Design and energy requirements for future marketing activities of gaseous hydrogen fuel for fuel cell vehicles

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Abstract

Rapid improvements in fuel cell technology are bringing fuel cell vehicles closer to commercialization. Air quality and climate change have been principal motivations for developing fuel cell vehicles, but air quality and greenhouse gas impacts can vary greatly depending upon the performance and design characteristics of the fuel supply system. The energy requirement of each possible fuel supply configuration is one of the basic parameters required to calculate the future emissions of the criteria pollutants and the greenhouse gases.

In this paper, we analyze the energy attributes of a hydrogen fuel supply system for fuel cell vehicles. We examine several pathways, focusing on the upstream part of the system. We use a component model of the Fuel Upstream Energy and Emissions Model (FUEEM) being developed at UC Davis using MatLab/Simulink software. To handle uncertainty in future technology attributes and system designs, as well as unreliability of some data, FUEEM uses probabilistic functions and relies on an international expert advisory panel to establish the major inputs. The statistical attributes of the Monte Carlo technique such as Latin hypercube sampling and rank order correlations among variables are handled in the component model using @Risk software.

We present results for alternative gaseous hydrogen fuel supply systems. We analyze high-pressure bulk storage vessels, transmission pipelines, local distribution pipelines and fuel stations, and present energy requirements for hydrogen compression by electric motors, natural gas reciprocating engines, and different pipelines lengths and pressures. Hydrogen losses (fugitive, venting, etc.) are considered in terms of energy loss. Local emissions associated with the use of natural gas engines are calculated too. The results are obtained in terms of probabilistic curves, which are very rich information for decision-making, showing maximum, minimum, mode, and mean values, along with the probability of each single value within the range.

1 Introduction

Direct hydrogen is the simplest and most efficient design for fuel cell vehicles. The hydrogen storage and the fuel infrastructure are the major uncertainties for the success of this technology. By the lack of better choices compressed gas was chosen as the most reliable option to be considered in the model since the cryogenic option presents a lot of concerns in terms of safety, energy requirement in the liquefaction process and the boil off losses. Trucks can transport hydrogen in the liquid form, however a high-energy cost must be paid in the liquefaction process and all this cost is lost in the vaporization process at the fuel station. Compressed gas can also be transported by truck but again this option is very expensive due to the low energy density of the gaseous hydrogen. Storage solutions such as metal hydrides have been studied for more than 20 years and show no signal of major breakthrough. Nanostructures are still in a very initial stage of development to be considered in the market in the next 10 years.

Based on these facts, two options can be considered in the case of a larger demand of hydrogen: pipelines and hydrogen production at the fuel station. A hydrogen pipeline can be considered as an intermediate process to move hydrogen from the hydrogen plant or plant bulk storage to the hydrogen fuel station.

The approach adopted in this study focuses on pipeline design parameters that contribute to the final efficiency and emission rates. Also, in order to handle uncertainty in future technology attributes and system designs, as well as unreliability of some data, the model FUEEM (Fuel Upstream Energy and Emissions Model) uses probabilistic functions and relies on an international expert advisory panel to establish the major inputs. The

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FUEEM expert network is composed of 25 to 30 experts from more than one dozen organizations and they have been actively involved over the last couple of years in discussing the topics presented in this paper. The information and data presented are the result of this effort and focus on the year 2010 as the time frame.

In general, hydrogen pipelines are more expensive than natural gas pipelines. Ogden [1] estimated the pipeline cost per mile around $ 1 million in a heavily populated area like Los Angeles. It is possible that some improvements may occur, for example according to Socolow [2] a new low-cost metal pipe can safely be used. Most of our experts agreed that the highest cost is the right over the land to place the pipeline. The eventual possibility of placing the hydrogen pipeline next to the existing natural gas pipeline may reduce the costs. For a larger hydrogen market, our previous discussion and other studies (Shelef et al, [3]; Mark, 1996 [4]; Ogden [5] and others) tend to conclude that hydrogen transportation by pipelines may be the cheapest pathway and therefore should be included as an option in the FUEEM. This study discusses the major topics for the energy requirement calculation of possible hydrogen fuel pipeline transportation and compression at the fuel stations.

According to Pottier and Blondin [6] the engineering design of pipelines for hydrogen gas are similar to those for natural gas (NG). However the existing emission models have been treating the issue at a very aggregated level leaving some room for a better treatment of the assumptions.

For example, Wang [7] uses a 1980's NG data were 250,000 miles of transmission lines (32" diameter) plus 900,000 of main distribution lines (12") and 520,000 miles of service lines (2") was used nationwide to transport 22 trillion cubic feet (TCF) of natural gas. Mixing all diameters and using a single linear relationship he came up with the necessity of 76,000 miles of pipeline to transport 1 TCF of hydrogen fuel. The rest of his assumptions are that the same NG pipeline length and size can carry the same amount H_2 using bigger compressors (3 to 3.5 times). Assuming that 98.6% of the consumed energy occurs in NG compressors and turbines and 1.4 % in electric compressors with no feed losses he came up with the pipeline efficiency of 94 %. In August of 1999 he published another report (Wang, [8]) where he assumes then feed losses of 13 %, which bring down the NG energy consumption to 86 % and electricity consumption of 1% to come up with a different pipeline efficiency of 97 %. Finally by January of 2000 a new report (Wang, [9]) assumed a pipeline efficiency of 95 % only stating a comparison with the NG pipeline efficiency of 97 % (all in LHV).

Bentley *et al.* [10] and Harvey [11] assume the efficiency of 97 % and DeLucchi [12] and [13]) assumes that hydrogen pipelines will use compressors powered by hydrogen internal combustion engines. Based on that and without any other statement DeLucchi assumes that 0.10 Btu of H_2 is consumed per each Btu of H_2 delivered by the pipeline (efficiency of 90.9 %). Accurex [14] assumes only liquid hydrogen transportation.

2 Energy Requirement and Pipeline design

To calculate the energy requirement and emissions associated with the hydrogen transportation process it is important to take into account parameters like the length and other technical characteristics of the transportation process. As discussed below, the gas is transported by pressurization at compression stations over distance to compensate the pressure drop in the pipe due to friction. The Figure 1 illustrates this concept. To have a flexible geographical analysis capability in the model it is our goal to generate all the transportation data per distance or in other words the pipeline distance is one input parameter in the model. The lack of association of the input assumptions with the distance was pointed out as one of the major difficulties of using Wang's model (1999) for local analysis.

One of the main concerns is the selection of the pipeline materials since hydrogen may cause embrittlement in some kind of steel used for NG transmission (Leeth, [15]; Mathis, [16]; Shelef et al, [3]; Pottier, [17] and others). Embrittlement is known as a decrease in the strength of certain steels caused by hydrogen. The problem occurs mainly in high strength steels and at high temperature. For more details see Thompson [18]. Plastic pipes (PVC - Polyvinyl Chloride and HDPE – High-density Polyethylene) normally used for NG distribution pipes cannot be used for hydrogen pipelines since their porosity is too big for the hydrogen molecular size (Socolow, 1997). Based on this material information and mainly based on the lack of natural gas pipeline system availability to delivered hydrogen in major urban areas, it is our assumption that it will be necessary to construct new dedicated hydrogen pipeline. The option considered by Ogden *et al.* [19] of using the existing NG pipeline system to transport a blend of 15 % to 20 % of H_2 by volume with NG will not be considered, since this design requires a separation process at the end of each line.

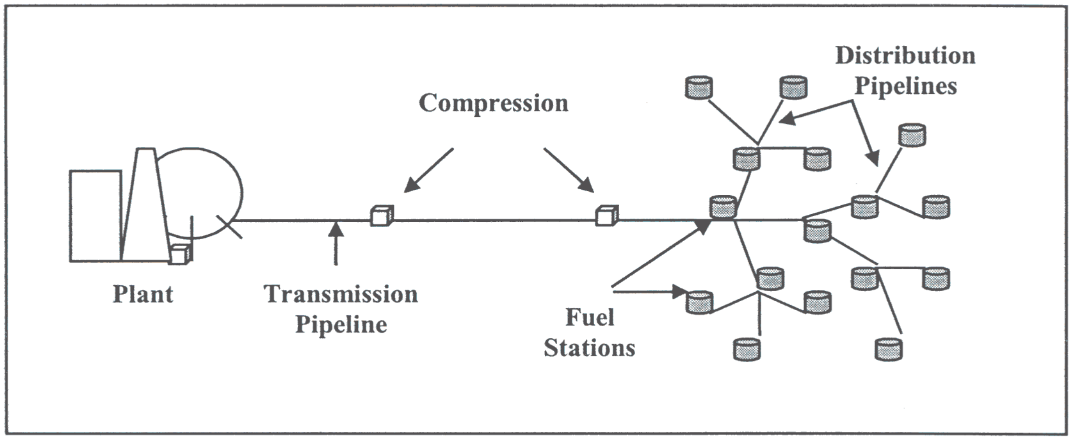


Figure 1: Schematic of a hydrogen fuel pipeline design

2.1 Pipeline Pressure

The assumption of dedicated hydrogen pipelines is important because the characteristics of the outlet pressure for the fuel station can be designed according to that. Using this argument Arthur D. Little [20] assumes as 1,000 psi (6.89 MPa) the pressure of the hydrogen delivered at fuel station, minimizing the compression requirement there and transferring it to a more centralized pipeline compression station. With this design they come up with the pipeline efficiency of 99.2%. According to Socolow [2] the existing American and European pipelines operate at pressures up to 1500 psi (10.34 MPa). Other studies (Ogden, [21] / [5] and Mark, [4]) assume the pressure of the hydrogen delivered at the fuel station as 200 psi (1.38 MPa) and Moore *et al.* [22] assume a variable pressure between 220 and 441 psi (1.52 to 3.04 MPa). In our study we generated various scenarios with hydrogen being delivered at different pressures at the fuel station including 200 and 1000 psi.

The pipeline inlet pressure is another variable in the calculation and it is related to the pressure of the hydrogen released by the PSA (Pressurized Swinging Adsorption) at the hydrogen plant. According to Patel *et al.* [23] this hydrogen flow pressure can vary between 420 and 450 psi (2.9 to 3.1 MPa) for a centralized plant. Our expert network advised us to use a distribution curve to determine this pressure with a minimum in 250 psi and a maximum value in 420 psi with a major tendency towards the minimum value. The main reason for this is that high-pressure operation implies in thicker catalyst tubes, increasing the cost. Also, low pressures favor the synthesis reactions and increase the efficiency. Using the @Risk software we determine a distribution curve and the main values can be seen at Table 1. If the plant works with bulk storage the inlet pipeline pressure will be the pressure of the bulk storage vessel.

2.2 Bulk Storage

None of the existing models that deal with the distribution of gaseous hydrogen mention or give details about having incorporated bulk storage in the calculation (Greet, DTI and Ogden). Regular pipelines directly connect the centralized production plant to the fuel stations but for this design two considerations must be taken into account:

- The pipeline will directly transmit the demand oscillations into the production characteristics. According to Thomas et. al. [24] a production surge factor must be considered in this case to establish the necessary plant size. Also, McAuliffe [25] suggests that a non-constant output of hydrogen decreases the efficiency of the production plant and this has not been considered in the models. Increasing the storage volume at the fuel station and synchronizing the supply time schedule may solve this problem and this option is included in this study. However it is good to point out that a bigger storage at the fuel station implies in a higher capital investment and the decentralized marketing network may not accept it. The capital cost increase is due to bigger storage tanks and the necessity of a reliable information network among the hydrogen plant and the all fuel stations.

- Mathis [16] states that line-pack storage can be used on a daily basis. It may be feasible for a long transmission line; however, it does not apply for a distribution network. For example, a 50-mile long pipeline holding hydrogen at 1,000 psi (6.90 MPa) should have a 4 ft (1.22m) diameter to store 30 MBtu of H_2 (28×10^3 GJ), the necessary amount to refuel approximately 80,000 vehicles in a day (supporting a fleet of around 700,000 vehicles @ 33 miles/day and 90 miles/gallon-gasoline-equiv.).

The solution for large volume hydrogen storage has been studied mostly in the late 70's and early 80's, immediately after the petroleum crisis. Underground storage using natural or specially created cavities has been pointed out as the alternative. Pottier [26] and Pottier and Blodin [6] give various examples of underground gas storage in France. Deep aquifers with porous and permeable geological layers, in general, are used for very high volumes (0.1 to 1×10^9 m^3) on an annual basis. McAuliffe [25] presents the regions within the USA, which contain this geological formation in the strata, and a great part of Southern California and Central Valley fit this classification. Pottier and Blodin [6] also state that the output gas may contain hydrogen sulfide (similar to NG) requiring a processing station to eliminate this compound.

In regions where salt layers exist, special cavities can be created by controlled dissolution. A single cavity can have the volume capacity of approximately 1×10^6 m^3 and several cavities can be built for weekly or daily storage purpose. According to Pottier and Blodin [6] the working pressure may vary from 0.6 to 1.8 times the hydrostatic pressure at the cavity roof translating to 60 to 180 atm (881.76 to 2645.27 psi) for a 1,000-meter deep cavity. Taylor *et al.* [27] compared five different alternatives to store hydrogen and determined that salt caverns is the lowest cost even though it involves a considerable initial capital investment. One of the disadvantages of salt caverns is that the working fluid must be saturated brine.

According to the FUEEM expert network it is not a good procedure to have variable output at the centralized hydrogen production plant. Efficiency loss, plant reliability and safety concerns were pointed out as motives for considering bulk storage. For them pipeline-pack storage will not be feasible due to the pipe diameter limitation in urban areas transforming it in a high-cost option with low benefits. On the other hand, salt cavities are a viable solution. However, they are geographically limited due to geological formations and may be prohibited for certain urban areas.

Carpetis [28] provides some data for high-pressure storage vessel including the operational pressure of 3336 psi (23.0 MPa). According to him this is the most economical aboveground short-term storage (less than 30 hours) for hydrogen. Based on all these information it was decided to include the option to work with high-pressure bulk storage in the range between 2900 and 3627 psi (20 to 25 MPa). The distribution curve is shown in Table 1.

2.3 Flow Rates x Pipeline Diameters

Other very important variables in the pipeline design are the gas flow rate in the pipe and the diameter considered in the design. The gas flow rate for transmission lines is related with the hydrogen plant output capacity and the flow rates for the distribution lines are related with the fuel station gas demand.

The FUEEM model works with two centralized hydrogen plant capacity: 27 mtpd (0.3125 kg/s) and 270 mtpd (3.125 kg/s). One factor to be considered is the percentage of the overall capacity that the plant is expected to operate. Moore *et al.* [22] assume that the production for a 300-mtpd and a 30-mtpd-plant capacity will be 270 mtpd and 27 mtpd (90 % of the plant capacity) respectively. We have checked a specific plant operation (35 mtpd) data for two months and it operated at that particular months in the range between 99.5 % and 100.5 % of its nominal capacity. For the pipeline design we are considering 100% of the plant capacity.

Another point that should be considered is the fuel station hydrogen demand and it will depend on the fuel station capacity. Ogden *et al.* [5] and [1] consider a fuel station demand of 1 Mscf/day (2,400 kg/day) and according to her it will be enough for a fleet of 9220 vehicles or a refueling of 654 vehicles per day. She considers the typical Los Angeles annual mileage traveled of 11,000 miles per year per car and the car fuel efficiency of 106 $mpgg_{eq}$ (miles per gallon of gasoline equivalent). Moore *et al.* [22] designed a Fuel Station for 500 cars per day considering the average hydrogen demand of 2.7 mtpd (2,700 kg/day). Thomas *et al.* [29] in their cost analysis study looked at different fuel station capacity from 100 vehicles per day to 1000 vehicles per day where each vehicle refuel 5.6 kg of hydrogen per time (560 to 5,600 kg/day). Patel et al [30] suggested a fuel station design for a 6,000 kg/day of hydrogen delivering. Finally, Mark [4] considered 267 fuel stations to deliver 606 MW of hydrogen or 1,377 kg/day per fuel station (HHV) in average. The FUEEM expert network decided to work with values between 350 and 500 cars per day and an average hydrogen demand of 4 kg of hydrogen per vehicle per refueling. The curves can be seen at Table 1.

Another important variable for the flow rate definition is the number of pipes transporting the hydrogen plant production and the connection between the transmission line and the distribution lines. Figure 2 shows two different approaches to the connection assumptions. In the first approach the calculation for transmission line and distribution line is done independently and the flow rate is constant in both line types. In the second approach, the flow rate in the transmission line decreases over the distance. Apparently all the detailed studies about this topic have been done independently (approach "a"). For example, a 606 MW (368 mtpd – HHV) hydrogen demand Mark [4] assumes 4 bulk-transmission lines to the cities, which translate into the transportation of around 92 mtpd per line. From the end of each transmission line, 17 local distribution lines (16 km each) delivered the hydrogen to about 67 fuel stations. Using the approach "a", for the calculation, the underline assumption is that around 4 fuel stations (67/17) are placed at the same location. Patel et al [30] have suggested the approach "b" as a more realistic design for a large regional gaseous hydrogen plant distribution. For a 30-mtpd plant a transmission pipeline of 30 miles has a connected distribution pipeline every 3 miles. For a 10 times bigger plant capacity, 10 similar transmission pipelines were considered. No further details were explored. The approach "b" is considered in this study.

For the definition of the number of pipes transporting the hydrogen plant production the experts suggested that we adopt a similar Patel et al [30] design for the distribution process or in other words a main distribution line for every 27-mtpd demand. For a remote transportation (assuming a 270 mtpd plant outside of the cities, for example) they suggested 2 transmission lines.

Leeth [15] reported some diameters of the existing hydrogen transmission pipelines. According to him there is a 203 mm (8") hydrogen pipeline in Texas and a hydrogen pipeline system in Germany in which much of the system is a 300 mm (11.8") pipeline. Pottier [17] also reports that L'Air Liquide Company pipelines in France and Belgium are mostly 100 mm (3.9") diameter. Ogden [21] and Mark [4] assume in their studies 3" for the distribution pipelines and Mark [4] assumes 6" for transmission pipelines. As a conclusion of our discussions and after some calculations we decided to use 8" for the transmission lines, 4" for the main distribution lines and 2" for the distribution lines.

2.4 Pipeline Length

Considering local conditions, there is an option of varying the length of the pipelines. Three different options were established for the distribution lines (20 to 30 miles, 34 to 46 miles, 48 to 62 miles). Another three options were established for the transmission lines (35 to 65 miles, 80 to 120 miles, 125 to 175 miles). All of them were treated as normal distribution curves.

Wang [8] assumed just one scenario in his model. He considers the hydrogen plant located at the natural gas fields and pipelines to transport the hydrogen from there into the market place. This design requires transmission lines longer than the biggest option in the FUEEM. However, the consensus is that natural gas is easier and cost less to transport than hydrogen and the natural gas pipelines are already in place. Therefore, new hydrogen plants will be built as closer as possible to the market area.

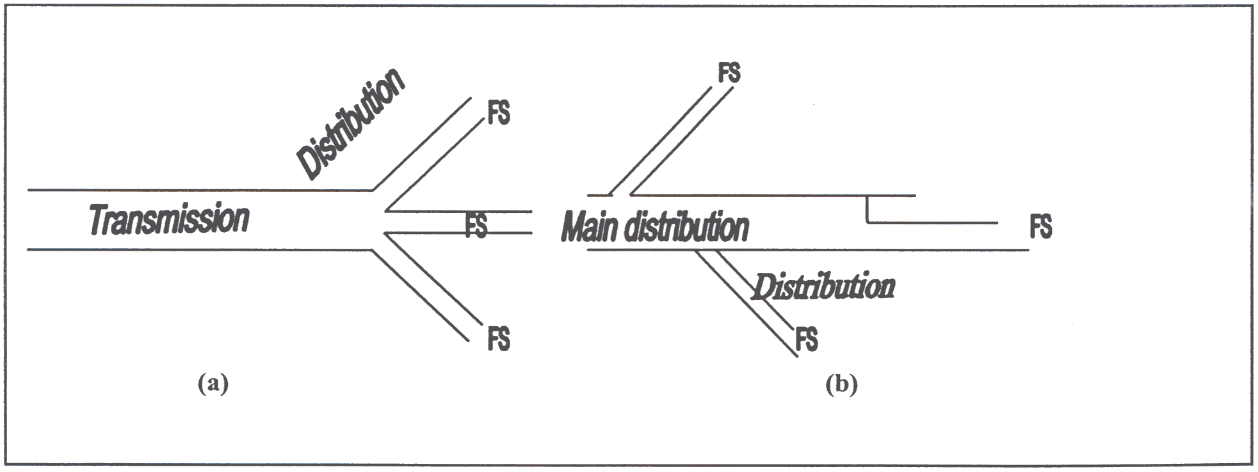


Figure 2: Two possible approaches for the flow rate assumption.

2.5 Hydrogen Compression

Once all the parameters like diameter, flow rates, pressures, etc. are defined the model is able to calculate the compressor power required to take hydrogen through the pipeline. According to Leeth [15] the gas industry has been using the isothermal flow of a compressible fluid as a basis for pipeline analyses. Pipe diameters, distance between compressor stations, pressure ratio, compressor power, etc. are usually the parameters of interest. Various equations have been used to describe the gas flow relationships among these parameters and many formulations have been developed in order to simplify calculations and answer specific questions (Leeth, [15]; White, [31]; Pottier, [17]; Ogden *et al.*, [21]). These equations are quite similar and are fairly basic equations of fluid dynamics. One of the equations used in the model is:

$$W = \frac{1}{\eta} mCpT \left[\left(\frac{P_2}{P_1} \right)^{\frac{(\gamma-1)}{\gamma}} - 1 \right] \tag{1}$$

where: W = compressor power, kW;
η = compressor efficiency;
m = mass flow rate, kg/s;
Cp = heat capacity, kJ/kg.K;
T = gas temperature, K;
P_1, P_2 = inlet and outlet pressures, Pa;
γ = ratio of heat capacities (C_P/C_V) of gas

Mathis [16] had compared the two major types of compressors used in the natural gas industry to boost the pressure along the pipelines: the reciprocating and the centrifugal compressors. According to him reciprocating compressors will have a serious sealing problem due to the rapid diffusion of relatively small hydrogen molecules and the attack by hydrogen on sealing materials in non-lubricate designs.

On the other hand centrifugal compressors will not produce the required pressure rates without extensive multi-staging; since pressure rise is the product of density and head rise, a lower density gas requires a higher head machine.

In a complementary report, Pottier [17] made a more updated study about compressors for hydrogen and according to him there are two compression technologies available for hydrogen: reciprocating compressors and centrifugal compressors. The latter are used extensively in natural gas compression stations for medium and large flows. For hydrogen, use of centrifugal compressors certainly creates more problems than the use of reciprocating ones. In fact the recompression rate for hydrogen is four times less than that for natural gas, for the same given tangential speed of the rotor. This requires a large number of stages. Also hydrogen tends to return to the inlet, due to its low specific gravity, thus decreasing centrifugal compressor efficiency. On the other hand, reciprocating compressors used for natural gas can be used for hydrogen without major design modifications. However, since hydrogen diffuses more readily, special attention must be given to sealing.

Also, Ogden *et al.* [21] suggested that to compress hydrogen a positive displacement reciprocal compressor would be needed. Centrifugal compressors cannot achieve these high pressures because of leakage and piston compressors have too high losses due to friction. Based on the information above we are considering only reciprocating compressors in our analysis. The necessary compressor power can be provided by different sources like electric motor, hydrogen internal combustion engine or natural gas internal combustion engine. In the model we are considering the electric and natural gas motors as options. The assumed efficiency curves for the compressors and for the motors were gotten in the literature and confirmed by some compressor manufacturers.

2.6 Hydrogen Refueling Station

Few gaseous hydrogen-refueling stations have been implemented so far to serve the demonstration program of fuel cell buses in cities like Chicago and Vancouver. The cost and complexity of fuel stations were always a subject of discussion but for the purpose of this study the compression requirement and the fugitive emissions are the only necessary variables to be considered. Most of the existing complexity of the fuel stations are related with safety concerns and the high cost is expected to be reduced with mass production. Ogden [1] estimates the cost of about US$1.7 million per station but a multi-stage compressor is specified to compress the gas from 200 psi to 8000 psi. Higher inlet pressure from the pipelines and lower final pressure in the storage vessel may reduce her figure.

The fuel station efficiencies assumed by the existing studies are: 92.8 % for Arthur D. Little [20] considering the inlet pressure of 1,000 psi. Initially Wang *et al.*[32] assumed 90 % and later on he changed that for 92 % (Wang, [8]). Hart and Bauen [33] present the figure of 92.3% but to compress H_2 from 1.0 bar (14.696 psi) to 250 bars (3627 psi) only. DeLucchi [34]considers in his model gaseous hydrogen stored on board of the vehicles in metal hydrides tanks. To pressurize the gas to 500 psi he considers that 0.03 Btu of electricity is consumed per each Btu of hydrogen compressed or in other words a compressor efficiency of 97.09 %.

An interesting DOE study [35] about the hydrogen refueling thermodynamics shows the relation among the gas temperature in the vehicle vessels, the refueling time and the final pressure of the vessel (after temperature stabilization). According to the study an overpressure of 800 psi is required to achieve the final pressure of 5000 psi in a 5 minutes refueling. Based on that a suggested total pressure of 5800 psi is the storage pressure at the fuel station vessel. Wang [8] and Thomas *et al.* [24] work with the overpressure of 1000 psi and Mark [4] states that this figure should be between 500 and 1000 psi. The assumed overpressure curve in the FUEEM model is around 950 psi as shown in Table 1.

2.7 Emissions

It is important to highlight again that we have so far presented the assumptions and results of a FUEEM component model, which is generating data about the energy requirements and emission rates for the FUEEM main model. It should be noted that hydrogen is not considered as a pollutant and therefore the fugitive emissions related to it account only as energy losses. The only emissions considered in this model occurred when natural gas is used as a fuel for the compressor motors. The assumed emissions rates were based in EPA-AP42 [36], Acurex [4], Workman Jr. *et al.* [37] and Wang [8] and treated as normal curves. These curves are shown in Table 2. The life cycle emissions for the electrical energy generation is being calculated in another component model.

3 The Model

Different scenarios were created to facilitate local analysis. The results of all scenarios are transported to the FUEEM main model and each of them is an alternative to be selected on the graphical user interface. Table 3 shows their major characteristics. The statistical attributes of the Monte Carlo technique such as Latin hypercube sampling and rank order correlations among variables are handled using @Risk software

4 Results

The main purpose of this component model is to generate data for the main model (FUEEM) but some analyses can be done in terms of energy requirements of similar scenarios. It is important to point out that other parameters like cost and safety must be taken into consideration too.

The energy requirements are presented in terms of efficiency in Table 4. Scenarios 1, 3 and 4 allow us to compare the conditions of hydrogen delivering at the Fuel Station at different pressures. Scenario 1, which delivers the hydrogen at around 3000 psi, presents in general a better efficiency than the other two, saying that is more efficient to work with high-pressure pipelines. However, we could notice that this fact has a limit since with pressures higher than 3000 psi the efficiency increase at the fuel Station does not compensate the efficiency decrease at the Compression Station. Also, the leakage, cost, maintenance and safety concerns increase with the increasing of the pipeline pressure.

Scenarios 2 and 5 both deliver the hydrogen at 1000 psi at the FS. The only difference is that scenario 2 has a bulk storage, which is used during the night (12 hours), and a turbo-compressor that uses part of the energy of the bulk storage to boost the compression of hydrogen at the plant. The efficiency is higher for the scenario 5. This should be expected because of the energy recovery by the turbo-compressor is always smaller than the energy spent to compress the gas at the bulk storage. On the other hand, the no use of bulk storage imply in the use of a very good control system interconnecting all the fuel stations and the hydrogen plant in order not to have any variation on the plant production mass flow.

Analyzing the efficiency of the total transportation, storage and distribution activities of fuel hydrogen one can notice that existing studies overestimate the energy requirement of the system. With the total efficiencies between 88 to 92 % the major differences arise in the calculation of the compression at the fuel station.

The emissions generated when the natural gas is the fuel for the compressor motors were calculated by multiplying the rates presented in Table 2 and the amount of natural gas consumed as fuel. The amount of

Table 1: Input Data

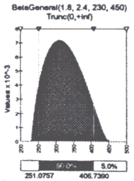
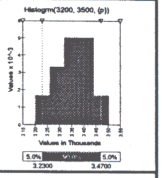
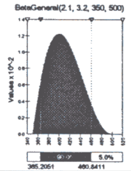
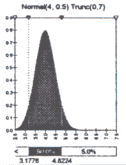
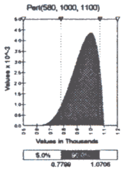
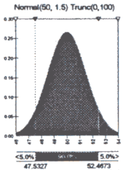
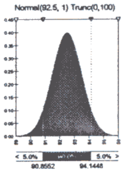
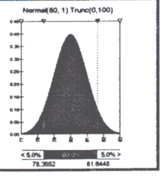
Parameters	**Unit**	**Min/Max (90% Confidence)**	**Mode**	**Mean**	**Curve Shape**
Pipeline Inlet Pressure	psi	251 / 407	309.7	324.3	
	MPa	1.73 / 2.81	2.14	2.24	
Bulk Storage Vessel Pressure	psi	3230 / 3470	3356	3356	
	MPa	22.27 / 23.92	23.14	23.14	
Vehicles per day	cars	365 / 461	400.0	407.4	
Hydrogen demand per vehicle	kg	3.2 / 4.8	4.0	4.0	
Refueling over pressure	psi	780 / 1071	1000.0	946.7	
	MPa	5.38 / 7.38	6.89	6.53	
Compressor efficiency	%	47 / 52	50	50	
Electric motor efficiency	%	91 / 94	92.51	92.5	
NG motor efficiency	%	78 / 82	80	80	

Table 2: Emission Rates Stationary NG Reciprocating Engine

Pollutant	mean	standard deviation
	(g/GJ of NG consumed)	
NOx	55.00	7.75
CO	250.00	44.71
NMOG	20.01	6.03
CH_4	300.00	60.61
N_2O	1.80	0.06
PM_{10}	9.00	1.20
$PM_{2.5}$	19.61	3.07
SOx	0.25	0.03
CO_2	49000.00	2409.5

Table 3: Scenarios

Scenario	Flow Rate (mtpd)	Bulk Storage	Transmission Line	Pipeline Inlet Pressure at FS (psi / MPa)
1	270	yes	yes	2300 to 3000 / 16 to 21
2	270	yes / turbo-compressor	no	1000 / 6.90
3	270	no	yes	200 / 1.38
4	270	no	yes	1000 / 6.90
5	270	no	no	1000 / 6.90
6	27	yes	no	3080 to 3120 / 21.2 to 21.5
7	27	no	no	1000 / 6.90
8 (decentralized)	2.7	no	no	N/A

natural gas consumed (in GJ) per GJ of hydrogen delivered can be calculated using the energy efficiency (Table 4) in the following formula:

$$NG = (100/\text{Effic.}) - 1 \qquad (2)$$

It is important to highlight that in this model, for all scenarios, we have a distribution curve for each given result. These curves are not presented here due to space limitations.

Table 4: Results

Scenario		Bulk Storage (BS) or Compression Station (CS)				Fuel Station				Total ST&D			
		Electric		NG		Electric		NG		Electric		NG	
		Short	Long	Short	Long	Short	Long	Short	Long	Short	Long	Short	Long
1 (BS)	Effic. (%)	94.34	94.33	93.51	93.51	98.84	98.82	98.67	98.65	93.24	93.22	92.26	92.24
	Stand. Dev.	0.500	0.500	0.568	0.568	0.069	0.071	0.080	0.081	0.503	0.503	0.572	0.573
2 (BS)	Effic. (%)	95.92	95.92	95.06	95.06	95.97	95.97	95.38	95.38	92.05	92.05	90.64	90.64
	Stand. Dev.	0.483	0.483	0.548	0.548	0.155	0.156	0.180	0.180	0.507	0.507	0.577	0.577
3	Effic. (%)	98.59	97.42	98.37	97.03	90.63	90.63	89.33	89.33	89.35	88.30	87.87	86.68
	Stand. Dev.	0.472	0.532	0.544	0.611	0.369	0.367	0.420	0.416	0.573	0.629	0.654	0.714
4	Effic. (%)	97.24	96.68	96.82	96.18	95.97	95.97	95.38	95.38	93.32	92.78	92.35	91.73
	Stand. Dev.	0.398	0.459	0.457	0.527	0.155	0.156	0.180	0.180	0.424	0.484	0.487	0.555
5	Effic. (%)	97.58	97.50	97.22	97.12	95.97	95.97	95.38	95.38	93.65	93.56	92.72	92.64
	Stand. Dev.	0.368	0.371	0.422	0.425	0.155	0.156	0.180	0.180	0.398	0.404	0.449	0.456
6 (BS)	Effic. (%)	94.34	94.34	93.51	93.51	98.86	98.85	98.69	98.68	93.26	93.26	92.29	92.28
	Stand. Dev.	0.504	0.504	0.569	0.569	0.069	0.070	0.078	0.079	0.509	0.509	0.571	0.571
7	Effic. (%)	97.58	97.50	97.22	97.12	95.97	95.97	95.38	95.38	93.65	93.56	92.72	92.64
	Stand. Dev.	0.368	0.371	0.422	0.425	0.155	0.156	0.180	0.180	0.398	0.404	0.449	0.456
8	Effic. (%)	N/A	N/A	N/A	N/A	92.40	N/A	91.32	N/A	92.40	N/A	91.32	N/A
	Stand. Dev.	N/A	N/A	N/A	N/A	0.583	N/A	0.651	N/A	0.583	N/A	0.651	N/A

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