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Milestone Report

Update of Hydrogen from Biomass — Determination of the Delivered Cost of Hydrogen

Milestone Completion Report

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Update of Hydrogen from Biomass - Determination of the Delivered Cost of Hydrogen

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Executive Summary

The purpose of this analysis was to assess the economic feasibility of producing hydrogen from biomass via two thermochemical processes: 1) gasification followed by reforming of the syngas, and 2) fast pyrolysis followed by reforming of the carbohydrate fraction of the bio-oil. In each process, water-gas shift is used to convert the reformed gas into hydrogen, and pressure swing adsorption is used to purify the product. This study was conducted to incorporate recent experimental advances and any changes in direction from previous analyses. The systems examined are based on the Battelle/FERCO low pressure indirectly-heated biomass gasifier, the Institute of Gas Technology (IGT) high pressure direct-fired gasifier, and fluidized bed pyrolysis followed by coproduct separation. The pyrolysis case assumes a bio-oil feed which is shipped from remote locations to the hydrogen production plant.

The delivered cost of hydrogen, as well as the plant gate hydrogen selling price, were determined using both a cash flow spreadsheet and Crystal Ball® risk assessment software. This software is able to predict the sensitivity of the hydrogen selling price to changes in various analysis parameters, and determines which of the parameters contribute the greatest uncertainty to the results. All of the parameters are varied at once, giving a combined uncertainty of hydrogen selling price.

Several cases were run for each of the biomass conversion technologies at varying plant sizes and internal rate of return (IRR) values. Three hydrogen production rates were examined for the gasification technologies: 22,737 kg/day, 75,790 kg/day, and 113,685 kg/day. For the pyrolysis case, because some of the bio-oil is used in the production of the coproduct, only the small and medium plant sizes were studied. Even with several remote pyrolysis plants, the feed required for the large plant would likely be more than could be economically secured. The base case analysis assumes an after-tax IRR of 15%, which is a value typically required by investors. Cases were also tested at a 20% and 10% after-tax IRR and a 0% pre-tax IRR. The 20% case was chosen because these technologies are new and thus result in a higher risk. The 0% case represents the pre-tax break-even point, or the production cost of hydrogen. The 10% IRR cases are presented for illustrative purposes only, as such a low rate would probably be unacceptable to investors with multiple investment opportunities.

For any given IRR, the plant gate hydrogen selling price is lowest for the pyrolysis case ($9-10/GJ for a 15% after-tax IRR), followed by the Battelle/FERCO gasifier plant ($14-17/GJ for a 15% after-tax IRR), and then the IGT gasifier system ($16-21/GJ for a 15% after-tax IRR). As the plant size increases, the hydrogen selling price decreases due to economy of scale. The delivered cost is important because even if the hydrogen is produced cheaply, the cost to store and transport the hydrogen will make a difference in determining if the hydrogen is economical. Six likely scenarios for hydrogen use were examined, and the cheapest storage and delivery methods were identified. For these six options, storage and delivery adds between $1 and $10/GJ to the plant gate cost, resulting in a delivered cost of hydrogen between $9.9/GJ and $32.7/GJ (using a 15% after-tax IRR) for all cases studied.

For both of the gasification options (Battelle/FERCO and IGT), the two variables having the largest effect on the uncertainty in the hydrogen selling price are hydrogen production factor and operating capacity. Combined, these two variables account for roughly 51-76% of the uncertainty in the hydrogen selling price depending on the plant size and IRR. For the pyrolysis case, the bio-oil feedstock cost, pyrolytic lignin selling price, and yield of carbohydrate from the bio-oil are the largest contributors to variance, and combine to account for 81-94% of the variability. Roughly 40-45% of the contribution comes from the bio-oil feedstock cost alone.

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Units of Measure

Metric units of measure are used in this report. Therefore, material consumption is reported in units based on the gram (e.g., kilogram or megagram), energy consumption based on the joule (e.g., kilojoule or megajoule), and distance based on the meter (e.g., kilometer). When it can contribute to the understanding of the analysis, the English system equivalent is stated in parenthesis. The metric units used for each parameter are given below, with the corresponding conversion to English units.

Mass:	kilogram (kg) = 2.205 pounds
	megagram (Mg) = metric tonne (T) = 1 x 10^6 g = 1.102 ton (t)
Distance:	kilometer (km) = 0.62 mile = 3,281 feet
Volume:	cubic meter (m^3) = 264.17 gallons
	normal cubic meters (Nm^3) = 0.02628 standard cubic feet (scf) at a standard temperature & pressure of 15.6°C (60°F) and 101.4 kPa (14.7 psi), respectively
Pressure:	megapascals (MPa) = 145 pounds per square inch
Energy:	kilojoule (kJ) = 1,000 Joules (J) = 0.9488 Btu
	gigajoule (GJ) = 0.9488 MMBtu (million Btu)
	kilowatt-hour (kWh) = 3,414.7 Btu
	gigawatt-hour (GWh) = 3.4 x 10^9 Btu
Power:	megawatt (MW) = 1 x 10^6 J/s
Temperature:	°C = (°F - 32)/1.8

Hydrogen Equivalents:

1 kg H2 = 423.3 scf gas = 11.126 Nm^3 gas
= 142 MJ (HHV basis) = 120 MJ (LHV basis)

Abbreviations and Terms

BCL -	Battelle Columbus Laboratory
EIA -	Energy Information Administration
FERCO -	Future Energy Resources Corporation
GJ -	gigajoule (denotes energy)
HHV -	higher heating value
HTS -	high temperature shift
IGT -	Institute of Gas Technology
IRR -	internal rate of return
kWh -	kilowatt-hour (denotes energy)
LHV -	lower heating value
LTS -	low temperature shift
NREL -	National Renewable Energy Laboratory
PSA -	pressure swing adsorption
U.S. DOE -	United States Department of Energy

1.0 Introduction

Hydrogen has the potential to be a clean alternative to the fossil fuels currently used in the transportation sector. This is especially true if the hydrogen is manufactured from renewable resources, primarily sunlight, wind, and biomass. Analyses have been conducted to assess the economic feasibility of producing hydrogen from biomass via two thermochemical processes: 1) gasification followed by reforming of the syngas, and 2) fast pryolysis followed by reforming of the carbohydrate fraction of the bio-oil. This study was conducted to update previous analyses of these processes in order to include recent experimental advances and any changes in direction from previous analyses. The systems examined were gasification in the Battelle/FERCO low pressure indirectly-heated gasifier followed by steam reforming, gasification in the Institute of Gas Technology (IGT) high pressure direct-fired gasifier followed by steam reforming, and pyrolysis followed by coproduct separation and steam reforming. In each process, water-gas shift is used to convert the reformed gas into hydrogen, and pressure swing adsorption is used to purify the product. The delivered cost of hydrogen, as well as the plant gate hydrogen selling price, were determined. All analyses included Latin Hypercube sampling to obtain a detailed sensitivity analysis.

2.0 Process Descriptions

Block flow diagrams of the three options for producing hydrogen from biomass are shown in Figure 1. Not shown on this diagram is the heat integration. The gasifier systems incorporated biomass drying and steam production with the process heat available. After meeting the process steam requirements, excess steam at 0.7 MPa and 3.4 MPa (100 psi and 500 psi) was produced for export. The same is true for the steam balance of the pyrolysis process. For all three systems, the base case assumes that the excess steam is sold to a nearby consumer.

One gasification option is based on a low pressure, indirectly-heated gasifier, like that developed at Battelle Columbus Laboratories (BCL) specifically for biomass gasification. Future Energy Resources Corporation (FERCO) now owns the rights to this technology and is demonstrating it at the existing McNeil power plant in Burlington, Vermont. This system is called an indirectly-heated system because the heat necessary for the endothermic gasification reactions is supplied by hot sand circulating between the char combustor and the gasification vessel. After clean-up, the syngas is cooled so that it can be compressed to the pressure required for the pressure swing adsorption (PSA) unit plus the expected pressure losses in the reactors. Following compression, the gasifier product gas is steam reformed and passed through two water-gas shift reactors to produce a gas concentrated in H_2 and CO_2. Finally, the hydrogen is purified in the PSA prior to storage and distribution.

The second gasification system uses the IGT gasifier, which is a direct-fired high pressure gasifier. Much of the process scheme has steps similar to the Battelle/FERCO system. The major system components for the IGT hydrogen production process include biomass handling and drying, gasification, for which an air separation unit is required, hot gas clean-up, reforming, shift conversion, and hydrogen purification.

The third technology studied in this analysis is fast pyrolysis of biomass followed by coproduct separation and steam reforming to produce hydrogen. Biomass is dried and then converted to an oil by very quick exposure to heated particles in a fluidized bed. The char and gases produced are combusted to supply heat to the reactor, while the product oils are cooled and condensed. For this analysis, it was assumed that the bio-oil would be produced at several smaller plants which are closer to the sources of biomass, such that lower cost feedstocks can be obtained. The bio-oil is then shipped by truck from these locations to

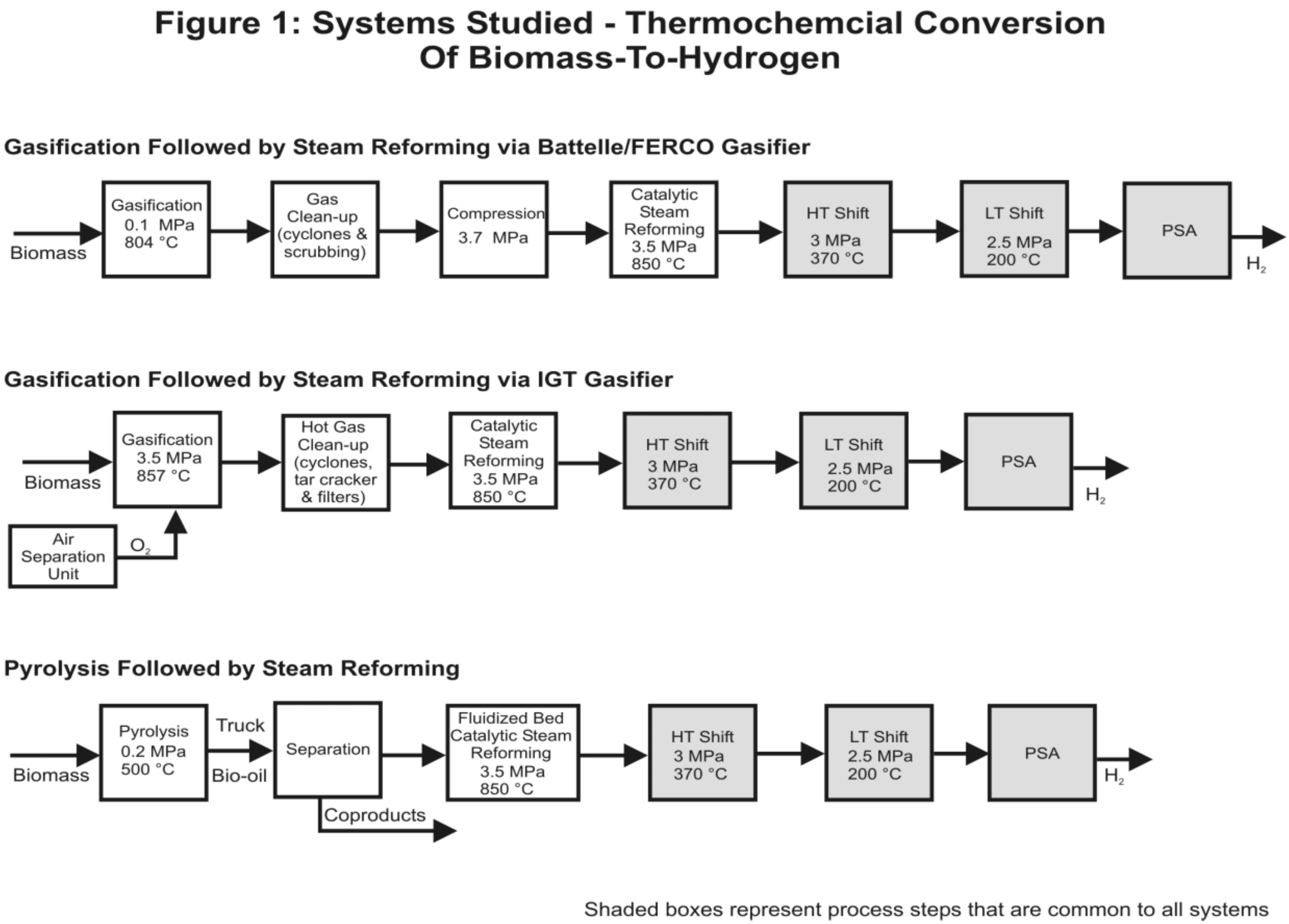

Figure 1: Systems Studied - Thermochemical Conversion of Biomass-to-Hydrogen

the hydrogen production facility. It is more economical to produce bio-oil at remote locations and then ship the oil, since the energy density of bio-oil is higher than biomass. Once the bio-oil arrives, a water extraction process separates the lignin-derived coproduct from the carbohydrate fraction of the oil. Hydrogen is produced from the carbohydrate fraction by steam reforming and shift conversion, followed by PSA for purification. The coproduct can be substituted for some of the phenol used to make phenol formaldehyde resins, used as wood adhesives. NREL is partnering with a major forest product manufacturer and several resin manufacturers to demonstrate the production process and performance attributes of several wood composites containing this material. Approximately 0.57 billion kg (1.25 billion pounds) of phenol are used in phenol formaldehyde resin manufacture each year. Laboratory tests have demonstrated that half of this phenol could be substituted with the lignin-derived component of bio-oil. From the mass balance performed for this study, this translates into about 60 million kg/year hydrogen, or enough to fuel about 20 million fuel cell vehicles (assuming 3 kg H_2/week/vehicle). The lignin-derived fraction can also be converted into a fuel additive that boosts the octane number of gasoline. Because the market for the resin is well understood and thought to be sufficiently large, and the process for producing the fuel additive is relatively new, the resin feed was the only coproduct incorporated into this analysis. Similar to the way that several coproducts can be derived from petroleum, a wide slate of products are likely from bio-oil. Therefore, the pyrolysis-based technology offers the opportunity for increased market potential and better economics as research on bio-oil continues.

In the gasifier cases, the primary reformer used to crack the methane and higher hydrocarbons in the gasifier product gas is based on the design of reformers used in conventional steam methane reforming. The gas flows through catalyst-filled tubes, which are set in a firebox that combusts the PSA offgas. In the pyrolysis system, a fluidized bed reformer is used to avoid the formation of coke deposits on the catalyst. The required steam-to-carbon ratio in the gasifier cases was set at 3:1 based on the fact that the gasifier produces a gas that will reform in a manner similar to that found in conventional steam methane reforming. Because the carbohydrate-fraction of the bio-oil contains higher hydrocarbons, a higher steam-to-carbon ratio of 7-9 will be required. A steam/carbon ratio of 7:1 was assumed for the pyrolysis oil reformer. Once the synthesis gas is produced in the reformer, there are several unit operations that are common to all of the systems: high temperature shift (HTS), low temperature shift (LTS), and PSA. The HTS and LTS reactors convert the majority of the CO into CO_2 and H_2 through the water-gas shift reaction ($CO + H_2O \Leftrightarrow CO_2 + H_2$). A PSA unit is used to separate the hydrogen from the other components in the shifted gas stream, mainly CO_2, and unreacted CO, CH_4, and other hydrocarbons.

3.0 System Design Assumptions

For both of the gasification technologies studied in this analysis, three plant sizes were examined. Only two plant sizes were studied for hydrogen via pyrolysis due to the fact that a significant portion of the oil (35% in the base case) that is produced from the biomass goes to the coproduct rather than to hydrogen. The biggest plant size results in a biomass feed rate that is considered to be too large to economically transport bio-oil, even from several remote locations. The hydrogen production rate for each technology was kept constant at 22,737 kg/day, 75,790 kg/day, and 113,685 kg/day for the small, medium, and large plants, respectively. In each system, the biomass feed rate was adjusted to obtain the desired hydrogen production rate. Table 1 gives the plant sizing statistics for each technology.

Only two plant sizes were studied for hydrogen via pyrolysis. However, because a portion (35% in the base case) of the oil that is produced from the biomass goes to the coproduct rather than to hydrogen , the largest plant size was not considered to be feasible for pyrolysis due to the large quantity of biomass that would be required. Even with several remote pyrolysis plants, transporting the large amount of bio-oil required would render the transportation. The hydrogen production rate for each technology was kept constant at 22,737 kg/day, 75,790 kg/day, and 113,685 kg/day for the small, medium, and large plants, respectively. In each system, the biomass feed rate was adjusted to obtain the desired hydrogen production rate. Table 1 gives the plant sizing statistics for each technology.

Table 1: Hydrogen Plant Size Statistics

H_2 production rate @ 100% capacity (kg/day)	Biomass feed rate for each technology (bone dry Mg/day)			Bio-oil feed rate (bone dry Mg/day)
	Battelle/FERCO	IGT	Pyrolysis	Pyrolysis
22,737	314	311	542	310
75,790	1,046	1,035	1,806	1,035
113,685	1,569	1,553	N/A	N/A

Each of the gasifier systems and parts of the pyrolysis case were modeled in ASPEN Plus©. The gasifiers were modeled using run data from the Battelle Columbus Laboratory (BCL) 9 Mg/day test facility and the IGT 9 Mg/day test facilities. The primary reformer for these two systems was simulated as an equilibrium reactor with an 7°C approach temperature. The reformer for the bio-oil case was modeled in ASPEN Plus© using conversion rates and steam requirements from recent experimental data (Czernik, 2000). Bio-oil was assumed to be purchased and is therefore the feedstock for the pyrolysis case. ASPEN Plus© was used to model the remaining process steps. For all three systems, the HTS and LTS were modeled as stoichiometric reactors with 70% and 75% conversion of the CO, respectively, based on a previous NREL gasification analysis (SRI 1994). Based on conversations with industrial gas producers, the shifted gas stream must contain at least 70 mol% hydrogen before it can be purified in the PSA unit. Purifying streams more dilute than this decreases the purity and recovery of the hydrogen. Therefore, part of the PSA hydrogen product stream is recycled back into the PSA feed. The recovery of hydrogen in the PSA is 85% when purifying a 70 mol% H_2 stream. The offgas stream from the PSA unit is used to fuel the reformer. In the pyrolysis case, the higher steam-to-carbon ratio and the higher reforming efficiency necessitate the addition of natural gas to supply part of the heat required for the reforming reactions. The energy and material balance data from the simulations were used to size and cost the major equipment.

4.0 Capital Cost Data

Unless stated otherwise, the majority of the equipment costs were obtained using Questimate©, a software package that performs detailed process plant cost estimates. This package, by Icarus Corporation, contains design and cost bases for over 250 types of liquid, gas, and solids handling and processing equipment. All capital costs were equated to January 2000 U.S. dollars, using the Marshall & Swift equipment cost index.

The cost of the biomass handling and drying and both gasification trains were estimated from literature data and previous studies. The cost of the Battelle/FERCO gasification section was scaled from the following references: Breault and Morgan (1992), Double (1988), Dravo Engineering Companies (1987), Weyerhaeuser (1992), Wan and Fraser (1989), and Wright and Feinberg (October 1993). The IGT gasifier equipment was determined using cost data from Craig and Mann (October 1996), Stone & Webster, *et al* (June 1995) and Wright and Feinberg (October 1993). The biomass handling and drying was obtained from a combination of the previously mentioned gasification references. The oxygen plant capital and operating cost were taken from literature data along with information from industry contacts (Pietruszkiewecz, *et al*, 1988; Shelton, 1999; SRI, 1995; and Winter, 1997). The cost of the primary reformers for the gasification cases were based on the cost and design data in SRI's *Options for Refinery Hydrogen* (1994). Literature values were also used to determine the capital and operating cost of the PSA unit (Scheneel, *et al*, 1983 and SRI 1994). The cost of producing bio-oil at a distributed pyrolysis facility was taken from Beckman (May 1998). Costs for extracting the pyrolysis oil into the carbohydrate and lignin fractions were determined using detailed mass balances and Questimate©. The fluidized bed reformer used for the pyrolysis case was estimated in Questimate© using reactor parameters defined by laboratory experiments (i.e., height/diameter ratio, free board height/bed height, space velocity, heat transfer requirements).

5.0 Risk Assessment/Stochastic Modeling Methodology

This study uses risk analysis, or stochastic modeling, to predict the sensitivity of the hydrogen selling price to changes in various analysis parameters. Crystal Ball®, a software package offered by Decisioneering, aids in risk assessment decisions by giving results and probabilities for those results. This software tool has the ability to vary several parameters at once, thus identifying the combined uncertainty of the results. Additionally, Crystal Ball® predicts which variables have the most influence on the study outcome. When the user defines each variable, they also specify the type of distribution, the range for that variable in the analysis, and the most likely value so that Crystal Ball® has a starting point. The software operates within Microsoft Excel®.

There are several types of probability distributions, and selecting which type to use depends on the conditions surrounding that variable. Crystal Ball® contains 12 distribution types and four of them characterized the variables in this study: triangular, normal, uniform, and custom. The triangular distribution was used for variables where the minimum, maximum, and most likely values were known. Examples of this include the selling price of steam and many of the capital investment cost factors. A normal distribution was used for variables where the most likely value was known, where there was an equal chance that the variable could be above or below the mean, and where the variable was apt to be in the proximity of the mean. The biomass feedstock cost is one example of this. A uniform distribution was used in instances where there was an equal possibility that any value between the minimum and maximum were likely to occur; for instance, the ratio of the percent equity to the percent debt. Custom distributions were constructed manually for variables where situations arose such that the variable could not be described using the other distribution types or in instances where more detailed information was available. The variables studied in this analysis and specifics regarding their probability distributions are given in the following section.

6.0 Crystal Ball® Assumption Variables

Crystal Ball® generates random numbers for a probability distribution over the entire range of possible values, based on the assumption variables. For this reason, a large number of trials are required to obtain accurate results for the true shape of the distribution. With Latin Hypercube sampling, an assumption's probability distribution is divided into intervals of equal probability. Crystal Ball then generates an assumption value for each interval according to the interval's probability distribution. Compared with conventional Monte Carlo sampling, Latin Hypercube sampling is more precise because the entire range of the distribution is sampled in a more even, consistent manner.

The following is a list of the variables that were changed in the analysis. The variables are listed randomly and should not be considered to be organized relative to importance. In order to define a variable in the Crystal Ball® software, the cell in the Excel® spreadsheet must contain a distinct value; not a calculated one. Therefore, for several variables, it was necessary to use a multiplier or factor to change the desired parameter. When this situation pertains to a specific variable, it is further discussed in the list below. In addition to the following discussion, Appendix A contains the data and probability distribution figures used for each assumption variable.

Variable: *Biomass feedstock cost*
The base case cost of the biomass feedstock used in the gasification analyses was $16.50/dry Mg for the small plant size and $46.20/dry Mg for the medium and large plants. A normal distribution was applied to all three plant sizes. Because of costs associated with handling and transporting the biomass, costs lower than $10/dry Mg are unlikely, even for biomass residues (Marie Walsh, 2000). Higher costs will be incurred if energy crops are required. For the medium and large sized plants, the mean was set at $46.20/dry Mg, with a 10% standard deviation. Additionally, lower and upper limits of $16.50 and $60.50 per dry Mg were assigned. For the small plant size, the mean value of the biomass cost was assumed to be $16.50/dry Mg, with a 10% standard deviation and a minimum cost of $10/dry Mg. As stated previously, even if biomass residues are used some cost will be incurred and consequently, there will not be a zero feedstock cost.

Variable: *Pyrolysis oil (bio-oil) feedstock cost*
The production and transportation costs of manufacturing bio-oil from biomass are reflected in the bio-oil feedstock cost. For the pyrolysis feed, the base case used a bio-oil cost of $0.12/kg in a triangular distribution. The pyrolysis bio-oil feed used a triangular distribution with $0.12/kg being the most likely cost and a range from $0.10-$0.17/kg. These costs are based on data from Beckman (2000), assuming a residue biomass feedstock.

Variable: *Operating capacity factor*
The base case uses an average operating capacity of 90%. The amount of time that the hydrogen plant operates can vary depending on factors such as downtime due to maintenance. Therefore, the mean was set at 100% with a standard deviation of 10%. Although a normal distribution was used, the minimum and maximum values were restricted to 0% and 110%, respectively. An operating capacity greater than 100% is possible if hydrogen demand was high and the plant operated past its design limits.

Variable: *Percent of capital recovered as salvage*
At the end of the hydrogen plant's life, the base case assumes that 10% of the depreciable capital can be recovered as salvage. A normal distribution with a standard deviation of 1 percentage point (or 10% of 10%) was used for this variable.

Variable: *Percent equity*
Because each of the hydrogen production systems studied here are new technologies, they are considered high-risk. Therefore, when examining the debt/equity ratio, a greater allocation of equity is appropriate. The base case assumed 50% equity with a uniform distribution from 50% to 100%.

Variable: *Interest rate*
The mean interest rate for debt was set at 10% based on the high-risk nature of these new technologies. For the sensitivity runs, a normal distribution with a one percentage point standard deviation was assumed.

Variable: *Wage rate*
The wage rate is based on the 1995 PEP yearbook estimate of $28.75/hr which includes both fringe benefits and shift overlap (SRI, 1995). This rate was updated using Chemical Engineering magazine's hourly earnings index for chemical and allied products to ratio the 1995 estimate to an early 2000 rate

(1992, 1995, 1999, 2000). This current wage rate was calculated at \$32.15/hr, but because this increase of the wage rate had a minimal affect on the hydrogen selling price in the analysis, a normal distribution was assumed for this variable with a mean of \$28.75/hr and a 10% standard deviation.

Variable: *Hydrogen production factor*
Often a process will perform better or worse than the actual design. In order to compensate for this, the hydrogen production factor was assigned a uniform distribution from 0.9 to 1.1. This means that the system has an equal probability of producing between 90% to 110% of the design hydrogen production rate. This is different from operating capacity factor, and is meant to capture the possibility of lower hydrogen yield. Changes in the upstream syngas composition would result in composition changes from the shift reactors and possibly changes in the overall energy balance. Because these process steps were modeled in ASPEN Plus®, a change in the syngas composition could not be assessed with Crystal Ball®. Therefore, any deviation in the production rate from the design amount was assumed to be solely due to the PSA unit.

Variable: *Capital cost multipliers*
Multipliers were used for scaling the capital costs of the biomass handling and drying operations, gasifier (Battelle/FERCO and IGT analyses only), reformer, PSA unit, oxygen plant (IGT analysis only), Battelle/FERCO syngas compressor, pyrolysis air compressor, and other pyrolysis equipment. These were the most expensive pieces of equipment and combined, result in about 90% of the total capital cost for each system studied. Note that for the pyrolysis case, the equipment costs are only those associated with the conversion of the bio-oil to hydrogen because the capital cost of the pyrolysis plant is included in the bio-oil feedstock cost. A cost multiplier of 1.0 means that the capital cost as determined by Questimate© or literature sources was the actual cost of the equipment. A multiplier greater that 1.0 indicates that the capital cost was greater than the estimated value while a number less than 1.0 means that the cost would be less. In other words, the actual equipment cost ended up to be the determined cost times the specified cost factor. For example, a cost multiplier of 0.90, means that the cost of that particular piece of equipment was actually 90% of the predicted cost. Each piece of equipment was assumed to have a uniform distribution with a minimum and maximum value as listed in table 2.

Table 2: Equipment Cost Multipliers

Equipment	Minimum	Maximum
Biomass handling & drying	0.9 - 1.00 (20% probability that the cost is in this range)	1.00 - 1.30 (80% probability that the cost is in this range)
Gasifier	0.9 - 1.00 (20% probability that the cost is in this range)	1.00 - 1.30 (80% probability that the cost is in this range)
Reformer	0.80	1.20
PSA unit	0.70	1.30
Oxygen plant	0.80	1.20
Battelle/FERCO syngas compressor	0.90	1.10
Pyrolysis air compressor	0.85	1.15
Other pyrolysis equipment	0.70	1.30

Variable: *Cost factors for capital investment*
In these analyses, cost factors were used to estimate the equipment installation costs. These factors are for estimating the capital investment based on the total delivered equipment cost. A triangular distribution was used for each parameter and the following table contains the minimum, most likely, and maximum values used in the sensitivity analysis. The values are based on ranges given in Garrett (1989) and Peters and Timmerhaus (1991).

Table 3: Direct and Indirect Cost Multipliers

Parameter	Minimum	Most Likely	Maximum
electrical	10%	11%	15%
instrumentation	10%	18%	35%
piping	50%	66%	70%
buildings	15%	18%	30%
land	4%	6%	10%
yard improvements	5%	10%	15%
service facilities	40%	70%	80%
engineering & construction	35%	74%	80%
contingencies	25%	42%	80%

Variable: *Pyrolytic lignin (coproduct) selling price*
Pyrolytic lignin comes from the lignin-derived phenolic fraction and is obtained through an extraction process. This coproduct can be used as a substitute for phenol in the manufacture of a wood adhesive or as a high octane fuel additive. However this study only considered the wood adhesive byproduct because little information is known about the fuel additive and a great deal of experimental and marketing work has been done on the adhesive. The pyrolytic lignin selling price of \$0.44/kg is a fraction (two-thirds) of the current market cost of phenol which is \$0.66/kg. A normal distribution was used to model this selling price with a mean of \$0.44/kg with a 10% standard deviation.

Variable: *Yield of carbohydrate from bio-oil*
The carbohydrate fraction is what remains after the phenolic fraction is water extracted from bio-oil. NREL researchers have confirmed that the yield of this carbohydrate fraction is 65% of the bio-oil entering the extraction process (Personal communication Kelley, Scahill, and Czernik, 2000). A triangular distribution models this yield, ranging from 59-75% and a likeliest value of 65%.

Variable: *Percent of moisture of bio-oil*
This value is taken from Beckman (1998), where the minimum and maximum values are the two moisture levels used in his studies. These values are 22.43% and 23.38% and a uniform distribution is used between the two values.

Variable: *Natural gas requirement multiplier*
The amount of natural gas needs to be varied according to the heat required for the reformer. The most likely value for this multiplier is one, using the natural gas requirement taken from ASPEN Plus'® calculation for additional fuel necessary to heat the reformer. This multiplier is modeled using a triangular distribution ranging from 30% below to account for opportunities for improvements and 10% above the multiplier of one.

Variable: *Cost of natural gas*
The Energy Information Administration reports the current average city gate price of natural gas as $3.00/1,000 scf (EIA 2000). The cost of natural gas has a triangular distribution range based on trends from the past, which varies from $2.98-$3.52/1,000 scf with the likeliest value set at $3.00/1,000 scf.

Variable: *Cost of electricity*
The cost of electricity was based on data from the Energy Information Administration (U.S. DOE, 1999). The average retail price of electricity for industrial and commercial users in 1998 was $0.045/kWh and $0.074/kWh, respectively. To account for variations in electricity prices in various regions throughout the U.S., a triangular distribution was set up ranging from $0.04-$0.08/kWh with the likeliest value being $0.05/kWh.

Variable: *Steam selling price*
Based on data listed in Peters and Timmerhaus (1991) and Turton, *et al* (1998), the steam selling price was set up as a triangular distribution with the most likely values being $5.15/Mg of steam and $7.88/Mg of steam, for the 0.7 MPa and 3.4 MPa (100 psi and 500 psi) steam respectively. The minimum value was set at zero for both steam pressures, in the event that a nearby steam buyer is unavailable. The maximum selling price for the 0.7 MPa steam was set at $7.08/Mg and the maximum for the 3.4 MPa steam was set at $8.60/Mg.

Variable: *Working capital*
In these analyses, the working capital is determined to be a percentage of the total fixed capital investment. This variable was modeled using a triangular distribution with a range of 10-20% and the likeliest value being 18%, based on percentages given in the following literature sources: Garrett (1989), Peters and Timmerhaus (1991), and Turton, *et al* (1998).

Variable: *River water and boiler feed water costs*
The water costs were determined based on utility costs in Peters and Timmerhaus (1991) and Turton, *et al* (1998). Because only one value could be found for the cost of boiler feed water, a normal distribution was assumed for this variable with a mean of $2.54/1,000 liters and a standard deviation of 10%. Because there was a range of values for river water costs, a triangular distribution was set up with the minimum, likeliest, and maximum value being $0.02/1,000 liters, $0.05/1,000 liters, and $0.07/1,000 liters, respectively.

7.0 Hydrogen Storage and Transportation Scenarios

The previous analyses of these gasification and pyrolysis systems examined only the plant gate hydrogen selling price. However, for any application the delivered cost is important because even if the hydrogen is produced cheaply, the cost to store and transport the hydrogen will make a difference in determining if the hydrogen is economical. In order to determine the effect of hydrogen storage and transport on the delivered cost of hydrogen, six likely scenarios for hydrogen use were examined. They are presented in Table 4.

Table 4: Hydrogen Storage and Transport Scenarios

Scenario	Hydrogen usage	Assumptions
1	bulk delivery	16 km (10 mi) one-way
2	bulk delivery	160 km (100 mi) one-way
3	bulk delivery	1,610 km (1,000 mi) one-way
4	on site consumption	12 hours of storage; no transport
5	gas station supply	weekly hydrogen delivery; driving distance of 160 km (100 mi) round trip; supplying multiple stations along the way; hydrogen use of 263 kg/day (580 lb/day) per gas station
6	pipeline	3 km (1.9 mi) to the nearest pipeline infrastructure; no storage; an additional 160 km (100 mi) pipeline for hydrogen delivery to end user for which the cost is shared by 5 companies

In each case, the cheapest delivery and storage methods were identified, along with the associated incremental cost that must be added to the production cost to get the total delivered cost of hydrogen. The cost of storing and transporting hydrogen depends on the amount of hydrogen the customer needs and how far their site is from the production facility. The most economical modes of storage and delivery (i.e., liquid, compressed gas, metal hydride or pipeline delivery) will also vary depending on production rate and distance. For example, while liquid hydrogen delivery is one of the cheapest methods of transporting hydrogen long distances, it requires a large capital investment for a liquefaction facility and there can be significant transfer losses during loading and unloading. This large capital investment at the production site, along with product losses, can make another method of delivery more cost effective. The hydrogen storage and transport costs were determined using a spreadsheet model developed at NREL (Amos, 1998).

8.0 Discounted Cash Flow Cases

The economic analysis method used to determine the plant gate hydrogen selling price was discounted cash flow rate of return. The hydrogen selling price is calculated for a specified after-tax internal rate of return. An Excel® worksheet was set up for each technology but because a macro was necessary to calculate the hydrogen selling price for a given IRR after each iteration in Crystal Ball®, the IRR could not be varied in the sensitivity analysis. Four separate analyses were run in order to examine the effect of IRR on the hydrogen selling price. The base case analysis assumes an after-tax rate of return of 15% which is a value typically required by investors. Cases were also tested at a 20% and 10% after-tax IRR and a 0% pre-tax IRR. The 20% case was chosen because these technologies are new and thus result in a higher risk. The 0% case represents the pre-tax break-even point, or production cost of hydrogen. The 10% case is included mostly for illustrative purposes, as it is unlikely that an investor will be willing to accept such a low rate for novel technologies such as those studied here.

9.0 Analysis Results

The following sections discuss the results from the analysis. These include the capital cost of each system examined, plant gate hydrogen selling price, the delivered cost of hydrogen, and the sensitivity results from Crystal Ball®.

9.1 Results - Capital Cost

The resulting capital costs for each system are shown in Table 5. The IGT technology has the highest capital investment followed by Battelle/FERCO and then pyrolysis, although it is important to remember that the cost of pyrolyzing the biomass is rolled into the price of the bio-oil feedstock. For the IGT system, the oxygen plant and gasifier each account for about 25% of the total capital investment. The highest capital cost items for the Battelle/FERCO system are the compressors. In total, the compressors make up 32% of the total installed capital, with the compressor used to boost the pressure of the gasifier product gas accounting for 22% of the total equipment cost. In the pyrolysis case, the reformer and PSA account for the majority of the capital costs, at 31% and 51%, respectively.

Table 5: Total Fixed Capital Investment

H_2 production rate (kg/day)	Total Installed Capital Investment (million US$)		
	Battelle/ FERCO	IGT	Pyrolysis*
22,737	53.8	72.0	18.8
75,790	128.8	169.4	59.4
113,685	172.3	227.2	N/A

* The pyrolysis capital costs include extraction of the bio-oil, conversion of the carbohydrate-fraction to hydrogen, and hydrogen purification. The capital costs for bio-oil production are included in the bio-oil feedstock cost.

9.2 Results - Plant Gate Selling Price: Predicted and Mean

Since the plant gate hydrogen selling price is one of the desired results from the analysis, the cell containing its calculated value was set up as a forecast cell. This means that statistical values such as the mean, median, mode, and standard deviation were determined. Appendix B contains statistics definitions useful for interpreting the results generated by Crystal Ball®. The detailed statistical data and frequency charts of the hydrogen selling price for each of the cases studied in the analysis are given in Appendix C. Table 6 lists two values for each case, the predicted hydrogen selling price from the Excel® cash flow spreadsheet, labeled as "pred.", and the mean hydrogen selling price as determined by Crystal Ball®. The mean hydrogen selling price takes all of our assumptions and uncertainties into account. Depending on the technology and plant size, the predicted plant gate hydrogen selling price ranges from $8.7 to $20.6/GJ for an IRR of 15%. The pyrolysis case produces the cheapest hydrogen, followed by the Battelle/FERCO gasifier, and then the IGT system. The hydrogen selling price increases with an increasing IRR, and decreases as the plant size increases due to economy of scale. In most instances, the predicted hydrogen selling price is less than the sensitivity analysis mean. This is expected because Crystal Ball®'s sensitivity analysis incorporates the variance of the assumptions into the hydrogen selling price. For the gasifier systems, the predicted hydrogen selling price is fairly close to the mean (within $1/GJ) except for the higher 20% IRR cases. The pyrolysis cases had a predicted hydrogen selling price that was usually about $2/GJ lower than the sensitivity results. The difference between the predicted and mean hydrogen selling price is twice the difference of the gasifier cases, demonstrating that there is a greater variability built into the pyrolysis assumptions. It is easier to reform the gasifier product gas than it is to reform the carbohydrate fraction of the bio-oil. Additionally, there is significant uncertainty regarding the selling price of the adhesives coproduct.

Table 6: Predicted Plant Gate Hydrogen Selling Price and Mean Sensitivity Price from Crystal Ball®

Technology	H_2 production rate (kg/day)	Plant Gate H_2 Selling Price: Predicted and Mean Value ($/GJ)			
		0% IRR (pre-tax) "production cost"	10% IRR (after-tax)	Base case 15% IRR (after-tax)	20% IRR (after-tax)
Battelle/ FERCO	22,737	pred. = 7.90 mean = 7.68	pred. = 14.29 mean = 14.19	pred. = 17.08 mean = 17.62	pred. = 20.18 mean = 21.49
	75,790	pred. = 8.81 mean = 8.80	pred. = 13.39 mean = 13.48	pred. = 15.39 mean = 15.99	pred. = 17.65 mean = 18.77
	113,685	pred. = 8.41 mean = 8.44	pred. = 12.48 mean = 12.61	pred. = 14.29 mean = 14.84	pred. = 16.28 mean = 17.31
IGT	22,737	pred. = 8.40 mean = 8.02	pred. = 16.91 mean = 16.87	pred. = 20.64 mean = 21.57	pred. = 24.81 mean = 26.89
	75,790	pred. = 8.95 mean = 8.78	pred. = 14.95 mean = 15.04	pred. = 17.61 mean = 18.38	pred. = 20.54 mean = 22.09
	113,685	pred. = 8.48 mean = 8.36	pred. = 13.79 mean = 13.93	pred. = 16.16 mean = 16.90	pred. = 18.77 mean = 20.21
Pyrolysis	22,737	pred. = 6.57 mean = 8.55	pred. = 9.17 mean = 11.07	pred. = 10.24 mean = 12.41	pred. = 11.41 mean = 13.77
	75,790	pred. = 5.30 mean = 7.41	pred. = 7.70 mean = 9.75	pred. = 8.69 mean = 10.94	pred. = 9.79 mean = 12.27

9.3 Results - Delivered Cost of Hydrogen

In the sensitivity analysis, the cost of hydrogen was determined in terms of the plant gate cost. The cost to store and transport the hydrogen was then added to this cost. As discussed in section 7.0 above, six different storage and transport options were examined. In each case, the cheapest delivery and storage method was identified. Table 7 gives the total cost of storage and transportation for each option studied as well as the methods. The cheapest storage and transport methods were the same for most plant sizes with three differences denoted in the table by an asterisk (*). It is apparent that the option of bulk storage with a transport distance of 1,610 km (1,000 mi) has significantly higher storage and transport costs ($9 to $12/GJ of hydrogen) than a shorter transport distance of 16 km (10 mi), onsite consumption, or pipeline transport (around $1-$4/GJ for each of these options). Overall, for the options studied in this analysis, storage and delivery adds $1 to $10/GJ to the plant gate cost.

Table 7: Hydrogen Storage and Transport Costs for Each of the Six Options

H_2 production rate @ 100% capacity (kg/day)	Total storage & transport cost of hydrogen ($/GJ of hydrogen)					
	option 1 (gas/pipeline)	option 2 (gas/pipeline)	option 3 (liquid/rail)	option 4 (gas/none)	option 5 (gas/pipeline)	option 6 (none/pipeline)
22,737	$3.32	$10.26 (gas/metal hydride)*	$12.01 (liquid/ liquid rail)*	$1.53	$7.56 (gas/metal hydride)*	$3.94
75,790	$1.78	$6.67	$9.93	$1.23	$6.67	$1.26
113,685	$1.53	$4.85	$9.41	$1.15	$4.85	$0.92

<u>option - with cheapest storage and transport in parenthesis</u>
1: bulk delivery - 16 km (10 mi) one way
2: bulk delivery - 160 km (100 mi) one way
3: bulk delivery - 1,610 km (1,000 mi) one way
4: on site consumption - 12 hours of storage; no transport
5: gas station supply - weekly deliveries; driving distance of 160 km round trip; supply multiple stations along the way; hydrogen use of 263 kg/day per gas station
6: pipeline - 3 km to nearest infrastructure; no storage; an additional 160 km pipeline distance for delivery to end user for which the cost is shared by 5 companies

* Cheapest storage and transport method as denoted in parenthesis is different than that specifically listed under each option.

Figure 2 shows a breakdown of the storage and transport costs for the 75,790 kg/day plant size. The y-axis shows the incremental cost that must be added to the plant gate cost in order to get the delivered cost of hydrogen. The solid portion of each bar is the storage cost and the bubbled section is the contribution from transportation. The cheapest storage and delivery options are denoted in parentheses and in half of the cases, gas storage with pipeline transport is the lowest cost choice. Although the total incremental cost for storage and transport is not exactly the same for the other two plant sizes (as indicated above in Table 7), in general, the other plant sizes have similar distribution percentages between the amount of cost that comes from storage versus transport. For example, for option 3 (bulk storage & 1,610 km) the total cost associated with storage and transport is $12.01/GJ, $9.93/GJ, and $9.40/GJ for the 22,737 kg/day, 75,790 kg/day, and 113,685 kg/day plant size, respectively. Of the total cost, 83% ($9.97/GJ) is associated with storage for the 22,737 kg/day plant, 80% ($7.95GJ) of the cost is associated with storage for the 75,790 kg/day plant, and 79% ($7.44/GJ) of the cost is associated with storage for the 113,685 kg/day plant.

From section 9.2 above, the predicted plant gate hydrogen selling price ranges from $8.7/GJ to $20.6/GJ for a 15% IRR. Adding the storage and transport costs results in a delivered cost of hydrogen between $9.9/GJ and $32.7/GJ (at 15% IRR). Table 8 summarizes the predicted plant gate hydrogen selling price, the mean selling price from the sensitivity analysis and the delivered cost of hydrogen for each of the cases studied in the analysis.

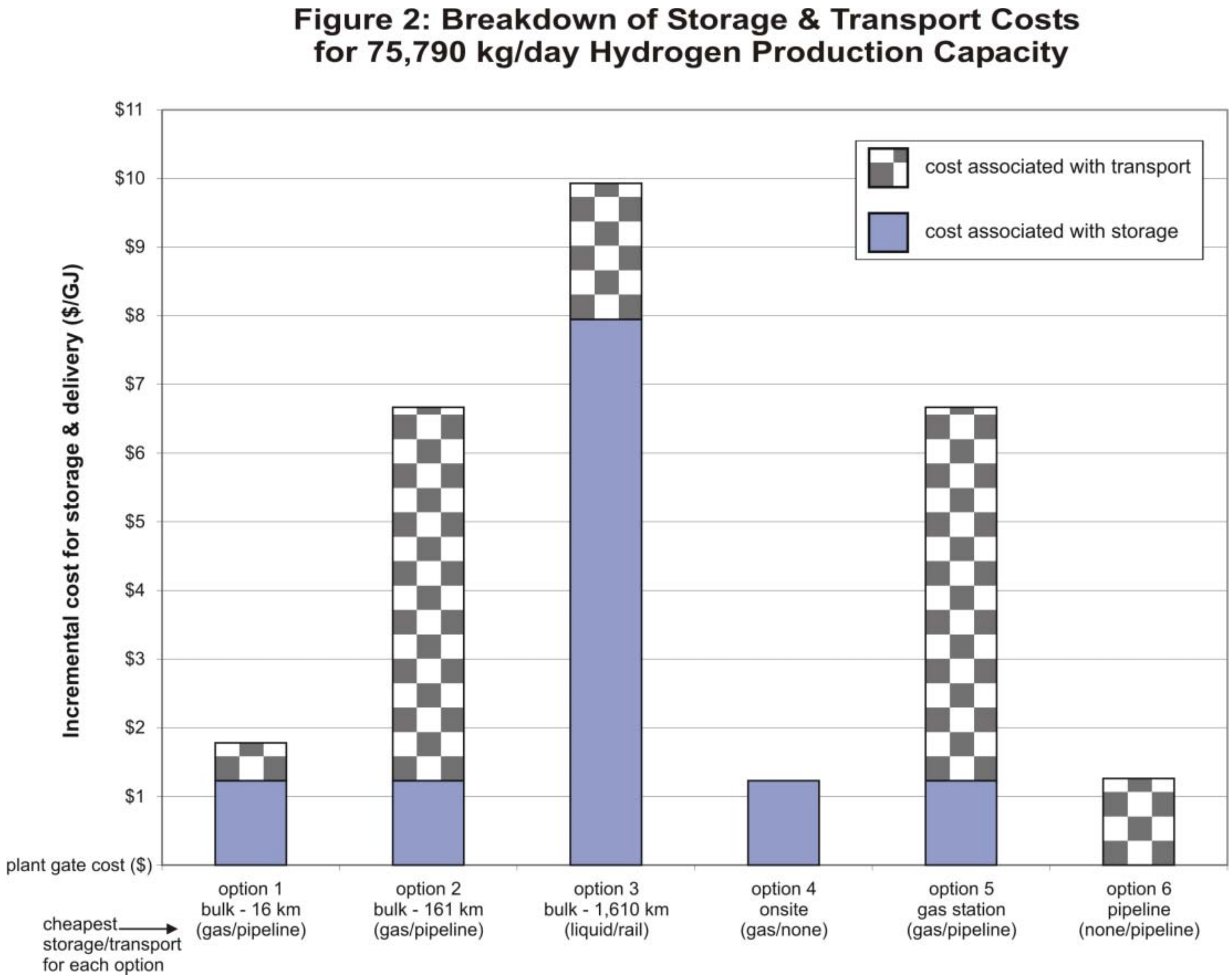

Figure 2: Breakdown of Storage & Transport Costs for 75,790 kg/day Hydrogen Production Plant

Table 8: Plant Gate & Delivered Hydrogen Costs

Technology	Hydrogen production rate (kg/day)	IRR *	Predicted plant gate H2 selling price ($/GJ)	Sensitivity analysis mean plant gate H2 selling price ($/GJ)	Option 1 - 6 = delivered cost of H2 ($/GJ) = predicted gate price + storage + transport cost					
					option 1	option 2	option 3	option 4	option 5	option 6
Battelle/Ferco	22,737	0% (pre-tax)	$7.90	$7.68	$11.22	$18.16	$19.91	$9.43	$15.46	$11.84
		10% (after-tax)	$14.29	$14.19	$17.61	$24.55	$26.30	$15.82	$21.85	$18.23
		15% (after-tax)	$17.08	$17.62	$20.40	$27.34	$29.09	$18.61	$24.64	$21.02
		20% (after-tax)	$20.18	$21.49	$23.50	$30.44	$32.19	$21.71	$27.74	$24.12
Battelle/Ferco	75,790	0% (pre-tax)	$8.81	$8.80	$10.59	$15.48	$18.74	$10.04	$15.48	$10.07
		10% (after-tax)	$13.39	$13.48	$15.17	$20.06	$23.32	$14.62	$20.06	$14.65
		15% (after-tax)	$15.39	$15.99	$17.17	$22.06	$25.32	$16.62	$22.06	$16.65
		20% (after-tax)	$17.65	$18.77	$19.43	$24.32	$27.58	$18.88	$24.32	$18.91
Battelle/Ferco	113,685	0% (pre-tax)	$8.41	$8.44	$9.94	$13.26	$17.82	$9.56	$13.26	$9.33
		10% (after-tax)	$12.48	$12.61	$14.01	$17.33	$21.89	$13.63	$17.33	$13.40
		15% (after-tax)	$14.29	$14.84	$15.82	$19.14	$23.70	$15.44	$19.14	$15.21
		20% (after-tax)	$16.28	$17.31	$17.81	$21.13	$25.69	$17.43	$21.13	$17.20
IGT	22,737	0% (pre-tax)	$8.40	$8.02	$11.72	$18.66	$20.41	$9.93	$15.96	$12.34
		10% (after-tax)	$16.91	$16.87	$20.23	$27.17	$28.92	$18.44	$24.47	$20.85
		15% (after-tax)	$20.64	$21.57	$23.96	$30.90	$32.65	$22.17	$28.20	$24.58
		20% (after-tax)	$24.81	$26.89	$28.13	$35.07	$36.82	$26.34	$32.37	$28.75
IGT	75,790	0% (pre-tax)	$8.95	$8.78	$10.73	$15.62	$18.88	$10.18	$15.62	$10.21
		10% (after-tax)	$14.95	$15.04	$16.73	$21.62	$24.88	$16.18	$21.62	$16.21
		15% (after-tax)	$17.61	$18.38	$19.39	$24.28	$27.54	$18.84	$24.28	$18.87
		20% (after-tax)	$20.54	$22.09	$22.32	$27.21	$30.47	$21.77	$27.21	$21.80
IGT	113,685	0% (pre-tax)	$8.48	$8.36	$10.01	$13.33	$17.89	$9.63	$13.33	$9.40
		10% (after-tax)	$13.79	$13.93	$15.32	$18.64	$23.20	$14.94	$18.64	$14.71
		15% (after-tax)	$16.16	$16.90	$17.69	$21.01	$25.57	$17.31	$21.01	$17.08
		20% (after-tax)	$18.77	$20.21	$20.30	$23.62	$28.18	$19.92	$23.62	$19.69
Pyrolysis	22,737	0% (pre-tax)	$6.57	$8.55	$9.89	$16.83	$18.58	$8.10	$14.13	$10.51
		10% (after-tax)	$9.17	$11.07	$12.49	$19.43	$21.18	$10.70	$16.73	$13.11
		15% (after-tax)	$10.24	$12.41	$13.56	$20.50	$22.25	$11.77	$17.80	$14.18
		20% (after-tax)	$11.41	$13.77	$14.73	$21.67	$23.42	$12.94	$18.97	$15.35
Pyrolysis	75,790	0% (pre-tax)	$5.30	$7.41	$7.08	$11.97	$15.23	$6.53	$11.97	$6.56
		10% (after-tax)	$7.70	$9.75	$9.48	$14.37	$17.63	$8.93	$14.37	$8.96
		15% (after-tax)	$8.69	$10.94	$10.47	$15.36	$18.62	$9.92	$15.36	$9.95
		20% (after-tax)	$9.79	$12.27	$11.57	$16.46	$19.72	$11.02	$16.46	$11.05

9.4 Results - Variables Affecting the Cost of Hydrogen

The sensitivity chart shows the influence that each variable has on the analysis. For this study, the sensitivities are displayed as a percentage of the contribution to variance. In other words, the chart shows the contribution of each variable to the uncertainty in the hydrogen selling price. Appendix D contains the sensitivity charts of each case for the three technologies studied. The following is a discussion of the results and trends shown in these charts.

For the gasification plants, a change in the hydrogen production factor and in the operating capacity factor have the greatest influence on the uncertainty in the hydrogen selling price. Combined, these two variables account for roughly 51-76% of the uncertainty in the hydrogen selling price depending on the plant size and IRR. Table 9 shows the contribution to variance for the two variables. The data in this table were taken from the sensitivity charts in Appendix D. Of all the variables studied in this analysis, these two have the largest effect on the amount of hydrogen produced by the system per dollar of capital and operating expenses. It is interesting to note that as the IRR increases, the contribution to variance from the hydrogen production factor decreases significantly (about 7% for each 5% increase in the IRR). The uncertainty from this variable becomes less because at higher rates of return, the capital cost of the system and in particular the way that this cost is financed has a greater impact on the overall economics. The uncertainty in the hydrogen selling price due to changes in the debt/equity ratio becomes quite large at an after-tax IRR of 20% (roughly 19-22% for all gasification cases studied). Table 10 shows the contribution to variance for the percent equity. It is obvious that the plant size does not really change the amount of uncertainty associated with this variable.

Table 9: Variables with Largest Contribution to Variance for the Gasification Systems

Gasifier	H_2 production rate (kg/day)	Variable	Contribution to variance by %			
			0% IRR (pre-tax)	10% IRR (after-tax)	Base case 15% IRR (after-tax)	20% IRR (after-tax)
Battelle/ FERCO	22,737	- H_2 production factor - operating capacity	43.5 27.4	35.6 41.9	29.6 39.5	24.1 35.3
	75,790	- H_2 production factor - operating capacity	45.9 7.8	43.9 25.1	37.1 27.5	30.7 27.7
	113,685	- H_2 production factor - operating capacity	45.1 6.2	44.2 22.4	38.1 25.6	31.6 26.1
IGT	22,737	- H_2 production factor - operating capacity	39.2 31.4	31.3 40.9	25.9 36.9	21.2 32.2
	75,790	- H_2 production factor - operating capacity	45.1 10.3	40.0 28.0	33.4 29.1	27.7 27.7
	113,685	- H_2 production factor - operating capacity	44.8 8.5	40.9 25.9	34.3 27.6	28.0 26.7

Table 10: Contribution to Variance from Percent Equity for the Gasification Systems

Gasifier	H_2 production rate @ 100% capacity (kg/day)	Contribution to variance by %			
		0% IRR (pre-tax)	10% IRR (after-tax)	Base case 15% IRR (after-tax)	Base case 20% IRR (after-tax)
Battelle/ FERCO	22,737	4.7	1.6	11.8	23.3
	75,790	1.7	1.4	10.1	20.1
	113,685	1.4	1.4	9.3	19.3
IGT	22,737	9.1	1.3	12.0	24.1
	75,790	4.4	1.1	10.2	21.1
	113,685	3.9	1.0	9.8	20.7

For the 75,790 and 113,685 kg/day plants, the biomass feedstock cost accounts for 70-75% of the operating expenses for each of the gasification systems. For the 22,737 kg/day plant size, because a waste feedstock is used, the biomass price accounts for 33-37% of the total operating expenses. Table 11 shows the contribution to variance values for the biomass feedstock cost which were taken from the sensitivity charts. The biomass feedstock cost has a larger effect on the Battelle/FERCO system because the capital cost of this system is lower than that for the IGT system. Changes in the biomass feedstock cost result in a larger uncertainty of the hydrogen selling price at lower IRRs. Additionally, as the plant size increases the contribution to variance from the biomass feedstock cost increases. This is especially true when going from a waste feedstock (the 22,737 kg/day plant size) to a dedicated biomass crop (the other 2 plant sizes).

Table 11: Contribution to Variance from Biomass Feedstock Cost for the Gasification Systems

Gasifier	H_2 production rate @ 100% capacity (kg/day)	Contribution to variance by %			
		0% IRR (pre-tax)	10% IRR (after-tax)	Base case 15% IRR (after-tax)	20% IRR (after-tax)
Battelle/ FERCO	22,737	4.3	1.1	0.6	0.4
	75,790	31.0	12.6	7.8	4.9
	113,685	33.3	14.6	9.3	6.0
IGT	22,737	4.1	0.8	0.4	0.2
	75,790	31.3	9.8	5.5	3.1
	113,685	34.3	11.6	6.7	3.8

Changing one capital cost factor (i.e., cost associated with instrumentation, piping, etc) at a time has a very small effect on the hydrogen selling price. However, all of the cost factors combined add up to a contribution to variance of about 5-7% for the gasification cases. The same is true in regards to the total capital cost. However, for the IGT system, the gasifier cost and the oxygen plant cost each contribute about 4-7% to the uncertainty of the hydrogen selling price while the overall capital cost contributes around 13-15% to the uncertainty. Because the overall capital cost of the Battelle/FERCO system is less than the IGT system, the uncertainty contributed by the total capital cost is not as large. For the Battelle/FERCO system, the uncertainty in the hydrogen selling price as a result of the overall capital equipment cost is in the range of 4-7%. Additionally, unlike the hydrogen production factor and operating capacity factor, the capital cost factors and the capital costs vary only slightly with changes in the after-tax IRR and in the plant size (see Appendix D).

The pyrolysis case has completely different variables contributing to uncertainty in the sensitivity analysis. Where hydrogen production factor and operating capacity were the largest uncertainty factors in the gasification cases, these two variables were only a small percentage of the contribution to variance in the pyrolysis case. The sensitivity charts for each pyrolysis case can be found in Appendix D. Table 12 shows the top three variables which offer the largest uncertainty in the mean hydrogen selling price for the pyrolysis case: bio-oil feedstock cost, pyrolytic lignin selling price, and yield of carbohydrate from the bio-oil. Combined, these three variables account for 81-94% of the uncertainty in the hydrogen selling price, where approximately half of that contribution is from the bio-oil feedstock cost. Because the production and transportation costs are included in the bio-oil feedstock cost, this variable has a large variance in comparison to the other variables. The pyrolytic lignin selling price's contribution to uncertainty is high because the coproduct selling price varies with the market and is fairly uncertain. However, it should be noted that a conservative estimate of this price was used in the analysis.

Table 12: Variables with Largest Contribution to Variance for the Pyrolysis Case

H_2 production rate (kg/day)	Variable	Contribution to variance by %			
		0% IRR (pre-tax)	10% IRR (after-tax)	Base case 15% IRR (after-tax)	20% IRR (after-tax)
22,737	Bio-oil feedstock cost	45.4	41.6	40.8	38.2
	Pyrolytic lignin selling price	26.8	26.0	23.5	24.0
	Yield of carbohydrate from bio-oil	21.2	19.6	18.7	18.4
75,790	Bio-oil feedstock cost	45.8	44.0	42.6	39.0
	Pyrolytic lignin selling price	27.4	27.3	25.6	24.3
	Yield of carbohydrate from bio-oil	21.0	20.0	18.7	19.6

10.0 Recommendations and Implications

For all of the technologies examined, research should be focused on reducing the costs associated with those variables that have the largest contribution to variance. For the gasification plants, the amount of hydrogen produced has the greatest effect on the uncertainty associated with the calculated price of hydrogen. Therefore, efforts should be focused on maximizing the reforming and shift conversions, along with maximizing the economical recovery of hydrogen from the PSA. The total installed capital investment, and specifically, the costs associated with biomass preparation and gasification are areas which deserve additional attention. This is especially true for the IGT system which operates at a high pressure, resulting in larger expenses for handling and gasification as well as some operating difficulties associated with pressurized biomass feeding systems. Additionally, the IGT gasifier must be oxygen-blown in order to minimize the amount of nitrogen in the syngas. The air separation unit accounts for roughly 25% of the total installed capital cost; therefore, the development of a cheaper oxygen generating technology could significantly reduce the system capital cost.

For the pyrolysis case, the resulting economics are strongly dependent on the parameters associated with the bio-oil feedstock and the coproduct. The bio-oil feedstock cost has the largest effect on the uncertainty of the hydrogen selling price. Therefore, future work points to performing a detailed evaluation of the pyrolysis plant in conjunction with the bio-oil conversion plant, using the same stochastic modeling method outlined in this report. This will determine which specific components such as pyrolysis plant capital cost, biomass feedstock price, bio-oil yield, or transportation expense affect the cost of hydrogen from the pyrolysis system most significantly.

This study demonstrates that hydrogen can be produced economically from biomass. The pyrolysis-based technology, in particular, because it has coproduct opportunities, has the most favorable economics. However, the gasification processes also produce hydrogen for less than many other renewable technologies. An added benefit of biomass as a renewable feedstock is that it is not intermittent, but can be used to produce hydrogen when needed. Uncertainties exist, however, and must be addressed through increased research and validation projects. With scientific and engineering advancements, biomass can be viewed as a key economically-viable component to a renewably-based hydrogen economy.

It is important to continue using risk assessment for analysis in the Hydrogen Program because this technique accounts for uncertainties in the assumptions. As shown in this study, the mean hydrogen selling price as determined from Crystal Ball® was higher than the predicted price calculated in the Excel® cash flow spreadsheets. In future studies, a combination of uncertainties could result in a large difference between predicted and mean values. This stochastic modeling method pinpoints areas with the greatest contribution to variance, thus showing areas requiring additional research.

11.0 References

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Appendices

Appendix A - Probability Distributions

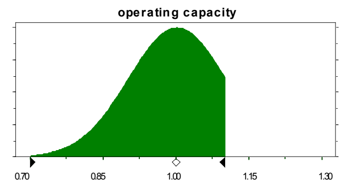
Assumptions

Assumption: operating capacity

Normal distribution with parameters:

Mean	1.00
Standard Dev.	0.10

Selected range is from 0.00 to 1.10

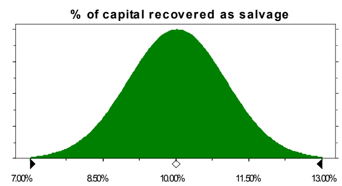


Assumption: % of capital recovered as salvage

Normal distribution with parameters:

Mean	10.00%
Standard Dev.	1.00%

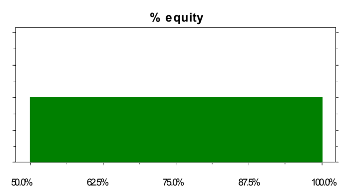
Selected range is from -Infinity to +Infinity



Assumption: % equity

Uniform distribution with parameters:

Minimum	50.0%
Maximum	100.0%

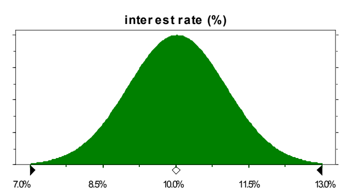


Assumption: interest rate (%)

Normal distribution with parameters:

Mean	10.0%
Standard Dev.	1.0%

Selected range is from -Infinity to +Infinity

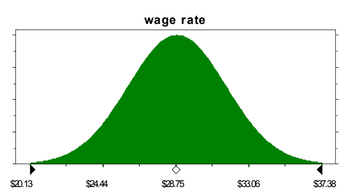


Assumption: wage rate

Normal distribution with parameters:

Mean	$28.75
Standard Dev.	$2.88

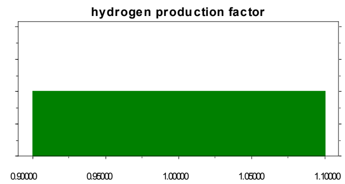
Selected range is from -Infinity to +Infinity



Assumption: hydrogen production factor

Uniform distribution with parameters:

Minimum	0.90000
Maximum	1.10000

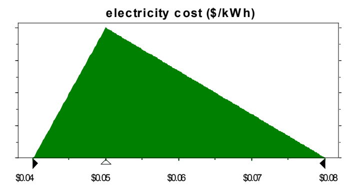


Assumption: electricity cost ($/kWh)

Triangular distribution with parameters:

Minimum	$0.04
Likeliest	$0.05
Maximum	$0.08

Selected range is from $0.04 to $0.08

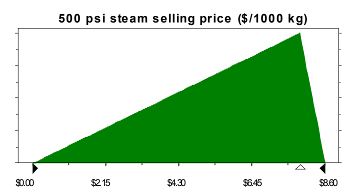


Assumption: 500 psi steam selling price ($/1000 kg)

Triangular distribution with parameters:

Minimum	$0.00
Likeliest	$7.88
Maximum	$8.60

Selected range is from $0.00 to $8.60

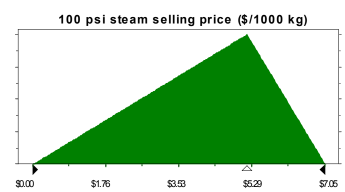


Assumption: 100 psi steam selling price ($/1000 kg)

Triangular distribution with parameters:

Minimum	$0.00
Likeliest	$5.18
Maximum	$7.05

Selected range is from $0.00 to $7.05

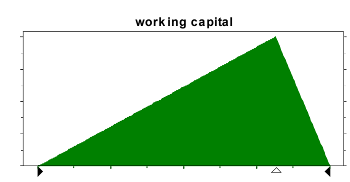


Assumption: working capital

Triangular distribution with parameters:

Minimum	10.00%
Likeliest	18.00%
Maximum	19.80%

Selected range is from 10.00% to 19.80%

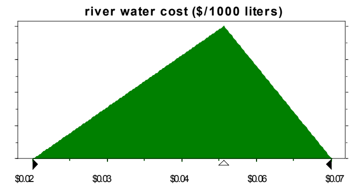


Assumption: river water cost ($/1000 liters)

Triangular distribution with parameters:

Minimum	$0.02
Likeliest	$0.05
Maximum	$0.07

Selected range is from $0.02 to $0.07

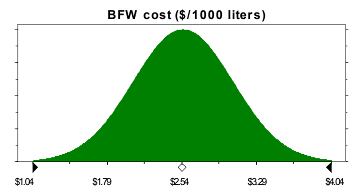


Assumption: BFW cost ($/1000 liters)

Normal distribution with parameters:

Mean	$2.54
Standard Dev.	$0.50

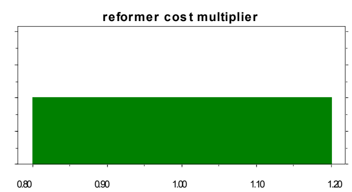
Selected range is from -Infinity to +Infinity



Assumption: reformer cost multiplier

Uniform distribution with parameters:

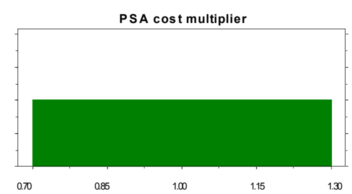
Minimum	0.80
Maximum	1.20



Assumption: PSA cost multiplier

Uniform distribution with parameters:

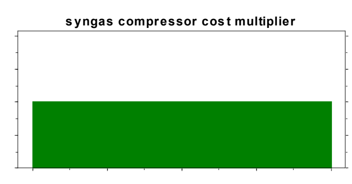
Minimum	0.70
Maximum	1.30



Assumption: syngas compressor cost multiplier

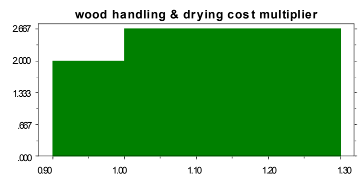
Uniform distribution with parameters:

Minimum	0.90
Maximum	1.10



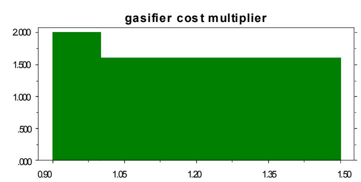
Assumption: wood handling & drying cost multiplier

Custom distribution with parameters:				Relative Prob.
Continuous range	0.90	to	1.00	0.200000
Continuous range	1.00	to	1.30	0.800000
Total Relative Probability				1.000000



Assumption: gasifier cost multiplier

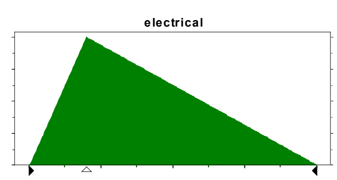
Custom distribution with parameters:				Relative Prob.
Continuous range	0.90	to	1.00	0.200000
Continuous range	1.00	to	1.50	0.800000
Total Relative Probability				1.000000



Assumption: electrical

Triangular distribution with parameters:	
Minimum	10.00
Likeliest	11.00
Maximum	15.00

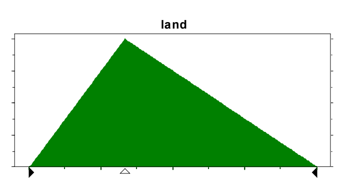
Selected range is from 10.00 to 15.00



Assumption: land

Triangular distribution with parameters:	
Minimum	4.00
Likeliest	6.00
Maximum	10.00

Selected range is from 4.00 to 10.00

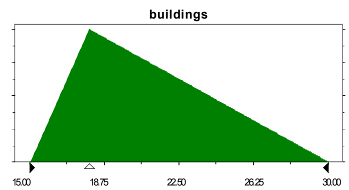


Assumption: buildings

Triangular distribution with parameters:

Minimum	15.00
Likeliest	18.00
Maximum	30.00

Selected range is from 15.00 to 30.00

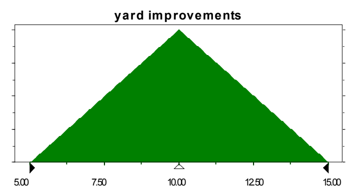


Assumption: yard improvements

Triangular distribution with parameters:

Minimum	5.00
Likeliest	10.00
Maximum	15.00

Selected range is from 5.00 to 15.00

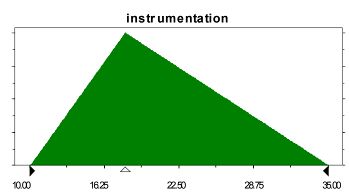


Assumption: instrumentation

Triangular distribution with parameters:

Minimum	10.00
Likeliest	18.00
Maximum	35.00

Selected range is from 10.00 to 35.00

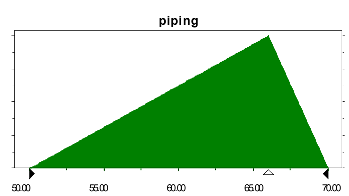


Assumption: piping

Triangular distribution with parameters:

Minimum	50.00
Likeliest	66.00
Maximum	70.00

Selected range is from 50.00 to 70.00

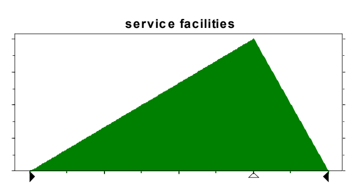


Assumption: service facilities

Triangular distribution with parameters:

Minimum	40.00
Likeliest	70.00
Maximum	80.00

Selected range is from 40.00 to 80.00

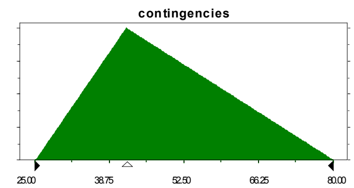


Assumption: contingencies

Triangular distribution with parameters:

Minimum	25.00
Likeliest	42.00
Maximum	80.00

Selected range is from 25.00 to 80.00

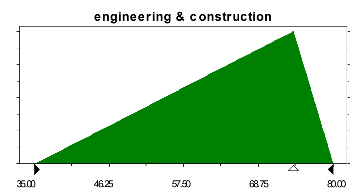


Assumption: engineering & construction

Triangular distribution with parameters:

Minimum	35.00
Likeliest	74.00
Maximum	80.00

Selected range is from 35.00 to 80.00

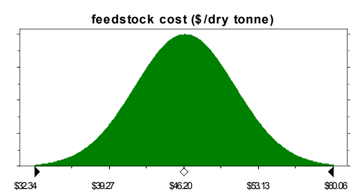


Assumption: feedstock cost ($/dry tonne) (medium & large plant)

Normal distribution with parameters:

Mean	$46.20
Standard Dev.	$4.62

Selected range is from $16.50 to $60.50

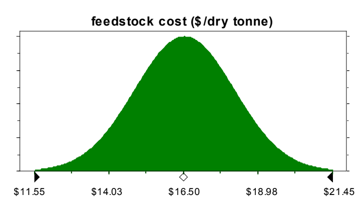


Assumption: feedstock cost ($/dry tonne) (small plant)

Normal distribution with parameters:

Mean	$16.50
Standard Dev.	$1.65

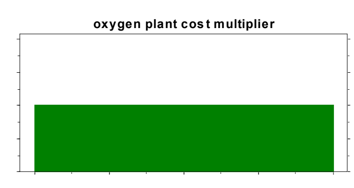
Selected range is from $10.00 to $21.61



Assumption: oxygen plant cost multiplier

Uniform distribution with parameters:

Minimum	0.80
Maximum	1.20

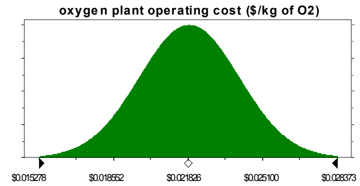


Assumption: oxygen plant operating cost ($/kg of O2)

Normal distribution with parameters:

Mean	$0.021826
Standard Dev.	$0.002183

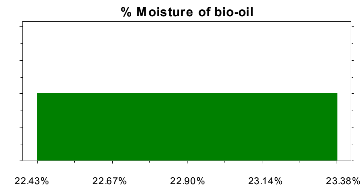
Selected range is from -Infinity to +Infinity



Assumption: % Moisture of bio-oil

Uniform distribution with parameters:

Minimum	22.43%
Maximum	23.38%

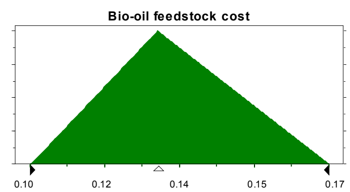


Assumption: Bio-oil feedstock cost

Triangular distribution with parameters:

Minimum	0.10
Likeliest	0.13
Maximum	0.17

Selected range is from 0.10 to 0.17

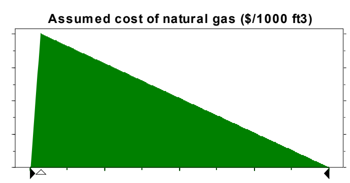


Assumption: Assumed cost of natural gas ($/1000 ft3)

Triangular distribution with parameters:

Minimum	2.98
Likeliest	3.00
Maximum	3.52

Selected range is from 2.98 to 3.52

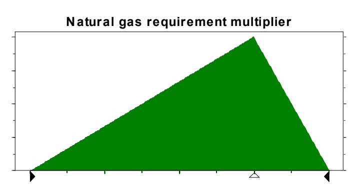


Assumption: Natural gas requirement multiplier

Triangular distribution with parameters:

Minimum	0.70
Likeliest	1.00
Maximum	1.10

Selected range is from 0.70 to 1.10

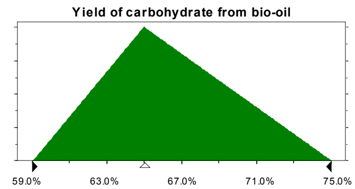


Assumption: Yield of carbohydrate from bio-oil

Triangular distribution with parameters:

Minimum	59.0%
Likeliest	65.0%
Maximum	75.0%

Selected range is from 59.0% to 75.0%

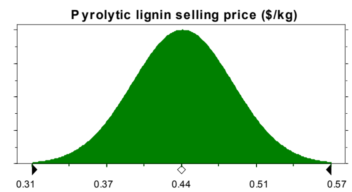


Assumption: Pyrolytic lignin selling price ($/kg)

Normal distribution with parameters:

Mean	0.44
Standard Dev.	0.04

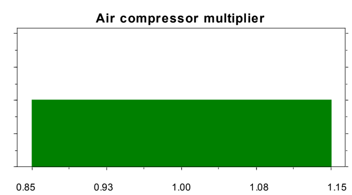
Selected range is from -Infinity to +Infinity



Assumption: Air compressor multiplier

Uniform distribution with parameters:

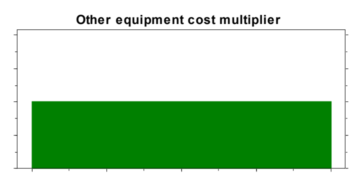
Minimum	0.85
Maximum	1.15



Assumption: Other equipment cost multiplier

Uniform distribution with parameters:

Minimum	0.70
Maximum	1.30



Appendix B – Statistics Terminology for Crystal Ball®

Mean
The mean is the arithmetic average of a set of data.

Median
The median is the middle value between the smallest and largest values in a data set.

Mode
The mode is the number that occurs most frequently in a set of values. Note that some of the following distributions have a dash (-) instead of a value for the mode. When using continuous distributions, it is likely that the forecast will not have two values that are exactly the same, so when this occurs, Crystal Ball® uses a dash (-) to indicate that the mode is undefined.

Variance
Variance measures the dispersion or spread of a set of values about the mean. It is also defined as the square of the standard deviation. Variance is small when values are close to the mean.

Skewness
Skewness describes the symmetry of a distribution. Zero skewness is perfectly symmetrical. If the skewness value is less than -1 or greater than 1, then the distribution is highly skewed. If the skewness value is between -0.5 and 0.5 then the distribution is fairly symmetrical.

Kurtosis
Kurtosis provides a measure of the degree of peakedness of a distribution. A normal distribution curve has a kurtosis of three. A kurtosis value less than three signifies a distribution that is flatter than a normal distribution and a value greater than three indicates a more peaked distribution.

Coefficient of variability
This coefficient of variability tells the user how much the forecast values vary relative to the mean. This value typically ranges from zero to one, but in rare cases where the standard deviation is unusually high, it can be greater than one.

Mean standard error
The mean standard error lets you determine the accuracy of the results and the number of trials necessary to ensure an acceptable level of error. It tells you the probability of an estimated mean deviating from the true mean by more than a specified amount.

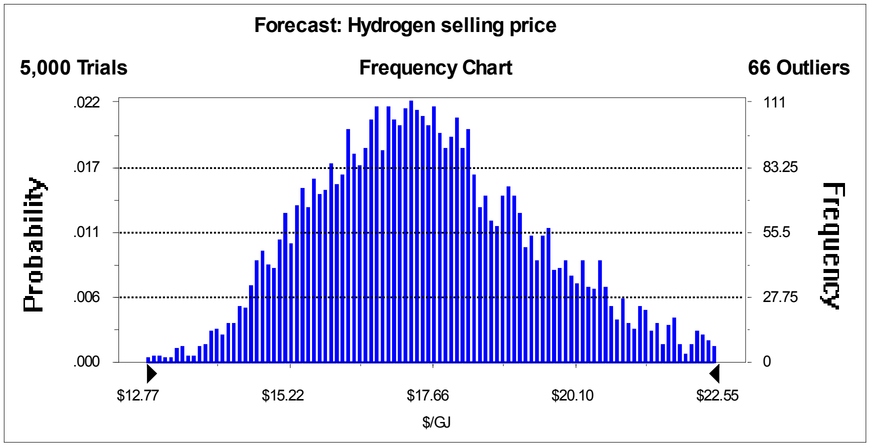
Appendix C - Statistical Data and Frequency Charts for Plant Gate Hydrogen Selling Price

C-1 BCL_REPORTsmall_15%.xls

Forecast: Hydrogen selling price

Summary:
Display Range is from $12.77 to $22.55 $/GJ
Entire Range is from $12.41 to $27.89 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	5000
Mean	$17.62
Median	$17.45
Mode	---
Standard Deviation	$1.95
Variance	$3.82
Skewness	0.53
Kurtosis	3.41
Coeff. of Variability	0.11
Range Minimum	$12.41
Range Maximum	$27.89
Range Width	$15.48
Mean Std. Error	$0.03



Percentiles:

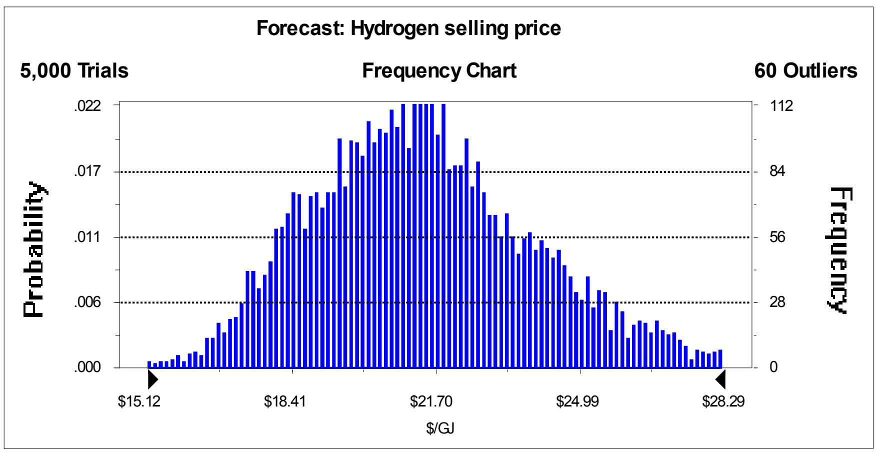
Percentile	$/GJ
0%	$12.41
10%	$15.24
20%	$15.95
30%	$16.51
40%	$16.99
50%	$17.45
60%	$17.94
70%	$18.47
80%	$19.19
90%	$20.26
100%	$27.89

C-2 BCL_REPORTsmall_20%.xls

Forecast: Hydrogen selling price

Summary:
Display Range is from $15.12 to $28.29 $/GJ
Entire Range is from $14.70 to $35.61 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.04

Statistics:	Value
Trials	5000
Mean	$21.49
Median	$21.27
Mode	$21.59
Standard Deviation	$2.61
Variance	$6.84
Skewness	0.53
Kurtosis	3.42
Coeff. of Variability	0.12
Range Minimum	$14.70
Range Maximum	$35.61
Range Width	$20.91
Mean Std. Error	$0.04



Percentiles:

Percentile	$/GJ
0%	$14.70
10%	$18.30
20%	$19.24
30%	$19.99
40%	$20.66
50%	$21.27
60%	$21.88
70%	$22.62
80%	$23.60
90%	$24.96
100%	$35.61

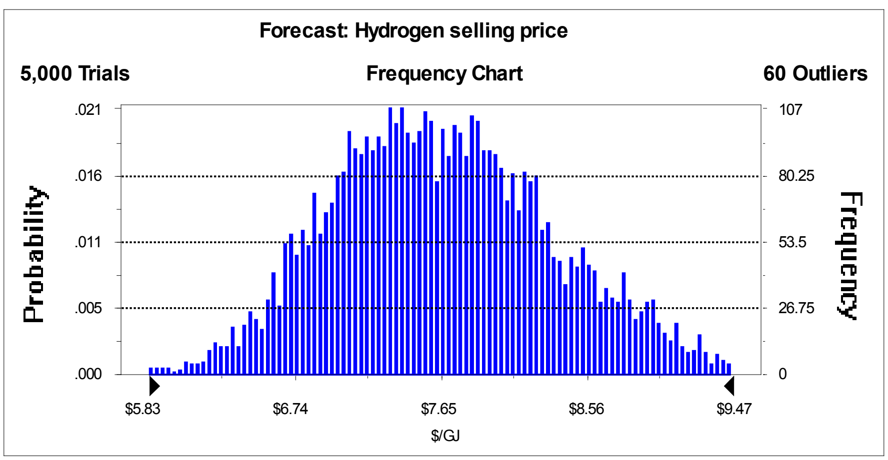
C3 BCL_REPORTsmall_0%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $5.83 to $9.47 $/GJ
Entire Range is from $5.53 to $10.81 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.01

Statistics:	Value
Trials	5000
Mean	$7.68
Median	$7.63
Mode	$8.20
Standard Deviation	$0.71
Variance	$0.51
Skewness	0.39
Kurtosis	3.16
Coeff. of Variability	0.09
Range Minimum	$5.53
Range Maximum	$10.81
Range Width	$5.27
Mean Std. Error	$0.01



Percentiles:

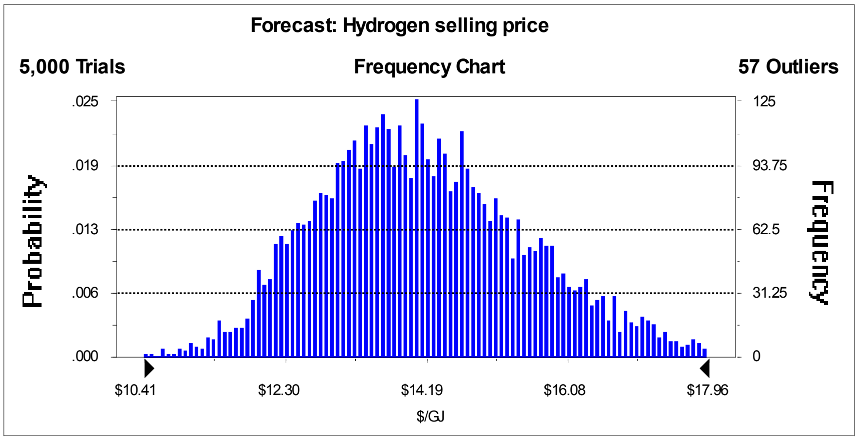
Percentile	$/GJ
0%	$5.53
10%	$6.81
20%	$7.07
30%	$7.27
40%	$7.45
50%	$7.63
60%	$7.83
70%	$8.02
80%	$8.26
90%	$8.64
100%	$10.81

C4 BCL_REPORTsmall_10%.xls

Forecast: Hydrogen selling price

Summary:
Display Range is from $10.41 to $17.96 $/GJ
Entire Range is from $10.36 to $21.15 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.02

Statistics:	Value
Trials	5000
Mean	$14.19
Median	$14.06
Mode	$13.15
Standard Deviation	$1.44
Variance	$2.07
Skewness	0.51
Kurtosis	3.34
Coeff. of Variability	0.10
Range Minimum	$10.36
Range Maximum	$21.15
Range Width	$10.79
Mean Std. Error	$0.02



Percentiles:

Percentile	$/GJ
0%	$10.36
10%	$12.43
20%	$12.95
30%	$13.35
40%	$13.69
50%	$14.06
60%	$14.43
70%	$14.83
80%	$15.37
90%	$16.10
100%	$21.15

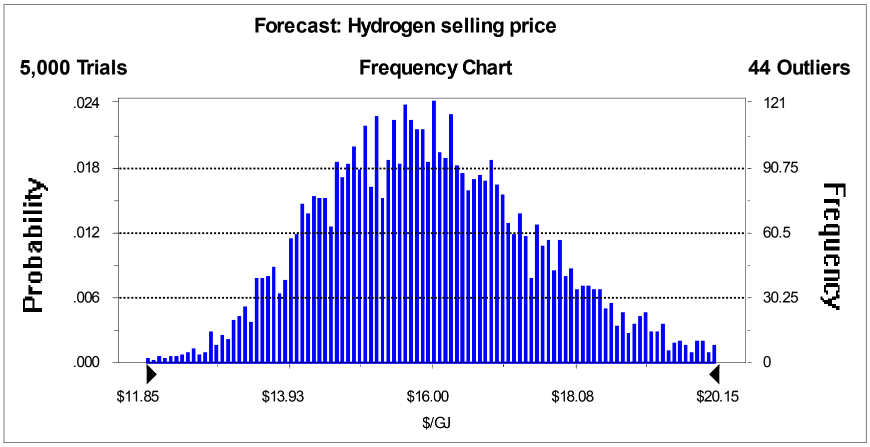
C5 BCL_REPORTmedium_15%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from \$11.85 to \$20.15 \$/GJ
Entire Range is from \$11.35 to \$23.62 \$/GJ
After 5,000 Trials, the Std. Error of the Mean is \$0.02

Statistics:	Value
Trials	5000
Mean	\$15.99
Median	\$15.88
Mode	\$15.06
Standard Deviation	\$1.58
Variance	\$2.50
Skewness	0.39
Kurtosis	3.15
Coeff. of Variability	0.10
Range Minimum	\$11.35
Range Maximum	\$23.62
Range Width	\$12.28
Mean Std. Error	\$0.02



Percentiles:

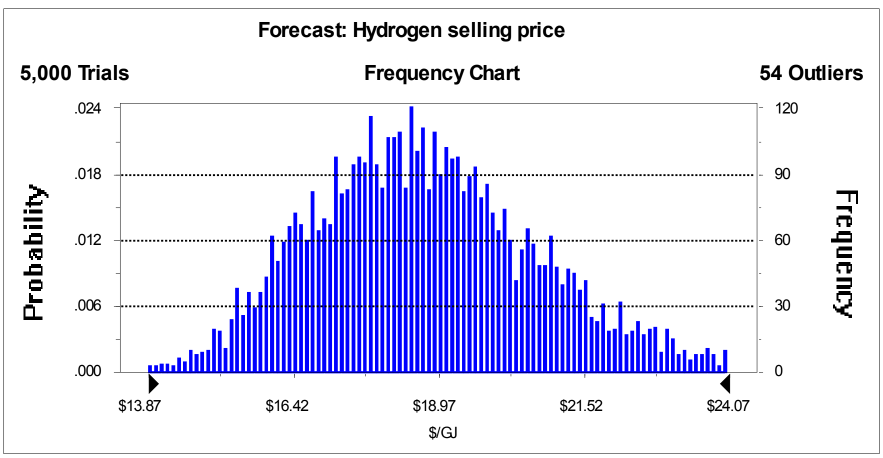
Percentile	\$/GJ
0%	\$11.35
10%	\$14.06
20%	\$14.62
30%	\$15.06
40%	\$15.49
50%	\$15.88
60%	\$16.28
70%	\$16.74
80%	\$17.28
90%	\$18.08
100%	\$23.62

C6 BCL_REPORTmedium_20%.xls

Forecast: Hydrogen selling price

Summary:
Display Range is from $13.87 to $24.07 $/GJ
Entire Range is from $13.02 to $29.16 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	5000
Mean	$18.77
Median	$18.61
Mode	---
Standard Deviation	$2.03
Variance	$4.11
Skewness	0.44
Kurtosis	3.25
Coeff. of Variability	0.11
Range Minimum	$13.02
Range Maximum	$29.16
Range Width	$16.15
Mean Std. Error	$0.03



Percentiles:

Percentile	$/GJ
0%	$13.02
10%	$16.28
20%	$17.02
30%	$17.60
40%	$18.13
50%	$18.61
60%	$19.14
70%	$19.69
80%	$20.44
90%	$21.44
100%	$29.16

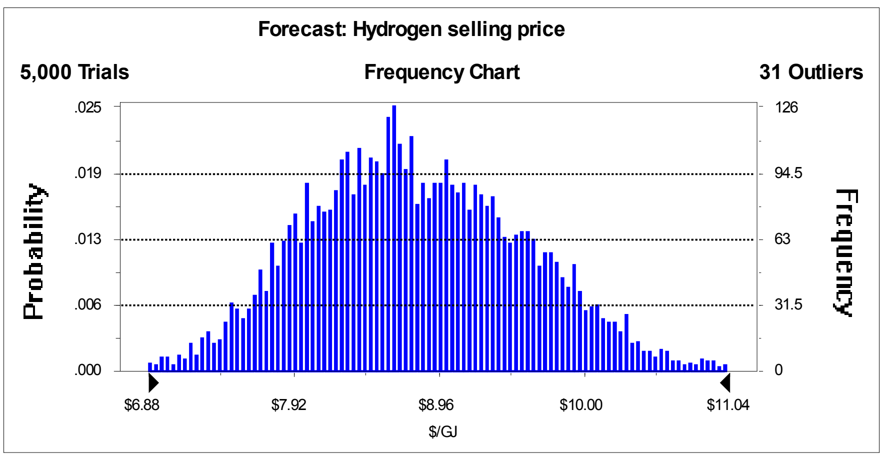
C7 BCL-REPORTmedium_0%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $6.88 to $11.04 $/GJ
Entire Range is from $6.06 to $11.68 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.01

Statistics:	Value
Trials	5000
Mean	$8.80
Median	$8.75
Mode	---
Standard Deviation	$0.78
Variance	$0.61
Skewness	0.16
Kurtosis	2.81
Coeff. of Variability	0.09
Range Minimum	$6.06
Range Maximum	$11.68
Range Width	$5.61
Mean Std. Error	$0.01



Percentiles:

Percentile	$/GJ
0%	$6.06
10%	$7.83
20%	$8.12
30%	$8.35
40%	$8.57
50%	$8.75
60%	$8.98
70%	$9.22
80%	$9.49
90%	$9.84
100%	$11.68

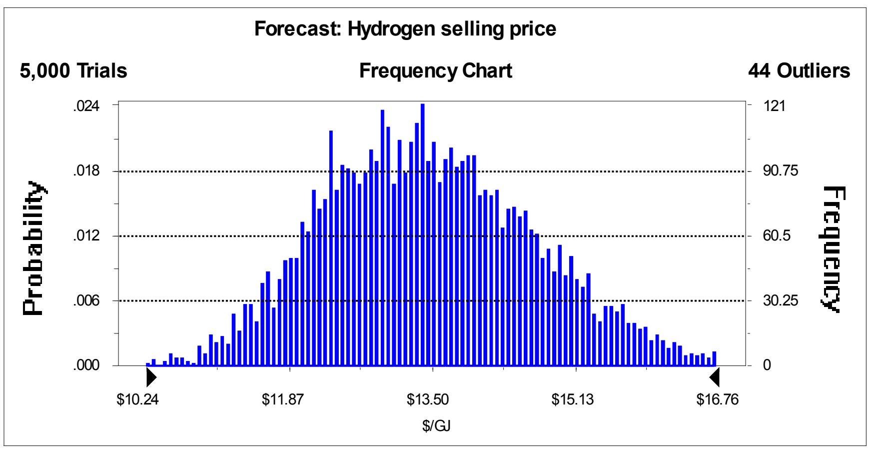
C8 BCL_REPORTmedium_10%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $10.24 to $16.76 $/GJ
Entire Range is from $9.81 to $18.69 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.02

Statistics:	Value
Trials	5000
Mean	$13.48
Median	$13.40
Mode	$14.44
Standard Deviation	$1.23
Variance	$1.51
Skewness	0.32
Kurtosis	3.00
Coeff. of Variability	0.09
Range Minimum	$9.81
Range Maximum	$18.69
Range Width	$8.89
Mean Std. Error	$0.02



Percentiles:

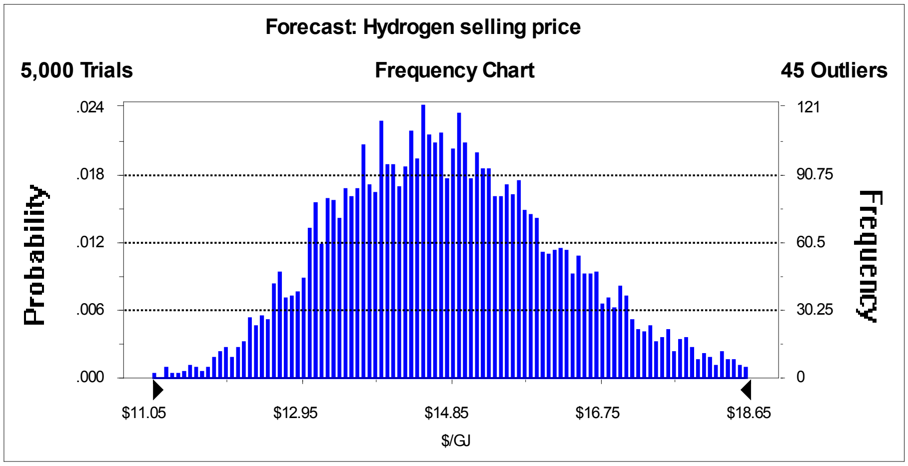
Percentile	$/GJ
0%	$9.81
10%	$11.98
20%	$12.40
30%	$12.78
40%	$13.09
50%	$13.40
60%	$13.74
70%	$14.09
80%	$14.52
90%	$15.11
100%	$18.69

C9 BCL_REPORTlarge_15%.xls

Forecast: Hydrogen selling price

Summary:
Display Range is from $11.05 to $18.65 $/GJ
Entire Range is from $10.55 to $21.62 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.02

Statistics:	Value
Trials	5000
Mean	$14.84
Median	$14.74
Mode	---
Standard Deviation	$1.45
Variance	$2.09
Skewness	0.37
Kurtosis	3.12
Coeff. of Variability	0.10
Range Minimum	$10.55
Range Maximum	$21.62
Range Width	$11.06
Mean Std. Error	$0.02



Percentiles:

Percentile	$/GJ
0%	$10.55
10%	$13.07
20%	$13.58
30%	$14.00
40%	$14.39
50%	$14.74
60%	$15.11
70%	$15.53
80%	$16.02
90%	$16.75
100%	$21.62

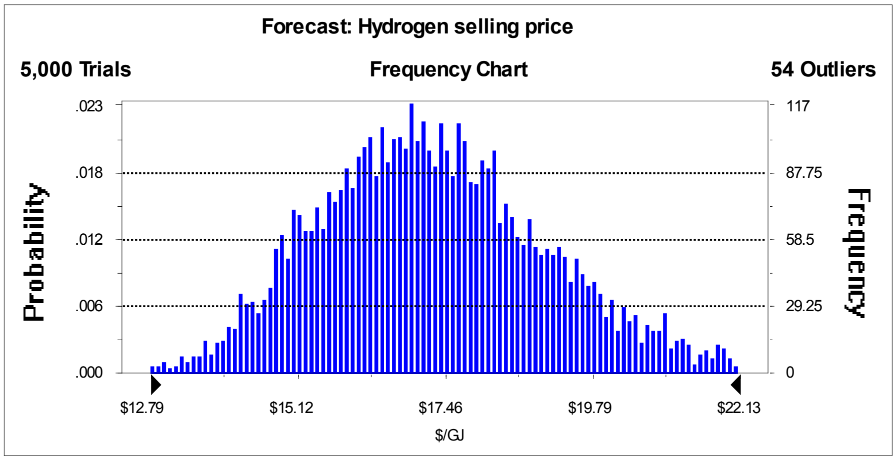
C10 BCL_REPORTlarge_20%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $12.79 to $22.13 $/GJ
Entire Range is from $12.02 to $26.54 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	5000
Mean	$17.31
Median	$17.17
Mode	---
Standard Deviation	$1.84
Variance	$3.39
Skewness	0.42
Kurtosis	3.22
Coeff. of Variability	0.11
Range Minimum	$12.02
Range Maximum	$26.54
Range Width	$14.52
Mean Std. Error	$0.03



Percentiles:

Percentile	$/GJ
0%	$12.02
10%	$15.04
20%	$15.73
30%	$16.26
40%	$16.73
50%	$17.17
60%	$17.66
70%	$18.16
80%	$18.82
90%	$19.74
100%	$26.54

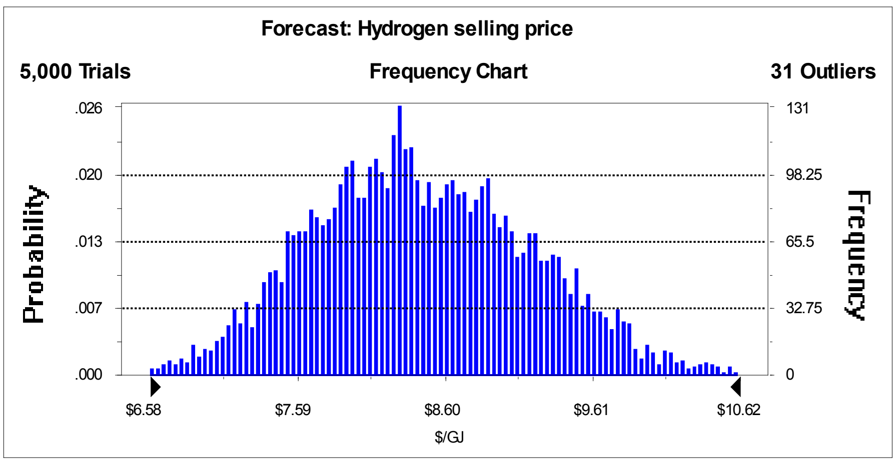
C11 BCL_REPORTlarge_0%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $6.58 to $10.62 $/GJ
Entire Range is from $5.77 to $11.31 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.01

Statistics:	Value
Trials	5000
Mean	$8.44
Median	$8.39
Mode	---
Standard Deviation	$0.76
Variance	$0.57
Skewness	0.15
Kurtosis	2.81
Coeff. of Variability	0.09
Range Minimum	$5.77
Range Maximum	$11.31
Range Width	$5.53
Mean Std. Error	$0.01



Percentiles:

Percentile	$/GJ
0%	$5.77
10%	$7.49
20%	$7.78
30%	$8.00
40%	$8.21
50%	$8.39
60%	$8.62
70%	$8.84
80%	$9.10
90%	$9.44
100%	$11.31

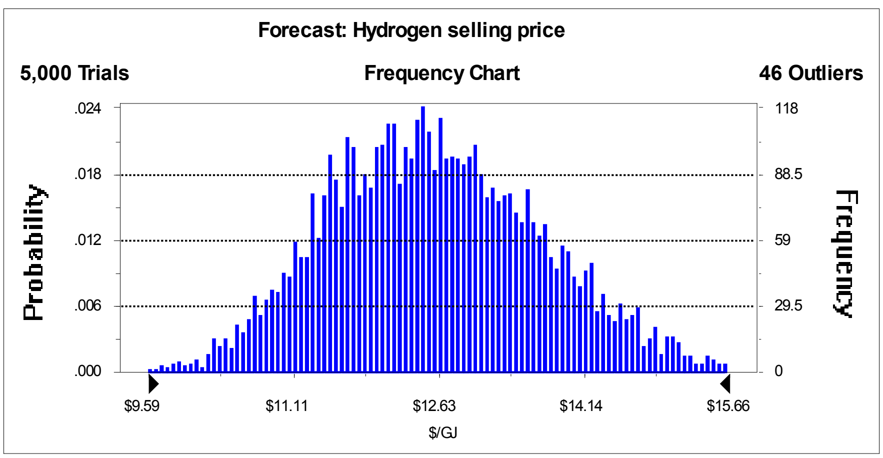
C12 BCL_REPORTlarge_10%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $9.59 to $15.66 $/GJ
Entire Range is from $9.14 to $17.27 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.02

Statistics:	Value
Trials	5000
Mean	$12.61
Median	$12.54
Mode	$12.99
Standard Deviation	$1.14
Variance	$1.31
Skewness	0.30
Kurtosis	2.97
Coeff. of Variability	0.09
Range Minimum	$9.14
Range Maximum	$17.27
Range Width	$8.13
Mean Std. Error	$0.02



Percentiles:

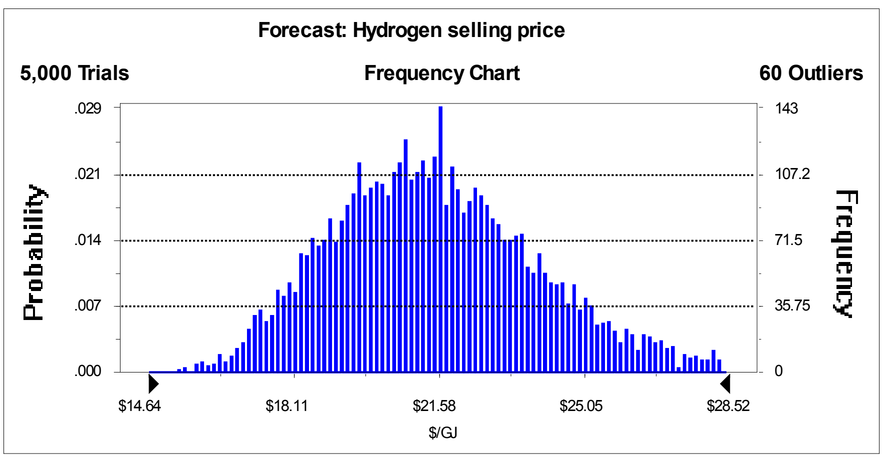
Percentile	$/GJ
0%	$9.14
10%	$11.20
20%	$11.62
30%	$11.96
40%	$12.26
50%	$12.54
60%	$12.85
70%	$13.18
80%	$13.59
90%	$14.14
100%	$17.27

C13 IGT_REPORTsmall_15%.xls

Forecast: Hydrogen selling price

Summary:
Display Range is from $14.64 to $28.52 $/GJ
Entire Range is from $14.59 to $34.84 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.04

Statistics:	Value
Trials	5000
Mean	$21.57
Median	$21.37
Mode	$18.50
Standard Deviation	$2.58
Variance	$6.68
Skewness	0.58
Kurtosis	3.64
Coeff. of Variability	0.12
Range Minimum	$14.59
Range Maximum	$34.84
Range Width	$20.25
Mean Std. Error	$0.04



Percentiles:

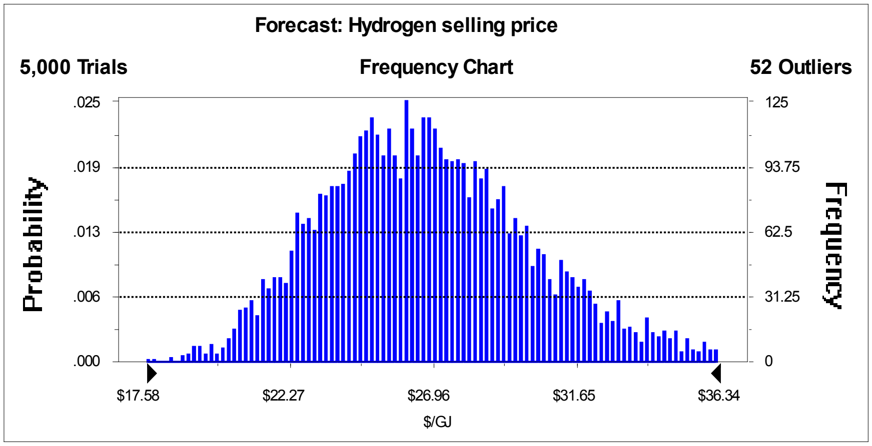
Percentile	$/GJ
0%	$14.59
10%	$18.46
20%	$19.38
30%	$20.09
40%	$20.75
50%	$21.37
60%	$21.97
70%	$22.71
80%	$23.60
90%	$24.94
100%	$34.84

C14 IGT_REPORTsmall_20%.xls

Forecast: Hydrogen selling price

Summary:
Display Range is from $17.58 to $36.34 $/GJ
Entire Range is from $17.51 to $45.32 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.05

Statistics:	Value
Trials	5000
Mean	$26.89
Median	$26.61
Mode	---
Standard Deviation	$3.51
Variance	$12.34
Skewness	0.56
Kurtosis	3.57
Coeff. of Variability	0.13
Range Minimum	$17.51
Range Maximum	$45.32
Range Width	$27.80
Mean Std. Error	$0.05



Percentiles:

Percentile	$/GJ
0%	$17.51
10%	$22.64
20%	$23.88
30%	$24.85
40%	$25.72
50%	$26.61
60%	$27.46
70%	$28.47
80%	$29.65
90%	$31.52
100%	$45.32

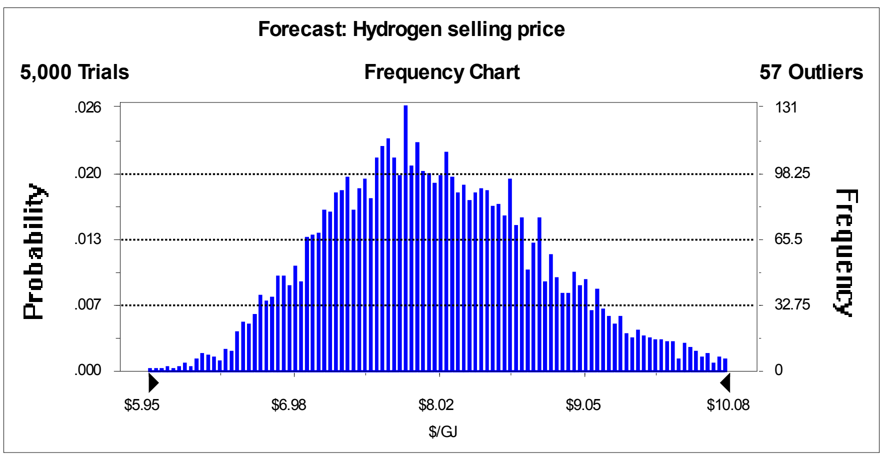
C15 IGT_REPORTsmall_0%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $5.95 to $10.08 $/GJ
Entire Range is from $5.86 to $11.52 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.01

Statistics:	Value
Trials	5000
Mean	$8.02
Median	$7.94
Mode	---
Standard Deviation	$0.79
Variance	$0.63
Skewness	0.51
Kurtosis	3.41
Coeff. of Variability	0.10
Range Minimum	$5.86
Range Maximum	$11.52
Range Width	$5.65
Mean Std. Error	$0.01



Percentiles:

Percentile	$/GJ
0%	$5.86
10%	$7.05
20%	$7.33
30%	$7.56
40%	$7.76
50%	$7.94
60%	$8.16
70%	$8.39
80%	$8.65
90%	$9.06
100%	$11.52

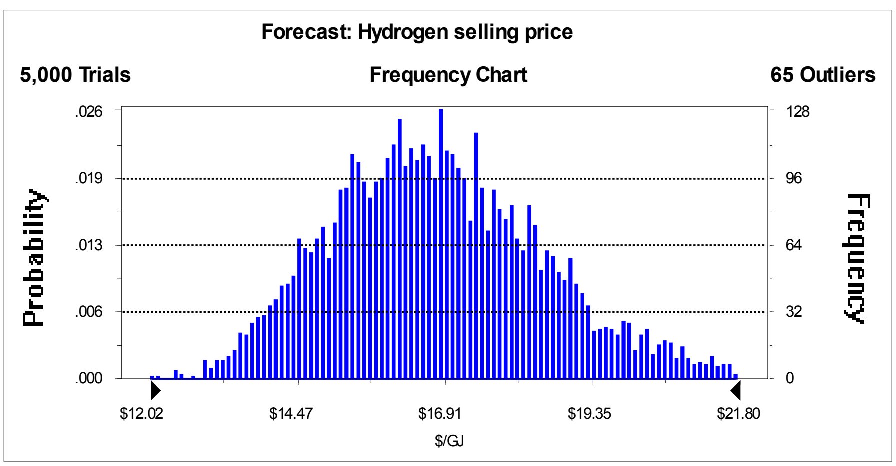
C16 IGT_REPORTsmall_10%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $12.02 to $21.80 $/GJ
Entire Range is from $11.92 to $25.68 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	5000
Mean	$16.87
Median	$16.71
Mode	$15.89
Standard Deviation	$1.85
Variance	$3.43
Skewness	0.59
Kurtosis	3.62
Coeff. of Variability	0.11
Range Minimum	$11.92
Range Maximum	$25.68
Range Width	$13.75
Mean Std. Error	$0.03



Percentiles:

Percentile	$/GJ
0%	$11.92
10%	$14.61
20%	$15.30
30%	$15.80
40%	$16.26
50%	$16.71
60%	$17.16
70%	$17.70
80%	$18.33
90%	$19.21
100%	$25.68

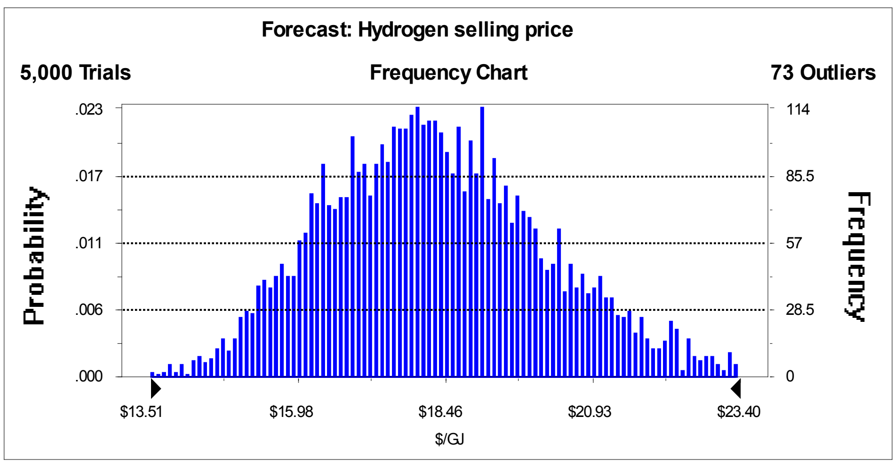
C17 IGT_REPORTmedium_15%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $13.51 to $23.40 $/GJ
Entire Range is from $12.74 to $27.54 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	5000
Mean	$18.38
Median	$18.22
Mode	---
Standard Deviation	$1.95
Variance	$3.80
Skewness	0.49
Kurtosis	3.39
Coeff. of Variability	0.11
Range Minimum	$12.74
Range Maximum	$27.54
Range Width	$14.80
Mean Std. Error	$0.03



Percentiles:

Percentile	$/GJ
0%	$12.74
10%	$16.01
20%	$16.69
30%	$17.27
40%	$17.77
50%	$18.22
60%	$18.72
70%	$19.26
80%	$19.92
90%	$20.95
100%	$27.54

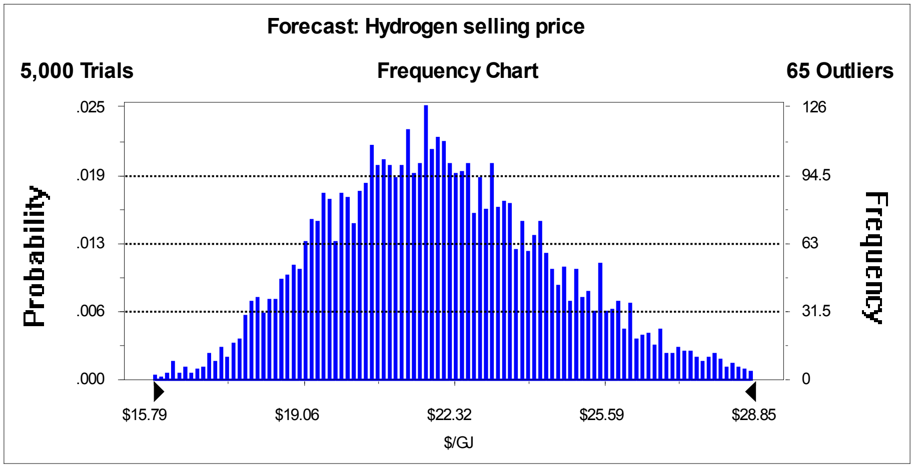
C18 IGT_REPORTmedium_20%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $15.79 to $28.85 $/GJ
Entire Range is from $14.84 to $34.82 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.04

Statistics:	Value
Trials	5000
Mean	$22.09
Median	$21.88
Mode	---
Standard Deviation	$2.57
Variance	$6.59
Skewness	0.50
Kurtosis	3.43
Coeff. of Variability	0.12
Range Minimum	$14.84
Range Maximum	$34.82
Range Width	$19.99
Mean Std. Error	$0.04



Percentiles:

Percentile	$/GJ
0%	$14.84
10%	$18.95
20%	$19.88
30%	$20.62
40%	$21.28
50%	$21.88
60%	$22.51
70%	$23.23
80%	$24.14
90%	$25.51
100%	$34.82

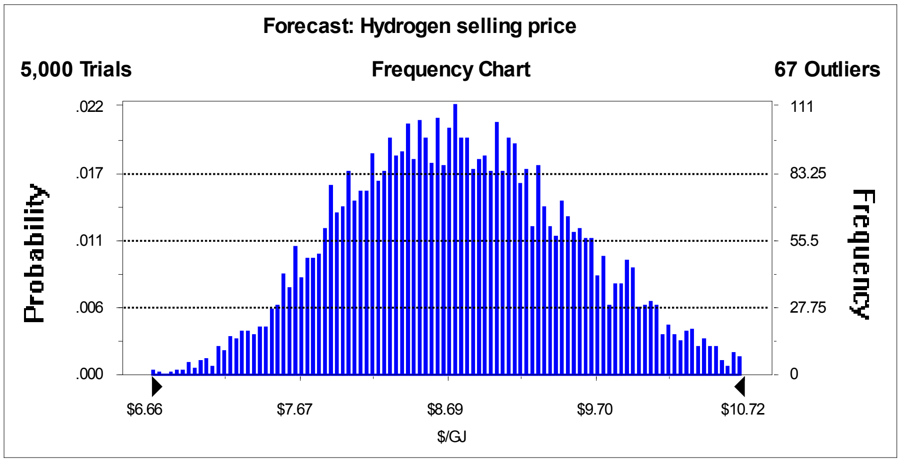
C19 IGT_REPORTmedium_0%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $6.66 to $10.72 $/GJ
Entire Range is from $6.49 to $11.74 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.01

Statistics:	Value
Trials	5000
Mean	$8.78
Median	$8.75
Mode	---
Standard Deviation	$0.80
Variance	$0.64
Skewness	0.26
Kurtosis	2.91
Coeff. of Variability	0.09
Range Minimum	$6.49
Range Maximum	$11.74
Range Width	$5.25
Mean Std. Error	$0.01



Percentiles:

Percentile	$/GJ
0%	$6.49
10%	$7.78
20%	$8.08
30%	$8.33
40%	$8.54
50%	$8.75
60%	$8.96
70%	$9.18
80%	$9.47
90%	$9.85
100%	$11.74

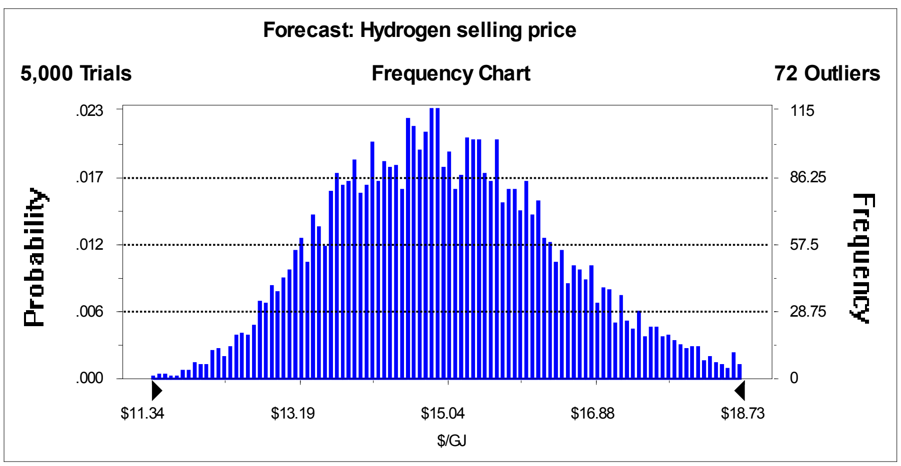
C20 IGT_REPORTmedium_10%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $11.34 to $18.73 $/GJ
Entire Range is from $10.85 to $21.22 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.02

Statistics:	Value
Trials	5000
Mean	$15.04
Median	$14.93
Mode	---
Standard Deviation	$1.46
Variance	$2.13
Skewness	0.44
Kurtosis	3.26
Coeff. of Variability	0.10
Range Minimum	$10.85
Range Maximum	$21.22
Range Width	$10.36
Mean Std. Error	$0.02



Percentiles:

Percentile	$/GJ
0%	$10.85
10%	$13.24
20%	$13.77
30%	$14.20
40%	$14.59
50%	$14.93
60%	$15.33
70%	$15.73
80%	$16.21
90%	$16.96
100%	$21.22

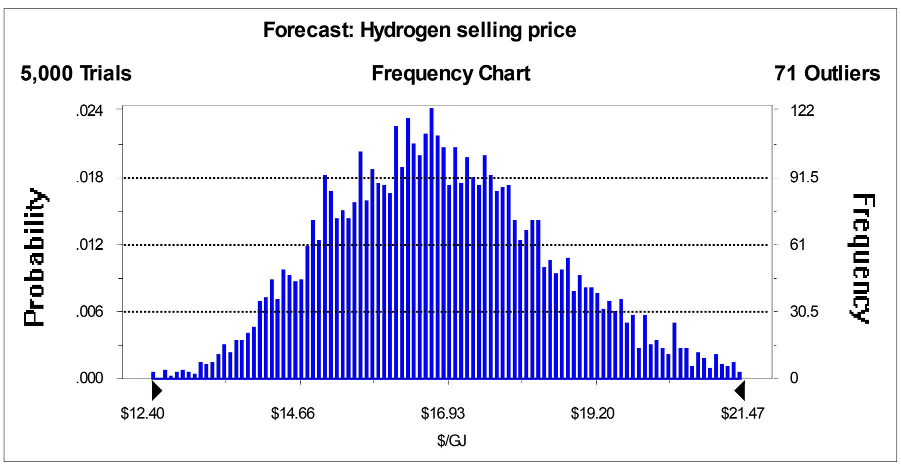
C21 IGT_REPORTlarge_15%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $12.40 to $21.47 $/GJ
Entire Range is from $11.71 to $25.03 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	5000
Mean	$16.90
Median	$16.77
Mode	---
Standard Deviation	$1.77
Variance	$3.13
Skewness	0.47
Kurtosis	3.34
Coeff. of Variability	0.10
Range Minimum	$11.71
Range Maximum	$25.03
Range Width	$13.31
Mean Std. Error	$0.03



Percentiles:

Percentile	$/GJ
0%	$11.71
10%	$14.75
20%	$15.36
30%	$15.88
40%	$16.35
50%	$16.77
60%	$17.22
70%	$17.70
80%	$18.30
90%	$19.24
100%	$25.03

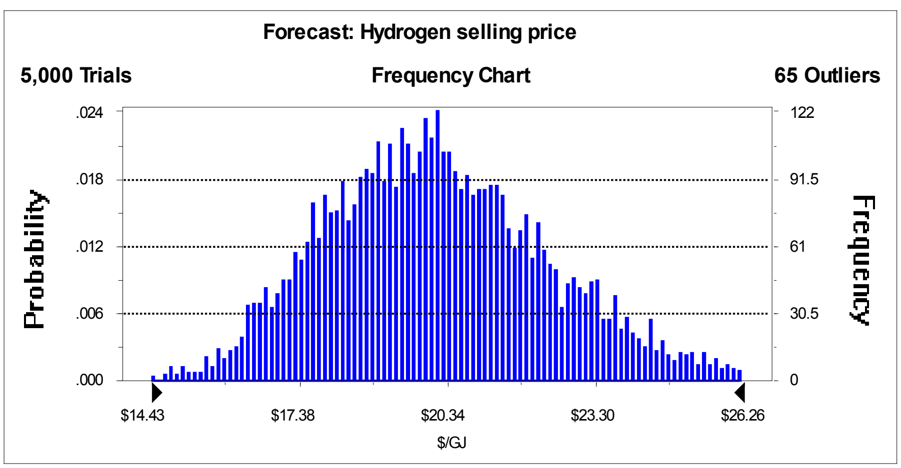
C22 IGT_REPORTlarge_20%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $14.43 to $26.26 $/GJ
Entire Range is from $13.57 to $31.53 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	5000
Mean	$20.21
Median	$20.03
Mode	---
Standard Deviation	$2.32
Variance	$5.37
Skewness	0.49
Kurtosis	3.39
Coeff. of Variability	0.11
Range Minimum	$13.57
Range Maximum	$31.53
Range Width	$17.96
Mean Std. Error	$0.03



Percentiles:

Percentile	$/GJ
0%	$13.57
10%	$17.39
20%	$18.21
30%	$18.89
40%	$19.47
50%	$20.03
60%	$20.59
70%	$21.27
80%	$22.07
90%	$23.29
100%	$31.53

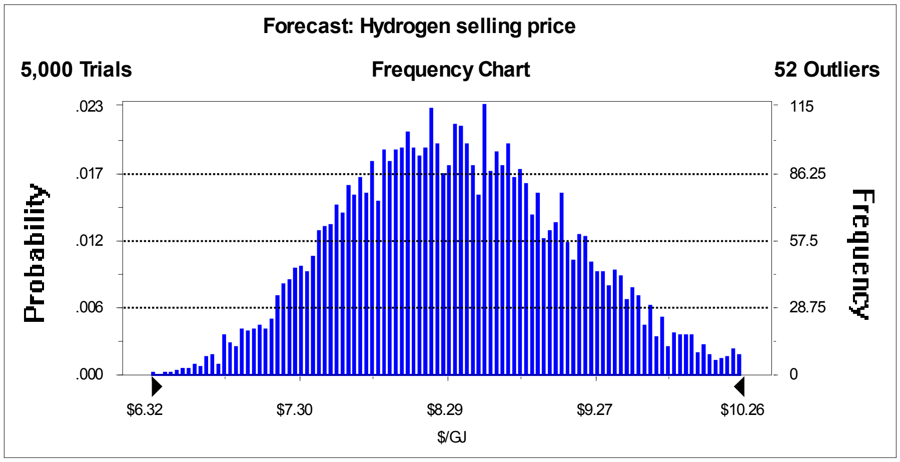
C23 IGT_REPORTlarge_0%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $6.32 to $10.26 $/GJ
Entire Range is from $6.14 to $11.08 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.01

Statistics:	Value
Trials	5000
Mean	$8.36
Median	$8.33
Mode	---
Standard Deviation	$0.76
Variance	$0.58
Skewness	0.24
Kurtosis	2.88
Coeff. of Variability	0.09
Range Minimum	$6.14
Range Maximum	$11.08
Range Width	$4.94
Mean Std. Error	$0.01



Percentiles:

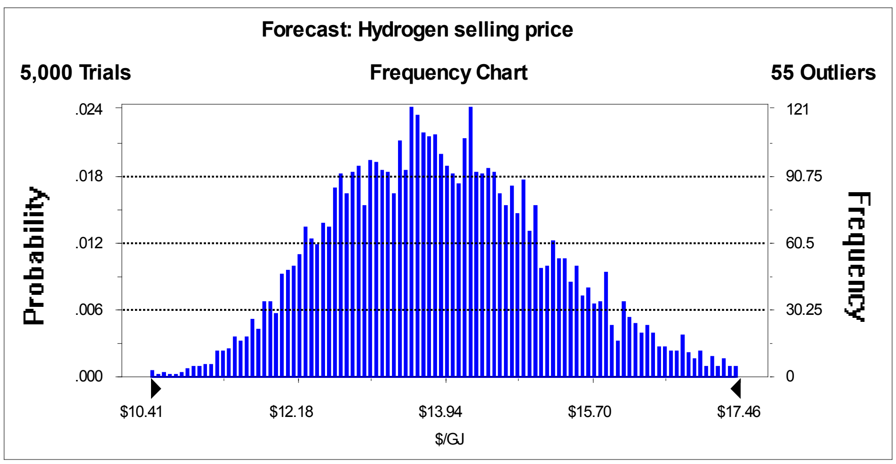
Percentile	$/GJ
0%	$6.14
10%	$7.41
20%	$7.69
30%	$7.92
40%	$8.13
50%	$8.33
60%	$8.53
70%	$8.74
80%	$9.01
90%	$9.37
100%	$11.08

C24 IGT_REPORTlarge_10%.xls

Forecast: Hydrogen selling price

Summary:
Display Range is from $10.41 to $17.46 $/GJ
Entire Range is from $10.03 to $19.45 $/GJ
After 5,000 Trials, the Std. Error of the Mean is $0.02

Statistics:	Value
Trials	5000
Mean	$13.93
Median	$13.83
Mode	---
Standard Deviation	$1.34
Variance	$1.79
Skewness	0.41
Kurtosis	3.20
Coeff. of Variability	0.10
Range Minimum	$10.03
Range Maximum	$19.45
Range Width	$9.41
Mean Std. Error	$0.02



Percentiles:

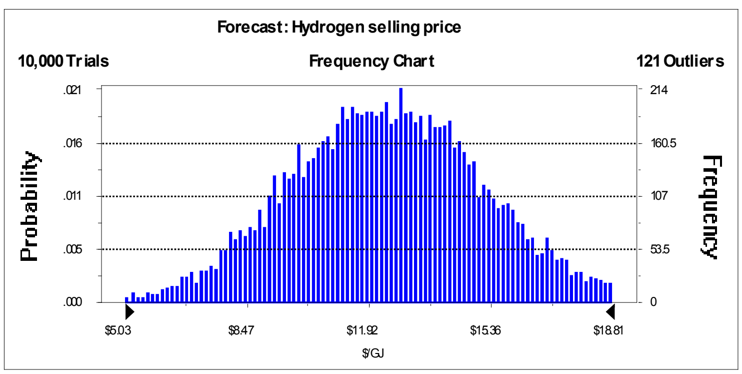
Percentile	$/GJ
0%	$10.03
10%	$12.27
20%	$12.77
30%	$13.15
40%	$13.52
50%	$13.83
60%	$14.20
70%	$14.56
80%	$15.00
90%	$15.69
100%	$19.45

C25 REPORT_pyr_small_15%.xls

Forecast: Hydrogen selling price

Summary:
Display Range is from $5.03 to $18.81 $/GJ
Entire Range is from $2.21 to $22.85 $/GJ
After 10,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	10000
Mean	$12.41
Median	$12.40
Mode	---
Standard Deviation	$2.75
Variance	$7.59
Skewness	0.02
Kurtosis	2.92
Coeff. of Variability	0.22
Range Minimum	$2.21
Range Maximum	$22.85
Range Width	$20.63
Mean Std. Error	$0.03



Percentiles:

Percentile	$/GJ
0%	$2.21
10%	$8.88
20%	$10.04
30%	$10.95
40%	$11.67
50%	$12.40
60%	$13.12
70%	$13.89
80%	$14.71
90%	$15.96
100%	$22.85

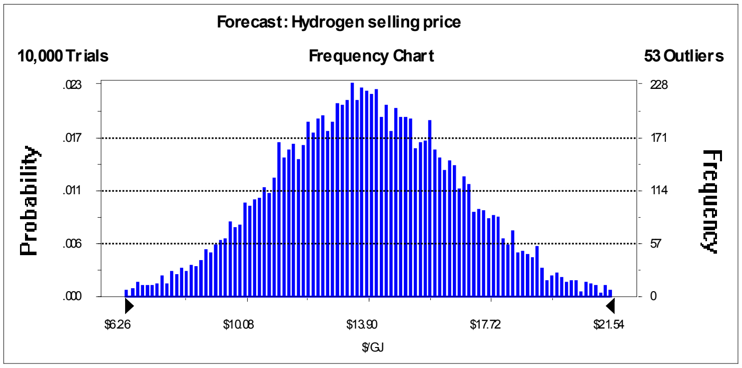
C26 REPORT_pyr_small_20%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $6.26 to $21.54 $/GJ
Entire Range is from ($0.27) to $23.30 $/GJ
After 10,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	10000
Mean	$13.77
Median	$13.76
Mode	---
Standard Deviation	$2.86
Variance	$8.15
Skewness	-0.01
Kurtosis	2.95
Coeff. of Variability	0.21
Range Minimum	($0.27)
Range Maximum	$23.30
Range Width	$23.57
Mean Std. Error	$0.03



Percentiles:

Percentile	$/GJ
0%	($0.27)
10%	$10.10
20%	$11.34
30%	$12.25
40%	$13.04
50%	$13.76
60%	$14.48
70%	$15.27
80%	$16.20
90%	$17.46
100%	$23.30

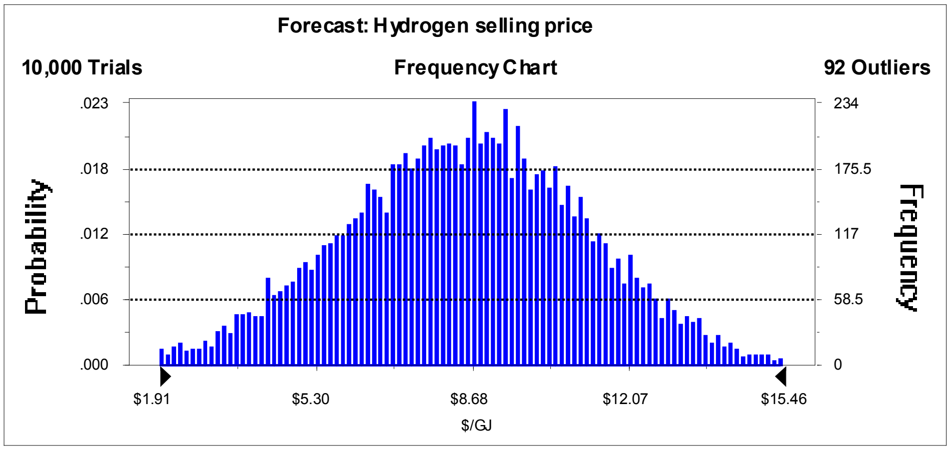
C27 REPORT_pyr_small_0%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $1.91 to $15.46 $/GJ
Entire Range is from ($1.04) to $16.87 $/GJ
After 10,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	10000
Mean	$8.55
Median	$8.60
Mode	$8.54
Standard Deviation	$2.62
Variance	$6.89
Skewness	-0.05
Kurtosis	2.87
Coeff. of Variability	0.31
Range Minimum	($1.04)
Range Maximum	$16.87
Range Width	$17.92
Mean Std. Error	$0.03



Percentiles:

Percentile	$/GJ
0%	($1.04)
10%	$5.10
20%	$6.32
30%	$7.18
40%	$7.90
50%	$8.60
60%	$9.25
70%	$9.95
80%	$10.78
90%	$11.90
100%	$16.87

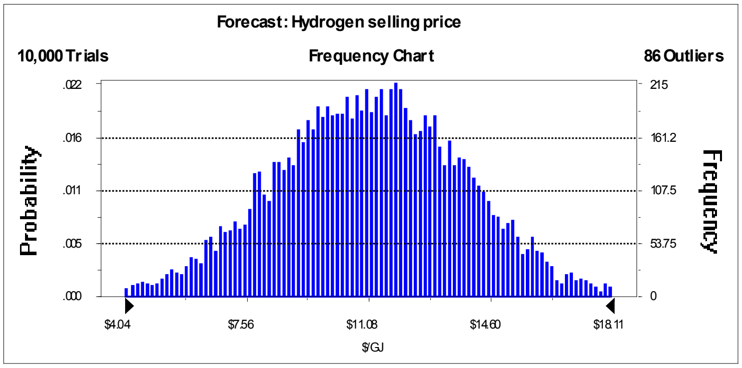
C28 REPORT_pyr_small_10%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $4.04 to $18.11 $/GJ
Entire Range is from $1.43 to $20.73 $/GJ
After 10,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	10000
Mean	$11.07
Median	$11.11
Mode	---
Standard Deviation	$2.73
Variance	$7.43
Skewness	-0.06
Kurtosis	2.90
Coeff. of Variability	0.25
Range Minimum	$1.43
Range Maximum	$20.73
Range Width	$19.29
Mean Std. Error	$0.03



Percentiles:

Percentile	$/GJ
0%	$1.43
10%	$7.59
20%	$8.76
30%	$9.63
40%	$10.38
50%	$11.11
60%	$11.81
70%	$12.56
80%	$13.40
90%	$14.54
100%	$20.73

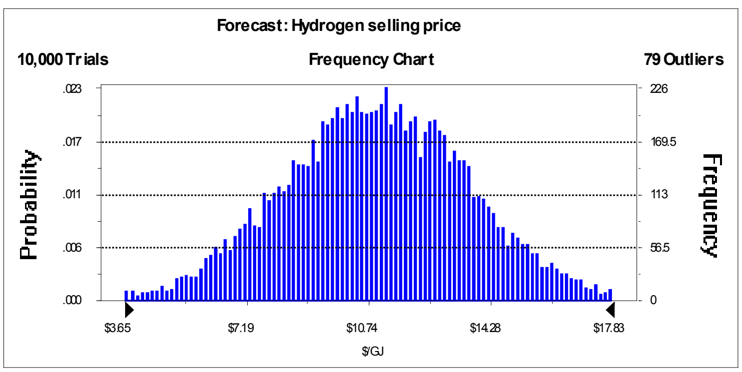
C29 REPORT_pyr_medium_15%.xls

Forecast: Hydrogen selling price

Summary:

Display Range is from $3.65 to $17.83 $/GJ
Entire Range is from ($0.29) to $20.39 $/GJ
After 10,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	10000
Mean	$10.94
Median	$10.96
Mode	---
Standard Deviation	$2.70
Variance	$7.28
Skewness	-0.04
Kurtosis	2.94
Coeff. of Variability	0.25
Range Minimum	($0.29)
Range Maximum	$20.39
Range Width	$20.68
Mean Std. Error	$0.03



Percentiles:

Percentile	$/GJ
0%	($0.29)
10%	$7.42
20%	$8.66
30%	$9.54
40%	$10.26
50%	$10.96
60%	$11.63
70%	$12.41
80%	$13.23
90%	$14.36
100%	$20.39

C30 REPORT_pyr_medium_20%.xls

Forecast: Hydrogen selling price

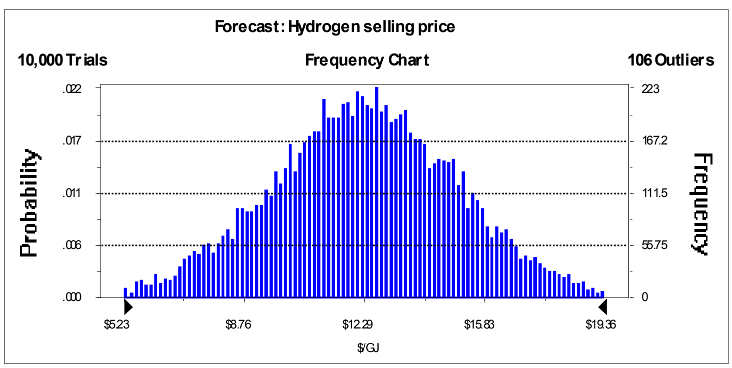
Summary:

Display Range is from $5.23 to $19.36 $/GJ

Entire Range is from $0.58 to $22.76 $/GJ

After 10,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	10000
Mean	$12.27
Median	$12.28
Mode	---
Standard Deviation	$2.78
Variance	$7.71
Skewness	-0.02
Kurtosis	3.03
Coeff. of Variability	0.23
Range Minimum	$0.58
Range Maximum	$22.76
Range Width	$22.18
Mean Std. Error	$0.03



Percentiles:

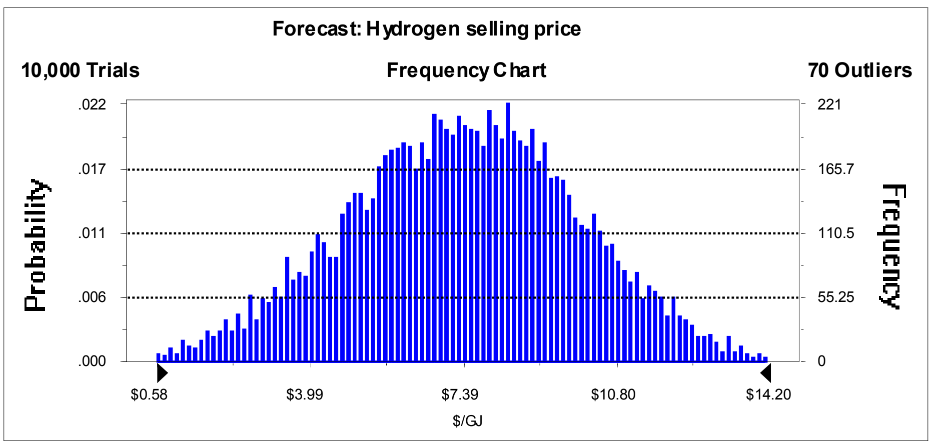
Percentile	$/GJ
0%	$0.58
10%	$8.68
20%	$9.98
30%	$10.86
40%	$11.60
50%	$12.28
60%	$12.97
70%	$13.71
80%	$14.63
90%	$15.80
100%	$22.76

C31 REPORT_pyr_medium_0%.xls

Forecast: Hydrogen selling price

Summary:
Display Range is from $0.58 to $14.20 $/GJ
Entire Range is from ($4.51) to $16.00 $/GJ
After 10,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	10000
Mean	$7.41
Median	$7.45
Mode	---
Standard Deviation	$2.59
Variance	$6.71
Skewness	-0.09
Kurtosis	2.92
Coeff. of Variability	0.35
Range Minimum	($4.51)
Range Maximum	$16.00
Range Width	$20.51
Mean Std. Error	$0.03



Percentiles:

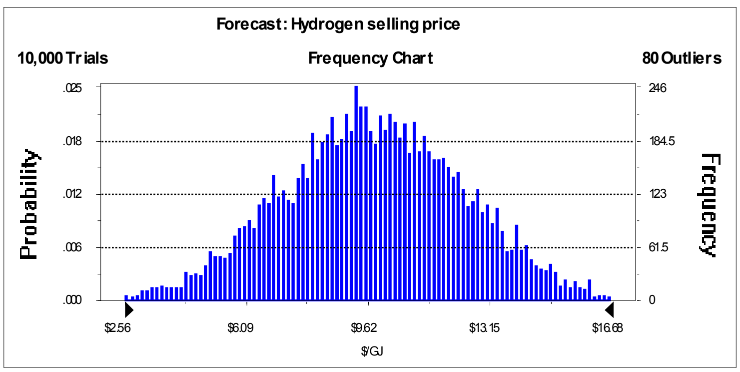
Percentile	$/GJ
0%	($4.51)
10%	$4.03
20%	$5.21
30%	$6.05
40%	$6.79
50%	$7.45
60%	$8.14
70%	$8.82
80%	$9.60
90%	$10.72
100%	$16.00

C32 REPORT_pyr_medium_10%.xls

Forecast: Hydrogen selling price

Summary:
Display Range is from $2.56 to $16.68 $/GJ
Entire Range is from ($0.37) to $22.13 $/GJ
After 10,000 Trials, the Std. Error of the Mean is $0.03

Statistics:	Value
Trials	10000
Mean	$9.75
Median	$9.73
Mode	---
Standard Deviation	$2.68
Variance	$7.16
Skewness	-0.04
Kurtosis	2.98
Coeff. of Variability	0.27
Range Minimum	($0.37)
Range Maximum	$22.13
Range Width	$22.51
Mean Std. Error	$0.03



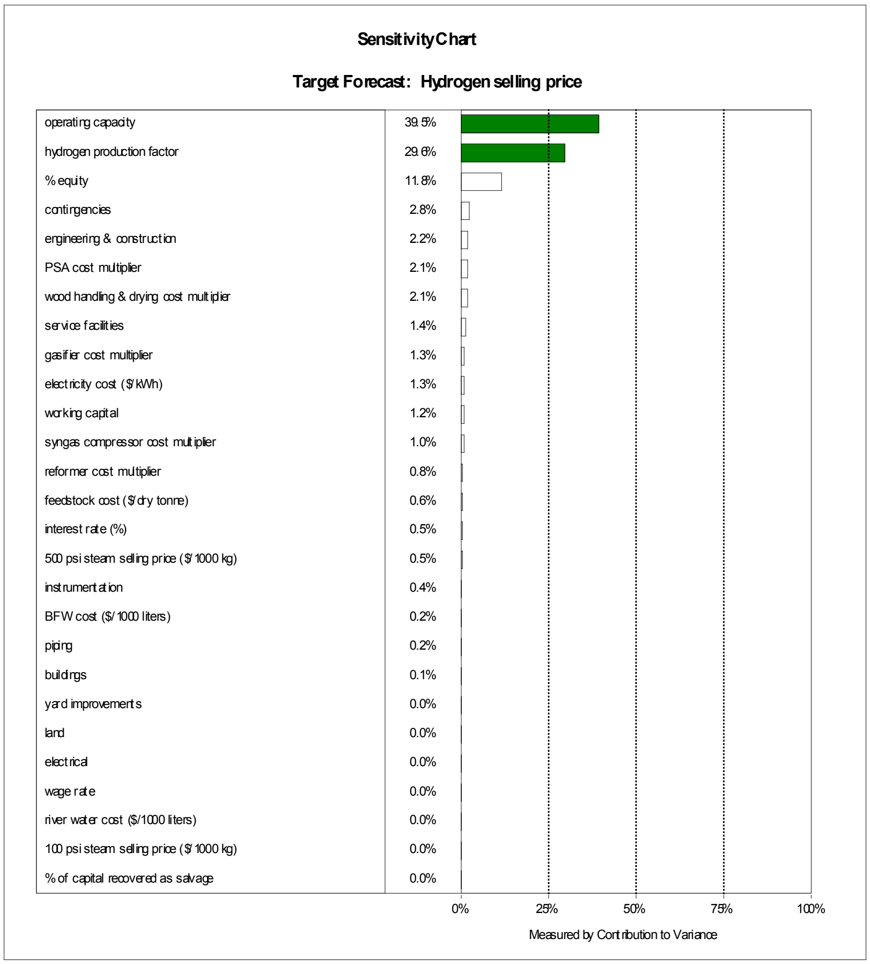
Percentiles:

Percentile	$/GJ
0%	($0.37)
10%	$6.29
20%	$7.50
30%	$8.37
40%	$9.09
50%	$9.73
60%	$10.44
70%	$11.18
80%	$12.03
90%	$13.19
100%	$22.13

Appendix D - Sensitivity Charts

D1 BCL_REPORTsmall_15%.xls

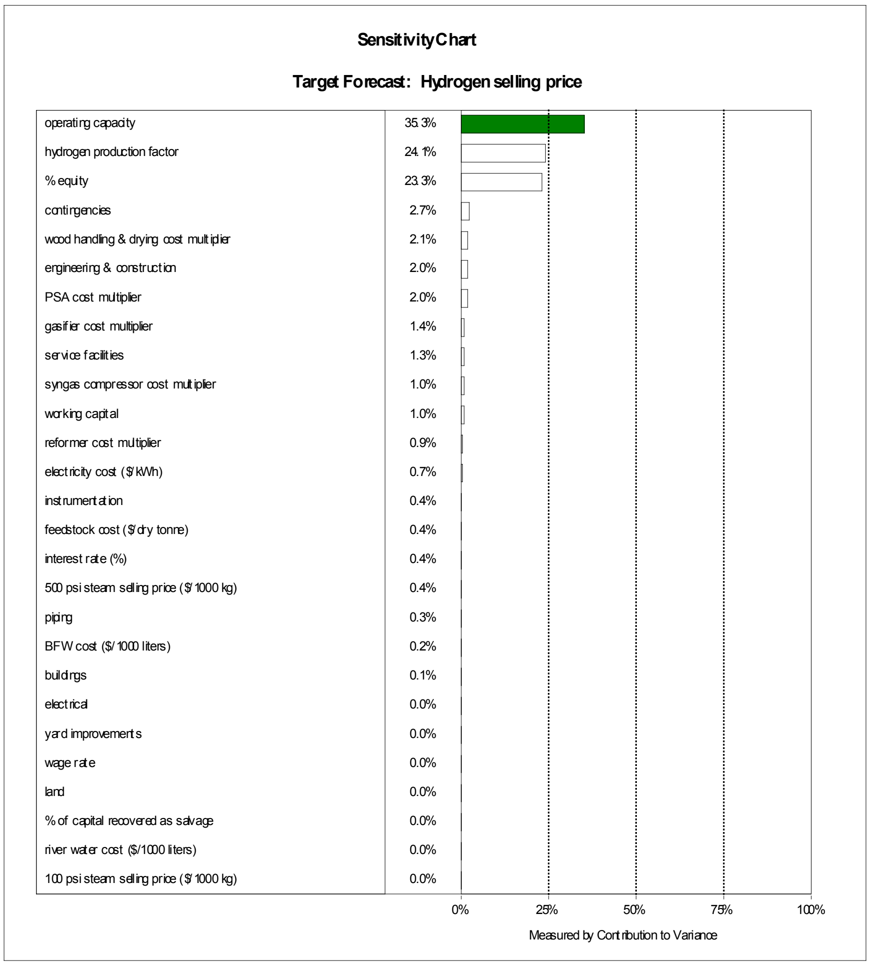
Crystal Ball Report
Simulation started on 5/2/00 at 10:50:48
Simulation stopped on 5/2/00 at 10:54:34



D2 BCL_REPORTsmall_20%.xls

Crystal Ball Report

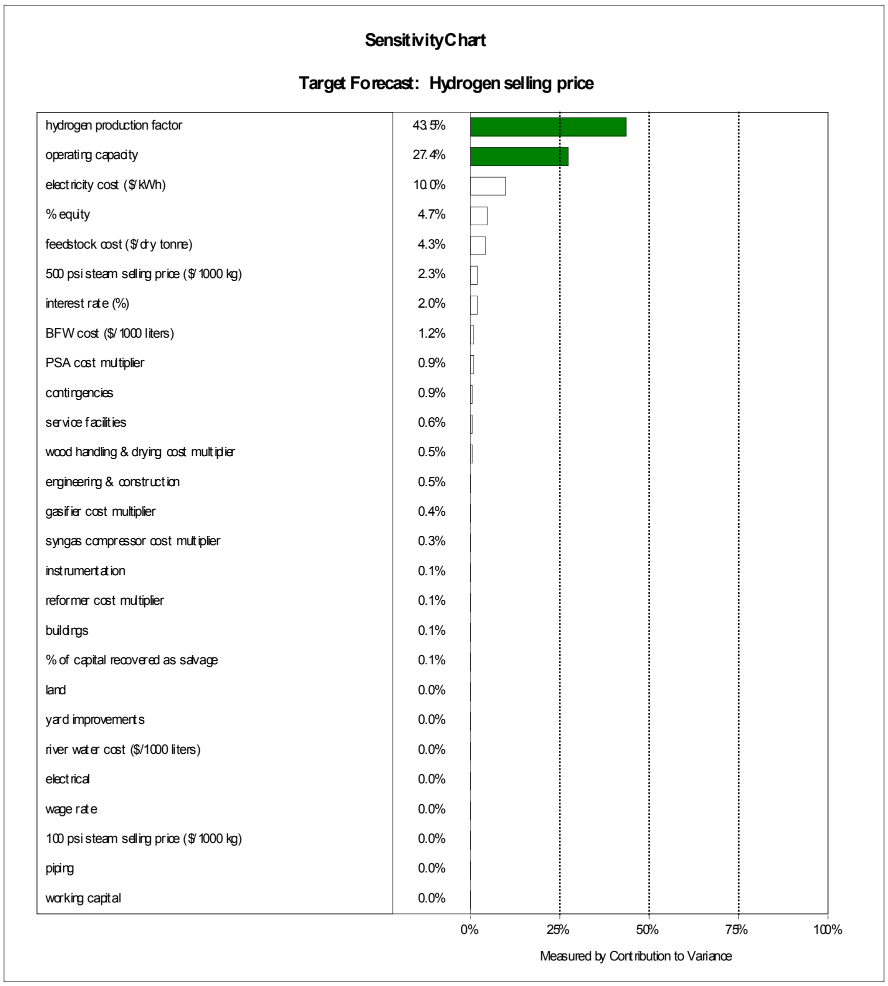
Simulation started on 5/2/00 at 10:56:34
Simulation stopped on 5/2/00 at 11:00:37



D3- BCL_REPORTsmall_0%.xls

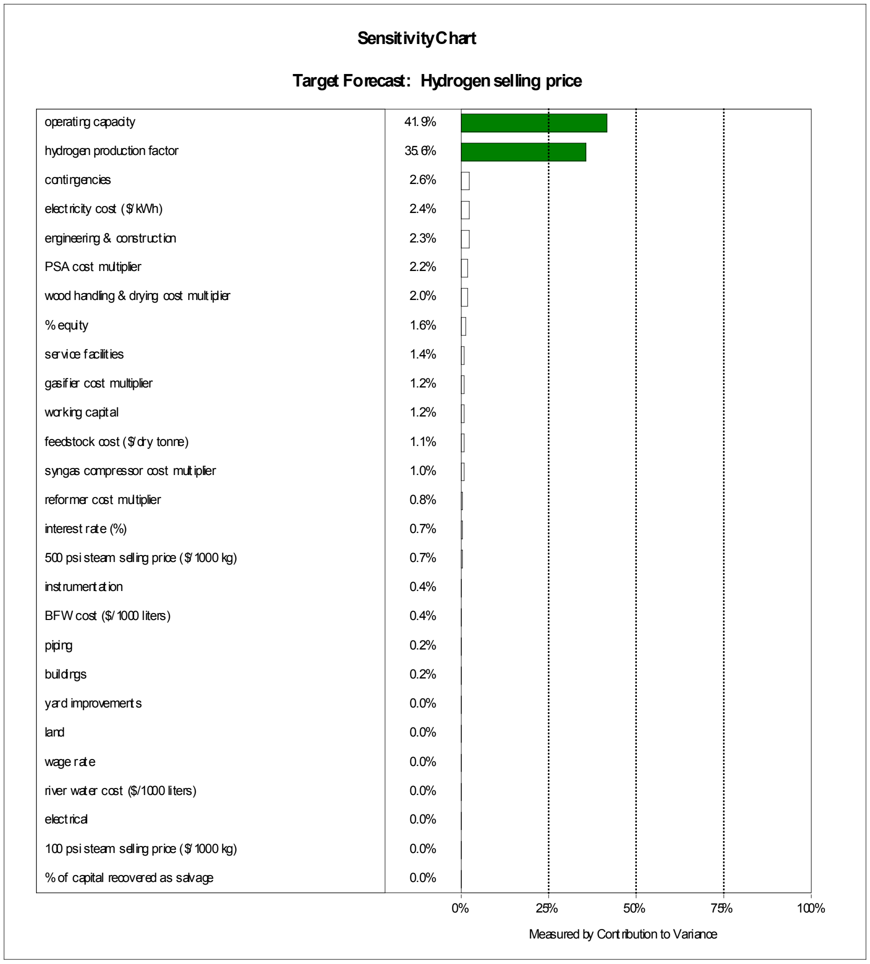
Crystal Ball Report

Simulation started on 5/2/00 at 10:30:49
Simulation stopped on 5/2/00 at 10:34:25



D4 – BCL_REPORTsmall_10%.xls

Crystal Ball Report
Simulation started on 5/2/00 at 10:39:43
Simulation stopped on 5/2/00 at 10:43:30

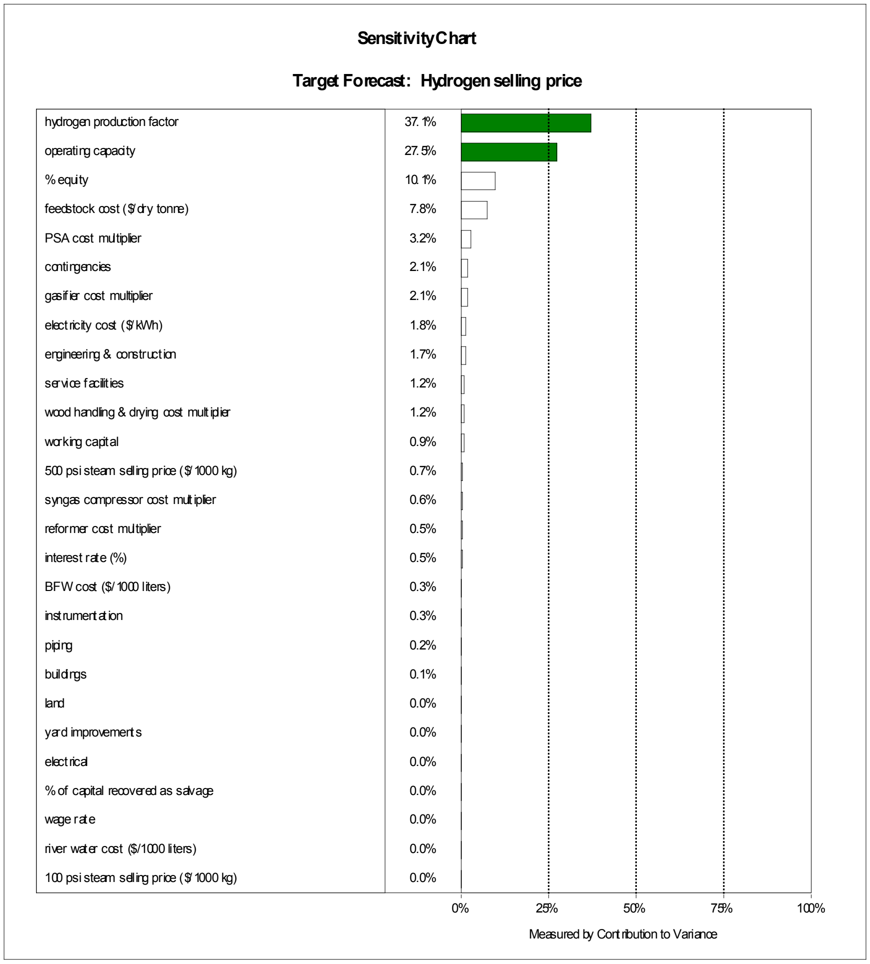


D5 – BCL_REPORTmedium_15%.xls

Crystal Ball Report

Simulation started on 4/14/00 at 10:44:53

Simulation stopped on 4/14/00 at 10:51:35

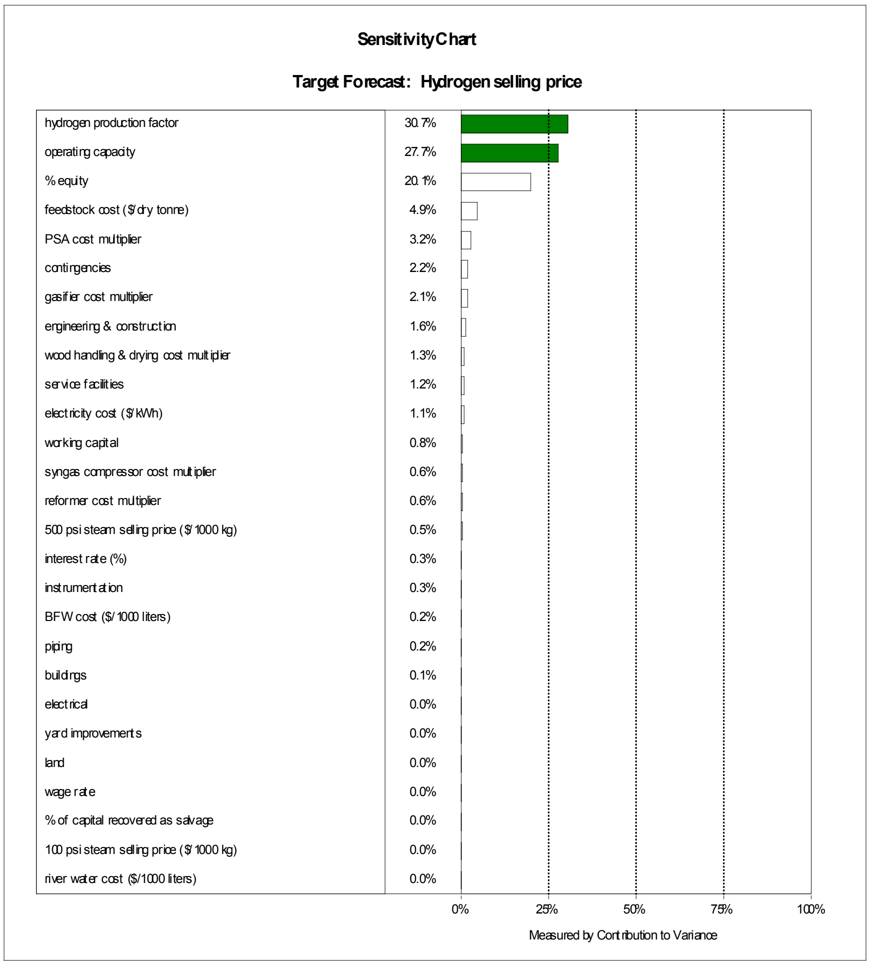


D6 – BCL_REPORTmedium_20%.xls

Crystal Ball Report

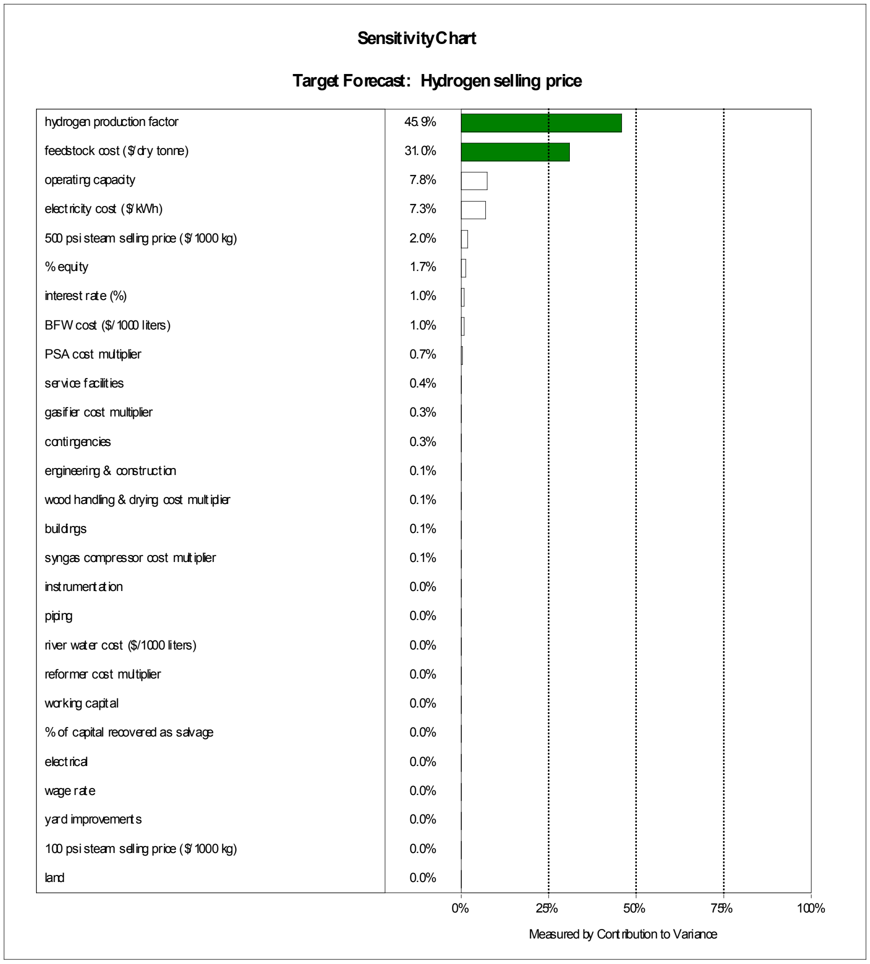
Simulation started on 4/14/00 at 11:02:37

Simulation stopped on 4/14/00 at 11:09:38



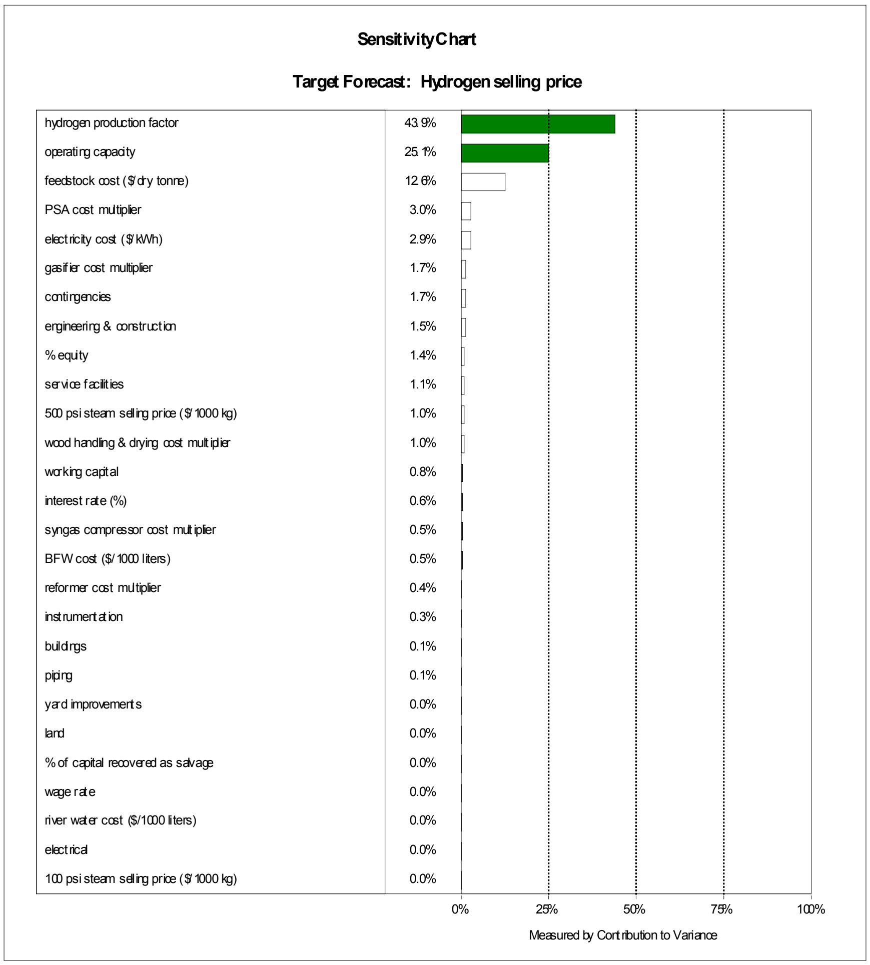
D7 – BCL_REPORTmedium_0%.xls

Crystal Ball Report
Simulation started on 4/14/00 at 11:20:15
Simulation stopped on 4/14/00 at 11:26:36



D8 – BCL_REPORTmedium_10%.xls

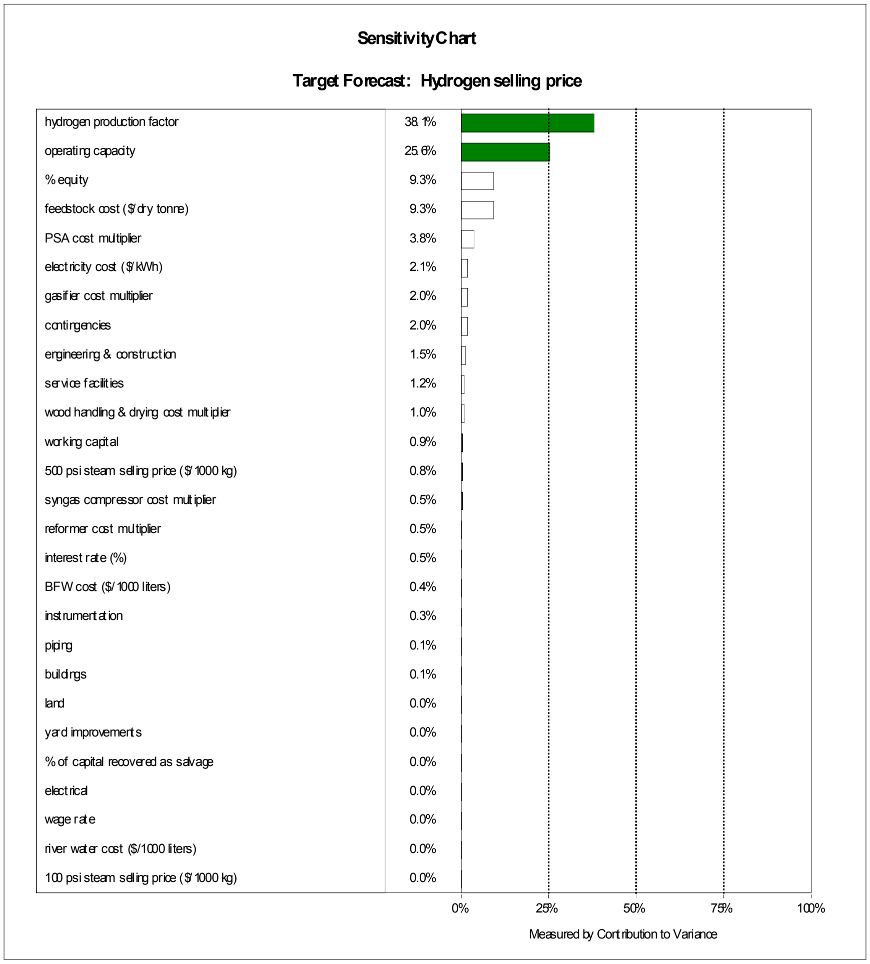
Crystal Ball Report
Simulation started on 4/14/00 at 10:53:48
Simulation stopped on 4/14/00 at 11:01:19



D9 – BCL_REPORTlarge_15%.xls

Crystal Ball Report

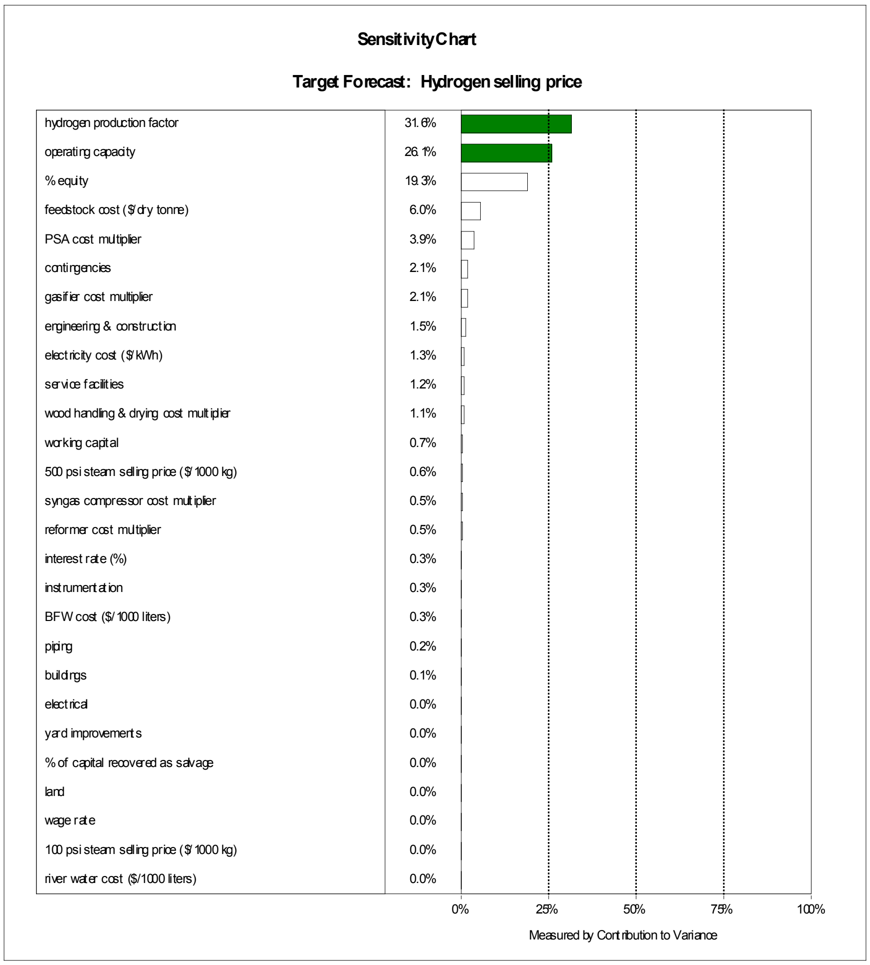
Simulation started on 4/14/00 at 11:41:49
Simulation stopped on 4/14/00 at 11:48:26



D10 – BCL_REPORTlarge_20%.xls

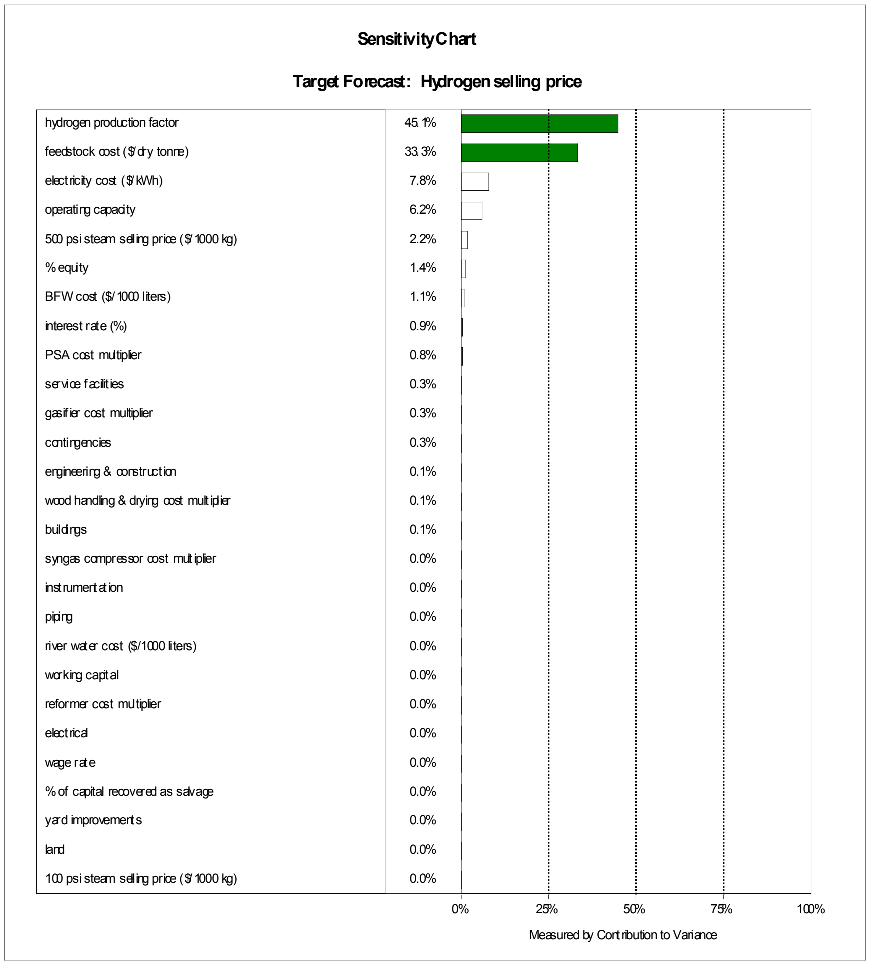
Crystal Ball Report

Simulation started on 4/14/00 at 11:58:40
Simulation stopped on 4/14/00 at 12:05:18



D11 – BCL_REPORTlarge_0%.xls

Crystal Ball Report
Simulation started on 4/14/00 at 12:07:41
Simulation stopped on 4/14/00 at 12:13:51

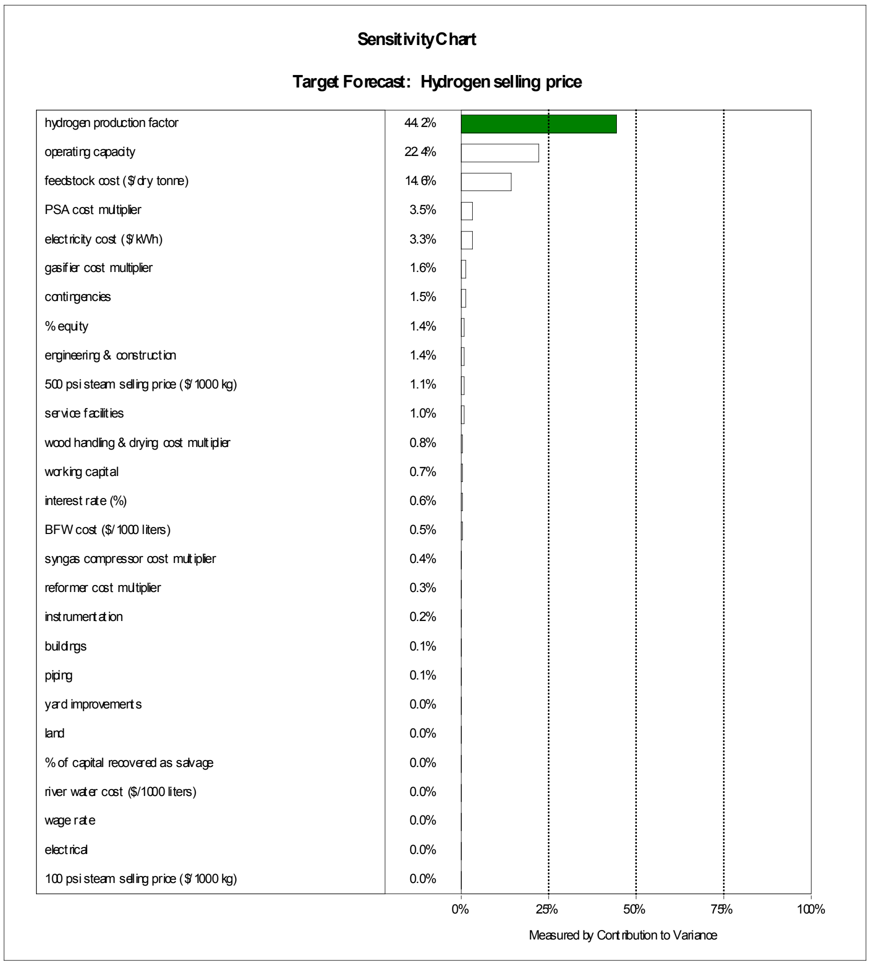


D12 – BCL_REPORTlarge_10%.xls

Crystal Ball Report

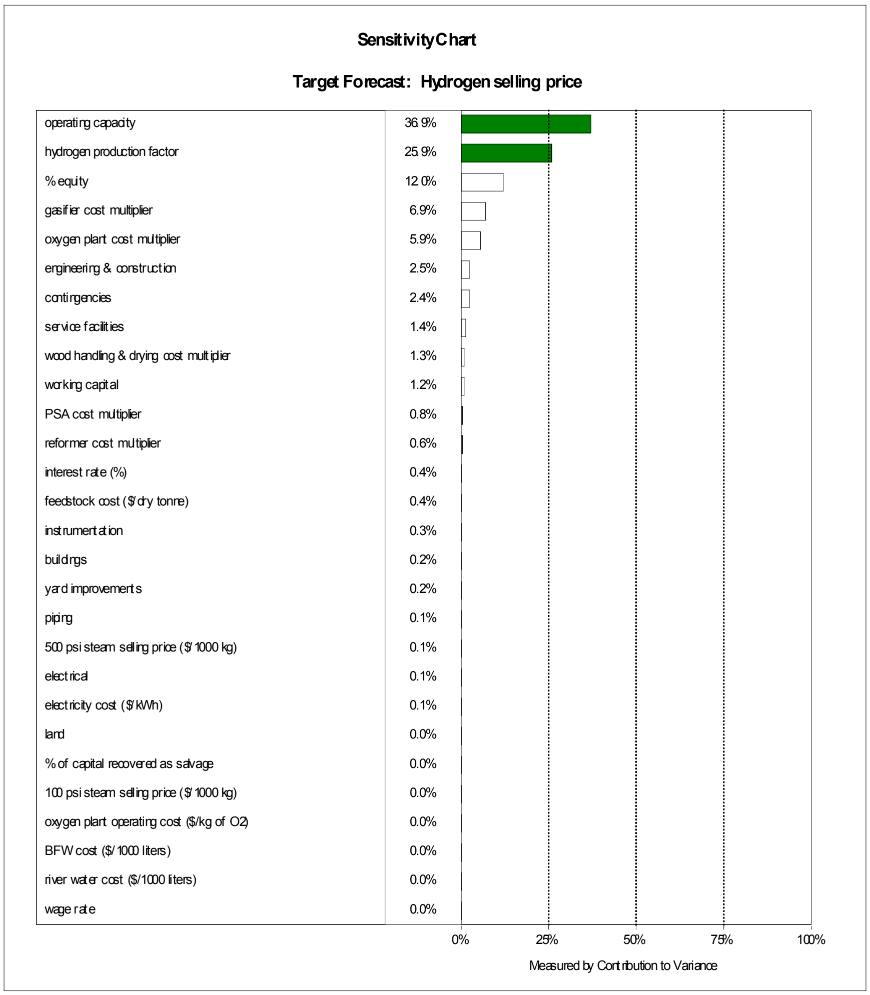
Simulation started on 4/14/00 at 11:50:04

Simulation stopped on 4/14/00 at 11:56:60



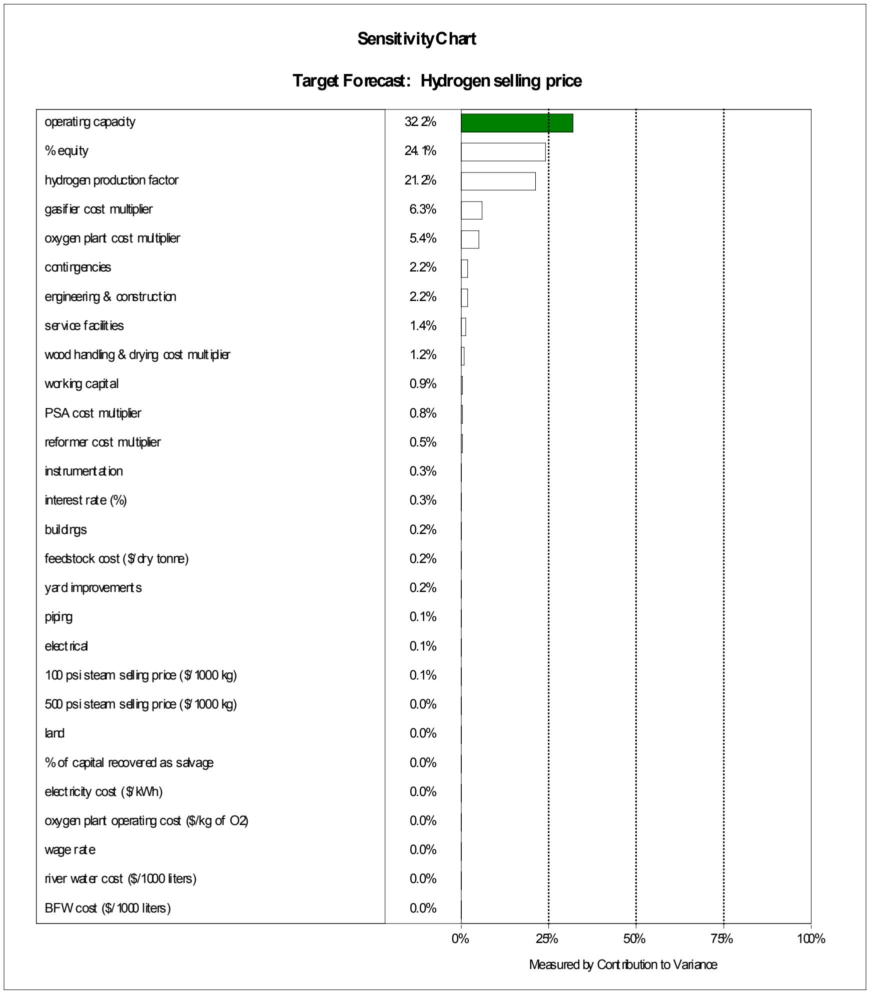
D13 – IGT_REPORTsmall_15%.xls

Crystal Ball Report
Simulation started on 5/2/00 at 11:26:17
Simulation stopped on 5/2/00 at 11:30:24



D14 - IGT_REPORTsmall_20%.xls

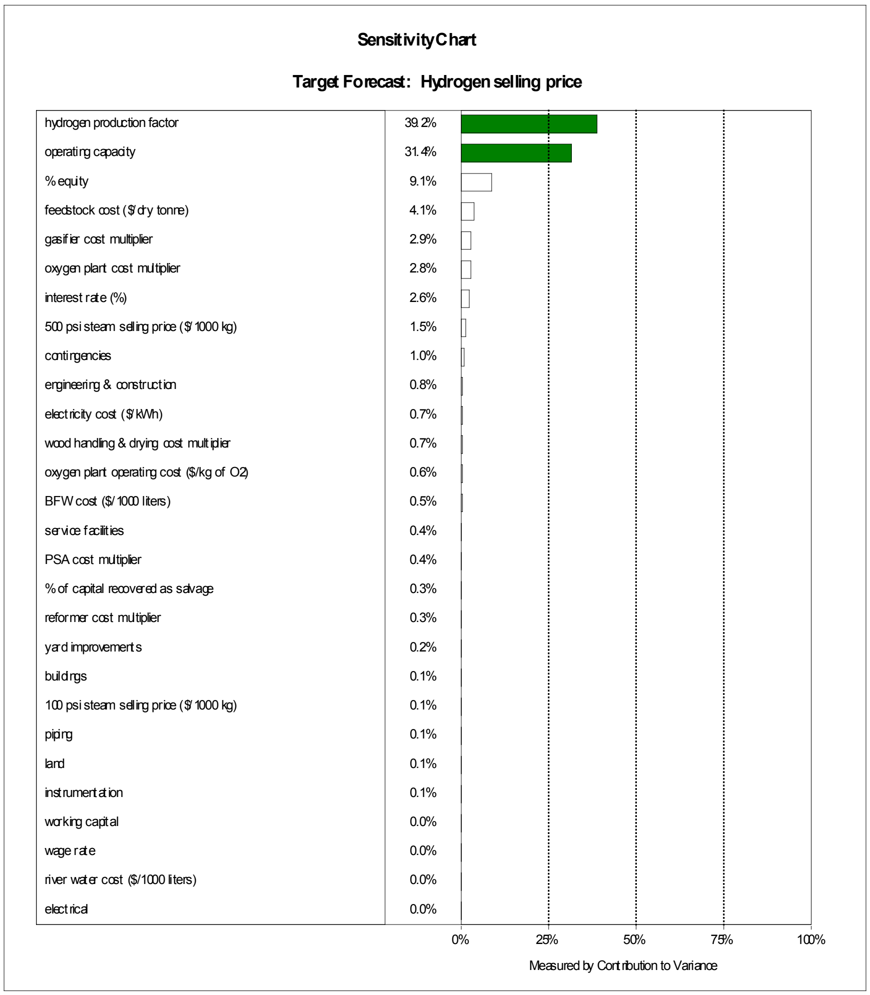
Crystal Ball Report
Simulation started on 5/2/00 at 11:43:27
Simulation stopped on 5/2/00 at 11:47:42



D15 – IGT_REPORTsmall_0%.xls

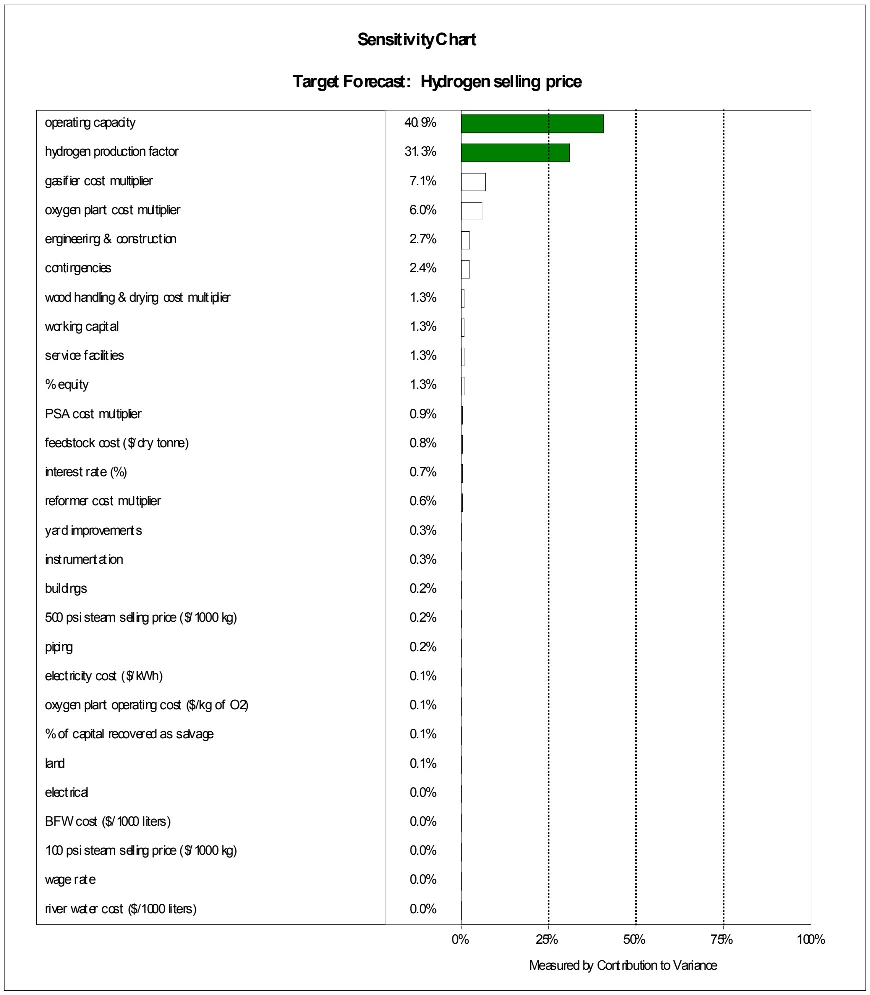
Crystal Ball Report

Simulation started on 5/2/00 at 11:08:08
Simulation stopped on 5/2/00 at 11:11:60



D16 – IGT_REPORTsmall_10%.xls

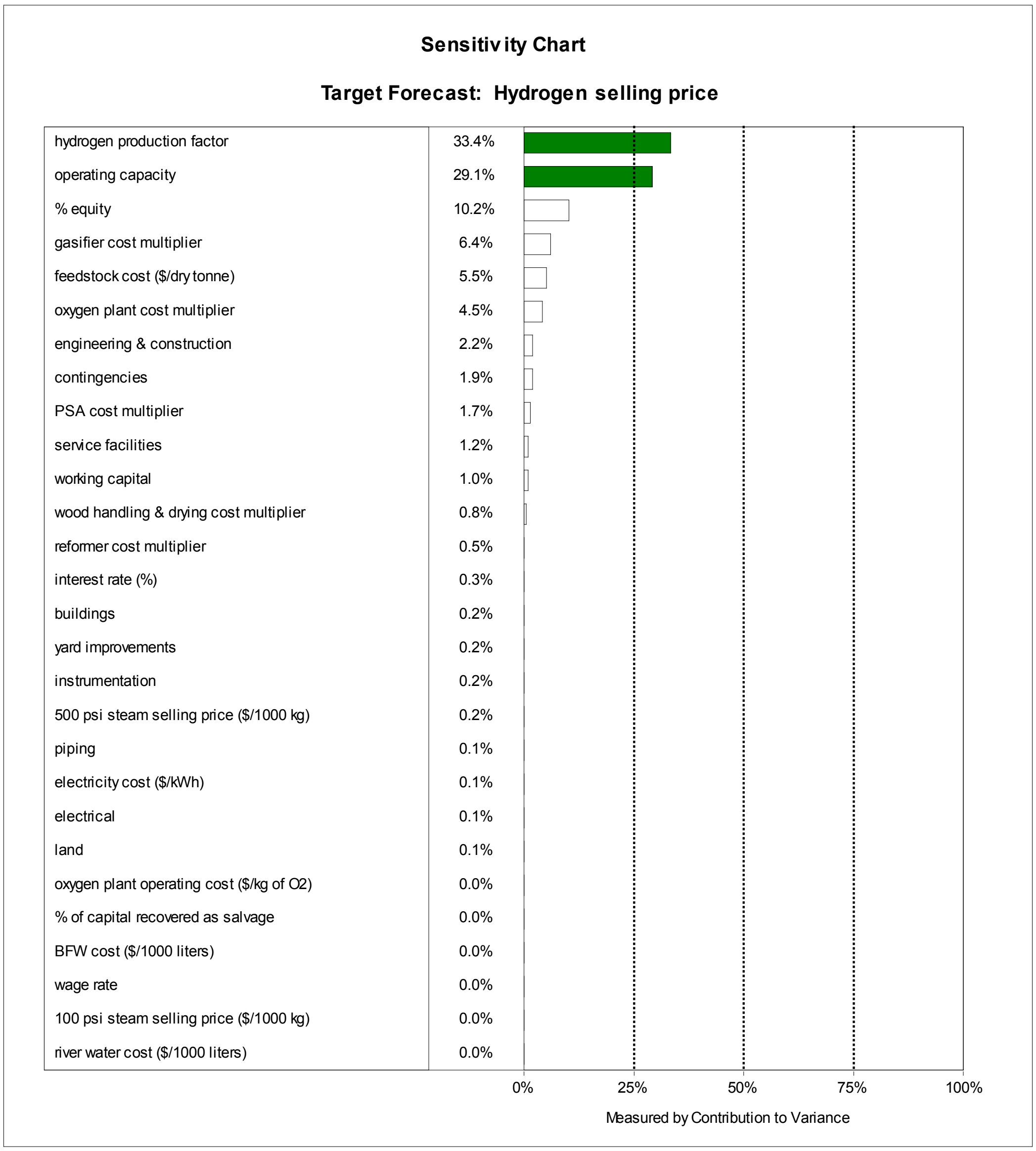
Crystal Ball Report
Simulation started on 5/2/00 at 11:20:10
Simulation stopped on 5/2/00 at 11:24:04



D17 - IGT_REPORTmedium_15%.xls

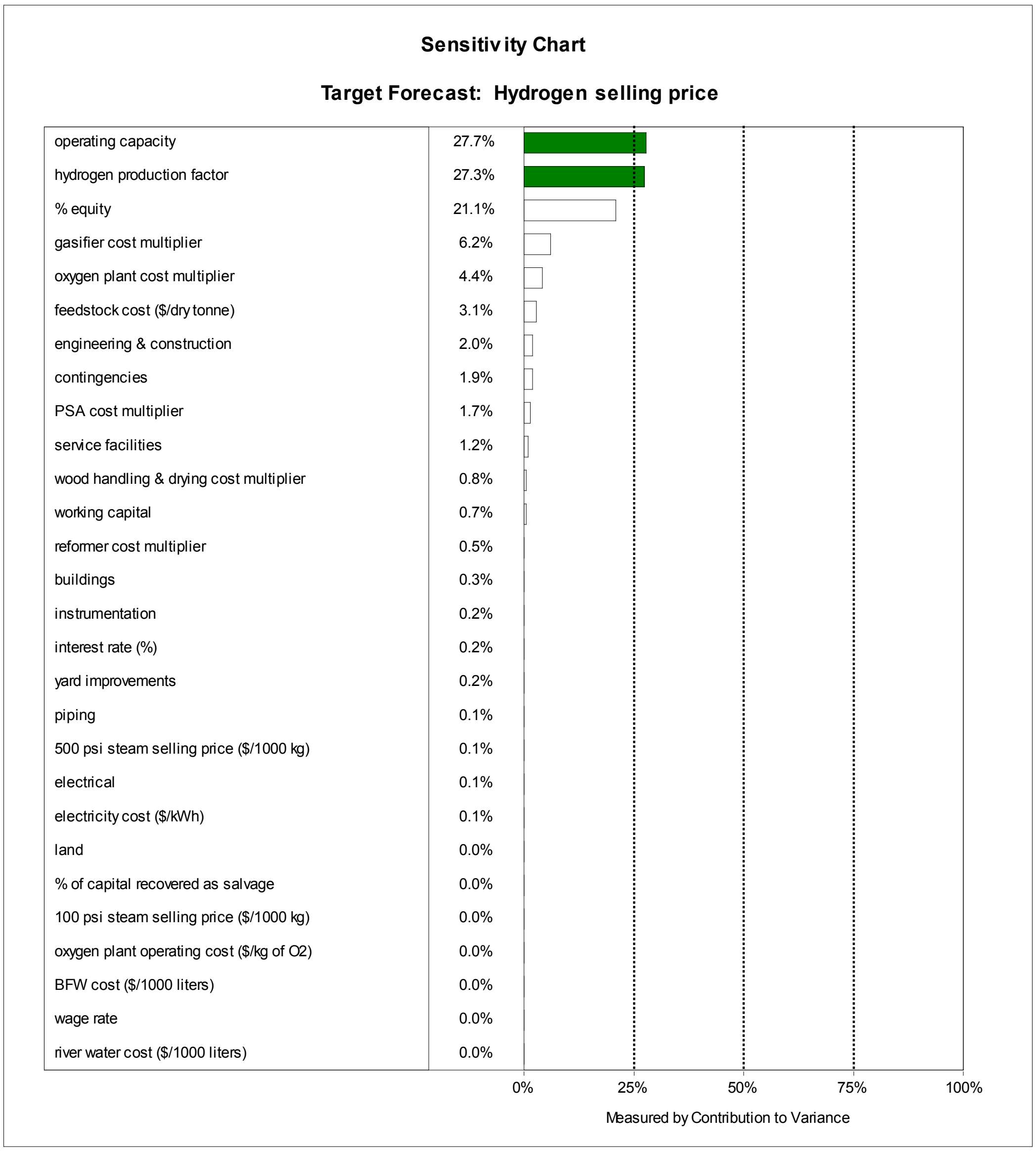
Crystal Ball Report

Simulation started on 4/18/00 at 12:10:58
Simulation stopped on 4/18/00 at 12:14:45



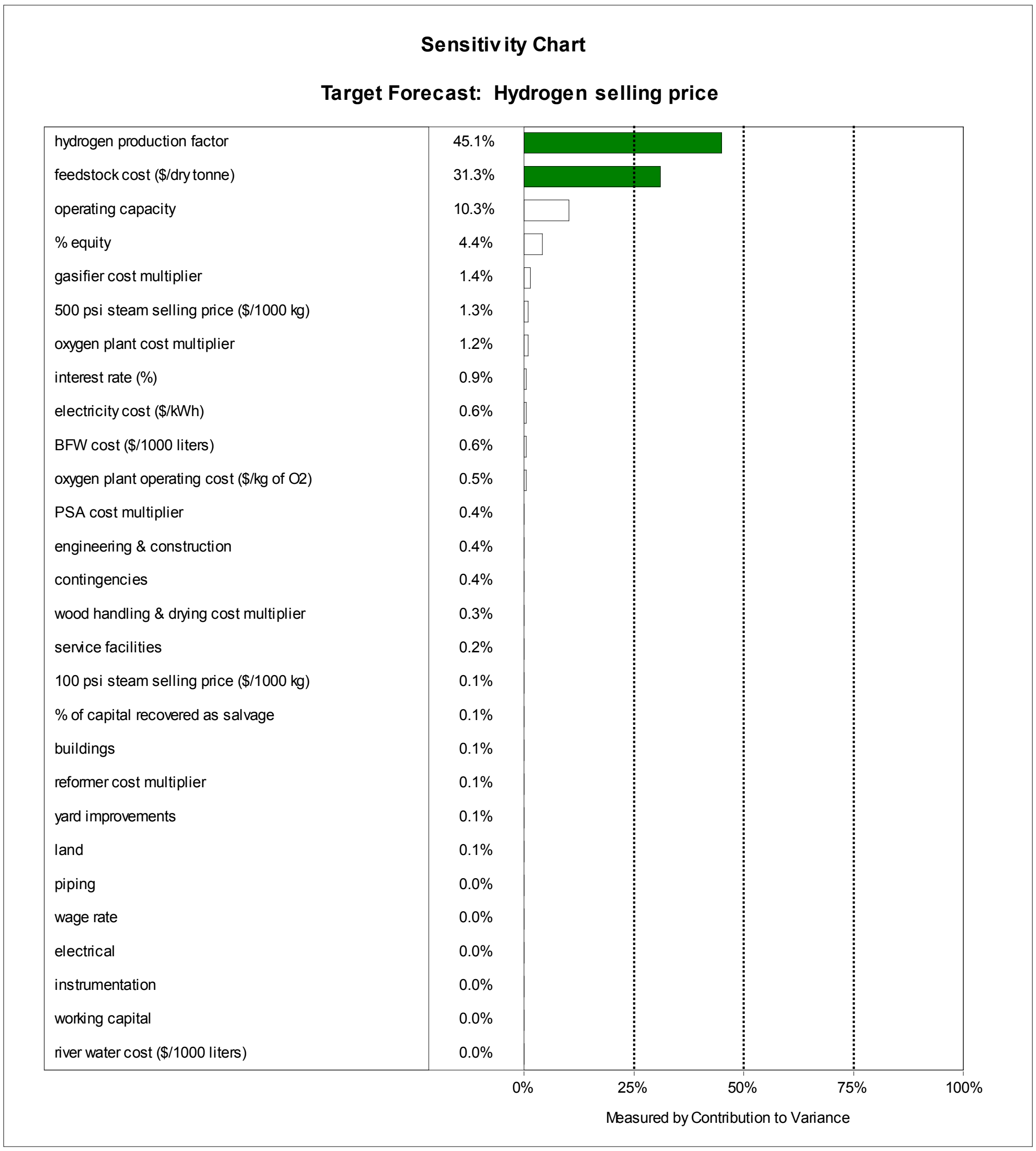
D18 – IGT_REPORTmedium_20%.xls

Crystal Ball Report
Simulation started on 4/18/00 at 12:25:17
Simulation stopped on 4/18/00 at 12:29:04



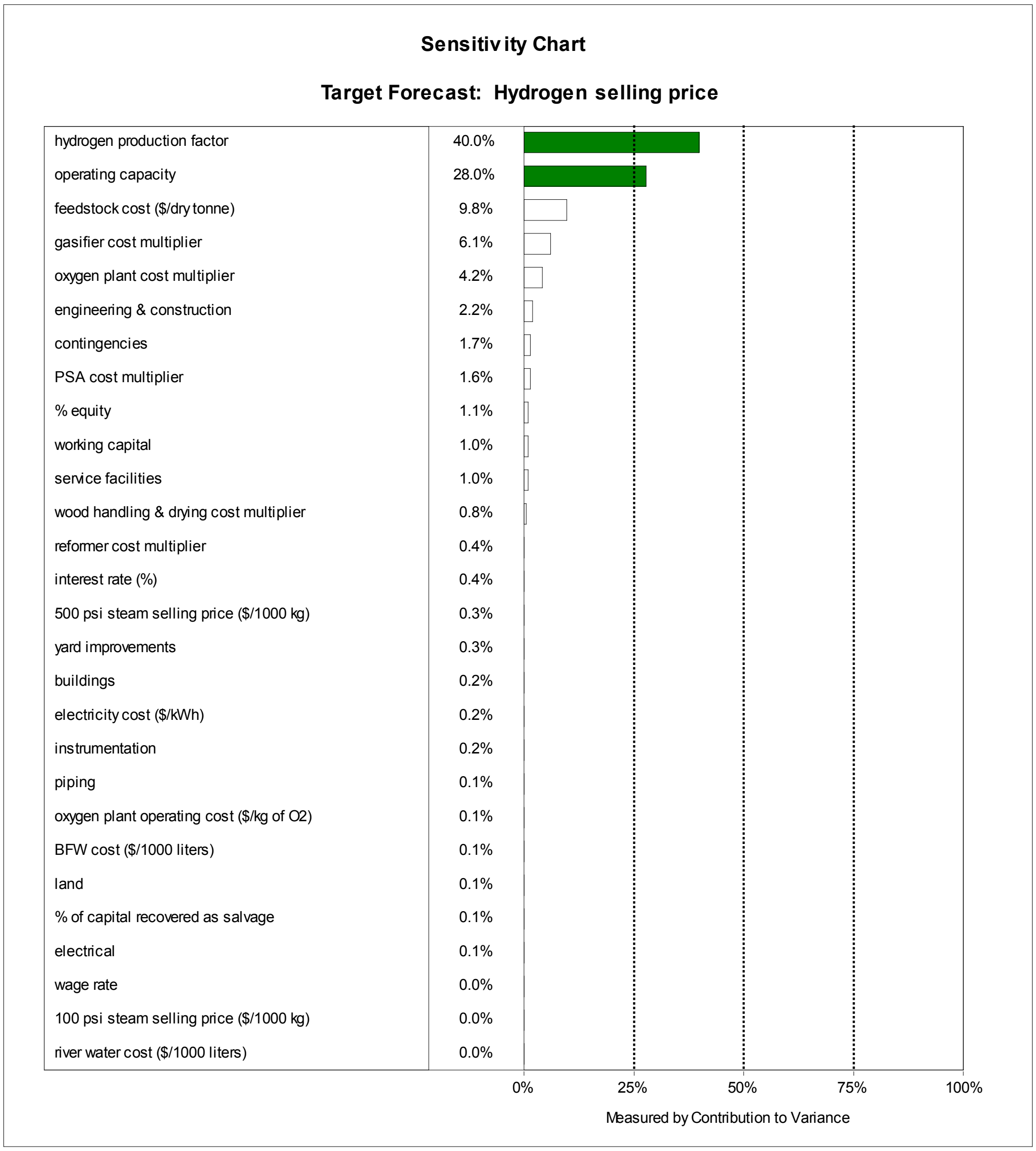
D19 – IGT_REPORTmedium_0%.xls

Crystal Ball Report
Simulation started on 4/18/00 at 11:37:05
Simulation stopped on 4/18/00 at 11:40:33



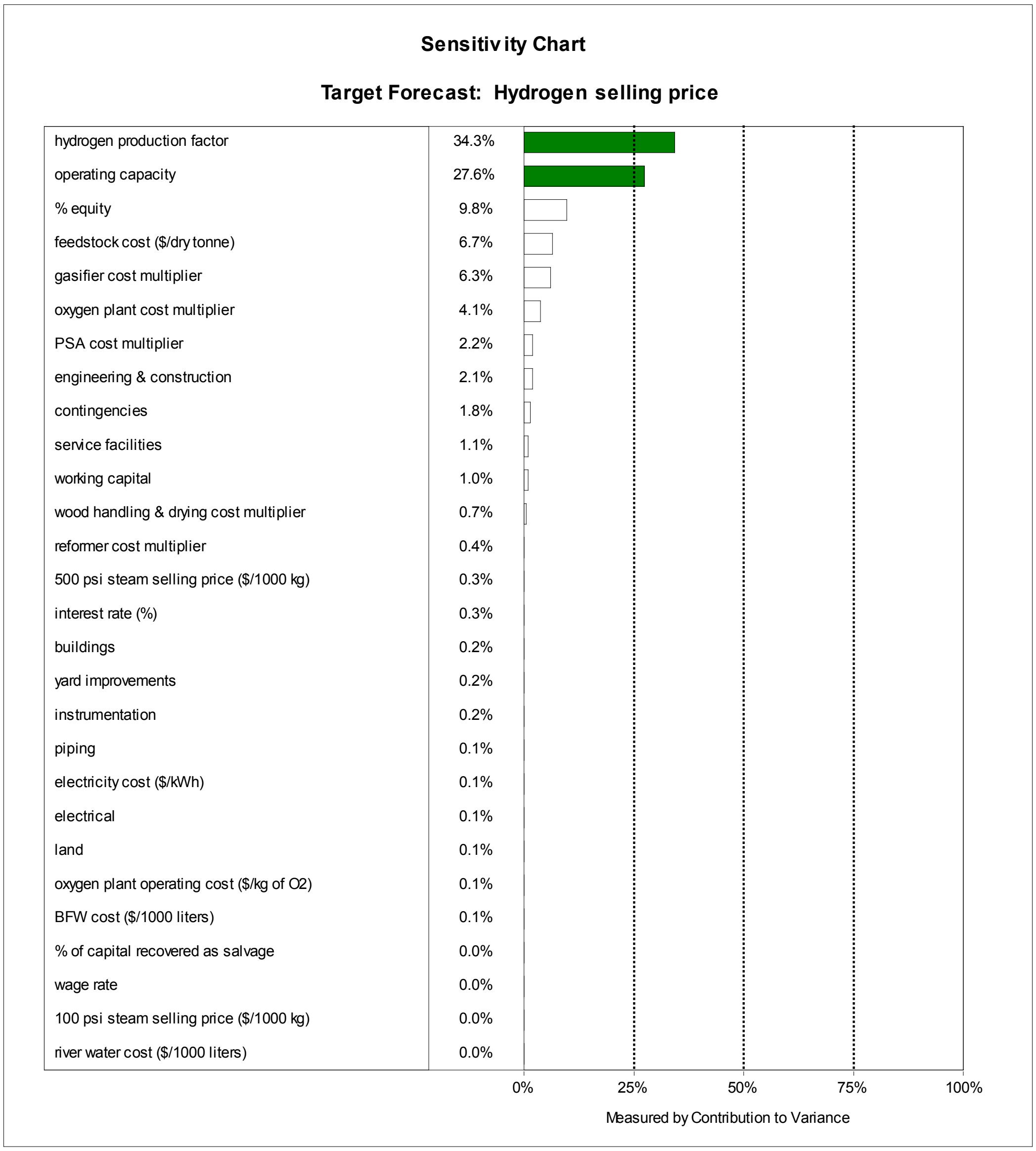
D20 – IGT_REPORTmedium_10%.xls

Crystal Ball Report
Simulation started on 4/18/00 at 12:19:42
Simulation stopped on 4/18/00 at 12:23:40



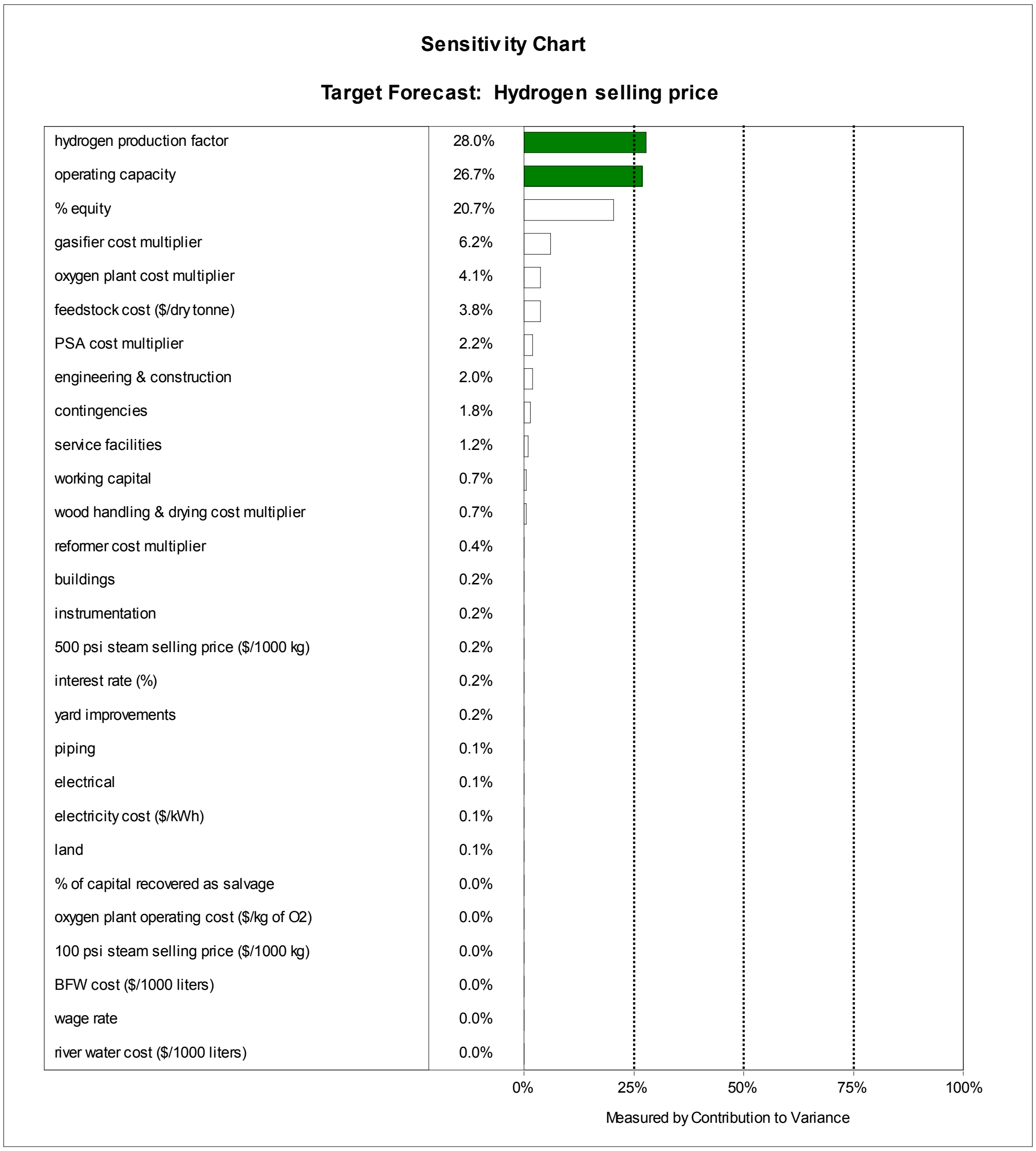
D21- IGT_REPORTlarge_15%.xls

Crystal Ball Report
Simulation started on 4/18/00 at 11:52:47
Simulation stopped on 4/18/00 at 11:56:24



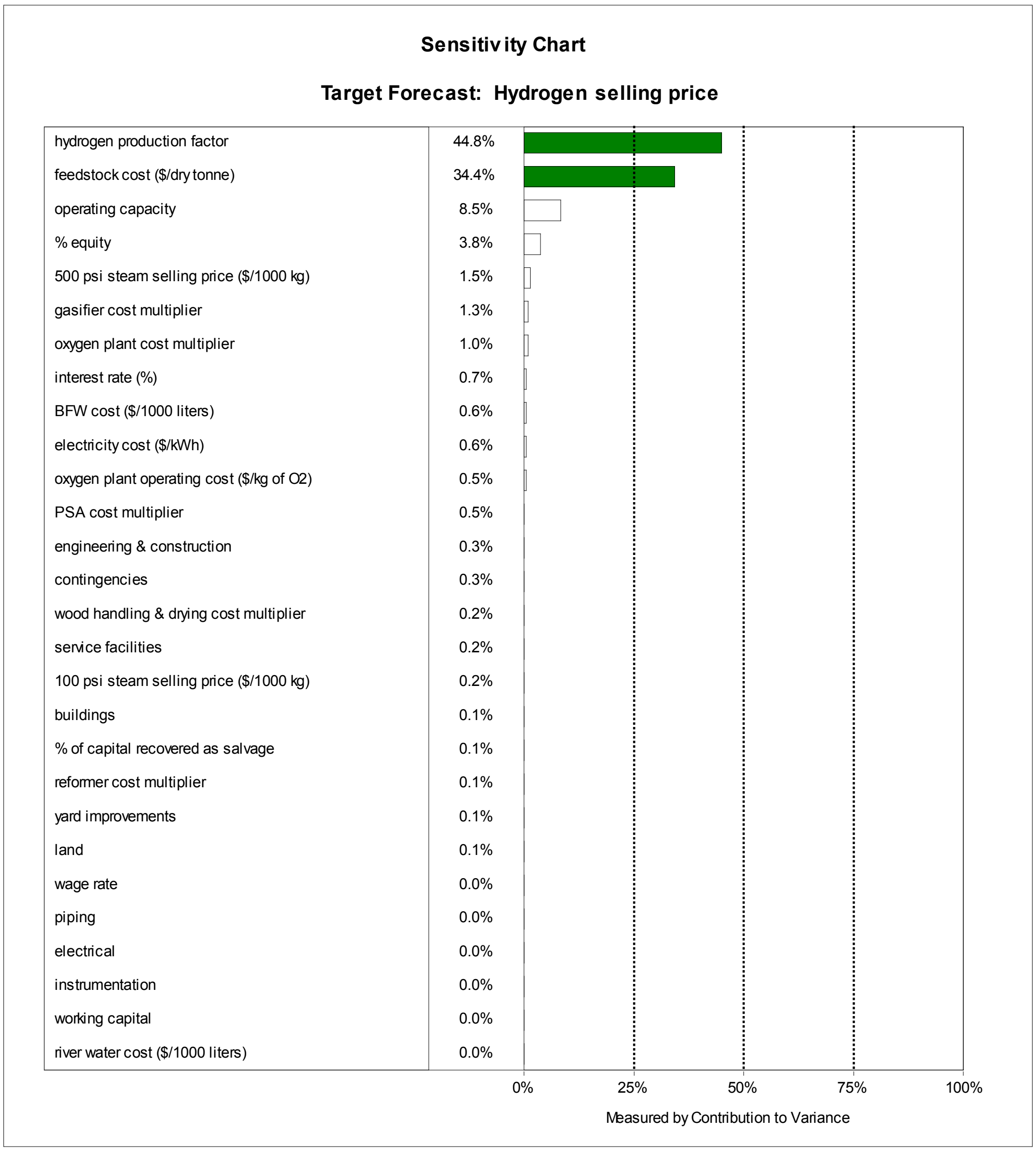
D22 – IGT_REPORTlarge_20%.xls

Crystal Ball Report
Simulation started on 4/18/00 at 12:06:29
Simulation stopped on 4/18/00 at 12:10:12



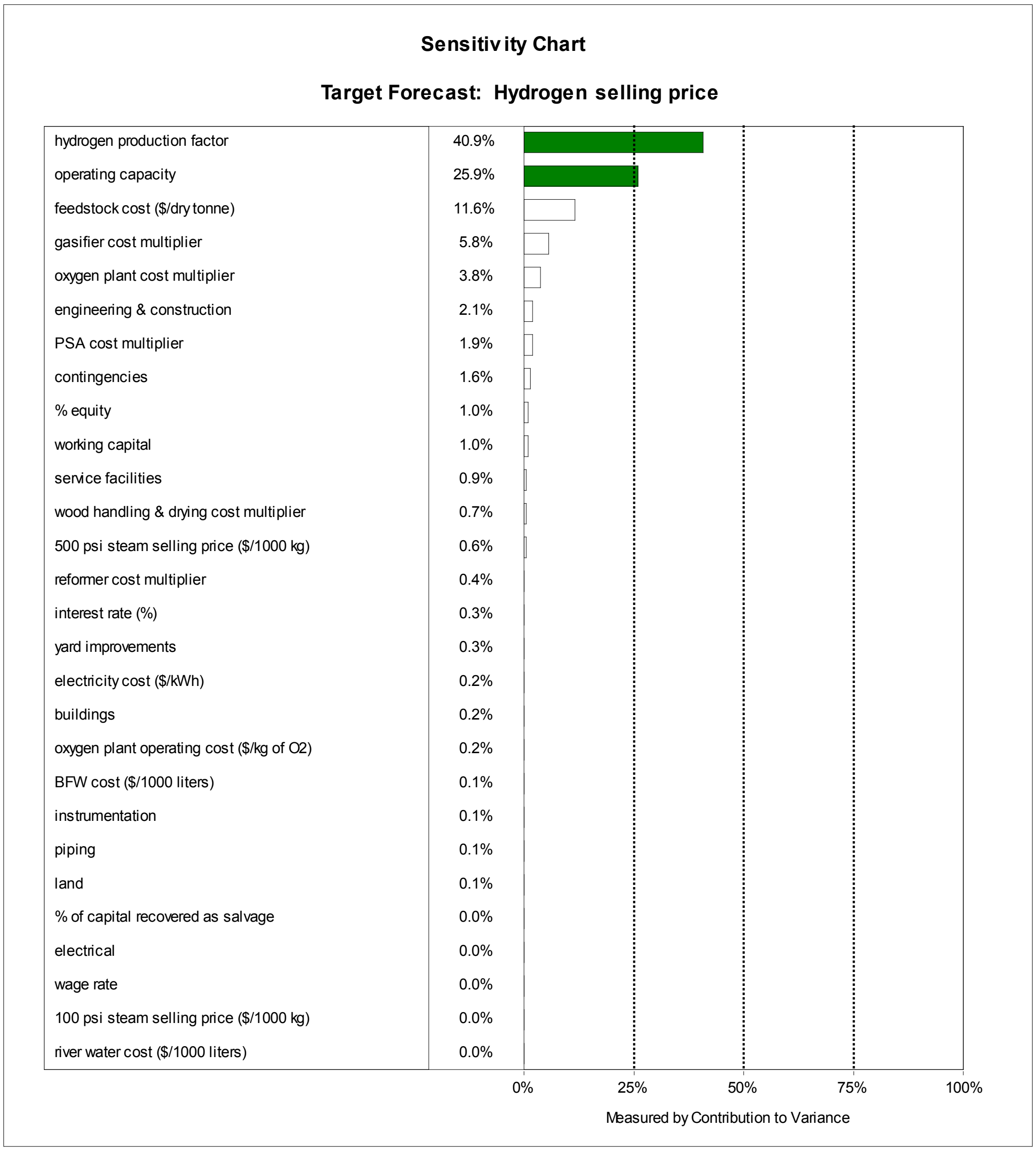
D23 – IGT_REPORTlarge_0%.xls

Crystal Ball Report
Simulation started on 4/18/00 at 11:42:27
Simulation stopped on 4/18/00 at 11:46:07



D24 – IGT_REPORTlarge_10%.xls

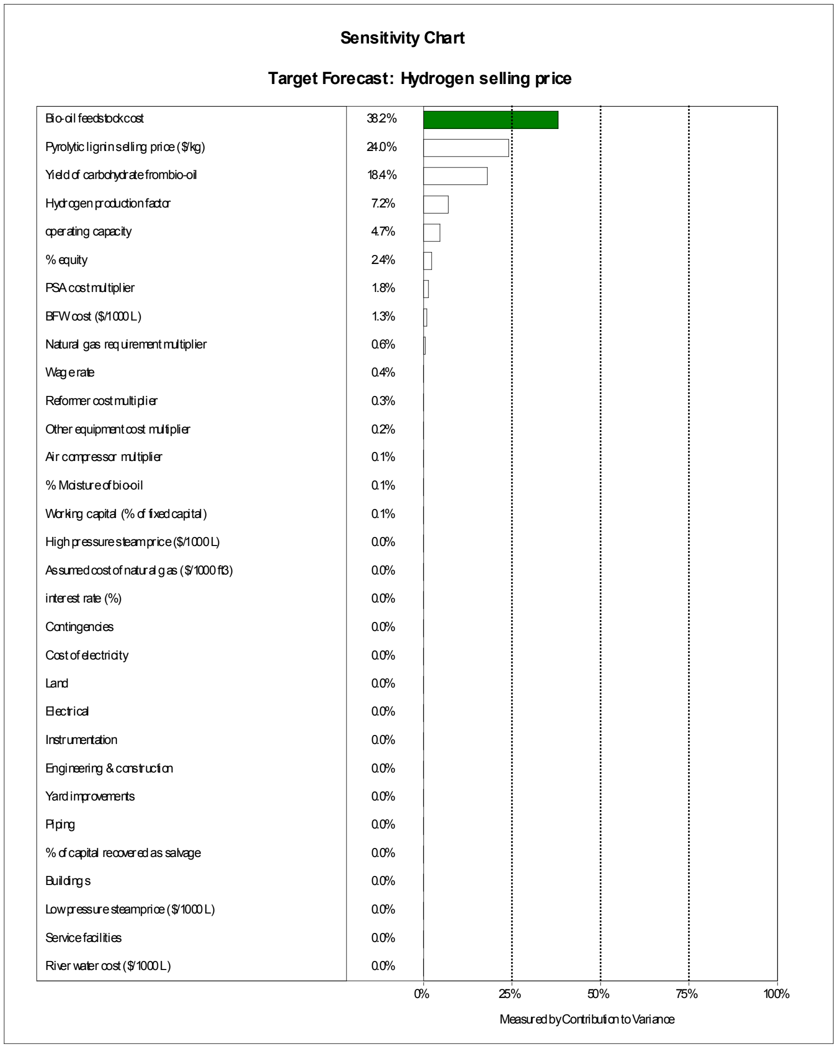
Crystal Ball Report
Simulation started on 4/18/00 at 11:59:25
Simulation stopped on 4/18/00 at 12:03:19



D25 – REPORT_pyr_small_20%.xls

Crystal Ball Report

Simulation started on 7/11/01 at 14:45:22
Simulation stopped on 7/11/01 at 14:48:22

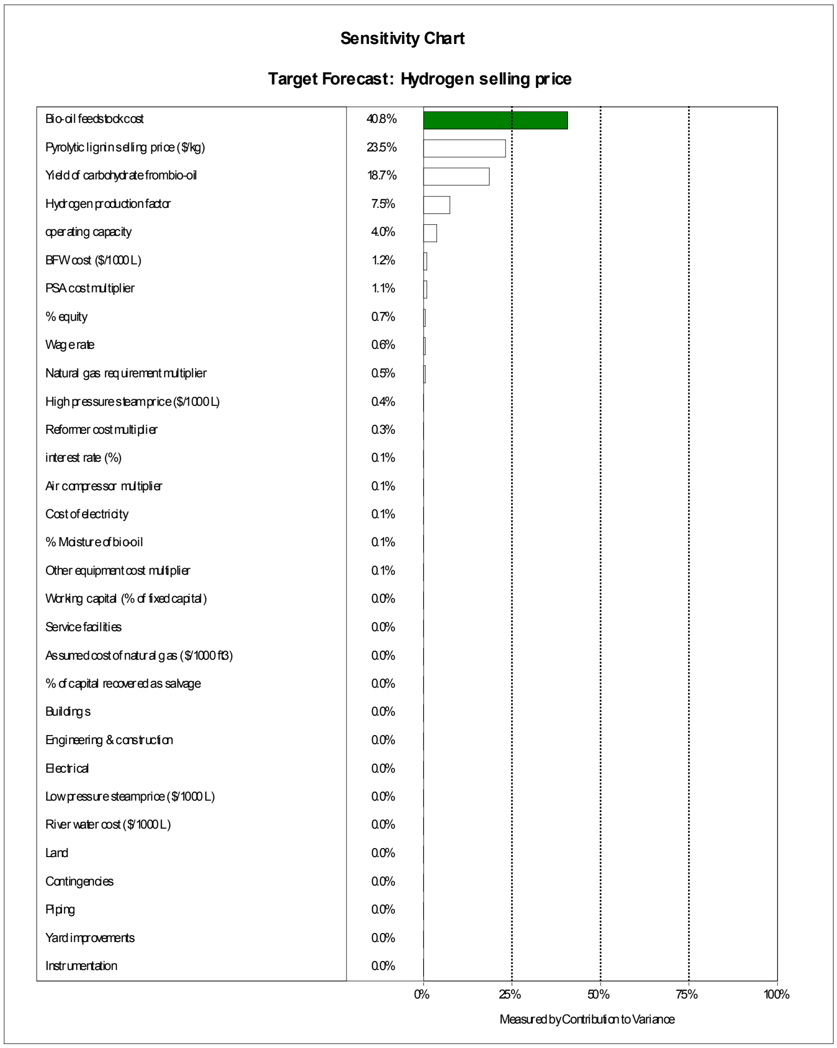


D26 – REPORT_pyr_small_15%.xls

Crystal Ball Report

Simulation started on 7/11/01 at 14:39:55

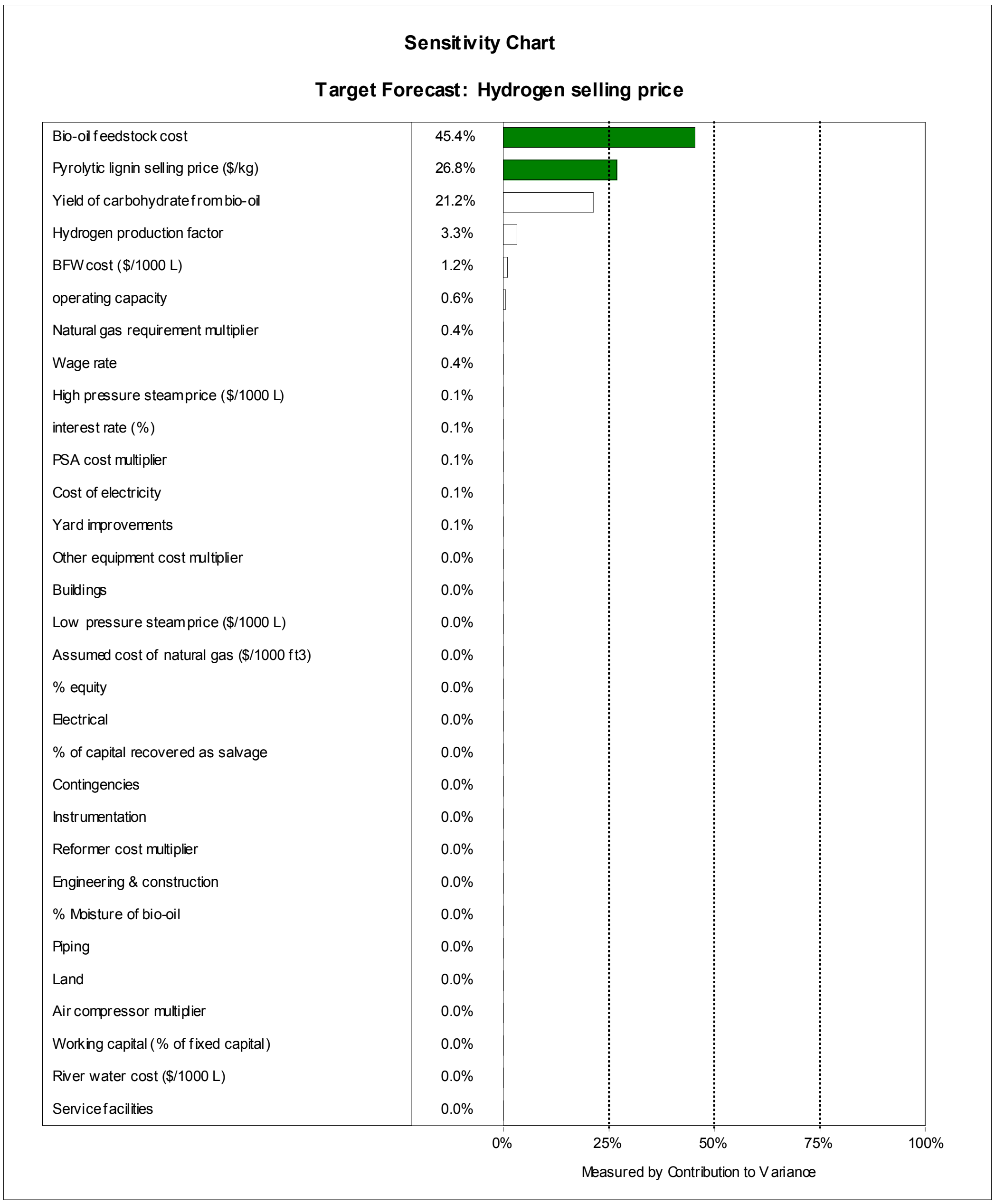
Simulation stopped on 7/11/01 at 14:43:07



D27 – REPORT_pyr_small_0%.xls

Crystal Ball Report

Simulation started on 7/11/01 at 14:39:23
Simulation stopped on 7/11/01 at 14:46:46

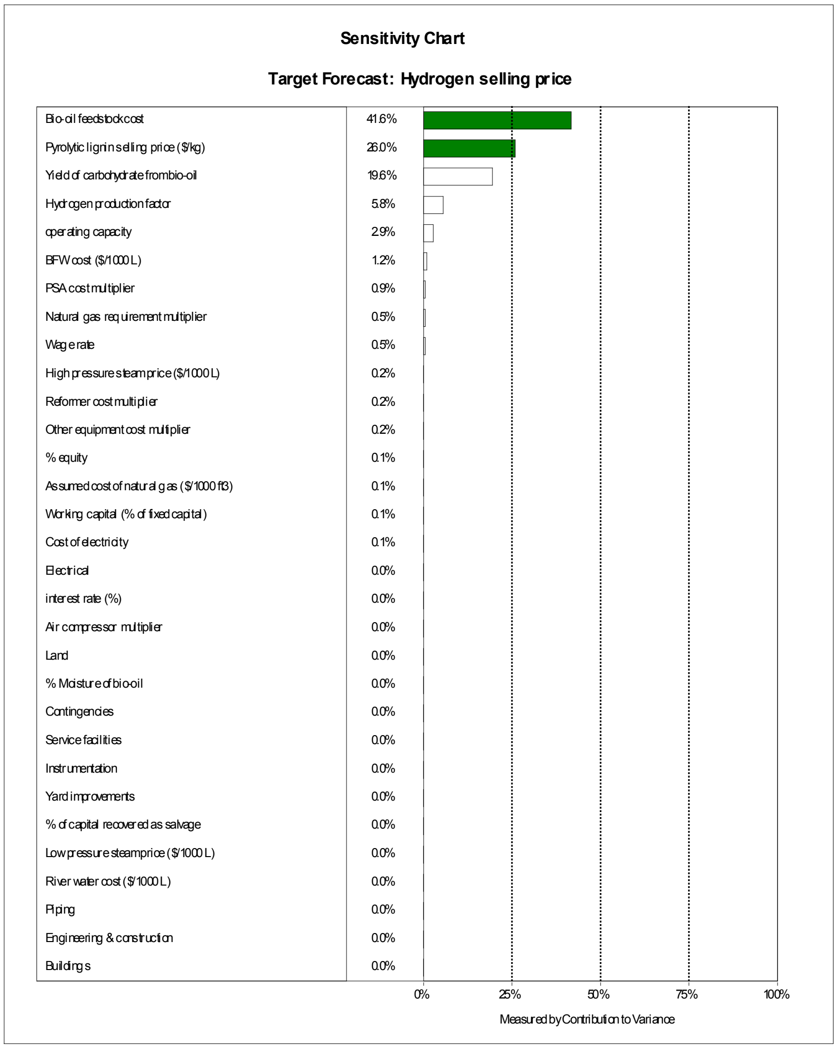


D28 – REPORT_pyr_small_10%.xls

Crystal Ball Report

Simulation started on 7/11/01 at 14:34:13

Simulation stopped on 7/11/01 at 14:37:18

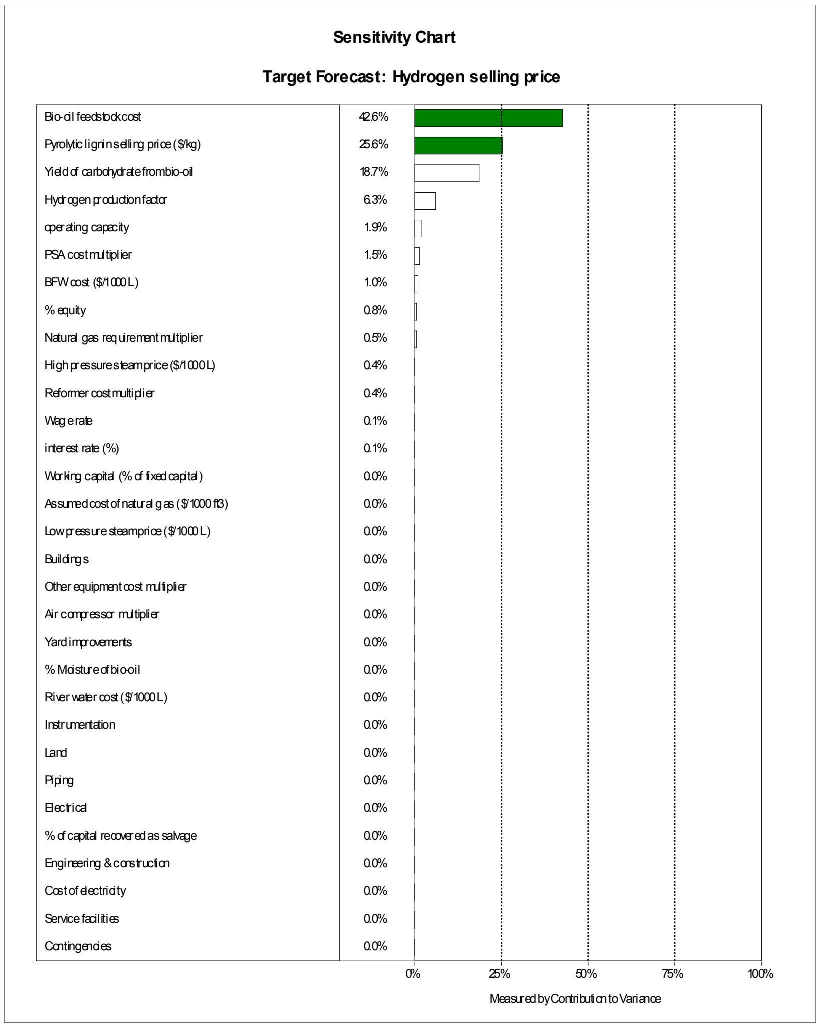


D29 – REPORT_pyr_medium_15%

Crystal Ball Report

Simulation started on 7/11/01 at 14:16:51

Simulation stopped on 7/11/01 at 14:20:40

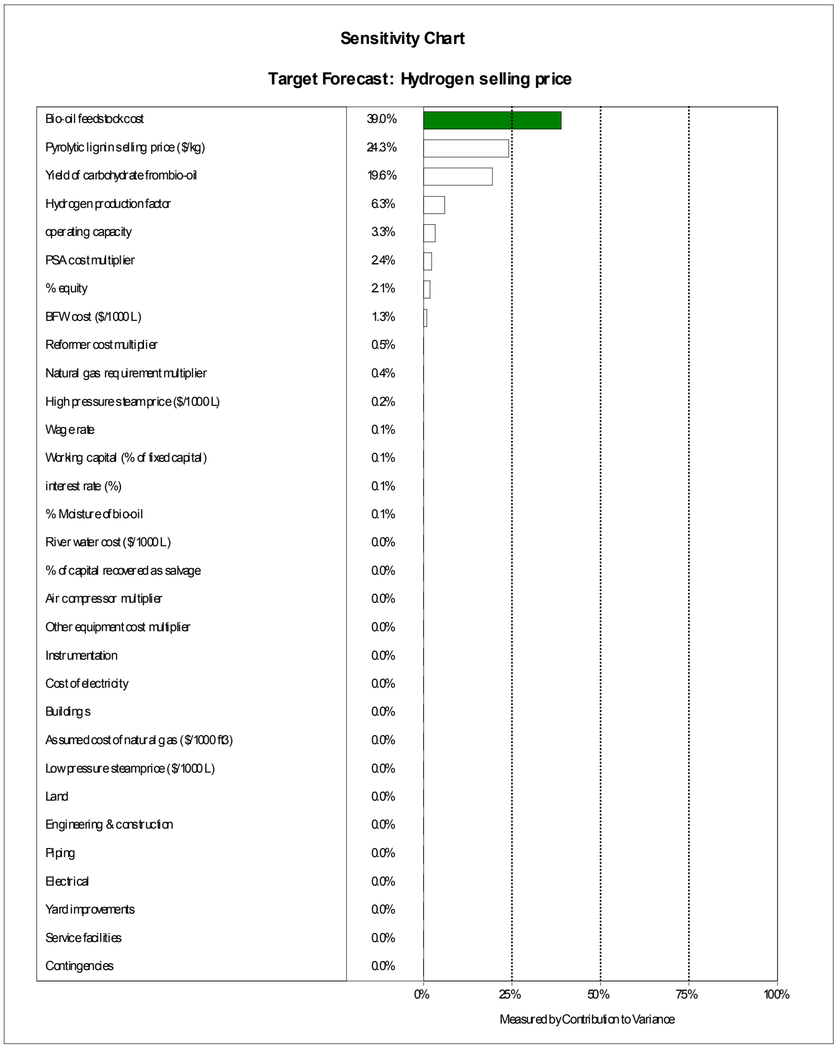


D30 – REPORT_pyr_medium_20%.xls

Crystal Ball Report

Simulation started on 7/11/01 at 14:22:07

Simulation stopped on 7/11/01 at 14:25:58

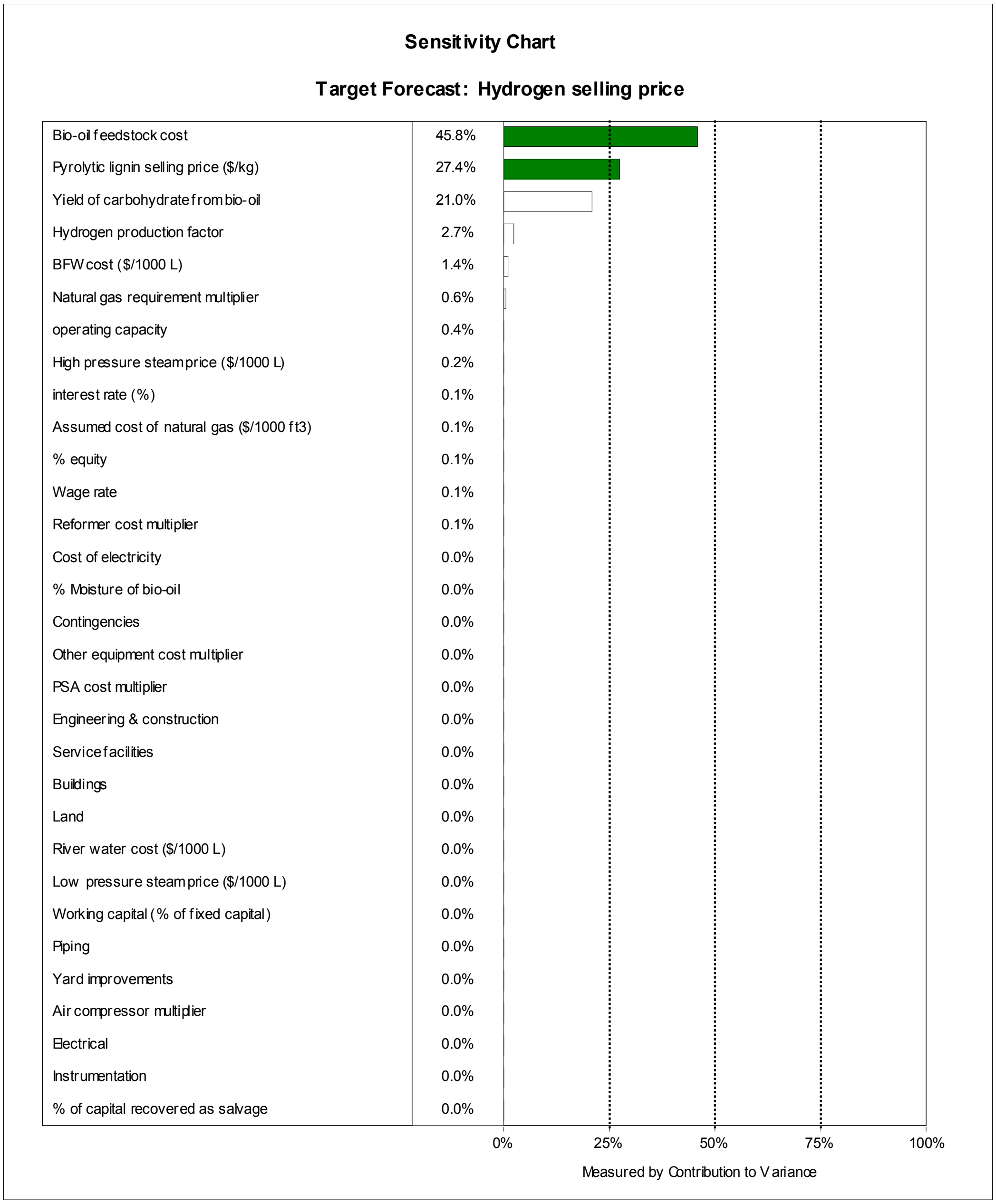


D31 – REPORT_pyr_medium_0%.xls

Crystal Ball Report

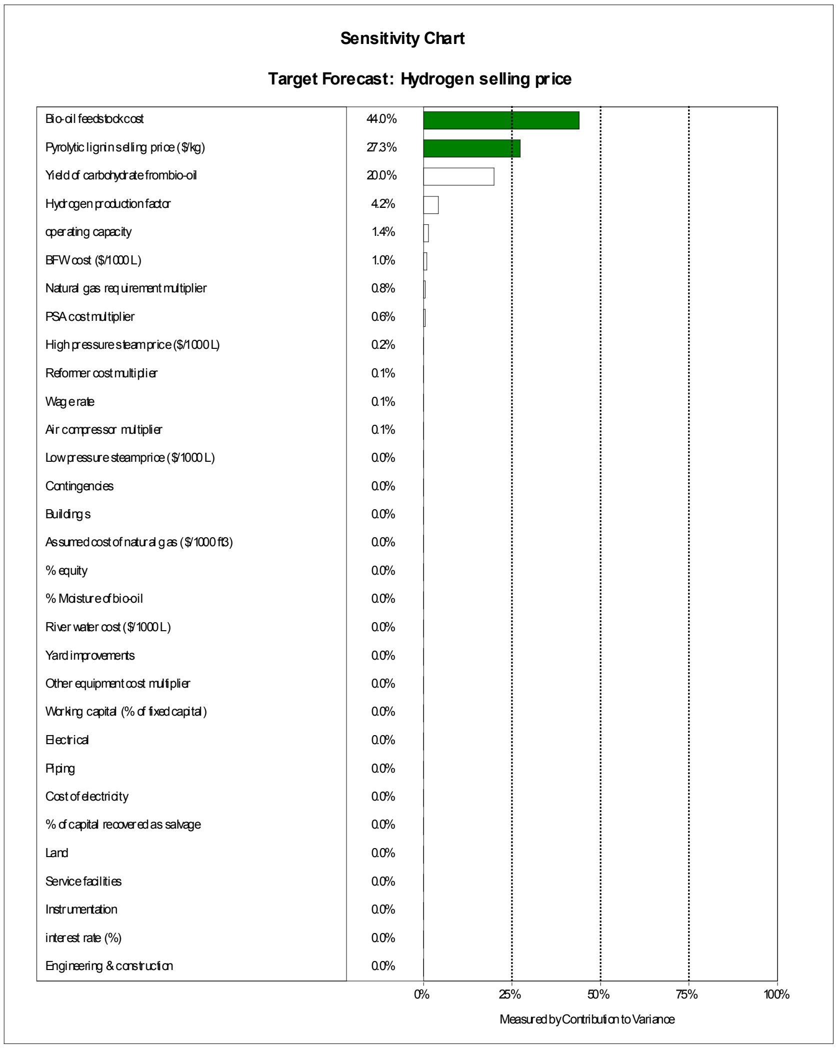
Simulation started on 7/11/01 at 14:50:23

Simulation stopped on 7/11/01 at 14:57:36



D32 – REPORT_pyr_medium_10%.xls

Crystal Ball Report
Simulation started on 7/11/01 at 14:08:43
Simulation stopped on 7/11/01 at 14:12:15



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Milestone report summarizing the economic feasibility of producing hydrogen from biomass via (1) gasification/reforming of the resulting syngas and (2) fast pyrolysis/reforming of the resulting bio-oil.

14. SUBJECT TERMS
Biomass-to-Hydrogen Cost; Biomass-to-Hydrogen Economics; Thermochemical Biomass-to-Hydrogen Conversion

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