SMALL MODULAR REACTORS FOR THE PRODUCTION OF HYDROGEN FUEL AT REMOTE SITES

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Abstract

Diesel fuel is commonly used at remote (off grid) sites as both a fuel for vehicles, as well as a consumable for power generation. The major disadvantage of diesel usage is the high cost to transport the fuel to these areas. In this paper hydrogen is proposed as an alternative fuel for remote areas. Hydrogen when consumed in a fuel cell can be used to provide electrical power to a vehicle as well as to an electrical grid. The study will quantify the effect that various variables have on the cost of using hydrogen as a fuel. The results will discuss both the feasibility of hydrogen as a fuel today, as well as the metrics that would be required for its use to be economically feasible with future technology and practices.

1. Introduction

The cost of fuel for vehicles and power production is significantly higher in remote off-grid areas than in urban grid-connected locations. This is primarily due to reliance on fossil fuels and the transportation costs associated with fuel delivery to remote areas. This paper will discuss at a high level the possibility of producing hydrogen as a fuel using a small modular nuclear reactor (SMR) coupled with hydrogen production technologies. The levelized cost and feasibility of hydrogen production will be discussed, and compared to the incumbent (fossil fuels delivered to the location). Nuclear plants are a dependable, carbon free source of electricity and process heat, and will likely become an increasingly crucial technology as generators and consumers continue to seek carbon emission reduction.

2. Background

Several SMR vendors have emerged in Canada in the last few years, and have initiated dialogues with the regulator, suppliers, utilities, governments, as well as potential consumers in regards to potential deployment of SMRs in Canada. A reason for SMR deployment in Canada is to offset or completely replace diesel consumption in remote or off-grid communities and mines. Diesel is frequently delivered to these sites via road or air for both electrical power generation and vehicle fuel. Currently, the cost of delivered diesel can range from approximately $1.25/L up to $2.00/L in some cases depending on site location and whether it is flown or driven in [1]. Both the energy demand and nominal cost of diesel in these locations is expected to rise over the next 40 years which has lead to the investigation of alternatives.

A proposed method of further reducing diesel consumption in these locations in conjunction with SMR deployment is the implementation of hydrogen as an energy storage medium and fuel. SMR deployment alone would not be capable of directly reducing diesel consumption for non-power generating applications such as transportation or mining vehicles.

3. Hydrogen Technologies Descriptions

Hydrogen technologies relevant to hydrogen used as a fuel include technologies used for the production, storage, distribution, and consumption of hydrogen.

3.1 Production Technologies

The following three hydrogen production methods are potentially suitable for integration with an SMR. The three methods vary in efficiency, maturity, and commercialization.

3.1.1 Low Temperature Electrolysis

Low temperature electrolysis (LTE) is a well understood and widely commercialized method of hydrogen production. Various low temperature electrolysis technologies exist and are commonly used. Two common technologies are alkaline cell electrolysis and polymer electrolyte membrane electrolysis. In an alkaline electrolysis cell a cathode and an anode are placed in an aqueous solution at low temperatures (<100°C). When sufficient current is run through the solution the water molecules separate collecting Hydrogen at the anode and Oxygen at the cathode [2]. Polymer electrolyte membrane (PEM) electrolysis cells, not to be confused with Proton Exchange Membrane (PEM) fuel cells, produces hydrogen via the electrolysis of water in a cell equipped with a solid polymer electrolyte. PEM electrolyzers overcome the issues of partial load and low current density experienced by alkaline cells. With both technologies, once the separation of hydrogen from oxygen occurs, the hydrogen can then be compressed and stored for future use while the oxygen by-product can be stored for other uses or sold. Electrical energy is the only energy input required to perform electrolysis, meaning that the electricity generated from an SMR could be directly used to produce hydrogen. Large scale commercially available electrolysers can generate from 1 to 2000 Nm^3 of hydrogen per day, with an average efficiency of approximately 45-55 kWh/kgH_2 produced [3]. For context, 1 kg H_2 contains approximately the same energy content as 1.003 US gallons of gasoline.

3.1.2 High Temperature Electrolysis

High temperature electrolysis (HTE) is a variation of electrolysis that uses steam as the electrolysing medium as opposed to water. The fluid contains a greater initial amount of thermal energy due to its higher temperature. As such less electricity is required to separate the water molecules resulting in a more electrically efficient process provided sufficient thermal energy is available [4]. SMRs lend themselves particularly well to this method of hydrogen production as waste thermal energy from an SMR can potentially be harnessed and used to generate steam for HTE.

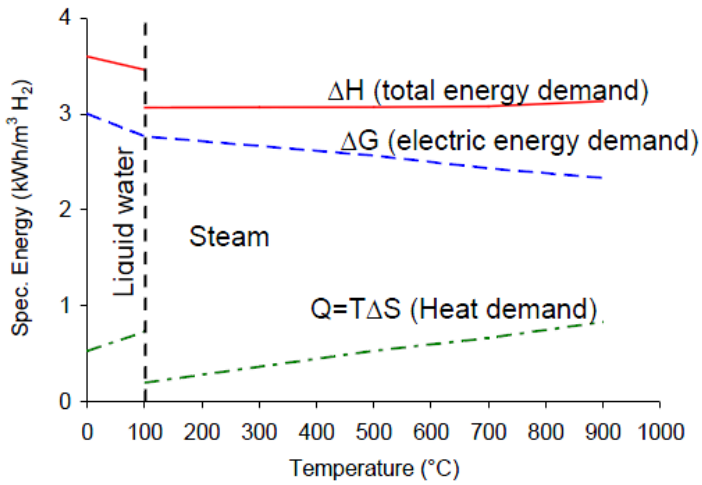

Figure 1 - Energy Required for Water Electrolysis at a Given Temperature [4]

3.1.3 Thermo-chemical Hydrogen Production Cycles

Thermo-chemical hydrogen production cycles are a developing technology that are yet to be commercialized. Cycles that have seen a considerable amount of research interest include the Sulfur-Iodine (SI) cycle, Copper Chlorine (CuCl) cycle, and the Hybrid Sulfur (HyS) cycle. With each of these cycles, while there are a number of reactions taking place the net reaction is the decomposition of water into hydrogen and oxygen, all other chemicals are recycled throughout the process. These cycles generally exhibit an overall improved efficiency over electrolysis since thermal energy is used directly and losses due to electricity conversion are not applicable or significantly reduced. None of these cycles have reached commercialization though several have been proven in a laboratory setting. The major disadvantage is that corrosive chemicals are created in the intermediate reactions and need to be controlled, requiring complex systems and high cost materials [2]. Another issue is that most cycles require extremely high operating temperatures before reaching maximum efficiency. For example, the SI cycle is approximately 60% efficient at 1000°C while only 38% efficient at 800°C [2]. Modern conceptual SMRs are not yet capable of supporting such high temperatures, especially as recoverable waste heat. As such these cycles are not considered feasible for use with an SMR at this juncture and will not be further analyzed in this paper.

3.2 Storage and Distribution Technologies

The two most common and developed methods of hydrogen storage are compressed gas storage and liquid hydrogen storage, both of which are established technologies commercially available. Additional storage and distribution technologies that are still in the research and development phases include metal hydrides, and underground storage; however, these will not be considered further in this paper. Storage and distribution is a complicated cost metric that will be largely undetermined until project conditions (quantity of hydrogen produced, the distance between the source and the consumer, and the intended end use of the product) are known.

3.3 Fuel Cell Technologies

A fuel cell is used to convert the chemical energy from stored hydrogen into electricity. Fuel cells are a well developed and commercialized technology most commonly used as primary or backup power for buildings in remote areas, temporary energy storage, or powering fuel cell vehicles. Fuel cells produce an electromotive force (emf) by allowing positively charged hydrogen ions to move from an anode to a cathode through an electrolyte. The anode and cathode are designed such that the hydrogen fuel undergoes oxidation reactions producing hydrogen ions (protons) and electrons. The hydrogen ions travel from anode to cathode through the electrolyte while the electrons travel through an external circuit producing direct current electricity. Materials used for the anode, cathode, and electrolyte vary depending on fuel cell technology which results in variations in efficiency, qualified power, operating temperature, and cost. On average, typical hydrogen fuel cell energy conversion efficiencies vary between 40-60% depending on technology, type, and scale. Polymer electrolyte membrane (PEM) type fuel cells often used in mobile applications such as hydrogen powered forklifts, automobiles, or heavy equipment are typically between 40-60% efficient. However, for large scale stationary applications molten carbonate (MCFC) or solid oxide (SOFC) fuel cells are used which on average see slightly higher efficiencies of approximately 60% [5].

4. Economics

The economic feasibility of the implementation of hydrogen as a fuel is dependent on a number of factors. To evaluate the economic feasibility of alternative fuels two major costs must be considered: the cost of production and the cost of consumption. To elaborate, an alternative fuel could be slightly more expensive to produce per unit energy; however, if the fuel can be consumed at a high efficiency or lower cost it may be more feasible than the incumbent technology. Alternatively, if the fuel is slightly cheaper to produce but is consumed at a low efficiency or high cost it may prove to be less feasible than the incumbent.

Ultimately the desired result is for the levelized cost of production of hydrogen as a fuel to be equal to or lower than the cost of delivering diesel fuel. In addition, the economics of hydrogen powered vehicles vs. diesel vehicles must be in favour of the former. An approximate range of levelized costs of production is calculated for hydrogen via low and high temperature electrolysis and compared to the existing cost of diesel. In addition, the costs and performance associated with hydrogen powered vehicles compared to diesel powered vehicles is discussed.

4.1 Costs of Fuel

Diesel fuel in Canada is commonly priced in $/L, whereas hydrogen is typically priced in $/kg. In order to compare these quantities the Gasoline Gallon Equivalent (GGE) is introduced. A GGE is defined as the amount of alternative fuel it takes to equal the energy content of one liquid gallon of gasoline [6]. The GGE's of hydrogen and diesel are defined by the following relationships presented in Table 1. The GGE unit allows the different fuels to be compared with a constant volume and a constant energy density.

Table 4-1 - Gasoline Gallon Equivalent of Hydrogen and Diesel [6]

Fuel	**GGE**
Hydrogen	0.88 kg/GGE
Diesel	3.33 L/GGE

The cost of diesel presented is reflective of typical delivered diesel costs seen by remote communities and mines in Ontario. Costs are calculated based on average 2015 diesel rack prices in cities nearest to remote communities with applicable provincial and federal taxes applied. Additional costs are added based on fuel delivery requirements under the assumption that approximately 65% of fuel is delivered by air and 35% by road or rail. Transportation costs consist primarily of the diesel fuel consumed by airplanes or tanker trucks during delivery. On average the forecasted delivered price of diesel for the next 5 years is approximately $1.30-1.50/L depending on transportation requirements and oil price trends [1].

The cost of hydrogen fuel is dependent on cost of electricity, electrolyser efficiency, and electrolyser unit costs. The levelized cost of electricity from SMRs is not as well understood or defined as it is for large nuclear power plants. This is due to the fact that most SMR designs are currently in early development phases and have not yet been built or operated. In addition, the cost of electricity can vary drastically depending on the scale of the SMR. The Abdulla et al. paper proposes potential levelized costs for small (45MWe) SMR plants in the range of $0.12-0.16/kWh [7]. The paper proposes a cost for a larger 225MWe reactor to be lower, at $0.08-0.11/kWh [7]. Some SMR vendors such as NuScale claim levelized costs of $0.10/kWh for a 540MWe unit [8]. A reactor for a remote site in Canada is most likely to be a smaller SMRs, or “micro” SMR, based on loading patterns and energy demand of remote communities and mines. On average, low temperature electrolysis units require approximately 4-5 kWh/m^3H_2 (45-55 kWh/kgH_2) [3]. In ideal conditions, high temperature electrolysis would require approximately 25% less electricity than low temperature electrolysis, only 2.5-3.5 kWh/m^3H_2 (30-40 kWh/kgH_2), with the remaining energy provided by pre-heated steam [4]. Under the assumption that waste heat from an SMR can be recovered to pre-heat steam, high temperature electrolysis is significantly less costly than low temperature electrolysis due to decreased electricity consumption. Additional costs for hydrogen production lie in capital and operating costs of the electrolysis unit as well as implementation of storage and distribution infrastructure.

The levelized cost of the standard electrolysis unit was estimated to be approximately $0.36/kg for a low temperature unit. This estimate is produced using capital cost, operating cost, and production metrics from the paper by Saur et al, and assuming a 40 year lifetime, a 7 year replacement period, and an a 8% discount rate[3]. The levelized cost for a high temperature electrolysis unit was not easily calculated as large scale units are still in the process of commercialization. For the purpose of the present study it was estimated to have a levelized cost 20% higher than the standard electrolysis cell $0.43/kg. The cost of transportation, storage and dispensing was estimated at $2/kg [9].

Based on the information presented above and considering hydrogen production from a SMR with an optimistic LCOE of 0.16/kWh, approximate costs of diesel, hydrogen via LTE, and hydrogen via HTE are presented in Table 2. Evidently, the cost of hydrogen per GGE is significantly higher than the cost of delivered diesel.

Table 4-2 - Cost of Production of Hydrogen Fuel

Fuel	Cost of Fuel	Cost of Fuel in GGE
Diesel	$1.40/L	$4.70
Hydrogen (via LTE)	$10.30/kg	$10.30
Hydrogen (via HTE)	$8.00/kg	$8.00

4.2 Costs and Efficiencies of Consumption

The efficiency and cost associated with hydrogen fuel consumption is considered in order to evaluate the feasibility of hydrogen as a fuel. To evaluate the cost of diesel engines vs. fuel cells the average annual cost of vehicle ownership and annual fuel expenses are calculated. A diesel powered vehicle is assumed to have an efficiency of approximately 7 L/100 km (2.1 GGE/100 km). A typical hydrogen fuel cell vehicle is assumed to have an efficiency of approximately 0.9 kgH_2/100 km (0.9 GGE/100 km) [10]. It is evident that although hydrogen fuel is more expensive the amount of fuel required to drive the same distance is less. To effectively compare the economics of diesel vs. hydrogen powered vehicles one must also consider the vehicle or engine cost. The current typical cost of hydrogen vehicles is approximately 2-3 times that of a gasoline or diesel powered vehicle [10].

In order to compare gasoline/diesel vehicles to hydrogen fuel cell vehicles the total yearly cost to operate the vehicle is considered. This cost includes the cost of purchasing the vehicle as well as the yearly maintenance and fuel costs. For this comparison it is assumed the Hydrogen is produced at the HTE cost quoted above. Purchase and maintenance costs are presented in the creti et al. paper from which an average annual ownership cost can be calculated based on a 10 year asset life. Annual fuel costs are calculated based on 15,000 km driven per year. Costs are presented in Table 4-3.

Table 4-3 - Vehicle Ownership Costs

Cost	ICE	FCEV
Annual Ownership cost	$ 5,900	$ 20,300
Capital Cost [9]	$ 24,000	$ 60,000
Annual Maintenance cost [9]	$ 2,400	$ 4,800
Annual Fuel Cost	$1,480	$1,080
Total Annual Cost	$7,380	$21,380

Based on the levelized cost of the vehicle, fuel, and maintenance, an electric fuel cell vehicle will cost approximately $21.5k/year while a diesel powered vehicle will cost approximately $7.5k/year. The increased cost of owning and operating a hydrogen electric vehicle has a greater effect on the economics than does the improved efficiency of hydrogen as a fuel.
An additional concern with hydrogen vehicles in remote areas though not related to economics is a fuel cell's ability to start-up and operate in colder temperatures. Most fuel cell vehicle manufacturers consider this an issue of the past and no is longer a primary concern when implementing this technology.

5. Critical Factors for Feasibility

The levelized cost of diesel and hydrogen fuel production estimated above is dependent on numerous variable factors as discussed. The critical key factors that have a noticeable effect on hydrogen and diesel fuel costs are discussed, in an effort to discern the future feasibility of hydrogen fuels.

5.1 Increased Cost of Diesel

A major factor in the feasibility of hydrogen as an alternative fuel is the cost of diesel fuel. Cost of diesel is currently at a 4 year low in Canada as shown in Figure 2. However, based on the forecasted crude oil price trend as presented in the EIA's Annual Energy Outlook 2015 (with projections to 2040) and current diesel rack prices the cost of delivered diesel may rise to higher than $3.00/L by 2040 [1]. At this point hydrogen fuel cell technologies may have developed to a point where they will be able to compete financially with diesel fuel and feasibility should be re-evaluated.

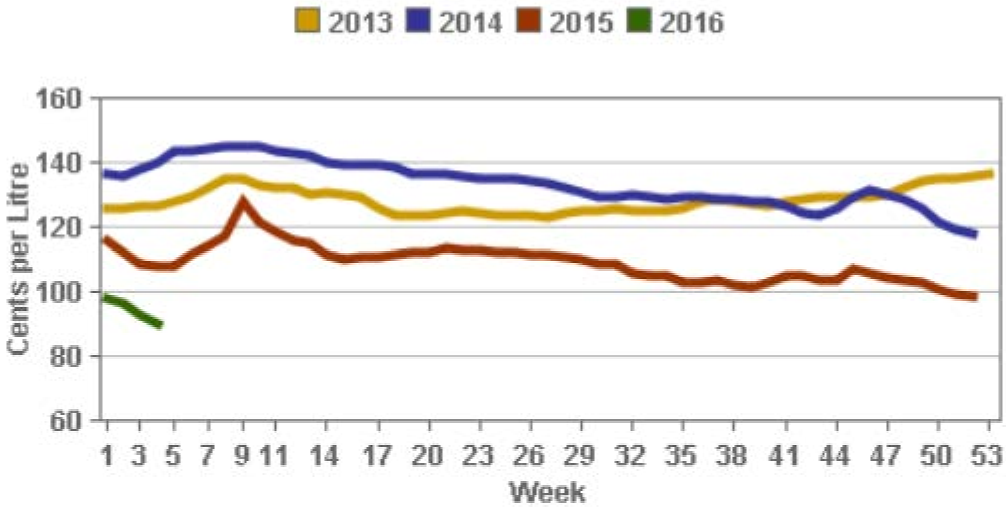

Figure 2 - Average retail price of Diesel in Canada [11]

It should be noted that the data presented in Figure 2 is an average diesel cost intended to show a trend and is not representative of actual diesel costs in the north, which will exceed this average value.

5.2 Decreased Levelized Cost of Electricity from SMRs

Cost of electricity is the major cost factor in hydrogen production by electrolysis. If electricity can be purchased or generated at a low price, hydrogen can be produced at a lower price. As discussed previously for the purposes of investigation, levelized cost of electricity from a SMR in a remote location in Canada was optimistically estimated to be $0.12-0.16/kWh, and a value of $0.16/kWh was used to perform initial assessments. Analysis was completed to assess the effect that a reduced levelized cost of SMR electricity would have on the overall levelized cost of hydrogen production. Two scenarios, a reduction of electricity cost by 10% and a reduction by 20% were assessed. The effect that this reduction had on the levelized cost of hydrogen production by both methods is detailed in Table 3 below.

Table 5-1: Effect of SMR LCOE on Hydrogen Prices

LCOE Change:	**0%**	**-10%**	**-20%**
Diesel	$4.70/GGE	$4.70/GGE	$4.70/GGE
Hydrogen (via LTE)	$10.30/GGE	$9.50/GGE	$8.70/GGE
Hydrogen (via HTE)	$8.00/GGE	$7.50/GGE	$6.90/GGE

From Table 3 it can be noted that a 10% decrease in SMR cost will reduce the price of hydrogen produced by LTE by $0.8/GGE and by HTE by $0.6/GGE.

It is evident that a significant decrease in cost of electricity is required in order for hydrogen production per GGE to be cost competitive with diesel. If cost of electricity from an SMR was to drop to a price competitive to grid connected electricity the feasibility of hydrogen as an alternative fuel for remote sites would be significantly improved.

5.3 Decreased Cost and Increased Efficiency of Electrolysis

As discussed previously the efficiency of the electrolysis unit is estimated to be 50 kWh_e/kg. The efficiency of the high temperature unit was estimated to be 35 kWh_e and 8 kWh_{th}/kg of hydrogen produced [3]. The levelized cost of a standard electrolysis unit was estimated to be \$0.36/kg and the cost of a high temperature unit was estimated to be \$0.43/kg. Analysis was completed to assess the effect that a reduced cost, and increased efficiency of the electrolysis unit would have on the overall levelized cost of hydrogen production. Four scenarios, a reduction of cost by 10%, a reduction of cost by 20%, an increase in efficiency of 10%, and an increase in efficiency of 20% were assessed. The effect that these changes had on the levelized cost of hydrogen production is detailed in Table 5-2 below.

Table 5-2 - Effect of Electrolysis Unit Cost and Efficiency on the cost of Hydrogen Fuel

Electrolysis Unit Cost Change	**0%**	**-10%**	**-20%**
Diesel	$4.70/GGE	$4.70/GGE	$4.70/GGE
Hydrogen (via LTE)	$10.30/GGE	$10.30/GGE	$10.30/GGE
Hydrogen (via HTE)	$8.00/GGE	$7.99/GGE	$7.95/GGE
Electrolysis Efficiency Change	**0%**	**+10%**	**+20%**
Diesel	$4.70/GGE	$4.70/GGE	$4.70/GGE
Hydrogen (via LTE)	$10.30/GGE	$9.50/GGE	$8.70/GGE
Hydrogen (via HTE)	$8.00/GGE	$7.50/GGE	$6.90/GGE

From Table 5-2 it can be noted that the effect of a 20% decrease in electrolysis unit cost is minimal. An increase in the electrolysis efficiency will reduce the price of hydrogen produced by LTE and HTE fairly significantly. This result indicated that the electrolysis efficiency has a greater bearing on the levelized cost of the hydrogen production than does the electrolysis unit cost.

5.4 Cost and Commercialization of Hydrogen Powered Vehicles

As discussed in Section 4.2 the fuel cell vehicle is currently significantly more expensive than an internal combustion powered vehicle. This higher expense has a greater bearing on the economics case than does the improved efficiency of the fuel cell engine. Diesel generation and vehicles are well developed technologies that have experienced significant advancement and evolution over the last few decades positioning them as the incumbent technology for remote power applications. Due to a competitive market for diesel gensets and vehicles, prices of these technologies are naturally lower compared to emerging technologies such as hydrogen fuel cells.

It is expected that the cost of fuel cells will continue to decrease in coming years at a much more significant rate than the cost of an ICE vehicle. The Creti et al. paper anticipates the cost of fuel cell vehicles will decrease by approximately 50% in the next 5 years [10]. If this decrease is realized the average yearly cost of ownership for these vehicles will decrease to approximately \$10,295/year. This is a significant improvement in the business case for a hydrogen vehicle but will not yet present a suitable business case. Based on the yearly fuel costs, and assuming now decrease in hydrogen production costs, the breakeven point would be reached when the yearly cost of ownership of the FCEV is approximately $400 more than its gasoline powered counterpart. In other words a yearly total ownership cost of approximately $7,900. This would require a decrease of approximately 60% in the cost of a FCEV. As such it can be concluded that the economic feasibility for fuel cell vehicles is several years from realization, regardless of the cost of the hydrogen fuel.

6. Conclusion

Hydrogen fuel produced by a small modular reactor is still some years away from making a viable economic case in remote areas. Significant improvements in production and consumption efficiency along with fuel cell and electricity cost decreases will need to be realized before this technology is feasible.

The current cost of hydrogen fuel cell vehicles significantly decreases the economic feasibility. In addition it is noted that the cost of electricity from an SMR is the major factor affecting the cost of hydrogen production. Expected future trends show a potentially significant decrease in hydrogen fuel cell vehicle costs and SMR levelized electricity. If the cost of hydrogen fuel cell vehicle and SMR electricity cost is reduced sufficiently it may present a viable alternative to internal combustion engine vehicles in the future.

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