Rapport SGC 210

Hydrogen Production for Refuelling Applications

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Executive Summary

Since 2007, Intelligent Energy (IE) has been involved in developing technologies and services in the hydrogen generation space with E.On Gas AB and The Swedish Gas Technical Centre. The aim of this work is to support the development of a high-profile demonstration of hydrogen generation technologies in a Swedish context. The overall objective of the demonstration is to deploy a reforming based hydrogen refilling station along the Swedish west coast; intermediate to the Malmö refuelling station and planned stations in Göteborg. In this way, the Norwegian hydrogen highway will be extended through the south of Sweden and down into Denmark.

The aim of the project's first phase, where this constitutes the final report, was to demonstrate the ability to operate the IE reforming system on the E.On/SGC site-specific fuel. During the project, a preliminary system design has been developed, based on IE's proprietary reformer. The system has been operated at pressure, to ensure a stable operation of the downstream PSA; which has been operated without problems and with the expected hydrogen purity and recovery. The safe operation of the proposed and tested system was first evaluated in a preliminary risk assessment, as well as a full HazOp analysis.

A thorough economic modelling has been performed on the viability of owning and operating this kind of hydrogen generation equipment. The evaluation has been performed from an on-site operation of such a unit in a refuelling context. The general conclusion from this modelling is that there are several parameters that influence the potential of an investment in a Hestia hydrogen generator. The sales price of the hydrogen is one of the major drivers of profitability. Another important factor is the throughput of the unit, more important than efficiency and utilization. Varying all of the parameters simultaneously introduce larger variations in the NPV, but 60% of the simulations are in the \$90 000 to \$180 000 interval. The chosen intervals for the parameters were:

- Hydrogen Sales Price (\$5 - \$7 per kg)
- Investment Cost (\$70 000 - \$130 000 per unit)
- Throughput (20 - 30 kg/day)
- Feedstock Cost (\$0.15 - \$0.45 per kg)
- Availability (85% - 95%)

The return-on-investment is between \$90 000 and \$180 000 in 60 % of the 5 000 simulation runs, which leads to the conclusion that given these assumptions the owning and operation of such a unit can be profitable.

As for the performance of the system, it is concluded to be within targets based on the different performance measures reported above. The conversion is in the expected range (80-85%), given the throughput of 16 kg of hydrogen per day. The efficiency as reported is in the acceptable range (~65%), with some room for improvement within the given system architecture, if desired. However, there is a trade-off between throughput, efficiency and cost that will have to be considered in every redesign of the system. The PSA chosen for the task has performed well during the 200+ hrs of operation and there is no doubt that it will be sufficient for the task. The same thing can be said with respect to the system performance with respect to thermo-mechanical stress; which was proven by operating the system for more than 500 hours and performing 58 start-and-stop cycles during the testing.

There does not seem to be any major differences between operating on natural gas or methane, based on the testing performed. The slight decrease in hydrogen production can be due to a difference in the H_2/CO ratio between the various fuels. As expected the efficiency increases with load as well as the hydrogen production rate.

Based on the results disseminated above, there is no indication why the current reactor system cannot be configured into a field deployable system. The operation of the system has given valuable experience that will be embedded into any field deployed unit.

Contents

Abbreviations

ASME	American Society of Mechanical Engineers
ATR	Auto-Thermal Reforming
BG	Biogas
BMG	Biomass-Derived Methane-Rich Gases
DG	Digester Gas
E.On	E.On Gas AB
FT	Fischer-Tropsch
HC	HydroCarbon
HCNG	Hydrogen/natural gas mixture
HazOp	Hazards and Operability study
IE	Intelligent Energy
kW	Kilowatt
kWh	Kilowatt hour
LEL	Lower Explosion Limit
LFG	Land-Fill Gas
LPG	Liquefied Petroleum Gas
MeOH	Methanol
NDIR	Non-Dispersive Infra-Red
NPV	Net Present Value
PID	Piping and Instrumentation Diagram
PLC	Programmable Logic Computer
PSA	Pressure Swing Adsorption
PSI	Pounds per Square Inch (14.7 PSI/ Bar)

POX	Partial Oxidation
RAMD	Reliability, Availability, Maintainability and Durability
SGC	Swedish Gas Technical Centre
slpm	Standard Litres Per Minute
SMR	Steam Methane Reforming
SNG	Substitute Natural Gas
TT	Temperature Transmitter
WGS	Water-Gas Shift

1 Introduction

Since 2007, Intelligent Energy (IE) has been involved in developing technologies and services in the hydrogen generation space with E.On Gas AB (E.On) and The Swedish Gas Technical Centre (SGC). The aim of this work is to support the development of a high profile demonstration of hydrogen generation technologies in a Swedish context. The overall objective of the demonstration is to deploy a reforming based hydrogen refilling station along the Swedish west coast; intermediate to the Malmö refuelling station and planned stations in Göteborg. In this way, the Norwegian hydrogen highway will be extended through the south of Sweden and down into Denmark.

The program, with the objective of field deploying a hydrogen generator, has been divided into several phases over a 36 month period and this report constitutes the end of the first phase. The phase has been operated as an SGC project with the project number 07.29 entitled Hydrogen Production for Refuelling Applications.

The project is a component of IE's sustained investment in developing hydrogen generation and fuel cell systems using a variety of feedstocks, for several purposes. The performed phase aimed to validate the operation of IE's small-scale reformer system using Sweden specific conditions; like for instance, Swedish gas conditions and market opportunities.

1.1 Background

Development of hydrogen generation equipment at IE has been performed since 2004, when Element One Energy was acquired. The work was accelerated in 2005with the acquisition of MesoFuel based in Albuquerque. The two locations have provided significant combined reformer development experience, including competence in non-catalyzed partial oxidation (POX), catalyzed POX, auto-thermal reforming (ATR) and steam reforming (SMR). The IE team has demonstrated successful reforming of a wide variety of fuels including liquefied petroleum gas (LPG), natural gas, ammonia, propane, diesel, synthetic diesel, soy-diesel, kerosene, methanol and ethanol. Experience of the staff with respect to hydrogen generation includes the design, development, manufacture and deployment of several technology platforms and pre-commercial products as part of IE and prior companies:

- 10 and 20 Nm^3/hr pure hydrogen generation systems (POX/PSA) for on-site industrial hydrogen generation and vehicular refuelling. This technology platform was marketed and deployed in pre-production volumes as a cost-competitive replacement for bottled hydrogen delivery;

- Compact ATR based 10 kWe reformer system for residential fuel cells. This technology platform was developed to pre-commercial levels and successfully integrated with several third party PEM fuel cell systems;

- Manufacture and validation of pre-commercial portable 100 We ammonia fuelled hydrogen generator;

- Completed validation testing of prototype 250 We propane fuelled hydrogen generators;

- Compact steam reformer system with integral PSA generating 7 Nm^3/hr of pure hydrogen, advanced liquid phase sulphur adsorbents and on-board, sulphur removal systems for auxiliary power applications fed with logistics fuels and safe ammonia and LPG storage systems; and

- Core to the Hestia unit is an integrated steam reformer/fuel processor and a hydrogen purification system based upon an advanced pressure swing adsorption unit (PSA). The reformer is based on a proprietary and exclusive advanced integrated steam reforming technology designed to provide inter-stage mixing to maximize chemical conversion efficiency and heat transfer. The reformer and water-gas shift catalyst system support high space velocities and reaction rates while incorporating both sulphur and oxygen tolerance. The catalyzed combustor is integral to the staged reformer elements and provides tailored temperature profiles and the ability to vary the temperature profile to enhance performance evaluations using the site specific fuels. The temperature profile within the water-gas shift reactor can also be adjusted and controlled independent of other parameters. The speed and cycle control of the rotary valves integral to the pressure swing adsorption unit provide additional enhanced control flexibilities to assess process parameters. (1)

The fuel intended to be used in the phased program is biogas, supplied via the natural gas grid. For the testing purposes in this phase, however, natural gas supplied via compressed cylinders purchased from a local supplier in Long Beach, California was used. In Sweden, biogas is produced e.g. via fermentation and upgraded to different qualities. The term biogas (BG) sometimes refers to a gas produced by the anaerobic digestion or fermentation of any biodegradable organic matter, such as manure, sewage sludge etc. A more narrow interpretation of the term however refers to gas produced by anaerobic digestion of agricultural and animal waste, whereas the raw material of digester gas (DG) is sewage/sludge and hence covered by the broader definition of biogas. (2)

Landfill gas (LFG) is the gaseous reaction product from degradation of organic matter in the waste disposed in landfills using anaerobic microorganisms. The gas is recovered using pipelines buried in the landfill. LFG contains high levels of CO_2 and impurities (3). There are several advantages to use Biomass-Derived Methane-Rich Gases (BMG). Firstly, the raw material is found locally and the need for transport is reduced, as are imports of conventional fuels. In most cases, BMG is derived from waste which would otherwise incur disposal costs. Furthermore, the methane which is extracted and used in the process could otherwise be released to the atmosphere and since it is a serious greenhouse gas (21 times as potent as carbon dioxide), be a contributor to the global warming problem. Another alternative would be combustion of this material but not without serious drying and/or addition of other fuels since it has a low heating value. (2)

The BMG can be used to produce pure hydrogen e.g. for fuel cell applications. There is also the possibility to use it in gas engines. It then needs less purification and the CO_2 could even be advantageous for use in a gas engine, whereas fuel cells are very sensitive to some impurities. (4)

BG and LFG are complex gas mixtures. Table 1 depicts some typical compositions of hydrocarbon gases.

Table 1 the composition of land-fill gas and bio gas, before upgrading **(5)**.

		LFG	**BG**	**Natural Gas***
Lower heating value	MJ/Nm^3	16	23	40
	kWh/Nm^3	4.4	6.5	11
	MJ/kg	12.3	20.2	48
Density	kg/Nm^3	1.3	1.2	0.83
Wobbe index, upper	MJ/Nm^3	18	27	55
Methane number		>130	>135	72
Methane	vol-%	45	65	89
Methane, variation	vol-%	35-65	60-70	-
Higher hydrocarbons	vol-%	0	0	10
Hydrogen	vol-%	0-3	0	0
Carbon monoxide	vol-%	0	0	0
Carbon dioxide	vol-%	40	35	0.9
Carbon dioxide, variation	vol-%	15-50	30-40	-
Nitrogen	vol-%	15	0.2	0.3
Nitrogen, variation	vol-%	5-40	-	-
Oxygen	vol-%	1	0	0
Oxygen, variation	vol-%	0-5	-	-
Hydrogen sulfide	ppm	<100 ppm	< 500	3
Hydrogen sulfide, variation	ppm	0-4000 ppmv (6)	0-4000	1-8
Ammonia	ppm	5	100	0
Total chlorine as Cl^-	mg/Nm^3	20-200	0-5	0

* Danish Natural Gas, average composition during 2005.

Other options for the reprocessing of BMG are summarised in **Fel! Hittar inte referenskälla.**. If the only unit operation is CO_2 removal, bio-methane is obtained. This is commonly used as vehicle fuel, in some cases this gas is also carburated using propane gas (LPG) before export to the natural gas grid. Substitute Natural Gas (SNG) is achieved if the CO_2 and CO goes through a methanation process. Methanol can also be produced. A final example is production of heavier (liquid) hydrocarbons such as synthetic gasoline or synthetic diesel.

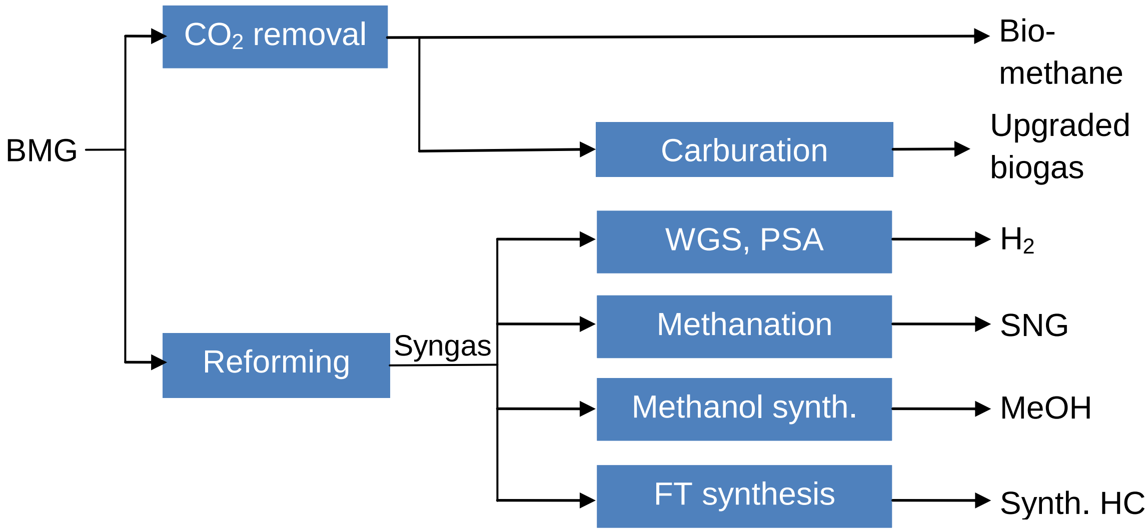

Figure 1 Production of alternative fuels from RMG. WGS = Water-Gas Shift, PSA=Pressure Swing Adsorption, SNG=Substitute Natural Gas, MeOH=methanol, FT=Fischer-Tropsch, HC=Hydrocarbons **(6)**

In this case, the gas that was used for hydrogen production is the one that is termed upgraded biogas. This gas is exported to the natural gas grid, mixed with the existing natural gas, and can be subtracted elsewhere in the gas grid. This means that the gas to be reformed is in its composition equal to the natural gas in the natural gas grid; please visit Table 1 for a description.

1.2 Disposition

After this introductory section which gives some background related to the project, the next section will contain the preliminary system design. It will also contain a risk assessment performed on the system before the operation, as well as the results and conclusions of the experimental work. The next section will give insight into the financial conditions behind owning and operating a small-scale hydrogen generator. This section starts by giving information on the model and continues by disseminating the results of Monte Carlo simulations using the model and finally the conclusions are given. In a final section, a summary of the work performed is given.

2 Experimental

In this section, the preliminary system design will be reported, as well as the findings of the Haz-Op performed on the system. The section will also contain the results from operating the system, as well as some conclusions that can be drawn from the operation.

2.1 Development of Preliminary System Design

For the purpose of this and other programs, IE has designed/assembled and successfully characterized a new annular, heat exchanger type reformer, which has now run more than 500 hours on pure methane. A commercially available PSA hydrogen purification unit was integrated with the reformer whereby the output purity from the system was routinely higher than 99.9%. The test system (A.K.A. Hestia) capacity was validated to produce a minimum of 15 kg/day of hydrogen and has also reached the expected level of thermal efficiency. Figure 2 shows the steam reformer and shift vessel piping and instrumentation (PID) diagram as the system is currently configured. The PSA and other sub-systems process schematics have been omitted from this report for the purpose of brevity.

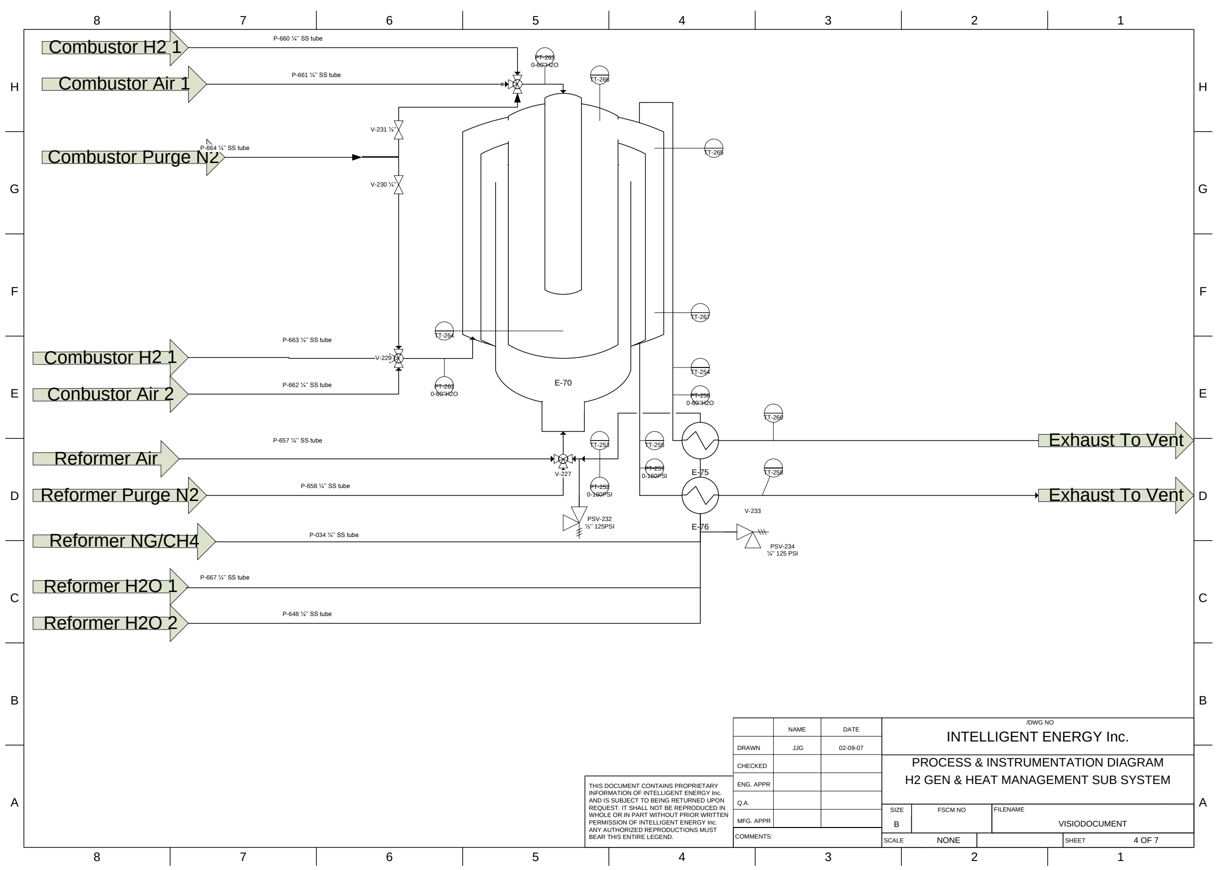

Figure 2: Piping and Instrumentation Diagram of reformer

The assembled test unit is shown in Figure 3 and Figure 4, where the system is shown in a non-packaged breadboard type set-up. In the figures, there is also the manual supervision equipment in the shape of gauges and rota-meters.

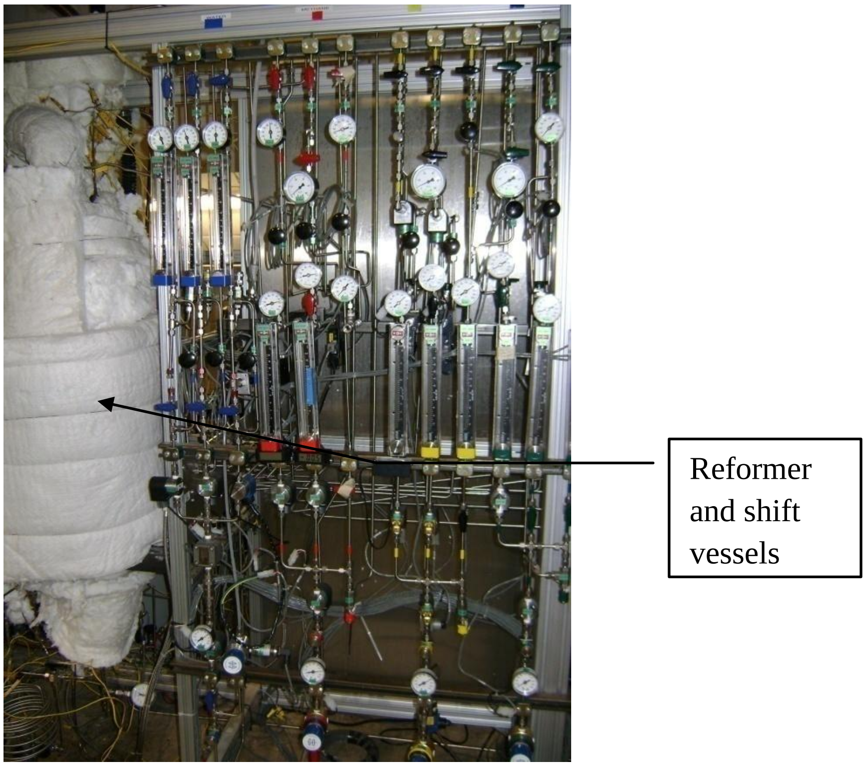

Figure 3: Hydrogen Generation Test Unit

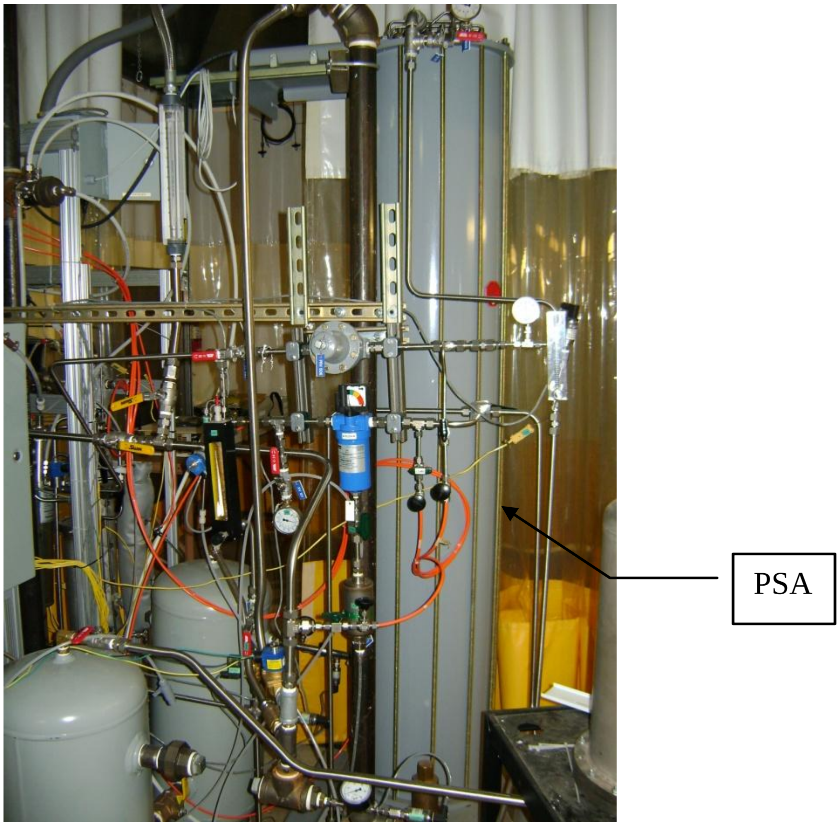

Figure 4: PSA Sub-System

The test unit is controlled through a programmable logic controller (PLC) and PC interface so that the operator can manipulate various parameters such as flow, pressure and temperature to gather data that are recorded/trended over time as the runs progress. Figure 5 shows one of four monitor interface screens providing real-time data from the reformer.

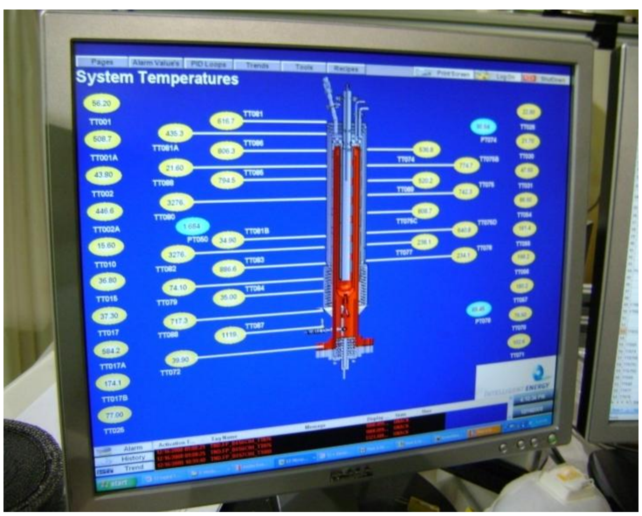

Figure 5: Graphical User Interface

Estimates of efficiency have been calculated according to procedures specified by ISO 16110-1 Part 2: “Procedures to Determine Efficiency”. Once the system reaches steady-state operation, the PSA delivers pure (within gas analyser calibration/detection limits) Hydrogen as recorded by a Siemens NDIR equipment seen in Figure 6.

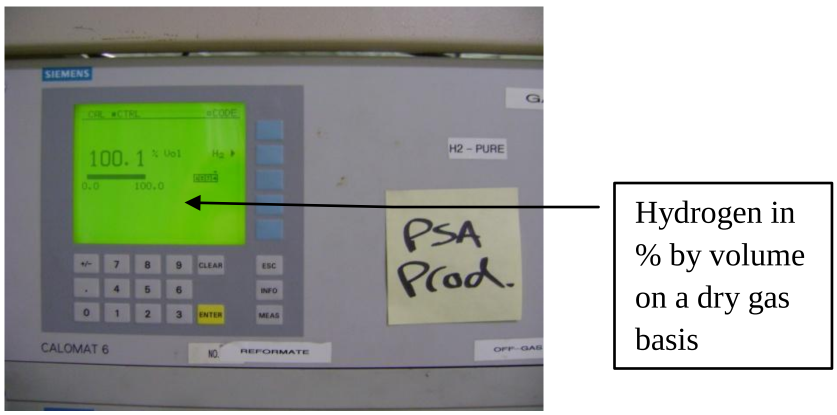

Figure 6: PSA Product Hydrogen

In the weeks between October and November 2008, IE began the design modifications necessary to begin testing our core Hestia reformer on natural gas. These modifications include the design and installation of a feed-gas pre-treatment compression sub-system whereby city gas is compressed to 100 psig. Figure 7 and Figure 8 depict the design and equipment respectively.

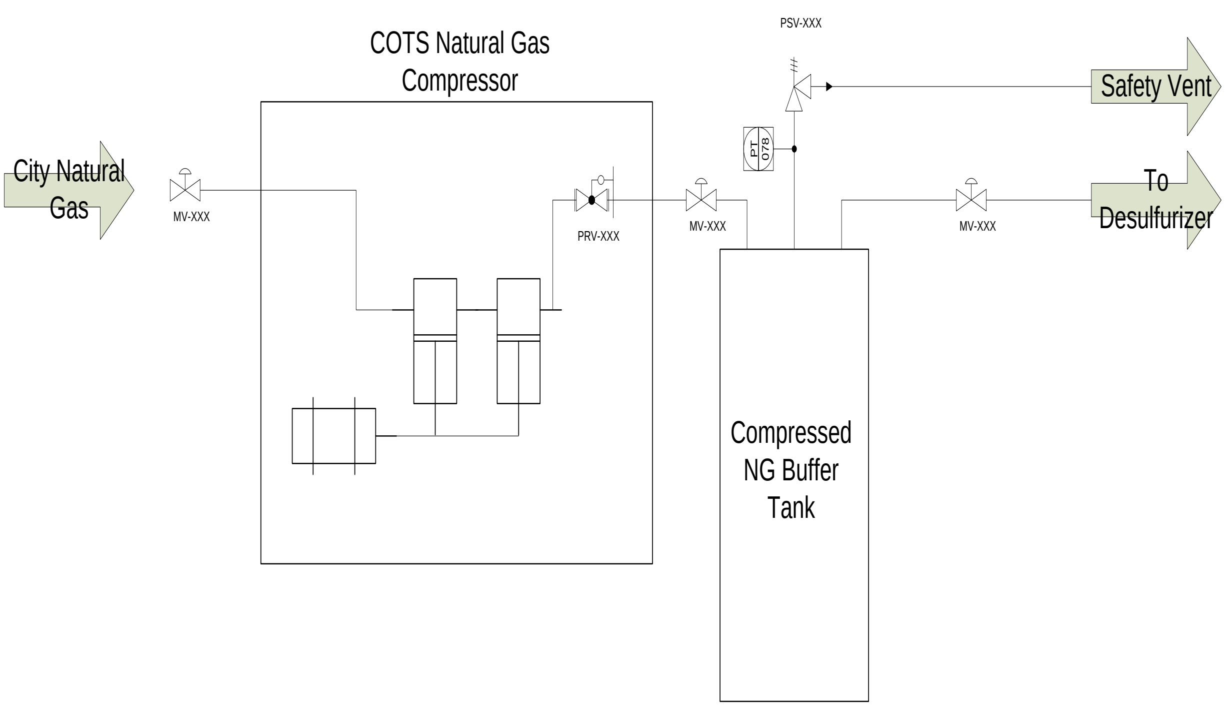

Figure 7: Piping and Instrumentation Diagram-Gas Delivery Sub-System

Figure 8: Natural Gas Compressor Installation

A sulfur removal and water trap have also been designed and installed. The sulfur removal traps have been packed with a purpose-built molecular sieve provided by W.R. Grace. Figure 9 and Figure 10 show the design and equipment respectively. Due to a short delay in getting this compressor/desulfuriser subsystem validated before the end of February, IE chose to use the bottled natural gas as described in other sections of this report.

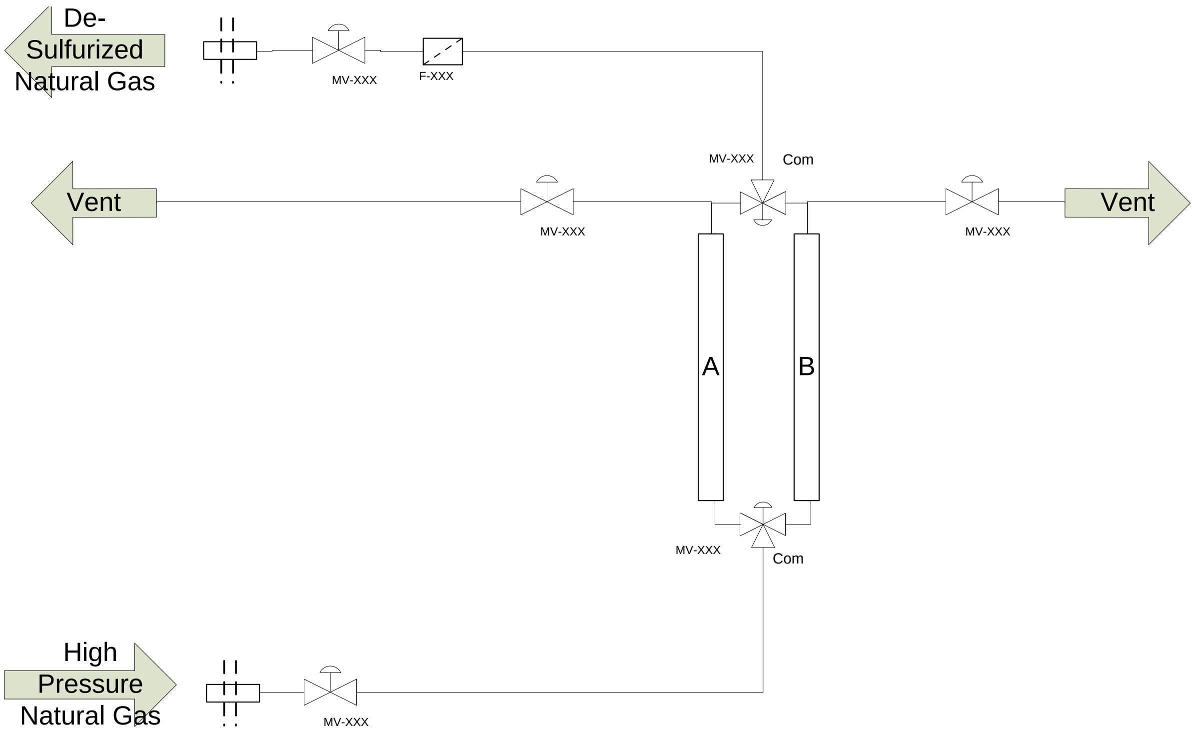

Figure 9: Piping and Instrumentation Diagram-Desulfurisation Sub-System

Figure 10: Desulfurisation Traps

2.2 HazOp

With safety in mind, IE has identified a risk assessment procedure that has served as the basis of a more formal hazards and operability (HazOp) analysis that were conducted around the hydrogen generation system during the month of January 2009. The following bullets show the primary safety issues that were addressed as part of this review:

- Fire / Explosions
- Electricity
- Use of work equipment
- Contact with hot surfaces
- Compressed gases/ pressurised systems
- Temperature,
- Review of MSDS data for materials used or generated in the process
- Personal protective equipment
- Potential deterioration of equipment

The likelihood of each risk was characterised according to the following scale:

- High 5
- Moderate 4
- Medium 3
- Low 2
- Very low 1

The severity of injury that could be caused was characterised according to the following scale:

- None 5
- High 4
- Medium 3
- Low 2
- None 1

Regarding hydrogen specifically, the potential for leakage is minimised through consistent application of proven engineering principles (i.e. ASME standards) to hardware design and through regular leak-testing of every test apparatus. Hydrogen gas and carbon monoxide gas detectors are used to order to detect a leak, if a leak were to occur. Gas detectors are integrated into testing system user interfaces so that operators will immediately be aware of a leak. Forced and/or induced ventilation is used in test areas in order to preclude the possibility of an explosion. Ventilation systems for testing are sized such that leakage of the full output of a system under test would be diluted to less than 25% of the lower explosive limit (LEL) as it was carried out of the building. Ventilation hoods are designed to preclude accumulation of hydrogen in "dead spots."

In addition to addressing the safety topics above, a high-level process system HazOp was conducted using PHA Works risk analysis software. The report generated from this exercise is included in Appendix A.

2.3 Results

In the July-December 2008 timeframe, IE completed more than 500 hours of testing on the newly redesigned tubular Hestia reactor configuration. Out of the approximately 500 hours of reforming, the PSA hydrogen purifier was integrated into the system producing more than 99.99% pure hydrogen for a total of 250 hours. The fuel used during this test was bottled methane, to simplify the data evaluations procedure. The core reactor also underwent 58 cold cycle start-ups (from room temperature to having produced fuel cell grade hydrogen at the unit's full capacity). These data are shown in Figure 11.

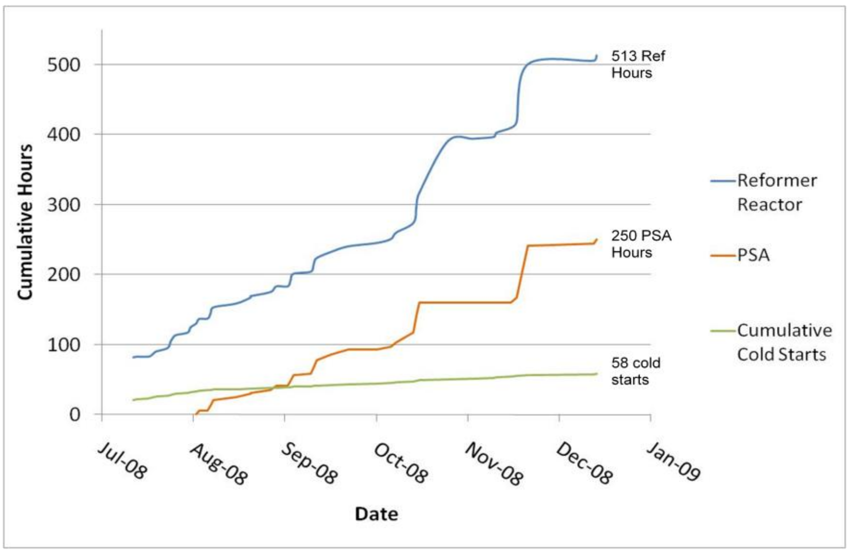

Figure 11: 500 hour reformer test performed on methane.

In addition to the 513 hours of testing on the Hestia reformer, the testing team was able to optimize process conditions such that thermal efficiency in the range of 65 to 70% was obtained, while producing 128 slpm of hydrogen or 16 kg/day. The system has been optimized for running at 65% efficiency, for a number of reasons. One reason is some finer points of temperature control in the combustor which will be alleviated in a new design which is currently being developed. In the design work, efficiency and throughput has been valued against each other and at this throughput, the 65% efficiency has been chosen. This efficiency (based on the entire system) has been calculated on a regular basis, Table 2.

Table 2: Repeated reformer efficiency runs.

Thermal Eff. (%)	Load (slpm)	Time	H_2O/C	Supp. Fuel (slpm)
65.24	69.5	2008-09-24 16:27	2.86	0
64.94	69.4	2008-09-24 17:29	2.87	0
65.47	69.8	2008-09-25 17:11	3.08	5.3
65.65	69.5	2008-10-01 11:20	3.04	5.3
65.85	70	2008-10-01 13:30	3.13	0
65.21	61	2008-10-01 15:00	3.26	4.6
65.07	70	2008-10-02 15:41	3.04	5
65.27	60.7	2008-10-02 16:00	3.01	6
65.32	62	2008-10-02 17:40	2.91	7

In addition to the reformer testing, a WGS reactor was installed to validate/repeat the data collected on carbon monoxide (CO) conversion, first collected on 2008-10-02. As can be seen in the bottom row of Table 3, adding water (70cm^3/min) to cool the synthesis gas decreased the amount of CO leaving the WGS reactor; thereby indicating that the same or better conversion efficiency can be achieved with the particular catalyst chosen for use in the hydrogen production system.

Table 3: Shift catalyst and shift reactor cooling validation

	Date	H_2O to Super heater (ccm)	H_2O to Quench (ccm)	H_2O to Shift (ccm)	CO to Shift (%, dga)	CO out shift (%, dga)	Thermal Efficiency (%)
Previous Shift Reactor	2008-10-02	107	40	0	13.3	3.6	65
New Shift Reactor	2008-10-28	40	20	70	11.5	1.5	69

After completing several cold-cycle start-ups on the reactor, the integrity of the system was of interest with respect to thermo-mechanical stress etc., especially whether any cracks or leaks were formed at either a fitting or welded location. Pressure tests were conducted to confirm that the high-pressure portion of the reactor did indeed hold-up to the high temperature (600-800°C) cycling over the course of its life to date. Figure 12 shows data from these tests.

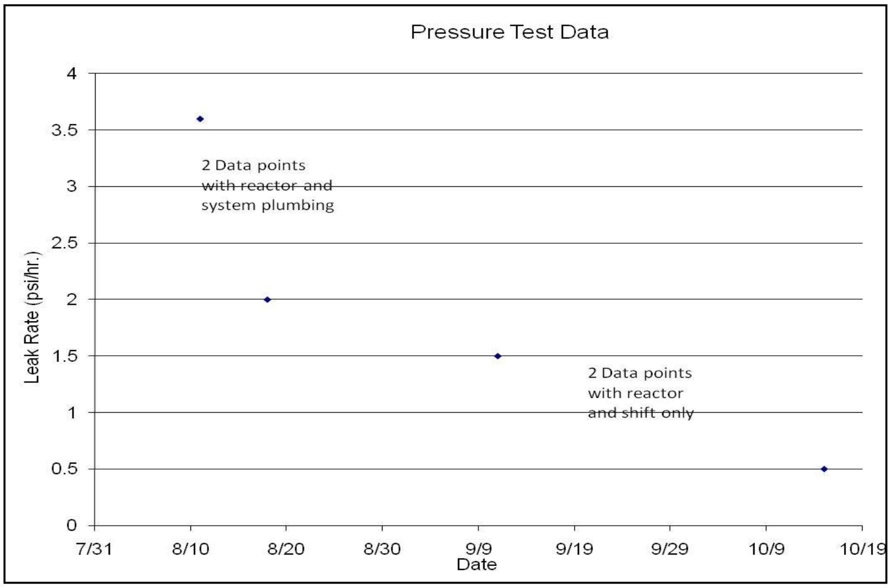

Figure 12: Reactor pressure vessel pressurisation test.

On October 15th the core reactor leak rate of 0.5psig/hr was even less than it was back on August 10th when it measured 3.6 psig/hr. This lower leak rate over time may be the result of compression fittings haven tightened up/sealed after having been heated several times.

To determine the influence of the reforming temperature on the conversion, said temperature was altered and the impact on the conversion was noted. Because of temperature distribution issues and insecurity in temperature indicators being placed at the exit temperature, several temperatures have been plotted and compared to the expected equilibrium composition, Figure 13.

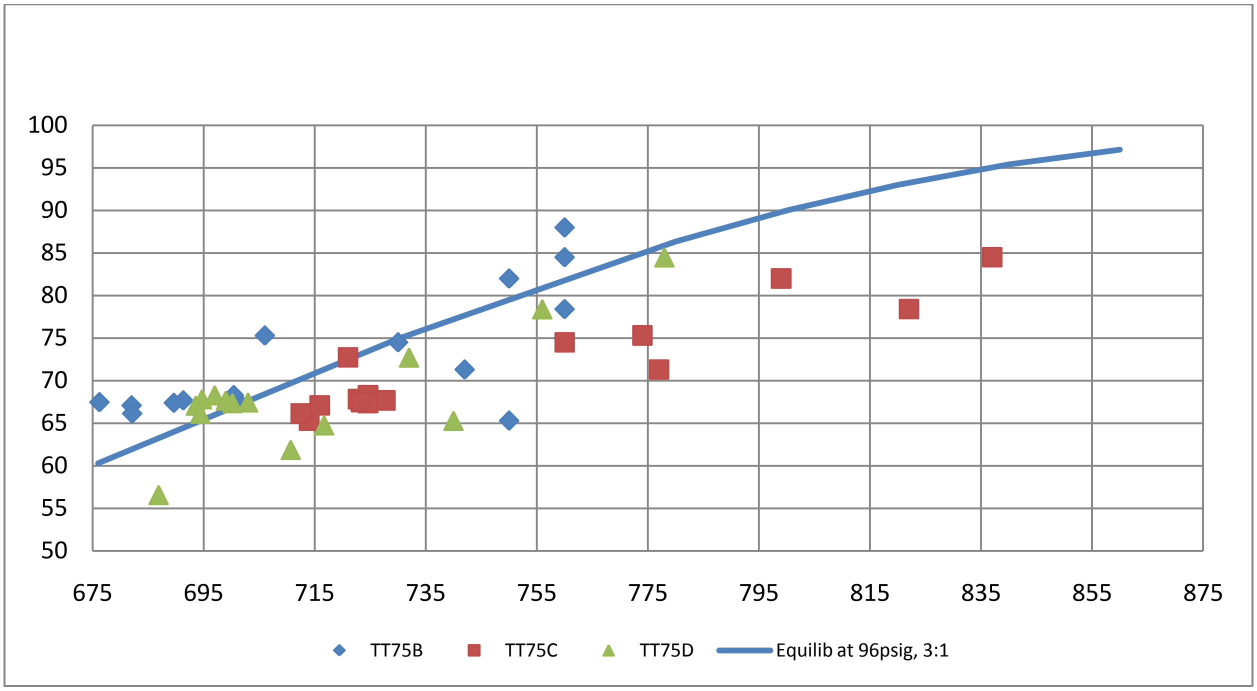

Figure 13: The effect of different temperatures on the conversion, at 70 slpm of methane feed to the unit and a steam-to-carbon ratio of 3; the equilibrium composition is calculated at the same steam-to-carbon ratio and 6.6 bar.

As can be seen in the figure, there is a strong correlation between the temperature and the conversion, as expected. The temperature that best corresponds to the actual reformer temperature is the one denoted TT75C (based on the data above and the positioning of the thermocouple). The reason that some of the conversions are above equilibrium is explained by the thermocouple positioning and small errors in measurement, however a majority of the data are in the expected area.

When investigating the overall efficiency of the system, calculated according to ISO 16110-1 part 2, the impact of several parameters have been investigated. A relevant parameter in the context is the steam-to-carbon ratio, which determines the driving force for the steam reforming reaction. However, the more steam required, the more steam needs to be boiled and inevitably increases heat losses. The effect of changing the steam-to-carbon ration on the system can be viewed in Figure 14.

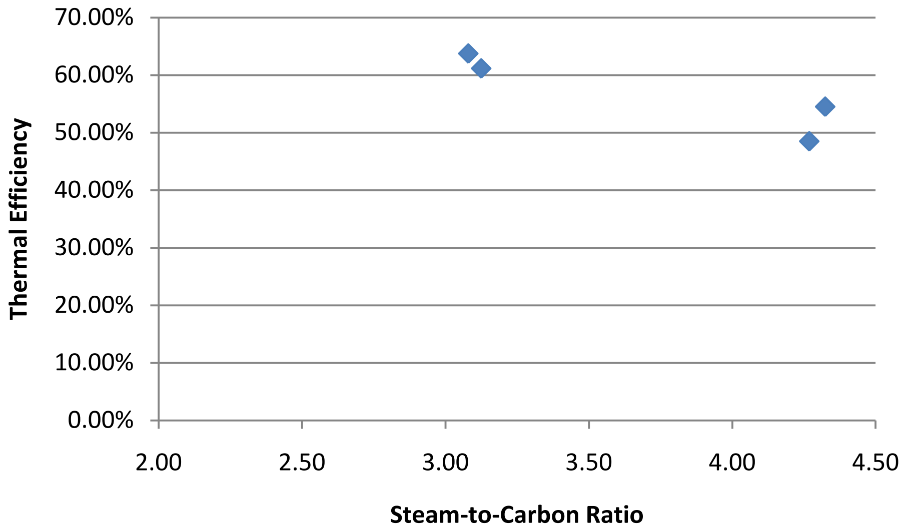

Figure 14: The effect of different steam-to-carbon ratios on the thermal efficiency, at 70 slpm of methane feed to the unit and a 6.5 bar pressure.

As per Figure 14, there is a distinct loss of efficiency when the steam-to-carbon ratio tails off. This indicates that the system should be operated at as low a steam-to-carbon ratio as possible, but ensuring enough steam is present to avoid carbon depositions. It is however plausible that in a different set-up, as for instance in a combined heat-and-power application, there is another optimal operating point. In this case, the heat produced and dissipated via the steam can be used (e.g. space heating).

By changing the system pressure, it was noted that the operability of the PSA got drastically worse. The operating point chosen for the experiments (6.5 bar) is a trade-off between the optimal reactor operating pressure and the PSA favoured operating pressure.

The use of a higher PSA recovery rate, with a lowering in hydrogen quality would be favourable in the production of hydrogen/natural gas mixtures (HCNG). The current PSA however, does not allow for a much higher output of product without making system alterations. It is however believed that performing such modifications would result in an efficient system for HCNG production, should that be of interest.

To exemplify the trade-off between efficiency and conversion the throughput was changed, Figure 15.

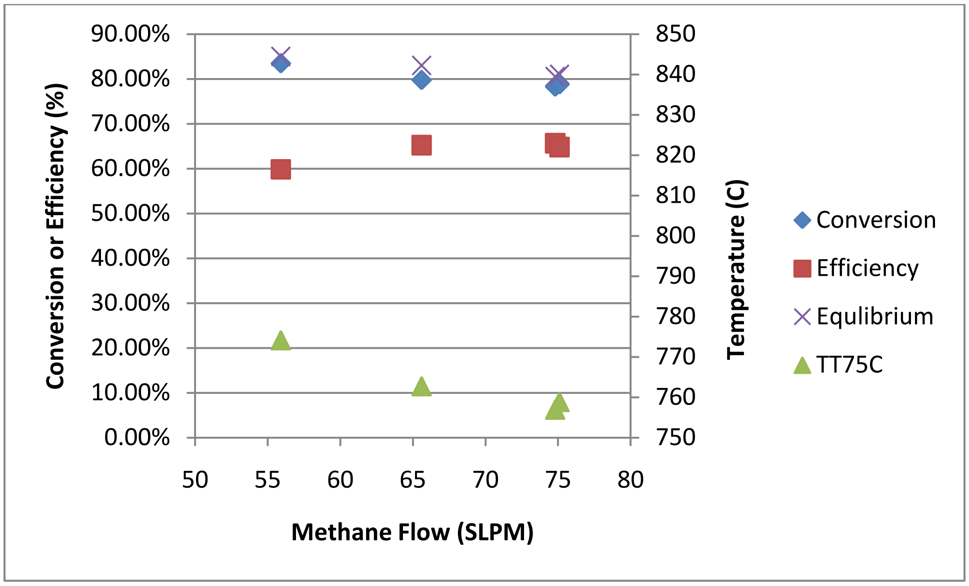

Figure 15: The impact of throughput on the thermal efficiency and conversion, at 70 slpm of methane feed to the unit and a 6.5 bar pressure.

It is obvious that there is a correlation between an increased throughput and a higher efficiency, despite a slight tailing-off in the conversion. The decrease in conversion can be explained by a decrease in the reformer exit temperature, as indicated in the figure. This is due to a higher endothermic heat load caused by the increase in reforming; and hence the equilibrium composition possible to reach is lowered. In Figure 16 the system performance, including efficiencies with PSA integrated and kW of H_2 in the reformate and in the product stream, is presented.

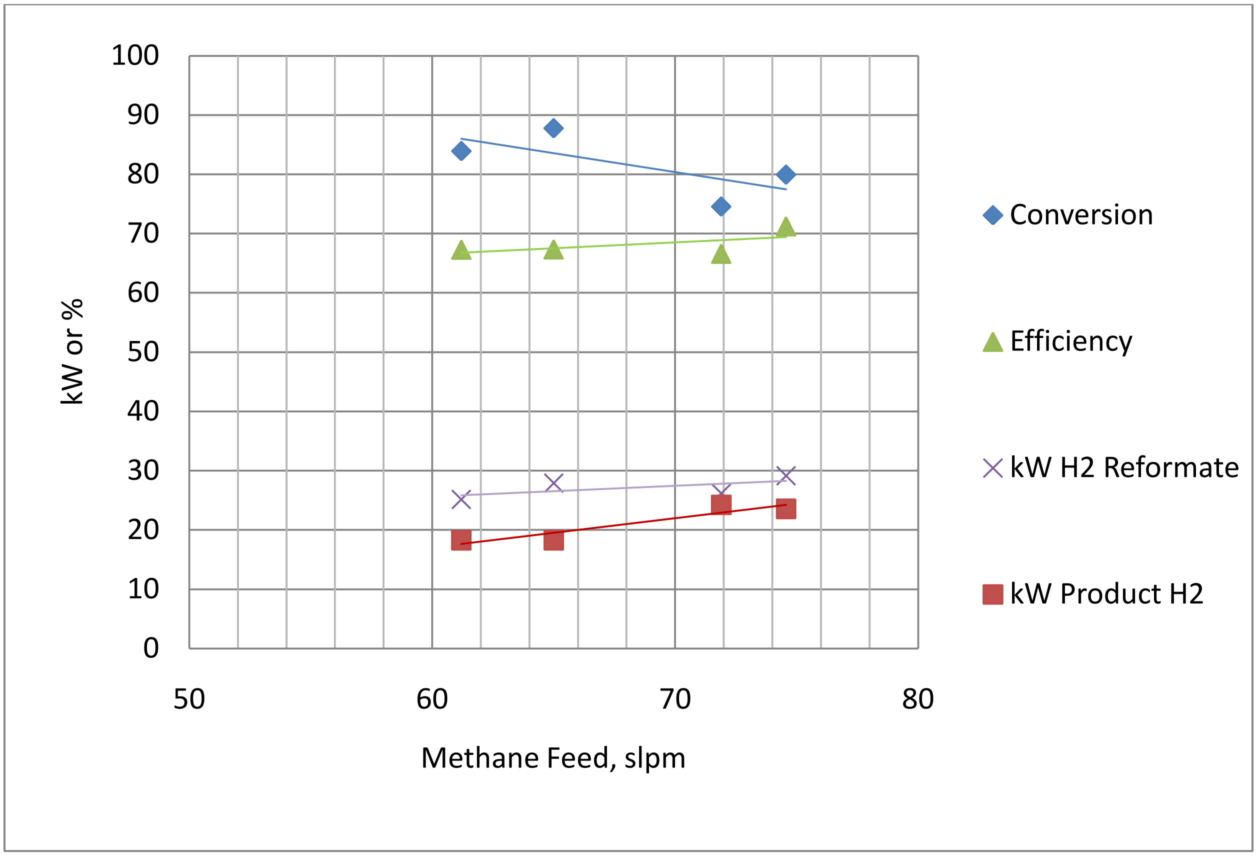

Figure 16: Summary on the system performance at different methane feed rates and at 6.5 bar pressure

As displayed before, the efficiency tails off with increased methane flow rate. This is due both to a more or less constant heat loss from the system, independent of load, and to the balance between the rejected gases from the PSA; that used as the reformer fuel. The reformer conversion is in the 70-80% range, depending on the feed rate. The carbon monoxide conversion in the water-gas shift is in the 80-85% range, with a PSA recovery of 70-73% at 6.5 bar. This in total gives a hydrogen production of 22-25 kW at 70-72 slpm of methane at a pressure of 6.5 bar, yielding an overall efficiency of 65-70% for the integrated system.

Natural gas operation was tested on multiple days. The objective was to demonstrate similar performance with natural gas compared to the bottled methane tests (much of the testing was done on bottled methane). The following data validated the similarity by a direct switch from methane to natural gas while temperatures and outputs remained similar on both feedstocks. The natural gas was fed at 15:15 then kept running until 17:55. Both flow rates were approximately 62 slpm. All conditions were held constant. The overall methane conversion in both cases was approximately 69%. Hydrogen production dipped from 142 slpm to 137 slpm as the natural gas was introduced. Efficiency also dipped slightly from 69% to 67.7% with the natural gas. The decrease may have been due to not optimising the control and temperature conditions during the natural gas runs combined with the fact that the natural gas contained some heavier hydrocarbons.

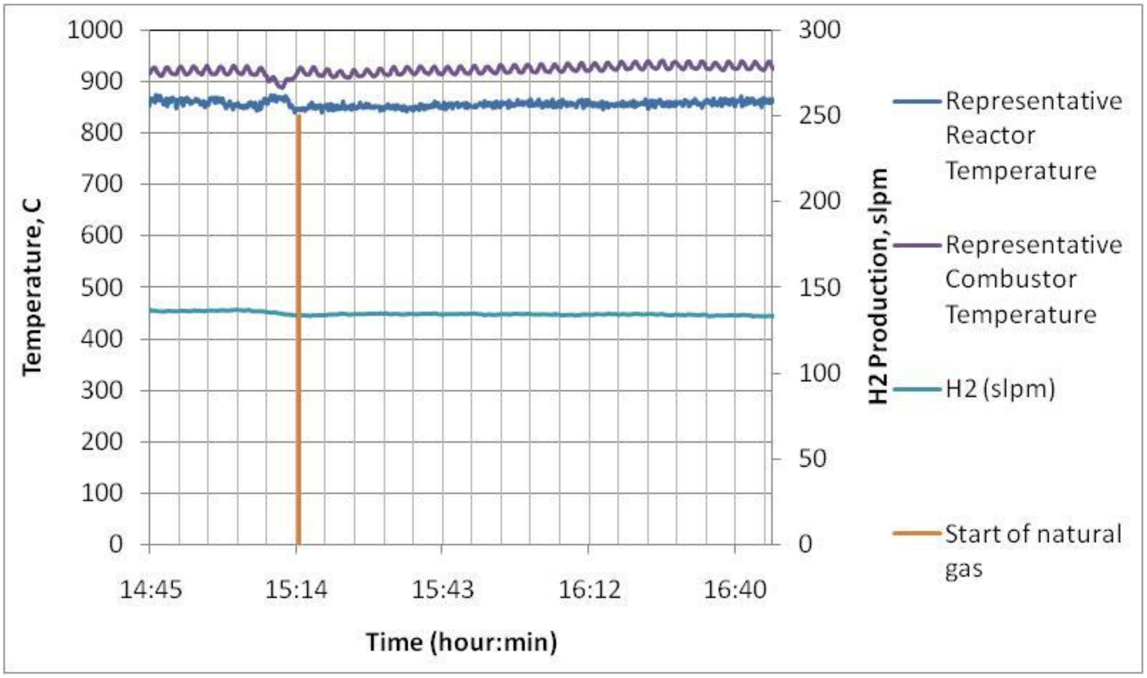

Figure 17: Methane testing followed by natural gas testing (similar results)

2.4 Conclusions

The system performance is concluded to be within targets, based on the different performance measures reported above. The conversion is in the expected range given the chosen throughput. The efficiency as reported is in the acceptable range, with some room for improvement within the given system architecture, if desired. However, there is a trade-off between throughput, efficiency and cost that will have to be considered in every redesign of the system. The PSA chosen for the task has performed well during the 200+ hrs of operation and there is no doubt that it will be sufficient for the task. There doesn't seem to be any major differences between operating on natural gas or methane, based on the testing performed. The slight decrease in hydrogen production can be due to a difference in the H_2/CO ratio between the various fuels. As expected the efficiency increases with load as well as the hydrogen production rate.

Based on the results disseminated above, there is no indication why the current reactor system cannot be configured into a field deployable system. The operation of the system has given valuable experience that will be embedded into any field deployed unit.

3 Financial Modelling

In this section the results from a financial modelling performed using the Intelligent Energy hydrogen production system is disseminated.

3.1 Introduction

To better facilitate E.On/SGC's understanding of the economics of owning and operating small-scale hydrogen generators for refuelling stations, the following calculations have been performed. Estimates are based on IE's existing Hestia model hydrogen generator, which produces 20-30 kg of hydrogen per day. The costing data are presented from an end-user perspective, i.e. for a standalone investment in an IE Hestia hydrogen generator. The underlying assumption is that a magnitude of 100 units is built each year, leading to some cost reduction through economies of scale. The assumptions on cost made in the model are based on experience with actual units built to date and supplier information on cost savings when in production. The financial model used takes a number of parameters into account, including:

- Cost of feedstock
- Hydrogen sales price
- Utility cost
- System performance
- System availability
- Investment costs
  - Hestia system
  - Product compression
  - Dispensing
  - Storage
  - Installation
- Operation and maintenance
- Periodic overhauls
- Cost of capital
- Equipment lifetime

The model results are presented as the net present value (NPV) of the investment, as the internal rate-of-return or the investment pay-back time. With the model it is also possible to create different scenarios for initial utilisation etc.

The model has been used to generate data on the system, using appropriate assumptions on utility costs, rate of return, lifetime, availability, system performance etc. The first section of this report contains general conclusions regarding the different parameters and their impact on the system cost. In the second part Monte Carlo simulations have been used to show relative influence of the various parameters, as well as combination effects of the chosen parameters.

3.2 Model Information and Results

The equipment cost of the Hestia unit is \$100 000, where the steam reforming reactor system comprises roughly 33% of total cost, the gas clean-up system 33% and the balance of plant the final 33%. The unit is assumed to have an overall efficiency of 65%, including the electrical power to operate the system balance of plant. The compression and dispensing is assumed to cost \$40 000, and a penalty of 5 kWh_e/kg of hydrogen produced is added for the compression to 400 bar. The system availability is assumed to be 90% and the cost of the storage \$11 000. The system is expected to require operation and maintenance of 5% of the investment cost yearly (replacing filters, valves etc.), as well as a major overhaul each 5 years (catalyst replacements etc.) to a 20% of the total investment cost. As for economic life time, it is assumed to be 20 years and the value of the system at that time is assumed to be \$0. The cost of capital was assumed to be 7%.

Based on the information given above with a natural gas price of \$0.32/kg, \$0.11/kWh_e and \$6/kg of hydrogen sold, the result is a NPV of about \$137 000, an internal rate-of-return of 14.1%, or a pay-back time of 6.5 years.

Two of the most discussed parameters in this set-up are efficiency and throughput. Changing the efficiency from 65% to 75% increases the NPV from \$137 000 to \$154 000, while changing the throughput from 25 to 27 kg of H_2 per day would increase the NPV from \$137 000 to \$164 000. It is hence technically less difficult to increase the returns-on-investment by improving throughput, than by improving efficiency.

Another factor impacting the investment is the cost of the feedstock, in this case natural gas. Changing the cost of the feedstock from \$0.32/kg to \$0.20/kg will increase the NPV by \$74 000 to \$211 000. However, a more important factor in determining the NPV is the sales price of the product hydrogen. Changing the sales price from \$6 to \$5 will lower the NPV by \$21 000 to \$116 000.

When using the model to simulate scenarios where the initial hydrogen demand is less than 100% the return-on-investment decreases due to the lower initial sales. If the initial demand is 50% of the design capacity and the annual market growth is 8% per year up to 100% of capacity, the NPV is lowered to \$93 000; using the same initial values as above.

3.3 Monte Carlo Simulations

Using a function that returns random values according to a triangular distribution described by three bounding points, a value for the Most Likely value (that lies half-way between the Upper and Lower bounds) will result in an equilateral triangle. By giving the half-way and upper/lower bounds as a basis for a Monte Carlo simulation, a number of cases within this realm can be investigated in an efficient manner. In the simulations performed below 5 000 cases have been generated and the results from these are shown in the figures. This kind of simulation also allows for variation of multiple parameters simultaneously, showing summary effects.

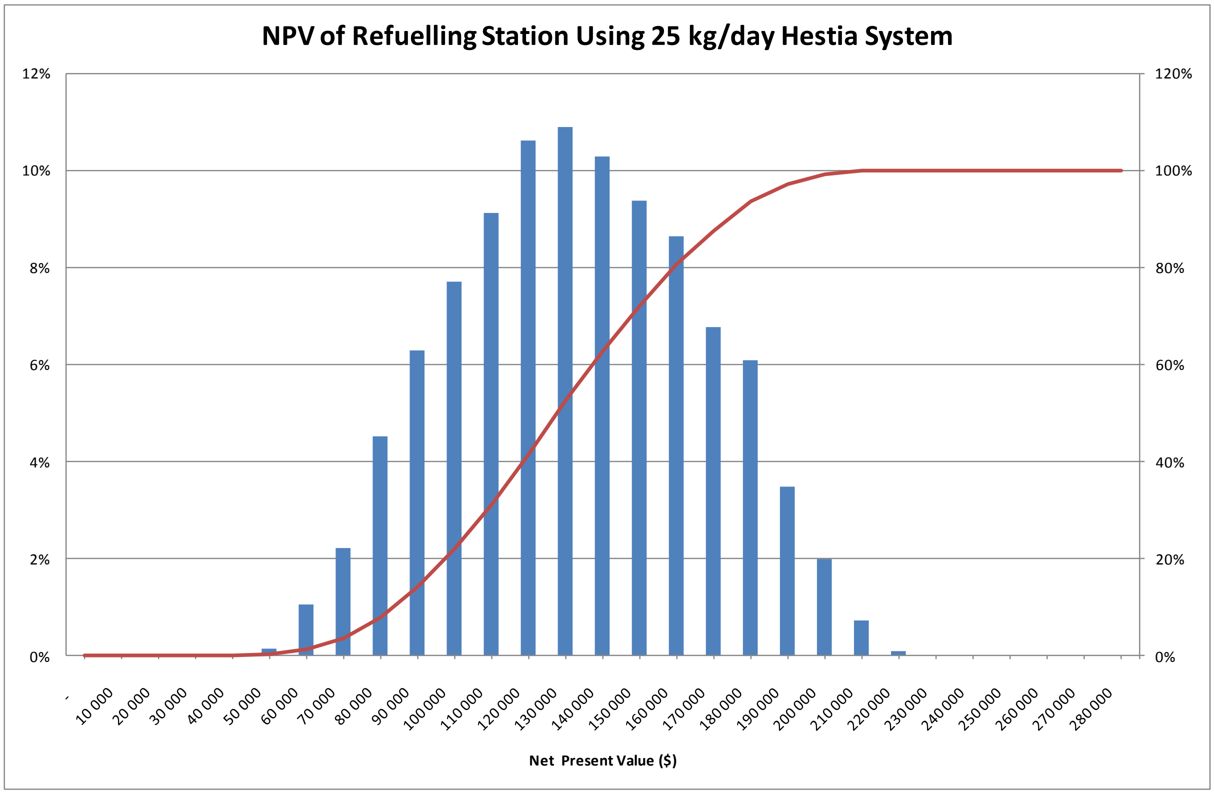

Figure 18 The results from Monte Carlo simulations using the hydrogen generator cost module and a sales price of hydrogen ranging from \$5 to \$7 per kg, with a \$6 per kg mid-point.

Performing a simulation as described above with a sales price of hydrogen ranging from \$5 to \$7 per kg, the NPV varies from \$50 000 to \$220 000. However, the majority of the data is found centred on \$130 000, Figure 18. The distribution is however wide, indicating that this is a parameter with high impact on the system. The result of varying the system specific investment cost from \$70 000 to \$130 000 is shown in Figure 19.

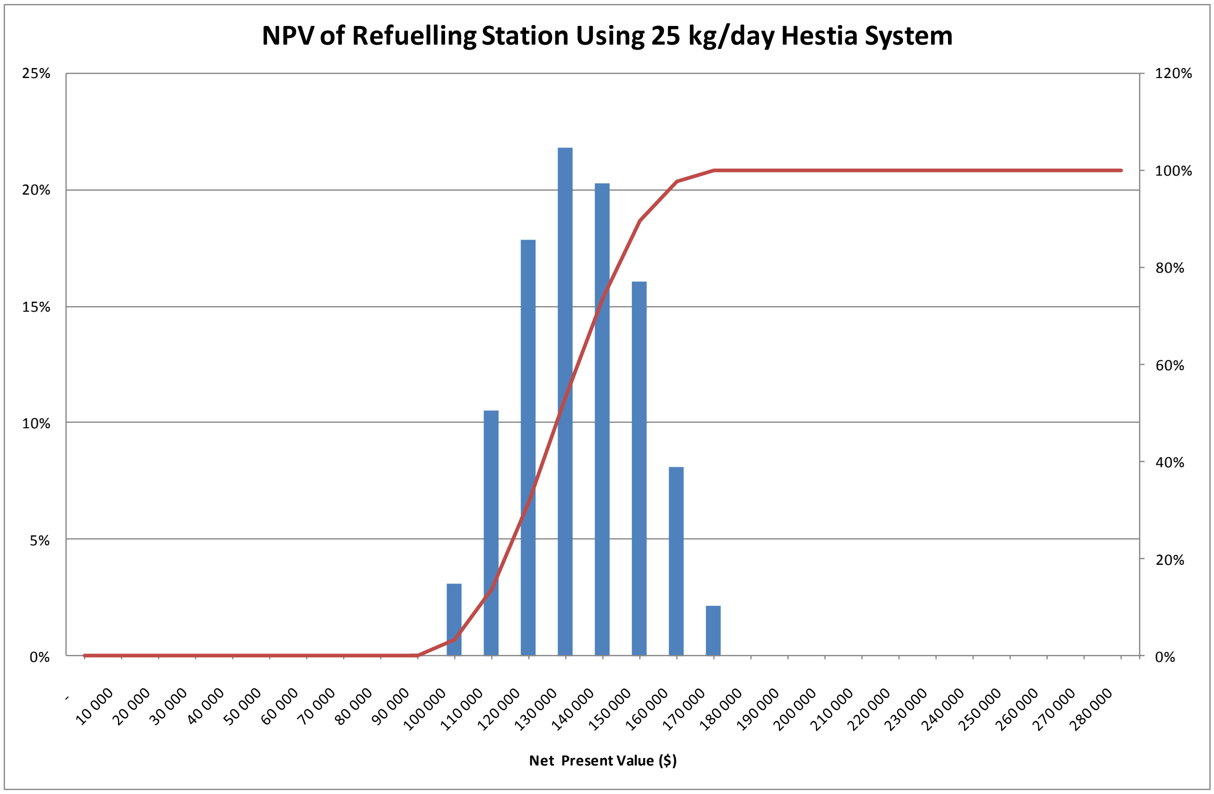

Figure 19 The results from Monte Carlo simulations varying the hydrogen generator cost ranging from $70 000 to $130 000, with a $100 000 mid-point.

As demonstrated the Hestia system investment cost does not have to high of an impact on the NPV. The results are again centred around $130 000 but only tails to $100 000 in the lower end and $170 000 in the higher end. By changing the throughput of the unit, lower costs per kg of produced hydrogen can be achieved. This is hence a parameter that influences the value of the investment significantly, Figure 20.

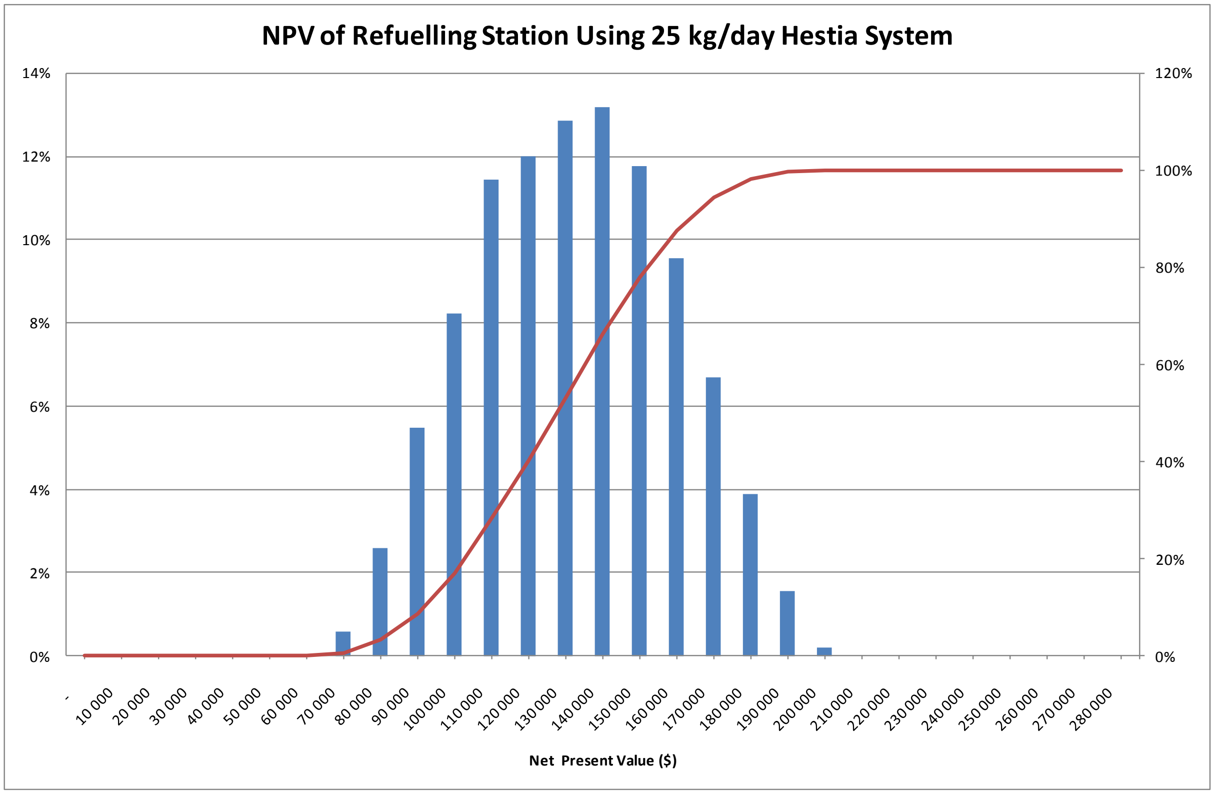

Figure 20 The results of varying the throughput from 20 kg/day to 30 kg/day, with a 25 kg/day mid-point.

By varying the throughput from 20 to 30 kg/day, with a 25 kg/day mid-point, the NPV range from $70 000 to $200 000, centred at $140 000. This makes this parameter one of the most important ones in the model. However, a significant change in the feedstock cost, from $0.15 to $0.45 per kilogram hydrogen, contribute to a smaller change, Figure 21.

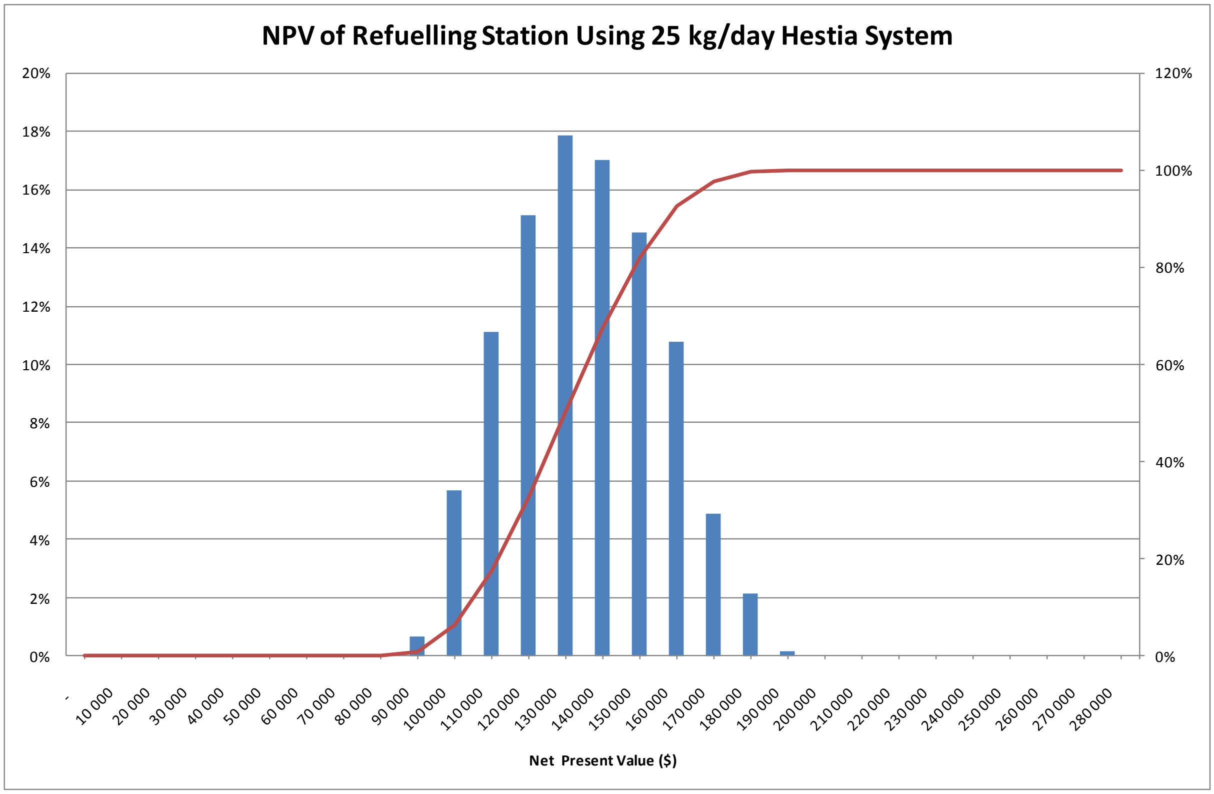

Figure 21 Results of varying the feedstock cost between \$0.15 and \$0.45, with a \$0.32 mid-point.

The range of the NPV in Figure 21, from \$90 000 to \$190 000 show that the feedstock cost is important but not decisive to the hydrogen production cost. Figure 22 show the result from varying the system availability from 85% to 95%.

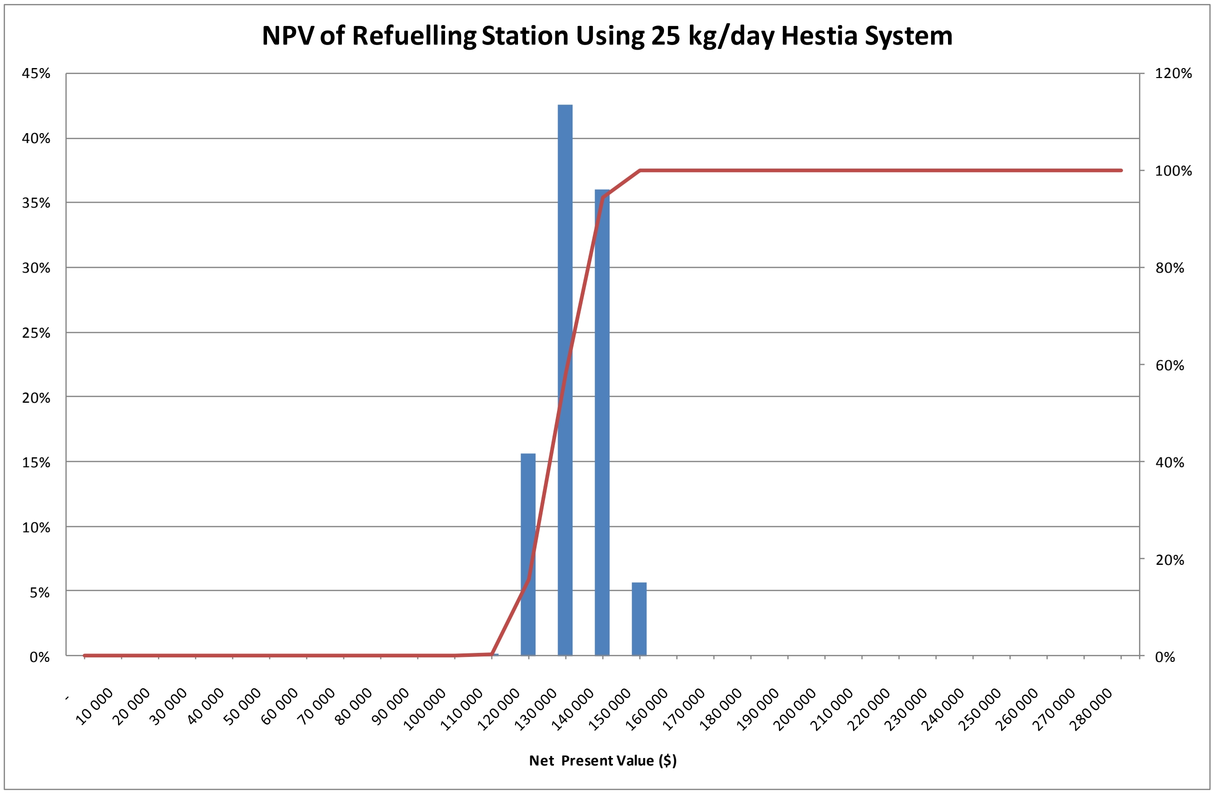

Figure 22 Simulating the system availability between 85% and 95 %.

The change in availability is one of the parameters that have the smallest impact on the NPV according to the simulations performed. Note however that this analysis only captures the effect of availability in the form of lost revenues associated with decreased hydrogen sales. In certain applications, particularly fleet applications, periods of unavailability could lead to far higher costs for the hydrogen generator owner, which would lead to higher impact on NPV for this factor. Thus IE is setting high targets for reliability, availability, maintainability and durability (RAMD) for the Hestia hydrogen generator.

In Figure 23 all of the parameters mentioned above have been changed simultaneously.

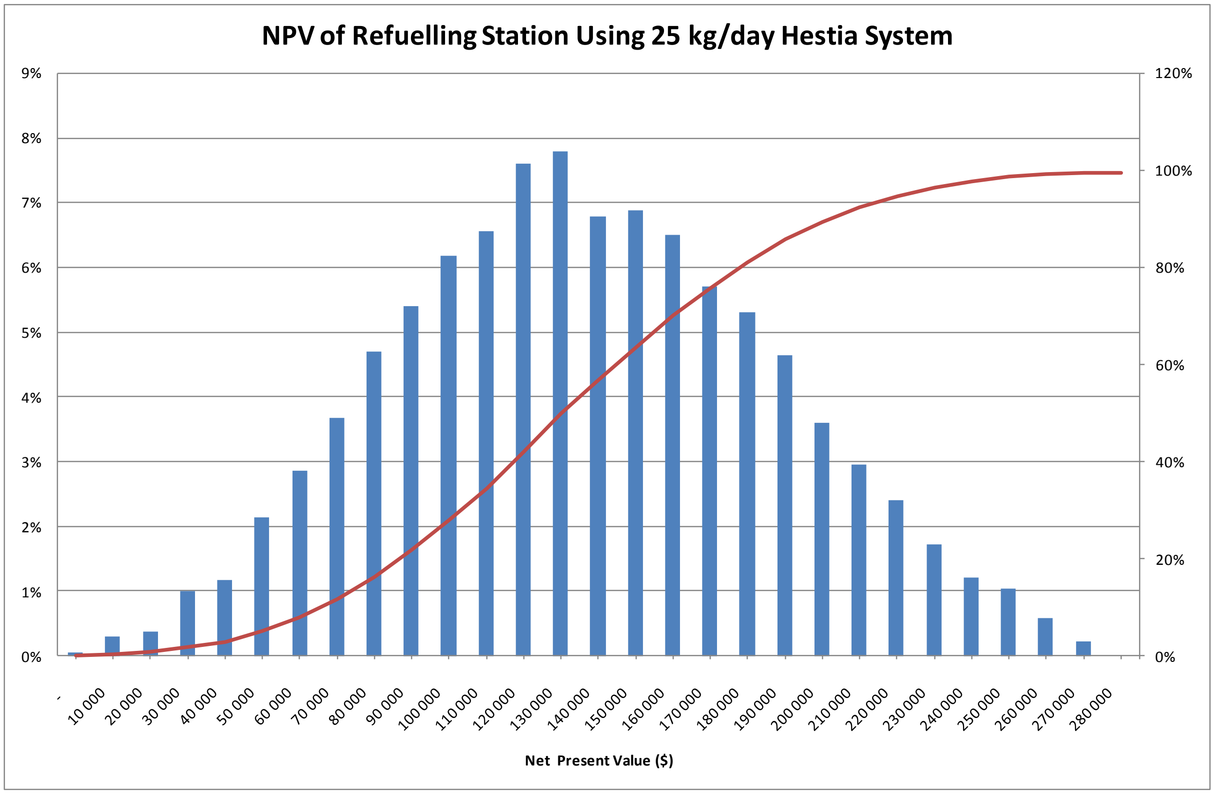

Figure 23 Variation of all parameters varied in figure 1 through 5, simultaneously.

When changing all parameters simultaneously the NPV distribution becomes quite broad, with tails from $0 to $270 000. However, 60% of the 5 000 cases simulated are in the $90 000 to $180 000, showing that even with uncertainty in each parameter, there is a potential benefit to the investment.

3.4 Conclusions

The general conclusion from this study is that there are several parameters that potentially influence the potential of an investment in a Hestia hydrogen generator. The sales price of the hydrogen is one of the major drivers of profitability. Another important factor is the throughput of the unit, more important than efficiency and utilisation. Varying all of the parameters simultaneously introduce larger variations in the NPV but, 60% of the simulations are in the $90 000 to $180 000 interval.

4 Summary

The aim of the project's first phase, where this constitutes the final report, was to demonstrate the ability to operate the IE reforming system on the E.On/SGC site-specific fuel. During the project, a preliminary system design has been developed, based on IE's proprietary reformer. The system has been operated at pressure, to ensure a stable operation of the downstream PSA; which has been operated without problems and with the expected hydrogen purity and recovery. The safe operation of the proposed and tested system was first evaluated in a preliminary risk assessment, as well as a full HazOp analysis.

A through economic modelling has been performed on the viability of owning and operating this kind of hydrogen generation equipment. The evaluation has been performed from an on-site operation of such a unit in a refuelling context. The general conclusion from this modelling is that there are several parameters that influence the potential of an investment in a Hestia hydrogen generator. The sales price of the hydrogen is one of the major drivers of profitability. Another important factor is the throughput of the unit, more important than efficiency and utilization. Varying all of the parameters simultaneously introduce larger variations in the NPV but, 60% of the simulations are in the \$90 000 to \$180 000 interval. The chosen intervals for the parameters were:

Hydrogen Sales Price (\$5 - \$7 per kg)

- Investment Cost (\$70 000 - \$130 000 per unit)
- Throughput (20 - 30 kg/day)
- Feedstock Cost (\$0.15 - \$0.45 per kg)
- Availability (85% - 95%)

The return-on-investment is between \$90 000 to \$180 000 in 60% of the 5 000 simulation runs, which leads to the conclusion that given these assumptions the owning and operation of such a unit can be profitable.

As for the performance of the system, it is concluded to be within targets based on the different performance measures reported above. The conversion is in the expected range (80-85%), given the throughput of 16 kg of hydrogen per day. The efficiency as reported is in the acceptable range (~65%), with some room for improvement within the given system architecture, if desired. However, there is a trade-off between throughput, efficiency and cost that will have to be considered in every redesign of the system. The PSA chosen for the task has performed well during the 200+ hrs of operation and there is no doubt that it will be sufficient for the task. The same thing can be said with respect to the system performance with respect to thermo-mechanical stress; which was proven by operating the system for more than 500 hours and performing 58 start-and-stop cycles during the testing.

There does not seem to be any major differences between operating on natural gas or methane, based on the testing performed. The slight decrease in hydrogen production can be due to a difference in the H_2/CO ratio between the various fuels. As expected the efficiency increases with load as well as the hydrogen production rate.

Based on the results disseminated above, there is no indication why the current reactor system cannot be configured into a field deployable system. The operation of the system has given valuable experience that will be embedded into any field deployed unit.

5 References

1. **Hulteberg, P.C., Burford, H., Duraiswamy, K., Porter, B., Woods, R.** A cost effective steam reformer for a distributed hydrogen infrastructure. *International Journal of Hydrogen Energy*. 2008, Vol. 33.

2. **Muradov, Nazim, Smith, Franklyn and T-Raissi, Ali.** Hydrogen Production by Catalytic Processing of Renewable Methane-rich Gases. *International Journal of Hydrogen Energy*. 2008, Vol. 33, 2023-2035.

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5. **Persson, Margareta.** *Biogas - Basdata om biogas*. Malmö : Svenskt Gastekniskt Center, 2006.

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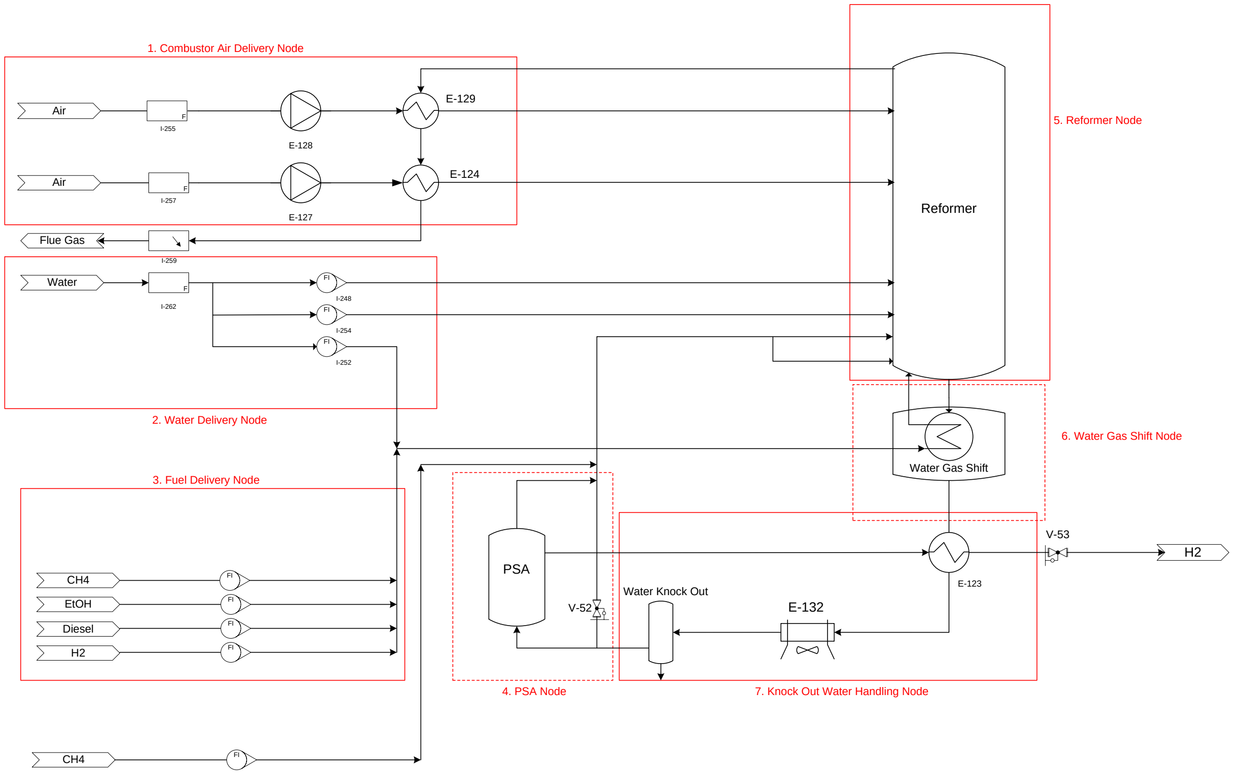
Appendix A

The hydrogen generator HazOp was first **divided** into separate nodes based on the function of each subsystem. The basis for this process/drawing is shown below. Following this drawing, a copy of the review session is described.



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Team for Session 1

Company: Intelligent Energy Inc.
Facility: IE LB Engineering Department

Page: 1

Session Date: February 17, 2009

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Dr. Christian Hulteberg, Consultant, 562 304 7677, Malmo, Sweden, Chemcial engineering, H2 Solution

Session Notes:

Worksheet

Company: Intelligent Energy Inc.
Facility: IE LB Engineering Department

Page: 1

Session: (1) 2/17/2009
Node: (1) Combustor Air Delivery Node
Drawings:
Parameter: Flow

Revision: (0)
Intention: To deliver air to the reformer combuster

Intention: To deliver air to the reformer combustor

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
No	Flow	line blockage	reformer combustor gets too hot	install stop-flow alarm	3	5	9		
		loss of power to blower	Above	install redundant/backup blower	3	5	9	Tie redundant/backup blower into logic and stop fuel flow to refomer	DA
		failure of blower	Above	above	3	5	9	above	
		line rupture-catastrophic leak	Above	above	3	5	9	above	
More	More Flow	control logic settings inaccurate	none	none	5	5	10	none	
Less	Less Flow	line blockage	refomer combustor gets too hot	intall stop-flow alarm	3	5	9		
		failure of blower	above	above	3	5	9		
		line rupture-catastrophic leak	above	above	3	5	9		

Session: (1) 2/17/2009
Node: (1) Combustor Air Delivery Node
Drawings:
Parameter: Temperature

Revision: (0)
Intention: To deliver air to the reformer combuster

Intention: Preheat air to combustor

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
More	More Temperature	reformer running too hot	meltdown	install upper temperature limit device that shuts off fuel to the combustor	3	5	9		
Less	Less Temperature	start up conditions (not at steady state)	none	none	5	5	10		

Session: (1) 2/17/2009
Node: (1) Combustor Air Delivery Node
Drawings:
Parameter: Pressure
Intention: To deliver and overcome pressure drop through combustor

Revision: (0)
Intention: To deliver air to the reformer combuster

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
More	More Pressure	line blockage	reformer runs too hot	intall high pressure alarm/switch to shut off fuel to combustor	3	4	8		
		blower runs to fast	above	above	3	5	9		

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Worksheet

Company: Intelligent Energy Inc.
Facility: IE LB Engineering Department

Page: 2

Session: (1) 2/17/2009
Node: (2) Water Delivery Node
Drawings:
Parameter: Flow

Revision: (0)
Intention: To deliver water to the reformer and shift

Intention: To deliver water to reformer and shift

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
No	No Flow	line blockage	pressure spike in line/rupture; reformer and shift can run too hot	install stop-flow alarm and/or pressure alarm and tie into fuel feed shut off	3	4	8	intstall check valve in water delivery line	DA
		pump failure	reformer and shift can run too hot	above	3	4	8		
		line rupture/leak	injury to personnel	above	4	4	9		
		flow control device failure	reformer and shift can run too hot	above; instll redundant device	3	5	9		
More	More Flow	control loop/meter not calibrated correctly	none	none	5	5	10		
Less	Less Flow	line blockage	pressure spike in line/rupture; reformer and shift can run too hot	install stop-flow alarm and/or pressure alarm and tie into fuel feed shut off	3	4	8		
		pump failure	reformer and shift can run too hot	above	3	4	8		
		line rupture/leak	injury to personnel	above	4	4	9		

Session: (1) 2/17/2009
Node: (2) Water Delivery Node
Drawings:
Parameter: Pressure
Intention: To deliver water and overcome pressure drops in the reformer and shift

Revision: (0)
Intention: To deliver water to the reformer and shift

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
More	More Pressure	line blockage downstream	line breakage/leakage; injury to personnel	intall pressure alarm and safety relieve valve in line	4	4	9		
		pump/controls not working properly	above	above	4	5	10		
Less	Less Pressure	no flow; less flow	reformer and shift can run too hot	install low-pressure alarm and tie into feed fuel shut off	3	4	8		

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Worksheet

Company: Intelligent Energy Inc.
Facility: IE LB Engineering Department

Session: (1) 2/17/2009
Node: (3) Fuel Delivery Node
Drawings:
Parameter: Flow

Revision: (0)
Intention: To deliver fuel to the reformer

Intention: To deliver fuel to the reformer

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
No	No Flow	line blockage	none	none	5	5	10		
		compressor/pump failure; loss of power	above	above	5	5	10		
		line rupture/leakage	above	above	5	5	10		
		run out of feedstock	above	above	5	5	10		
More	More Flow	supply pressure/flow and/or control algorithm of metering loop not set correctly	combustor can run too hot	over-flow sensing alarm/switch tied into fuel supply shut off	3	3	7		
Less	Less Flow	line blockage	none	none	5	5	10		
		compessor/pump failure; loss of power	above	above	5	5	10		
		line rupture/leakage	above	above	5	5	10		
Reverse	Reverse Flow	backfire/explosion in the combustor	line rupture/injury to personnel	install flame arrestor and/or check valve	1	3	3		

Session: (1) 2/17/2009
Node: (3) Fuel Delivery Node
Drawings:
Parameter: Pressure

Revision: (0)
Intention: To deliver fuel to the reformer

Intention: To deliver fuel to the reformer and shift vessel

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
More	More Pressure	line blockage	line rupture; injury to personnel; potentially explosive evironment	install over-pressure switch that shuts off fuel supply	1	3	3		
		compessor/pump and/or control metering algorithm set incorrectly	above	above	2	4	7		
Less	Less Pressure	line rupture/leakage	above	above	1	4	4		
		prime mover failure	none	none	2	4	7		
		exhaust fuel supply	none	none	5	5	10		

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Worksheet

Company: Intelligent Energy Inc.
Facility: IE LB Engineering Department

Page: 4

Session: (1) 2/17/2009
Node: (4) PSA Node
Drawings:
Parameter: Flow

Revision: (0)
Intention: To purify synthesis gas

Intention: To deliver synthesis gas to PSA

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
No	No Flow	line blockage; control valve failure; reformer not running	line rupture; backfire; explosion, release of CO	install no-flow alarm and/or switch to shut fuel feed	3	4	8		
More	More Flow	higher reformer load	none	none	5	5	10		
Less	Less Flow	lower reformer load; line blockage/leakage	explosion potential, release of CO	install CO, H2 monitors for leakage	2	3	6	tie gas sensors into shutdown protocol in the event of a release; less flow situation	

Worksheet

Company: Intelligent Energy Inc.
Facility: IE LB Engineering Department

Page: 5

Session: (1) 2/17/2009
Node: (5) Reformer Node
Drawings:
Parameter: Flow

Revision: (0)
Intention: Convert feed fuel to synthesis gas

Intention: To deliver fuel and water to catalysts bed

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
No	No Flow	line blockage	reformer runs too hot if combustor doesn't see flow	install no-flow alarm/switch to shut off feed fuel (suplimentary supply)	2	3	6		
		line rupture	potentially explosive environment	Install combustible gas detectors/alarms	2	4	7		
		Fuel delivery system failure	above (1)	install no-flow alarm/switch to shut off feed fuel (supplimentary supply)	3	4	8		
		Water delivery system failure	above (1)		3	4	8		
More	More Flow	compressor/pump running too high/control metering algorithm not set correctly	combustor gets too hot	install high-flow alarm/switch to shut off feed fuel supply	3	4	8		
Less	Less Flow	line blockage	above (1)	install low-flow alarm/switch to shut off feed fuel supply	3	4	8		
		Fuel delivery system failure	above	above	3	4	8		
		Water delivery system failure	above	above	3	4	8		

Session: (1) 2/17/2009
Node: (5) Reformer Node
Drawings:
Parameter: Temperature

Revision: (0)
Intention: Convert feed fuel to synthesis gas

Intention: To heat reformer such that fuel conversion is optimal

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
More	More Temperature	fuel to the combuster too much	melting of reactor and potentially explosive evironment or fire	install high-temperature alarm/limit switch to shut off fuel supply to combustor	2	3	6		
		lack of reformer fuel conversion	above	above	2	3	6		
Less	Less Temperature	lack of fuel to combustor; too much air to combustor	none	none	5	5	10		

Worksheet

Company: Intelligent Energy Inc.
Facility: IE LB Engineering Department

Page: 6

Session: (1) 2/17/2009
Node: (5) Reformer Node
Drawings:
Parameter: Pressure

Revision: (0)
Intention: Convert feed fuel to synthesis gas

Intention: To deliver fuel, water and air to the reformer

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
More	More Pressure	line blockage	reformer and/or combustor breakage leading to potentially explosive environment or fire; injury to personnel	install high-pressure alarm and/or switch and tie into prime mover device (s); intall pressure relieve valve and plumb to vent	2	4	7		
		flows too high resulting from prime mover malfunction; improper settings	above	above	2	4	7		
Less	Less Pressure	line rupture and/or leakage	potentially explosive environment; injury to personnel	intall low-pressure alarm and/or switch and tie into prime mover device (s)	2	4	7		
		flows too low resulting from prime mover malfunction; improper settings	none	none	5	4	10		

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Worksheet

Company: Intelligent Energy Inc.
Facility: IE LB Engineering Department

Session: (1) 2/17/2009 Revision: (0)
Node: (6) Water Gas Shift Node
Intention: To convert CO to CO2 and preheat reformer feed steam
Drawings:
Parameter: Flow
Intention: to deliver reformer gas to WGS

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
No	No Flow	process; not reforming	none	none	5	5	10		
		water; blockage in line	run away temperature in shift but not hot enough to melt; no risk to personnel	none	5	5	10		
		water; failure of pumps	above	none	5	5	10		
More	More Flow	process; reformer running too high	damage to catalyst; no risk to personnnel	none	4	5	10		
		water; prime mover running too high	above	none	4	5	10		

Session: (1) 2/17/2009 Revision: (0)
Node: (6) Water Gas Shift Node
Intention: To convert CO to CO2 and preheat reformer feed steam
Drawings:
Parameter: Temperature
Intention: to control the reaction conversion and cool exotherm; preheat steam

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
More	More Temperature	no water flow in quench coil	damage to catalyst; no risk to personnel	none	4	5	10		
		reforming rate too high	above	above	4	5	10		
Less	Less Temperature	too much water in quench coil	none	none	5	5	10		
		reforming rate too low	above	above	5	5	10		

Session: (1) 2/17/2009 Revision: (0)
Node: (6) Water Gas Shift Node
Intention: To convert CO to CO2 and preheat reformer feed steam
Drawings:
Parameter: Pressure
Intention: To deliver refromate and water to quench

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
More	More Pressure	reformer running at too high of a load	shift reactor gets hot; no risk of melting just to catalyst; no risk to personnel	none	5	5	10		
		water flow too high to quench	cools shift reactor; no risk to personnel	above	5	5	10		
		process;line blockage	line rupture; potentially explosive environment	install high-pressure alarm/limit switch and tie into fuel feed line	2	4	7		
		water; line blockage	line rupture; wet system/floor	install high-pressure alarm/limit switch and tie into water feed line	4	5	10		

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Worksheet

Company: Intelligent Energy Inc.
Facility: IE LB Engineering Department

Session: (1) 2/17/2009
Node: (6) Water Gas Shift Node
Intention: To convert CO to CO2 and preheat reformer feed steam
Drawings:
Parameter: Pressure

Revision: (0)

Intention: To deliver refromate and water to quench

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
Less	Less Pressure	reformer running too low	none	none	5	5	10		
		line leakage/upstream rupture	potentially explosive environment	intall low-pressure alarm/limit switch and tie into fuel and water feed line	2	4	7		

Worksheet

Company: Intelligent Energy Inc.
Facility: IE LB Engineering Department

Session: (1) 2/17/2009
Node: (7) Knock Out Water Handling Node
Drawings:
Parameter: Flow
Intention: to remove water from synthesis gas and cool before PSA

Revision: (0)
Intention: Remove water from synthesis gas; cool before PSA

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
No	No Flow	line blockage	pressure spike; line rupture; potentially explosive environment	Install no-flow alarm and/or limit switch and tie into fuel feed shut off	3	4	8	intall pressure relief valve also	DA
		reformer not running	none	none	5	5	10		
More	More Flow	reformer/prime movers running too high	pressure spike	install low-flow alarm	5	5	10		
Less	Less Flow	line blockage/leak upstream	pressure spike; line rupture; potentially explosive environment	Install low-flow alarm and/or limit switch and tie into fuel feed shut off	3	4	8		
		reformer running on lower load	none		5	5	10		

Session: (1) 2/17/2009
Node: (7) Knock Out Water Handling Node
Drawings:
Parameter: Temperature
Intention: To cool synthesis gas below dew point to condense water; cool pure hydrogen stream

Revision: (0)
Intention: Remove water from synthesis gas; cool before PSA

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
More	More Temperature	poor heat transfer in E123 and/or E132	water gets into PSA and/or damage to components; no risk to personnel	none	5	5	10		
		shift running too hot	above	above	5	5	10		
Less	Less Temperature	reformer/shift running low	none	none	5	5	10		

Session: (1) 2/17/2009
Node: (7) Knock Out Water Handling Node
Drawings:
Parameter: Pressure

Revision: (0)
Intention: Remove water from synthesis gas; cool before PSA

Intention: To deliver synthesis gas to the PSA

GW	DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	S	L	R	RECOMMENDATIONS	BY
More	More Pressure	line blockage	line breakage; potentially explosive environment; injury to personnel	install high-pressure alarm and/or limit switch and tie into feed flow algorithm intall relief valve	2	4	7		
Less	Less Pressure	line rupture/leakage	potentially explosive environment	install low-pressure alarm	2	4	7		

Severity Value Frequencies

Company: Intelligent Energy Inc.
Facility: IE LB Engineering Department

Page: 1

1	2	3	4	5	sum	
0	0	10	0	2	12	Combustor Air Delivery Node
0	0	7	0	1	8	Flow
0	0	1	0	1	2	Temperature
0	0	2	0	0	2	Pressure
0	0	6	4	1	11	Water Delivery Node
0	0	5	2	1	8	Flow
0	0	1	2	0	3	Pressure
3	2	1	0	8	14	Fuel Delivery Node
1	0	1	0	7	9	Flow
2	2	0	0	1	5	Pressure
0	1	1	0	1	3	PSA Node
0	1	1	0	1	3	Flow
0	7	6	0	2	15	Reformer Node
0	2	6	0	0	8	Flow
0	2	0	0	1	3	Temperature
0	3	0	0	1	4	Pressure
0	2	0	5	8	15	Water Gas Shift Node
0	0	0	2	3	5	Flow
0	0	0	2	2	4	Temperature
0	2	0	1	3	6	Pressure
0	2	2	0	6	10	Knock Out Water Handling Node
0	0	2	0	3	5	Flow
0	0	0	0	3	3	Temperature
0	2	0	0	0	2	Pressure
3	14	26	9	28	80	PROJECT TOTAL

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TOTAL P.11

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