Hydrogen Student Design Contest 2017

Clarington Energy Business Park Facility

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Final Design

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1 Executive Summary

The proposed location for the power-to-gas facility is The Clarington Energy Park, Bowmanville, Durham Region, Ontario, Canada. The park is immediately south of Hwy 401 and is in close proximity to the Darlington Nuclear Generating Station. This location was selected as it is in an industrial area with the appropriate zoning and centred in a dense and growing population of future H\textsubscript{2} users.

The proposed facility will make use of a 1500 kV powerline, one electrical substation, one 6000 L water storage tank, thirty-nine Hydrogenics HyLYZER 600 series electrolyzers, four 5000 kg liquid H\textsubscript{2} storage tanks, and six cryogenic tankers trucks to produce and deliver H\textsubscript{2} to consumers. Through analysis, it was determined the total daily demand for H\textsubscript{2} will be 8596 kg and total storage required is 12 695 kg/day. The Lakeshore East GO train route, Metrolinx East bus route, personal H\textsubscript{2} automobiles, and direct injection into Enbridge’s local natural gas main were all considered in meeting part of Durham Region’s H\textsubscript{2} infrastructure demand. Electrical power required for the electrolyzers will come from the grid supplied by Ontario’s low GHG-emitting generation plants.

90% of Ontario Electricity Grid is powered by low GHG-emitting energy sources such as nuclear at 55% and hydroelectric generation at 27%, which are primarily base load components of the supply. The remaining generation comes from wind, biofuel, solar, and then natural gas for high demand and makeup generation. Due to this high percentage of base load generation and contracted supply agreements over market price, the excess electricity is sold in the evenings and weekends to neighbouring jurisdictions at less than one cent per kWh or frequently at negative pricing. These losses are added to the Ontario ratepayers’ bills as a global adjustment cost.

This situation of oversupply of baseload allows for a very low allocation of cost of electricity at 1.21 cents/kWh that is higher than the average price and reduces the expense allocated to the ratepayers. Running the hydrogen production facility only when there is overabundance of clean electricity generation allows for emission free hydrogen generation at low cost. The cost of electricity is a major contributor to the operation of the hydrolyzer and the liquefiers and therefore a sensitive component to the cost structure of hydrogen. The cost of hydrogen is calculated to be US$ 5.90/kg providing a 41% margin if sales can be made at the US$ 10/kg level. This costing is applicable for the transportation pathways of trains, buses, and cars due to the high efficiency of fuel cells and the relative high price of transportation fossil fuels. It is not economical to sell hydrogen at natural gas prices due to the low price of natural gas.

The proposed facility has many possible failure modes that were investigated. Proper steps were taken to ensure this facility mitigated any potential risks identified in the design process. The FMEA analysis identified the largest risks associated with the design, one being overpressure. It also laid out the mitigation efforts used to minimize those risks, for the same example being pressure spill-back loops. Since hydrogen and fuel cell technology are newer, they have their own standards and codes such as CAN 1784-000, the Canadian Hydrogen Installation Code. It is important that the safety precautions laid out by standards such as these are followed to ensure smooth operation as well as maintenance for this facility.

Through the construction and implementation of this system the owner/operator and the Province of Ontario have an opportunity to invest in a sustainable technology capable of mitigating and reducing the province’s GHG emissions, keeping generated power in Ontario, reducing the cost of electricity, creating future jobs in Ontario and supporting a sustainable hydrogen economy.
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3 Introduction

Ontario’s vision of how electricity is produced, how our waste is managed, and how our sustainable growth is facilitated has shifted in recent years. This shift can be attributed to the global perception of climate change and commitments our legislation has made to reduce the effects of climate change on Ontarians and others around the world.

One of the major drivers of climate change and measures used to forecast the effects on society is the volume of GHGs) in the atmosphere for which humans are the largest contributors. Countries around the globe and the Province of Ontario have committed to reducing the GHGs released into the atmosphere to prevent and mitigate climate change. Although challenging, it is possible to reduce GHG emission and reverse the effects of climate change by implementing sustainable technologies such as electric vehicles and substituting them for our typical everyday commodities. Although these technologies do exist, the biggest challenge is overcoming not only the financial barrier, but the social-function barrier as well. In simple terms, these new technologies are typically expensive to own and operate and do not necessarily function in modern society.

Overcoming these barriers is the first step to meeting our environmental commitments. Power-to-gas is an emerging sustainable technology which utilizes electricity from the grid or renewable power generating sources and uses it to create hydrogen (H\textsubscript{2}) via a chemical process called electrolysis as illustrated in Figure 1. This technology is considered an energy storage method as electrical energy is converted into H\textsubscript{2} which can be used to support a number of different applications requiring power and a hydrogen based economy.

![Figure 1. Process Flow Diagram for the Clarington Energy Business Park Facility.](image-url)
4 Site Selection

The site selected will be located within the Clarington Energy Business Park (CEBP) at 1845 MegaWatt Drive in Clarington Township, Durham Region, Ontario, Canada. Figure 2 is a map of the area with the respective areas of interest labelled accordingly. Distances were approximated using Google Map [1].

<table>
<thead>
<tr>
<th>#</th>
<th>Feature</th>
<th>Distance</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>CEBP</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Darlington Nuclear Generating Facility</td>
<td>&lt; 4 km</td>
</tr>
<tr>
<td>3</td>
<td>Lake Ontario</td>
<td>&lt; 2 km</td>
</tr>
<tr>
<td>4</td>
<td>High Voltage Electrical Lines</td>
<td>&lt; 1 km</td>
</tr>
<tr>
<td>5</td>
<td>Hwy 418 Toll Road</td>
<td>&lt; 2 km</td>
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<tr>
<td>6</td>
<td>Hwy 401</td>
<td>&lt; 2 km</td>
</tr>
<tr>
<td>7</td>
<td>Proposed GO Train Terminus</td>
<td>&lt; 9 km</td>
</tr>
</tbody>
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Figure 2. Site map with features of interest. Exert from Schedule A [2].
This 24.28 acre site was selected due to the following characteristics:

- Located within an area actively promoting energy projects;
- Existing industrial infrastructure;
- Located in area with existing power generation professionals, trades persons, and other expertise;
- Proximity to markets and resources outlined in Table 1.

**Table 1: Distances to features of interest and their significance**

<table>
<thead>
<tr>
<th>#</th>
<th>Features of Interest</th>
<th>Distance</th>
<th>Significance</th>
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<tbody>
<tr>
<td>1</td>
<td>CEBP</td>
<td></td>
<td>Location. Space for Generation</td>
</tr>
<tr>
<td>2</td>
<td>Darlington Nuclear Generating Facility</td>
<td>&lt; 4 km</td>
<td>Source of Electricity</td>
</tr>
<tr>
<td>3</td>
<td>Lake Ontario</td>
<td>&lt; 2 km</td>
<td>Generation from wave and wind</td>
</tr>
<tr>
<td>4</td>
<td>High Voltage Electrical Lines</td>
<td>&lt; 1 km</td>
<td>Possible source of Electricity</td>
</tr>
<tr>
<td>5</td>
<td>Hwy 418 Toll Road</td>
<td>&lt; 2 km</td>
<td>Major Traffic Artery. H₂ for cars</td>
</tr>
<tr>
<td>6</td>
<td>Hwy 401</td>
<td>&lt; 2 km</td>
<td>Major Traffic Artery. H₂ for cars</td>
</tr>
<tr>
<td>7</td>
<td>Proposed GO Train Terminus</td>
<td>&lt; 9 km</td>
<td>H₂ for Train refueling</td>
</tr>
</tbody>
</table>

It is important to acknowledge that the project will be, “located on the Traditional Territory of the Mississaugas of Scugog Island First Nation. We are proud to acknowledge the lands and People of the Traditional Territories of the Mississaugas.” [3].

Communication on Nov 17, 2017 with the Manager of Business Development for the Clarington Board of Trade & Office of Economic Development [4] confirmed the site is available and an energy project located on this site would be congruent with current zoning by-laws. A rezoning would need to take place as there is currently a hold for redevelopment. Removal of the ‘Holding’, along with approval of the site plan. The site cost, assessed at the upper limit provided is approximately US$ 3.92 M.

The CEBP currently has many sites that are not being utilized. This is advantageous should it be determined that more land is required for the installation of renewable generation to meet electrical demands.
5 Design Data & Equipment Drawings

5.1 Power-to-Gas System Inputs (Electrical Power Supplies)

The following are the four power-to-gas system inputs:

1. 500 MWh/day surplus renewable power from Ontario’s electrical grid purchased during
   hours of surplus production based on analysis of Ontario’s Independent Electricity System
   Operator (IESO) power data - data directory [5];
2. Installed renewable energy systems (wave, wind, or solar); Optional for additional power
   and phase-in responding to growing demand or expected reduction in generating capacity
   available on grid;
3. Municipal water from Durham Region water main system;
4. Lake Ontario water with additional water treatment equipment (optional).

5.2 Power-to-Gas System Outputs (Hydrogen Gas Demands)

For this project, four major systems outputs were identified, and they are described in the following
sections.

5.2.1 GO Train (Lakeshore East Route)

The GO Train Lakeshore East route currently extends from Union Train Station located in
downtown Toronto, ON to Oshawa Terminal located in Oshawa, ON. This train route is planned
 to extend to Bowmanville, ON and to be in service by 2024 [6]. In addition, the province’s Minister
of Transportation, Del Duca, recently facilitated meetings with other provincial and federal
officials as well as international figures to discuss the viability of H$_2$ GO Trains [7]. This extension
is an opportunity to implement hydrogen infrastructure. We are proposing the transition of
Lakeshore East trains from diesel to compressed H$_2$.

The following method was used to approximate the mass of hydrogen (per day) required to support
the Lakeshore east route. First, the daily hydrogen requirement of a fuel cell train (Alstrom iLint
Coradia) was determined to be approximately 193 kg [8]. Next, the average distance of Coradia
tank was determined to be 700 km [9]. The distance between the proposed Bowmanville terminal
and Union Station was estimated to be 70 km [10]. Using this information, it was determine 19.3
kg are required per one way trip and total of **1930 kg/day** required for train route making
approximately 100 trips per day [11].

5.2.2 GO Bus/Metrolinx (Route 90 & 91)

In addition to the GO Train, the GO Bus/Metrolinx service in the area is also an opportunity to
implement a hydrogen infrastructure. For this demand, we calculated the mass of hydrogen which
would be required to support this bus service using the following methodology. First, the fuel
economy of a hydrogen fuel cell bus was located and determined to be 15.48 kg/100 km [12]. The
average distance travelled on these routes is approximately 108 km/trip [13]. The buses on this
route execute approximately 40 trips per day [14]. From this information, the total H$_2$ required was
calculated to be **670 kg/day**.

5.2.3 Hydrogen Fuel Cell Vehicles

Fuel Cell vehicles (FCV) are a possible replacement for gasoline fueled vehicles for a number of
reasons. One dominating factor is that a hydrogen powered vehicle can be refueled in similar
fashion and time to a gasoline powered vehicle. A tank of H\(_2\) will provide approximately the same distance as a comparable tank of gasoline therefore requiring equivalent refueling stops.

For comparison 1 kg of hydrogen provides about the same energy as a gallon of gasoline [13]. Fuel cell vehicles are about two and a half times more energy efficient than gasoline powered vehicles so an 11 lb. (5 kg) tank of H\(_2\) in a midsize car has a 311 mile (500 km) range [14] [15].

The average mileage for a new internal combustion engine vehicle (ICV) in 2015 was 24.8 mpg and with the average price of gas at $2.50/gallon in California the cost of a 311 mile (500 km) trip would cost US$ 31.31 [16]. For a FCV with an 11 lb. (5 kg) tank to travel the same 311 miles (500 km) the hydrogen would need to cost US$ 2.84/lb. (US$ 6.26 /kg). The retail price of hydrogen in California in the 3\(^{RD}\) Quarter of 2016 ranged from US$ 12.85/kg to US$ 16.78/kg [17].

A model for the growth of H\(_2\) vehicles in Ontario is estimated to be between 32,336 and 152,760 by 2020. The 3 scenarios are a (1) conservative growth assumption, (2) moderate growth, and (3) optimistic growth based on available fuel cell vehicles and new car sales in Ontario [B10] (reference Tables 1 & 2)

Extrapolating the hydrogen demand for the Clarington Energy Park based on 2016 population data the Oshawa and Clarington residences would be a reasonable drive to fill up their fuel cell vehicles. Oshawa and Clarington have 379,848 and 92,013 people respectively which represents approximately 3.5% of Ontario’s 13,448,494 population. This would be equivalent to between 714 and 3,375 kg of hydrogen per day by 2020 to meet demand [18]. For our sizing calculations of 2261 kg for a moderate volume. The 2261 kg of hydrogen per day equates to 452 vehicles with a 5 kg tank. Over a 12 hour period that would be 37 cars per hour.

A refueling station in Clarington to service this demand would require six H35/H70 dispensing units to handle 72 vehicles assuming an average 5 min refueling time. This number of dispensers can accommodate early adopters who may refuel at half a tank as has been shown in California where the average fill up is only 2.67 kg indicating they do not yet trust the vehicle range [17].

5.2.4 Enbridge Natural Gas Pipeline

Finally, introducing H\(_2\) gas into the natural gas line is an opportunity to support a hydrogen infrastructure. In Canada, a bulk of 5% H\(_2\) may be introduced into a natural gas line at any one time [18]. With this information, we propose introducing a continuous 1% H\(_2\) within local bounds (Durham Region) and supplying additional percentage based on surpluses observed during H\(_2\) production. The following methodology was used to determine the mass of H\(_2\) demand required per day to support this opportunity. The total maximum mass of natural gas consumed in Durham Region was determined to be 230,186 kg/day (month of February) [15]. Introducing a maximum 5% H\(_2\) with this mass of natural gas resulted in an overall maximum demand of 11,509 kg/day. Since a continuous 1% in the natural gas line was proposed, a corresponding approximation for this value was determined to be 2302 kg/day. To summarize, we proposed supplying a consistent 2302 kg/day of H\(_2\) into the natural gas line will keeping a maximum of 11,509 kg/day as an opportunity to supply higher percentage when surplus H\(_2\) production is observed.

To calculate the total H\(_2\) demand, a low, moderate and high estimate calculation was completed to account for variation in each demand and the uncertainty present in their calculation. The estimate calculations yielded the following results, 5616 kg/day (low), 7163 kg/day (moderate), and 8277 kg/day (high). The moderate estimate is carried at the total daily H\(_2\) demand (kg/day). A 20% buffer is added to the high estimate total as a safe-guard to ensure no shortage of H\(_2\) is experienced
5.3 Power-to-Gas System for Hydrogen Production

A sufficient amount of H$_2$ must be produced to reliably meet the system demand. To reiterate, the total expected H$_2$ demand is 8596 kg/day. This project proposes the production of H$_2$ gas via electrolysis supplied by surplus non-GHG electrical power available on Ontario’s electrical grid. To verify a sufficient amount of power is available to meet this demand, a significant amount of analysis pertaining to Ontario’s electrical grid was completed. To summarize analysis findings of Ontario’s Independent Electricity System Operator (IESO) power data, non-GHG surplus power is typically available in the early hours of the morning (24h00 to 08h00) and the late hours of the night (22h00 to 23h00) [19]. The average surplus for a 24 hour period ranged from 1351 MW to 287 MW [19] in the province of Ontario. Based on this, a conservative 500 MWh of reliable electrical power supply for the proposed system was determined. This was based on the scale local demand versus Ontario demand and the observed fluctuation in the hourly non-GHG supply versus consumer demand data. To simplify, 500 MWh of electrical power from Ontario’s electrical grid will be utilized by our system on a daily basis to produce H$_2$ to meet system demands.

For the purpose of calculation, an electrolyzer was selected to determine the amount of H$_2$ which could be produced using the 500 MWh of energy. This project proposes the use of a series of Hydrogenic’s Hylzer 600 Series electrolyzers. Each electrolyzer requires an input of 3 MW and can produce approximately 1350 kg of H$_2$ per day [8]. More information pertain to the electrolyzer will be provided in the ‘system equipment’ section below. Based on the available 500 MWh and the total daily demand, it was determined that a total of thirty-nine electrolyzer units (39 MW) are required as illustrated in Figure 3. Of the thirty-nine units, thirty-three will be used to produce H$_2$ to meet daily demand, while the remaining six are on warm standby and used to produce additional hydrogen or utilized during maintenance of other electrolyzers (see operations and maintenance section for more). The amount of land required to operate a plant of this size is approximately 55000 m$^2$ which is well within the proposed land allotted (24.28 acres or 98250 m$^2$).

![Figure 3. Isometric View of the Clarington Energy Business Park Power-to-Gas Facility.](image-url)
5.3.1 Power-to-Gas Water Purification/Filtration

A substantial amount of purified water must be supplied to support the proposed number of electrolyzer units. In the case of the proposed Hydrogenics HyLYZER 600 Series Electrolyzer, each require 1.4 L/Nm$^3$ of H$_2$ produced [8]. Each electrolyzer is rated to produce 620 Nm$^2$/h [8]. Therefore, it was determined each electrolyzer requires 868 L/h during normal operation. As a result, a total flow rate of purified water to support the proposed system is 33 852 L/h or 9.40 L/s. This project proposes the use of municipal water to achieve this flow rate. Detail pertaining to filtration/purification system equipment can be found below in the system equipment section.

5.3.2 Power-to-Gas System Storage

For the proposed project, the storage of H$_2$ is based on the inputs and outputs of the system. The storage system must be able to handle H$_2$ supply/demand fluctuations. To reiterate, the total daily H$_2$ demand is approximately 8596 kg/day. To meet this demand reliably, a mass of hydrogen exceeding the daily demand (within reason) should be produced and stored. A calculation similar to that of demand was completed to determine the total storage required for the system. In this case, a larger H$_2$ demand for the natural gas opportunity was assumed. A continuous 1% H$_2$ supply in the local natural gas line is proposed. For the purpose of this calculation, a 2% supply was assumed as well as another 20% buffer was added as a safe-guard to account for fluctuation in hydrogen production via electrolysis. This project proposed the use of four 5000 kg liquid H$_2$ tanks, one of which will be placed on warm standby for operation during tank maintenance and abnormal conditions.

5.3.3 Power-to-Gas System Distribution/Transportation

Distribution of hydrogen is largely dependent on the demand being supplied. This project proposed the supply of four demands, The GO Train, The Metrolinx East Bus Route, Hydrogen Powered Vehicles, and 1% Hydrogen concentration in local natural gas lines. To meet these demands reliably, a plan must be implemented for each. To support the GO Train, we proposed an onsite hydrogen fueling station for the trains of that route. This fueling station would be supplied by a fleet of six cryogenic & transport trucks. Similarly, a fueling station at a location of Metrolinx choosing is proposed. This fueling station would also be supported by transport of fuel from the proposed facility. For hydrogen powered personal automobiles, a series of fueling stations supported by the truck fleet are proposed in the major cities and towns of Durham Region. The first of the series would be Bowmanville, ON (approximately 10 km) and Oshawa, ON (approximately 15 km). Finally, to introduce 1% H$_2$ into the local natural gas pipelines, a direct connection to the facilities storage system is proposed.
5.4 Power-to-Gas Major System Equipment & Components

5.4.1 Power Supply

As discussed in the siting section (above), the proposed power-to-gas facility will be located a short distance from Ontario Power Generation’s Darlington Nuclear Generating Station. This is beneficial because the nuclear facility has its own switch yard (operated by Hydro One) and high voltage transmission lines (approximately 3 km), illustrated in Figure 4. The proposed facility has the opportunity to take advantage of this benefit. Hydro One (a power distribution company) owns and operates a 500 kV (high voltage) transmission line directly adjacent to the proposed facility [20]. These transmission lines may be used to deliver surplus electrical power on the grid to our facility to produce H₂ and operating other equipment such as pumps for the water purification/storage system and compressors for the H₂ storage system.

5.4.2 Power Conversion

Equipment to convert high voltage electrical power to that of the operating conditions of each electrolyzer will be required. As discussed above, this project proposes the use of 39 Hydrogenics HyLYZER 600 Series Electrolyzers. Each of this electrolyzers require an input power of 3 MW [8]. Due to this, transformers and electrical buses via a substation would be required to reduce the voltage of the input power to the electrolyzer operating voltage and distribute the required power to each electrolyzer unit.

5.4.3 Water Pumps

The project proposes the use of municipal water for consumption in the electrolyzer to produce H₂. Pumps must be rated for a flow rate greater than that of the rate of water consumption for all 39 electrolyzer units in full peak operation. This project proposed the use of three pumps to supply adequate water to the facility. At this time the operating pressure of the proposed system is not
fully understood and therefore the size of pump and the supplier of the pump has yet to be determined.

5.4.4 Water Purification & Storage

This project proposes the use of a water storage tank with a capacity of 6000 L (approximately 7 hr. supply). Municipal water will be pumped into the tank as required to stay above a minimum volume of 70%. Volume and flow of water released depends on the operation of the system. Each electrolyzer is equip with a water purification system to treat the water before it is consumed via electrolysis.

5.4.5 Electrolyzers

Thirty-nine Hydrogenics Hylzer 600 Series Electrolyzers are required (shown in Figure 6). The maintenance of each electrolyzer will be contracted to Hydrogenics (Mississauga, ON). Specifications pertaining to the selected electrolyzer can be found on the Hydrogenics website or in reference [B3].

![Figure 6. Hydrogenics Hylzer 600 Electrolyzer Unit.](image)

One of the most heavily weighted factors used for selecting an electrolyzer provider were the ratio of the production of hydrogen to electricity input for each electrolyzer, the inclusion of balance of system components, and low capital expenditure. Hydrogenics, a local electrolyzer company located in Mississauga Ontario, provides a more affordable business that can also provide economic growth in Ontario while reducing CAPEX and OPEX compared to other commercial electrolyzers. The HyLYZER 600 by Hydrogenics is able to produce 1350 kg/day at a rate of 53 kWh/kg with an efficiency of 75% HHV [15]. The input power required is 3.0 MW that is provided from clean electricity from the grid, as well as an output pressure of 30 bar [15]. Each container comes with controls, gas management, water filtration, cooling apparatus, and 4 stacks [5].

To minimize construction costs of the facility as well as to reduce the likelihood of hydrogen gas accumulation in the event of a leak, H₂ production will take place separated containers with no facility built around them. A typical container block by Hydrogenics is 25ft by 10ft and can be placed in an outdoor environment. Thirty-nine electrolyzers would be purchase to meet our weekly demand for hydrogen, while six electrolyzers are backup in case some units are not operational, or the capacity is needed.

5.4.6 Hydrogen Storage Tanks

The project proposes the use of four 5000 kg liquid H₂ storage tanks with a total capacity of 20,000 kg, shown in Figure 7. These tanks will be used to store the required H₂ for normal operation with a significant additional margin for abnormal or ‘cliff edge’ operation. Additional storage, though adding cost, gives operators the advantage of system reliability and operational safety.
during abnormal events. It is proposed that three of four storage tanks will be used during daily operation and the final will be kept on warm standby; only operated during abnormal or opportune times. Retaining 1 tank on reserve is advantageous when considering the operation and maintenance schedules of these components. If a failure were to occur, the reserve tank could be introduced into the system while the failure is addressed and corrected or while maintenance is completed.

**Figure 7. Hydrogen Storage Tanks**

5.4.7 O\textsubscript{2} Storage Tank

Typically, electrolyzers exhaust O\textsubscript{2} following the electrolysis process, but it is believed that if this O\textsubscript{2} was captured and stored it could be sold to a separate set of end-users. This project proposes a future investment in the storage of electrolysis reaction by-product O\textsubscript{2} as another possible revenue stream for the facility.

5.4.8 Hydrogen Transportation & Distribution

This project proposed the use of liquid H\textsubscript{2} capable tank trucks for the transport and distribution of H\textsubscript{2} fuel to the Metrolinx and personal automobile fueling stations. Typical H\textsubscript{2} tank trucks (as shown in Figure 8) can hold approximately 4565 kg of fuel per load [21]. It is proposed that a total of six trucks would initially be required to successfully transport the produced H\textsubscript{2} to the customers outlined above. The purchase of additional trucks (like the stand-by H\textsubscript{2} storage tank) presents an additional cost but is advantageous in operational reliability. As for the injection of H\textsubscript{2} into the existing natural gas line, a short piping system is required to reach the nearest gas main. The injection of H\textsubscript{2} gas into the pipeline will be monitored to ensure 1% is achieved at all times. It is proposed that if H\textsubscript{2} storage is at capacity, additional H\textsubscript{2} gas (up to the industry standard) of 5% will be introduced [18].

**Figure 8. Hydrogen Transport Truck**
5.4.9 **Hydrogen Fueling Stations**

The implementation of fueling stations is beyond the scope of this project which aims to implement a H$_2$ production facility. That is, the implementation of fueling stations is not considered in the cost analysis (or budget) of this project. H$_2$ customers (wholesalers), must implement the infrastructure necessary to store their required H$_2$ onsite to sell to civilian customers. However, partnerships with the facility operator are encouraged for H$_2$ customers to determine the most effective means of H$_2$ supply to end-users. Suggested fueling station locations are Bowmanville, ON (approximately 10 km) and Oshawa, ON (approximately 15 km). Fueling stations are proposed in these locations because they are the closest large population centres likely to contain end-users.

5.5 **System Schematics**

Figure 3 showed an isometric view of the Clarington Energy Business Park. Figures 9 and 10 are visual representations of the Clarington Energy Business Park Power-to-Gas Facility. These schematics are provided to aid in the visualization of the layout and scale of the facility. The approximately overall size of the facility is 55,000 m$^2$ on the approximate 100,000 m$^2$ (24.28 acre) lot. The design of equipment and respective systems was completed using Sketchup software.

![Figure 9. Power-to-Gas Facility. Aerial View with Distances.](image-url)
Figure 10. Schematic of the Clarington Energy Business Park Power-to-Gas Facility. Aerial View.
6 Cost Analysis

6.1 Local Electricity Cost & Design - Background on Electricity Cost in Ontario

The Independent Electricity System Operator (IESO) of Ontario controls the electricity market in Ontario by operating a wholesale electricity market where electricity is bought and sold at an hourly Ontario energy price (HOEP). The Independent Electricity Operator (IESO) has signed new renewable generators like wind, solar, biomass, small hydro, and natural gas generators to fixed rate generation contracts of 20+ years. The IESO has contracts for 26,671 MW of capacity, or 74% of all capacity in the province as of 2016 [22]. The remainder of the capacity is generated by Ontario Power Generation Corporation (OPG), owned by the Provincial Government. Fixed contract prices for OPG are set by the Ontario Energy Board (OEB). Ontario Power Generation (OPG) has 16,210 MW of installed capacity consisting of 66 hydroelectric plants and two nuclear plants as of 2017 [23].

Nearly all the electricity generators in the province of Ontario have a fixed rate contract with either the Independent Electricity System Operator (IESO) or the Ontario Energy Board (OEB). These fixed contract rates are significantly higher than the wholesale market hourly Ontario electricity price (HOEP). The IESO have added capacity to the system over the years while the demand for electricity since 2005 has decreased approximately 13% [22]. In 2016, the oversupply of electricity depressed the wholesale electricity market to its lowest levels ever.

In 2016 approximately 90% of our electricity production came from non-emitting sources that consist of nuclear, hydroelectric, wind, and solar. A large portion is base load production that are must run operations that result in excess power that must be sold to export markets at off peak times [24]. The excess electricity is sold to export markets at the wholesale price which is less than the contracted price to the generators. The difference (i.e., shortfall) in the price of the electricity is called the Global Adjustment (GA) which is added to the bills of the electricity consumers of Ontario. The Ontario electricity consumers are subsidizing the electricity generators for electricity exported to other markets. In 2015, the GA was approximately $1.5B. The electricity that is being exported at huge financial losses can be used for the Power-to-Gas project economically if designed to take advantage of the pricing of the wholesales market. As shown in Table 2, the GA is 80% of the price of electricity for a Direct Class A customer.

Table 2. Cost breakdown Electricity Pricing US$/MW November 2015 – April 2016 [25].

<table>
<thead>
<tr>
<th>Customer Class</th>
<th>Weighted HOP</th>
<th>Average Global Adjustment</th>
<th>Average Uplift</th>
<th>Effective Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Class A</td>
<td>8.16</td>
<td>39.02</td>
<td>1.27</td>
<td>48.45</td>
</tr>
<tr>
<td>Class B &amp; Embedded Class A</td>
<td>8.99</td>
<td>80.23</td>
<td>1.31</td>
<td>90.54</td>
</tr>
<tr>
<td>All Consumers</td>
<td>8.90</td>
<td>75.24</td>
<td>1.31</td>
<td>85.44</td>
</tr>
</tbody>
</table>

The methodology of the allocation of the GA under the Industrial Conservation Initiative (ICI) program is based on the percentage of the power used during the top five demand hours throughout the year. To be included in this program, the company must have a demand peak of greater than 5 MW which the power-to-gas project would qualify [26].
As shown in Table 3 the peaks all occurred within a 3 hour window during the late afternoon when people return home from work. It is also worth noting that the peaks occurred in the winter and summer seasons.

**Table 3. Top 5 Demand Peaks for Global Adjustment, 2015.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Peak Demand MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 5</td>
<td>5 p.m.</td>
<td>22,516</td>
</tr>
<tr>
<td>Jan 7</td>
<td>6 p.m.</td>
<td>21,814</td>
</tr>
<tr>
<td>Feb 19</td>
<td>8 p.m.</td>
<td>21,494</td>
</tr>
<tr>
<td>Aug 17</td>
<td>5 p.m.</td>
<td>22,383</td>
</tr>
<tr>
<td>Sept 2</td>
<td>5 p.m.</td>
<td>22,063</td>
</tr>
</tbody>
</table>

The wholesales market price of electricity has been recorded at some of the lowest levels since its inception between November 2015 and April 2016 during which one third of the hours the wholesale market price was at zero or below [25].

**6.2 Designing the Power-to-Gas System for Local Electricity Market Pricing**

The cost of electricity when producing hydrogen from water is the single largest component of the cost. It is for this reason an analysis was performed on the cost of electricity the raw feed stock for the hydrogen production. The H\textsubscript{2} production system is sized and designed to take advantage of the low cost of electricity during low demand periods. The low cost times are generally on the weekends and through the week in the evenings between midnight and 7 a.m.. The electrolyzers are sized and storage capacity are designed to run during these off peak times and store enough H\textsubscript{2} for the daily requirements. The storage capacity is oversized to hold hydrogen to handle any fluctuations in demand and allow to have reduced production through the week.

The plant under the ICI program and operating on weekends and between 12 a.m. and 7 a.m. during the week will not be running during any of the 5 peak periods of the year and therefore will not have to pay the GA charge that is over 80% of the electricity cost. This will only leave the HEOP price, lift charges and delivery making the cost of electricity very affordable and making the hydrogen cost competitive.

There average price of electricity HOEP price is less than 1 cent per kWh and one third of the time it is at zero or negative. The hydrogen production plant by paying 1.21 cents per kWh is above the average and therefore will reduce losses of selling at zero and negative prices that are incorporated in the global adjustment which is paid for by the Ontario rate payer in their electricity bill. By paying 1.21 cents per kWh it will reduce the Ontario rate payers’ bills via the global adjustment. The total cost of electricity is detailed below in Table 4 with the delivery and regulatory charges composing of 70% of the cost of electricity. The regulatory cost of electricity would be eliminated if in the future renewable energy generation was directly connected to the facility. This would help to offset the cost of optional renewable generation installations.
### Table 4. Electricity Cost Breakdown [25] [27].

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost c/kW US$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOEP (hourly Ontario electricity price)</td>
<td>1.21</td>
</tr>
<tr>
<td>Delivery</td>
<td>2.22</td>
</tr>
<tr>
<td>Regulatory Charge</td>
<td>0.48</td>
</tr>
<tr>
<td>Uplift Charge</td>
<td>0.13</td>
</tr>
<tr>
<td>Global Adjustment</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4.04</strong></td>
</tr>
</tbody>
</table>

6.3 Hydrogen Costing Breakdown

As seen in Table 5, the cost of electricity to produce H\(_2\) and liquefy it is the single largest cost component at 44%. It is for this reason that the hydrogen facility was designed to take advantage of off-peak low cost electricity. The second largest cost is the capital costs of the Hydrolyzers and then the maintenance of the Hydrolyzers and then the Liquefiers to convert it from gas to a liquid for storage and transportation.

### Table 5. Cost US$ of H\(_2\) per kg [27] [28].

<table>
<thead>
<tr>
<th>Source</th>
<th>Cost per kg US$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost of Electrolyzer</td>
<td>$1.90</td>
</tr>
<tr>
<td>Electrolyzer Maintenance</td>
<td>$0.76</td>
</tr>
<tr>
<td>Capital Cost of Liquefier</td>
<td>$0.40</td>
</tr>
<tr>
<td>Electrical Operating Cost of Liquefier</td>
<td>$0.41</td>
</tr>
<tr>
<td>Liquid Storage Tank</td>
<td>$0.02</td>
</tr>
<tr>
<td>Capital Cost of Initial Build per kg</td>
<td>$0.16</td>
</tr>
<tr>
<td>Capital Cost of Land per kg</td>
<td>$0.04</td>
</tr>
<tr>
<td>Cost of Electricity Electrolysis per kg</td>
<td>$2.17</td>
</tr>
<tr>
<td>Contingency per kg</td>
<td>$0.04</td>
</tr>
<tr>
<td><strong>Total Cost per kg</strong></td>
<td><strong>$5.90</strong></td>
</tr>
<tr>
<td><strong>Total Cost per Nm(^3)</strong></td>
<td><strong>$0.53</strong></td>
</tr>
</tbody>
</table>

The data from Table 5 is illustrated in Figure 11 (below)
6.4 Equipment Cost

Designing the production equipment to maximize the low cost of electricity has resulted in the following equipment size and storage capacities outlined in Table 6.

Table 6. Estimated Cost of Equipment [28] [17] [29].

<table>
<thead>
<tr>
<th>Technology</th>
<th>Specification</th>
<th>Quantity</th>
<th>Cost US$</th>
<th>Total US$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyzes 1MW W/ compressor up to 35bar</td>
<td>Hydrogenics HyLYZER®</td>
<td>39</td>
<td>$1.25 M</td>
<td>$48.8 M</td>
</tr>
<tr>
<td>Capital Cost Liquefier including compressors</td>
<td>724 kg/h</td>
<td>1</td>
<td>$25,600/kg/hr.</td>
<td>$18.5 M</td>
</tr>
<tr>
<td>and Cooling equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Storage Tank</td>
<td>5,000 kg</td>
<td>4</td>
<td>$31/kg</td>
<td>$0.6 M</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>$67.9M</strong></td>
</tr>
</tbody>
</table>
6.5 Costing Methodology

The electrolyzer was costed at US$ 1.25 Million per megawatt producing 18.75 kg of H\textsubscript{2} per hour per Megawatt and amortized over a life span of 35,000 hours. The maintenance cost is based on replacing the fuel cell stack at least once during the life of the electrolyzer at a cost of 40% of the initial price. The electricity cost is based on the above mentioned cost of electricity from the Ontario grid when only clean energy is abundant at US$ 4.04 cent per kWh and taking 4.6 kWh to produce one m\textsuperscript{3} of hydrogen. The capital cost of hydrogen liquefier was bases on a liquefying 725 kg/hr at a cost of US$ 25,600 /kg/hr, then amortized over the production for 15 years [28]. The electricity cost of operating the liquefaction is based on 10.2 kWh per kg of hydrogen at a cost of US$ 4.04 cents per kWh.

6.5.1 Financial considerations for replacement of Fossil Fuels for Cars, Trains, Busses

The replacement of fossil fuels with H\textsubscript{2} is a viable solution from an economic standpoint due to the efficiency of fuel cell vehicles. One kilogram of H\textsubscript{2} contains about the equivalent energy as one gallon of gasoline but Fuel Cell Vehicles are 2.5 times more efficient so they need less than half the amount of hydrogen. The estimated cost of hydrogen production is at US$ 5.90/kg which leaves margin to sell hydrogen at the prices around US$ 10/kg leaving a 41% margin on sales [30]. This price puts a typical fill up of a car at US$ 50 that will provide a 500 km range which is comparable to a fossil fuel cost. The higher efficiency of fuel cells for busses and trains would also make a hydrogen based infrastructure price competitive to today’s fossil fuel option.

6.5.2 Financial considerations for injecting Hydrogen into the Natural Gas lines

To inject hydrogen into the natural gas pipeline there would have to be a method of separating it from the natural gas at the exit and sell it at hydrogen prices for it to be economically viable.
7 Commercialization Analysis

The purpose of commercialization is to sell the concept of a new method or technology by highlighting the key features or function which are performed allowing the user to benefit or profit. The proposed system allows an operator such as a province, state, power generation, or emerging technologies company to make use of low cost, surplus electricity generated by low-GHG emitting power sources to create hydrogen through an electrolysis process to produce H\(_2\) gas. This gas can be stored and sold for a profit to numerous end-users in varying industries, not to mention, the operators would be contributing to a renaissance in sustainable H\(_2\) infrastructure and would become highly regarded experts in the field of hydrogen applications.

Adoption and investment in this technology has many attractive selling points which could be discussed in great detail. However, for the purpose of this report the most attractive benefits for potential operators are summarized and outlined as follows:

i. Power-to-gas is a flexible and versatile technology, capable of adapting to unique supply and demand situations while remaining profitable;

ii. Operators have the option to become energy independent through renewable installations (such as wind and solar) to eliminate their dependence on available grid surplus;

iii. Investment in power-to-gas gives progressive companies an edge over competitors exploring new technologies as possible first-of-a-kind operators;

iv. Companies will gain valuable operating experience and intellectual property pertaining to H\(_2\) production;

v. Reducing Ontario’s GHG emissions and overall footprint;


In addition to attractive benefits of owning and operating a power-to-gas system, it is important to describe the future opportunities of growth for the proposed power-to-gas system and the technology itself. Future opportunities are as follows:

i. After a status of ‘proven technology’ is achieved and profitability of operation is confirmed, operators have the opportunity to consider future facility expansion to meet the growing future demand of H\(_2\) use;

ii. In addition, new build opportunities are present in various locations around the Greater Toronto Area and other populated areas of Ontario as H\(_2\) demand increases throughout the province;

iii. Operators have to opportunity to design and implement their own fueling stations throughout the province to streamline and solidify the supply of H\(_2\) to civilian end-users.

Power-to-gas systems have many attractive selling points for owner/operators. In addition, power-to-gas systems have many different areas to grow and become more profitable for progressive/agile companies. As authors of this report, we believe the most important selling feature of this power-to-gas system is the fact that it is capable of creating and sustaining a local infrastructure and market for hydrogen gas.
8 Safety Analysis, Codes & Standards

8.1 Primary Areas of Concern and Overview

A relatively new technology, fuel cells and hydrogen gas have some associated safety hazards that must be addressed. While some risks are common to those of other compressed gas or liquid fuel, the combination of unique physical characteristics for hydrogen paired with the use of newly developed or unproven technologies warrant special concern.

Extra precaution must be taken specific to the unique properties of hydrogen gas and liquid. Primary areas of concern for hydrogen applications are the potential for leaks, exposure to the presence of a leak, and combustion of escaped hydrogen. Occurrence of all three of these events at the same time presenting the most significant concern.

Key components of a typical power-to-gas facility to consider include: Electrolyzer – Production System; Liquid Hydrogen Storage System; Liquid and Gas Hydrogen Distribution System; Liquid Hydrogen Fueling Station – Dispensing System

8.2 Common Modes of Failure and Effects

8.2.1 Electrolyzer

The primary risks associated with electrolyzer operation are electrical shock, exposure to gas or high heat, and the formation of potentially flammable or explosive mixtures of gases. These modules operate using large amounts of electrical power far above the levels to stop the human heart and risk of exposure to H₂ gas is every present from equipment failures or human error [31].

The most significant potential hazard is the formation of a flammable gas mixture in the presence of an ignition source [31]. During the electrolysis process, this is most likely to occur from a failed separation media within the module – a solid polymer electrolyte interface used to keep produced gasses separate [32]. This enables hydrogen and oxygen gasses to cross permeate through the electrolyte membrane, forming highly concentrated mixtures. High electrical currents passing through the electrolyte creates a potential source of ignition should the two gasses accumulate to a flammable mixture [32]. Consequences of such an event would be severe and increase exponentially with pressure, the incredibly high speed of propagations greatly increases the potential of spreading throughout the system and furthering the destruction.

8.2.2 Hydrogen Storage

Liquid hydrogen is always accompanied by a certain of gaseous hydrogen. Properties and hazards of both need considered. While the proposed system will have no onsite compressed gas storage, H₂ is produced by the electrolyzer in its gaseous state before being cooled to cryogenic temperatures for liquid storage and while it is being injected into the natural gas pipeline instead of being cooled for storage. This requires our system to have a hydrogen gas distribution system that is separate and additional to the cryogenic liquid hydrogen distribution system. Therefore the safety concerns associated with H₂ gas must still be carefully considered in addition to those for liquid hydrogen storage and distribution systems. The special physical properties of hydrogen in its gas and liquid state each present a different set of potential failures modes and effects.

8.2.3 Fire and Explosion

The potential to form and ignite flammable mixtures of hydrogen can be significantly greater than with other gases for several reasons. Under ambient conditions hydrogen exists as an invisible and
odorless gas, which even when ignited burns with a nearly invisible flame [33]. Therefore, detecting leaks is a very difficult process without proper scientific instrumentation. Hydrogen produces combustible mixtures in air at concentrations as low as 4% to an upper limit of 75% [33]. Even though hydrogen disperses very quickly, a tank rupture or high pressure leak is capable of emitting a highly combustible mixture in a very short time. Within poorly vented or enclosed areas, hydrogen can accumulate to levels for large explosions or even detonation if initiated.

If a combustible mixture of hydrogen and air does form, the likelihood for an explosion is relatively high given the ignition energy required (e.g., ignition is less than one tenth that of other common gaseous fuels such as propane, methane, or natural gas [34]). Thus even the smallest spark, like those produced from static electricity from the friction between clothing, can be enough to initiate an explosion. More hazardous than an explosion, however, is the risk of detonation, where the explosion expands at supersonic speeds, compared to subsonic speeds of typical explosions [34].

8.2.4 Health Effects from Exposure

Exposure to H₂ gas may dilute the oxygen concentration in air resulting in potential suffocation [33]. While nontoxic, breathing in pure hydrogen would likely cause immediate unconsciousness and probably result in death [34]. The concentration of H₂ gas required to produce this oxygen deficiency is easily within the flammable and or combustible range making the risk of fire and explosion the primary hazard associated with exposure to hydrogen gas.

Exposure to liquid hydrogen can produce severe cold burns upon contact with exposed skin from the extremely low temperatures [34]. Even brief exposure to cold boil-off gases or splashes too quick to burn skin, have the potential to injure delicate tissues such as eyes or gums. Additionally, any improperly insulated storage vessels or distribution components may reach temperatures low enough to produce similar cold burns if any exposed skin comes in contact, quickly freezing and being torn away [34].

8.2.5 Cold Embrittlement and Material Selection

Material and type of storage vessel should be determined based of the mechanical properties at low temperatures. Certain materials change from ductile to increasingly brittle with temperature, typically occurring at levels much higher than the temperatures for cryogenics [35] – referred to as low-temperature or cold embrittlement. At such low levels there is a significant difference between the cryogenic and ambient temperature conditions, inducing significant thermal contraction and expansion in most materials [35]. The effects from cryogenic conditions on the rest of the system must be carefully considered as well. In most applications, liquid hydrogen is first vaporized for use as a gas. This is because materials used for piping of gases – such as carbon steel – become brittle at temperatures below atmospheric [35].

8.2.6 Leaks and Ice Formation

Unlike leaks with gaseous H₂, typically liquid hydrogen leaks are easy to detect without specialized equipment. Ice formation is common with cryogenic systems, and often a leaking vessel or component will have frost or ice crystals form on the exterior [35]. Ice formation is not always a bad thing and sometimes can act as an extra layer of insulation in situations where the ice forms without the presence of a leak. In the presence of a leak, liquid hydrogen will sink to the ground until warming due to its higher density then air. During this transition, water vapor from the surrounding air will condense forming a white cloud fog. The cloud remains localized and will move horizontally or upwards as the hydrogen warms up [35]. Hydrogen near the ground will
typically warm faster and will quickly disperse and begin to rise up carrying the fog with it as it transitions to a gas.

8.2.7 Hydrogen Distribution System and Components

The primary cause of leaks in liquid hydrogen distribution systems is stress from thermal expansion and contraction. Material selection to reduce hydrogen exposure and cold embrittlement effects as with any component is crucial when selecting components for a distribution system. Piping, fittings, joints, and valves must be able to withstand stresses induced from thermal cycling between ambient to cryogenic temperature conditions [35]. Effects of thermal expansion and contraction experienced by distribution system components are often more than just those from the component itself, additional stresses from the thermal effects on the entire system act radially and longitudinally through pipes and fitting walls to other components.

Valve stems seals are the most likely to leak during service and require the same consideration as fitting types [35]. Since the actual internal mechanisms of valves may not be fitting with pressure relief devices, it is necessary to consider the effects of trapping liquid hydrogen inside. Whenever liquid hydrogen is warmed within a closed system, it can generate high pressures. In addition, the typically elastomers used to as seals for ambient temperatures can quickly fail after only a single thermal cycle from embrittlement [35]. If even a small leak is ignited at any valve, fitting, or joint, it could leak to a significantly larger release.

8.2.8 Hydrogen Dispensing System and Fueling Station

Vehicles powered by hydrogen fuel required for new specialized infrastructures to maintain their operation and increase use. With this the primary concern for hydrogen fueling stations is that the properties and risks associated with this gas are not widely understood by the public, unlike other fossil fuels (e.g., natural gas, petroleum, or diesel) which have been in use for many decades. Despite the process of refueling being relatively similar to that standard transportation fuels, the associated risks and common modes of failure may have very different implications with hydrogen. For example, exiting the dispenser with the injection hose or mechanism still attached, or crashing into a refueling vehicle or the pump, pose a much greater risk for fire or explosion from escaped H$_2$ than with other fuels.

8.2.9 Failure Modes and Effects Analysis (FMEA)

To organize the risks and safety concerns related to this project as well as quantify which concerns are higher priority, a failure mode and effects analysis was performed. In this work, the hydrogen aspects were the focus. The different components and functions relating to hydrogen were listed as well as the potential failure modes relating to each. The potential causes and effects for each of these failure modes were analyzed and a severity level was estimated for each of these failures. The severity level, assessing how much damage it would cause, is on a scale of 1 to 10, with 10 being the highest (e.g., a detonation event). A likelihood level was also estimated for each failure on a scale of 1 to 10, with 10 being the highest and most likely. The severity and likelihood levels were multiplied together to obtain an overall risk factor. The FMEA analysis is given in Figure 12.

Upon completion of the FMEA, it can be seen that there are a few failures that received a higher overall risk value than the majority. The highest risks observed through this analysis, with a final score of 60 were overpressure and intentional damage. The next five failures with the highest risk score, all coming in at 50 are, gas accumulation in the electrolyzer, storage overheating, storage tank impact, overpressure and accumulation of gas in distribution system.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyzer</td>
<td>Gas Leak</td>
<td>Asphyxiation</td>
<td>8</td>
<td>Power Loss</td>
<td>5</td>
<td>40</td>
<td>Gas detectors around electrolyzer</td>
</tr>
<tr>
<td></td>
<td>Water Contamination</td>
<td>Fire</td>
<td>2</td>
<td>Corrosion</td>
<td>6</td>
<td>12</td>
<td>Regular inspection as well as sensors</td>
</tr>
<tr>
<td></td>
<td>Gas Accumulation</td>
<td>Explosion</td>
<td>10</td>
<td>Low Water Levels</td>
<td>5</td>
<td>50</td>
<td>Regular inspection, as well as oxygen detectors</td>
</tr>
<tr>
<td></td>
<td>Charge Build-Up</td>
<td>Lack of Production</td>
<td>6</td>
<td>Equipment Failure</td>
<td>2</td>
<td>12</td>
<td>Level sensors incorporated into system</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Over-Pressure</td>
<td>Fire</td>
<td>10</td>
<td>Environment</td>
<td>6</td>
<td>60</td>
<td>Pressure spill-back loops</td>
</tr>
<tr>
<td>Storage</td>
<td>Under-Pressure</td>
<td>Implosion</td>
<td>8</td>
<td>Human Error</td>
<td>4</td>
<td>32</td>
<td>Flow control system</td>
</tr>
<tr>
<td></td>
<td>Overflow</td>
<td>Detonation</td>
<td>8</td>
<td>Equipment Failure</td>
<td>6</td>
<td>48</td>
<td>Manual valves to be used as backup</td>
</tr>
<tr>
<td></td>
<td>High Temperature</td>
<td>Fire</td>
<td>10</td>
<td>Operational Failure</td>
<td>5</td>
<td>50</td>
<td>Fire resistant coating</td>
</tr>
<tr>
<td></td>
<td>Low Levels</td>
<td>Implosion</td>
<td>6</td>
<td>Corrosion</td>
<td>6</td>
<td>36</td>
<td>Manual valves to be used as backup</td>
</tr>
<tr>
<td></td>
<td>Impact</td>
<td>Explosion</td>
<td>10</td>
<td>Human Error</td>
<td>5</td>
<td>50</td>
<td>Add a guard around tanks</td>
</tr>
<tr>
<td></td>
<td>Leak</td>
<td>Exposure</td>
<td>8</td>
<td>Corrosion</td>
<td>4</td>
<td>32</td>
<td>Material with high corrosion resistance</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Reversed Flow</td>
<td>Explosion</td>
<td>7</td>
<td>Human Error</td>
<td>3</td>
<td>21</td>
<td>Flow meter in nozzle to ensure one directional flow</td>
</tr>
<tr>
<td>Fueling</td>
<td>Leak or Line Failure</td>
<td>Suffocation</td>
<td>8</td>
<td>Component Failure</td>
<td>4</td>
<td>32</td>
<td>Gas detectors around fueling station</td>
</tr>
<tr>
<td></td>
<td>Intentional Damage</td>
<td>Possible Detonation event</td>
<td>10</td>
<td>Collision from Vehicle/Vandalism</td>
<td>6</td>
<td>60</td>
<td>Barriers for vehicles, security cameras for vandals</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Rupture of pipe</td>
<td>Exposure</td>
<td>8</td>
<td>Thermal stresses</td>
<td>5</td>
<td>40</td>
<td>Use high-grade piping that can withstand temperature changes.</td>
</tr>
<tr>
<td>Distribution</td>
<td>Overpressure</td>
<td>Explosion</td>
<td>10</td>
<td>Improper pressure relief</td>
<td>5</td>
<td>50</td>
<td>Pressure spill-back loops</td>
</tr>
<tr>
<td></td>
<td>Accumulation of gas</td>
<td>Explosion</td>
<td>10</td>
<td>Improper ventilation of relief</td>
<td>5</td>
<td>50</td>
<td>Proper ventilation setup, no potential accumulation points</td>
</tr>
<tr>
<td>Process Control</td>
<td>Uncontrolled inflow and outflow</td>
<td>Compression failure</td>
<td>6</td>
<td>Control System Failure</td>
<td>6</td>
<td>36</td>
<td>Backup control system which opens and shuts necessary valves when the system is failing</td>
</tr>
<tr>
<td>Systems</td>
<td>Overpressure in components</td>
<td>Detonation event</td>
<td>10</td>
<td>Blocked pipes, valve failures</td>
<td>6</td>
<td>80</td>
<td>Pressure spill-back loops</td>
</tr>
</tbody>
</table>
8.2.10 Controlling and Mitigating Associated Hazards

The proposed system will be designed and constructed adhering to strict code and putting hydrogen safety first. Proper measures can be put into place to control and mitigate the potential hazards identified above and will be explained further in this section.

To mitigate risks associated with electrolyzers, they are located outdoors for maximum ventilation. Being able to exclude a ventilation system improves reliability as well as reduces cost. Along with that sensors will be used to monitor the mixture of gasses.

In regards to the storage, several mitigation techniques will be used to ensure maximum safety. First, only fire-retardant insulations will be used, and vehicle guards will be placed around any tank of hydrogen to ensure no incidental contact. Also, operators and other personnel will be trained extensively on the potential signs of a leak to report it and get to safety.

In the distribution system, one of the most important precautionary measures is proper material selection. The material chosen should be able to handle the thermal stresses that it may undergo, also the pipe should be laid in open trenches with easy to access points for regular inspection. Only fire resistant valves should be used.

The hydrogen fueling/dispensing system is an area of high risk. Mitigation efforts start with placing barriers around any tanks and installing flow meters into the pumps to ensure no reverse flow. Gas detectors will also be implemented to ensure that a leak does not go unnoticed.

The system will be designed such that the pressure-relief discharge is at a safe location and constructed in a manner where liquid or gas can escape from the vessel without being impeded by buildings or structures or site characteristics, such as hills. Similarly, the design of pressure-relief devices and vent piping should be done in a way where moisture cannot collect and freeze, creating interference. The safe discharge of all exhaust, pressure, and hydrogen, away from potential ignition sources is essential.
9 Codes and Standards

There are many codes and standards that must be adhered to when designing and building anything. Hydrogen itself has its own set of specific codes and standards, which were followed throughout the design to mitigate risks. A list of these codes and standards is presented in Table 7.

<table>
<thead>
<tr>
<th>Code/Standard</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFPA 2</td>
<td>Hydrogen Technologies Code</td>
</tr>
<tr>
<td>NFPA 52</td>
<td>Vehicle Fuel Systems Code</td>
</tr>
<tr>
<td>NFPA 55</td>
<td>Compressed Gases and Cryogenic Fluids Code</td>
</tr>
<tr>
<td>NFPA 70</td>
<td>National electrical code – fuel cell systems</td>
</tr>
<tr>
<td>CAN 1784-000</td>
<td>Canadian Hydrogen Installation Code</td>
</tr>
<tr>
<td>SAE J2600</td>
<td>Compressed Hydrogen Surface Vehicle Fueling Connection Devices</td>
</tr>
<tr>
<td>ASME B31.12</td>
<td>Standard on Hydrogen Piping</td>
</tr>
<tr>
<td>ASME Boiler and Pressure Vessel Code</td>
<td>Boiler and Pressure Vessel Code</td>
</tr>
<tr>
<td>ISO 22734-1:2008</td>
<td>Hydrogen Generators Using Water Electrolysis</td>
</tr>
<tr>
<td>OSHA Regulation 29 CFR 1910 Subpart H</td>
<td>Safe storage, use, and handling of hydrogen in the workplace</td>
</tr>
</tbody>
</table>

Canadian Hydrogen Installation Code (CAN 1784-000) was followed. This code lays out the installation requirements for hydrogen utilization equipment, hydrogen storage tanks, hydrogen piping systems, and any other accessories [9]. That same code also requires the gas detectors to be present around tanks and fueling stations to detect leaks. The ASME B31.12 Standard on Hydrogen Piping provides guidelines for the design and installation of the piping system, which also includes material selection guidelines. The ASME Boiler and Pressure Vessel Code requires the pressure relief system to be problem free as the code calls for it not to be set up incorrectly. It can be observed that by following these general standards and codes, the majority of the failure modes identified in Figure 12 can be mitigated.
10 Operations and Maintenance

Along with regulatory operations on H\textsubscript{2} and O\textsubscript{2} production, it is important to monitor water consumption from Durham region using a water meter [36]. This will quantify the annual amount of water used to determine the yearly rate for water consumed.

10.1 Equipment Monitoring

Operations and Maintenance towards hydrogen systems will be invested into the system components such as reforming, controls, process utilities, compression, storage, safety, etc. because this facility would be dealing with large scale commercialized hydrogen production [37]. However, maintenance can be minimized using automated or remotely monitored systems. Regulatory inspection would be made towards water and hydrogen pressures in the pipe to ensure safe flow rate. Standardize checks by licensed personnel for equipment from pumps, valves, storage tanks, pipe connections, etc., to ensure they meet operating conditions and observe any damages.

10.2 Hydrogen Containment

Regulatory maintenance checks are mandatory for hydrogen storage vessels that follow the industry codes and standards set by ASME Boiler and Pressure Vessel Code (BPVC), Canadian Standards Association (CSA), International Organization for Standardization (ISO), etc. These regulatory inspections examine safety and reliability over time due to fatigue and embrittlement. It is important to follow the recommendations set by the vessel manufacture, as well as having a third party to provide a thorough inspection considering our facility will have multiple large hydrogen storage tanks [38]. Furthermore, as the facility will be handling liquid hydrogen, qualified personnel are responsible for the safe transfer of liquid hydrogen into the storage vessels and for the proper transporting methods.

10.3 Grid Monitoring

Grid monitoring is required to manage the power distribution from the grid and determine the availability of clean generated electricity. Such a system requires a Supervisory Control and Data Acquisition (SCADA) solution, which communicates over other control systems and networks. These control systems provide measurements, monitoring, metering, security, and other necessary functions for grid activities [39]. For electrical devices to communicate, wireless sensor networks (WSN) are required. Such a system will be operated through human interface for active response times and manual control in case any failures were to occur (e.g., a grid blackout).

10.4 Electrolyzers

With a life span of 15 years for the HyLYZER 600 electrolyzer, maintenance requirements is 2-3% per year of CAPEX [40]. Maintenance costs are usually towards the sensors, cleaning and replacing filters (air, water), corrosion checks, and other critical components. Daily inspection on daily H\textsubscript{2} and O\textsubscript{2} production along with water purity before entering the electrolyzer to ensure level of deionization grade is met in accordance to ISO 3696. The electrolysis process has to meet ISO 22734-1:2008 and gas detection according to NFPA 2 standards. With the only replacement cost being the stack, this requires roughly 40% of the total capex, which would occur 1 or 2 times during the life span of the electrolyzer [40]. Operation cost vary depending on the operating conditions of the electrolyzer on site.
10.5 Additional Generation

With electricity production needed once the Pickering Power Plant is decommissioned in 2024, additional renewable energy power plants are required to make up the expected capacity decrease.

10.5.1 Photovoltaic System

Daily inspection checklist to ensure PV system is operating a peak efficiency. Inspection includes: PV modules, PV inverter, cabling, disconnects, and grounding. System monitoring which requires special equipment and ensure sensors calibrated to manufacturing guidelines. Corrective action is taken with regards to defects found during inspection; severe defects should be taken as a priority and managed safely.

10.5.2 Wind System

With the development of an onshore wind farm, the turbine companies that supplies the turbines provide a contract and warranty for operations and maintenance that is 5-10 years [41]. Reliability of turbine components is the key factor for a successful wind farm as there can be unexpected premature mechanical failures throughout the operation of the turbine [42].

Different simulations modeling can be used to monitor and assess wind power, as well as optimize operation and maintenance. One type of modeling that can be used is an Arena-based modeling simulation that models the operation of the turbine until failure, repair required and inspection of wind turbines to reduce maintenance costs and increase the effectiveness of wind availability [42].

This onshore wind turbine farm is in compliance with the Canadian Standards Association (CSA), which provide the necessary guidelines for grid connection, tower design, foundations, electrical safety, environmental design considerations etc. An example of such a regulation is CAN/CSA-C22.2 No 257, which discusses the safe interconnection of the inverter-based-micro-distributed resource to a low voltage distribution system [43] [44].

10.5.3 Wave Power

The potential for more advanced renewable energy technology is promising with the facility being close to Lake Ontario. The operator is responsible for troubleshooting, repair, maintenance, and optimization of the plant [45]. Equipment maintenance is regulatory as lake water and contaminants can cause corrosion and degradation. Fatigue loads needs to be assessed that can result in failure during operations, which means simulation modeling is conducted to reduce failure rate and increase reliability [45] [46].
11 Environmental Analysis

This project will be required to have a formal environmental analysis performed. As defined by the Canadian Environmental Assessment Act, 2012 (CEAA 2012) Section 15 [47], the National Energy Board (NEB) will be the Responsible Authority for reviewing this project. Section 5 lists that the Impact to Wildlife, Impact to Land, and Impact to Aboriginal Peoples should be considered, and Section 19 suggests this be done for the conditions of operation, and the conditions of a malfunction or accident.

For the analysis, malfunction or accident and conditions of operation are defined as follows:

Malfunction or Accident (MA): Major accidents and malfunctions as identified in the safety are: leak, ignition, and exposure to gaseous hydrogen, liquid hydrogen, and liquid refrigerant

Conditions of Operation (CofO): The operation phase will see electricity and water as inputs to the system. The outputs will be hydrogen and oxygen. Oxygen will be released to the environment, and the hydrogen will be have one of two pathways; H₂ gas will be stored on site for end uses, or injected into the NG pipeline. End uses include using the hydrogen in on-site fuel cells to generate electricity if demand is needed, transportation of hydrogen to the train terminus for the refueling of GO Trains and Buses, and transportation of hydrogen to a car refueling station.

11.1.1 Impact to Wildlife

The impact to fish habitat as defined by the Fisheries Act, 1985 [48] will have no significant increased impact under the CofO for this facility. No evidence was found that there would be any impact to fish habitat as a result of an MA at the facility.

The impact to aquatic species as defined in the Species at Risk Act [49] will again see no significant impact from a MA or under the CofO for this facility. No evidence was found that there would be any impact on aquatic species as a result of an MA at the facility.

There could be an impact on migratory birds as defined by the Migratory Birds Convention Act [50]. Due to the proximity to Lake Ontario, it is reasonable to assume that migratory birds may be in the vicinity of the facility. The release of oxygen into the atmosphere has the potential to affect migratory birds and any person or animal in the vicinity. If the Canadian standard or 23% oxygen by volume, up from the atmospheric norm of 21%, is taken as the standard for an oxygen enriched environment [51], oxygen sensors will need to be placed around the property to ensure that oxygen is not being released to the environment too quickly. This is a safety measure for both migratory birds and humans on the site.

Issues could arise from an MA on the site as identified in the Health Effects from an incident with the hydrogen storage tanks. Mitigation methods are as outlined in the safety section for the selection of materials to avoid an MA.

11.1.2 Impact on Land

There is no significant impact from CofO or an MA to federal lands, nor to any province or territory outside the province of Ontario, nor to any country outside of Canada.

11.1.3 Impact on Aboriginal Peoples

Discussions with Haley Cochrane, the Indigenous Assistant Recruitment Officer at UOIT, have indicated that there will probably not be any increased impact to Aboriginal Peoples with respect
to the criteria outlined in CEAA 2012 Section 15 from CofO. There would be an impact as mentioned above to any person in the area in the event of an accidental release of oxygen in quantities that exceed 23% atmospheric oxygen.

Attempts to contact a spokesperson from the Mississaugas of Scugog Island First Nation by Ms. Cochrane on behalf of the project were not returned. It would be beneficial to make contact with someone from the Mississaugas of Scugog Island First Nation to verify this information. Further discussion with Ms. Cochrane led to the recommendation that as a sign of respect and to strengthen reconciliation efforts, a representative from the Mississaugas of Scugog Island First Nation should be invited to attend the opening of the facility and perform a smudging ceremony.

11.2 Greenhouse Gas Emissions Reductions

Ontario has set very aggressive GHG reduction targets starting from 1990 levels. The targets are a 15% reduction by 2020, 37% reductions by 2030, and 80% by 2050 [52]. The introduction of a hydrogen infrastructure to support transportation systems and to reduce fossil fuel use would greatly help in achieving the provincial emission reduction goals.

The estimated number of fuel cell vehicles in Oshawa and Clarington by 2020 is 3240 that would have otherwise been internal combustion engine vehicles (ICV). The average ICV contributes 4600 kg of Carbon Dioxide (CO\textsubscript{2}) to the environment on an annual basis [53]. Since the hydrogen production plant will only run when clean energy is used to produce electricity there will be no emissions created by the production of hydrogen. No emission are produced when a fuel cell vehicle generates electricity to propel the vehicle using hydrogen so a savings of 14,904 tons of CO\textsubscript{2} will be reduced from the environment per year as a result of the hydrogen production plant.

The Ontario GO Trains GHG emissions are 13.32kg – 15.37kg/CO\textsubscript{2}/km/train [54]. Based on the 100 train trips made to Clarington each day at 70 km per trip for a total of 7000 km at 13.32kg - 15.37 kg/CO\textsubscript{2}/km/train totals 93,240 kg to 107,590 kg of CO\textsubscript{2} potential savings converting to hydrogen per day or 34,032 to 39,270 metric tons per year.

Natural gas created 53.07 kg CO\textsubscript{2}/ MBtu and 1 Btu is 27.8 m\textsuperscript{3} making the emissions 1.91 kg of CO\textsubscript{2} emissions per m\textsuperscript{3} of natural gas [55]. Replacing the natural gas with hydrogen on a one to one ratio will reduce the emissions of CO\textsubscript{2}. Hydrogen contains 0.012 GJ of energy per m\textsuperscript{3}, whereas natural gas contains 0.0373 GJ of energy per m\textsuperscript{3} so it takes 3.11 m\textsuperscript{3} of H\textsubscript{2} to replace the energy in 1 m\textsuperscript{3} of natural gas. The plant will generate 2302 kg of H\textsubscript{2} or 24,612 m\textsuperscript{3} which will offset the equivalent of 8,240 m\textsuperscript{3} of natural gas at the 3:1 ratio reducing 1.91 kg of CO\textsubscript{2} per m\textsuperscript{3} or 4,314 kg/day. This production will reduce CO\textsubscript{2} emissions by 1574 metric tons a year.

The two bus routes that are proposed to be powered by hydrogen travel 108 km per trip and 40 trips per bus is 4320 km per day at 0.822 kg CO\textsubscript{2} per km is 3551 kg per day. This results in 1296 tons of CO\textsubscript{2} reduction per year [56].
12 Policy and Regulation Analysis

A hydrogen economy in Ontario is a stepping stone for meeting the objectives of both Ontario’s Long Term Energy Plan 2017 and Canada’s Mid-Century Long-Term Low-GHG Development Strategy that resulted from the Paris Agreement. The following barriers have been identified through the development of this project and require attention to develop a viable hydrogen economy in Ontario.

12.1 Social License

The first barrier that must be overcome or always taken into consideration is social license. Without the support of local communities for the development of a hydrogen infrastructure in general, and for a power-to-gas system specifically, no project will be encouraged to thrive. Many initial reactions to hydrogen will involve reference to the Hindenburg. To overcome this barrier, it is important to initiate conversations with the public about the benefits of hydrogen production and infrastructure in the local area. The advantages highlighted would be:

- Increased energy security;
- Increased job opportunities;
- Reduction of GHG emissions;
- Reduction in electricity bills (by decreasing overall GA).

12.2 Education

Education to achieve social license would involve going where people are to engage. This may take the form of distributing pamphlets or asking people to supply email addresses to send out information about hydrogen technologies and the benefits. Areas where these activities could take place would be:

- Farmer’s markets;
- Malls;
- Local festivals;
- Forums open to the public;
- Discussions at universities;
- Visits to public/secondary schools.

While education of the public is required to gain social license, education of policy makers, education for emergency response personnel, and training of individuals to work in the facilities is also required. Section 12 includes an example of a one page brief to be used to educate policy makers in Ontario and Canada on the benefits of acting now to encourage the development of Hydrogen Infrastructure.

12.3 Hydrogen Infrastructure

H₂ Pipeline injection into the pipeline will not be a realistic goal to consider until the beginning of the next decade in Ontario. Funding must be set aside to expedite investigations by Enbridge to determine how much hydrogen the current system will support, what users will be effected by the addition of hydrogen, how the hydrogen will impact older infrastructure, and how much of the infrastructure needs to be upgraded to allow hydrogen to safely be introduced to the natural gas pipelines as a means of both storage and transportation. Many of the questions from the public regarding any hydrogen infrastructure will revolve around safety.
12.4 Safety Standards

The development of a new infrastructure will require the development of new safety standards. While the ISO is working to develop these standards under ISO/TC 197, these standards are still in working groups and have yet to be finalized, though it is anticipated this will be completed at the end of 2018 [57].

12.5 Economic Incentives

As with the development of any new infrastructure, investment must be made. Due to the relatively new nature of hydrogen-based technologies, the costs to install and operate these facilities is currently larger and less cost-effective than traditional technologies if the effects of GHG emissions are not taken into account. It is imperative that money be set aside not only for trial projects in hydrogen as is currently laid out in Ontario’s Long Term Energy Plan 2017, but also for money or in kind to be directed towards the development of full-scale production facilities.
One Page Brief for Politicians

Developing a Hydrogen Economy in Ontario

_UOIT FESNS Hydrogen Power-to-Gas Team – Fall 2017_  
_h2policygrp@gmail.com_

**Summary**

The use of hydrogen will be required in order to meet targets set by Canada to reduce GHG emissions set out in the Paris Agreement and will be valuable in order for Ontario to meet the objectives set out in the Ontario’s Long-Term Energy Plan 2017.

**Issues**

- Social License is required for any major infrastructure project to proceed in a timely manner with little resistance from local populations;
- Emergency Responders (ERs) are not yet equipped to deal with hydrogen technology related issues;
- Older natural gas infrastructure in Ontario may not support.

**Background**

- Significant push-back from locals tends to result from energy projects, such as wind in Southern Ontario that do not have significant input from the public, or are fast-tracked;
- A new technology requires new procedures to ensure the safety of ERs;
- Injection of hydrogen into Natural Gas pipelines can be an effective way to store and transport hydrogen using existing infrastructure.

**Rational**

- To avoid the NIMBY effect of hydrogen projects, public education is necessary;
- To ensure the safe and effective decisions when dealing with a new technology;
- Better research will lead to better decisions.

**Recommendation**

- Provide funding to aid in the education of the public about hydrogen technologies;
- Encourage the development of procedures to be used by ERs when dealing with hydrogen-related incidents;
- Direct funding for research toward investigating the effects the injection of hydrogen into the natural gas infrastructure that currently exists and to develop recommendations for areas that need improvement.

**Contact**

For further information, please contact us at _h2policygrp@gmail.com_
14 References


[10] Google, "Courtice GO Station to Union Station," Google, 2017. [Online]. Available: https://www.google.ca/maps/dir/Courtice+Rd,+Courtice,+ON/Union+Station,+65+Front+St+W,+Toronto,+ON+M5J+1E6/@43.7978086,-79.634003,9z/data=!3m1!4b1!4m13!4m12!1m5!1m1!1s0x89d50391a0fff7d9:0x53664cf0490e3241!2m2!1d-78.7733225!2d43.9015853!1m5!1m1!1s0x882b34d. [Accessed 06 11 2017].


WHAT IS POWER-TO-GAS?

Water + Electricity = Gas

The goal of our power to gas system is to produce hydrogen gas with the use of water and electricity.

Primary Business Address
Clarington Energy Park
1845 MegaWatt Drive
Clarington, ON, Canada

Phone: 905-526-HGAS
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Presented By
Craig Robinson
Brett Marshall
Anantavahmini Jeyarajasingam
Riyad Khan
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Arick Amaral
David Wotten

Faculty Advisor
Dr. Matthew Kaye
Associate Professor
Faculty of Energy Systems and Nuclear Science

Driving Durham Without Gasoline
OUR POWER TO GAS PROCESS

BENEFITS OF THE SYSTEM?

- Moves Canadian hydrogen infrastructure from demonstration projects to utility scale
- Utilizes power generated by low greenhouse gas emitting sources in the province of Ontario
- Reduces CO₂ emissions by a projected 57,000 metric tons per year
- Converts cheap electricity leaving the province to a different form of energy with multiple applications
- Improves Ontario’s economy by providing jobs of various skills and talents
- Opens opportunities for market expansion
- Meets the changing needs of different communities due to Modular design
University of Ontario IT Final Submission Link

https://www.dropbox.com/sh/nnhgati97wrwp1g/AABaK9zwQKYcGjMydZ20lx9a?dl=0