RESEARCH REPORT

GREEN ENERGY FOR REMOTE HOUSING IN THE NORTH: ASSESSMENT OF AN INTEGRATED ENERGY SYSTEM UTILIZING FUEL CELLS

EXTERNAL RESEARCH PROGRAM

Canada

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Green Energy for Remote Housing in the North: Assessment of an Integrated Energy System Utilizing Fuel Cells

Final Report

Prepared by

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Submitted to

Canada Mortgage and Housing Corporation

June 30, 2005

This project was partially funded by Canada Mortgage and Housing Corporation (CMHC) under the terms of the External Research Program, but the views expressed are the personal views of the authors and do not represent the official views of CMHC.

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Executive Summary

The main objectives of this project were to assess fuel cell technology, to analyze its feasibility for stationary applications in the Canadian Far North, and to conduct economic analysis for integrating renewable energy with hydrogen and fuel cells.

Different types of fuel cells were assessed with respect to their applicability to northern communities. Companies developing these were contacted and some were visited. A survey was sent out to the main fuel cell developers to gain knowledge on their progress, as well as to inform them on our initiatives. Two 1 kW hydrogen fuel cells were acquired from Ballard Power Systems and were interconnected with other equipment necessary to run load in the laboratory setting. Testing was successfully performed under conditions that were similar to those found in a home or home office environment.

The project was conducted to determine if fuel cells are economically feasible for stationary purposes in five communities in the Inuvialuit region of Northwest Territories [1]: Inuvik (pop. 2,894) , Tuktoyaktuk (pop. 930), Sachs Harbour (pop. 114), Holman (pop. 398), and Paulatuk (pop. 286). However, major analysis, conclusions and recommendations are based on the conditions found in Holman, which we studied for a possible pilot project.

The basic premise of this project was to study the deployment of a 2 kW or 3 kW hydrocarbon-based fuel cell in a single home to replace the grid electricity supplied from diesel and natural gas generators presently used by the Northwest Territories Power Corporation (NTPC). The costs of deploying the fuel cells over a 10 to 20 year period were compared to the present total cost of energy for single homeowners. An additional case study was conducted to see the feasibility of a 50 to 80 kW hydrocarbon fuel cell system in an apartment complex in Inuvik. An alternative option was also considered, where a part or all of the community was powered by a stack of hydrocarbon fuel cells based at a central location, such as the present power plants of NTPC and fuelled by the current fuel. It was beyond the scope of this project to purchase such fuel cells and/or to conduct their physical testing.

An Economic feasibility study was also conducted for the integrated wind-hydrogen-fuel cell system. In our model, wind energy was used to produce hydrogen for fuel cells. By using renewable energy, no fossil fuels are required, thus leading to a large decrease in toxic emissions and greenhouse gases. The analyses are based on a system, which comprises one or more wind turbines, electrolysers, hydrogen storage tanks and fuel cells. Four different scenarios were considered for the Hamlet of Holman, where wind power generation seems most feasible out of all 5 communities studied:

1. a wind-H_2 storage solution to supply the total power consumption for 10% of the community.
2. a wind-H_2 storage solution to supply the total power consumption for 20% of the community.
3. a wind-H_2 storage solution to supply the total power consumption for 50% of the community.
4. a wind-H_2 storage solution to supply the total power consumption for 100% of the community.

A number of key assumptions were made. These include the assumption that the current government subsidies could be given directly to the homeowners or investors deploying the integrated technologies described here. These also include the assumption that energy cost from fossil fuel will not decrease and that long term mortgages are available at 8% interest or less. Finally all these considerations are based on the premise that the system will have an operational lifetime of 10 years or more.

Two main modelling and analysis tools were utilized. HOMER™ from the U.S. National Renewable Energy Laboratory was used for simulation and to identify the size and number of pieces of equipment under any given scenario. On the other hand, RETScreen® from Natural Resources Canada was used to perform fiscal analysis.

Generally speaking, it can be concluded that deployment of fuel cells for the remote communities in the Arctic are likely to be economically feasible. It is more likely to happen when the capital costs are financed over the longer time period or when money is invested as a lump-sum, i.e. without obtaining any financing. It is also dependent on a number of other factors, including the type of fuel and its availability.

It can be safely concluded that solid oxide fuel cells are currently more financially attractive for deployment beyond the Arctic Circle due to the existing infrastructure for the supply of its fuels. Our analysis indicates that hydrocarbon fuel cells are financially viable as replacement for diesel generators, either for single homes or for part/whole community in most of the communities and scenarios studied. On the other hand, hydrogen fuel cells are technologically more advanced than hydrocarbon fuel cells and it appears more likely that a project based on hydrogen fuel cells will be successful on its technological merit. However, the barriers about the easy availability of hydrogen fuel and its safety need much great attention. An integrated renewable-hydrogen-fuel cell system is not currently feasible in most of the scenarios studied, except when a community wide power demand exceeds 120 kW and when a project lifetime is 15 years or more. The availability of wind also needs to be taken into account, suggesting Holman and Sachs Harbour as likely project locations, whereas Inuvik, Paulatuk and Tuktoyaktuk may not be as suitable for a wind-hydrogen project.

During this study many technological and socio-cultural challenges were identified, including isolation, the high cost of transportation, limited access to technical information as well as a general lack of well-trained personnel available. We conclude that if a project were to be carried out in the northern communities, it will require additional effort and expenses to ascertain adequate contact with northern residents and to ensure that training facilities are established as part of the project.

Résumé

Les principaux objectifs de ce projet étaient d'évaluer la technologie des piles à combustible, d'analyser sa faisabilité pour les applications stationnaires dans le Grand Nord canadien et d'effectuer une analyse économique de l'intégration de l'énergie renouvelable aux piles à hydrogène et à combustible.

Différents types de piles à combustible ont été évalués en fonction de leur applicabilité dans les collectivités nordiques. Nous avons communiqué avec des entreprises qui travaillent au développement de ces piles et certaines ont été visitées. Nous avons envoyé un questionnaire aux principaux développeurs de piles à combustible afin de nous tenir au courant de leurs progrès et de les informer à propos de nos initiatives. Deux piles à hydrogène de 1 kW fournies par Ballard Power Systems ont été interconnectées avec d'autres pièces de matériel nécessaires à la création de la charge en laboratoire. Les essais ont été effectués avec succès dans des conditions semblables à celles qui existent en milieu résidentiel ou professionnel.

Il s'agissait d'établir si les piles à combustible se prêtaient économiquement à des installations stationnaires mises en place dans cinq collectivités de la région d'Inuvialuit des Territoires du Nord-Ouest [1] : Inuvik (pop. 2 894) , Tuktoyaktuk (pop. 930), Sachs Harbour (pop. 114), Holman (pop. 398) et Paulatuk (pop. 286). Cependant, les principales analyses, conclusions et recommandations se fondent sur les conditions que l'on retrouve à Holman, endroit que nous avons étudié dans l'éventualité d'y mener un projet pilote.

Le fondement de ce projet était d'étudier l'installation d'une pile à combustible à base d'hydrocarbure de 2 kW ou 3 kW dans une maison individuelle afin de remplacer l'électricité du réseau fournie par des génératrices au diesel et au gaz naturel actuellement utilisées par la Northwest Territories Power Corporation (NTPC). Les coûts de l'installation des piles à combustible sur une période de 10 à 20 ans ont été comparés au coût total actuel de l'énergie pour les propriétaires de maison individuelle. Une autre étude de cas a été réalisée afin de déterminer la faisabilité d'un système à piles aux hydrocarbures de 50 à 80 kW dans un immeuble d'appartements à Inuvik. Une autre option a aussi été examinée, dans le cadre de laquelle une partie ou l'ensemble de la collectivité était alimenté par un groupe de piles aux hydrocarbures situé dans un endroit central, comme c'est actuellement le cas des centrales de la NTPC, et alimenté par le combustible utilisé à l'heure actuelle. Il n'étai pas prévu d'acheter de telles piles ou de les mettre à l'essai.

Une étude de faisabilité économique a aussi été effectuée pour le système intégré de pile à hydrogène-éolien. Dans notre modèle, l'énergie éolienne était utilisée afin de produire l'hydrogène destiné aux piles à combustible. En se servant de l'énergie renouvelable, on évite l'emploi d'un combustible fossile et on contribue ainsi à une importante réduction des émissions toxiques et de gaz à effet de serre. Les analyses se fondent sur un système comportant une ou plusieurs turbines éoliennes, des électrolyseurs, des réservoirs à hydrogène et des piles à combustible. Quatre scénarios différents ont été examinés pour le hameau de Holman, lieu parmi les cinq collectivités à l'étude où la production d'énergie éolienne est la plus réalisable :

1. une solution de stockage de H_2 produit par l'énergie éolienne suffisante pour répondre à la consommation d'énergie totale de 10 % de la collectivité;

2. une solution de stockage de H_2 produit par l'énergie éolienne suffisante pour répondre à la consommation d'énergie totale de 20 % de la collectivité;
3. une solution de stockage de H_2 produit par l'énergie éolienne suffisante pour répondre à la consommation d'énergie totale de 50 % de la collectivité;
4. une solution de stockage de H_2 produit par l'énergie éolienne suffisante pour répondre à la consommation d'énergie totale de 100 % de la collectivité.

Un certain nombre d'hypothèses a été émis : les subventions gouvernementales actuelles pourraient être accordées directement aux propriétaires ou aux investisseurs faisant appel aux technologies intégrées décrites dans le présent document; les coûts de l'énergie provenant de combustibles fossiles ne diminueront pas et les prêts hypothécaires à long terme seront disponibles à un taux d'intérêt de 8 % ou moins. Toutes ces suppositions se fondent sur le fait que le système aura une durée utile d'au moins 10 ans.

Deux principaux outils de modélisation et d'analyse ont été utilisés. HOMER^MC, du U.S. National Renewable Energy Laboratory, a servi à des fins de simulation et à établir la puissance et le nombre de pièces d'équipement requis pour n'importe quel scénario donné. D'autre part, RETScreen®, de Ressources naturelles Canada, a servi à faire l'analyse financière.

En règle générale, on peut conclure que l'installation de piles à combustible pour les collectivités des régions éloignées de l'Arctique est, selon toute vraisemblance, économique à réaliser. Selon toute probabilité, elle est plus susceptible de se concrétiser lorsque les coûts en immobilisation sont financés sur une longue période ou que l'argent est investi sous forme de somme forfaitaire, c.-à-d. sans avoir à obtenir de financement. Cette installation est également tributaire d'un certain nombre d'autres facteurs, notamment du type de combustible et de sa disponibilité.

On peut, sans se tromper, tirer la conclusion que les piles à oxyde solide sont pour le moment plus attrayantes financièrement pour une installation au-delà du cercle polaire en raison de l'infrastructure existante d'approvisionnement de ces combustibles. Notre analyse indique que les piles aux hydrocarbures sont financièrement viables pour le remplacement des génératrices au diesel, que ce soit pour les maisons individuelles ou pour une partie ou l'ensemble de la collectivité, et ce, pour la plupart des collectivités et des scénarios étudiés. D'autre part, les piles à hydrogène sont plus perfectionnées du point de vue technologique que les piles aux hydrocarbures, et il semble qu'un projet faisant appel aux piles à hydrogène est plus susceptible de réussir grâce à ses qualités techniques. Toutefois, les obstacles que présentent la facilité à se procurer de l'hydrogène comme combustible et sa sécurité méritent qu'on s'y attarde longuement. Un système intégré de piles à hydrogène renouvelable n'est pas actuellement réalisable dans le contexte de la majorité des scénarios étudiés, sauf lorsque la demande en énergie de l'ensemble d'une collectivité dépasse 120 kW et lorsque la durée d'un projet est de 15 années ou plus. On doit aussi tenir compte de la présence du vent, ce qui fait que Holman et Sachs Harbour sont les meilleurs endroits pour réaliser le projet, alors que Inuvik, Paulatuk et Tuktoyaktuk peuvent ne pas se prêter aussi bien à la réalisation d'un projet faisant appel à de l'hydrogène produit par l'énergie éolienne.

Au cours de la présente étude, de nombreux défis technologiques et socioculturels ont été mis en évidence, notamment l'isolement, le coût élevé du transport, l'accès limité à l'information technologique de même que la pénurie générale de main-d'œuvre qualifiée. Nous en venons à la conclusion que si un projet devait être réalisé dans les collectivités nordiques, il exigerait que des efforts et des dépenses supplémentaires soient faits afin d’assurer une bonne communication avec les résidents du Nord et de garantir que des installations de formation sont prévues dans le cadre du projet.

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Acknowledgements

We gratefully acknowledge Canada Mortgage and Housing Corporation (CMHC) and the Energy Secretariat of Resources, Wildlife and Economic Development (RWED) of the Government of Northwest Territories for providing research grants for this project. The funding from the National Research Council's Industrial Research Assistance Program (IRAP) and the Training on-the-Job Program of Education, Culture and Employment of the Government of Northwest Territories for hiring a research assistant is also greatly appreciated. We would particularly like to acknowledge Thomas Green (CMHC), Aleta Fowler (INAC), Craig d'Entremont (IRAP), and Dennis Bevington and Pietro de Bastiani (both from RWED) for their guidance and support during the course of this project. We would also like to express our gratitude to Dr. Evgueniy Entchev and Ron Alward (both from Natural Resources Canada) for their valuable input. Finally we gratefully acknowledge the following people and companies for supplying us with valuable information and product support: Terry Rafferty (Northwest Territories Power Corporation), Tom Lambert (U.S. National Renewable Energy Laboratory), Gary Schubak (Ballard), Nick Kovicks (Ballard), Terry Kimmel (Pivotal Power), Colin Picott (Pivotal Power), Ken Ripley (Xantrex), Stuart Energy, Proton Energy, Ballard, Global Thermoelectric, Energy Visions, Hydrogenics, IDA Tech and Xantrex.

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A. Abstract

Fuel cell technologies were investigated for their appropriateness in the remote communities of the Arctic. Several companies are now in the process of field testing and demonstrating fuel cell applications for the stationary and mobile markets. Fuel cells are becoming more cost-effective and have shown good promise as an alternative to the polluting diesel power generating plants. A commercially available small fuel cell was tested under laboratory conditions to simulate conditions at a typical home. Performance measurements were conducted and the unit is set up as a demonstration system for education and public awareness.

We also conducted the techno-economic feasibility of integrating renewable energy systems to produce hydrogen for the power and space heating requirements of a cluster of homes. Modelling and financial analysis was done using widely recognized software tools, HOMER™ and RETScreen®. The analysis was conducted using several scenarios. Our results indicate that the integrated wind-hydrogen-fuel cell systems are economically viable for most of the cases covering more than 20% of the population of a small community, such as Holman.

B. Introduction

In remote communities of the Canadian north, diesel generators are commonly used. Electricity produced is very expensive and the environmental impact is significant. The rate of greenhouse gas emissions per capita in NWT is one of the highest in the world at 27.5 tonnes. Diesel power plants are usually located in the middle of small towns and the exhaust contains up to 40 different chemicals classified as "toxic air contaminants" [2]. Diesel exhaust is classified as a carcinogen and short-term exposure may cause irritation to the eyes, nose and throat as well as coughing, chest tightness, wheezing and inflammatory responses in the airways and lungs.

Millions of people die yearly around the world due to poor air quality, often as a direct result from burning fossil fuels. Burning fossil fuels as well as the emitted greenhouse gases also lead to global warming, which is changing the earth's climate yearly, affecting the plants and animals around the world. Hydrocarbons used as fuel are also required for materials vital to living; the more these are consumed, the more the world will be depleted of necessary resources. By using renewable energies, the risk of oil spills and other great catastrophes are minimized. The key message here is that it is much better socially and economically to use renewable energies to generate electricity wherever possible.

Ratification of the Kyoto Accord introduced Greenhouse Gas Emission credits, which earn money for the clean energy producer in return for cutting down on emissions. These savings may exceed the monetary losses in using clean energy sources over the less expensive diesel. To improve public health, create more new jobs and improve overall economy, this is a definite incentive to seek and deploy alternative energy technologies to replace the conventional generators.

A clean alternative energy technology that is rapidly approaching technological maturity is the use of fuel cells, both hydrocarbon and hydrogen based. The main benefit of fuel cells lies in their higher overall efficiency as compared to most conventional systems that produce electricity. The increased efficiency lies in the more direct conversion of chemical to electrical energy, avoiding heat losses from combustion. In addition to naturally higher electrical efficiency, fuel cells also have the potential of becoming an acceptable source of residential heating, thus increasing the total energy efficiency even more. However, there are several challenges ahead to bring these to the marketplace. One of the main challenges is to demonstrate suitable methodology to produce and transport hydrogen efficiently, economically and safely in an environmentally friendly manner. Due to substantial increase in the government funding globally, there are several demonstrations currently in place, mainly in the transportation sector. Also, the stationary fuel cell prototypes are being beta tested [3].

This project focussed on the identification, performance testing and deployment of stationary fuel cells for remote communities in the Arctic. The feasibility of different types of stationary fuel cells was conducted. Models were developed to integrate these with renewable energy sources for the production and storage of hydrogen. Different scenarios were studied, including "zero-consumption" of diesel for a part or whole of the community. For early market adoption of the technology, the use of locally available current infrastructure for fuels was studied to install fuel cells in individual homes. There is no fuel cell currently available that can use diesel directly; however, based on existing technology for natural gas and LPG, the use of diesel for fuel cells was assumed possible for the purpose of this investigation. Additional reforming devices are likely to be required for this purpose but will not significantly differ from those already part of contemporary natural gas fuel cells.

B.1. Technologies

B.1.1. Fuel Cell Technology

Conventional generators, such as internal combustion engines, use mechanical energy from combustion to generate electrical energy. Fuel cells, on the other hand, allow the controlled oxidation of a fuel to generate electrical energy directly via an electrochemical process. The most common fuel for fuel cells is hydrogen, but fuel cells using methanol as well as fuel cells converting hydrocarbons to hydrogen are also available.

B.1.1.1 Types of Fuel Cells

The following are different types of fuel cells being developed globally:

- Proton Exchange Membrane (PEMFC)
- Solid Oxide Fuel Cells (SOFC)
- Alkaline Fuel Cells (AFC)
- Direct Methanol Fuel Cells (DMFC)
- Phosphoric Acid Fuel Cells (PAFC)
- Molten Carbonate Fuel Cells (MCFC)

Table 13 in App-2.1 gives a brief comparison of these types of fuel cells. These were assessed for stationary applications and the companies developing them were surveyed (see App-2.3). The main goal of this assessment was to determine how appropriate each type would be for use in the Arctic communities. Based on this assessment, hydrogen/PEMFC and hydrocarbon/SOFC were selected for detailed study. Additional information on all other types of fuel cells can be found in App-2.1.

B.1.1.2 Proton Exchange Membrane Fuel Cells

Hydrogen fuel cells use hydrogen gas as fuel. In the redox process:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \quad (1)$$

two electrons are transferred. In a fuel cell, the two gases, hydrogen and oxygen, are not allowed to mix directly as in combustion. Instead they are separated by a membrane electrolyte. The gases then undergo the following reactions at the appropriate electrode surface:

$$\text{At the anode: } H_2 \rightarrow 2H^+ + 2e^- \quad (2)$$
$$\text{At the cathode: } \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (3)$$

The electronic current passes through an electrical circuit, thus converting chemical energy available from the reaction directly into electrical energy. The membrane electrolyte allows H^+ to pass through, but not the reactant gases, water or electrons. This membrane is generally a polymer electrolyte like Nafion™, thus these fuel cells are often referred to as Polymer Electrolyte Membrane (PEM) fuel cells.

The theoretical energy content of hydrogen is calculated by using the redox potential of the H_2/O_2 couple as $E^o = 1.229$ V. As an ideal gas, the molar volume of hydrogen is $V_m = 22.4$ L/mol or 0.0224 m^3/mol. Using the conversion factor 1 C = 1 A s and the Faraday constant, F=96,486 C/mol e^-, one can determine the energy content of hydrogen to be 2.94 kWh/m^3 H_2 by the following equation:

$$\text{Energy content of hydrogen} = n * F * E_r / V_m \quad (4)$$

where n is the number of electrons transferred and E_r is the actual redox potential at which the reaction occurs. It should be noted that due to kinetic constraints the redox reaction generally does not proceed at $E_r = E^o = 1.229$ V. Instead, a redox potential $E_r = 0.7$ V is a more generally accepted voltage to be used for fuel cell operation. Using this number, the available energy content of hydrogen would be obtained as 1.68 kWh/m^3 H_2. The electrical efficiency of the fuel cell is then obtained by dividing the amount of energy obtained from a cubic meter of hydrogen by the amount theoretically available. The efficiency is thus calculated to be 57%.

In contrast to many other gases, hydrogen storage is generally referenced in kg instead of m^3. Thus a more convenient number to consider for energy production from stored hydrogen may be 18.9 kWh/kg.

B.1.1.3 Solid Oxide Fuel Cells

Solid oxide fuel cells use hydrocarbons, currently natural gas or propane, but diesel is being considered. To achieve this, there is a built-in reformer to convert these hydrocarbons into hydrogen. For natural gas or methane, this is based on the equilibrium:

$$CH_4 + H_2O \leftrightarrows 3\ H_2 + CO \qquad (5)$$

In contrast to the 40-120°C operating temperature of hydrogen fuel cells, the temperature in hydrocarbon fuel cells generally exceeds 600°C. Thus, instead of a polymer transporting protons, the membrane is generally a high-temperature oxide ion conductor. These ionic conductors are generally referred to as solid oxides; from which Solid Oxide Fuel Cells (SOFC) derive their name. Despite these apparent differences, the operating principle of the fuel cell does not differ from that of the hydrogen fuel cell described above and it is still the reaction of hydrogen and oxygen from which the energy is derived. The heat required for the initial reforming process is generally obtained from burning the product gas and converting CO, as well as unused $H_{2,}$ to heat:

$$2\ CO + O_2 \rightarrow 2CO_2 \qquad (6)$$

Similar to the hydrogen fuel cell, reactions 2, 3, 5 and 6 are individual steps in the overall reaction of Methane combustion:

$$CH_4 + 3O_2 \rightarrow CO_2 + 2H_2O$$

In the conversion of methane, 8 electrons are transferred, of which 6 can be used directly in the production of electrical energy. Following equation 4 and comparing to two electrons transferred per mole of hydrogen this, indicates that methane should have approximately three times the energy density of hydrogen. The electrical efficiency of SOFCs has been reported to be 55% [4]. As additional electrical losses are expected to be 18%, the electric efficiency of natural gas fuel cells may be as low as 46%, however.

As opposed to natural gas, which consists primarily of methane, diesel is a complex mixture of hydrocarbons. While to date no fuel cells are commercially available that use diesel, it could be subjected to the same reforming process as methane. The hydrogen thus generated could then be used in a fuel cell that is insensitive to impurities. This study is primarily an economic feasibility study only, and therefore it has been assumed that a diesel fuel cell, once available, will be priced similar to a natural gas fuel cell

Diesel fuel has an average energy density of 36 MJ/L [5] or 10 kWh/L. In order to calculate the amount of diesel fuel required, the same fuel cell efficiency was assumed as for the natural gas fuel cell, 55%. Therefore the amount of electricity retrieved from the diesel fuel is equal to 55% of the amount of energy available. Thus the energy available from diesel fuel via a fuel cell is assumed to be 5.5 kWh/L.

B.1.2. Hydrogen Production and Storage

B.1.2.1 Electrolyzers to be used with Hydrogen Fuel Cells

Electrolysis describes the splitting of water to Hydrogen and Oxygen. This is essentially the reverse of the process that occurs in the fuel cell. Some design modifications are generally made to allow for compressing the resulting Hydrogen gas. Just like in the fuel cell, hydrogen evolution does not occur at the ideal 1.229 V, instead 1.47 V is a more commonly accepted value [6, 7]. Using this value, the minimum amount of energy needed to generate 1 m^3 of H_2 is calculated to be 3.52 kWh/m^3 H_2.

Just like in the fuel cell there are additional electrical losses incurred in the operation of the electrolyzer. In addition, energy is needed to pressurize the product gas. Thus, the reported value is 4.8 kWh/m^3 of H_2 [8].

Different types and sizes of electrolyzers were investigated. Due to the economies of scale, the costs of electrolyzers decrease significantly with increasing hydrogen production rates. However, the maximum size of electrolyzers each company manufactures is limited. Moreover, the designs generally suggest a modular connection of multiple electrolyzers once that limit is exceeded. Thus the capital cost savings available from plant scale-up are limited at the high end.

Series 300 of H_2 IGEN® from Stuart Energy is a 3 Nm^3/h H_2 electrolyzer [8]. It has a membrane exchange area of 300 cm^2 and produces hydrogen at 25 bar. After a de-oxidization drier unit the hydrogen produced is at purity acceptable for PEM fuel cells, with less than 2-ppm oxygen. The unit requires 4.3 kWh of electricity per Nm^3 of hydrogen; however the efficiency decreases with the peripherals and internal resistances so 4.9 kWh/Nm^3 is required [8]. The output of the unit is dependent on the current being drawn and therefore the rate at which hydrogen is produced is based on how much is required. The unit operates on DC power and therefore can be directly connected to the wind turbine. It adapts to the input power, allowing the turbine to change the power it is generating with the change in wind speeds without any energy losses. The electrolyzer is a low maintenance unit with only minimal supervision required. The price for the electrolyzer is approximately USD 85,000 and the de-oxidization drier is approximately USD 25,000 with a total cost of USD 100,000 or CAD 150,000. Stuart Energy has designed larger systems, series 1000 which are able to produce 3 to 100 Nm^3/h H_2 having a membrane exchange transfer area exceeding 1000 cm^2. The 100 Nm^3/h system is priced at USD 1.2 million; leading prices of these systems are just more than twice the cost of the smaller, series 300 system, leading to a cost of ca. 2,800 USD/kW.

Proton Energy manufactures the HOGEN series of polymer membrane electrolyzers [9]. Sizes range from 40 to 240 scfh or 1 to 7 Nm^3/h H_2. The base cost of the 40 scfh model is USD 52,000 and a significantly discounted cost of USD 105,000 for the 240 scfh model [10]. This suggests a range of prices from 13,000 USD/kW down to 4000 USD/kW.

Teledyne systems used to make the TITAN EC 750, a 42 Nm^3/h H_2 system for ca. USD 450,000, resulting in a per kW cost of ca. 3,000 USD/kW [11, 12]. Personal communication with Teledyne suggests that the EC 750 was a custom built system and that Teledyne has shifted its focus to produce smaller, more modular systems, but the pricing is taken as an indication of expected development of electrolyzer costs with increasing size.

Norsk Hydro is a major manufacturer of electrolyzers in the multi kW range [13]. However, we were not able to obtain pricing on any of their products.

B.1.2.2 Hydrogen Storage Systems

The current driving force for the development of low-cost hydrogen storage is the emerging automotive market. While various hydrogen storage solutions are available, the cost of raw material, weight and filling speed have led to high pressure (5,000 to 10,000 psi) gas cylinders made from composite materials. Dynetek and Quantum Technologies currently manufacture these cylinders. Cylinders manufactured by Dynetek vary in storage volume from about 1 to 5 kg [14]. The 5 kg tanks of interest are about 40 cm in diameter and 2 m in height and weigh about 90 kg or roughly 18 times the weight of the contained hydrogen. Projected storage costs are about 5 USD/kWh or 200 USD/kg H_2 [15].

B.1.3. Renewable Energy Sources

The most common sources of renewable energy are wind, solar and small hydro. Of these, wind and solar were considered as renewable energy inputs in our proposed integrated energy system. Small hydro was not considered because of the short summer and the lack of suitable locations for hydro facilities in the investigated northern communities.

Details of these technologies are beyond the scope of this report. These are well-proven technologies and are being pushed by the government agencies in terms of incentives, etc. In our case, these are considered for use to produce clean (green) hydrogen on demand and for storage, when excess renewable energy is available.

B.2. Appropriateness for Fuel Cells for Stationary Applications in the North

B.2.1. PEM Fuel Cells

These are the most advanced fuel cells in the power range from two to five kilowatts. However, the large drawback of these fuel cells is that they require high purity hydrogen, whereas using direct methane (natural gas) would be more economically efficient for northern communities. Using these for a small home would only be possible if a reformer was in place, or the technology of electrolyzing water was present for the individual home. Therefore, natural gas, or water, would be piped to the home and the available technology would be used to create hydrogen to be fed to the fuel cell. The ambient allowable temperatures of 5 to 40^{o}C would be adequate for the Northwest Territories; however, the fuel cells would need to be in a housing unit of some kind to ensure the temperatures experienced do not go below 0^{o}C. Since these operate at a temperature of 80^{o}C, the heat and water produced will be at 80^{o}C and therefore these may be used for space heating and drinking water, respectively. These additional uses will add to the overall efficiency of the fuel cells.

B.2.2. Solid Oxide Fuel Cells

Due to the high temperature of these fuel cells they would typically only be used for large applications such as a MW power plant. However, much development has been made for small scale SOFCs to be used in the home using cogeneration to increase the efficiency. These have a huge advantage over the lower temperature fuel cells as they can directly consume hydrocarbons as the fuel, largely increasing the efficiency and decreasing the overall cost and size of the system. This type of fuel cell would be ideal for the north, as natural gas is abundant in the northern communities.

B.2.3. Alkaline Fuel Cells

These could be used in remote Arctic locations as they are suitable for low ambient temperatures and have a very quick start up with no additional warming required; therefore making them ideal for colder temperatures. These are also composed of cheaper materials; however, the price of any fuel cell system depends on the abundance at which they are being produced. At the present time these types of fuel cells are receiving limited funding, as they are not suitable for a large range of uses. As well, it would be difficult to use these in northern communities, as pure hydrogen and oxygen, which are required, are not available in great abundance. Research is being conducted to help improve the Alkaline Fuel cells with the problem of precipitated carbonates, but at the present time there is still much to be done.

B.2.4. Direct Methanol Fuel Cells

These may not be ideal for the north, as the research is not yet fully developed. There are still many problems with these fuel cells and therefore these will probably not be in the commercialization stage for many years to come. As well, they are just large enough for homes in the Arctic as the largest ones are 2 to 3 kW in size and the fuel cells required for the north should be approximately 2 to 5 kW. Therefore these would only meet the lowest requirements and a larger unit would be preferred in case any problems arise.

B.2.5. Phosphoric Acid Fuel Cells

These could be used in the northern communities for personal home use, yet they may be too large. The hydrogen once again would need to be produced through reformation or hydrolysis, as the fuel cells cannot operate directly with hydrocarbons. Once the infrastructure is in place for individual reformers or hydrolysis, then these fuel cells are definitely a possibility as they have already been used in colder climates. As well, the additional heat produced is at a perfect temperature for co-generation, thereby increasing the efficiency of the system.

B.2.6. Molten Carbonate Fuel Cells

These fuel cells could be used for a power plant in the north, as the efficiency is very high when cogeneration takes place. However, they require much time to start up, as the temperature must reach operational; this makes them unlikely for individual uses. They do have a huge advantage as they can use hydrocarbons directly, thus abolishing the need for an additional reforming device. Currently these are not largely being developed in Canada, yet they are heavily being researched in Japan, Germany and the US. In the US one of the main developers is Fuel Cell Energy Inc.

C. Methodolgy

C.1. Survey of Fuel Cell Companies

A survey of key fuel cell developers was conducted. A survey questionnaire (see App-2.3.1) was developed and sent out to the main fuel cell companies in Canada. This survey asked questions about their technology, availability, cost, etc. Specific query was made regarding their involvement in testing and evaluation of fuel cells in the Arctic environment. It was emailed to the executives of a dozen companies. Follow-up was made by calling them. Responses from fuel cell manufacturers are summarized in table 15 under App-2.3. The received surveys were analyzed to assess cost and availability of different types of fuel cell solutions.

C.2. Community Consultations

In February 2003, we visited the Beaufort Sea communities of Tuktoyaktuk, Sachs Harbour, Holman and Paulatuk. All these communities are in the Inuvialuit region of the Northwest Territories (see App- 1 for the map). These consultations were a follow-up on the Distributed Generation workshop, which was held in Inuvik just prior to starting this project in February 2002. Community visits were combined with our pre-feasibility study for wind energy. It was important to combine the 2 visits because of our interest in determining the potential of producing hydrogen from excess wind capacity. All renewable and emerging energy sources (including fuel cells) were discussed with members of these communities, who showed great interest in replacing conventional power sources.

After community consultations in Inuvik and the four Beaufort Sea communities, cost analyses were carried out for installing fuel cells for stationary power generation using an integrated wind system with hydrogen fuel cells and storage. The analysis also involved installing 2 and 3kW residential fuel cells in homes to replace the natural gas generator in Inuvik and the current diesel generators in most of the communities. The cost of electricity in these northern communities is extremely high and therefore a fuel cell system is likely to prove to be an economically viable option.

C.3. Data Collection

NWT Power Corporation was consulted for information about the current system of power generation and distribution to these communities. This information was used to conduct the following analysis. Current costs of electricity [16] and diesel fuel for heating purposes [17] in each community are shown in Table 1. The cost of diesel changes depending on the price of the fuel at the time of purchase. The Power Corporation charges the consumer the electricity cost per kilowatt-hour (kWh) before subsidies as well as the shortfall rider in every community. The shortfall rider is a charge the power corporation adds on depending on the year, the town and the previous year’s profits. The power corporation adds the rider when they have not made enough profit the year before to cover their costs; they then add the shortfall rider to make up the loss of the previous year. These change yearly and are often not in effect.

Private consumers in the Northwest Territories pay a monthly fee of CAD 18 in addition to the cost of consumed energy. The territorial government subsidizes the cost per kWh exceeding the cost of electricity in Yellowknife, which is currently $0.1788/kWh [16] up to a maximum of 700 kWh/month [18]. Energy used in excess of 700 kWh/month is billed at the local cost of energy (Table 1).

Table 1

Cost of energy in northern communities studied				
NWT town	Diesel CAD/litre [a)]	Electricity CAD/kWh (before subsidies) [b)]	Shortfall Rider CAD/kWh [c)]	Subsidy CAD/kWh [d)]
Inuvik	0.7004 [e)]	0.3872	0.0632	0.2131
Tuktoyaktuk	0.80	0.6161	0.0801	0.4420
Paulatuk	0.91	0.9432	0.1509	0.7691
Sachs Harbour	0.92	0.9775	0.1243	0.8034
Holman	0.93	0.7239	0.0665	0.5498
Susidized cost (Yellowknife level)		0.1741		

[a)] values from Sept. 2003 [17]. [b)] values in effect June 2004 [16]. [c)] 2003 value, based on previous year's (2002) profits of NTPC. [d)] Difference between un-subsidized electricity rates and Yellowknife energy cost. e) Value from June 2004 [19].

Consumer cost of Natural Gas for Inuvik, as of June 22, 2004, is 14.70 CAD/GJ [20], which corresponds to 0.59 CAD/m^3 or 0.053 CAD/kWh.

C.4. Modeling and Analysis

The modeling in this report was performed using HOMER™ and RETScreen®. HOMER™ was used for the analysis of hourly supply and demand data and technical simulation of the project. RETScreen® was used for detailed financial analysis and the final feasibility assessment.

C.4.1. HOMER™

HOMER™ [21] is published by the U.S. Department of Energy's National Renewable Energy Laboratory (NREL). It is designed for detailed modeling of energy systems based on hourly demand and supply capabilities. The particular strength of this software is that given a number of different system configurations, e.g. 1 to 10 fuel cells, it will determine the one that will result in the lowest cost of energy while still meeting supply and demand requirements. HOMER™ is currently undergoing restructuring towards version 2.1 and the preliminary version 2.1beta was used for the studies shown here.

C.4.2. RETScreen®

RETScreen® is published by Natural Resources Canada (NRCan). It is primarily designed for financial feasibility assessment of renewable energy projects based on system cost and avoided cost of energy. The particular strength of this software is to provide a detailed framework of expected costs and a detailed financial analysis while still supplying some basic checks and balances to ascertain production meets demand.

D. Performance Testing and Demonstration of a Fuel Cell

When hydrogen becomes readily available as part of the infrastructure, the use of hydrogen fuel cells for residential power supply could be considered. To determine the validity of such a set-up, a limited amount of grant funding from the Energy Secretariat of the Government of Northwest Territories was secured to purchase a system for the testing and demonstration of a fuel cell. Due to the lack of choices for the commercial availability of small fuel cell systems, 2 units of NEXA® PEMFC with a total combined capacity of 2.4 kW were purchased from Ballard Power Systems. These fuel cells are based on PEM (Proton Exchange Membrane or Polymer Electrolyte Membrane) technology and convert hydrogen and oxygen to water at low temperatures. Since they do not produce much heat and no pollution they are particularly well suited for indoor use.

Beside fuel cell stacks, other components, accessories and supplies were needed and ordered. These included a DC/DC converter, an inverter, computer to record and display data, and 99.999% pure hydrogen. The system has been set up as a demonstration unit at the Aurora Research Institute (ARI) energy laboratory and is fully functional as an integrated energy system along with the already available wind turbine and PV arrays. Some performance data has been collected and is detailed hereunder.

D.1. Installation of NEXA® Fuel Cell in Testing System

A desirable set-up for a fuel cell in residential application is shown in Figure 1. It shows the conversion of variable DC output from the fuel cell to the AC output for an electrical load for a single home. The load is primarily supplied from the fuel cell, but battery power or grid power can be used when sufficient power is not available from the fuel cell alone. This would also allow maintenance on the fuel cell without losing residential power.

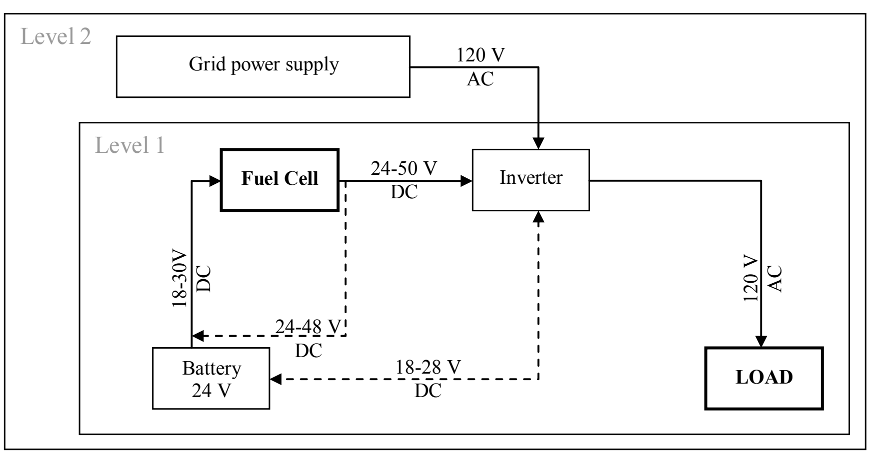


Figure 1: Schematic diagram of a fuel cell with accessories for a home setting. The dotted lines show an optional connection to recharge batteries from the Fuel Cell operation.

For the demonstration project at ARI, where constant power supply does not need to be guaranteed, the fuel cell was connected as shown in Figure 2. It shows the conversion of variable DC output from the fuel cell to the AC output for an electrical load. The DC-DC converter introduces additional power losses, but allows for the use of a cheap automotive inverter perfectly suited for a small demonstration system. Materials used to complete the demonstration system were:

- Fuel cell (Ballard Power Systems NEXA®, see spec sheet in Appendix 5[22])
- DC-DC Converter (Pivotal Power O312[a])
- Inverter (Motomaster Eliminator 1200)
- Hydrogen (cylinders, 99.99% purity, EMCO)
- Hydrogen regulator (Praxair)
- Batteries (24V, Caterpillar)
- Batteries (12V, CS3)
- Various electrical components such as switches and wiring
- Windows PC computer for monitoring fuel cell performance

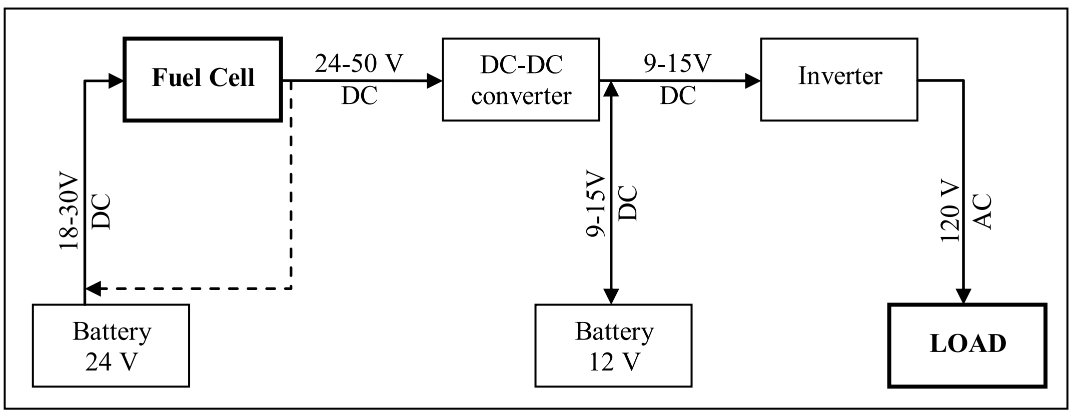


Figure 2: Schematic diagram of a setup used at Aurora Research Institute.

Installation of the fuel cell posed some technical challenges, which are likely to be typical of a residential installation. These challenges are discussed in further detail in section G. Appendix 4 describes some modifications to improve a commercial fuel cell module for use in a single household setting. Installation was done using a set-up as shown in Figure 2. The important steps in this procedure were:

- **Connecting the FC to the hydrogen cylinder:** NEXA® specifications indicate that the fuel cell will operate in a range of 70-1720 kPa (10-250 psig). As the pressure in a commercial hydrogen cylinder is about 17 MPa (2500 psi), a pressure regulator was used. The hydrogen hose supplied as part of the NEXA® installation kit was found to fit the regulator directly after removing the originally supplied hose adapter from the regulator.

[a] This DC-DC converter has been custom-built by Pivotal Power for IDA Tech. Schematics of the output voltage control circuit as supplied by Pivotal Power can be found in appendix 4.

- **Connecting the fuel cell to batteries:** Two 12V batteries were connected in series (24V) and then attached to the inputs of the fuel cell. In this set-up provisions need to be made to recharge the batteries. According to Ballard, it should be safe to short-circuit the output of the fuel cell as shown in Figure 1 [23]. However, some control mechanism should be in place to avoid overcharging the batteries, as it can happen if the charging voltage exceeds 28.2 V.
- **Connecting the FC module to power conditioning devices** such as an inverter or the DC-DC converter. Additional wiring not supplied as part of the installation kit was required to connect the load relay to the converter. Also the installation manual suggested that a blocking diode should be used to prevent fuel cell damage from polarity changes at the load. Personal communication with Ballard suggests that this diode should only be used if power-conditioning hardware does not ensure that polarity changes cannot occur [24]. The use of a diode is deprecated because a typical diode voltage drop of 0.7 V in combination with a current of about 50A at full power will dissipate 35 W as heat at the diode [24]. Its use is better avoided by using proper power conditioning hardware.
- **Connecting the DC-DC converter to batteries and an inverter**: A 12 V battery was required at the output of the Pivotal Power DC-DC converter. It was found that regulation of the output voltage to a value sufficiently low to be compatible with charging a lead acid battery or operating the inverter (ca. 14.1 V) required changing a calibration resistor inside the DC-DC converter. This change was straightforward but did require the ability to solder SMD sized resistors (see Appendix 4: for more details).

D.2. Technical evaluation

D.2.1. Testing at Open Circuit, i.e., No Load

Initial power-up testing was performed without a load connected to the fuel cell. The fuel cell performance was monitored under open circuit conditions using the NEXAMON software supplied by Ballard. The resulting observations were:

- The fuel cell will successfully deal with air and water initially trapped in the hydrogen supply line when establishing the connection between gas cylinder and fuel cell. This is achieved by using the standard purge cycle designed to remove depleted fuel gas (Figure 3a).
- The fuel cell draws about 50W power for its own operation (Figure 3a). This is consistent with the manufacturer's specification that the fuel cell is expected to draw up to 60W from the batteries during start-up.
- Stack voltage depends on hydrogen concentration in fuel gas and decreases with time as hydrogen content in the fuel gas mixture is depleted, even at open circuit (Figure 4a).
- Significant acoustic noise levels are experienced in the start-up and purge periods due to high-speed fan operation, suggesting that the fuel cell should be mounted in a sound proofed location.

a)

b)

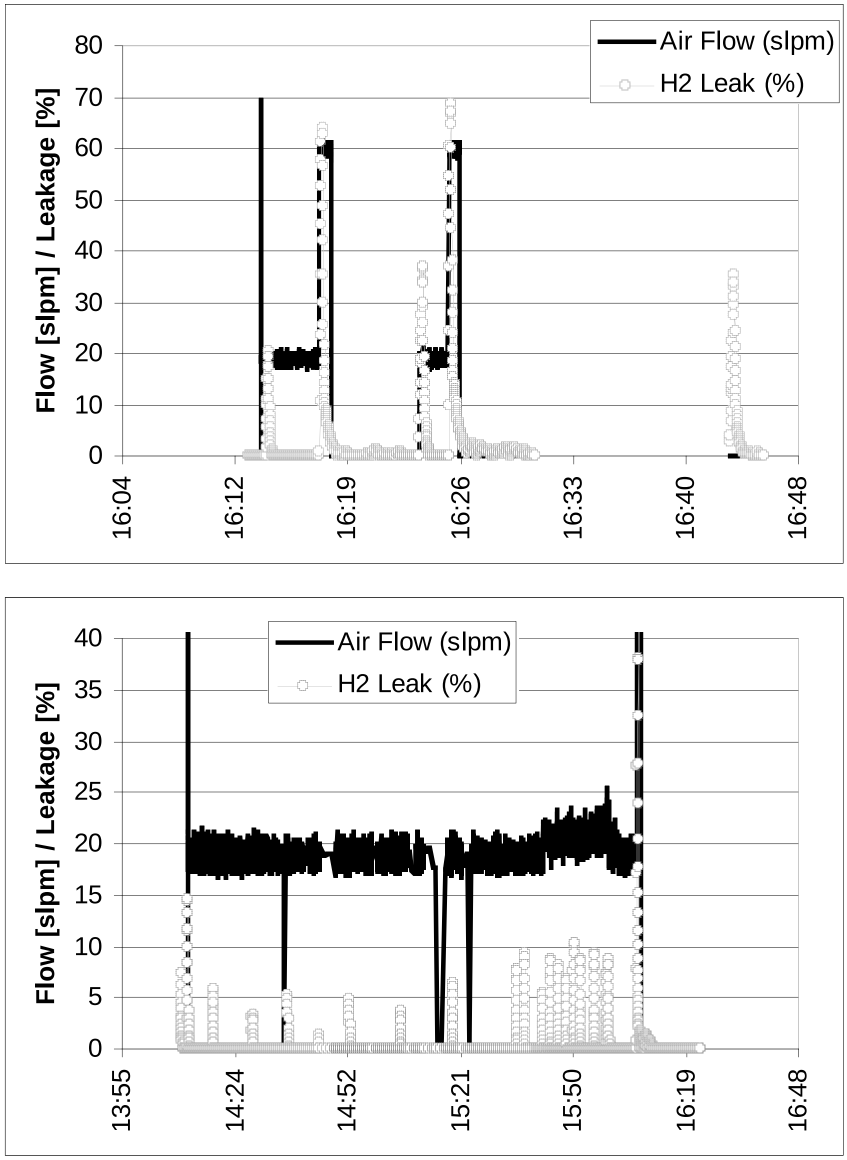
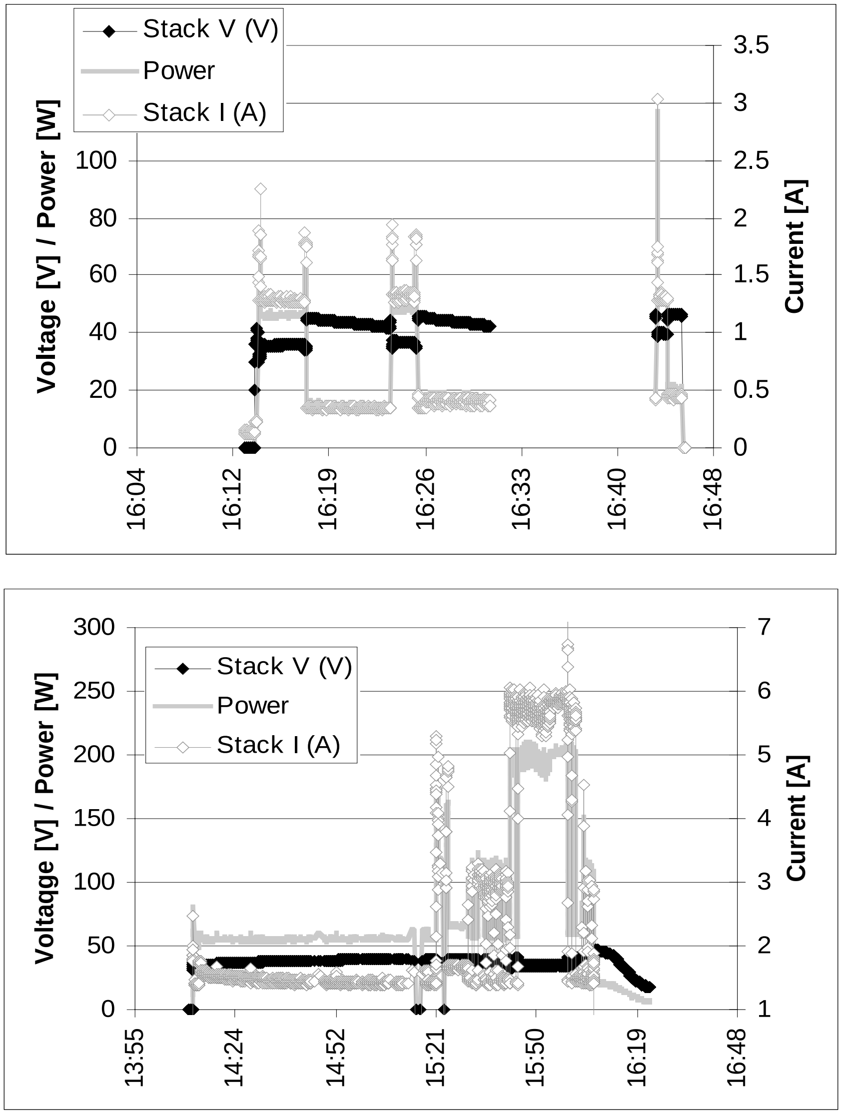


Figure 3: (a) Initial start-up under open circuit conditions: spikes represent purge cycles. (b) Start-up and operation under load. Load increase leads to more frequent purge cycles.

a)



b)

Figure 4: (a) Stack voltage decreases even without external load as hydrogen is depleted. (b) Stack voltage decreases with increased load.

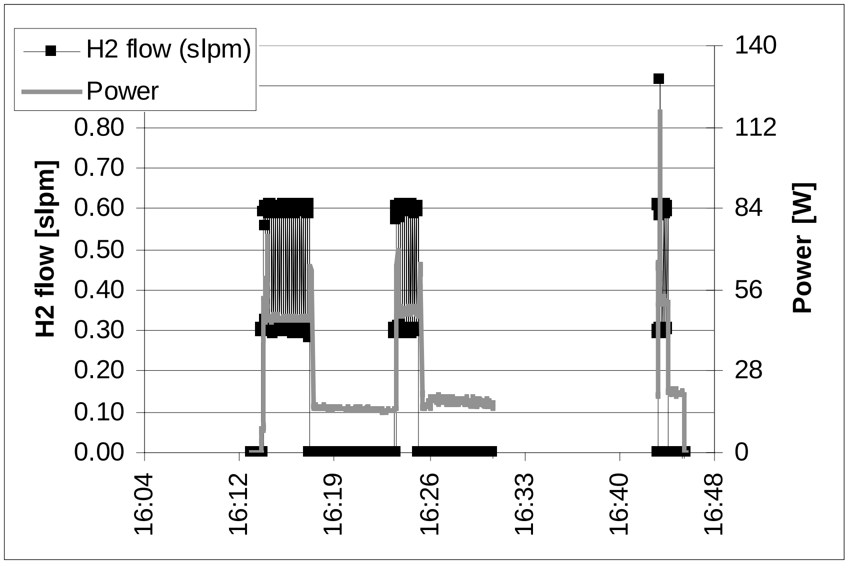
D.2.2. Testing under Load

Testing under load was performed using the modified DC-DC converter and Inverter as shown in Figure 2. To simulate the load fluctuations expected in residential use, a computer, monitor and laser printer were used as load. From the casual testing performed, the following observations were made:

- Fuel consumption increases with power demand (Figure 5) but about 0.1-0.4 slpm H_2 is spent on maintaining fuel cell operation even if no load is present (Figure 5a).
- The higher loads lead to faster fuel consumption and to higher fluctuations in output voltage with increased power requirements (Figure 6).

- Higher loads lead to increased stack temperature. The fuel cell has not been run under sufficient load or for sufficient time to determine what the maximum operating temperature is. Ballard specifications suggest operating temperature may be in excess of 55°C, indicating that the fuel cell should be mounted in a well-ventilated area.
- A significant amount of water is produced in the process, especially if the fuel cell is operated at high power output. A simple estimate shows that at an average power output of 250 W, a 40 L/250 psi gas cylinder will last for ca. 16 days and produce about 6 L of water.
- The spikes in power demand due to the operation of the laser printer (Figure 6) show that the maximum power rating of the fuel cell and inverter needs to be significantly higher than average demand, especially if high power devices such as stoves or laser printers should be operated off the fuel cell.
- The recorded power spikes when the laser printer engages exceed the theoretical power rating for the fuel cell. This is likely possible due to capacitive buffering in the system. However, this suggests that in a single home scenario a battery as shown in Figure 1 should be employed to load level short current spikes.

a)



b)

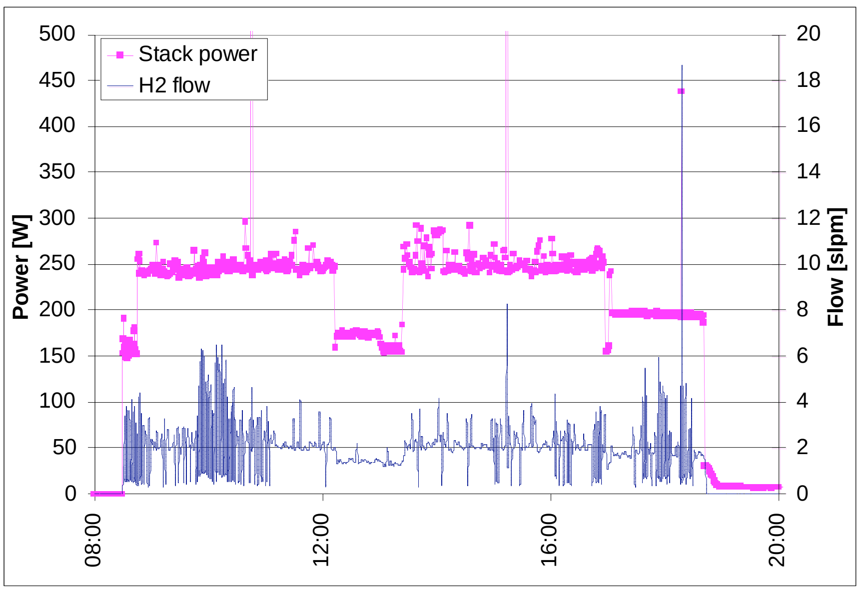


Figure 5: (a) Hydrogen consumption without external load. (b) Hydrogen consumption increases with increasing load

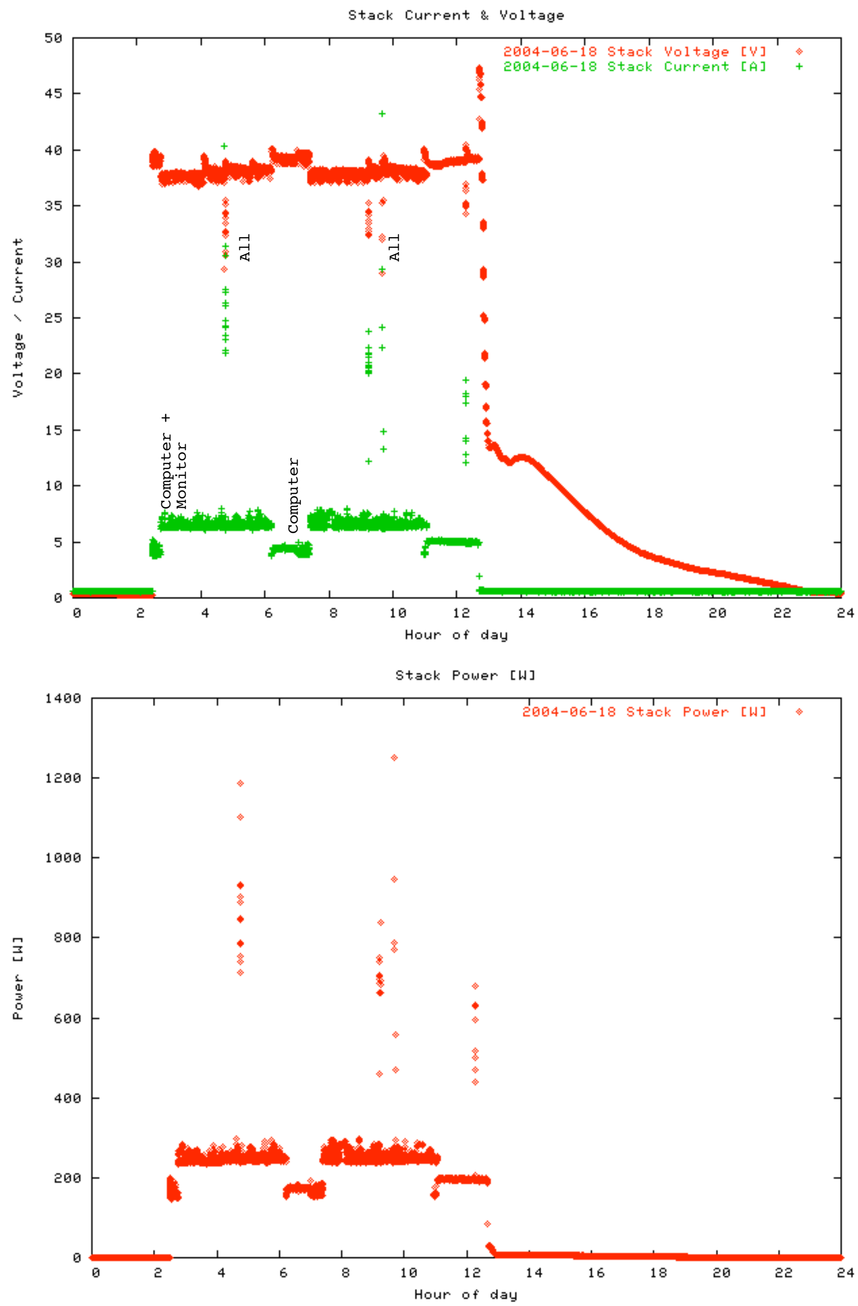


Figure 6: (a) Stack voltage decreases and current increases with (b) power demand. Three main consumption levels: computer only (180W); computer and monitor (250W); computer, monitor and laser printer (up to 1400W).

E. Method for Financial Analysis using RETScreen®

RETScreen® does not have a convenient module for the financial analysis of fuel cells. For integrated wind-hydrogen-fuel cell systems, it was found convenient to use the wind module of RETScreen®. The required data for wind and wind turbines was entered in appropriate places. However, the cost data for the electrolyser, hydrogen storage systems and fuel cells was calculated and inserted as a single item under "other". For analysis of solid oxide fuel cells, the data entered in the WIND2000 spreadsheet was modified to reflect the costs of a fuel cell rather than wind turbines. It should thus be understood that any reference to renewable energy (RE) on the analysis sheet is representative of the energy obtained from natural gas or diesel via a hydrocarbon fuel cell.

The values for the following important parameters were obtained using RETScreen® analysis, which were then used to assess the financial viability and leverage of each project:

Year to positive cash flow: Assuming debt financing, net cash flow (income from project minus the expenditures) may be negative for the first few years. This number indicates the year in which positive cash flow is reached. The lesser the number of years the better it is. It is apparent that the larger projects are preferred, but it is also apparent that a longer amortization period (20 as opposed to 15 years) aids in achieving positive cash flow earlier due to lower interest payments.

Year to break even: This is the time needed to become debt-free. At this point the total income equals the total project debt. If the project was terminated at this point, no debt would remain and the investors would retain the project equity. This value allows one to judge the risk rather than financial benefit and it is preferred to keep this number low. Shorter mortgage terms help in decreasing this time. In addition the larger projects have a better ratio of cash flow to initial investment. This helps pay off debts more quickly and leads to a shorter time leading up to the break-even point.

Net Present Value (NPV): This is the effective value of the project at the end of its lifetime in present day dollars. Thus NPV accounts for value losses due to inflation. In addition, NPV is generally discounted by an additional profit factor dependent on the policies of the investors, generally including the cost of borrowing money or lost asset interest. Thus, higher NPV is generally better but the discount rate needs to be taken into account and calculations need to be repeated if different investors prefer different discount values (*see IRR/ROI below for a more convenient approach*). Based on NPV, it is clear from the table that the larger projects are to be preferred. However, since NPV also increases with project size, the return on investment should be considered as well.

Internal Rate of Return (IRR) / Return on Investment (ROI): IRR/ROI show the effective discount rate at which the NPV would become 0. Thus using IRR/ROI is preferred over NPV because it gives an indication of profitability independent of project volume and because it avoids the need to recalculate NPV for different discount values. Thus, a project with an IRR/ROI of 9% would be acceptable to investors requiring a 7% discount rate but not to those requiring 10% or more. On the other hand, a project with IRR/ROI of 28% would be acceptable to both investors requiring a 7% and

10% discount rate.

Annual savings: The project income from the avoided cost of conventional energy expressed as present value. This could alternatively be interpreted as revenue from the sale of produced energy at the local utility prices.

Effective cost of energy: This is the cost of energy produced by the system. This cost must be less than the price of energy from the local utility and the lower this cost is the more financially viable the project becomes.

F. Economic Feasibility of Fuel Cell Systems

The economic feasibility of using fuel cells to meet residential power requirements was studied in the Inuvialuit region of the Northwest Territories. Two types of fuel cells were considered; the Solid Oxide Fuel Cells (SOFC) and Proton Exchange Membrane Fuel Cells (PEMFC). Due to the easy availability of diesel and/or natural gas in the region, the use of a solid oxide fuel cell (SOFC) was considered appropriate for “standalone” applications. These are also referred here as hydrocarbon fuel cells and are discussed under section F.1. Because PEMFC require hydrogen as a fuel, this option was considered only where it is economically feasible to produce hydrogen locally using wind turbines. This is discussed under “integrated” systems section F.2.

F.1. Solid Oxide Fuel Cell Systems

The feasibility of deploying fuel cells as standalone units for power applications was studied in single housing units and in an apartment complex. For the purpose of this study, standalone means largely independent of the grid system, except in emergency situations. Only those fuel cells are employed which are able to utilize presently available fuels. This will generally be diesel, but in Inuvik both diesel and locally produced natural gas are available. The prototypes of hydrocarbon based solid oxide fuel cells are becoming available and are considered appropriate for analysis here. These run on natural gas and diesel, the fuels currently used by the Northwest Territories Power Corporation (NTPC) to operate their power plants in the communities discussed here. Unfortunately, this approach still produces greenhouse gases, particularly CO_2. However, such fuel cells have the following significant advantages over the conventional internal combustion engines:

- Fuel Cells are inherently more energy efficient (ca. 55% [4]) than the diesel generation technology currently employed by NTPC (ca. 34% [25]).
- The technology employed in fuel cells ascertains that no particulate exhaust and very little other GHGs, particularly NOx, are produced.
- Fuel cells have fewer moving parts than combustion engines and thus don’t require large quantities of lubricants, which reduce the likelihood of spills and their environmental impact.
- The significantly lower initial investment cost means that individual fuel cells could be financially attractive to single homeowners.

We studied the following 3 options for solid oxide fuel cell systems:

1. The first is a “standalone” option where fuel cell is installed in a residential dwelling. Economic analyses are performed for installation of an SOFC in a single home in all five selected communities. The system’s feasibility was studied assuming the absence of the grid system except in cases of emergency.
2. In addition, the viability of installing “standalone” SOFC stacks was conducted for an apartment complex in Inuvik.
3. The third option studied is for community power in the same 5 towns.

F.1.1. Cost Estimates for Solid Oxide Fuel Cells

The projected cost of solid oxide fuel cells within the next 3 years is estimated at 3,000 USD/kW [32]. This corresponds to 4,110 CAD/kW. Moreover, for any energy system there are additional costs involved, such as installation, electrical requirements, services, and contingencies. For most plants these are estimated as a percentage of the total plant costs. Since fuel cells are considered an esoteric piece of equipment, the cost of fuel cells is not a good basis for which to apply these percentages, as the price estimated would be much higher than actual. Due to this reason, we calculated the additional costs based on running an equivalent turbine system. So an approximate cost of a 3kW turbine system was used for estimating additional fees for a 3kW fuel cell system. For a 2kW fuel cell system a 2kW turbine system was used to estimate the additional fees. The additional cost of turbines is assumed to be approximately 600 USD/kW [33] or 822 CAD/kW. If the system is a 3kW system, then the total equipment cost used to calculate the additional costs is CAD 2466 and the additional costs are summarized in Table 2. It should be re-emphasized that the CAD 2466 cost of the gas turbine was used solely as an estimation tool for the additional costs, not for the fuel cell itself. Similarly the additional cost for the 2kW fuel cell was based on CAD 1644 for a 2kW gas turbine. The total cost estimates are listed in Table 2.

Table 2.

Additional Costs for SOFC installation, based on 2/3kW Gas Turbines			
		2 kW	3 kW
Equipment cost			
Fuel Cell cost		**8,220**	**12,330**
Installation costs based on Gas tubine			
Gas turbine cost [1)]		1,645	2,465
Fraction of turbine cost			
Installation	40%	658	986
Electrical	40%	658	986
Services	15%	247	370
Contingencies	20%	329	493
Total installation cost		**1,892**	**2,835**
Total Fuel Cell and Installation		**10,112**	**15,165**
Cost per kW		**5,056**	**5,055**

[1)] This cost was only used to estimate installation cost.

Table 2 shows that the total cost for the 2kW system is CAD 10,112 and CAD 15,165 for the 3 kW system, or ca. 5,055 CAD/kW.

The operating cost is the price of fuel required and the O&M expenses. For the single home system O&M was assumed fairly low at ca. 13% of the cost of the fuel cell because the home owners are likely to do it largely on their own at very low cost. For the larger systems, visits by technicians incurring significant travel expenses were taken into account, raising the O&M component to about 36% of the fuel cell cost.

F.1.2. Discussion of Results for Single Homes

The economic feasibility of deploying a single 2 or 3 kW SOFC was studied for an individual home in the Inuvialuit region. The cost of the single home system was calculated using two different methods:

- In the lump-sum method it was assumed that the cost of the fuel cell system was paid up front without requiring a bank loan, i.e., the debt ratio of the project was assumed to be 0.
- Using the financing method a bank loan was used at 8% interest compounded annually and paid back monthly to be amortized over a period of 10, 15 or 20 years.

The following discussion only interprets the values achieved for a hydrocarbon-based fuel cell. Table 3 summarizes results for a single home in Holman. See App-6.1.1 for detailed cost analyses and financial results of a 3 kW fuel cell in a home in Holman. Figures 10 and 11 in this appendix show cumulative cash flows for the lump sum payment and 10-year loan term, respectively. It is apparent that the project is financially viable in both the lump sum and debt-financed scenarios. However, in the debt-financed scenario the break-even point lies farther in the future.

Table 3.

RETScreen results for single household in Holman				
Fuel Cell Power	**2kW**	**2kW**	**2kW**	**2kW**
Mortgage term	**0**	**10**	**15**	**20**
Project term	**10**	**10**	**15**	**20**
Year to positive cash flow	4.9	2.8	2.2	2.0
Year to break even	4.9	6.4	7.1	7.8
Initial cost	$ 10,949.11	$ 10,949.11	$ 10,949.11	$ 10,949.11
Annual cost	$ 1,643.98	$ 2,867.79	$ 2,603.37	$ 2,480.37
Annual savings	$ 3,750.90	$ 3,750.90	$ 3,750.90	$ 3,750.90
NPV (@ 7%)	$ 5,397.66	$ 5,014.00	$ 10,539.43	$ 14,878.42
IRR / ROI	16.4%	35.8%	46.7%	51.1%
Effective cost of Energy	0.5791	0.5894	0.5140	0.4775
Fuel Cell Power	**3kW**	**3kW**	**3kW**	**3kW**
Mortgage term	**0**	**10**	**15**	**20**
Project term	**10**	**10**	**15**	**20**
Year to positive cash flow	4.9	2.8	2.2	2.0
Year to break even	4.9	6.4	7.1	7.8
Initial cost	$ 16,423.16	$ 16,423.16	$ 16,423.16	$ 16,423.16
Annual cost	$ 2,465.97	$ 4,301.62	$ 3,905.01	$ 3,720.52
Annual savings	$ 5,626.34	$ 5,626.34	$ 5,626.34	$ 5,626.34
NPV (@ 7%)	$ 8,096.99	$ 7,521.52	$ 15,809.67	$ 22,318.16
IRR / ROI	16.4%	35.8%	46.7%	51.1%
Effective cost of Energy	0.5791	0.5894	0.5140	0.4775

Thus, considering the technological status of SOFCs, the lump-sum project is to be preferred. It is unrealistic at this point to assume a fuel cell lifetime exceeding 10 years. Thus, additional examination for the other northern communities was based on a lump sum financed 10-year project (Table 4). This shows that hydrocarbon fuel cells would be feasible in all communities except Inuvik. Due to their high cost of energy, the financial incentive would be particularly high for the communities of Paulatuk and Sachs Harbour if GNWT energy subsidies could be secured.

Table 4.

RETScreen results for single household in all five communities					
Fuel Cell Power	**3 kW**	**3 kW**	**3 kW**	**3 kW**	**3 kW**
Mortgage term	**0**	**0**	**0**	**0**	**0**
Project term	**10**	**10**	**10**	**10**	**10**
Location	**Inuvik**	**Tuktoyaktuk**	**Paulatuk**	**Sachs Harbour**	**Holman**
Year to positive cash flow	more than 10	5.9	3.3	3.1	4.9
Year to break even	more than 10	5.9	3.3	3.1	4.9
Initial cost	$ 16,423.16	$ 16,423.16	$ 16,423.16	$ 16,423.16	$ 16,423.16
Annual cost	$ 1,716.38	$ 2,203.07	$ 2,558.63	$ 2,593.53	$ 2,465.97
Annual savings	$ 3,009.42	$ 4,788.49	$ 7,330.80	$ 7,597.39	$ 5,626.34
NPV (@ 7%)	$ (6,390.93)	$ 3,636.22	$ 20,602.38	$ 22,399.98	$ 8,096.99
IRR / ROI	-2.2%	11.4%	28.8%	30.4%	16.4%
Effective cost of energy	0.5015	0.5511	0.5748	0.5770	0.5791
NTPC cost of energy	0.3872	0.6161	0.9432	0.9775	0.7239

As current SOFC technology is fairly new, it is not safe to make the assumption that a fuel cell will last more than 10 years. It should also be noted that the anticipated escalation in the cost of diesel is not accounted for. Further these calculations are based on the assumption that the fuel cell will operate close to full power most of the time. From the usage data, however, the difference between maximum (450 kW) and minimum (150 kW) daily power consumption appears to be 3:1, suggesting that the fuel cell will on average be operating at 66% (300 kW) or less of its maximum power rating. All these calculations are based on the comparison of real energy cost as charged by NTPC to all customers without any government subsidies.

F.1.3. Discussion of Results for an Apartment Complex

A cost analysis was performed on an SOFC system to provide all the power requirements for a small apartment complex in Inuvik. The apartment complex is owned by the housing corporation and has 22 bachelor apartments. The occupants currently pay only $0.06/kWh; the Housing Corporation and the government subsidize the remainder. In 2002, the apartment building consumed 82,609 kWh, costing the Housing Corporation $32,176. For this analysis, we considered using natural gas as the fuel of choice for fuel cells due to its current use for space heating in the apartment complex and because its environmental and health benefits far exceed that of diesel.

A 50 kW fuel cell system was considered for analysis because our preliminary assessment showed that it could provide the electricity needs of the occupants based on the previous year's consumption. The same procedure was used as in the previous section for a single home and included the same assumptions about the instalment costs, etc. The overall capital cost of the system was approximated at $252,750. The fuel required every year was based on the energy consumption in 2002 of 82,609 kWh, and was calculated in the same way as for natural gas previously. It was calculated that 1215.4m^3 of natural gas was required, costing approximately $10,000 in the first year. Each subsequent year the cost of fuel is estimated to increase by 2% and the worth of the dollar is expected to depreciate by 3%. The maintenance fee is estimated to be approximately $1000 per year.

The results of the RETScreen® analysis are summarized in table 5. It should be noted that the wind energy module was used as in the previous case and fuel cell costs were entered as costs for additional energy equipment. Avoided cost of energy used for the analysis is the NTPC's rate of electricity in Inuvik of 0.3872/kWh without any government subsidies.

Table 5. RETScreen Results for an Apartment Complex in Inuvik

Fuel Cell Power	50 kW	80 kW
Mortgage Term	10	10
Project Term	10	10
Year to positive cash flow	9.2	5.0
Initial cost	$283,525	$453,200
Annual cost	$13,200	$72,255
Annual savings	$48,735	$90,646
NPV @7%	($17,760)	$66,624
IRR/ROI	2	17.3

The key fiscal parameters from this analysis for a 50 kW fuel cell are not very exciting for investors. For example, the net present value is negative and the return on investment is 2%. Also, the year-to-positive cash flow is towards the end of the project term. Therefore, an alternative analysis was performed using a moderately larger (i.e. 80 kW) SOFC system. It is anticipated to have several advantages over the smaller 50 kW system. For example, it should provide enough power based on an average consumption of 700 kWh per dwelling rather than that based on the low historical usage in that complex. It can provide substantial increase in available power, which can then be sold back to the grid if it exceeds normal consumption. However, no provision is made for that in our calculations. The initial capital cost increased proportionately, but the annual costs increased dramatically due to much higher interest payments on the debt. The financial analysis shows it to be a much better investment option. For example, the year to positive cash flow decreases to 5.0 years and the return on investment increases to 17.3%, compared to 9.2 years and 2%, respectively for the 50 kW system. For both scenarios the environmental benefits are much greater with the fuel cell systems than the current grid power, and are likely to outweigh the economic losses. See App-6.1.2 for the cost analysis, financial summary and cumulative cash flow diagram for the representative 80 kW system.

F.1.4. Discussion of Results for Community Power

In this study we considered four scenarios for meeting the "total" power consumption needs of the "part" or "whole" of the Hamlet of Holman:

1. 10% of the community using SOFC stacks (referred hereunder as "scenario 10")
2. 20% of the community using SOFC stacks (referred hereunder as "scenario 20")
3. 50% of the community using SOFC stacks (referred hereunder as "scenario 50")
4. 100% of the community using SOFC stacks (referred hereunder as "scenario 100")

It was assumed that the fuel cells would be installed in a central location and would replace a portion of NTPC's power generation capacity. The costs for engineering, training and commissioning, etc. were additional expenses not encountered in the standalone systems discussed above. Due to the magnitude of the project, only debt financing was examined, assuming a 75% debt ratio.

The results of various scenarios for community power in Holman are summarized in Table 6. For detailed cost analysis and financial results, see tables and figures under App-6.1.3. The following discussion only interprets the values achieved for a hydrocarbon fuel cell.

Table 6.

Comparison of RETScreen results for Holman [1)]				
	Scenario 10	**Scenario 20**	**Scenario 50**	**Scenario 100**
Mortgage term	**10**	**10**	**10**	**10**
Year to positive cash flow	4.4	1.9	1.5	1.3
Year to break even	7.7	5.3	4.5	4.2
Initial cost	$ 429,326.31	$ 678,940.98	$ 1,537,991.53	$ 2,923,823.06
Annual cost	$ 138,116.37	$ 234,507.48	$ 537,787.35	$ 1,042,473.52
Annual savings	$ 158,505.60	$ 317,011.20	$ 786,478.17	$ 1,585,056.01
NPV (@ 7%)	$ 86,133.53	$ 526,161.13	$ 1,671,360.84	$ 3,718,957.14
IRR / ROI	20.7%	53.1%	69.7%	79.4%
Effective cost of Energy	0.6686	0.5551	0.5078	0.4853
	Scenario 10	**Scenario 20**	**Scenario 50**	**Scenario 100**
Mortgage term	**15**	**15**	**15**	**15**
Year to positive cash flow	3.2	1.6	1.3	1.2
Year to break even	8.4	5.9	5.1	4.7
Initial cost	$ 429,326.31	$ 678,940.98	$ 1,537,991.53	$ 2,923,823.06
Annual cost	$ 127,748.16	$ 218,111.09	$ 500,644.91	$ 971,863.31
Annual savings	$ 158,505.60	$ 317,011.20	$ 786,478.17	$ 1,585,056.01
NPV (@ 7%)	$ 264,487.91	$ 943,419.70	$ 2,782,811.31	$ 6,019,683.49
IRR / ROI	33.3%	63.2%	79.4%	89.0%
Effective cost of Energy	0.5979	0.4992	0.4567	0.4371
	Scenario 10	**Scenario 20**	**Scenario 50**	**Scenario 100**
Mortgage term	**20**	**20**	**20**	**20**
Year to positive cash flow	2.8	1.5	1.2	1.1
Year to break even	9.3	6.6	5.7	5.3
Initial cost	$ 429,326.31	$ 678,940.98	$ 1,537,991.53	$ 2,923,823.06
Annual cost	$ 122,925.54	$ 210,484.54	$ 483,368.65	$ 939,020.00
Annual savings	$ 158,505.60	$ 317,011.20	$ 786,478.17	$ 1,585,056.01
NPV (@ 7%)	$ 404,471.98	$ 1,271,226.22	$ 3,656,250.41	$ 7,827,972.68
IRR / ROI	37.9%	67.5%	83.7%	93.4%
Effective cost of Energy	0.5637	0.4721	0.4320	0.4138

[1)] All calculations done assuming a debt ratio of 75%.

It is evident from the results that all of the examined scenarios have positive net present values. The profitability of the project increases significantly with increasing project size. However, the effective cost of energy achieved with the best systems is found to lie between the government subsidized residential rate and the real cost of power charged by NTPC. It is thus important to note that economic feasibility of these systems depends on securing the standard government energy subsidy. Finally it should be pointed out that assuming a lifetime of more than 10 years for the fuel cells is not necessarily justified.

F.2. Integrated Wind-Hydrogen-Fuel Cell "Zero Consumption" System

In this analysis, a "zero-consumption" system implies that all energy demand is satisfied from a renewable energy source, i.e. no diesel is consumed.

F.2.1. System Design for "Zero Consumption"

In this study wind power was chosen as a well proven renewable power technology applicable for energy production in the Northwest Territories. Since wind is a variable resource, a means of storing energy for peak demand or low wind times is needed. Lead-acid batteries are normally used for this purpose. However, this is not viable in extreme cold climates of the arctic, as efficiency of the batteries is lost with declining temperatures and ultimately they tend to freeze. Based on this and the high number of power cycles expected over the system lifetime, an alternative storage medium is needed. Hydrogen is widely considered as the currently most appropriate energy storage medium to address these issues.

The system is designed to operate on three levels as shown in Figure 7 and listed below in the order of preference:

1. All available wind power is preferentially used directly, incurring only transmission and distribution (T&D) losses.

2. If more wind power is available than can currently be used, the excess wind energy is converted to hydrogen using an electrolyzer and stored in high-pressure hydrogen tanks. During times when the available wind energy is insufficient to supply the demand, stored hydrogen is converted to electrical energy using the Fuel Cell. This path includes T&D losses but also losses from the hydrogen storage system. The total efficiency of the storage system is ca. 34% which means that the total energy produced by the renewable source may have to significantly exceed the energy delivered to users, but the storage guarantees constant energy supply.

3. If excess wind energy is available and the storage tanks are completely filled, the excess energy can be exported to the local utility grid. Similarly, if not enough wind power is available and the storage tanks are empty, the demand can be supplied directly from the grid.

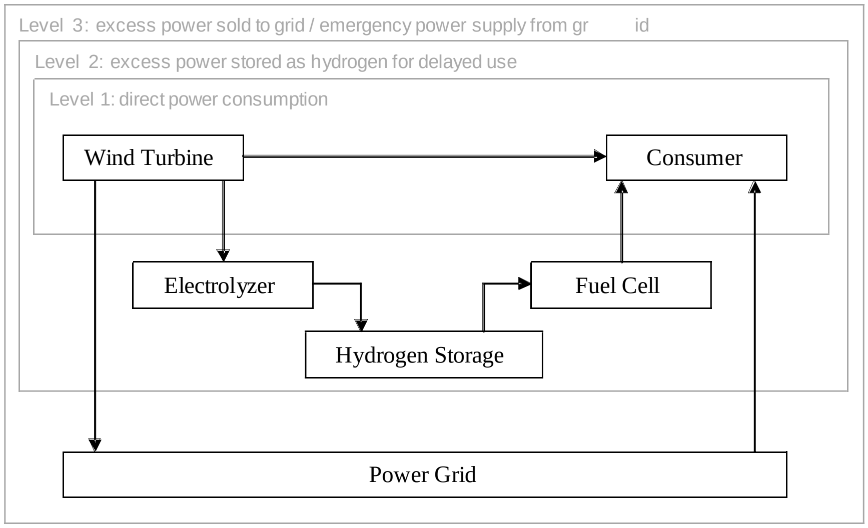


Figure 7: Energy use in zero-consumption setup: power is used directly if possible, stored as hydrogen if not immediately needed and only imported/exported to the grid in emergencies.

F.2.2. Dimensioning "Zero Consumption" System using HOMER™

In this study we considered four scenarios for meeting the "total" power consumption needs of the "part" or "whole" of the Hamlet of Holman:

1. a wind-H_2 storage solution to supply the total power consumption for 10% of the community (referred hereunder as "scenario 10") .
2. a wind-H_2 storage solution to supply the total power consumption for 20% of the community (referred hereunder as "scenario 20").
3. a wind-H_2 storage solution to supply the total power consumption for 50% of the community (referred hereunder as "scenario 50").
4. a wind-H_2 storage solution to supply the total power consumption for 100% of the community (referred hereunder as "scenario 100").

In all these scenarios, a central power system is envisioned. To ascertain that the community (as defined in 1 through 4 above) will not draw power from the grid, it has to be ensured that the energy available from wind can supply the demand. Due to the efficiency losses in converting electrical energy to hydrogen and back, a significantly higher power rating is required on the wind turbines than the conventional wind-diesel systems (i.e. with no hydrogen storage). Thus all these considerations are based on a system with enough production and storage capacity to supply the expected energy demand without relying on the existing grid.

The power demand and the total energy consumption were determined from detailed data obtained from NTPC [25-27]. Monthly averages for wind data were obtained [28] and scaled up by a factor of 1.5 assuming a better location and higher wind speeds at the hub height of 25 m as compared to the cited data measured at 10 m. Hourly data, for the same location, presumably synthesized using a statistical model, were adopted from [26]. Using this data with HOMER™ [21], the minimum number of wind turbines needed to supply the required power for a grid independent wind-hydrogen system was determined to be 3, 5, 13 and 23 for scenarios 10, 20, 50 and 100, respectively. Table 7 shows the monthly values for wind speed, power consumption and power available from wind based on 23 AOC 15/50 wind turbines for scenario 100.

Table 7: Data for whole community (scenario 100)

Holman Electrical consumption and power available from wind				
Month	**Wind speed [m/s]**[1]	**Total consumption [kWh]**	**Power from wind [kW]**[2]	**Excess**[3]
JAN.	6.07	201,200	317,864	158%
FEB.	5.18	159,867	254,908	159%
MAR.	6.22	169,933	320,902	189%
APR.	7.55	156,867	455,721	291%
MAY	6.81	150,333	385,303	256%
JUNE	6.22	138,300	330,500	239%
JULY	5.77	127,500	305,071	239%
AUG.	5.92	145,200	303,422	209%
SEP.	7.7	159,900	455,219	285%
OCT.	8.73	182,200	539,509	296%
NOV.	7.7	185,300	452,082	244%
DEC.	7.4	175,000	445,269	254%
Annual		1,951,600	4,565,770	234%

1) Based on data from [28] and scaled by 1.5 for better location. 2) Based on wind speed and 23 AOC 15/50 turbines. 3) Excess energy produced for storage

Using the same HOMER™ model, the dimensions of Fuel Cells, Electrolyzer and hydrogen storage tanks were determined for each of the 4 scenarios (Table 8).

Table 8.

Wind-Storage "zero consumption" 1)				
	scenario 10	scenario 20	scenario 50	scenario 100
Max demand [kW]	56.5	113	282	565
Wind turbines	3	5	13	23
Wind power [kW]	150	250	650	1150
FC power [kW]	60	100	400	600
Electrolyzer [kW]	60	140	450	800
Hydrogen Storage [kg]	900	1700	4000	9000

1) The term "zero consumption" signifies that all the energy supplied to a certain part of a community is sourced from renewable resources. The remainder of the community may still use fossil fuel.

From Tables 7 and 8 two things become obvious: (1) the maximum power available from wind turbines far exceeds the average demand, and (2) the relative number of wind turbines needed to ascertain sufficient power supply decreases with increasing project size. It should be re-emphasized that the amount of power available from the turbines has to significantly exceed demand due to the constraint that "zero consumption" should be achieved. It is thus to be expected that projects for larger power demand will be more economically attractive.

It should also be emphasized that if the project encompasses only a small fraction of the total community's power consumption, e.g. 10%, wind-grid system may be feasible and financially more attractive. Thus it can be concluded that it is most attractive to establish "zero consumption" projects for whole communities or as steps towards a fully renewable energy supply.

F.2.3. Discussion of Results for the "Zero Consumption" System

Financial analysis for the "zero consumption" system was performed with RETScreen® [29] using the WIND2000 module and the general assumptions from a previous study [28]. The costs of the fuel cell, electrolyser and hydrogen storage were added to the variable cost fields using the assumptions in Table 9. Currently RETScreen®'s determination of the financial viability of a renewable energy system is based on the avoided cost of energy, but the WIND2000 module does not have the means of accounting for energy lost in the inefficiencies of the hydrogen storage system. To address this issue and to allow RETScreen® to use a correct estimate, the energy demand was determined using HOMER™. The "Wind energy absorption rate" in RETScreen® was then set to a sufficiently low number to produce the same amount of "Renewable energy delivered" in RETScreen® as previously determined using HOMER™. This approach allows realistic assessment of the avoided cost of electrical energy while not changing any of the other modeling parameters used by RETScreen®.

Table 9.

Assumptions for RETScreen® analysis [1)]	
Training	This cost includes \$100/hour for training, \$100 per diem, \$200/day accommodation and \$3,000 for airfare. The total training time is estimated at 21 days to account for the generally lower initial qualification of the personnel available in northern locations.
Commissioning	This includes \$100/hour for fees, \$100 per diem, \$200/day accommodation and \$3,000 for airfare.
Road Construction	The length of road needed is estimated to be 1 km
Balance of Plant transportation	This is estimated to be \$20,000 to account for the high cost of transportation to Holman.
Fuel Cell Cost	The cost of hydrogen fuel cells was assumed at USD 1,000/kW, based on sufficiently large fuel cells.
Electrolyzer cost	Electrolyzer cost was assumed at USD 2,000/kW based on current prices for electrolyzers of 17kW or more [10, 30].
Hydrogen storage cost	Cost of hydrogen storage was assumed at USD 200/kg following NREL predictions [15].
Transport cost	Transport costs were based on quadrupling the transport cost Calgary-Inuvik (\$0.46/lb) to account for higher distance and lower availability of transport [31].

1) For all other parameters the values from [28] were used.

Table 10 summarizes various fiscal parameters obtained using RETScreen® analysis to establish the viability of the renewable energy-hydrogen-fuel cell system. See App-6.2 for detailed analyses and financial results. It is safe to interpret that a project supplying only little power (scenario 10) would be considered borderline or unacceptable. Some of the results are discussed below.

Table 10.

Comparison of RETScreen results for "zero consumption" scenarios				
	Scenario 10	**Scenario 20**	**Scenario 50**	**Scenario 100**
Mortgage term	**15**	**15**	**15**	**15**
Year to positive cash flow	more than 15	14.7	13.1	8.5
Year to break even	more than 15	14.9	14.3	12.5
Initial cost	$ 1,516,585.78	$ 2,501,037.57	$ 6,335,187.41	$ 11,427,288.49
Annual cost	$ 192,423.45	$ 312,484.82	$ 767,158.41	$ 1,386,155.55
Annual savings	$ 161,480.62	$ 318,067.90	$ 801,531.10	$ 1,603,796.20
NPV (@ 7%)	$ (530,323.32)	$ (284,984.10)	$ (510,330.89)	$ 699,806.77
IRR / ROI	-	0.4%	2.5%	10.1%
Effective cost of Energy	0.9746	0.7923	0.7725	0.6906
	Scenario 10	**Scenario 20**	**Scenario 50**	**Scenario 100**
Mortgage term	**20**	**20**	**20**	**20**
Year to positive cash flow	more than 20	10.4	9.4	6.5
Year to break even	more than 20	16.0	15.4	13.5
Initial cost	$ 1,516,585.78	$ 2,501,037.57	$ 6,335,187.41	$ 11,427,288.49
Annual cost	$ 175,387.64	$ 284,390.66	$ 695,995.23	$ 1,257,792.79
Annual savings	$ 161,480.62	$ 318,067.90	$ 801,531.10	$ 1,603,796.20
NPV (@ 7%)	$ (335,182.63)	$ 155,513.80	$ 648,398.48	$ 3,115,837.50
IRR / ROI	-3.9%	9.4%	10.9%	16.7%
Effective cost of Energy	0.8557	0.6929	0.6725	0.6006

- Year-to-positive cash flow numbers and the IRR/ROI values indicate that the larger projects are financially quite attractive. Thus those supplying more energy (scenario 100) are to be preferred. It is also apparent that a longer amortization period (20 as opposed to 15 years) aids in achieving these parameters earlier due to lower interest payments. The same conclusion can be drawn from the NPV.
- It is clear from this study that shorter mortgage terms help in decreasing the break-even point. In addition the larger projects have a better ratio of cash flow to initial investment. This helps pay off debts more quickly and leads to a shorter time leading up to the break-even point.
- The values for the "effective cost" of energy make it clear that in Holman (with current energy costs of 0.7239 CAD/kWh); a small project designed for "scenario 20" is a borderline case. However, a similar project built in another community with favourable wind conditions but higher current cost of energy, e.g. Sachs Harbour at 0.9775 CAD/kWh, would make a small project like this more financially attractive. The two larger scenarios (50 and 100) have effective energy costs significantly below the current energy cost in Holman and many other northern communities and are thus immediately attractive.

It must also be taken into account that the cost of energy produced from fossil fuels is most likely to increase in the future. In contrast, the cost of energy from the renewable sources will decrease once the system is fully amortized and only the recurring costs need to be covered. Thus, an overall conclusion from this analysis could be drawn that the integrated system modeled here is definitely preferred over the conventional diesel system.

G. Challenges

As the use of renewable energy in general and fuel cells in particular moves from it's infancy to full market availability, challenges other than purely economical have to be faced by the early adopters. Some of these key issues and challenges were identified as part of this project.

G.1.1. Technological Challenges

- **Availability of hardware and expertise needed for fuel cell connections:** Alternative energy sources (Wind, Solar and Fuel Cells) generally produce energy at variable voltage levels but maximum power output may significantly vary with voltage and energy source. Thus sophisticated power conditioning devices such as rectifiers, DC-DC converters (more efficient than solid state regulators) and inverters are generally needed. Due to the only recent emergence of standards on distributed energy generation this generally means that a lot of the power conditioning functionality needs to be duplicated for each power source, leading to additional space requirements and costs.

  In particular, we experienced problems with hardware (IDA Tech DC-DC converter, 1kW, nominal 12V) which, by apparent manufacturer labelling should have been perfectly suited for interconnecting a fuel-cell source via power conditioning (DC-DC converter, IDA Tech) and inverter (Motomaster) to feed residential energy needs. Due to design incompatibilities, however, the DC-DC converter and inverter could not easily be interfaced and the resulting combination is likely significantly less efficient than an inverter capable of power conditioning. However, a grid-tie inverter with 24V nominal input and conforming to CSA standards is currently unavailable.

- **Availability of small electrolyzers**: While the usage of hydrogen as energy storage fuel in remote locations appears technically feasible and generally preferable over the use of lead-acid batteries for the long-term storage of energy, this does not currently appear economically feasible, even in remote communities with high-energy cost. The main reason for this is the high cost of electrolyzers in general and the lack of electrolyzers in the 1-5 kW range (60-300 slm).

- **Hydrogen storage:** High-pressure compressed hydrogen storage technology is available, but is currently used primarily for transportation applications, so no off-the-shelf solutions are available.

G.1.2. Economic challenges

- **Cost of energy storage:** Any "zero consumption" scenario will depend on the availability of energy storage for load balancing. Using hydrogen as a storage medium is currently very expensive because electrolyzers are disproportionately expensive when compared to fuel cells.

- **Service life of hydrogen storage equipment**: Fuel cells and electrolyzers are fairly recent developments and have not been optimized to guarantee a long service life. This is a significant economical challenge because the high price of equipment needs to be amortized over short periods of time.

G.1.3. Challenges to Research and Development

During this research project it also became clear that there are some additional challenges to researchers trying to investigate the use of fuel cells and renewable energy sources, specifically for fringe markets such as the arctic and for research performed in Canada rather than the US:

- **Economic viability for customers vs. manufacturers**: While hydrogen as storage fuel has promise of being economically viable, due to the energy cost savings, the potential market is very small. Thus, development of hydrogen storage for remote areas is not necessarily economically interesting to the manufacturers of Fuel Cell products.
- **Fiscal constraints**: Companies have shown plenty of interest, but due to the lack of proper funding it is difficult for us to convince them to test their technologies in northern Canada. Canadian and US companies prefer to do research in Alaska where huge government grants are available for testing and evaluation of fuel cells. European companies like Norsk Hydro do their research in the more conveniently located European north.
- **Personnel:** Hiring of well-qualified staff in the Canadian North is difficult primarily due to their non-availability and the cost associated with hiring a person in the north. This is especially true for short-term assignments or consultants from southern Canada. In addition, the highly transitory nature of employment in the north leads to problems ensuring quality and reliability of work done and with ensuring proper documentation and maintenance of assets.
- **Communities**: Remote, distant, cold and sparsely populated. We need to combine trips, which makes it very inconvenient at times.

H. Conclusions

H.1. Financial Viability

Our analysis shows that stationary fuel cells for remote communities in the arctic are likely to be economically feasible. However, questions such as the fuel type and availability need to be resolved.

Table 11.

Comparison of RETScreen results based on total consumption in Holman		
	hydrogen	**hydrocarbon**
Mortgage term	***10*** [1)]	**10**
Year to positive cash flow	*more than 10*	1.5
Year to break even	*more than 10*	4.5
Initial cost	*$ 11,427,288.49*	$ 1,537,991.53
Annual cost	*$ 1,662,124.08*	$ 537,787.35
Annual savings	*$ 1,603,796.20*	$ 786,478.17
NPV (@ 7%)	*$ (2,383,408.66)*	$ 1,671,360.84
IRR / ROI	*-14.0%*	69.7%
Effective cost of Energy	*0.8767*	0.5078
Mortgage term	**15**	**15**
Year to positive cash flow	13.1	1.3
Year to break even	14.3	5.1
Initial cost	$ 6,335,187.41	$ 1,537,991.53
Annual cost	$ 767,158.41	$ 500,644.91
Annual savings	$ 801,531.10	$ 786,478.17
NPV (@ 7%)	$ (510,330.89)	$ 2,782,811.31
IRR / ROI	2.5%	79.4%
Effective cost of Energy	0.7725	0.4567
Mortgage term	**20**	**20**
Year to positive cash flow	9.4	1.2
Year to break even	15.4	5.7
Initial cost	$ 6,335,187.41	$ 1,537,991.53
Annual cost	$ 695,995.23	$ 483,368.65
Annual savings	$ 801,531.10	$ 786,478.17
NPV (@ 7%)	$ 648,398.48	$ 3,656,250.41
IRR / ROI	10.9%	83.7%
Effective cost of Energy	0.6725	0.4320

[1)] Note that this option is currently not economically feasible. Data is only included for completeness.

Our integrated energy model for "zero consumption" of diesel uses excess energy generated from say wind to produce hydrogen, which is then stored and used on-demand. Analysis of this model clearly shows that it is financially viable to power remote northern communities entirely from the integrated wind-hydrogen-fuel cell system assuming a community wide power demand exceeding 120 kW and a project lifetime of 15 years or more (Table 11). The total power demand needs to exceed 120 kW so that the fixed project costs and the excess supply become small in comparison with the project revenue. Of course the availability of wind also needs to be taken into account, suggesting Holman and Sachs Harbour as likely project locations, whereas Inuvik, Paulatuk and Tuktoyaktuk may not be as suitable for a wind project. It is apparent that the maximum power available from wind has to significantly exceed the maximum demand, but at the high cost of energy in northern communities this is still preferable over the use of diesel generators. Due to significant costs involved in the construction of roads and transmission lines, the wind-hydrogen-fuel cell integrated system should be placed in close proximity to each other and close to the community.

Due to an existing infrastructure for the transport and storage of diesel or natural gas, hydrocarbon fuel cells may also be considered to increase the electrical efficiency of power generation. A number of prototypes of SOFC are being tested for stationary applications in various places, but none in the Canadian arctic. Our analysis indicates that hydrocarbon fuel cells are financially viable as replacement for diesel generators, either for part/whole community or for single homes. Thus, if an integrated renewable-hydrogen system is not currently feasible, hydrocarbon fuel cells show promise as an intermediate step on the way to completely renewable energy supply.

Following the findings summarized in Table 11, the solid oxide fuel cells are currently more financially attractive due to the lower initial infrastructure costs. However, hydrogen fuel cells are technologically more advanced than hydrocarbon fuel cells and it appears more likely that a project based on hydrogen fuel cells will be successful on its technological merit.

H.2. Environmental Benefits

Hydrogen fuel cells (PEMFC), using hydrogen produced from renewable sources, do not contribute to GHG emissions. Thus, from an environmental perspective the "zero consumption" scenario analyzed here is preferable over the use of hydrocarbon fuel cells (SOFC) or hydrogen fuel cells using conventional energy for hydrogen production. However, hydrocarbon fuel cells will improve the overall efficiency of energy production as compared to diesel generators and thus reduce GHG emissions, as listed in Table 12.

Table 12.

GHG reduction from using fuel cells				
	Scenario 10	Scenario 20	Scenario 50	Scenario 100
GHG reduction "zero consumption" [t_{CO2}]	198	390	982	1,966
GHG reduction hydrocabon FC [t_{CO2}] [1)]	76	149	375	751

[1)] This is based on the assumption that both generators and fuel cells are using diesel.

H.3. Recommendations

Northern communities with high-energy prices are the ideal location for building integrated energy systems modelled here to lead Canada towards an environmentally friendly future. Due to its significant benefits, remote communities north of the Arctic Circle can become early market adopters of the hydrogen and fuel cell technologies. However, strong boost needs to be given by providing additional incentives. It is recommended that

1. Government agencies should provide financial assistance to the industry to develop prototypes for field-testing and demonstration in the Arctic.

2. Government of Northwest Territories should support the energy systems described here by granting the same "subsidies" as are given to the consumers using conventional energy. Additional incentives should be provided to homeowners and investors to bring these technologies to early commercialization.

3. Considering the technological problems currently associated with SOFC and the likely increasing price of fossil fuels, hydrocarbon fuel cells should be considered only as an “interim” solution until cleaner systems using PEMFC become more economically feasible.

4. Finally, since fuel cells are still not commercially available, an “interim” measure would be to minimize diesel use by building wind-hydrogen systems (without fuel cell) using diesel as a back up.

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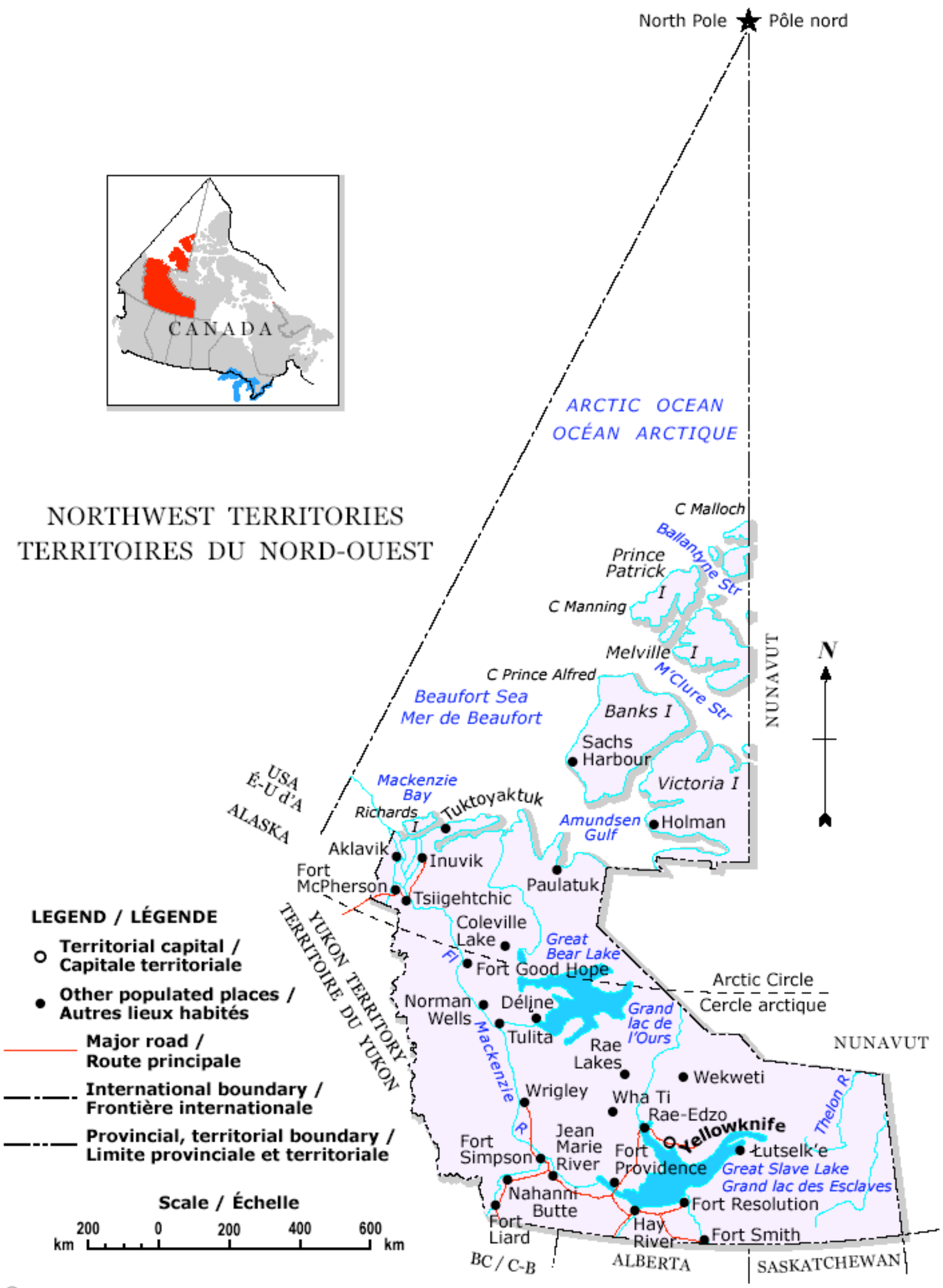
Appendices

Appendix 1: Map of the Northwest Territories



Appendix 2: Fuel Cell Technologies and Manufacturers

This appendix contains information on fuel cell types and manufacturers. Most manufacturers specialize on one type but have experience with one or more others. Table 13 lists the most prominent types of fuel cells, while Table 14 gives details on various fuel cell manufacturers.

App-2.1. Types of Fuel Cells

App-2.1.1. Proton Exchange Membrane Fuel Cells

These fuel cells, better known as PEMFCs are the leading fuel cells of today. These employ a polymer as the electrolyte which is a proton exchange membrane, and the catalysts used are usually composed of platinum; these expensive materials lead to a high cost for the PEMFC. They employ hydrogen of high purity for the fuel and oxygen from air as the oxidant. The hydrogen may be from hydrocarbons, alcohols, or electrolyzed water, as long as it only contains trace amounts of impurities.

The efficiency of these fuel cells is found to be approximately 40-50% [4] and have a power production of anywhere from 1 to 500kW. They are currently being developed for transportation and stationary applications. These operate at a temperature of approximately 80^{o}C, and may be employed at an ambient temperature of 0 to 40^{o}C. These are ideal for transportation and small applications as they are able to easily vary their output in order to meet the shifts in power demand; as well, they have a quick start-up at ambient temperature.

The PEM fuel cells being used for stationary applications are currently being developed and researched by many companies throughout Canada and the world. The top developers in Canada are Ballard Power Systems (perhaps the leading fuel cell developer in the world), Plug Power, and Hydrogenics.

In 1999 the cost of PEM fuel cells used for stationary applications was estimated to be USD8000 per kW. This is expected to decline rapidly with their rise in the market to an estimated future cost of USD300/kW. In comparison, the current cost of a gas turbine or gas engine is approximately USD600/kW, and therefore these are expected to be competitive in the future [33].

App-2.1.2. Solid Oxide Fuel Cells

These fuel cells are the other type used for large power generation. They operate at a high temperature between 600^{o}C and 1000^{o}C and due to this they take extended periods of time for start up in order to reach operating temperature. These usually employ a solid ceramic electrolyte consisting of zirconium oxide with small amounts of yttria [4]. This is an oxygen ion conducting electrolyte and therefore the oxygen ions flow from the cathode to the anode, unlike the lower temperature fuel cells where the hydrogen ions flow from the anode to cathode. These employ a nickel based catalyst as apposed to a platinum base. The electrons are created at the anode and flow through an external circuit to create the electricity and arrive at the cathode to reduce the oxygen in air to create the oxygen ions. The oxygen ions oxidize the fuel at the anode as long as it contains some hydrogen. Therefore, this type of fuel cell also does not require pure or reformed hydrogen at the surface of the anode and as a result natural gas or diesel can be used directly, abolishing the need of an additional reforming system.

These fuel cells can reach efficiencies of up to 60% and cogeneration can raise this to 80%. They have been designed for 5kW to 500 kW in size and many are in current working situations. These may be manufactured in 2 different configurations; one consists of an array of tubes, and the other is the conventional stack of plates that is used for the other types of fuel cells.

There are many companies focusing their attention on solid oxide fuel cells. In the US one major company is Siemens-Westinghouse, which is developing large-scale fuel cells to be used for power plants in the range of 200kW to a few MW. In Canada there are two major companies, Fuel Cell Technologies, and Fuel Cell Energy (formerly Global Thermoelectric Inc.). Fuel Cell technologies (see 0) are currently designing a 5 kW system to be used for individual homes that include a co-generation system for additional heat and hot water, approaching an efficiency of 90%. These are expected to cost approximately 1000 USD/kW when in high consumption, and use hydrocarbons directly. Fuel Cell Energy is currently testing a 2kW system and boasts to be a world leader in Solid Oxide Fuel Cell development.

App-2.1.3. Phosphoric Acid Fuel Cells

These fuel cells operate at a higher temperature than the PEMs, 160 to 220^{o}C. They use phosphoric acid as the electrolyte and employ platinum as the catalyst to speed up the reaction. An advantage these fuel cells have is that the small amount of carbon monoxide produced in the fuel cell, which is usually a result when hydrogen and air are used, does not poison the electrodes as it does in other fuel cells. In fact, PAFCs have a tolerance of about 1.5% CO concentration in the cells. As well, the electrolyte in these fuel cells can operate above the boiling temperature of water, which is usually a drawback for other acid electrolytes that depend on water for conductivity. Other fuel cells must have a cool down system to ensure the temperature of the fuel cell is always below the boiling point of water. The only drawback is that using an acid increases the susceptibility of the materials to corrosion and therefore this must be taken into account when choosing the proper materials [34].

The fuel used by these is once again hydrogen and the oxidant is oxygen, which may be used from air. The hydrogen can be retrieved from a reforming process or electrolyses. If reformation is used on a hydrocarbon containing sulphur, this must be removed prior to the reforming process.

Table 13. Comparison of Different Types of Fuel Cells

Type of fuel cell	Electrolyte	Operating T	Fuel	Oxidant	Efficiency	Power	Developer	Cost in 1999 (USD/kW)	Uses	Commercial Availability
Proton-exchange Membrane (PEMFC)	polymer, proton exchange membrane	80°C	hydrogen, may come from hydrocarbons or methanol	O_2/Air	40–50%	10W to 500 kW	Ballard, Plug Power, Hydrogenics, Palcan Fuel Cell Co	550-8000	transportation, stationary	Limited for Research, Testing & Evaluation
Solid Oxide (SOFC)	ceramic as stabilised zirconia and doped perovskite	600 to 1000°C	natural gas, propane, hydrogen, etc.	O_2/Air	45-60%	5 to 5000kW	Global Thermoelectric, Fuel Cell Technologies, Siemens-Westinghouse	10000	Small to Large Power plants and some individual home uses	Limited demos under company supervision
Phosphoric Acid (PAFC)	phosphoric acid	160 to 220°C	hydrogen from hydrocarbons and alcohol	O_2/Air	40–50%	5 to 500kW	ONSI	3000	stationary-cogeneration	Limited for Research, Testing & Evaluation
Molten Carbonate (MCFC)	molten salt such as nitrate, sulphate, carbonates	620 to 660°C	hydrogen, natural gas, propane, marine diesel	CO_2/O_2/ Air	50–60%	250 to 5000kW	Fuel Cell Energy Inc.	5000	power plants, commercial uses	Limited demos under company supervision
Alkaline (AFC)	potassium hydroxide (KOH)	small: 0 to 80°C	pure hydrogen, or hydrazine	O_2/Air	50–55%	60W to 200kW	Astris Fuel Cells	2000	stationary, transport	Not available
Direct Methanol (DMFC)	polymer	room temp to 70°C	liquid methanol	O_2/Air	40–55%	up to a few kW	Energy Visions	N/A	portable, electric cars	Not available

Table 14. Comparison of Fuel Cell Manufacturers

Fuel Cell Company	**Specialty Fuel Cell Type**	**Fuels Used**	**Primary Uses of Fuel Cells**	**Working Model**	**Cold Climate Testing**	**Additional Details**
Ballard Power Systems Inc.	PEMFC	Ultra pure hydrogen	transportation, portable, and stationary	Nexa Power Unit, 1.2kW	no	Aurora Research Institute has purchased 2 Nexa FCs.
Fuel Cell Technologies	SOFC	SOFC-hydrogen	residential, industrial, commercial, and remote applications	working on small scale units of 1 to 50kW, focusing on 5kW model	Currently testing their system at the University of Alaska, Fairbanks	5kW system is expected to be $1000/kW when fully commercialized
Global Thermoelectric Inc.	SOFC	Natural Gas, Propane, reformed hydrogen	residential applications, and for remote areas	working on 2kW to 10kW sized models	no	Company was recently purchased by Fuel Cell Energy Inc.
Hydrogenics Corporation	PEMFC	hydrogen	transportation, stationary, portable and diagnostic equipment	have developed many power generation systems containing fuel cells	Some testing done in Antarctica	also develop FC testing and controlling systems
Siemens-Westinghouse	SOFC	Natural Gas	residential, commercial and industrial	world's largest fuel cell, 200kW, in operation at the University of Toronto	no	Kinectrics are contractors with the testing of the system.

The efficiency of these fuel cells is estimated to be between 40 and 50%; however this can be increased to 80% when co-generation takes place. This is where the produced heat is used for heating purposes such as space heating in houses. As well, the hot water produced may be used for additional heating purposes and eventually for drinking water. These types of fuel cells have been most commonly used for stationary applications, as the heat produced is at such a high temperature that co-generation is able to take place. As well, their high operating temperatures allow for more tolerance to impure hydrogen.

At the present time, the city of Anchorage, Alaska is operating a 1MW power plant composed of five 200kW phosphoric acid fuel cells. The temperature in this city is similar to most Canadian northern communities and therefore proves that PAFCs are suitable for cold climates. As well, since PAFCs have a higher tolerance to impurities, this allows for different methods of producing hydrogen. The plant in anchorage currently uses a reforming system with natural gas, which is in abundance in the Mackenzie Delta region. These are of much larger size than the previous fuel cells, where they usually have a power production of 5 to 500kW. There is no large developer in Canada at the moment working on phosphoric acid fuel cells; however there are companies around the world such as ONSI in the US. They currently have a fuel cell on the market, PC25™C, which is available at 3250 USD/kW, but the price of these is expected to drop with an increase in commercialization.

App-2.1.4. Molten Carbonate Fuel Cells

These types of fuel cells operate at approximately 650^{o}C and employ molten salts as the electrolyte, e.g. nitrates, sulphates, or carbonates. These operate quite differently from other fuel cells. The lower temperature fuel cells produce electricity from the hydrogen being oxidized by the platinum catalyst on the anode, the hydrogen ions traveling to the cathode and combining with the oxygen ions to produce water. At the same time, the electrons exchanged travel through an external circuit in order to create the electricity. In the molten carbonate fuel cells the salts in the electrolyte melt and conduct carbonate ions (CO_3^{2-}) from the cathode to the anode. The hydrogen at the anode reacts with the carbonate ions to produce water, carbon dioxide, and electrons. At the cathode the carbon dioxide from the anode reacts with the oxygen in air, as well as the electrons produced, to reform carbonate ions that then replenish the electrolyte. The electrons being transferred from the anode to the cathode travel through an external circuit to produce the electricity [35].

MCFCs have a few advantages in that they can extract hydrogen from a number of different hydrocarbons by either an internal or external reformer. Therefore, they can either use hydrogen at the anode, or other hydrocarbons such as natural gas or diesel. The high operating temperature allows a greater tolerance to carbon monoxide, allowing even coal-based fuel to be used. The catalysts employed are usually of a nickel base, which are significantly cheaper than platinum, leading to a large advantage these fuel cells have over many others. They exhibit an efficiency of approximately 60% and it can increase to 80% when the heat produced is used for cogeneration. Currently these fuel cells have been designed and displayed at producing up to 2 MW; however others are being designed for 50 to 100 MW. Due to the high temperature of these fuel cells, they are usually only used for large stationary applications such as power plants. Their projected cost in 1999 was 5000 USD/kW and is expected to decrease to 600 USD/kW in the future as commercialization of these develops.

These fuel cells are in the same category as solid oxide fuel cells, as they are both high temperature, large power producing cells. The main disadvantages of these fuel cells compared to the solid oxide fuel cells are the difficulty of working with a liquid electrolyte, and the complexity of the reaction. The reaction causes the carbonate ions to be consumed at the cathode and therefore carbon dioxide must be injected at the cathode to insure electricity is continuously being produced.

App-2.1.5. Alkaline Fuel Cells

These were the first type of fuel cells, originally used in the spacecrafts in the 1960's to provide electricity to the crew as well as drinking water.

AFCs typically employ a potassium hydroxide (KOH) electrolyte between the anode and cathode. They use hydrogen as a fuel and oxygen as the oxidant. Their efficiency is found to be between 50-55% [4]. However it has also been stated to be close to 70% [36]. These range in power production between 60W and 200kW. Due to the type of fuel cell, the materials required are much cheaper than those needed for a Proton Exchange Membrane Fuel Cell.

These types of fuel cells have been designed for ambient temperatures ranging from -25 to 50^{o}C, and a humidity of 5 to 95% [37]. They operate at a temperature of approximately 60^{o}C and therefore the heat produced by the fuel cells is also at this temperature. These have been designed for stationary applications as well as small transport purposes and as stated previously, for space applications. Prototypes of these are currently being designed for electric golf carts.

Their cost was estimated [33] in 1999 to be approximately $2000 per kW. They are currently being developed in Canada by Astris Fuel Cells, located in Mississauga, Ontario, who boast to be the leading Alkaline Fuel Cell developers in Canada. Currently they are distributing 2 fuel cells for educational purposes having a power production of 60W and 240W; these may be purchased for $600 and $2400, respectively. They have also developed a power stack available from 300W to 2400W to be purchased, however the price for this has not yet been presented.

The alkaline fuel cell has the highest efficiency among the fuel cells as oxygen is reduced more rapidly in alkaline electrolytes. As well, these are able to employ non-noble electrocatalysts, therefore reducing the costs. However, there is one major disadvantage of these fuel cells; the alkaline electrolytes react with carbon dioxide to precipitate carbonates that interfere with the chemical reaction occurring inside the cell. This problem restricts alkaline fuel cells to specific applications where only pure hydrogen and pure oxygen may be used. Therefore these are appropriate for small power aerospace and defence applications, as apposed to stationary commercial purposes. Due to this setback, the research funding has been minimal for Alkaline Fuel Cells.

App-2.1.6. Direct Methanol Fuel Cells

These fuel cells use liquid Methanol directly, and therefore do not require any additional reforming of the fuel. The methanol is directly oxidized at the anode side of the fuel cell using oxygen from air as the oxidant. These require a polymer to be used as the electrolyte in the fuel cell and the catalysts most commonly employed contain platinum.

These are currently being designed for small mobile applications, usually supplying a power of 10-100W, however they have also been designed to produce up to a few kW. Liquid fuels have a higher energy density per volume than gaseous fuels, but not per weight. Therefore, smaller containers of fuel are required; however, a large amount is still needed. An advantage these fuel cells have over the previous ones is that the convenience of using liquid fuels is much greater in the transportation sector as the infrastructure is currently in place for liquid refuelling stations, as opposed to hydrogen refuelling stations, which have still not been proven safe or economical. These fuel cells do not require a large hydrogen storage system or a reforming system, making them much smaller and more cost effective when compared to the PEMFC.

The main problems are catalyst poisoning by the methanol, as well as methanol crossover and flooding. These problems lead to a rapid degradation of the catalysts employed on the cathode and therefore of the fuel cells. As well, the amount of platinum catalyst required is much greater than for the hydrogen/air PEM fuel cell.

Direct methanol fuel cells have an operating temperature of 70^{o}C [38] and therefore do not require complicated materials for high temperatures. Their efficiency can approach 40-55%; however, this may degrade rapidly due to the problems previously mentioned. These are currently being designed to replace batteries for portable purposes such as laptop computers and cell phones. They are also being looked at to be used in electric cars, as the fuel is much safer to handle than compressed hydrogen. A large advantage of the DMFC is that the methanol can be produced from biomass that is a renewable resource.

Currently, Energy Visions is the leading developer of Direct Methanol fuel cells in Canada and they are doing their research at the National Research Council of Canada located in Ottawa, Ontario [38].

App-2.2. Major Fuel Cell Companies

All major fuel cell developers were investigated. The descriptions of the fuel cell companies include the type of fuel cells they have designed, their current projects and where they stand in the fuel cell industry. Canada has the lead in this technology and therefore we decided to interview them first. However, for a study to be comprehensive, we understood the value of including all international developers. We visited three companies, Fuel Cell Energy (formerly Global Thermoelectric), Ballard Power Systems and Kinectrics, for onsite demonstration of their systems and to survey their technical staff. Also, we discussed the plans of other companies with their management teams at 3 conferences in Montreal, Calgary and Vancouver.

App-2.2.1. Ballard Power Systems Incorporated

Ballard (http://www.ballard.com) is regarded as the world's leading developer in proton exchange membrane fuel cells (PEMFCs) used for transport, portable and stationary applications. Their main focus is on the development, manufacturing and commercialization of PEM fuel cell systems.

Ballard was founded in 1979 and started developing PEM fuel cells in 1983, with the first model in 1989. Since then they have been developing fuel cell engines for cars and buses around the world. Ballard Power Systems is partnering up with other world leading companies such as DaimlerChrysler and Ford, among many. In 2001 the Nexa power module was completed, which is their first commercially available fuel cell product. It has a power rating of 1.2kW and runs off of hydrogen with a purity of 99.99%. Its maximum fuel consumption is 18.5 SLPM (standard litres per minute) at rated power.

Ballard is currently designing a 1kW co-generation fuel cell system for stationary applications in partnership with EBARA of Japan. The unit contains a reformer, the fuel cell and a co-generation system that utilizes the thermal energy in the heat produced, thus leading to an overall efficiency of 81%. They are currently designing a 250 kW stationary fuel cell system to be used for a complex of 50 to 60 family homes. It is now in place and undergoing testing which should be complete in 2004.

App-2.2.2. Fuel Cell Technologies Inc.

Fuel Cell Technologies (http://www.fct.ca) is focused on developing solid oxide fuel cells (SOFCs) for residential, industrial, commercial, and remote applications, as well as developing the aluminium fuel cell power system for underwater applications and remote power production. They are currently working on "small scale" SOFC power systems of 1 to 50kW in power. Their main focus is on the 5kW system, which is the typical amount of electricity consumed for the average 2000ft^2 homes. This system will also take advantage of co-generation due to the high operating temperature of the fuel cell being between 700^{o}C and 1000^{o}C. This will make use of the heat and hot water produced leading to an efficiency of 85%. When this is compared to the efficiency of a conventional heating system of 35%, the savings to the homeowner is large in the amount of fuel required. Fuel Cell Technologies estimate the payback period of this unit to be 4 years when compared to the conventional methods. The price of the unit is expected to approach $1000/kW when full commercialization is in effect.

Fuel Cell Technologies is also developing an aluminium air fuel cell power system to be used in the arctic under extreme cold conditions and limited sunlight. The system is composed of 12 cells working in series providing approximately 50 W of power each. It has been observed to run for 2 weeks and is developed to have a shelf life of 10 years. It has been tested in the town of Alert, Northwest Territories and was monitored and operated at the company's laboratories in Kingston, Ontario. This unit has a large advantage over zinc-air primary batteries, normally used for this purpose, due to the weight of the refuelling kit only being 1000 kg, compared to the 9000 kg of batteries.

App-2.2.3. Fuel Cell Energy Ltd. (formerly Global Thermoelectric Inc.)

Fuel Cell Energy (http://www.fuelcellenergy.com) has only recently acquired Global Thermoelectric Inc. Global Thermoelectric's focus has been on developing solid oxide fuel cells to be used for residential applications, using natural gas and propane as fuel. They have designed a high power density fuel cell, allowing their cells to be smaller and lighter but still providing the same amount of electricity. A decrease in material leads to a decrease in cost, which would be a great benefit for fuel cells at the present time. They are also looking to decrease the operating temperature of the SOFC to below 700^{o}C; this allows for cheaper materials to be used.

Global Thermoelectric boasts their fuel cells ability to tolerate carbon monoxide at the anode. Where a PEM fuel cell needs pure hydrogen, and therefore an additional separation processes is required to retrieve pure hydrogen from the other gases produced in the reforming stage, the SOFC can tolerate the reformed hydrogen with the carbon monoxide and carbon dioxide created from the reformer. As well, SOFCs are capable of using the hydrocarbons directly as the fuel and therefore an additional reforming stage is not required.

The company is currently testing various fuel cell designs in order to have a strong base for field trials in the near future. Most of the projects they are currently working on are of 2kW size, however their main focus is on fuel cells of 2kW to 10 kW size for stationary applications.

Global Thermoelectric Inc. has developed strategic partnerships with many other companies in the energy sector, such as Enbridge Gas, Superior Propane and Advanced Measurements, among many. In July of 2002, Global Thermoelectric Inc. reported testing a 2kW system developed in collaboration with Enbridge gas.

App-2.2.4. Hydrogenics Corporation

Hydrogenics Corporation (http://www.hydrogenics.com) is focused on developing Proton Exchange Membrane fuel cells used for transportation, stationary applications, portable devices and diagnostic equipment. They have developed 5 distinct power generation products using PEM fuel cells, as well as a number of fuel cell testing and controlling systems. They have power modules of 5, 25 and 40kW sizes, and power generators producing AC power of 1 to 5kW. They have also created a DC/DC fuel cell generator of 100W to 1kW in size, and a very large 25kW one. In addition to these products, Hydrogenics have also developed fuel cell stacks of 10W to 25kW. They also have operations in the USA, Japan and Germany.

Hydrogenics recently announced that they will be supplying General Hydrogen with 6 of their 10 kW HyPM-LP (2) power modules. General Hydrogen is a company out of Vancouver, BC that develops and installs hydrogen-based energy delivery systems [39]. These power modules were designed based on Hydrogenics' 20kW module that was sold to John Deere last year. The 10kW model is targeted at lightweight vehicles and power generation applications. Compared to Hydrogenics past models, these models have higher efficiencies, lower costs, smaller size and improved manufacturability, hopefully leading to earlier commercialization of the power modules.

App-2.2.5. Siemens-Westinghouse

Siemens Westinghouse (http://www.siemenswestinghouse.com) is demonstrating the world's largest solid oxide fuel cell at the University of Toronto in Mississauga (UTM). This SOFC currently supplies the university with 8% of its electricity and hot water, equivalent to the amount of energy used by 200 households in one year. It is fuelled by natural gas and has a power rating of 250 kW, currently the world's largest SOFC. Kinectrics (formerly R&D division for Ontario Hydro) has conducted testing and evaluation of this system at their facility. Prior to licensing it to UTM, the $18 million project was funded by Ontario Power Generation, the Government of Canada, Siemens Westinghouse Power Corporation and the US Department of Energy. The design of the SOFC allows it to satisfy many applications such as residential, commercial and industrial. It has an electrical efficiency of 50% and overall efficiency of 85% when the waste heat is used for additional requirements.

App-2.3. Survey of Fuel Cell Manufacturers

The following companies were solicited for information on the type of fuel cells they currently have under development, the technological stage of current developments and their expectations for market availability and pricing of products:

- Ballard (Canada)
- Energy Visions (Canada)
- Fuel Cell Technologies (Canada)
- Global Thermoelectric (Canada)
- Hydrogenics (Canada)
- IDA Tech (U.S.)
- Nuvera (U.S.)
- Palcan (Canada)
- PEM Technologies (Canada)
- Plug Power (U.S.)
- Siemens-Westinghouse (Global)

App-2.3.1. Survey Questionnaire

1. Are you designing systems for stationary applications?

2. Has your fuel cell system been extensively tested for residential use?
   If so:
   a) What is the coldest climate in which your system has been tested?
   b) Where has it been tested?

3. Are you currently developing systems within our power requirement range (2-5kW)?

   If so:
   a) What is the rated power and what type of system is it?
   b) What are its performance characteristics?
   c) Is it a standalone system?

4. Temperature range:

   a) What is the ambient temperature range for fuel cell start-up?
   b) At what ambient temperature will your fuel cell system operate?
   c) What is the operating temperature of your system?

5. a) What type of fuel does your system require?
   b) If hydrogen, what is the purity?

6. If you are using a fuel other than hydrogen:

   a) Does your system use direct oxidation or a reformer?
   b) What type of reformation process does your system use?

7. a) What is your estimated price per kW in 2003?
   b) What is your projected price five years from now?

8. What stage of development and testing is your system currently in?

9. If your units were in high demand, how many would you be able to produce?

10. a) How long do you expect your unit to operate for?
    b) What type of maintenance agreements do you have? I.e. warranties, replacements, etc.

11. Efficiency:

a) What is the electrical efficiency of your fuel cell?
b) Is there a co-generation system attached?
c) If so, what is the proposed thermal power outage?
s) What is the estimated overall efficiency?

12. Use in arctic climates
   a) Do you feel that your system is suitable for the arctic climates and fits our requirements?
   b) Are you interested in testing and demonstrating your system in the Arctic?
   c) Would you be interested in developing an integrated energy system using H_2 from natural resources?

13. Additional Comments:

App-2.3.2. Survey responses

Of the 11 companies surveyed only 4 replied (Table 15). The replies indicate that active development of fuel cells is still under way, particularly to increase service life and decrease cost. It is also clear, however, that some companies like Ballard or IDA Tech have started to actively market available products. This shows that fuel cells represent a technology at the beginning or market readiness.

Table 15

Response from Fuel Cell Manufacturers regarding Survey					
		Energy Visions	**Global Thermoelectric**	**Hydrogenics**	**IDATech**
1	**stationary**	no	yes	yes	yes
2	**residential**	no	no	no	no
a	**coldest climate**	-	-	-	indoor use
b	**locations**	-	-	-	Europe, Pacific northwest
3	**range 2-5kW**	yes	yes	yes	yes
a1	**power**	500W-5kW	2and 5kW	up to 10kW	1kW, 4.6kW, other on demand
a2	**type**	DMFC	SOFC, Natural Gas, 100V, on-grid	PEM	PEM
b	**characteristics**	-	29-35% AC efficiency	Load following, use for mobile power	-
c	**standalone**	yes (needs MeOH)	yes	yes	yes
4a	**ambient startup**	ca. -40C	room temperature	0-40C	-20-50C
b	**ambient operation**	80C	room temperature	0-40C	-20-50C
c	**operating temp.**	90C	700-750C	50-80C	several hundred C
5a	**fuel**	MeOH	natural gas	hydrogen	MeOH, natural gas, LPG
b	**H2 purity**	-	-	99.9999, no trace sulfur	-
6a	**reformer**	no	yes	no	yes
b	**reformation process**	-	steam reformer, 75-78% efficiency	-	steam reforming, metal membrane purification
7a	**$/kW 2003**	CAD 4000	-	-	-
7b	**$/kW 2008**	CAD 1500	CAD1200-1500	USD500-3000	USD1500
8	**development stage**	pre-commercial prototype	laboratory prototype	pre-commercial demonstration	pre-commercial and prototype
9	**response to demand**	follow market within 1 year	1 per month	100-300 per year	follow market
10a	**Lifetime**	>5 years guaranteed	>1 year	-	-
b	**Warranties and maintenance**	-	-	warranties	-
11	**electrical efficiency**	40-50%	29-35%	ca. 50%	reselling stacks … depends on source
a	**co-generation**	no	no	no	most
b	**thermal power**	-	-	-	similar to electrical
c	**total efficiency**	40-50%	29-35%	ca. 50%	30-35%
12a	**fit for arctic climates**	maybe	yes	only backup power	no
b	**interest in arctic applications**	yes	yes	yes, backup power	maybe
c	**integrated system using H2**	no	maybe	yes	yes
13	**comments**	Methanol fuel cells have big advantages over hydrogen and use a cheap, storable and transportable fuel	-	-	-

Appendix 3: Technical Collaboration and Presentations

As part of this project, R&D collaborations were sought proactively with other institutions and technology developers, both nationally and globally. The principal investigator on this project, Dr. Bak Chauhan, worked towards promoting distributed generation by developing strategic partnerships. He initiated a dialogue with Europeans for strengthening hydrogen and fuel cells research cooperation. He presented and published some of the results of this research project in the conference proceedings.

The following is a list of publications and professional activities associated with this project:

1. B. Chauhan, "Economic Feasibility of Hydrogen from Renewable Energy in the Arctic", Proceedings of the Hydrogen & Fuel Cells Conference, September 25-28, 2004, Toronto.
2. B. Chauhan, "EU/Canada Forum on Research Cooperation: Hydrogen and Fuel Cell Technology Development", Proceedings of the Hydrogen & Fuel Cells Conference, June 8-11, 2003, Vancouver.
3. B. Chauhan, "Arctic Fuel Cells Initiative: Opportunities and Challenges of Hydrogen and Fuel Cell Technologies in the Arctic", Proceedings of the Hydrogen & Fuel Cells Conference, June 8-11, 2003, Vancouver.
4. B. Chauhan, Chaired a session on Hydrogen Storage at the Hydrogen & Fuel Cells Conference, June 8-11, 2003, Vancouver.
5. B. Chauhan, Attended Canadian Fuel Cell Systems Symposium, February 26-28, 2003, Calgary.
6. B. Chauhan, "Canadian Fuel Cells R&D", Presented at the European Research Conference, November 11-13, 2002, Brussels.
7. B. Chauhan, "Potential Applications of Fuel Cells for Housing in the Arctic", World Hydrogen Energy Conference, June 6-9, 2002, Montreal.
8. B. Chauhan, "Importance of Alternative Fuels in the Arctic: Hydrogen for Fuel Cell Applications", Globe Environmental Conference, March 2002, Vancouver.
9. B. Chauhan, "Fuel Cells for Stationary Applications in the North", Distributed Generation Workshop, February 26-27, 2002, Inuvik.

These conferences provided an excellent opportunity to interact with a large number of peers and to discuss technical details about available products at their trade shows.

Appendix 4: Pivotal Power O312

App-4.1. Modification of O312 Output Voltage

The Pivotal Power O312 DC-DC converter was designed as part of a load control station custom built for IDA Tech. It was designed as a controlled current, variable power current-source and intended to be connected to load-levelling batteries on the converter output. Surprisingly however, the factory default for the output voltage is set at 16V, significantly higher than the ca. 14.1 V that would allow safe charging of a lead acid battery without risk of overcharging. In our set-up this caused problems with the automotive inverter that would not accept DC voltages exceeding 15.45 V.

Personal communication with Pivotal Power:

> *As shown below (Figure 8), three resistors (R44, R55 and R45) are related maximum output voltage limit. During maximum output voltage limit period, feedback circuits keep the voltage of R45 as 2.5V, so maximum output voltage can be modified by changing the value of R44 and R55. The relation is:*
>
> *(R44+R55)=((Vout_limit/2.5)-1)*10K*

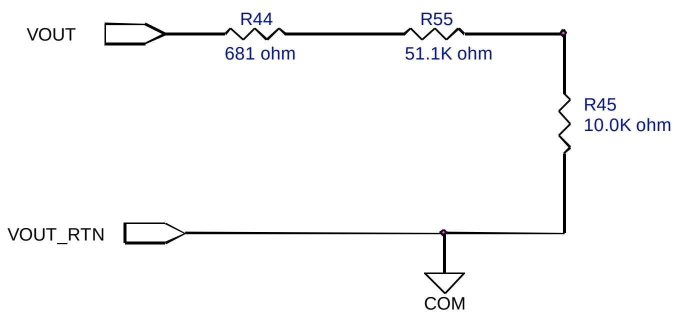


Figure 8: Relevant portion of DC-DC converter circuit board.

It was also indicated that only the series value of the resistors was relevant and that one of the resistors could thus be short-circuited. Thus R44 (figure 9) was short-circuited and R55 was replaced with a 47K (5%) resistor, which resulted in an output voltage of 14.1 V.

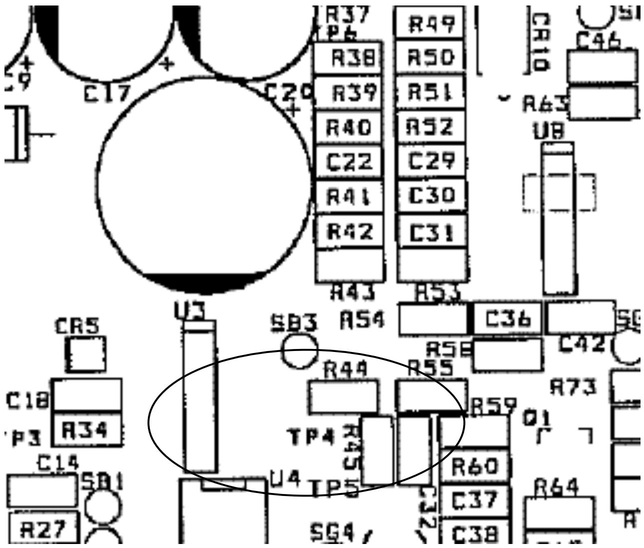


Figure 9: Relevant portion of DC-DC converter circuit board.

App-4.2. Operation: Output Battery, Reset and Current Control

The O312 needs to be connected to a 12V battery on the output side. Without power on the output side it will not power up. Additionally the O312 has two control inputs (see user's guide below) that need to be controlled to allow the converter to power up. A signal up to 1 V/20 mA needs to be applied at the current input to allow the converter to maintain its output voltage and supply power. Subsequently a 5V (TTL) signal needs to be applied and released on the RESET input. No current will be supplied while the RESET input is active.

In our setup it was recognized that the current control is an opto-coupled resistor circuit and thus a higher input voltage will lead to maximum current. This is safe as long as the voltage does not thermally destroy the control resistor. Thus a 1.5 V "D" cell was connected across this input. Further it was recognized that TTL levels will generally consider voltages exceeding 3.5V as "on" and 3 "D" cells in series were connected across the RESET input to initiate operation.

App-4.3. O312 User’s Guide

1kW Fuel Cell Power Conversion Sub-System
Model 312
- USER’S GUIDE -

Introduction

Specifications

- Remote Monitoring
- Remote Control
- Protection
- Power Conversion Quality

Installation

- Mounting
- Ventilation
- Electrical connections
- Safety precautions
    - Electrical Shorting
    - Reverse Polarity

Introduction

1kW FC PCSS is a non-isolated 1.25kW DC/DC converter that accepts a DC voltage from 21V to 46V and output a maximum of 15.45V or 100A with the peak efficiency of equal to or over 90%. The output current is controlled via pins 1- 9 (I-limit return) of the 15 pins D-Sub connector. Unit is automatically set to Standby mode at the initial DC input connection until a RESET command is activated via pins 5 - 9(reset return). It has three Remote Monitoring outputs are Input/Output Voltages and unit Status, these signals are full scaled from 0 – 5V. Detailed 15-pin D-Sub configuration is shown in Table 16.

Specifications (Preliminary)

Storage Temperature Range	-20 - 60ϒC
Operating Temperature Range	0 - 50ϒC
Humidity Range	0 – 95% non-condensing
Minimum Efficiency	90% at 1000W from the Stack
Output Voltage Range	9.0 – 15.5V
Input Voltage Range	21.0 – 46.0V
Noise	To be tested
Radio Frequency Interference	To be tested
Reliability	15,000 hours minimum at 25ϒC
Warranty	3000 operating hours or one year
Size	4.72in H x 14.92in W x 3.74in D 11.98cm H x 37.89cm W x 9.5cm D
Weight	Approximately 14.0lbs max

Remote Monitoring

V_Stack	0 – 5V, 0 to 55V input ±2% accuracy
V_Output	0 – 5V, 0 to 20V output ±2% accuracy
STATUS	0 – 5V, logic output 0 = OFF/FAULT 1 = RUN

Remote Control

RESET	0 – 5V, opt-coupler with 100⎮ in series 0 = no change 1 = RESET
I_Limit	I_Limit can be either a current sources or voltage sources through 50⎮ input impedance. Current: 0 – 20mA, 0 – 100A output, ±3%. Voltage: 0 – 1.0V, 0 – 100A output, ±3%.

Protection
Protection enables latched shutdown or standby mode to prevent unit from re-energizing if any of the fault condition has recovered. Unit can be remotely re-enabled using the RESET pin.

Input Under Voltage	20.5V ±0.2V
Output Over Voltage	16.0V ±0.2V
Output Under Voltage	9.0V ±0.2V
Over Temperature	85ϒC Heat sink temperature
Short Circuit	140Apk -10A/+20A through the DC/DC Converter.

Power Conversion Quality

Output Voltage Ripple	±2% peak-to-peak at 14.7V (588mVp-p) with resistive load at 1000W from Stack
Input Current Ripple	Maximum ±20% peak-to-peak while drawing 1kW from Stack

Installation

Electrical Connections
Unit is equipped with ¼” brass studs for both input and output.
Chassis ground is attached directly to the case of unit.
The control connector is a 15-pin D-Sub connector and the shell is electrical connected to the case or chassis ground. The pin-out of each connector is as follows:

Pin Number	Signal
1	I-limit
2	Stack voltage
3	Output voltage
4	Status
5	Reset
6	Output Current
7, 8	No connect/reserved
9	Ground (I-Limit return)
10	Ground (stack voltage return)
11	Ground (output voltage/ current return)
12	Ground (status return)
13	Ground (reset return)
14, 15	No connect/reserved
Shell	Tied to chassis ground

Table 16. Interface Connector Pinout

Mounting
Mounting requires six #8-32 3/8”screws fastening to the PEM nuts located on the top of the unit. If a longer screw type is used, the length of the screw shall **not** be inserting more than ¼” from the surface of the unit.

Ventilation
Unit is designed to draw air from 0ϒC to the maximum of 50ϒC and at least 30 CFM from the side centre of the unit and exhaust to the top left of the unit. Unit shall be mounted so that the exhausted air will not be re-circulated back into the air intake.

Reverse Polarity
1kW FC PCSS is not equipped with input reverse polarity protection. Reverse polarity will cause internal damage to semiconductors and electrolytic capacitors. ***Therefore, ensure the polarity is correct before powering up the unit.***

Electrical Shorting
1kW FC PCSS is equipped electronics output short circuit protection, and with an 80A fuse at the input and a150A fuse at the output side. These fuses are beside the terminal connections for easy access, identification, and failure detection.
In the event of the internal component failure, an 80A fuse at the input side is used for the protection. If the output is shorted the electronic protection will not allow the current to exceed 140Apk -10A/+20A. The output fuse is used if the output is mistakenly reversed during connection and to minimize damage to the internal components as well as preventing electrical fire.

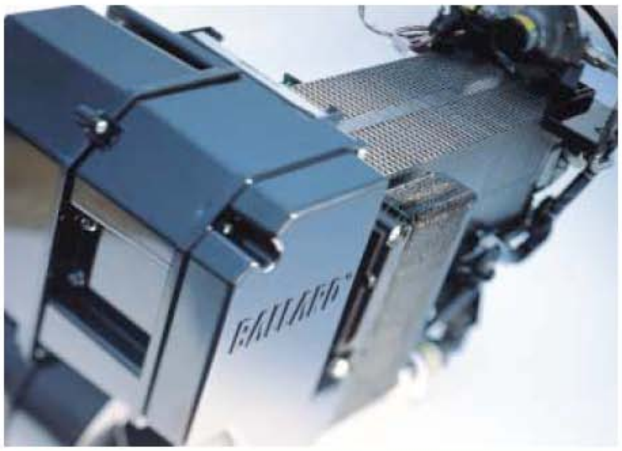
Appendix 5: Nexa Spec Sheet

Ballard® fuel cell power module

Nexa®

power generation

BALLARD®
power to change the world®



NEXA®

Ballard Power Systems introduces the Nexa® power module, the world's first volume-produced proton exchange membrane (PEM) fuel cell module designed for integration into a wide variety of stationary and portable power generation applications. Using Ballard's PEM technology, the Nexa® power module converts hydrogen fuel and oxygen (from air) in a non-combustive electro-chemical reaction to generate up to 1200 watts of unregulated DC electrical power.

Emitting heat and water as by-products of power generation, the Nexa® power module allows original equipment manufacturer products to be used in indoor environments and other locations not possible with conventional internal combustion engines. The Nexa® power module's quiet operation and compact size make it ideal for integration into uninterruptible power supply systems, emergency power generators, and recreational and portable products. And unlike battery technology with limited run-times, the Nexa® power module is capable of providing full extended run backup or intermittent electrical power for as long as fuel is supplied to the unit.

Brought to you by Ballard — the world leader in PEM fuel cell technology. The Nexa® power module is backed by over 15 years of experience in the development of premium fuel cell products for transportation, stationary and portable applications.

Specifications

Performance :	Rated net power	1200 watts[1]
	Rated current	46 Amps[1]
	DC voltage range	22 to 50 Volts
	Operating lifetime	1500 hours
Fuel :	Composition	99.99% dry gaseous hydrogen
	Supply pressure	10 to 250 PSIG
	Consumption	≤ 18.5 SLPM[2]
Operating Environment :	Ambient temperature	3°C to 30°C *(37°F to 86°F)*
	Relative humidity	0% to 95%[3]
	Location	Indoors and outdoors[4]
Physical :	Length x width x height	56 x 25 x 33 cm *(22 x 10 x 13 in)*
	Weight	13 kg *(29 lbs)*
Certification :		CSA, UL
Emissions :	Liquid water	0.87 liters *(30 fluid oz.)* maximum per hour[2]
	Noise	≤ 72 dBA @ 1 meter
Integration :	Fuel interface	45° flared tube fitting for 1/4" OD tubing – metallic
	Electrical interface	#8 AWG electrical wire
	Control interface	Full duplex RS 485

[1] Beginning of life, sea level, rated temperature range.
[2] At rated net power.
[3] Non-condensing.
[4] Unit must be protected from inclement weather, sand and dust.

Specifications and descriptions in this document were in effect at the time of publication. Ballard Power Systems Inc. reserves the right to change specifications or to discontinue products at any time (10/03).

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Appendix 6: RETScreen® Tables

App-6.1. Solid Oxide Fuel Cells

RETScreen® does not have a convenient module for the financial analysis of fuel cells dependent solely on non-renewable resources, such as hydrocarbons. The WIND2000 module was used and the data entered in the spreadsheet was modified to reflect the costs of a hydrocarbon fuel cell rather than wind turbines. It should thus be understood that any reference to renewable energy (RE) on the analysis sheet is representative of the energy obtained from natural gas or diesel via a hydrocarbon fuel cell.

App-6.1.1. Hydrocarbon Fuel Cells for Single Homes

The effective cost of 2 kW and 3 kW fuel cells does not significantly differ. As with the larger hydrocarbon scenarios, the 10-year term is examined because of technological limitation to fuel cell lifespan.

Table 17: Cost analysis for 3 kW residential hydrocarbon fuel cell, lump sum.

RETScreen ® Cost Analysis - Wind Energy Project

Type of project: Standard | Currency: Canada | Cost references: None

Initial Costs (Credits)	Unit	Quantity	Unit Cost		Amount		Relative Costs	Quantity Range	Unit Cost Range
Feasibility Study									
Other	Cost	0	CAD	-	CAD	-		-	-
Sub-total:					CAD	-	0.0%		
Development									
Other	Cost	0	CAD	-	CAD	-		-	-
Sub-total:					CAD	-	0.0%		
Engineering									
Other	Cost	0	CAD	-	CAD	-		-	-
Sub-total:					CAD	-	0.0%		
Renewable Energy (RE) Equipment									
Wind turbine(s)	kW	2	CAD	-	CAD	-		-	-
Spare parts	%	3.0%	CAD	-	CAD	-		-	-
Transportation	turbine	0	CAD	-	CAD	-		-	-
FC installed	Cost	1	CAD	15,373	CAD	15,373		-	-
Sub-total:					CAD	15,373	93.6%		
Balance of Plant									
Wind turbine(s) foundation(s)	turbine	0	CAD	-	CAD	-		-	-
Wind turbine(s) erection	turbine	0	CAD	-	CAD	-		-	-
Road construction	km	0.00	CAD	40,000	CAD	-		-	-
Transmission line and substation	project	0	CAD	50,000	CAD	-		-	-
Control and O&M building(s)	building	0	CAD	35,000	CAD	-		-	-
Transportation	project	1	CAD	-	CAD	-		-	-
Transportation: FC	Cost	1	CAD	1,050	CAD	1,050		-	-
Sub-total:					CAD	1,050	6.4%		
Miscellaneous									
Training	p-d	0	CAD	-	CAD	-		-	-
Commissioning	p-d	0	CAD	-	CAD	-		-	-
Interest during construction	%	0.0%	CAD	16,423	CAD	-		-	-
Contingencies	%	0%	CAD	16,423	CAD	-		-	-
Sub-total:					CAD	-	0.0%		
Initial Costs - Total					CAD	16,423	100.0%		

Annual Costs (Credits)	Unit	Quantity	Unit Cost		Amount		Relative Costs	Quantity Range	Unit Cost Range
O&M									
Land lease	%	2.0%	CAD	5,626	CAD	113		-	-
Property taxes	%	0.6%	CAD	5,626	CAD	34		-	-
Insurance premium	%	4.0%	CAD	5,626	CAD	225		-	-
Transmission line maintenance	%	3.0%	CAD	-	CAD	-		-	-
Parts and labour	kWh	7,772	CAD	0.169	CAD	1,314		-	-
Community benefits	-	0	CAD	-	CAD	-		-	-
Travel and accommodation	p-trip	0	CAD	3,000	CAD	-		-	-
General and administrative	%	5%	CAD	1,686	CAD	84		-	-
FC O&M	Cost	1	CAD	612	CAD	612		-	-
Contingencies	%	5%	CAD	1,686	CAD	84		-	-
Annual Costs - Total					CAD	2,466	100.0%		

Periodic Costs (Credits)		Period	Unit Cost		Amount		Interval Range	Unit Cost Range
Drive train	Cost	10 yr	CAD	-	CAD	-	-	-
Blades	Cost	15 yr	CAD	-	CAD	-	-	-
					CAD	-	-	-
End of project life	Credit	-	CAD	-	CAD	-		*Go to GHG Analysis sheet*

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Table 18: Financial summary for 3 kW residential hydrocarbon fuel cell, lump-sum

RETScreen® Financial Summary - Wind Energy Project

Annual Energy Balance

Project name		Hol-DieselFC	Grid peak load	kW	1
Project location		Holman			
Renewable energy delivered	MWh	8	GHG analysis sheet used?	yes/no	No
Excess RE available	MWh	-			
Firm RE capacity	kW	-			
Grid type		Isolated-grid			

Financial Parameters

Avoided cost of energy	CAD/kWh	0.7239	Debt ratio	%	0.0%
RE production credit	CAD/kWh	-			
			Income tax analysis?	yes/no	No
Energy cost escalation rate	%	2.0%			
Inflation	%	2.0%			
Discount rate	%	7.0%			
Project life	yr	10			

Project Costs and Savings

Initial Costs				**Annual Costs and Debt**		
Feasibility study	0.0%	CAD	-	O&M	CAD	2,466
Development	0.0%	CAD	-			
Engineering	0.0%	CAD	-			
RE equipment	93.6%	CAD	15,373	**Annual Costs - Total**	**CAD**	**2,466**
Balance of plant	6.4%	CAD	1,050			
Miscellaneous	0.0%	CAD	-	**Annual Savings or Income**		
Initial Costs - Total	100.0%	**CAD**	**16,423**	Energy savings/income	CAD	5,626
				Capacity savings/income	CAD	-
Incentives/Grants		CAD	-			
				Annual Savings - Total	**CAD**	**5,626**
Periodic Costs (Credits)						
Drive train		CAD	-			
Blades		CAD	-			
		CAD	-			
End of project life - Credit		CAD	-			

Financial Feasibility

			Calculate RE production cost?	yes/no	Yes
Pre-tax IRR and ROI	%	16.4%			
After-tax IRR and ROI	%	16.4%			
Simple Payback	yr	5.2	Project equity	CAD	16,423
Year-to-positive cash flow	yr	4.9			
Net Present Value - NPV	CAD	8,097			
Annual Life Cycle Savings	CAD	1,153			
Profitability Index - PI	-	0.49	RE production cost	CAD/kWh	0.5791

Yearly Cash Flows

Year #	Pre-tax $	Cumulative $	Remaining Debt $	Net Value $
0	(16,423)	(16,423)	-	(16,423)
1	3,224	(13,200)	-	(13,200)
2	3,288	(9,912)	-	(9,912)
3	3,354	(6,558)	-	(6,558)
4	3,421	(3,137)	-	(3,137)
5	3,489	352	-	352
6	3,559	3,912	-	3,912
7	3,630	7,542	-	7,542
8	3,703	11,245	-	11,245
9	3,777	15,022	-	15,022
10	3,852	18,874	-	18,874
11	-	18,874	-	18,874
12	-	18,874	-	18,874
13	-	18,874	-	18,874
14	-	18,874	-	18,874
15	-	18,874	-	18,874
16	-	18,874	-	18,874
17	-	18,874	-	18,874
18	-	18,874	-	18,874
19	-	18,874	-	18,874
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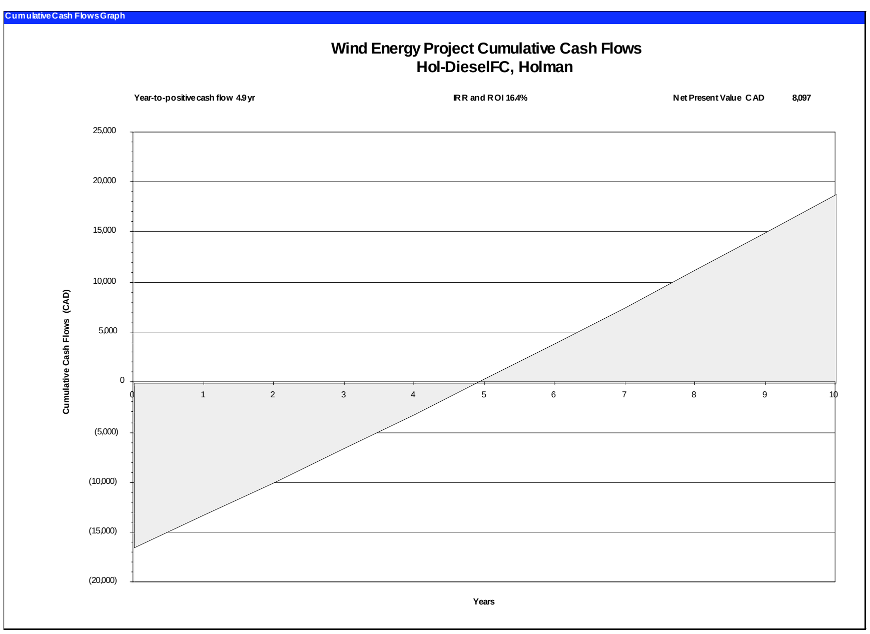

Figure 10: Cumulative cash flow for 3 kW residential hydrocarbon fuel cell, lump sum.

Table 19: Cost analysis for 3 kW residential hydrocarbon fuel cell for 10 year term.

RETScreen ® Cost Analysis - Wind Energy Project

Type of project: Standard | Currency: Canada | Cost references: None

Initial Costs (Credits)	Unit	Quantity	Unit Cost	Amount	Relative Costs	Quantity Range	Unit Cost Range
Feasibility Study							
Other	Cost	0	CAD -	CAD -		-	-
Sub-total:				CAD -	0.0%		
Development							
Other	Cost	0	CAD -	CAD -		-	-
Sub-total:				CAD -	0.0%		
Engineering							
Other	Cost	0	CAD -	CAD -		-	-
Sub-total:				CAD -	0.0%		
Renewable Energy (RE) Equipment							
Wind turbine(s)	kW	2	CAD -	CAD -		-	-
Spare parts	%	3.0%	CAD -	CAD -		-	-
Transportation	turbine	0	CAD -	CAD -		-	-
FC	Cost	1	CAD 15,373	CAD 15,373		-	-
Sub-total:				CAD 15,373	93.6%		
Balance of Plant							
Wind turbine(s) foundation(s)	turbine	0	CAD -	CAD -		-	-
Wind turbine(s) erection	turbine	0	CAD -	CAD -		-	-
Road construction	km	0.00	CAD 40,000	CAD -		-	-
Transmission line and substation	project	0	CAD 50,000	CAD -		-	-
Control and O&M building(s)	building	0	CAD 35,000	CAD -		-	-
Transportation	project	1	CAD -	CAD -		-	-
Transportation: FC	Cost	1	CAD 1,050	CAD 1,050		-	-
Sub-total:				CAD 1,050	6.4%		
Miscellaneous							
Training	p-d	1	CAD -	CAD -		-	-
Commissioning	p-d	1	CAD -	CAD -		-	-
Interest during construction	%	0.0%	CAD 16,423	CAD -		-	-
Contingencies	%	0%	CAD 16,423	CAD -		-	-
Sub-total:				CAD -	0.0%		
Initial Costs - Total				CAD 16,423	100.0%		

Annual Costs (Credits)	Unit	Quantity	Unit Cost	Amount	Relative Costs	Quantity Range	Unit Cost Range
O&M							
Land lease	%	2.0%	CAD 5,626	CAD 113		-	-
Property taxes	%	0.6%	CAD 5,626	CAD 34		-	-
Insurance premium	%	4.0%	CAD 5,626	CAD 225		-	-
Transmission line maintenance	%	3.0%	CAD -	CAD -		-	-
Parts and labour	kWh	7,772	CAD 0.169	CAD 1,314		-	-
Community benefits	-	0	CAD -	CAD -		-	-
Travel and accommodation	p-trip	0	CAD 3,000	CAD -		-	-
General and administrative	%	5%	CAD 1,686	CAD 84		-	-
FC O&M	Cost	1	CAD 612	CAD 612		-	-
Contingencies	%	5%	CAD 1,686	CAD 84		-	-
Annual Costs - Total				CAD 2,466	100.0%		

Periodic Costs (Credits)		Period	Unit Cost	Amount		Interval Range	Unit Cost Range
Drive train	Cost	10 yr	CAD -	CAD -		-	-
Blades	Cost	15 yr	CAD -	CAD -		-	-
				CAD -		-	-
End of project life	Credit	-	CAD -	CAD -		*Go to GHG Analysis sheet*	

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Table 20: Financial summary for 3 kW residential hydrocarbon fuel cell for 10 year term

RETScreen® Financial Summary - Wind Energy Project

Annual Energy Balance

Project name		Hol-DieselFC	Grid peak load	kW	1
Project location		Holman			
Renewable energy delivered	MWh	8	GHG analysis sheet used?	yes/no	No
Excess RE available	MWh	-			
Firm RE capacity	kW	-			
Grid type		Isolated-grid			

Financial Parameters

Avoided cost of energy	CAD/kWh	0.7239	Debt ratio	%	75.0%
RE production credit	CAD/kWh	-	Debt interest rate	%	8.0%
			Debt term	yr	10
			Income tax analysis?	yes/no	No
Energy cost escalation rate	%	2.0%			
Inflation	%	2.0%			
Discount rate	%	7.0%			
Project life	yr	10			

Project Costs and Savings

Initial Costs			
Feasibility study	0.0%	CAD	-
Development	0.0%	CAD	-
Engineering	0.0%	CAD	-
RE equipment	93.6%	CAD	15,373
Balance of plant	6.4%	CAD	1,050
Miscellaneous	0.0%	CAD	-
Initial Costs - Total	100.0%	**CAD**	**16,423**
Incentives/Grants		CAD	-
Periodic Costs (Credits)			
Drive train		CAD	-
Blades		CAD	-
		CAD	-
End of project life - Credit		CAD	-

Annual Costs and Debt		
O&M	CAD	2,466
Debt payments - 10 yrs	CAD	1,836
Annual Costs - Total	**CAD**	**4,302**
Annual Savings or Income		
Energy savings/income	CAD	5,626
Capacity savings/income	CAD	-
Annual Savings - Total	**CAD**	**5,626**

Financial Feasibility

			Calculate RE production cost?	yes/no	Yes
Pre-tax IRR and ROI	%	35.8%			
After-tax IRR and ROI	%	35.8%			
Simple Payback	yr	5.2	Project equity	CAD	4,106
Year-to-positive cash flow	yr	2.8	Project debt	CAD	12,317
Net Present Value - NPV	CAD	7,522	Debt payments	CAD/yr	1,836
Annual Life Cycle Savings	CAD	1,071	Debt service coverage	-	1.76
Profitability Index - PI	-	1.83	RE production cost	CAD/kWh	0.5894

Yearly Cash Flows

Year	Pre-tax	Cumulative	Remaining Debt	Net Value
#	$	$	$	$
0	(4,106)	(4,106)	18,357	(22,462)
1	1,388	(2,718)	16,190	(18,908)
2	1,452	(1,265)	14,104	(15,369)
3	1,518	253	12,094	(11,841)
4	1,585	1,838	10,159	(8,321)
5	1,654	3,492	8,296	(4,805)
6	1,723	5,215	6,504	(1,289)
7	1,795	7,010	4,781	2,229
8	1,867	8,877	3,123	5,753
9	1,941	10,818	1,530	9,288
10	2,017	12,835	0	12,835
11	-	12,835	-	12,835
12	-	12,835	-	12,835
13	-	12,835	-	12,835
14	-	12,835	-	12,835
15	-	12,835	-	12,835
16	-	12,835	-	12,835
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44	-	12,835		
45	-	12,835		
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48	-	12,835		
49	-	12,835		
50	-	12,835		

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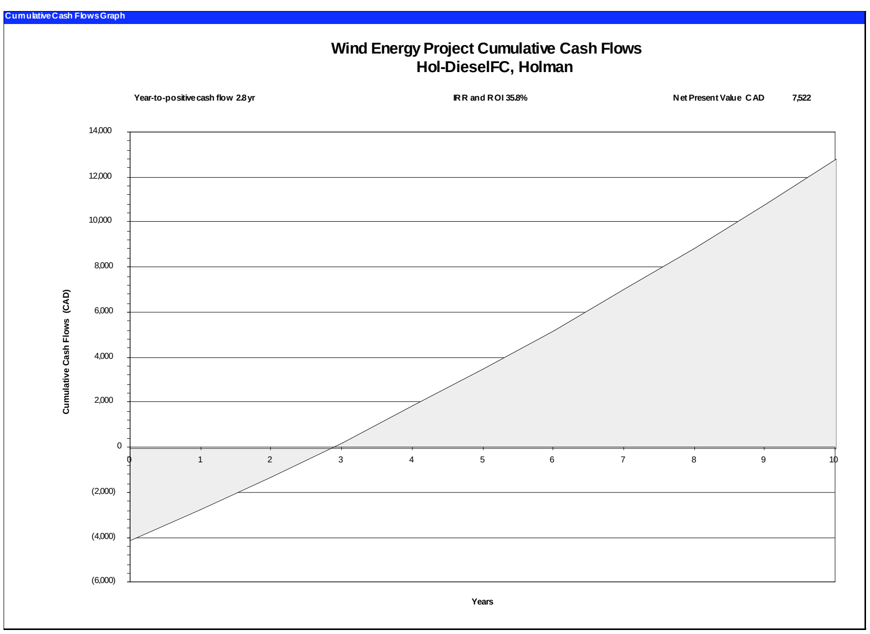

Figure 11: Cumulative cash flow for 3 kW residential hydrocarbon fuel cell for10 year term.

App-6.1.2. Solid Oxide Fuel Cells for Apartment Complex in Inuvik

Table 21: Cost analysis for 80 kW hydrocarbon fuel cell.

Initial Costs (Credits)	Unit	Quantity	Unit Cost	Amount
Feasibility Study				
Feasibility study	Cost	0		$ -
Sub-total:				**$ -**
Development				
Development	Cost	0		$ -
Sub-total:				**$ -**
Engineering				
Engineering	Cost	0		$ -
Sub-total:				**$ -**
Energy Equipment				
Wind turbine(s)	kW	0		$ -
Spare parts	%	3.0%	$ -	$ -
Transportation	turbine	2		$ -
SOFC - 80kW	Cost	1	$404,000	$404,000
Sub-total:				**$404,000**
Balance of Plant				
Balance of plant (Transportation)	Cost	1	$8,000	$8,000
Sub-total:				**$8,000**
Miscellaneous				
Contingencies	%	10%	$412,000	$41,200
Interest during construction	0.0%	12 month(s)	$453,200	$ -
Sub-total:				**$41,200**
Initial Costs - Total				**$453,200**

Annual Costs (Credits)	Unit	Quantity	Unit Cost	Amount
O&M				
O&M (Fuel and Maintenance)	Cost	1	$18,000	$18,000
Contingencies	%	20%	$18,000	$3,600
Annual Costs - Total				**$21,600**

Table 22. Financial summary for 80 kW hydrocarbon fuel cell for 10-year term

RETScreen® Financial Summary - Wind Energy Project

Annual Energy Balance							
Project name			Inuvik FC	Peak load	kW	80	
Project location			Inuvik				
Renewable energy delivered		MWh	234				
Excess RE available		MWh	18				
Firm RE capacity		kW	-				
Grid type			Off-grid				
Financial Parameters							
Avoided cost of energy		$/kWh	0.3872	Debt ratio	%	75.0%	
RE production credit		$/kWh		Debt interest rate	%	8.0%	
				Debt term	yr	10	
				Income tax analysis?	yes/no	No	
Avoided cost of excess energy		$/kWh	-				
Energy cost escalation rate		%	2.0%				
Inflation		%	2.0%				
Discount rate		%	7.0%				
Project life		yr	10				
Project Costs and Savings							
Initial Costs				**Annual Costs and Debt**			
Feasibility study	0.0%	$	-	O&M	$	21,600	
Development	0.0%	$	-				
Engineering	0.0%	$	-	Debt payments - 10 yrs	$	50,655	
Energy equipment	89.1%	$	404,000	**Annual Costs and Debt - Total**	$	**72,255**	
Balance of plant	1.8%	$	8,000				
Miscellaneous	9.1%	$	41,200	**Annual Savings or Income**			
Initial Costs - Total	100.0%	$	**453,200**	Energy savings/income	$	90,646	
				Capacity savings/income	$	-	
Incentives/Grants		$	-				
				Annual Savings - Total	$	**90,646**	
Periodic Costs (Credits)							
Drive train		$	-				
Blades		$	-				
		$	-				
End of project life - Credit		$	-				
Financial Feasibility							
				Calculate energy production cost?	yes/no	No	
Pre-tax IRR and ROI		%	17.3%				
After-tax IRR and ROI		%	17.3%				
Simple Payback		yr	6.6				
Year-to-positive cash flow		yr	5.0	Project equity	$	113,300	
Net Present Value - NPV		$	66,624	Project debt	$	339,900	
Annual Life Cycle Savings		$	9,486	Debt payments	$/yr	50,655	
Benefit-Cost (B-C) ratio		-	1.59	Debt service coverage	-	1.39	

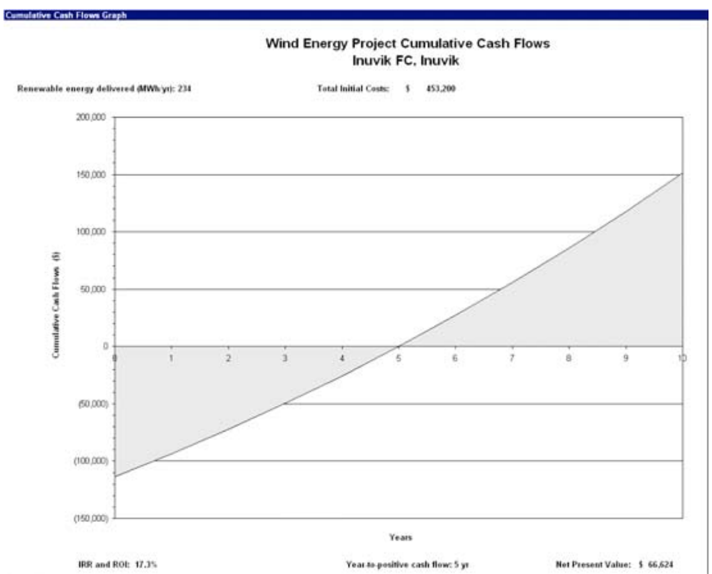

Figure 12: Cumulative cash flow for 80 kW hydrocarbon fuel cell for10-year term

App-6.1.3. Hydrocarbon Fuel Cells for Community Power in Holman

Table 23. Cost analysis for hydrocarbon fuel cell “scenario 100” for 10 year term.

RETScreen ® Cost Analysis - Wind Energy Project

Type of project:	Standard	Currency:	Canada	Cost references:	None

Initial Costs (Credits)	Unit	Quantity	Unit Cost	Amount	Relative Costs	Quantity Range	Unit Cost Range
Feasibility Study							
Other	Cost	0	CAD -	CAD -		-	-
Sub-total:				CAD -	0.0%		
Development							
Other	Cost	0	CAD -	CAD -		-	-
Sub-total:				CAD -	0.0%		
Engineering							
Other	Cost	0	CAD -	CAD -		-	-
Sub-total:				CAD -	0.0%		
Renewable Energy (RE) Equipment							
Wind turbine(s)	kW	655	CAD -	CAD -		-	-
Spare parts	%	3.0%	CAD -	CAD -		-	-
Transportation	turbine	13	CAD -	CAD -		-	-
FC	Cost	1	CAD 2,512,194	CAD 2,512,194		-	-
Sub-total:				CAD 2,512,194	85.9%		
Balance of Plant							
Wind turbine(s) foundation(s)	turbine	13	CAD -	CAD -		-	-
Wind turbine(s) erection	turbine	13	CAD -	CAD -		-	-
Road construction	km	1.00	CAD 40,000	CAD 40,000		-	-
Transmission line and substation	project	1	CAD 50,000	CAD 50,000		-	-
Control and O&M building(s)	building	1	CAD 35,000	CAD 35,000		-	-
Transportation	project	1	CAD -	CAD -		-	-
Transportation: FC	Cost	1	CAD 7,500	CAD 7,500		-	-
Sub-total:				CAD 132,500	4.5%		
Miscellaneous							
Training	p-d	10	CAD 1,020	CAD 10,200		-	-
Commissioning	p-d	3	CAD 1,487	CAD 4,460		-	-
Interest during construction	%	0.0%	CAD 2,644,694	CAD -		-	-
Contingencies	%	10%	CAD 2,644,694	CAD 264,469		-	-
Sub-total:				CAD 279,129	9.5%		
Initial Costs - Total				CAD 2,923,823	100.0%		

Annual Costs (Credits)	Unit	Quantity	Unit Cost	Amount	Relative Costs	Quantity Range	Unit Cost Range
O&M							
Land lease	%	2.0%	CAD 1,585,056	CAD 31,701		-	-
Property taxes	%	0.6%	CAD 1,585,056	CAD 9,510		-	-
Insurance premium	%	4.0%	CAD 1,585,056	CAD 63,402		-	-
Transmission line maintenance	%	3.0%	CAD 50,000	CAD 1,500		-	-
Parts and labour	kWh	2,189,606	CAD 0.169	CAD 370,243		-	-
Community benefits	-	0	CAD -	CAD -		-	-
Travel and accommodation	p-trip	5	CAD 3,000	CAD 15,000		-	-
General and administrative	%	5%	CAD 491,356	CAD 24,568		-	-
FC O&M	Cost	1	CAD 101,476	CAD 101,476		-	-
Contingencies	%	20%	CAD 491,356	CAD 98,271		-	-
Annual Costs - Total				CAD 715,672	100.0%		

Periodic Costs (Credits)		Period	Unit Cost	Amount	Interval Range	Unit Cost Range
Drive train	Cost	10 yr	CAD -	CAD -	-	-
Blades	Cost	15 yr	CAD -	CAD -	-	-
				CAD -	-	-
End of project life	Credit	-	CAD -	CAD -		*Go to GHG Analysis sheet*

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Table 24: Financial summary for hydrocarbon fuel cell "scenario 100" for 10 year term

RETScreen® Financial Summary - Wind Energy Project

Annual Energy Balance

Project name		Hol-DieselFC	Grid peak load	kW	565
Project location		Holman			
Renewable energy delivered	MWh	2,190	GHG analysis sheet used?	yes/no	No
Excess RE available	MWh	-			
Firm RE capacity	kW	-			
Grid type		Isolated-grid			

Financial Parameters

Avoided cost of energy	CAD/kWh	0.7239	Debt ratio	%	75.0%
RE production credit	CAD/kWh	-	Debt interest rate	%	8.0%
			Debt term	yr	10
			Income tax analysis?	yes/no	No
Energy cost escalation rate	%	2.0%			
Inflation	%	2.0%			
Discount rate	%	7.0%			
Project life	yr	10			

Project Costs and Savings

Initial Costs				**Annual Costs and Debt**		
Feasibility study	0.0%	CAD	-	O&M	CAD	715,672
Development	0.0%	CAD	-			
Engineering	0.0%	CAD	-	Debt payments - 10 yrs	CAD	326,802
RE equipment	85.9%	CAD	2,512,194	**Annual Costs - Total**	**CAD**	**1,042,474**
Balance of plant	4.5%	CAD	132,500			
Miscellaneous	9.5%	CAD	279,129	**Annual Savings or Income**		
Initial Costs - Total	100.0%	**CAD**	**2,923,823**	Energy savings/income	CAD	1,585,056
				Capacity savings/income	CAD	-
Incentives/Grants		CAD	-			
				Annual Savings - Total	**CAD**	**1,585,056**
Periodic Costs (Credits)						
Drive train		CAD	-			
Blades		CAD	-			
		CAD	-			
End of project life - Credit		CAD	-			

Financial Feasibility

			Calculate RE production cost?	yes/no	Yes
Pre-tax IRR and ROI	%	79.4%			
After-tax IRR and ROI	%	79.4%			
Simple Payback	yr	3.4	Project equity	CAD	730,956
Year-to-positive cash flow	yr	1.3	Project debt	CAD	2,192,867
Net Present Value - NPV	CAD	3,718,957	Debt payments	CAD/yr	326,802
Annual Life Cycle Savings	CAD	529,496	Debt service coverage	-	2.71
Profitability Index - PI	-	5.09	RE production cost	CAD/kWh	0.4853

Yearly Cash Flows

Year #	Pre-tax $	Cumulative $	Remaining Debt $	Net Value $
0	(730,956)	(730,956)	3,268,019	(3,998,975)
1	559,970	(170,986)	2,882,393	(3,053,378)
2	577,706	406,720	2,510,884	(2,104,164)
3	595,796	1,002,516	2,153,083	(1,150,567)
4	614,248	1,616,764	1,808,590	(191,826)
5	633,069	2,249,832	1,477,015	772,817
6	652,266	2,902,098	1,157,980	1,744,119
7	671,847	3,573,946	851,115	2,722,831
8	691,820	4,265,766	556,062	3,709,704
9	712,193	4,977,959	272,470	4,705,489
10	732,973	5,710,932	0	5,710,932
11	-	5,710,932	-	5,710,932
12	-	5,710,932	-	5,710,932
13	-	5,710,932	-	5,710,932
14	-	5,710,932	-	5,710,932
15	-	5,710,932	-	5,710,932
16	-	5,710,932	-	5,710,932
17	-	5,710,932	-	5,710,932
18	-	5,710,932	-	5,710,932
19	-	5,710,932	-	5,710,932
20	-	5,710,932	-	5,710,932
21	-	5,710,932		
22	-	5,710,932		
23	-	5,710,932		
24	-	5,710,932		
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50	-	5,710,932		

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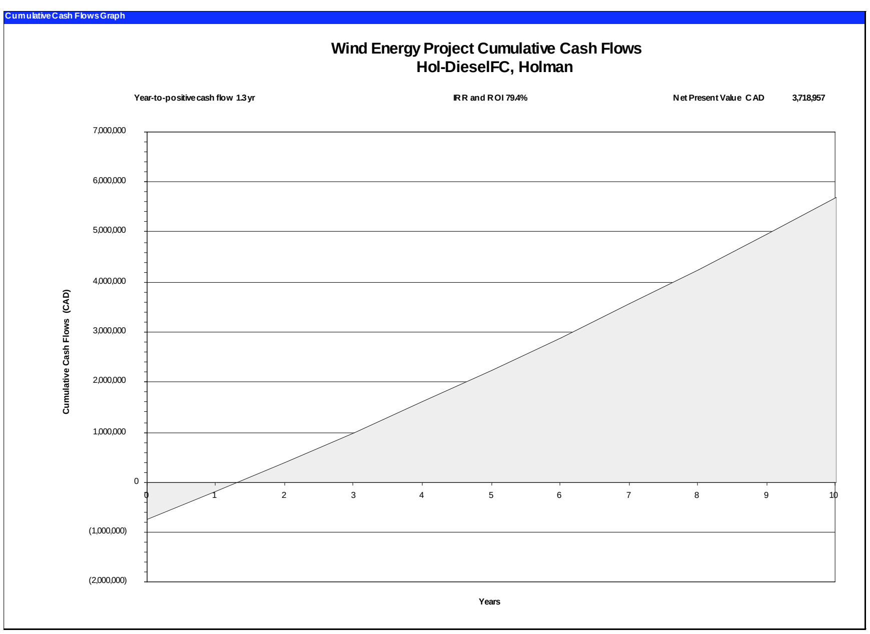

Figure 13: Cumulative cash flow for hydrocarbon fuel cells "scenario 100" for 10 year term.

Table 25. Cost analysis for hydrocarbon fuel cell “scenario 20” for 10 year term.

RETScreen ® Cost Analysis - Wind Energy Project

Type of project: Standard | Currency: Canada | Cost references: None

Initial Costs (Credits)	Unit	Quantity	Unit Cost	Amount	Relative Costs	Quantity Range	Unit Cost Range
Feasibility Study							
Other	Cost	0	CAD -	CAD -		-	-
Sub-total:				CAD -	0.0%		
Development							
Other	Cost	0	CAD -	CAD -		-	-
Sub-total:				CAD -	0.0%		
Engineering							
Other	Cost	0	CAD -	CAD -		-	-
Sub-total:				CAD -	0.0%		
Renewable Energy (RE) Equipment							
Wind turbine(s)	kW	131	CAD -	CAD -		-	-
Spare parts	%	3.0%	CAD -	CAD -		-	-
Transportation	turbine	3	CAD -	CAD -		-	-
FC	Cost	1	CAD 477,442	CAD 477,442		-	-
Sub-total:				CAD 477,442	70.3%		
Balance of Plant							
Wind turbine(s) foundation(s)	turbine	3	CAD -	CAD -		-	-
Wind turbine(s) erection	turbine	3	CAD -	CAD -		-	-
Road construction	km	1.00	CAD 40,000	CAD 40,000		-	-
Transmission line and substation	project	1	CAD 50,000	CAD 50,000		-	-
Control and O&M building(s)	building	1	CAD 35,000	CAD 35,000		-	-
Transportation	project	1	CAD -	CAD -		-	-
Transportation: FC	Cost	1	CAD 1,450	CAD 1,450		-	-
Sub-total:				CAD 126,450	18.6%		
Miscellaneous							
Training	p-d	10	CAD 1,020	CAD 10,200		-	-
Commissioning	p-d	3	CAD 1,487	CAD 4,460		-	-
Interest during construction	%	0.0%	CAD 603,892	CAD -		-	-
Contingencies	%	10%	CAD 603,892	CAD 60,389		-	-
Sub-total:				CAD 75,049	11.1%		
Initial Costs - Total				CAD 678,941	100.0%		

Annual Costs (Credits)	Unit	Quantity	Unit Cost	Amount	Relative Costs	Quantity Range	Unit Cost Range
O&M							
Land lease	%	2.0%	CAD 317,011	CAD 6,340		-	-
Property taxes	%	0.6%	CAD 317,011	CAD 1,902		-	-
Insurance premium	%	4.0%	CAD 317,011	CAD 12,680		-	-
Transmission line maintenance	%	3.0%	CAD 50,000	CAD 1,500		-	-
Parts and labour	kWh	437,921	CAD 0.169	CAD 74,049		-	-
Community benefits	-	0	CAD -	CAD -		-	-
Travel and accommodation	p-trip	5	CAD 3,000	CAD 15,000		-	-
General and administrative	%	5%	CAD 111,471	CAD 5,574		-	-
FC O&M	Cost	1	CAD 19,282	CAD 19,282		-	-
Contingencies	%	20%	CAD 111,471	CAD 22,294		-	-
Annual Costs - Total				CAD 158,621	100.0%		

Periodic Costs (Credits)		Period	Unit Cost	Amount	Interval Range	Unit Cost Range
Drive train	Cost	10 yr	CAD -	CAD -	-	-
Blades	Cost	15 yr	CAD -	CAD -	-	-
				CAD -	-	-
End of project life	Credit	-	CAD -	CAD -		*Go to GHG Analysis sheet*

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Table 26. Financial summary for hydrocarbon fuel cell “scenario 20” for 10 year term

RETScreen® Financial Summary - Wind Energy Project

Annual Energy Balance

Project name		Hol-DieselFC	Grid peak load	kW	113
Project location		Holman			
Renewable energy delivered	MWh	438	GHG analysis sheet used?	yes/no	No
Excess RE available	MWh	-			
Firm RE capacity	kW	-			
Grid type		Isolated-grid			

Financial Parameters

Avoided cost of energy	CAD/kWh	0.7239	Debt ratio	%	75.0%
RE production credit	CAD/kWh	-	Debt interest rate	%	8.0%
			Debt term	yr	10
			Income tax analysis?	yes/no	No
Energy cost escalation rate	%	2.0%			
Inflation	%	2.0%			
Discount rate	%	7.0%			
Project life	yr	10			

Project Costs and Savings

Initial Costs				**Annual Costs and Debt**		
Feasibility study	0.0%	CAD	-	O&M	CAD	158,621
Development	0.0%	CAD	-			
Engineering	0.0%	CAD	-	Debt payments - 10 yrs	CAD	75,887
RE equipment	70.3%	CAD	477,442	**Annual Costs - Total**	**CAD**	**234,507**
Balance of plant	18.6%	CAD	126,450			
Miscellaneous	11.1%	CAD	75,049	**Annual Savings or Income**		
Initial Costs - Total	100.0%	**CAD**	**678,941**	Energy savings/income	CAD	317,011
				Capacity savings/income	CAD	-
Incentives/Grants		CAD	-			
				Annual Savings - Total	**CAD**	**317,011**
Periodic Costs (Credits)						
Drive train		CAD	-			
Blades		CAD	-			
		CAD	-			
End of project life - Credit		CAD	-			

Financial Feasibility

			Calculate RE production cost?	yes/no	Yes
Pre-tax IRR and ROI	%	53.1%			
After-tax IRR and ROI	%	53.1%			
Simple Payback	yr	4.3	Project equity	CAD	169,735
Year-to-positive cash flow	yr	1.9	Project debt	CAD	509,206
Net Present Value - NPV	CAD	526,161	Debt payments	CAD/yr	75,887
Annual Life Cycle Savings	CAD	74,914	Debt service coverage	-	2.13
Profitability Index - PI	-	3.10	RE production cost	CAD/kWh	0.5551

Yearly Cash Flows

Year #	Pre-tax $	Cumulative $	Remaining Debt $	Net Value $
0	(169,735)	(169,735)	758,867	(928,602)
1	85,672	(84,064)	669,320	(753,384)
2	88,903	4,839	583,052	(578,213)
3	92,198	97,037	499,967	(402,930)
4	95,560	192,598	419,973	(227,375)
5	98,989	291,587	342,978	(51,391)
6	102,487	394,073	268,895	125,179
7	106,054	500,127	197,637	302,490
8	109,693	609,820	129,123	480,697
9	113,405	723,225	63,270	659,955
10	117,190	840,415	0	840,415
11	-	840,415	-	840,415
12	-	840,415	-	840,415
13	-	840,415	-	840,415
14	-	840,415	-	840,415
15	-	840,415	-	840,415
16	-	840,415	-	840,415
17	-	840,415	-	840,415
18	-	840,415	-	840,415
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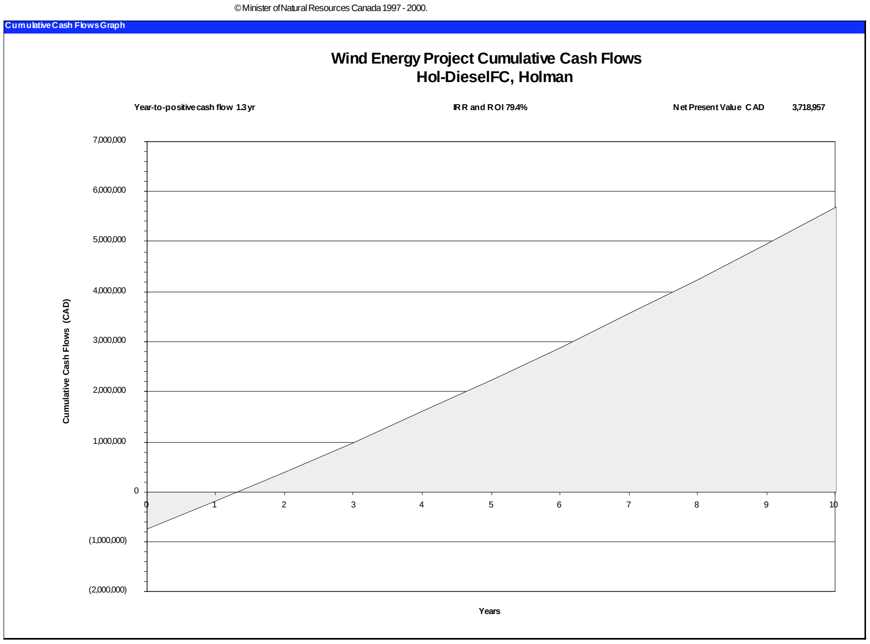

Figure 14: Cumulative cash flow for hydrocarbon fuel cells “scenario 20” for 10 year term.

App-6.2. Integrated Wind-Hydrogen-Fuel Cell “Zero Consumption”

Table 27. All data in this section is based on the AOC 15/50 performance.

RETScreen ® Equipment Data - Wind Energy Project

Wind Turbine Characteristics		Estimate	Notes/Range
Wind turbine rated power	kW	50	*See Product Database*
Hub height	m	25.0	6.0 to 100.0
Rotor diameter	m	15	7 to 72
Swept area	m_	177	35 to 4,075
Wind turbine manufacturer		Atlantic Orient	
Wind turbine model		AOC 15/50	
Energy curve data source	-	Custom	Weibull wind distribution
Shape factor	-	1.6	1.0 to 3.0

Wind Turbine Production Data

Wind speed (m/s)	Power curve data (kW)	Energy curve data (MWh/yr)
0	-	-
1	-	-
2	-	-
3	-	16.4
4	-	46.5
5	2.5	85.9
6	8.0	125.5
7	14.5	159.0
8	24.0	183.6
9	32.5	199.4
10	40.0	208.0
11	48.5	211.1
12	55.0	210.1
13	59.0	206.3
14	63.0	200.7
15	64.0	194.1
16	64.5	-
17	65.0	-
18	-	-
19	-	-
20	-	-
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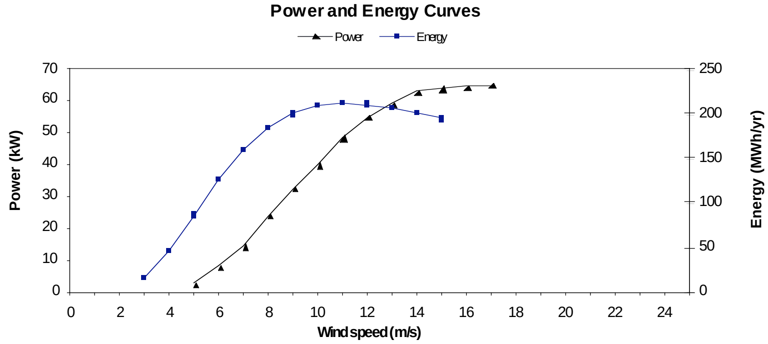
24	-	-
25	-	-

Power and Energy Curves



Return to Energy Model sheet

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Table 28: Cost analysis for “zero consumption” “scenario 100” for 20 year term.

RETScreen ® Cost Analysis - Wind Energy Project

Type of project: Standard | Currency: Canada | Cost references: None

Initial Costs (Credits)	Unit	Quantity		Unit Cost		Amount	Relative Costs	Quantity Range	Unit Cost Range
Feasibility Study									
Other	Cost	1	CAD	23,000	CAD	23,000		-	-
Sub-total:					CAD	23,000	0.2%		
Development									
Other	Cost	1	CAD	25,000	CAD	25,000		-	-
Sub-total:					CAD	25,000	0.2%		
Engineering									
Other	Cost	1	CAD	60,000	CAD	60,000		-	-
Sub-total:					CAD	60,000	0.5%		
Renewable Energy (RE) Equipment									
Wind turbine(s)	kW	1,150	CAD	2,430	CAD	2,794,500		-	-
Spare parts	%	3.0%	CAD	2,794,500	CAD	83,835		-	-
Transportation	turbine	23	CAD	25,000	CAD	575,000		-	-
FC/Electrolyzer/Storage	Cost	1	CAD	5,405,405	CAD	5,405,405		-	-
Sub-total:					CAD	8,858,740	77.5%		
Balance of Plant									
Wind turbine(s) foundation(s)	turbine	23	CAD	7,500	CAD	172,500		-	-
Wind turbine(s) erection	turbine	23	CAD	7,500	CAD	172,500		-	-
Road construction	km	1.00	CAD	40,000	CAD	40,000		-	-
Transmission line and substation	project	1	CAD	50,000	CAD	50,000		-	-
Control and O&M building(s)	building	1	CAD	35,000	CAD	35,000		-	-
Transportation	project	1	CAD	20,000	CAD	20,000		-	-
Transportation: FC etc.	Cost	1	CAD	41,000	CAD	41,000		-	-
Sub-total:					CAD	531,000	4.6%		
Miscellaneous									
Training	p-d	15	CAD	1,500	CAD	22,500		-	-
Commissioning	p-d	5	CAD	1,500	CAD	7,500		-	-
Interest during construction	%	0.0%	CAD	9,497,740	CAD	-		-	-
Contingencies	%	20%	CAD	9,497,740	CAD	1,899,548		-	-
Sub-total:					CAD	1,929,548	16.9%		
Initial Costs - Total					CAD	11,427,288	100.0%		

Annual Costs (Credits)	Unit	Quantity		Unit Cost		Amount	Relative Costs	Quantity Range	Unit Cost Range
O&M									
Land lease	%	2.0%	CAD	1,586,266	CAD	31,725		-	-
Property taxes	%	0.6%	CAD	1,586,266	CAD	9,518		-	-
Insurance premium	%	4.0%	CAD	1,586,266	CAD	63,451		-	-
Transmission line maintenance	%	3.0%	CAD	50,000	CAD	1,500		-	-
Parts and labour	kWh	2,191,278	CAD	0.020	CAD	43,826		-	-
Community benefits	-	0	CAD	-	CAD	-		-	-
Travel and accommodation	p-trip	5	CAD	3,900	CAD	19,500		-	-
General and administrative	%	5%	CAD	169,519	CAD	8,476		-	-
FC/Electrolyzer/Storage	Cost	1	CAD	172,973	CAD	172,973		-	-
Contingencies	%	20%	CAD	169,519	CAD	33,904		-	-
Annual Costs - Total					CAD	384,872	100.0%		

Periodic Costs (Credits)		Period		Unit Cost		Amount		Interval Range	Unit Cost Range
Drive train	Cost	10 yr	CAD	-	CAD	-		-	-
Blades	Cost	15 yr	CAD	-	CAD	-		-	-
					CAD	-		-	-
End of project life	Credit	-	CAD	-	CAD	-		*Go to GHG Analysis sheet*	

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Table 29: Financial summary for “zero consumption” “scenario 100” for 20 year term

RETScreen® Financial Summary - Wind Energy Project

Annual Energy Balance

Project name		Hol-AOC-17FC	Grid peak load	kW	565
Project location		Holman			
Renewable energy delivered	MWh	2,191	GHG analysis sheet used?	yes/no	Yes
Excess RE available	MWh	1,653	Net GHG emission reduction	t_{CO2}/yr	1,966
Firm RE capacity	kW	-	Net GHG emission reduction - 20 yrs	t_{CO2}	39,318
Grid type		Isolated-grid			

Financial Parameters

Avoided cost of energy	CAD/kWh	0.7239	Debt ratio	%	75.0%
RE production credit	CAD/kWh	0.008	Debt interest rate	%	8.0%
RE production credit duration	yr	10	Debt term	yr	20
RE credit escalation rate	%	0.0%			
GHG emission reduction credit	CAD/t_{CO2}	-	Income tax analysis?	yes/no	No
Avoided cost of excess energy	CAD/kWh	-			
Energy cost escalation rate	%	2.0%			
Inflation	%	2.0%			
Discount rate	%	7.0%			
Project life	yr	20			

Project Costs and Savings

Initial Costs				**Annual Costs and Debt**		
Feasibility study	0.2%	CAD	23,000	O&M	CAD	384,872
Development	0.2%	CAD	25,000			
Engineering	0.5%	CAD	60,000	Debt payments - 20 yrs	CAD	872,921
RE equipment	77.5%	CAD	8,858,740	**Annual Costs - Total**	**CAD**	**1,257,793**
Balance of plant	4.6%	CAD	531,000			
Miscellaneous	16.9%	CAD	1,929,548	**Annual Savings or Income**		
Initial Costs - Total	100.0%	**CAD**	**11,427,288**	Energy savings/income	CAD	1,586,266
				Capacity savings/income	CAD	-
Incentives/Grants		CAD	-	RE production credit income - 10 yrs	CAD	17,530
				Annual Savings - Total	**CAD**	**1,603,796**
Periodic Costs (Credits)						
Drive train		CAD	-			
Blades		CAD	-			
		CAD	-			
End of project life - Credit		CAD	-			

Financial Feasibility

			Calculate RE production cost?	yes/no	Yes
Pre-tax IRR and ROI	%	16.7%	Calculate GHG reduction cost?	yes/no	No
After-tax IRR and ROI	%	16.7%			
Simple Payback	yr	9.4	Project equity	CAD	2,856,822
Year-to-positive cash flow	yr	6.5	Project debt	CAD	8,570,466
Net Present Value - NPV	CAD	3,115,837	Debt payments	CAD/yr	872,921
Annual Life Cycle Savings	CAD	294,113	Debt service coverage	-	1.42
Profitability Index - PI	-	1.09	RE production cost	CAD/kWh	0.6006

Yearly Cash Flows

Year #	Pre-tax $	Cumulative $	Remaining Debt $	Net Value $
0	(2,856,822)	(2,856,822)	17,458,419	(20,315,241)
1	370,031	(2,486,791)	16,253,788	(18,740,579)
2	394,540	(2,092,251)	15,090,359	(17,182,610)
3	419,538	(1,672,713)	13,966,965	(15,639,678)
4	445,037	(1,227,676)	12,882,472	(14,110,147)
5	471,045	(756,630)	11,835,771	(12,592,401)
6	497,574	(259,056)	10,825,785	(11,084,841)
7	524,633	265,577	9,851,464	(9,585,887)
8	552,234	817,811	8,911,786	(8,093,975)
9	580,386	1,398,198	8,005,755	(6,607,557)
10	609,102	2,007,300	7,132,400	(5,125,100)
11	620,862	2,628,161	6,290,776	(3,662,615)
12	650,737	3,278,899	5,479,965	(2,201,067)
13	681,210	3,960,109	4,699,070	(738,961)
14	712,293	4,672,402	3,947,219	725,183
15	743,997	5,416,400	3,223,562	2,192,838
16	776,336	6,192,735	2,527,273	3,665,463
17	809,321	7,002,056	1,857,545	5,144,511
18	842,966	7,845,022	1,213,596	6,631,426
19	877,283	8,722,305	594,662	8,127,643
20	912,288	9,634,593	-	9,634,593
21	-	9,634,593		
22	-	9,634,593		
23	-	9,634,593		
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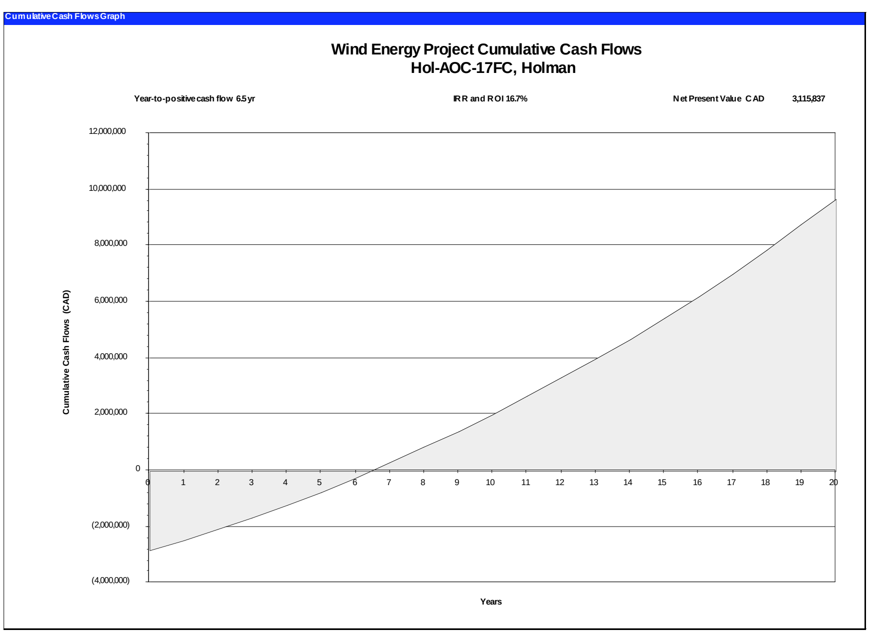

Figure15: Cumulative cash flow for “zero consumption” “scenario 100” for 20 year term.

Table 30: Cost analysis for “zero consumption” “scenario 20” for 20 year term.

RETScreen ® Cost Analysis - Wind Energy Project

Type of project:	Standard	Currency:	Canada	Cost references:	None

Initial Costs (Credits)	Unit	Quantity	Unit Cost	Amount	Relative Costs	Quantity Range	Unit Cost Range
Feasibility Study							
Other	Cost	1	CAD 23,000	CAD 23,000		-	-
Sub-total:				**CAD 23,000**	0.9%		
Development							
Other	Cost	1	CAD 25,000	CAD 25,000		-	-
Sub-total:				**CAD 25,000**	1.0%		
Engineering							
Other	Cost	1	CAD 60,000	CAD 60,000		-	-
Sub-total:				**CAD 60,000**	2.4%		
Renewable Energy (RE) Equipment							
Wind turbine(s)	kW	250	CAD 2,430	CAD 607,500		-	-
Spare parts	%	3.0%	CAD 607,500	CAD 18,225		-	-
Transportation	turbine	5	CAD 25,000	CAD 125,000		-	-
FC/Electrolyzer/Storage	Cost	1	CAD 972,973	CAD 972,973		-	-
Sub-total:				**CAD 1,723,698**	68.9%		
Balance of Plant							
Wind turbine(s) foundation(s)	turbine	5	CAD 7,500	CAD 37,500		-	-
Wind turbine(s) erection	turbine	5	CAD 7,500	CAD 37,500		-	-
Road construction	km	1.00	CAD 40,000	CAD 40,000		-	-
Transmission line and substation	project	1	CAD 50,000	CAD 50,000		-	-
Control and O&M building(s)	building	1	CAD 35,000	CAD 35,000		-	-
Transportation	project	1	CAD 20,000	CAD 20,000		-	-
Transport: FC etc.	Cost	1	CAD 7,500	CAD 7,500		-	-
Sub-total:				**CAD 227,500**	9.1%		
Miscellaneous							
Training	p-d	15	CAD 1,500	CAD 22,500		-	-
Commissioning	p-d	5	CAD 1,500	CAD 7,500		-	-
Interest during construction	%	0.0%	CAD 2,059,198	CAD -		-	-
Contingencies	%	20%	CAD 2,059,198	CAD 411,840		-	-
Sub-total:				**CAD 441,840**	17.7%		
Initial Costs - Total				**CAD 2,501,038**	100.0%		

Annual Costs (Credits)	Unit	Quantity	Unit Cost	Amount	Relative Costs	Quantity Range	Unit Cost Range
O&M							
Land lease	%	2.0%	CAD 314,591	CAD 6,292		-	-
Property taxes	%	0.6%	CAD 314,591	CAD 1,888		-	-
Insurance premium	%	4.0%	CAD 314,591	CAD 12,584		-	-
Transmission line maintenance	%	3.0%	CAD 50,000	CAD 1,500		-	-
Parts and labour	kWh	434,578	CAD 0.020	CAD 8,692		-	-
Community benefits	-	0	CAD -	CAD -		-	-
Travel and accommodation	p-trip	5	CAD 3,900	CAD 19,500		-	-
General and administrative	%	5%	CAD 50,455	CAD 2,523		-	-
FC/Electrolyzer/Storage	Cost	1	CAD 30,270	CAD 30,270		-	-
Contingencies	%	20%	CAD 50,455	CAD 10,091		-	-
Annual Costs - Total				**CAD 93,339**	100.0%		

Periodic Costs (Credits)		Period	Unit Cost	Amount		Interval Range	Unit Cost Range
Drive train	Cost	10 yr	CAD -	**CAD -**		-	-
Blades	Cost	15 yr	CAD -	**CAD -**		-	-
				CAD -		-	-
End of project life	Credit	-	CAD -	**CAD -**		*Go to GHG Analysis sheet*	

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Table 31: Financial summary for “zero consumption” “scenario 20” for 20 year term

RETScreen® Financial Summary - Wind Energy Project

Annual Energy Balance

Project name		Hol-AOC-17FC	Grid peak load	kW	113
Project location		Holman			
Renewable energy delivered	MWh	435	GHG analysis sheet used?	yes/no	Yes
Excess RE available	MWh	401	Net GHG emission reduction	t_{CO2}/yr	390
Firm RE capacity	kW	-	Net GHG emission reduction - 20 yrs	t_{CO2}	7,798
Grid type		Isolated-grid			

Financial Parameters

Avoided cost of energy	CAD/kWh	0.7239	Debt ratio	%	75.0%
RE production credit	CAD/kWh	0.008	Debt interest rate	%	8.0%
RE production credit duration	yr	10	Debt term	yr	20
RE credit escalation rate	%	0.0%			
GHG emission reduction credit	CAD/t_{CO2}	-	Income tax analysis?	yes/no	No
Avoided cost of excess energy	CAD/kWh	-			
Energy cost escalation rate	%	2.0%			
Inflation	%	2.0%			
Discount rate	%	7.0%			
Project life	yr	20			

Project Costs and Savings

Initial Costs				**Annual Costs and Debt**		
Feasibility study	0.9%	CAD	23,000	O&M	CAD	93,339
Development	1.0%	CAD	25,000			
Engineering	2.4%	CAD	60,000	Debt payments - 20 yrs	CAD	191,052
RE equipment	68.9%	CAD	1,723,698	**Annual Costs - Total**	**CAD**	**284,391**
Balance of plant	9.1%	CAD	227,500			
Miscellaneous	17.7%	CAD	441,840	**Annual Savings or Income**		
Initial Costs - Total	100.0%	**CAD**	**2,501,038**	Energy savings/income	CAD	314,591
				Capacity savings/income	CAD	-
Incentives/Grants		CAD	-	RE production credit income - 10 yrs	CAD	3,477
				Annual Savings - Total	**CAD**	**318,068**
Periodic Costs (Credits)						
Drive train		CAD	-			
Blades		CAD	-			
		CAD	-			
End of project life - Credit		CAD	-			

Financial Feasibility

			Calculate RE production cost?	yes/no	Yes
Pre-tax IRR and ROI	%	9.4%	Calculate GHG reduction cost?	yes/no	No
After-tax IRR and ROI	%	9.4%			
Simple Payback	yr	11.1	Project equity	CAD	625,259
Year-to-positive cash flow	yr	10.4	Project debt	CAD	1,875,778
Net Present Value - NPV	CAD	155,514	Debt payments	CAD/yr	191,052
Annual Life Cycle Savings	CAD	14,679	Debt service coverage	-	1.20
Profitability Index - PI	-	0.25	RE production cost	CAD/kWh	0.6929

Yearly Cash Flows

Year #	Pre-tax $	Cumulative $	Remaining Debt $	Net Value $
0	(625,259)	(625,259)	3,821,043	(4,446,302)
1	38,102	(587,157)	3,557,391	(4,144,548)
2	42,616	(544,541)	3,302,757	(3,847,298)
3	47,220	(497,322)	3,056,885	(3,554,206)
4	51,916	(445,406)	2,819,527	(3,264,933)
5	56,705	(388,701)	2,590,440	(2,979,141)
6	61,591	(327,110)	2,369,389	(2,696,499)
7	66,574	(260,535)	2,156,144	(2,416,679)
8	71,657	(188,878)	1,950,481	(2,139,359)
9	76,842	(112,036)	1,752,182	(1,864,218)
10	82,130	(29,906)	1,561,035	(1,590,941)
11	84,048	54,142	1,376,833	(1,322,691)
12	89,550	143,692	1,199,375	(1,055,682)
13	95,162	238,854	1,028,464	(789,610)
14	100,886	339,740	863,909	(524,169)
15	106,725	446,465	705,526	(259,061)
16	112,680	559,146	553,132	6,013
17	118,755	677,901	406,552	271,348
18	124,951	802,852	265,614	537,238
19	131,271	934,123	130,151	803,972
20	137,718	1,071,841	-	1,071,841
21	-	1,071,841		
22	-	1,071,841		
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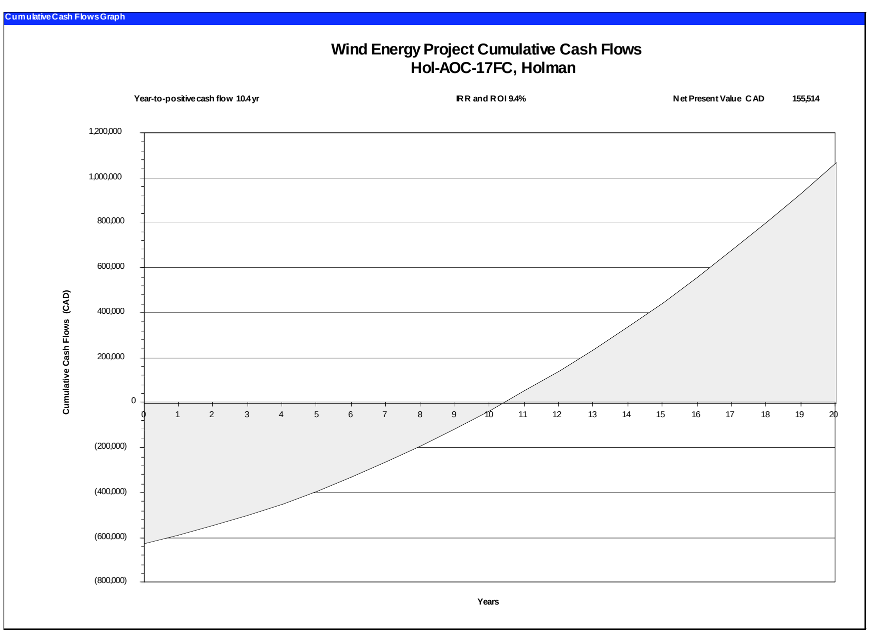

Figure 16: Cumulative cash flow for “zero consumption” “scenario 20” for 20 year term.