/h | 4.33 | 7.35 | | |
| NG to Feedstock | kg/h | 26,231 | 26,231 | 30,014 | 30,014 |
| NG to fuel | kg/h | 4,332 | 7,347 | 0 | 0 |
| Total Feedstock and fuel | kg/hr | 30,563 | 33,578 | 30,014 | 30,014 |
| % Feed | % | 0.86 | 0.78 | 1 | 1 |
| % Fuel | % | 0.14 | 0.22 | 0 | 0 |
| LHV | MJ/kg | 46.5 | 46.5 | 46.5 | 46.5 |
| Total Energy Input | MW | 395 | 434 | 388 | 388 |
| | MMBTU/h | 1,347 | 1,480 | 1,323 | 1,323 |
| Make up water | kg/h | 59,700 | 42,100 | 62,827 | 62,827 |
| Outlet Stream | | | | | |
| Hydrogen to Battery Limits | t/h | 8.994 | 8.994 | 8.994 | 8.994 |
| | kg/hr | 8,994 | 8,994 | 8,994 | 8,994 |
| | Nm3/h | 100,000 | 100,000 | 100,000 | 100,000 |
| | SCF/h | 3,730,997 | 3,730,997 | 3,730,997 | 3,730,997 |
| LHV | MJ/kg | 119.96 | 119.96 | 119.96 | 119.96 |
| Total Energy in Product | MW | 300 | 300 | 300 | 300 |
| Captured $CO_2$ | kg/h | | 80048 | | 71857 |
| | tonne/h | | 80.05 | | 71.86 |
| $CO_2$ emitted | kg/hr | 80,910 | 8,880 | 79,501 | 7,644 |
| | tonne/h | 80.91 | 8.88 | 79.50 | 7.64 |
| Power Balance | | | | | |
| Gross Power Output from COGEN Plant | MWe | 11.5 | 11.7 | | |
| $H_2$ Plant | MWe | -1.216 | -1.314 | -1.1 | -11.03 |
| COGEN Plant Auxiliaries, Utilities BOP | MWe | -0.366 | -1.677 | | |
| $CO_2$ Capture Plant | MWe | | -2.001 | | |
| $CO_2$ Compression and Drying | MWe | | -6.282 | | -5.64 |
| Export Power to the Grid | MWe | 9.918 | 0.426 | -1.1 | -16.67 |
| | | | | | |
| Specific Consumption | | | | | |
| NG to Feedstock | MJ/Nm3 $H_2$ | 12.20 | 12.20 | 13.96 | 13.96 |
| NG to Fuel | MJ/Nm3 $H_2$ | 2.01 | 3.42 | 0.00 | 0.00 |
| Total (Feedstock + Fuel) | MJ/Nm3 $H_2$ | 14.21 | 15.61 | 13.96 | 13.96 |
| | | | | | |
| Electricity component, (negative is credit) | MJth/h | -55,789 | -2,396 | 6,188 | 93,753 |
| Total (Feedstock + Fuel + Power Fuel) | MJ/Nm3 $H_2$ | 11.64 | 12.17 | 14.02 | 14.89 |
| Utility (Feed and fuel / hydrogen output) | MMBTU / 1000scf | 0.361 | 0.397 | 0.355 | 0.355 |
| Utility (Feed and fuel / hydrogen output) | kWh/kg | 43.89 | 48.22 | 43.10 | 43.10 |
| Plant Performance | | | | | |
| Specific $CO_2$ Emissions | kg/NM3 $H_2$ | 0.81 | 0.09 | 0.80 | 0.08 |
| Specific $CO_2$ Captured | kg/NM3 $H_2$ | | 0.80 | | 0.72 |
| Overall $CO_2$ Capture Rate (Case Specific) | % | | 90% | | 90% |
| Overall $CO_2$ Avoided (compared to base case) | % | | 89% | 2% | 91% |
| Specific $CO_2$ Emissions | kg$CO_2$/kg $H_2$ | 9.00 | 0.99 | 8.84 | 0.85 |

Table 8 through
Table 11 show the detailed results when determining total plant cost from direct materials cost. GTI assumed the SMR and CHG utilities costs to be equivalent. GTI did not give any advantage to the CHG for low cost modular construction and applied the same multiplication factors to direct material costs to achieve total installed costs as those applied by IEAGHG for the SMR cases. GTI simply used the exact same utility costs for the utilities and balance of plant direct material costs for the CHG that IEACHG used for the SMR. When capture was added to the SMR the utility and balance of plant increased, GTI applied this same cost increase to the CHG with capture. It may be noticed that the CHG $CO_2$ compression costs are slightly lower than the SMR $CO_2$ compression costs, this is due to the lower $CO_2$ volume flowrate in the captured $CO_2$ stream as discussed above. The CHG cases do not have a power island because they do not have a power generating steam turbine.

*Table 8. Total Installed Cost and Total Plant Cost for the Base Case SMR without CO2 Capture*

| | Hydrogen Plant (USD) | Power Island (USD) | Utilites and BOP (USD) | Total Cost (USD) |
|---|---|---|---|---|
| Direct Material | $50,810,658 | $10,691,261 | $23,543,508 | $85,045,427 |
| Construction | $32,100,014 | $7,048,812 | $22,243,169 | $61,391,996 |
| Direct Field Cost | $82,910,672 | $17,740,073 | $45,786,677 | $146,437,422 |
| Other Costs | $2,354,601 | $603,327 | $1,611,371 | $4,569,299 |
| EPC Services | $15,926,344 | $2,604,426 | $8,412,857 | $26,943,626 |
| Total Installed Costs | $101,191,616 | $20,947,826 | $55,810,905 | $177,950,348 |
| Project Contingency | $20,238,323 | $4,189,565 | $11,162,181 | $35,590,070 |
| Total Plant Cost (TPC) | $121,429,940 | $25,137,392 | $66,973,086 | $213,540,417 |

*Table 9 Total Installed Cost and Total Plant Cost for the Base Case SMR with CO2 Capture*

| | Hydrogen Plant | Power Island | Utilites and BOP | CO2 Capture | CO2 Compression | Total Cost (USD) |
|---|---|---|---|---|---|---|
| Direct Material | $50,810,658 | $7,951,930 | $32,237,418 | $53,628,684 | $16,664,577 | $161,293,266 |
| Construction | $32,100,014 | $5,043,967 | $28,216,485 | $29,742,915 | $8,244,225 | $103,347,606 |
| Direct Field Cost | $82,910,672 | $12,995,897 | $60,453,903 | $83,371,599 | $24,908,802 | $264,640,872 |
| Other Costs | $2,354,601 | $354,752 | $1,976,116 | $2,038,572 | $659,538 | $7,383,578 |
| EPC Services | $15,926,344 | $1,854,951 | $10,759,963 | $13,646,691 | $3,614,968 | $45,802,916 |
| Total Installed Costs | $101,191,616 | $15,205,599 | $73,189,981 | $99,056,862 | $29,183,307 | $317,827,365 |
| Project Contingency | $20,238,323 | $3,041,619 | $14,638,496 | $19,812,372 | $5,837,161 | $63,567,971 |
| Total Plant Cost (TPC) | $121,429,940 | $18,247,218 | $87,828,477 | $118,869,233 | $35,020,469 | $381,395,336 |

*Table 10 Total Installed Cost and Total Plant Cost for the CHG without CO2 Capture*

| | H2 Plant | Utilities and BOP | Total Cost |
|---|---|---|---|
| Direct Material | $22,979,251 | $23,543,508 | $46,522,759 |
| Construction | $14,517,314 | $22,243,169 | $36,760,483 |
| Direct Field Cost | $37,496,565 | $45,786,677 | $83,283,242 |
| Other Costs | $1,064,874 | $1,611,371 | $2,676,245 |
| EPC Services | $7,202,730 | $8,412,857 | $15,615,587 |
| Total Installed Costs | $45,764,169 | $55,810,905 | $101,575,074 |
| Project Contingency | $9,152,834 | $11,162,181 | $20,315,015 |
| Total Plant Cost (TPC) | $54,917,003 | $66,973,086 | $121,890,089 |

*Table 11 Total Installed Cost and Total Plant Cost for the CHG with CO2 Capture*

| | H2 Plant | CO2 Compression | Utilities and BOP | Total Cost |
|---|---|---|---|---|
| Direct Material | $28,030,010 | $15,535,417 | $32,237,418 | $75,802,844 |
| Construction | $17,708,169 | $7,685,612 | $28,216,485 | $53,610,266 |
| Direct Field Cost | $45,738,179 | $23,221,029 | $60,453,903 | $129,413,110 |
| Other Costs | $1,298,930 | $614,849 | $1,976,116 | $3,889,895 |
| EPC Services | $8,785,865 | $3,370,024 | $10,759,963 | $22,915,852 |
| Total Installed Costs | $55,822,974 | $27,205,902 | $73,189,981 | $156,218,857 |
| Project Contingency | $11,164,595 | $5,441,180 | $14,637,996 | $31,243,771 |
| Total Plant Cost (TPC) | $66,987,568 | $32,647,082 | $87,827,977 | $187,462,628 |

The detailed variable operating costs for the four cases evaluated are presented in Table 12. From this table it is clear that the natural gas consumption is the dominant variable costs, however the electricity import costs for the CHG with capture are significant, mostly due to the hydrogen and $CO_2$ compressors.

*Table 12 Yearly variable costs for the four cases evaluated*

| Yearly Variable Costs | Base SMR | | SMR with 90% Capture | | CHG without Capture | | CHG with 90% Capture | |
|---|---|---|---|---|---|---|---|---|
| Includes 95% availability | Consumption | Operating costs | Consumption | Operating costs | Consumption | Operating costs | Consumption | Operating costs |
| Consumables | Hourly kg/h | USD/year | Hourly kg/h | USD/year | Hourly kg/h | USD/year | Hourly kg/h | USD/year |
| Feedstock + Fuel | | | | | | | | |
| Natural Gas | 30,563 | $33,631,100 | 33,578 | $36,948,764 | 30,014 | $33,026,824 | 30,014 | $33,026,824 |
| Auxiliary Feedstock | | | | | | | | |
| Raw make-up water | 59,700 | $124,159 | 42,100 | $87,556 | 62,827 | $130,664 | 62,827 | $130,664 |
| Chemicals | | $124,913 | | $124,913 | | $279,619 | | $279,619 |
| Catalysts | | $399,720 | | $399,720 | | $99,930 | | $99,930 |
| Total Yearly Operating Costs | | $34,279,892 | | $37,560,953 | | $33,537,037 | | $33,537,037 |
| Revenues from electric by-product | MW | USD/year | MW | USD/year | MW | USD/year | MW | USD/year |
| Electricity sales /cost | 9.92 | $3,301,504 | 0.43 | $141,807 | -1.1 | -$613,331 | -16.67 | -$9,293,214 |

The breakdown of labor costs assume by IEAGHG for the SMR cases is presented in Table 13. The reason for the non-round number for the annual salary is a result of converting from Euros in the IEAGHG report to US dollars for this analysis.

*Table 13. Summary of operating labor staff requirements and total annual labor costs*

| Operating Labor Costs | Steam Reformer | | | Steam Reformer + CO2 Capture | | | |
|---|---|---|---|---|---|---|---|
| | Reformer + Utilities | Total | Notes | Reformer + Utilities | CO2 Capture | Total | Notes |
| Operations | | | | | | | |
| Area Responsible | 1 | 1 | daily position | 1 | | 1 | daily position |
| Assistant Area Responsible | 1 | 1 | daily position | 1 | | 1 | daily position |
| Shift Superintendent | 5 | 5 | 1 position/ shift | 5 | | 5 | 1 position/ shift |
| Eletrical Assistant | 5 | 5 | 1 position/ shift | 5 | | 5 | 1 position/ shift |
| Shift Supervisor | 5 | 5 | 1 position/ shift | 5 | | 5 | 1 position/ shift |
| Control Room Operator | 5 | 5 | 1 position/ shift | 5 | 5 | 10 | 2 positions/ shift |
| Field Operator | 5 | 5 | 1 position/ shift | 5 | | 5 | 1 position/ shift |
| Subtotal | | 27 | | | | 32 | |
| Maintenance | | | | | | | |
| Mechanical Group | 3 | 3 | daily position | 3 | | 3 | daily position |
| Instrument Group | 3 | 3 | daily position | 3 | | 3 | daily position |
| Electrical Group | 3 | 3 | daily position | 3 | | 3 | daily position |
| Subtotal | | 9 | | | | 9 | |
| Laboratory | | | | | | | |
| Superintendent + Analysts | 2 | 2 | daily position | 2 | | 2 | daily position |
| Subtotal | | 2 | | | | 2 | |
| Total | | 38 | | | | 43 | |
| Cost for personnel | | | | | | | |
| Yearly individual average cost | | | $74,948 | | | $74,948 | |
| Total Cost | | | $2,848,005 | | | $3,222,743 | |

The maintenance costs were assumed to be 1.5% of the total plant costs. With the compact hydrogen generator having a significantly lower direct materials costs, the resulting maintenance costs for the technology as calculated in Table 14 are significantly lower than those for SMR. This lower materials cost also results in a lower insurance and taxes for the CHG as presented in Table 15 which contains a summary of the total annual operating and maintenance costs. As a result the total fixed annual operating and maintenance costs for the compact hydrogen generator are significantly lower than for SMR. The variable costs of the CHG without capture are roughly equivalent to SMR's variable costs, however the CHG does have an advantage when there is capture, mainly due to lower feedstock costs. The fixed and variable cost advantages of the CHG are negated by the electricity import costs, and the total annual operating and maintenance costs are roughly equivalent for the cases without capture and the same can be said for the cases with capture.

*Table 14. Summary of maintenance costs for the four different cases evaluated.*

| Case | Maintenance Costs % of TPC | TPC (USD) | Maintenance Costs USD/year |
|---|---|---|---|
| SMR | 1.50% | $213,540,417 | $3,203,106 |
| SMR with Capture | 1.50% | $381,395,336 | $5,720,930 |
| CHG | 1.50% | $121,890,089 | $1,828,351 |
| CHG with Capture | 1.50% | $187,462,628 | $2,811,939 |

*Table 15. Total Operation and Maintenance costs for the four cases evaluated*

| Annual O&M Costs | SMR | SMR with Capture | CHG | CHG with Capture |
|---|---|---|---|---|
| **Fixed Costs** | $/year | $/year | $/year | $/year |
| Direct Labor | $2,848,005 | $3,222,743 | $2,848,005 | $2,848,005 |
| Adm./gen Overheads | $1,238,775 | $1,653,329 | $1,238,775 | $1,238,775 |
| Insurance and local taxes | $2,135,404 | $3,813,953 | $1,218,901 | $1,874,626 |
| Maintenance | $3,203,106 | $5,720,930 | $1,828,351 | $2,811,939 |
| Subtotal | $9,425,290 | $14,410,955 | $7,134,032 | $8,773,345 |
| **Variable Costs (Availability 95%)** | | | | |
| Feedstock & Fuel | $33,631,100 | $36,948,764 | $33,026,824 | $33,026,824 |
| Raw Water (Makeup) | $124,159 | $87,556 | $130,664 | $130,664 |
| Chemicals & Catalysts | $524,633 | $524,633 | $379,549 | $379,549 |
| Subtotal | $34,279,892 | $37,560,953 | $33,537,037 | $33,537,037 |
| **Total Fixed & Variable Costs** | $43,705,182 | $51,971,908 | $40,671,069 | $42,310,383 |
| **Other Revenues** | | | | |
| Electricity Export/Import | -$3,301,504 | -$141,807 | $613,331 | $9,293,214 |
| **Other Costs** | | | | |
| CO2 Transportation and Storage | | $8,320,518 | | $6,704,899 |
| Annual O&M Costs | $40,403,678 | $60,150,619 | $41,284,401 | $58,308,496 |

Table 16 contains a summary of the costs contributing toward the total capital requirements of the four evaluated plants. Here the low material cost advantage of the CHG continues to benefit the CHG resulting in lower costs than SMR for contingencies, spare, parts, startup CAPEX, fuel cost, operating and maintenance costs, owners costs, and interest during construction. The higher catalyst cost requirements of the SMR results in larger working capital costs than for the CHG cases.

*Table 16. Total Capital Requirements for the four cases evaluated.*

| | Steam Methane Reformer | SMR with 90% Carbon Capture | Compact Hydrogen Generator | CHG with 90% Carbon Capture |
|---|---|---|---|---|
| Total Project Cost | $177,950,348 | $317,827,365 | $101,575,074 | $156,218,857 |
| Contingencies | $35,590,070 | $63,567,971 | $20,315,015 | $31,243,771 |
| Sub total | $213,540,417 | $381,395,336 | $121,890,089 | $187,462,628 |
| Spare Parts | $1,067,702 | $1,906,977 | $609,450 | $937,313 |
| Startup & Comissioning Cost | | | | |
| Startup CAPEX | $4,270,808 | $7,627,907 | $2,437,802 | $3,749,253 |
| Additional Fuel Cost | $700,648 | $769,766 | $688,059 | $688,059 |
| O&M | $1,512,778 | $2,235,918 | $1,169,089 | $1,414,986 |
| Catalyst & Chemicals | $203,875 | $431,215 | $147,495 | $147,495 |
| Owners Cost | $14,947,829 | $26,697,674 | $8,532,306 | $13,122,384 |
| Interest during Construction | $41,148,586 | $73,493,716 | $23,487,848 | $36,123,476 |
| Working Capital | $45,389 | $2,543,639 | $280,935 | $280,935 |
| Subtotal | $63,897,615 | $115,706,812 | $37,352,984 | $56,463,900 |
| Total Capital Requirements | $277,438,032 | $497,102,148 | $159,243,073 | $243,926,528 |

GTI calculated the Levelized Cost of Hydrogen using the methodology from the IEAGHG report which was defined as the "price of hydrogen which enables the present value from all sales of hydrogen (including additional revenue from the sale of electricity) over the economic lifetime of the plant to equal the present value of all costs of building, maintaining, and operating the plant over its lifetime." A discounted cash flow was tabulated keeping prices for fuel and other costs constant over the 25 operating years of the plant. GTI replicated these calculations for the SMR cases, (Table 17, and Table 18) and created new tables for the CHG (Table 19 and Table 20), The price of hydrogen was then adjusted to set the cumulative discounted cash flows to zero, this price is the levelized cost of hydrogen with the units of $ per kg H2.

*Table 17. Summary of cash flows for steam methane reforming without CO2 Capture*

| | | Fixed Cost | | | | | Variable Cost | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| End of Year | Investment Cost | Direct Labor | Admin & General Overhead | Insurance and Local Taxes | Maintenance | Total Fixed O&M | Feedstock Cost | Fuel Cost | Make Up Water | Chemicals | Catalyst | Total Variable O&M Cost | Electricity Export to the grid | CO2 Tax | CO2 T&S | Total Costs before hydrogen revenues | Revenue from Hydrogen Sale | Total non discounted cash flow | Discounted Cash Flow | Cumulative Discounted Cash Flows |
| 0 | -58,172,009 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -58,172,009 | 0 | -58,172,009 | -58,172,009 | -58,172,009 |
| 1 | -101,657,302 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -101,657,302 | 0 | -101,657,302 | -91,583,155 | -149,755,164 |
| 2 | -96,452,986 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -96,452,986 | 0 | -96,452,986 | -78,283,407 | -228,038,571 |
| 3 | -21,155,736 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -21,268,378 | -3,512,432 | -91,486 | -124,913 | -399,720 | -25,396,929 | 2,432,687 | 0 | 0 | -53,545,268 | 56,993,672 | 3,448,404 | 2,521,443 | -225,517,127 |
| 4 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 24,336,734 | -201,180,393 |
| 5 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 21,924,986 | -179,255,407 |
| 6 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 19,752,240 | -159,503,168 |
| 7 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 17,794,810 | -141,708,357 |
| 8 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 16,031,361 | -125,676,996 |
| 9 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 14,442,667 | -111,234,329 |
| 10 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 13,011,412 | -98,222,917 |
| 11 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 11,721,993 | -86,500,924 |
| 12 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 10,560,354 | -75,940,570 |
| 13 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 9,513,832 | -66,426,738 |
| 14 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 8,571,020 | -57,855,718 |
| 15 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 7,721,640 | -50,134,078 |
| 16 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 6,956,432 | -43,177,646 |
| 17 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 6,267,056 | -36,910,590 |
| 18 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 5,645,996 | -31,264,594 |
| 19 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 5,086,483 | -26,178,110 |
| 20 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 4,582,417 | -21,595,693 |
| 21 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 4,128,304 | -17,467,389 |
| 22 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 3,719,193 | -13,748,196 |
| 23 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 3,350,624 | -10,397,572 |
| 24 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 3,018,580 | -7,378,992 |
| 25 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 2,719,442 | -4,659,550 |
| 26 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 2,449,947 | -2,209,603 |
| 27 | 0 | -2,848,005 | -1,238,775 | -2,135,404 | -3,203,106 | -9,425,290 | -28,864,228 | -4,766,873 | -124,159 | -124,913 | -399,720 | -34,279,892 | 3,301,504 | 0 | 0 | -40,403,678 | 77,348,555 | 36,944,876 | 2,207,160 | -2,443 |
| 28 | 45,389 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 45,389 | 0 | 45,389 | 2,443 | 0 |

*Table 18. Summary of cash flows for steam methane reforming with 90% CO2 capture*

| | | Fixed Cost | | | | | Variable Cost | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| End of Year | Investment Cost | Direct Labor | Admin & General Overhead | Insurance and Local Taxes | Main-tenance | Total Fixed O&M | Feedstock Cost | Fuel Cost | Make Up Water | Chemicals | Catalyst | Total Variable O&M Cost | Electricity Export to the grid | CO2 Tax | CO2 T&S | Total Costs before hydrogen revenues | Revenue from Hydrogen Sale | Total non discounted cash flow | Discounted Cash Flow | Cumulative Discounted Cash Flows |
| 0 | -103,805,320 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -103,805,320 | 0 | -103,805,320 | -103,805,320 | -103,805,320 |
| 1 | -181,356,032 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -181,356,032 | 0 | -181,356,032 | -163,383,812 | -267,189,132 |
| 2 | -172,174,508 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -172,174,508 | 0 | -172,174,508 | -139,740,693 | -406,929,825 |
| 3 | -39,766,288 | -3,222,743 | -1,653,329 | -3,813,953 | -5,720,930 | -14,410,955 | -21,268,378 | -5,957,027 | -64,515 | -124,913 | -399,720 | -27,814,553 | 104,489 | 0 | -6,130,908 | -88,018,215 | 92,734,295 | 4,716,080 | 3,448,357 | -403,481,469 |
| 4 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 43,527,496 | -359,953,972 |
| 5 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 39,213,960 | -320,740,012 |
| 6 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 35,327,892 | -285,412,120 |
| 7 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 31,826,930 | -253,585,190 |
| 8 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 28,672,910 | -224,912,280 |
| 9 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 25,831,450 | -199,080,829 |
| 10 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 23,271,577 | -175,809,252 |
| 11 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 20,965,385 | -154,843,868 |
| 12 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 18,887,734 | -135,956,134 |
| 13 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 17,015,976 | -118,940,157 |
| 14 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 15,329,709 | -103,610,449 |
| 15 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 13,810,548 | -89,799,901 |
| 16 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 12,441,935 | -77,357,965 |
| 17 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 11,208,951 | -66,149,014 |
| 18 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 10,098,154 | -56,050,861 |
| 19 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 9,097,436 | -46,953,425 |
| 20 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 8,195,888 | -38,757,536 |
| 21 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 7,383,683 | -31,373,853 |
| 22 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 6,651,967 | -24,721,887 |
| 23 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 5,992,763 | -18,729,124 |
| 24 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 5,398,885 | -13,330,238 |
| 25 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 4,863,861 | -8,466,378 |
| 26 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 4,381,857 | -4,084,521 |
| 27 | 0 | -2,848,005 | -1,653,329 | -3,813,953 | -5,720,930 | -14,036,218 | -28,864,228 | -8,084,537 | -87,556 | -124,913 | -399,720 | -37,560,953 | 141,807 | 0 | -8,320,518 | -59,775,882 | 125,853,686 | 66,077,804 | 3,947,618 | -136,903 |
| 28 | 2,543,639 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2,543,639 | 0 | 2,543,639 | 136,903 | 0 |

*Table 19. Summary of cash flows for the compact hydrogen generator without CO2 capture*

| | | Fixed Cost | | | | | Variable Cost | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| End of Year | Investment Cost | Direct Labor | Admin & General Overhead | Insurance and Local Taxes | Main-tenance | Total Fixed O&M | Feedstock Cost | Fuel Cost | Make Up Water | Chemicals | Catalyst | Total Variable O&M Cost | Electricity Export to the grid | CO2 Tax | CO2 T&S | Total Costs before hydrogen revenues | Revenue from Hydrogen Sale | Total non discounted cash flow | Discounted Cash Flow | Cumulative Discounted Cash Flows |
| 0 | -33,266,032 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -33,266,032 | 0 | -33,266,032 | -33,266,032 | -33,266,032 |
| 1 | -58,164,083 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -58,164,083 | 0 | -58,164,083 | -52,400,074 | -85,666,106 |
| 2 | -55,193,992 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -55,193,992 | 0 | -55,193,992 | -44,796,682 | -130,462,788 |
| 3 | -12,338,031 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -24,335,555 | 0 | -96,279 | -279,619 | -99,930 | -24,811,383 | -451,928 | 0 | 0 | -44,735,374 | 46,050,709 | 1,315,335 | 961,762 | -129,501,027 |
| 4 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 13,973,654 | -115,527,373 |
| 5 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 12,588,877 | -102,938,496 |
| 6 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 11,341,331 | -91,597,165 |
| 7 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 10,217,415 | -81,379,750 |
| 8 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 9,204,879 | -72,174,871 |
| 9 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 8,292,683 | -63,882,188 |
| 10 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 7,470,886 | -56,411,302 |
| 11 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 6,730,528 | -49,680,774 |
| 12 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 6,063,539 | -43,617,236 |
| 13 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 5,462,647 | -38,154,588 |
| 14 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 4,921,304 | -33,233,284 |
| 15 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 4,433,607 | -28,799,677 |
| 16 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 3,994,241 | -24,805,436 |
| 17 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 3,598,415 | -21,207,021 |
| 18 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 3,241,815 | -17,965,206 |
| 19 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 2,920,554 | -15,044,652 |
| 20 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 2,631,130 | -12,413,522 |
| 21 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 2,370,387 | -10,043,134 |
| 22 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 2,135,484 | -7,907,650 |
| 23 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 1,923,860 | -5,983,790 |
| 24 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 1,733,207 | -4,250,584 |
| 25 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 1,561,448 | -2,689,136 |
| 26 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 1,406,710 | -1,282,426 |
| 27 | 0 | -2,848,005 | -1,238,775 | -1,218,901 | -1,828,351 | -7,134,032 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -613,331 | 0 | 0 | -41,284,401 | 62,497,391 | 21,212,990 | 1,267,306 | -15,120 |
| 28 | 280,935 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 280,935 | 0 | 280,935 | 15,120 | 0 |

*Table 20. Summary of cash flows for the compact hydrogen generator with 90% CO2 capture*

| | | Fixed Cost | | | | | Variable Cost | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| End of Year | Investment Cost | Direct Labor | Admin & General Overhead | Insurance and Local Taxes | Maint-enance | Total Fixed O&M | Feedstock Cost | Fuel Cost | Make Up Water | Chemicals | Catalyst | Total Variable O&M Cost | Electricity Export to the grid | CO2 Tax | CO2 T&S | Total Costs before hydrogen revenues | Revenue from Hydrogen Sale | Total non discounted cash flow | Discounted Cash Flow | Cumulative Discounted Cash Flows |
| 0 | -51,085,369 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -51,085,369 | 0 | -51,085,369 | -51,085,369 | -51,085,369 |
| 1 | -89,281,929 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -89,281,929 | 0 | -89,281,929 | -80,434,170 | -131,519,540 |
| 2 | -84,672,992 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -84,672,992 | 0 | -84,672,992 | -68,722,499 | -200,242,039 |
| 3 | -18,886,238 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -24,335,555 | 0 | -96,279 | -279,619 | -99,930 | -24,811,383 | -6,847,631 | 0 | -4,940,452 | -64,259,050 | 66,900,950 | 2,641,900 | 1,931,735 | -198,310,305 |
| 4 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 21,399,304 | -176,911,001 |
| 5 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 19,278,652 | -157,632,349 |
| 6 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 17,368,155 | -140,264,194 |
| 7 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 15,646,986 | -124,617,208 |
| 8 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 14,096,384 | -110,520,823 |
| 9 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 12,699,445 | -97,821,378 |
| 10 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 11,440,942 | -86,380,437 |
| 11 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 10,307,155 | -76,073,282 |
| 12 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 9,285,725 | -66,787,557 |
| 13 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 8,365,518 | -58,422,039 |
| 14 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 7,536,503 | -50,885,536 |
| 15 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 6,789,642 | -44,095,894 |
| 16 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 6,116,795 | -37,979,100 |
| 17 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 5,510,626 | -32,468,474 |
| 18 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 4,964,528 | -27,503,946 |
| 19 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 4,472,547 | -23,031,399 |
| 20 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 4,029,322 | -19,002,077 |
| 21 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 3,630,020 | -15,372,057 |
| 22 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 3,270,288 | -12,101,769 |
| 23 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 2,946,206 | -9,155,563 |
| 24 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 2,654,239 | -6,501,324 |
| 25 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 2,391,207 | -4,110,117 |
| 26 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 2,154,240 | -1,955,877 |
| 27 | 0 | -2,848,005 | -1,238,775 | -1,874,626 | -2,811,939 | -8,773,345 | -33,026,824 | 0 | -130,664 | -279,619 | -99,930 | -33,537,037 | -9,293,214 | 0 | -6,704,899 | -58,308,496 | 90,794,146 | 32,485,650 | 1,940,757 | -15,120 |
| 28 | 280,935 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 280,935 | 0 | 280,935 | 15,120 | 0 |

The final results of the TEA are displayed in Table 21. In this table it can be seen that the total capital cost of the compact hydrogen generator is about 43% less than the capital cost for a baseline SMR without carbon capture. With 90% carbon capture the compact hydrogen generator has about 51% lower capital requirements than the baseline steam methane reformer with capture. In fact, it can be seen that the compact hydrogen generator with 90% capture has lower capital costs than a baseline steam methane reformer without carbon capture. This cost advantage results in a 19.2% lower cost of hydrogen without carbon capture and 27.9% lower cost of hydrogen with carbon capture.

*Table 21. Summary of Total installed cost, Total capital requirements, and levelized cost of hydrogen for the four hydrogen plants evaluated*

| | Total Installed Cost | % lower than baseline | Total Capital Requirements | % lower than baseline | LCOH $/kg | % lower than baseline |
|---|---|---|---|---|---|---|
| SMR | $177,950,348 | | $277,438,032 | | $1.03 | |
| CHG w/o CO2 Capture | $101,575,074 | 42.9% | $159,243,073 | 42.6% | $0.84 | 19.2% |
| SMR with 90% CO2 Capture | $317,827,365 | | $497,102,148 | | $1.68 | |
| CHG with 90% CO2 Capture | $156,218,857 | 50.8% | $243,926,528 | 50.9% | $1.21 | 27.9% |

A sensitivity analysis was performed to demonstrate the effect of user inputs on the capital costs of the plant and the cost of hydrogen. The discount rate was the only factor that had any effect on the total capital requirements. The effect of these user inputs on the cost of hydrogen is presented in Table 22 and displayed graphically in Figure 6. Within this figure it can be seen that large changes in the cost of process water, electricity, $CO_2$ transport and storage, and the capacity factor did not have large influences over the cost of hydrogen. The electricity purchase price did have a small effect on the price of hydrogen for the CHG with capture. The two factors that have the largest effect on the levelized cost of hydrogen are the natural gas price and the discount rate.

*Table 22. Sensitivity analysis for dependence of total capital requirements and levelized cost of hydrogen on several variables.*

| Variable | | Units | Steam Methane Reforming | Compact Hydrogen Generator | Steam Methane Reforming with 90% Capture | Compact Hydrogen Generator with 90% Capture | Steam Methane Reforming | Compact Hydrogen Generator | Steam Methane Reforming with 90% Capture | Compact Hydrogen Generator with 90% Capture |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Total Capital Requirement MM$ | | | | Levelized Cost of Hydrogen $/kg | | | |
| Natural Gas Price | Low | 1.5 $/MMBTU (LHV) | $277 | $159 | $497 | $244 | $0.81 | $0.61 | $1.44 | $0.99 |
| | Standard | 3 $/MMBTU (LHV) | $277 | $159 | $497 | $244 | $1.03 | $0.84 | $1.68 | $1.21 |
| | High | 10 $/MMBTU (LHV) | $279 | $161 | $499 | $246 | $2.09 | $1.87 | $2.84 | $2.25 |
| Process Water | Low | 0 $/gallon | $277 | $159 | $497 | $244 | $1.03 | $0.83 | $1.68 | $1.21 |
| | Standard | 0.000946 $/gallon | $277 | $159 | $497 | $244 | $1.03 | $0.84 | $1.68 | $1.21 |
| | High | 0.01 $/gallon | $277 | $159 | $497 | $244 | $1.05 | $0.85 | $1.69 | $1.23 |
| Electricity Sales Price | Low | 30 $/MWh | $277 | $159 | $497 | $244 | $1.05 | $0.84 | $1.68 | $1.21 |
| | Standard | 40 $/MWh | $277 | $159 | $497 | $244 | $1.03 | $0.84 | $1.68 | $1.21 |
| | High | 60 $/MWh | $277 | $159 | $497 | $244 | $1.01 | $0.84 | $1.68 | $1.21 |
| Electricty Purchase Price | Low | 40 $/MWh | $277 | $159 | $497 | $244 | $1.03 | $0.83 | $1.68 | $1.16 |
| | Standard | 67 $/MWh | $277 | $159 | $497 | $244 | $1.03 | $0.84 | $1.68 | $1.21 |
| | High | 80 $/MWh | $277 | $159 | $497 | $244 | $1.03 | $0.84 | $1.68 | $1.24 |
| $CO_2$ Transport and Storage | Low | -20 $/tonne | $277 | $159 | $497 | $244 | $1.03 | $0.84 | $1.68 | $1.21 |
| | Standard | 12.49 $/tonne | $277 | $159 | $497 | $244 | $1.03 | $0.84 | $1.68 | $1.21 |
| | High | 50 $/tonne | $277 | $159 | $497 | $244 | $1.03 | $0.84 | $1.68 | $1.21 |
| Discount Rate | Low | 10% | $274 | $157 | $490 | $241 | $0.99 | $0.81 | $1.60 | $1.17 |
| | Standard | 11% | $277 | $159 | $497 | $244 | $1.03 | $0.84 | $1.68 | $1.21 |
| | High | 20% | $311 | $178 | $557 | $273 | $1.54 | $1.13 | $2.59 | $1.66 |
| 1st Year Capacity Factor | Low | 35% | $277 | $159 | $497 | $244 | $1.06 | $0.85 | $1.73 | $1.24 |
| | Standard | 70% | $277 | $159 | $497 | $244 | $1.03 | $0.84 | $1.68 | $1.21 |
| | High | 95% | $277 | $159 | $497 | $244 | $1.02 | $0.83 | $1.65 | $1.20 |

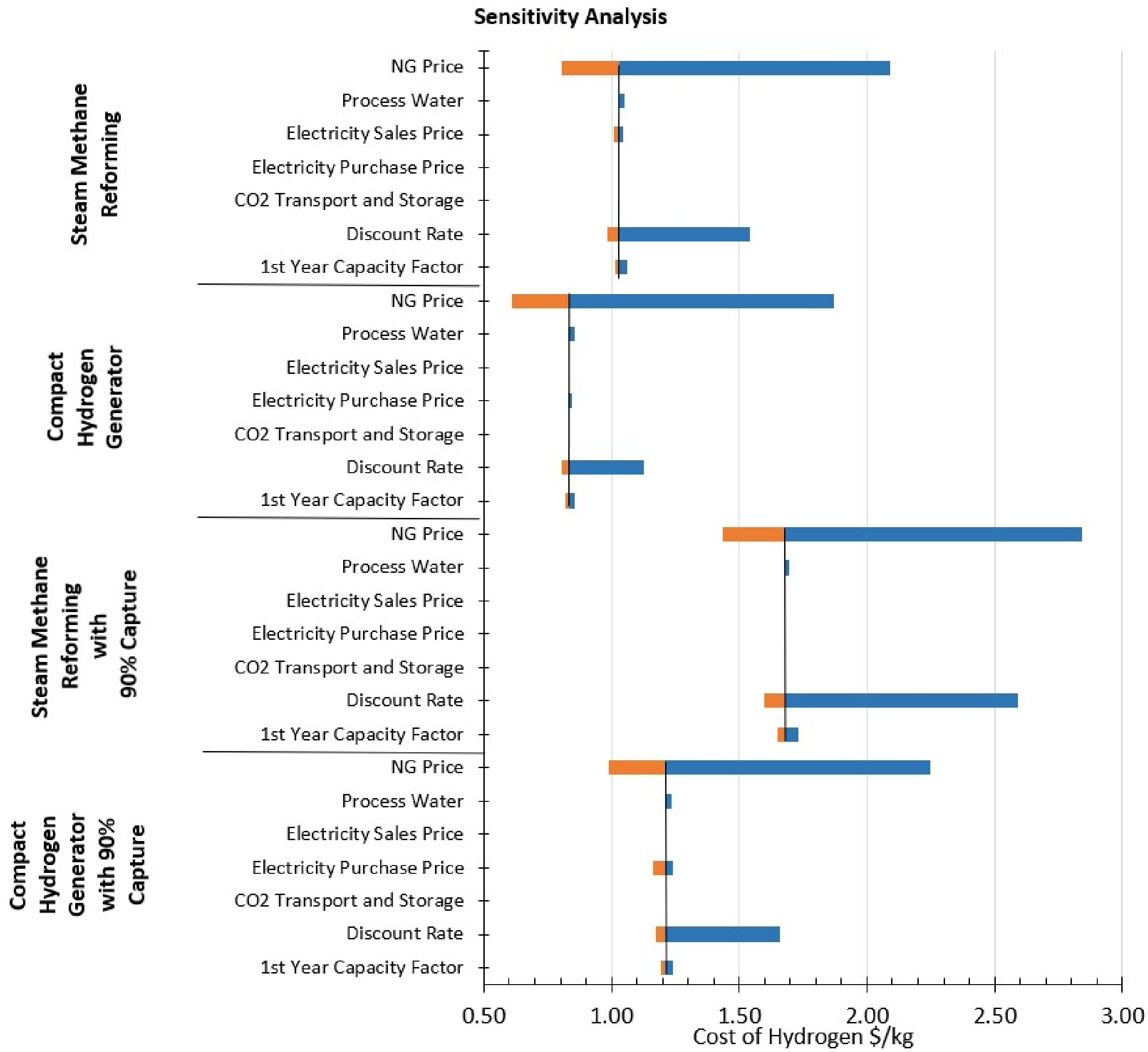


*Figure 6. Sensitivity of cost of hydrogen on several variables whose values are listed in Table 22*

## Conclusions

The detailed techno-economic assessment that began with reliable direct material cost information for the CHG (from CB&I Howe-Baker) and used methodology from a reputable EPC and designer of commercial SMRs (Foster-Wheeler) has demonstrated the CHG can deliver hydrogen at a lower price than SMR with and without carbon capture. The lower costs of 19% without capture and 28% with capture exceed our target of minimum 15% lower cost of hydrogen. The lower cost is primarily due to lower material costs that translated into a 43% lower CAPEX without capture and 51% lower CAPEX with capture. The savings are greater with carbon capture because the compact hydrogen generator does not need additional CO2 from flue gas separation equipment, it does however have the added capital cost of CO2 compression, transportation and storage, just as SMR does. These findings demonstrate that the CHG has significant costs advantages and that further development of the technology is warranted.