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Design studies of infrastructural development for applications of hydrogen energy technologies

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DESIGN STUDIES OF INFRASTRUCTURAL DEVELOPMENT FOR APPLICATIONS OF HYDROGEN ENERGY TECHNOLOGIES

by

YOUSIF M. H. HAMAD

A DISSERTATION

Presented to the Faculty of the Graduate School of the

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In Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

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Approved
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PUBLICATION DISSERTATION OPTION

This dissertation has been made in the format of the option of publication. Two published journal papers are included. The first paper, "Molten Carbonate Fuel Cell Combined Heat, Hydrogen and Power System: Feedstock Analysis," has been accepted and published in *Energy Science and Technology*. Thus, pages 6 to 18, the pages on which this article appears, were formatted according to that journal's specifications.

The second paper, "A Design for Hydrogen Production and Dispensing for northeastern United States, along with its Infrastructural Development Timeline," has been accepted and published in *International Journal for Hydrogen Energy*. Therefore, this article page 19 to 69 was formatted according to that journal's specifications.

ABSTRACT

Countries around the world are trying to reduce their energy consumption, fossil fuel usage, and greenhouse gas (GHG) emissions. According to the International Energy Outlook 2012 released by the U.S. Energy Information Administration (EIA), the estimated fuel economy and greenhouse gas emissions standards proposed for light-duty vehicles for model years 2017-2025 has an increase of 44% in fuel economy and a reduction of 34% in GHG emissions. The use of alternative fuel vehicles and renewable energy sources are, therefore, inevitable toward achieving this goal. Biogas has untapped potential as an alternative energy source. This immediately available resource would allow countries to reduce their greenhouse gas emissions, energy consumption, and reliance on fossil fuels. This energy source is created by the anaerobic digestion of a feedstock. Sources for feedstock include organic and inorganic wastes, agricultural wastes, animal by-products, and industrial wastes, each a renewable energy source. A fuel cell can utilize the methane present in biogas using integrated heat, power, and hydrogen systems. A study was performed on both energy flow and resource availability to ascertain not only the type but also the source of feedstock needed to run a fuel cell system continuously while maintaining maximum capacity. A hydrogen fueling infrastructure was also created for the northeastern United States. The infrastructure is to be implemented between 2013 and 2025. The design itself gives priority to customer convenience with minimal additional investments. Extensive research has been done on a generating hydrogen supply from factories and other potential sources that can satisfy the demand in that region. Several markers (e.g., population density, traffic density, legislations, and growth patterns) have driven the process of estimation of the demand.

DEDICATION

I would like to dedicate this work to my parents for their continued support. Without their encouragements, I would not be able to accomplish and fulfill my dreams.

Unfortunately, both of them have passed away before and during my study at Missouri S&T. I owe a debt of gratitude to my parents which I can never repay.

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I would like to express my gratitude to the Department of Mechanical and Aerospace Engineering at Missouri University of Science and Technology. My graduate research assistantship within this department provided me with financial support during my academic studies.

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TABLE OF CONTENTS

Page

SECTION

PAPER

SECTION

LIST OF ILLUSTRATIONS

Page

Paper I

Paper II

LIST OF TABLES

Page

Paper I

Paper II

SECTION

1. INTRODUCTION

1.1. BACKGROUND

The use of energy around the world is continuously growing. According to the International Energy Outlook 2012 by the U.S. Energy Information Administration (EIA), the U.S. Energy Information Administration predicted that the total world energy demand will increase from 2008 to 2035 by approximately 44%. In the other sense, the world energy will rise from 505 quadrillion British thermal units (Btu) that is 18389 gigawatt-years (GWy) in 2008 to 770 quadrillion Btu (25744 GWy) in 2035 [1]. Fossil fuels, including liquid fuels, natural gas, and coal, are predicted to supply approximately 80% of the world's energy by 2035 [2]. Unfortunately, this increase in energy will also increase emission. These emissions are the world's energy-related carbon dioxide expected to increase from 30.2 billion metric tons in 2008 to 43.2 billion metric tons by 2035 [2].

Fossil fuel-based energy carriers that are currently satisfying most of the world's energy demands, in both developed and developing countries, are becoming depleted. Political unrest in the supply regions has many nations turning to homegrown energy resources. The global warming created by the use of fossil fuels has not only limited the options for possible energy sources but also constrained greenhouse gas (GHG) emissions. The estimated fuel economy and greenhouse gas emissions standards proposed for light-duty vehicles (LDVs) for model years 2017-2025 have an increase of 44% in fuel economy and a reduction of 34% in GHG emissions [1]. These GHGs can do irreparable damage to the environment [3]. These environmental consequences have reached a level of impact that forcing governments to take action.

The transportation sector in the United States consumed 94 percent of the petroleum supplied in 2008 [4]. Roughly 33% of all GHG emissions in the United States are from the transportation sector. This amount of emissions has been increasing at an average of 1.7 % annually since 1990 [5]. More than 90% of total local GHG emissions are the result of fossil fuel consumption [6]. The U.S. Department of Energy is working to reduce carbon emissions from the transportation sector by 80% by 2050.

The number of hydrogen fuel cell vehicles must be increased in the transportation sector if GHG emissions are to be reduced significantly. Fuel cell vehicles were introduced commercially by different major car manufacturers by 2015 [5]. Hydrogen derived from renewable energy sources is a practical solution. It can serve as a sustainable energy provider while leaving a zero-carbon footprint at its point of use [17, 8].

Kim and Moon [9] discussed the effect of using hydrogen within Korea's transportation sector. They found that hydrogen production from renewable and nuclear resources is a practical possibility that could cover 76% of the road transportation sector by 2044. Nel and Cooper [10] predicted the energy resources, considering the logistics of fossil fuel reserves and institutional intelligence, for both the nuclear and the renewable energy sector. Chiari and Zecca [11] discussed emission control policies that were implemented for three emission scenarios (high, medium and low) on three different dates (2025, 2100 and 2200). They realized that the atmospheric CO_2 concentration could reach a climax of 500 ppm, below projections of high emission scenarios of 540 ppm.

Shafiee and Topal [12] presented a new formula that can be used to calculate fossil fuel reserves. They calculated fossil fuel depletion time using two methodologies, a modified Donald Klass'formula in order to compute fossil fuel depletion and calculating the time that fossil fuels depleted by computing ratio of consumption to reserves. They examined fossil fuels, oil and gas, estimating that depletion would continue for 40 and 70 years, respectively. The use of both alternative fuel vehicles and renewable energy sources is therefore necessary toward achieving this goal.

1.2. LITERATURE REVIEW

Researchers have clearly identified a need for renewable energy technologies. Hall [13] presented a strategy that uses renewable energy sources as a low-carbon energy strategy developed up to 2050. This strategy should be deployed on a large scale to avoid a scenario in which global warming is increased. Renewable energy (e.g., regional wind and marine clusters) can produce for large-scale. A renewable infrastructure is its primary obstacle.

Hydrogen derived from renewable energy sources is a practical solution to the present day problems associated with greenhouse gas emissions and the world's dependence on fossil fuels. It can serve as a sustainable energy provider while leaving a zero-carbon footprint at its point of use. Koplow and Dernbach [14] discussed increasing global efforts to restrain GHG emissions. The United State government subsidized fossil fuel production and consumption, a conflicting action to the reduction of GHG emissions. Dhillon and Wuehlisch [15] estimated that the emission of CO_2 is the primary contributor to global warming, responsible for approximately 60% of the problem. The global surface temperature is currently0.8 ˚C. it is expected to increase between 1.4 and 5.8 ˚C during the twenty-first century.

Dorian, Franssen and Simbeck [16] identified four critical challenges in energy: adapting to a decrease in oil reserves, achieving energy security, combating environmental degradation, and meeting the growing needs of a developing world. a transition to a non-carbon-based global economy would help with overcoming these challenges.

Correlje and Lindewe [17] examined the consequences of geopolitical developments for the security of oil and natural gas supply and the adequacy of potential policy instruments in the context of two contrasting storylines along which the world system may develop. These are known as Markets and Institutions and Regions and Empires, respectively.

Poeschl, Ward and Owende [18] conducted a life cycle assessment of multiple biogas production and utilization pathways. They worked to identify areas of potential environmental impacts and their mitigation strategies to enhance the environmental sustainability of biogas deployment. This life-cycle assessment utilized an anaerobic digester as its functional unit. The digester needs a 1 ton feedstock mixture to produce biogas. This study provided important conclusions on the impact of feedstock types, the utilization of biogas pathways, and the necessity of digestate process and handling units. Poeschl, Ward and Owende [18] also examined the replacement of fossil fuels and chemical fertilizers with equivalent energy values of biogas and nutrient content of the digestate, respectively.

Zhao and Melaina [19] discussed existing alternative fuel vehicle (AFV) programs currently in use in both the United States and China. Lessons learned during the deployment of AFVs were utilized to suggest necessary policy recommendations, thus allowing for China’s effective transition to hydrogen vehicles.

Research on the implementation of hydrogen as an energy carrier in the transportation sector has been rather limited. Even with the introduction of the ‘Transition to Hydrogen Economy’ initiative nearly a decade ago, the present market for hydrogen is more focused on refining and chemical processing. A hydrogen fueling infrastructure has slowly begun to emerge in the United States. This country currently contains approximately 60 hydrogen fueling stations. Approximately 23 of these stations are located in the state of California itself. Of the available 60 fueling stations, approximately 50 are nonretail-ready. Leading vehicle manufacturers consider hydrogen to be a practical solution to the world energy crises and also to be a viable solution for the problems associated with greenhouse gases. the automobile industry has been limited in its introduction of hydrogen fuel cell vehicles because so few fueling infrastructure exist. In summary, a hydrogen fueling infrastructure needs to be developed in the United States [20–24].

1.3. OUTLINE OF DISSERTATION

The following section of this dissertation is composed of two journal articles. These papers embrace the use of different alternative energy technologies in real-world applications. Each paper contains a literature review that is related to that paper topic.

The first paper included is “Molten Carbonate Fuel Cell Combined Heat, Hydrogen and Power System: Feedstock Analysis.” This study was focused on concerning energy flow and resource availability to ascertain both the type and source of feedstock to run a fuel cell system unceasingly while maintaining maximum capacity. The results of this study were used to identify a FuelCell Energy 1500 unit (a molten carbonate fuel cell) that can meet 91% of the fuel requirements on campus. This particular fuel cell will provide electric power, thermal energy to heat the anaerobic digester, hydrogen for transportation, auxiliary power to the campus, and myriad possibilities for more applications.

The second paper included is “A Design for Hydrogen Production and Dispensing for Northeastern United States, Along with its Infrastructural Development Timeline.” This work was conducted in an effort to provide an introductory feasibility study that addressed the implementation of a hydrogen fueling infrastructure in the Northeast quadrant of the United States. It was a collaborative effort between the H_2 Design Solution Team at Missouri University of Science and Technology (Missouri S&T). The research was focused on the mass production of hydrogen. The research utilized the naturally occurring methane from biomass waste that is commonly referred to as the Landfill Gas-Hydrogen. Several hydrogen processes were identified. Various strategies are provided here for the implementation of a sustainable hydrogen energy supply in the Northeast quadrant of the United States.

This paper also includes discussions that are focused on desirable production facility characteristics, potential locations, and optimum fueling station sites. A discussion on transportation, storage and dispensing equipment, and imperative codes and standards is also included. A detailed infrastructural developmental timeline is provided to ensure a continuous supply of hydrogenthat meets expected demand for a period of 13 years (from 2013 through 2025). Finally, illustrative design layouts are provided for nonspecific hydrogen production and fueling facilities. The design presented herein prioritizes customer convenience and minimizes capital expenses.

PAPER

I. Molten Carbonate Fuel Cell Combined Heat, Hydrogen and Power System: Feedstock Analysis

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ABSTRACT

Biogas is an untapped potential in regards to an alternative energy source. This immediately available resource will allow countries to reduce their greenhouse gas emissions, energy consumption, and reliance on fossil fuels. This energy source is created by anaerobic digestion of feedstock. Sources for feedstock include organic and inorganic waste, agricultural waste, animal by-products, and industrial waste. All of these sources of biogas are a renewable energy source. Specifically a fuel cell can utilize the methane present in biogas using integrated heat, power, and hydrogen systems. A study was performed concerning energy flow and resource availability to ascertain the type and source of feedstock to run a fuel cell system unceasingly while maintaining maximum capacity. After completion of this study and an estimation of locally available fuel, the FuelCell Energy 1500 unit (*a molten carbonate fuel cell*) was chosen to be used on campus. This particular fuel cell will provide electric power, thermal energy to heat the anaerobic digester, hydrogen for transportation, auxiliary power to the campus, and myriad possibilities for more applications. In conclusion, from the resource assessment study, a FuelCell Energy DFC1500^{TM} unit was selected for which the local resources can provide 91% of the fuel requirements.

KEYWORDS: Molten carbonate fuel cell, tri-generation and feedstock.

INTRODUCTION

Biogas is a potentially enormous source of renewable energy. It is produced by the anaerobic digestion of wastewater, organic and inorganic waste, agricultural waste, industrial waste, and lastly animal by-products. Biogas can be treated to produce Hydrogen, Power and Heat (CHHP) by utilizing a molten carbonate fuel cell. This paper will examine the development of a CHHP system at the Missouri University of Science and Technology (Missouri S&T) campus located in Rolla, Missouri, USA. The CHHP system is capable of producing enough power for the campus so that air pollution will decrease; in turn, making the community healthier (Hamad, el al., 2013; Agll, el al., 2013; Yu, el al., 2013). The electric power purchased by campus will consequently reduce. An additional benefit of the CHHP system is the higher efficiency at which it operates compared to other distribution plants of similar dimensions. The hydrogen produced can be a power source for diverse purposes on the university campus. These can include but are not limited to personal transportation, reserve power supplies, portable power, and mobility/utility applications. Within the vicinity of the Missouri S&T campus are a variety of feedstock that can be utilized for consumption to produce biogas were ascertained. A study on energy flow and resource availability was executed to pinpoint the type and source of feedstock necessitated to continuously run the CHHP at maximum capacity to produce electricity, heat recovery, and hydrogen (Pecha, et al., 2013; Braun, 2010; Ghezel-Ayagh, McInern, Venkataraman, Farooque, & Sanderson, 2011).

1. BACKGROUND

The Missouri S&T campus is one of four universities within the University of Missouri system, which includes UM Columbia, UMSL, and UMKC. The campus is comparatively smaller than the other three with only 284 acres (1.15km2). Roughly 6,760 students attend Missouri S&T in Rolla, Missouri, which has a population of 20,000. This is a diminutive city in a rural area located on Interstate 44 between Springfield and St. Louis, Missouri. One of the largest purchasers of electricity from the city of Rolla is Missouri S&T. The yearly consumption of power is approximately 2.6 GWh/yr. The greatest demand for electricity is expressed as 6.4 MWe. Presently the electrical power consumed at the university is acquired from Rolla Municipal Utilities (RMU). This power is then allocated from the substation and switchgear situated at the campus power plant. The university also produces electricity using a thermal power plant that employs a backpressure steam turbine, which accounts for a supplementary 10% of electricity. The university power plant was constructed in 1945 and is fueled by coal and woodchips. This fuel delivers steam to the University for space heating, chilled water via absorption chillers, and backpressure steam turbines. The research exhibited in this paper was implemented as a piece of the 2011-2012 Hydrogen Student Design Contest. The contest regulations stipulate the use of FuelCell Energy fuel cell and biogas with 60% methane and 40% carbon dioxide (Hamad, el al., 2013; Agll, el al., 2013).

2. RESOURCE ASSESSMENT

2.1. Feedstock Source Identification

During the assessment, “locally available feedstock” was defined as one which is within 20 km of Rolla. The largest source of feedstock is Municipal Solid Waste (MSW) averaging 60 tons/day. Of this, approximately 33% is organic waste including 17% food waste. The campus plans to partner with the City of Rolla and will start an ‘‘Organic Waste Collection Program’’ to collect organic waste. Currently, the city offers residential curbside collection of recyclable materials at no extra cost. The second largest resource is the rejects and waste resulting from change over at the Royal Canin dog and cat nutrition company located in Rolla. The Royal Canin waste is currently disposed at a landfill facility 40 km from the company.

Potential feedstock from the campus includes food waste, sanitary sewer, and woodchips. Food waste collected daily is mixed with the trash and the sanitary sewer is connected to the city’s main sewer lines. Another potential feedstock source from the campus is unused woodchips that the campus will have available when the existing power plant is decommissioned as planned. Other feedstock considered in the analysis includes waste from the local winery and brewery, timber from Mark Twain National Forest (MTNF), and wastewater from the city treatment plant.

Based on the location of the feedstock two facilities were allocated. Facility A can be used for organic wastes. This feedstock will then undergo anaerobic digestion. Collection and anaerobic digestion of waste water will be off-campus at the treatment plant (Facility B).

2.2. Energy Conversions

After identifying the amount of feedstock, the amount of fuel that can be generated using anaerobic digestion was estimated (Salminen, & Rintala, 2002). Figure 1 illustrates the production of methane from the feedstock using an anaerobic digester (AD). This process utilizes a new technology which combines the separation of acid gases into a single pressure swing adsorption (PSA) unit. By combing these steps, this technology reduces capital and operating costs. The quantity of locally available feedstock and the estimated fuel production at each facility is tabulated in Table 1.

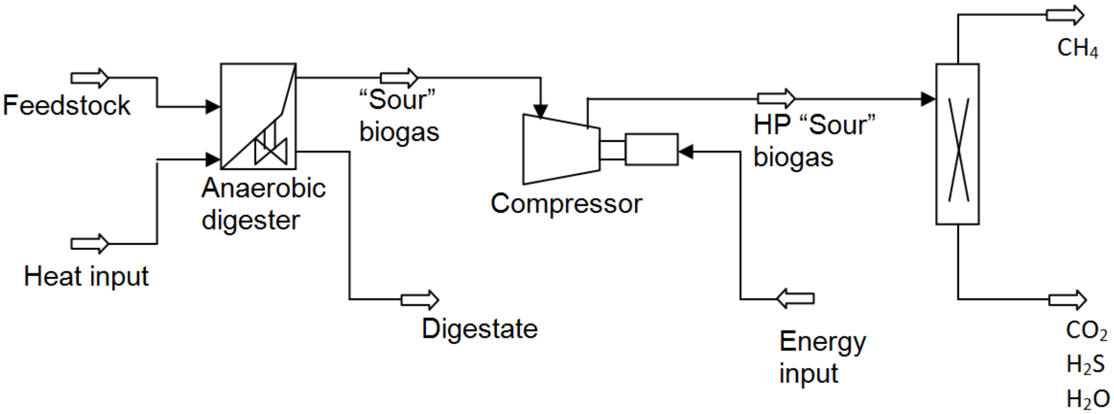

Figure 1 Process Model Developed in Aspen HYSYS®

Based on the equipment datasheet for DFC1500™ (Pecha, et al., 2013; Spencer, et al., 2013) 307 m^3/h of fuel is required with a heat content of 35 MJ/m^3. From Table 1, we can see that the available feedstock can readily supply this entire amount of fuel. However, because wood chips and timber have a slow digestion rate, the use of these may not be considered prudent. From the rest of the available feedstock 260 m^3/h of methane may be obtained at a heat content of 37.6 MJ/m^3, which is equivalent to 91% of the fuel cell requirement. Therefore, based on these calculations only one DFC1500™ can be installed in the Facility A. Also because of the low methane production at Facility B an investment of CHHP plant does not seem practical and therefore was avoided.

Table 1 Energy Conversions at Each Potential Facility

Facility	Type of feedstock	Quantity	Gas production /quantity	Equivalent methane		Refs.
				L/s	m^3/h	
A	MSW	17 tons/day[b]	0.22 m^3/kg ODS[d]	43.3	155.9	(Appels, 2011; Owens & Chynoweth, 1993)
	Dog cat food waste	7 tons/day	240 m^3/t FM[e]	19.4[a]	69.8	(Weiland, 2010)
	Food waste	2 tons/day	240 m^3/t FM[e]	5.6[a]	20.2	(Weiland, 2010)
	Wood chips	5 tons/day	0.13 m^3/kg ODS[d]	7.5	27	(Appels, 2011; Owens & Chynoweth, 1993)
	Grape skin, rice hull	4.5 tons/day (Aug-Oct)	0.28 m^3/kg ODS[d]	3.6	13	(Appels, 2011; Owens & Chynoweth, 1993)
	Vines	0.5 tons/day (Dec-Feb)	0.12 m^3/kg ODS[d]	0.2	0.7	(Appels, 2011; Owens & Chynoweth, 1993)
	Brewery waste	0.25 tons/week	0.39 m^3/kg ODS[d]	0.2	0.7	(Appels, 2011; Owens & Chynoweth, 1993)
	Timber	5 tons/day	0.13 m^3/kg ODS[d]	7.5	27	(Appels, 2011; Owens & Chynoweth, 1993)
	Sub total			87.3	314.3	
B	Waste water	14,320 m^3/day	2 m^3/h biogas gas per 0.455 m^3	5.7[a]	20.5[a]	

a Assuming biogas yield consist of 60% methane by volume and 90% methane recovery from the PSA unit.

b With 85% collection rate.

c Annual average.

d Methane yield

e Biogas yield

3. COMBINED HEAT, HYDROGEN, AND POWER SYSTEM TECHNICAL DESIGN

The design presented in this paper consists of an anaerobic digestion system, a combined heat, hydrogen and power unit and hydrogen post-processing system (Hamad, el al., 2013). These systems were designed based on the results from the feedstock assessment and the expected biogas production from local resources (Hamad, el al., 2013). Consequently, a DFC1500^{TM} unit was selected for the CHHP system for which local resources can provide 91% of the fuel requirements. The daily unmet fuel need will be supplied by natural gas purchased from the local utility company.

3.1. Site Plan and Location

The selected location to install the system is adjacent to the existing 'Alternative Fuels Station' and future 'Green Hotel and Convention Center' in the Campus Master Plan developed in 2009. By doing so, the design is compliant with the University's Master Plan and maximized the chances for implementation. Currently, Missouri S&T has a 350 bar hydrogen fueling station, an electric vehicle charging station, a hydrogen research and development garage, and a renewable energy transit depot in the alternative fuels station area.

The amount of feedstock and generate methane has a direct impact on the design and selection of the anaerobic digestion and combined heat, hydrogen, and power systems. The hydrogen post-processing system is designed considering the on campus demand, while, using a fuel utilization factor of 65% (Hamad, el al., 2013). The following section describes the major components of the AD and CHHP system.

3.2. Feedstock Delivery System and Storage

Section 2 provides the feedstock collection and transportation strategies. A steel building, figure 2, will be used for storage of this feedstock. The building is designed for avoiding any damage from external elements (Miao, el al., 2011). The storage facility contains a macerator to reduce the size of feedstock to be of diameter less than 0.05 m. This process helps in increasing the methane production. The macerator uses a 15 kW_e

Taskmaster® 1600 shedder from Franklin Miller Inc. (Iacovidou, Ohandja, Gronow, & Voulvoulis, 2012).

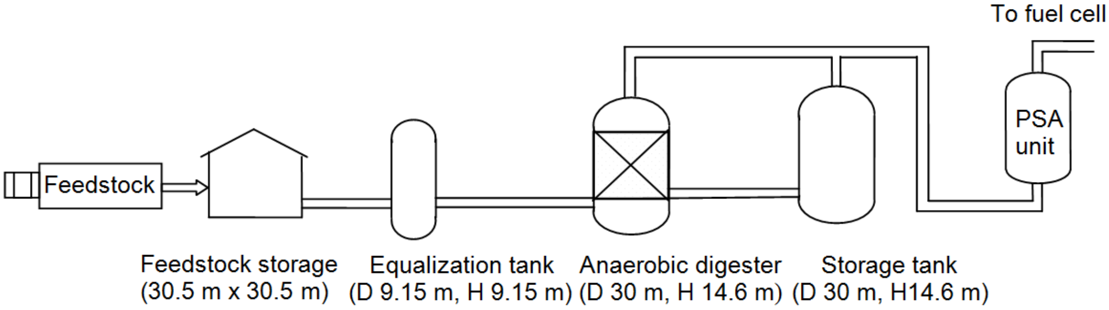

Figure 2 Conversion of Feedstock into Biogas

3.3. Feedstock-to-Fuel Conversion System

The process flow of the feedstock-to-fuel conversion can be seen in Figure 2. Initially the feedstock is kept in a storage silo, made of cement, and later is transferred to the hygienisation unit. This transfer is performed using a screw feeder. The temperature of the feedstock is raised to 70 ^{0}C in this process, while, being cured for one hour. The elevated temperature curing allows for the elimination of the pathogens (Hamad, el al., 2013; Agll, el al., 2013). The feedstock is then sent to an equalization tank wherein this biomass is mixed to create a homogenous mixture. This homogenous mixture is then fed to the AD, a complete-mix type from Siemens (Refer Table 2 for its details). The digester is jacketed at 40 ^{0}C. The digester contains a reliable JetMix™ Vortex Mixing system. This system performs intermittent mixing while suspending the organic and inorganic wastes. The mixing system is not affected by the tank level and also reduces dead spots. The system also has the capability to mix multiple tanks using central pumping facility. This reduces the total equipment cost of the digester system.

Table 2 Digester Data

Tank side water depth	12.8 m
Tank wall height (below grade)	14.6 m
Tank diameter	30.5 m
Cone per tank	892 m^3
Tank wall thickness	0.30 m
Floor slope	1:6
Quantity of solids to digester	27×10^3 kg/day
Detention time	20 days
Volatile solids concentration	80%
Anticipated solids reduction	50%
Anticipated gas yield	0.93 m^3/kg VS destroyed
Anticipated biogas production	425 m^3/h
Anticipated natural gas equivalent	260 m^3/h
Volatile Solids (VS)	

Using the above procedure, we get biogas, digestate and water (Holm-Nielsen; Al Seadi; Oleskowicz-Popiel, 2009). The digestate is then sent back to the storage tank, later collected and transported to the facility. This storage tank is also an insulated concrete tank which can also hold biogas in case the allocated biogas storage tank is full.

3.4. Gas Treatment System and Fuel Storage

The gas treatment system uses the biogas from the anaerobic digestion system as its input feed. The gas treatment system is comprised of the PSA unit that helps in deriving pure form of methane (Hamad, el al., 2013; Agll, el al., 2013; Krishna, 2012; Adhikari & Fernando, 2005; Locher, & Meyer, & Steinmetz, 2012). The design has a total of four adsorbers to ensure a continuous stream of high quality methane. While carbon dioxide (CO_2), hydrogen sulfide (H_2S) and other impurities in one set of tanks are desorbing, biogas will be fed to the second set of tanks for adsorption. The product from this gas treatment system is pipe line quality natural gas which is fed into the fuel cell.

Even though the DFC® fuel cell units can handle 60% methane and 40% carbon dioxide without affecting its efficiency, the design included the PSA unit for the following reasons:

a. The DFC® fuel cell units cannot accept H_2S, water (H_2O), and other impurities in its input fuel. Therefore, biogas treatment is necessary before feeding it into the fuel cell under all conditions.

b. Inlet fuel pressure to the fuel cell should be between 2 – 2.4 bar. If the fuel contains 40% carbon dioxide, it will impact the sizing of the equipment downstream the fuel cell. For example, the design will require a higher capacity heat exchanger, water gas shift reactor, and hydrogen purification or separation system. The DFC1500™ requires 307 m^3/h of natural gas at 35 MJ/m^3. If biogas is utilized, the fuel cell system will require 477 m^3/h of biogas as fuel to operate. This will increase the size of the equipment downstream the fuel cell by 55% and will increase its capital cost which is not desirable.

c. The biogas output from the digester can vary due to disruption in the feedstock availability or other unforeseeable reasons. In this case, the system will have to use natural gas purchased from utility company to provide any unmet fuel demand by the fuel cell. It was estimated that the systems downstream the fuel cell will run at 78.5% of its normal capacity if the fuel quality changes from 100% biogas to 50% biogas and 50% natural gas.

d. The product gas from the PSA unit is expected to have an average heat content of 37 MJ/m^3 which is roughly equal to the average heat content of natural gas consumed in Missouri (38 MJ/m^3) through 2007–2010. Hence, the fuel cell unit will receive a consistent fuel throughout its operation.

An energy analysis that determined the net of fossil fuel savings, and the savings in green house gases, has been performed in detail. The same can be found in Agll et al (2013).

4. CONCLUSION

This paper provides the feedstock analysis and design of combined heat, power, and hydrogen systems to be used at a university campus. An energy flow and resource availability study was performed to identify the type and source of locally available feedstock, required to continuously run the fuel cell system at peak capacity. It was found that the anticipated methane production after biogas treatment is 260 m^3/h with a heat content of 37 MJ/m^3. Following the resource assessment study, a FuelCell Energy DFC1500^{TM} unit was selected for which the local resources can provide 91% of the fuel requirements. The CHHP system provides electricity to power the university campus, thermal energy for heating the AD, and hydrogen for transportation, back-up power and other needs.

5. ACKNOWLEDGEMENTS

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II. A Design for Hydrogen Production and Dispensing for northeastern United States, along with its Infrastructural Development Timeline

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ABSTRACT

Countries are trying to reduce their energy consumption, fossil fuel usage, and greenhouse gas emissions. Recent guidelines generated by various government agencies indicate an increase in the fuel economy, with a reduction in green house gases. The use of both alternative fuel vehicles and renewable energy sources is thus necessary toward achieving this goal. This paper proposes a hydrogen fueling infrastructure design for the Northeastern United States. The design provides an implementation plan for a period of 13 years (from 2013 to 2025). This design gives priority to customer convenience with minimum additional investments for its implementation. Extensive research has been conducted on generating a hydrogen supply from factories and other potential sources that can satisfy demand in the region. Markers (e.g. population density, traffic density, legislation, and growth pattern) have driven the process of demand estimation.

Keywords**:** Hydrogen vehicles; renewable energy; dispensing; Infrastructure.

Introduction

Fossil fuel-based energy carriers that are currently satisfying most of the energy demands, in both developed and developing countries; are becoming depleted. Political unrest in the supply regions has many nations turning to home energy grown resources. Global warming caused by the use of fossil fuels has not only limited the options for possible energy sources but also constrained greenhouse gas (GHG) emissions. The estimated fuel economy and greenhouse gas emissions standards proposed for light-duty vehicles (LDVs) for model years 2017-2025 have an increase of 44% in fuel economy and a reduction of 34% in GHG emissions [1]. The Use of both alternative fuel vehicles and renewable energy sources is therefore necessary toward achieving this goal. Hydrogen derived from renewable energy sources is a practical solution to this problem. It can serve as a sustainable energy provider while leaving a zero-carbon footprint at its point of use [2, 3]. Kim and Moon [4] discussed the effect of using hydrogen in the transportation sector of Korea. They found that hydrogen production from renewable and nuclear resources is a practical possibility that could cover 76% of the road transportation sector by 2044.

Surveys conducted in the United States have also suggested a similar trend, projecting a substantial increase in the use of hydrogen powered fuel cell vehicles. Feasibility studies on basic infrastructural needs have become extremely essential to the success of this shift. Approximately five years ago, designing a Hydrogen Community [5] conducted a feasibility study on the implementation of a hydrogen fueling infrastructure for the state of California. This study systematically determined the optimum fueling method, its storage and dispensing, and the cost incurred to the end user. Although this model study can be modified to determine the best practices for the implementation of a hydrogen infrastructure across the entire United States, the unique geographical characteristics of various regions do not allow such.

California is located close to a petroleum rich portion of the United States. This location allows the state to utilize the hydrogen production facilities already available in the vicinity. Hydrogen production infrastructures are not so readily available in other portions of the country. Thus, a region-specific feasibility study is needed to determine a successful method of implementation.

This study focused on the northeast quadrant of the United States. This region does not contain any petroleum resources and, as a result, cannot readily produce hydrogen. This work examined the geographical characteristics of the region to provide an optimum method of hydrogen production, transportation, storage, and dispensing. The results indicate that the hydrogen produced from biomass may be best approach for the northeast of United States. They also suggest that liquid hydrogen transport and storage facilities when the resources are scattered. Additionally, the hydrogen should be dispensed in a gaseous form to avoid the safety concerns related to liquid hydrogen [6, 7].

Hydrogen has long been known to be an energy carrier. Holladay et al. [8] and Bicakova and Straka [9] compiled a wide range of hydrogen production technologies, including fuel processing, biological conversion, and thermo-chemical conversion processes. They also suggest that biomass, in the near term, is most likely the renewable organic substitute to petroleum. Ni et al. [10], Kalinci et al. [11], and Kirtay [12] examined hydrogen production technologies that use biomass as the raw material. They discussed the alternative thermochemical and biological processes used to convert (abundantly available) biomass to produce clean hydrogen. Based on their analyses, they suggested the use of gasification rather than using the pyrolysis process. A novel gasification process known as Reaction Integrated Novel Gasification was also proposed. This work, however, was done at a laboratory scale. Balat and Kirtay [13] presented a discussion on the viability of hydrogen production from biomass. They suggested that, because of the lack of a hydrogen infrastructure, it is advisable to begin with steam methane reforming and then gradually move towards hydrogen production from biomass.

Bjorklund et al. [14] examined a possible enhancement of waste management and transportation by integrating two emerging technologies, municipal solid waste (MSW) gasification and fuel cell vehicles (FCVs). They propose fueling FCVs with hydrogen produced from gasified MSW through 2010-2020. Material and energy flows are modeled for MSW management scenarios and transportation scenarios. Bjorklund et al. [14] suggested that when compared to incineration and landfilling, gasification is not only more efficient but also more environmentally friendly.

Demirbas et al. [15] discussed possible methods that can be used to convert organic wastes into biofuels. They suggested that waste to energy technologies can be used to produce biogas, syngas, liquid biofuels, and pure hydrogen. They examined that biomass can be considered as the best option and also discussed the most potential for meeting the future fuel demands.

Many researchers have provided strategies that would allow an effective introduction of hydrogen in the transportation sector. Gim et al. [16] provided a mathematical model to suggest a strategy for implementing a cost-effective centralized hydrogen supply system. They also provided an estimation method for hydrogen demand that can be used to predict what fuel cell cars that will reach the markets. Based on these estimations, Gim et al. [16] suggested a decentralized hydrogen production in terms of on-site hydrogen production until 2040, and centralized production and distribution after that. Considering the already available pipeline network, they suggested the use of pipeline distribution after the year 2040.

Farrell et al. [17] studied the impact of hydrogen fuels on numerous factors, including the fuel transition period, vehicle design, usage patterns, infrastructure development, and operational challenges. They provided a strategy that introduces hydrogen as a transportation fuel. They also recommended beginning the implementation with heavy-duty vehicles. Experiences incurred with this implementation can be used to wisely introduce it for low duty vehicles.

Zhao and Melaina [18] discussed the findings of existing alternative fuel vehicle (AFV) programs in the both US and China. Lessons learned in the deployment of AFVs were provided and utilized to suggest necessary policy recommendations, thus allowing for China's effective transition to hydrogen vehicles.

Research on the implementation of hydrogen as an energy carrier in the transportation has been rather limited. Even with the introduction of 'Transition to Hydrogen Economy' initiative about a decade ago, the present market for hydrogen is more focused towards refining and chemical processing. Hydrogen fueling infrastructure in the United States has just slowly begun to emerge. Currently the Unites States contains about 60 fueling stations. About 23 of these hydrogen fueling stations are located in the state of California itself. From the available 60 fueling stations about 50 stations are nonretail-ready. Leading vehicle manufacturers consider hydrogen as a practical solution to the world energy crises, and also a viable solution for the problems associated with greenhouse gases. In absence of the fueling infrastructure, the automobile industry has been limited in its introduction of hydrogen fuel cell vehicles. In summary, there is a need for a development of hydrogen fueling infrastructure [19–23].

This work attempts to provide an introductory feasibility study for the implementation of the hydrogen fueling infrastructure in the northeast US. This work was a collaborative effort between the H2 Design Solution Team of Missouri University of Science and Technology (Missouri S&T) thus far. It focused on the mass production of hydrogen, utilizing the naturally occurring methane from biomass waste (commonly referred to as Landfill Gas-Hydrogen). Several hydrogen processes were identified. Various strategies are provided here for the implementation of a sustainable hydrogen energy supply in the Northeast quadrant of the United States. This paper also discusses desirable production facility characteristics, evaluates potential locations, and provides a list of optimum fueling station sites. A discussion on transportation, storage and dispensing equipment, and imperative codes and standards is also included. A detailed infrastructural developmental timeline is provided to ensure a continuous supply of hydrogen, meeting the expected demand for a period of 13 years (from 2013 through 2025). Finally, illustrative design layouts are provided for nonspecific hydrogen production and fueling facilities. The design presented herein prioritizes customer convenience while minimizing capital expenses.

Background

Missouri S&T is the home of Missouri's only hydrogen production and fuel dispensing station. The station is a high pressure, three-stage dispensing facility that produces 4kg of hydrogen per day. The current configuration provides hydrogen fuel at 5000 psig. The Missouri S&T design team has learned the pragmatic nature of this technology with a prototype fuel cell, plug-in, hybrid electric (FC-PHEV) power train vehicle. The H2Design Solution team has been a successful participant of the Hydrogen Student Design Contest. The H2 Design Solution team has consistently placed in the top five finishing teams.

The feasibility study presented in this paper was a part of the hydrogen student design contest submission for the year 2012-2013. The contest managing committee provided the hydrogen demand data for a time period of 13 years (from 2013 to 2025). This data is listed in Table 1. The feasibility study presented here is based on this data. Constraints were generated for hydrogen production, storage, transportation, and dispensing to determine the most suitable pathway for implementing a hydrogen fueling infrastructure in three phases: the early adoption phase, the market penetration phase, and the commercialization phase. The best possible hydrogen production, storage, and transportation methodologies are identified. A detailed list of feed stock sources and fueling locales that can meet these constraints is also identified. This data was used to generate an infrastructure development timeline.

Table 1 – Estimated demand for hydrogen from 2013 to 2020.		
Year	Estimated average (kg per day)	Estimated average (kg per year)
2013	20	7,320
2014	100	36,600
2015	500	183,000
2016	2,000	732,000
2017	7,500	2,745,000
2018	22,500	8,235,000
2019	60,00	21,960,000
2020	150,000	54,900,000

Hydrogen Source Identification

A thorough study of all possible hydrogen production processes was conducted to determine the most optimal process available. It was demanded that are no hydrogen producer currently in use is capable of satisfying the demand during 2013-2025 timeframe. The largest existing production facility in the area was commissioned in 1982 and expanded in 1993. Praxair, Inc. (in Niagara, NY) can produce 36,000 kg of liquid hydrogen per day [24]. In this study, it was considered to have an existing customer base. Thus, the company would need to grow to support the needs of this project. In the following paragraphs, additional hydrogen production technologies are examined so that a technology can be identified that is suitable for implementation in the northeastern United States.

Hydrogen is the most abundant element in the universe. Unfortunately, it is not found alone on earth. Hydrogen production occurs by any one of several processes, having a variety of feedstock types that produce hydrogen along with by-products. Table 2 provides an extensive list of hydrogen production processes with their acceptable feedstock types and byproducts.

Table 2 – Hydrogen production methods and their feedstock.

Hydrogen production method	Feedstock	Byproduct
Gasification	biomass, petroleum, coke, and coal	CO, CO_2
Steam methane reforming	natural gas	CO_2
Electrolysis	water	O_2
Methanol reforming	methanol	CO_2
Gasoline reforming	gasoline	CO, CO_2

Gasification is a process whereby either organic or fossil based carbonaceous materials are converted into methane, carbon monoxide, hydrogen and carbon dioxide. One disadvantage of this method is the production of carbon dioxide as a by-product. Gasification is relatively expensive and only about 45% efficient [25]. Steam methane reforming is the conversion of natural gas into hydrogen and carbon monoxide. It is currently the primary source of hydrogen production. It does produce GHG, utilizing a nonrenewable fossil feedstock, and an efficiency of 65% [26].

Electrolysis is only clean source of hydrogen production currently available. Greenhouse gas (GHG) emissions from this process can be eliminated when the processes of breaking water into hydrogen and oxygen is performed with renewable electricity, e.g. solar-hydrogen. Solar energy generates electricity for the electrolysis process, producing hydrogen as a result.

Methanol reforming converts methanol to both hydrogen and carbon dioxide through a reaction with steam. Similarly, a gasoline reformer [27] uses vaporized gasoline, steam, and air passed through a catalyst-packed cylinder to produce a mixture of gases with a high enough hydrogen concentration to power a fuel cell. Carbon monoxide also present in this gas mixture passes through a secondary processor. Introduced to water vapor, it forms carbon dioxide with additional hydrogen.

These hydrogen production methods can be separated into two categories:

- Centralized installation facility

- On-site installation facility

Steam methane reforming, methanol, and gasoline reforming are suited to an on-site installation. Gasification, steam methane reforming, and electrolysis may have a centralized installation. Differences inherent in these installations are advantageous at different times in the hydrogen adoption process. During the early adoption phase, initial hydrogen demand is low and can be met easily using an on-site installation. A centralized facility requiring high capital expenditure is not recommended to satisfy the low demands associated with the early adoption phase. As hydrogen's acceptance drives the demand for it, a central installation will be more capable of satisfying demand.

The use of Pugh chart aided in the identification of the best production technique available for each of these two installations as shown in Table 2. These techniques are rated from one to three (where one is the lowest and three is the highest), allowing for the prioritization of criteria to reflect in the total score. The criteria selected for the evaluation of hydrogen production techniques used by an on-site installation was as follows:

- Cost of additional infrastructure: An on-site installation is only applicable in the early adoption phase, and a smaller investment will provide a higher rate of return. This investment includes additional storage and equipment required for hydrogen production. The most affordable infrastructure identified in this study weighted three.
- Time for commissioning: Success of the early adoption phase relies on the immediacy with which the hydrogen production process can be expedited. Accelerated commissioning was awarded a weight of three.
- Feedstock availability: A technology using an easily obtained feedstock is preferred. A weight of two was assigned for this criterion.
- Cost of hydrogen per kilogram: A technology that is well-proven will have a relatively low cost of production as compared to a technology that is in its research phase. A more affordable technology is preferred. A weight of two was assigned for this criterion.

Table 3 – Pugh chart identifying the best possible on-site hydrogen production method.

Criterion	Weight	Steam methane reforming	Methanol reforming	Gasoline reforming
Cost of additional infrastructure	3	-	-	+
Time for commissioning	3	+	-	+
Feedstock availability	2	+	-	+
Cost of hydrogen per kilogram	2	++	-	--
Total score		6	-10	4

The criteria selected for the evaluation of hydrogen production techniques used by a centralized installation was as follows:

- Type of feedstock required: The overall cost of producing hydrogen is reduced when its feedstock does not require additional processing. In this study, feedstock carried a weight of three.
- GHG emission: The most preferred hydrogen production method is that with the lowest GHG emission. Here, emission had a weight of two.
- Secondary benefit: A production technique with the secondary benefit of a useful by-product was weighted three.
- Cost of production, transportation, and storage: A lower cost to manufacture will result in more affordable hydrogen for the consumer. The modes of transportation and storage considered were the same for all methods to maintain consistency. Liquid tankers were the preferred transportation, and the cryogenic storage of liquid hydrogen was favored. The direct impact on the end-user cost made this criterion a priority, thus earning a weight of three.
- Process efficiency: An efficient process has a positive effect on the total cost of production. Here, it was given a weight of two.

Table 4 – Pugh chart identifying the best possible centralized hydrogen production method

Criterion	Weight	Steam methane reforming	Gasification (renewable)	Electrolysis
Type of feedstock required	3	-	+	+
GHG emissions	2	-	-	+
Secondary benefits	3	-	++	-
Combined cost of production, transportation, and storage	3	++	+	-
Efficiency	2	+	-	+
Total score		0	8	1

The combined data listed in the above Pugh charts suggests that steam methane reforming be used during the early adoption phase using on-site installation facilities. The gasification of renewable sources becomes favored as consumption requirements increase, and the primary hydrogen production method shifts to centralized installation facilities. Renewable sources of biogas were utilized in this design to produce hydrogen, heat, and electricity [26] by using fuel cells. Excess electricity produced is recommended to generate additional hydrogen through the electrolysis of water.

Tables 5 and 6 provide extensive lists of both renewable feedstock sources and their locations. Referring to Table 6 and the studies presented in [26, 28–31], the wastewater treatment plants should be used only as secondary sources of hydrogen. The abundant organic waste available from the densely populated region will satisfy projected energy needs. The estimated average hydrogen production (kg/day) for the northeastern portion of the US is provided in Table 7. This estimation calculated from the data in Table 5 and the method presented in [26, 28–31] assumes that 30% of the total waste currently available (tons/year) is organic. Table 7 provides a conservative estimate of potential hydrogen production per day, which also considers future population growth.

Table 5 – Comprehensive list of biomass sources and their locations in northeast U.S.

Label	PA[a]	Capacity (tons/year)[d]	NY[a]	Capacity (tons/year)[d]
A	Taylor	826,659	University of Bridgeport	[c]
B	Washington	58,590	Auburn	37,800
C	Bethlehem	94,724	Boonville	200,000
D	Easton	54,270	Bath	75,632
E	Hegins	741,893	Binghamton	166,667
F	Morgantown	1,069,342	Chaffee	314,904
G	Shippensburg	149,967	Jamestown	190,323
H	Conestoga	441,586	Morrisonville	191,581
I	Plainfield Township	352,908	Rodman	382,080
J	Lebanon	30,559	Walton	25,943
K	Morrisville	757,132	Johnstown	43,412
L	Imperial	207,906	Albany	445,571
M	Zelienople	62,022	Monroe	787,245
N	Dunmore	1,793,422	Angelica	142,857
O	Erie	397,761	Canastota	66,316
P	Narvon	1,453,993	Bergen	541,813
Q	Johnstown	225,774	Niagara	777,517
R	Montgomery	491,965	Waterloo	2,491,212
S	York	323,457	Cohoes	101,463
T	Monroeville	116,541	Fulton	61,609
U	Somerset	1,099,387		
V	Greencastle	422,236		
W	Burlington	153,050		
X	Birdsboro	143,269		
Y	Evans City	152,998		
Z	Cairnbrook	418,671		
AA	Library	67,448		
BB	Davidsville	356,669		
CC	Irwin	98,696		
DD	Kersey	1,339,007		
EE	Mt. Jewett	35,518		

Table 5 Comprehensive list of biomass sources and their locations in northeast U.S. (cont.)

Label	MA [a]	Capacity (tons/year)[d]	MD [a]	Capacity (tons/year)[d]
A	Barre	37,979	University of Maryland College Park	[b]
B	Chicopee	153,402	Newark	56,575
C	Dartmouth	88,235	White Marsh	173,767
D	Westminster	103,763	Severn	78,065
E	Southbridge	96,875	Salisbury	23,822
F	Barnstable	12,987	Curtis Bay	393,785
G	Hampden	42,308	Frederick	91,637
H	Nantucket	12,369	Marriottsville	71,143
I			Waldorf	48,695
J			Hagerstown	55,567
K			Street	74,433
L			Elkton	73,678
M			Frostburg	106,663
N			Westminster	22,028
O			Oakland	31,534
P			Ridgely	67,500

[a] Only the sources available within the set time period selected. A number of other sources are currently operating. These sources however, are scheduled to shut down before 2015 and were thus omitted from this list.

[b] This facility is a conceptual design with a target production of 1300 kg of hydrogen per day [32].

[c] This facility is a conceptual design with a target production of 124 kg of hydrogen per day.

[d] The capacity (tons/year) of the waste was estimated by considering the total waste available now divided by the collection period (current date – start date of the landfill).

Table 6 – Comprehensive list of waste water treatment plants and their locations.

Label	Location in MA	Estimated waste water (MGD) [a]	Location in MD	Estimated waste water (MGD) [a]
A	Amherst	2.44	Baltimore	43.37
B	Ashfield	0.13	Easton	1.12
C	No. Billerica	2.73	Ocean City	0.50
D	Boston	43.76	Salisbury	2.13
E	Bridgewater	1.76		
F	Brockton	6.60		
G	Dartmouth	2.15		
H	South Deerfield	0.13		
I	Suffolk	51.17		
J	Edgartown	0.26		
K	Fairhaven	1.13		
L	Fall River	6.23		
M	North Andover	1.90		
N	Greenfield	1.27		
O	Haverhill	4.29		
P	Lowell	7.53		
Q	Millbury	0.89		
R	New Bedford	6.66		
S	Three Rivers	0.21		
T	Pittsfield	3.11		
U	Shelburne Falls	0.12		
V	Chicopee	3.87		
W	Springfield	10.72		

[a] The estimation of wastewater takes into account the population and average wastewater per person in US

Table 6 – Comprehensive list of waste water treatment plants and their locations (cont.)

Label	Location in NY	Estimated waste water (MGD) [a]	Location in PA	Estimated waste water (MGD) [a]
A	Brooklyn	87.51	Ambler	0.45
B	Astoria	156.16	Carlisle	1.34
C	Coney Island	4.20	Lancaster	4.20
D	Cortland	1.34	Philadelphia	107.56
E	Amherst	8.57	Pittsburgh	21.53
F	Auburn	1.93	Wilkes-Barre	2.90
G	Johnstown	0.61		
H	Bronx	97.45		
I	Jamaica	15.18		
J	Geneva	0.93		
K	Brooklyn	87.51		
L	Niagara Falls	3.51		
M	New York	577.19		
N	Staten Island	32.94		
O	Rockaway	9.10		
P	Schenectady	4.64		
Q	Syracuse	10.16		
R	Rochester	14.76		

[a] The estimation of wastewater takes into account the population and average wastewater per person in US

Table 7 – Estimated hydrogen and electricity production.

State	MA	MD	NY	PA	Total
Hydrogen (kg/day)	7,470	19,960	96,140	175,890	299,460
Electricity (kW/day)	16,090	42,990	207,110	386,940	653,130

The data listed in Table 7 suggests that the estimated hydrogen production from landfills will sufficiently accommodate the projected energy use.

The following hydrogen production methods are suggested for use during the various phases of transition to a hydrogen economy (based on the suggested hydrogen demand):

- On-site installation facilities with steam methane reforming are suggested for the early adoption phase (2013 to 2015).
- A combination of on-site installation facilities with steam methane reforming and centralized installation facilities with gasification is suggested during the market penetration phase (2015 to 2020).
- A complete transition to centralized installation facilities with gasification and electrolysis is suggested during the commercialization phase (2020 to 2025).

Fueling Locale Identification

All possible hydrogen fueling locales need to be evaluated according to the minimal existing hydrogen fueling infrastructure available in the northeastern US. Three considerations for a location's selection for candidacy include the following:

- The use of new investments to facilitate a custom set-up of the hydrogen fueling station,
- The use of an existing private and/or public hydrogen fueling facilities,
- The use of an existing private infrastructure for gasoline stations.

Northeastern portion of the US does not have any hydrogen fueling facilities open for public use. Existing facilities are used for private research only. However, these were not considered during the development phase presented in this paper. A Pugh chart using weights assigned to each of the criterion evaluates each candidate location according to the following considerations:

- Set-up time: The United States is only now beginning to transition to a hydrogen economy. The public will not accept any further delay caused by the lack of availability. One is the weight assigned.

- Accessibility: A facility that is easily accessible is preferred to one with a remote location. Both customer satisfaction and profit potential are directly related to accessibility. Accessibility is the most important factor. Accessibility was weighted three.
- Additional cost: A fueling station requires an investment in dispensing and storage. Additional costs include personnel wages, security system costs, and franchise fees. Fewer costs are preferred but do not relate to either customer adoption or satisfaction. Additional cost earned a weight of two.

Existing gasoline infrastructures should be used as they offer the most seamless transition from hydrogen. Previous efforts have proven to be successful. The accessibility of existing gasoline stations provides customer convenience and reduces the challenges of discontinuous innovation. The identification of market leader candidates for the installation of hydrogen fueling stations requires further research in the northeast region of the United States. Table 9 provides details on both the various market leaders and their available gasoline infrastructures.

Table 8 – Pugh chart for identifying strategy for fueling station locations.

Criterion	Weight	New installations	Existing hydrogen infrastructure	Existing gasoline infrastructure
Set-up time	1	-	+	+
Accessibility	3	+	-	+
Additional costs	2	-	-	++
Total score		-0	-4	8

Table 9 – Gasoline fuel stations in the northeast urban hubs for various market leaders.

	Washington DC	Philadelphia	New York	Boston	Total
Shell	359	136	338	160	993
BP	189	172	378	60	799
Exxon Mobil	312	164	397	79	952
Sunoco	211	340	301	128	980
7Eleven	431	211	340	118	1100

Shell is the only company having experience with combined gasoline and hydrogen fueling stations. It has a combined fueling station in Washington D.C. [33]. Shell is actively researching best practices for facilities combining gasoline and hydrogen fueling stations [34, 35]. Shell presently has around seven hydrogen fueling stations, one of it being the combined gasoline and hydrogen facility. Considering the company's research and developmental activities and the know-how of the technology this feasibility study has considered utilizing the Shell stations in the early adoption phase. Although other companies can also be a practical option, the most seamless transition from gasoline stations to hydrogen fueling stations may be achieved with the use of a tried and tested technology/facility, as the ones presented by Shell.

A comprehensive list of Shell Stations, their addresses, GPS locations, and contact numbers can be conveniently extracted from the Shell Station Finder web portal. Using this data and the following criteria the fueling locales have been selected.

- Traffic density: A station in the middle of the high traffic zone will get priority over a station in a low traffic density zone. Such a station will be able to provide hydrogen to almost all of the projected hydrogen vehicles and therefore would reduce the need for additional stations.
- Land availability: Based on the authors philosophy of combined gasoline and hydrogen stations, additional equipment for storage, processing, and dispensing will be required. These modifications will need sufficient space to ensure safety.

- Safety: Due to the high flammability of hydrogen, stations should be kept some distance away from the main streets. Vehicle accidents potentially leading to a severe thermal event are hazardous to the fueling station and the area immediately surrounding it.
- Population density: A station in a high population density zone is not preferred due to the high flammability of hydrogen.
- Source location: Source location has no effect on a on-site installation. For a centralized installation, fueling stations must be within a distance range allowing favorable transportation costs. Stations on highways will be given preference.
- Customer convenience: A station that is currently convenient to customers due to its strategic location is given preference over other stations.
- Proximity to other stations: A station that lies within the average radius of 1.5 miles of a selected station is not considered.
- Adherence to codes and standards: Stations should have sufficient space for safe installation of hydrogen storage and processing equipment. In addition the station layout should comply with the minimum code requirements. A nonspecific illustrative layout is provided for reference to facilitate the application of these criteria, Fig. 1. The station must provide sufficient separation between gasoline and hydrogen dispensers.

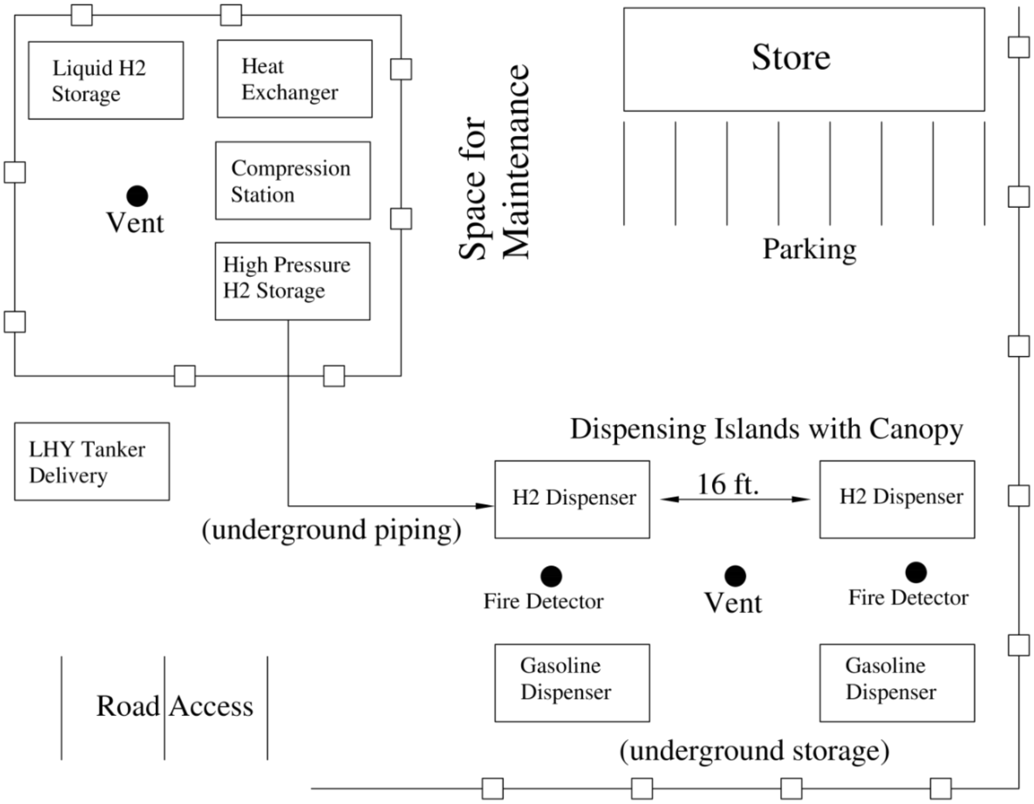


Figure 1 – An illustrative facility layout for combined gasoline & hydrogen fueling stations [36, 37].

Table 10 – Addresses of fuel locales for early adoption and market penetration phase.

Fuel station label	Near Boston, MA	Near New York City, NY	Near Philadelphia, PA	Near Washington, DC
A	655 William T Morrissey Boulevard, Boston, MA	1500 Bruckner Boulevard, Bronx, NY	1033 Kaighns Avenue, Camden, NJ	3355 Benning Road Northeast, Washington, DC

Table 10 – Addresses of fuel locales for early adoption and market penetration phase. (cont.)

B	345 Bennett Highway, Boston, MA	1810 Tonnelle Ave, North Bergen, New Jersey	2361 Admiral Wilson Boulevard, Pennsauken Township, NJ	3617 Forestville Road, District Heights, MD
C	384 Washington Street, Braintree, MA	3080 John F Kennedy Boulevard, West Jersey City, NJ	1135 Vine Street, Philadelphia, PA	3250 Kenilworth Avenue, Hyattsville, MD
D	2760 Washington Street, Boston, MA	197 12th Street Jersey City, NJ	1058 Delsea Drive, Westville, NJ	6201 New Hampshire Avenue, Washington, DC
E	1365 Centre Street, Boston, MA	112 Atlantic Avenue, New York, NY	121 South Black Horse Pike, Bellmawr, NJ	Wisconsin Avenue Northwest, Washington, DC
F	225 Waverley Oaks Road, Boston, MA	2 Bushwick Avenue, Brooklyn, NYC, NY	6200 North Broad Street, Philadelphia, PA	6717 Old Dominion Drive, McLean, VA
G	915 Waltham Street, Boston, MA	3802 21st Street, Long Island City, NY	7011 New Falls Road, Levittown, PA	5630 Lee Hwy, Arlington, VA
H	875 Highland Avenue, Boston, MA	235 Saint Nicholas Avenue, New York, NY	9801 Bustleton Avenue, Philadelphia, PA	3100 Columbia Pike, Arlington, VA
I	934 Massachusetts Avenue, Boston, MA	300 New Jersey 3, Secaucus, NJ	228 Bustleton Pike, Feasterville-Trevose, PA	801 North Washington Street, Alexandria, VA
J	293 Cambridge Road, Boston, MA	163 West 29th Street, New York, NY	400 Baltimore Pike, Springfield, PA	4420 Wheeler Road, Oxon Hill, MD

Note: Stations selected for early adoption phase are highlighted in grey. Fueling locales could not be expanded for commercialization phase due to lack of data. Appropriate data is generated to add necessary fueling locales.

Using the specified hydrogen demand (Table 1) and the selection criteria above the authors have listed preferred, existing Shell stations in Table 10. These locations are identified by their transition phase practicality. The authors suggest a strategic implementation of combined gas and hydrogen stations to accommodate the wide range in specified hydrogen demand.

Hydrogen Transportation and Storage

Transportation and storage of hydrogen is a coupled system. Four methods of hydrogen transport are:

- Pipeline transport
- High pressure tube trailers
- Low pressure cryogenic tanker trailers
- Metal-hydride canisters

These transportation pathways are compared by the following criteria and a Pugh chart is shown determining the best overall transportation and storage strategy. Appropriate weights from one to three have been assigned to these criteria:

- Cost of transportation: Transportation directly affects the consumers cost per kg of hydrogen. It is a determining factor in the eventual profitability of the project. Transport costs are weighted two
- Safety: Hydrogen is flammable. Compromised safety during transport will result in increased costs and is unacceptable. Safety's is paramount and weight is three.
- Flexibility: A mode of transport that offers flexibility in its design would be preferred. A weight of two is assigned for this criterion.
- Effect on dispensing and on-board storage [26]: A mode of transport requiring special dispensing, on-board storage would not be preferred. A weight of one has been assigned for this criterion.

Table 11 – Pugh chart for selection mode of transport.

Criterion	Weight	Pipeline	High-Pressure tube trailer	Liquid tankers	Metal-hydride canisters
Cost of transportation/infrastructure required for transportation	2	--	++	+	+
Safety	3	+	-	+	+
Flexibility	2	-	+	++	+
Effect of dispensing and on-board storage	1	+	+	+	-
Total Score		-2	4	10	6

Based on the above Pugh chart, the authors recommend using low pressure cryogenic tanker trailers as the preferred mode of transport. It is competitive in cost and using low pressure liquid hydrogen (100 psig) at cryogenic temperatures (-425 ° F) permit transferring hydrogen to on-site liquid hydrogen tanks from which it can be dispensed to gaseous hydrogen tank vehicles as well as liquid hydrogen tank vehicles [38–40]. Thus, stations are able to provide hydrogen for a wider range of vehicles. This also idealizes the on-board storage system's mass to weight ratio [41].

Combined Gasoline and Hydrogen Fueling Station

The authors suggest liquid hydrogen tankers as the primary mode of transport. The liquid hydrogen arriving at a facility must be preprocessed before dispensed to gaseous hydrogen tanks. Fig. 2 shows the process flow diagram for this preprocess. A combined gasoline and hydrogen fuel station with pre-processing requires attention to ensure a safer operation.

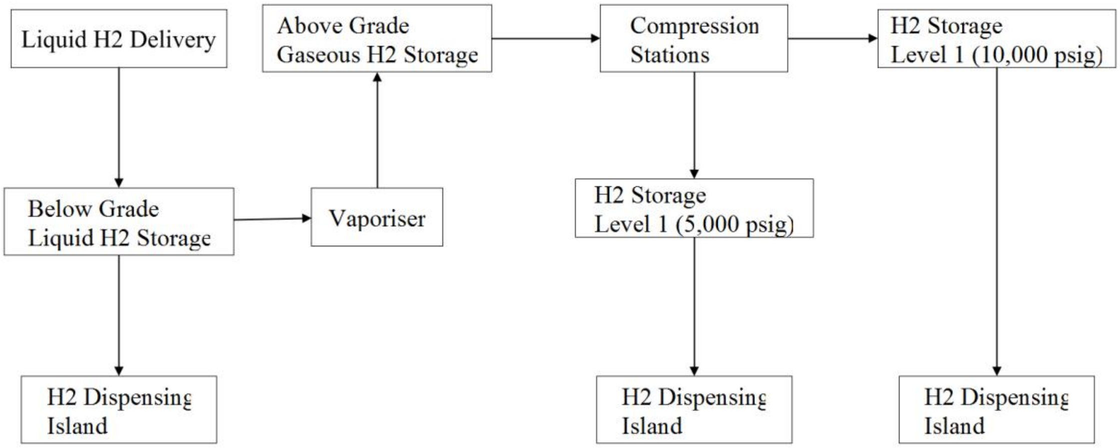


Figure 2 – Preprocessing at the hydrogen fueling station facility.

Infrastructure Development Timeline

As mentioned earlier, the design will utilize benefits from both the decentralized installation and the centralized installation to develop an optimum, and user friendly hydrogen fueling infrastructure. The authors suggest the decentralized installation for the early adoption phase 2013-2015, while the centralized production and distribution is suggested for the market penetration 2015-2020, and commercialization phases.

Early adoption phase (2013-2015)

The maximum demand for the early adoption phase is 500 kg/day of hydrogen. Table 10 identifies the locations that can serve as fueling locales for this introductory phase. A proven, off the shelf technology by Nuvera, PowerTap®, uses natural gas to produce hydrogen; these natural gas reformers facilitate immediate hydrogen production. They have a capacity of 50 kg/day of hydrogen. Considering the 12 sites selected for this phase, the hydrogen produced would be more than enough to satisfy the early adaption demands.

Market penetration phase (2015-2020) and commercialization phase (2020-2025)

The authors suggest using a centralized installation for both of these phases considering the increasing demand for hydrogen. Secondary facilities satisfy sudden changes in the market trend. The following discussion provides details of the installation of the primary and secondary facilities.

Suggested production and storage sites and second-tier distribution

The authors recommend the Seneca Meadows landfill near Waterloo, NY, to be the optimal site for placement of a central storage and production facility, upon considering all landfills in the New England area, and their annual biomass production. The vicinity of the commercial city of Waterloo also adds to the benefit of selecting the Seneca Meadows site.

This particular site is suggested because of its following characteristics:

1. *Readily available land in the region near the Landfill*

The southeast quadrant of the landfill shows a 250,000 sq. ft. plot having plenty of room for a facility to be constructed. The facility could expand, and even explore the possibility of underground storage based on USGS data. Fig. 3 is an aerial view of the landfill, via GPS. The lower right quadrant of the landfill shows unoccupied hillside. In addition, nearby property could be used as additional storage as required by the commercialization phase. Further investigation of the topographical region shown in Fig. 3 reveals readily accessible land available for the construction of an underground storage facility, which would provide an option for long-term storage of hydrogen production. This rural location alleviates the political, and safety issues of hydrogen production and storage facilities being close to a large population.

Figure 3 – Aerial image of the Seneca Meadows landfill.

2. *Ease of access to major cities*

The cities of Providence, RI, and Baltimore, MA, are also included with the cities in consideration for this competitive study. Waterloo, NY, is within 300-350 miles of all points of highway 95 between Washington D.C. and Boston. This is within the typical delivery range of large truck transportation. The liquid hydrogen transport occurs at moderate pressures. Thus, it is an ideal mode of transport for the proposed infrastructure. The shortest route will be taken to cycle the fuel through the cities during the 2015-2020, and 2021-2025 time periods. The former time period will be referred to as Period 1 while the latter referred as Period 2.

The abbreviation "DC" stands for "Distribution Center." It indicates storage sites, and transport to fueling locations near their respective locations, with overlapping routes, when demand spikes in particular cities. The locations indicated as "active" during Period

1 represent the total accumulation of fueling locales and the initial source of the Waterloo production facility. The sub-locations rendered as “active” during only Period 2 are locations on major interstate road intersections on which other major fueling cities lie on. These second-tier distribution centers will serve as complementary locations built to compliment demand increases in the indicated fueling cities. The distribution centers will service cities as follows in Table 12.

The above table shows these within close proximity to the primary fueling cities. All DC’s are within safe travel range of large-transport trucks, of both the Waterloo location and each city-client.

Table 12 – Labels for the cities and corresponding time periods for each label on Figure 3.

Label	City	State	Function	Period 1 status	Period 2 status
1	Waterloo	New York	source/ DC	active	active
2	Washington D.C.	District of Columbia	Fueling	active	active
3	Baltimore	Maryland	Fueling	active	active
4	Philadelphia	Pennsylvania	Fueling	active	active
5	New York City	New York	Fueling	active	active
6	Providence	Rhode Island	Fueling	active	active
7	Boston	Massachusetts	Fueling	active	active
8	York	Pennsylvania	DC	inactive	active
9	Allentown	Pennsylvania	DC	inactive	active
10	Newburgh	New York	DC	inactive	active
11	Hartford	Connecticut	DC	inactive	active

Table 13 – Second-tier distribution centers and the cities to which they supply.

Distribution center	Distance from Waterloo, NY	Supplied cities	Distance (miles)
York, PA	256.8 miles	Washington D.C.	95.3 [c]
		Baltimore	52.1 [b]
		Philadelphia	102.2 [d]
Allentown, PA	221.7 miles	Baltimore	148 [d]
		Philadelphia	62 [b]
		New York City	88.6 [c]
Newburgh, NY [a]	227.4 miles	New York City	66.6 [b]
		New Haven, CT [a]	73.6 [c]
		Providence	179.7 [d]
Hartford, CT	295.8 miles	New Haven, CT [a]	39.1 [b]
		Providence	87.1 [c]
		Boston	102.3 [d]

[a] These sites serve as potential sites which should be activated in higher-than-expected demand scenarios.

[b] are primary city-clients for the indicated distribution center.

[c] are secondary city-clients for the indicated distribution center.

[d] are signifies emergency order only sites.

3. *Amount of hydrogen production possible*

According to the Environmental Protection Agency (EPA), on average, any landfill-produced gas is 50% methane-based by-product. This is the focus of the gasification process in the study. Optimistically, if 33% of the total biomass of a location is considered to be organically viable, then according to online data, the Seneca Meadows landfill produces 2,491,212 tons of waste a year, yielding 830,404 tons of organic material annually. The DFC 1500, processes 39.2 tons-per-day of biomass feedstock, and produce 650 kg of hydrogen-per-day, while producing excess power in the range of 1500 kilowatts [29, 30], The DFC 3000 processes 78.2 tons-per-day of biomass feedstock, and produce 1875 kg/day of hydrogen-per-day along with producing excess power in the range of 3000 kilowatts.

Theoretically, using the Waterloo, NY plant location, when operational and operating at maximum capacity would produce the following table:

The authors assumed an annual increase of 1.5% in the total waste available. The maximum capacity operation, that is, 50% of the waste is converted to biomass (EPA average) is considered for this estimation.

Table 14 – Estimated hydrogen production for Waterloo, NY landfill.

Year	Waste availabl [b]	Biomass conversion [b]	Feedstock available [b]	No. of DFC 1500 units required	Estimated hydrogen production [c]	Estimated hydrogen production [c]	Expected demand [b]
2013	6825.3	35588.7	3,412	Not applicable. Facility being constructed during this period. The demand is satisfied by on-site installation.			7.32
2014	7166.5	3583.3	3,583				36.6
2015	7524.8	3762.4	3,762				183
2016	7901.1	3950.5	3,950	100	65,506	23,909,796	732
2017	8296.1	4148.1	4,148	105	68,781	25,105,286	2745
2018	8710.9	4355.5	4,355	111	72,220	26,360,550	8235
2019	9146.5	4573.2	4,573	116	75,831	27,678,578	21960
2020	9603.8	4801.9	4,801	122	79,623	29,062,506	54900
2021[a]	10084	5042	5,042	128	83,604	30,515,632	86,525

[a] Forecast

[b] (tons/day)

[c] (kg/day)

The data for the year 2021 was forecasted using the below polynomial regression of the previous demand data, Fig. 4.

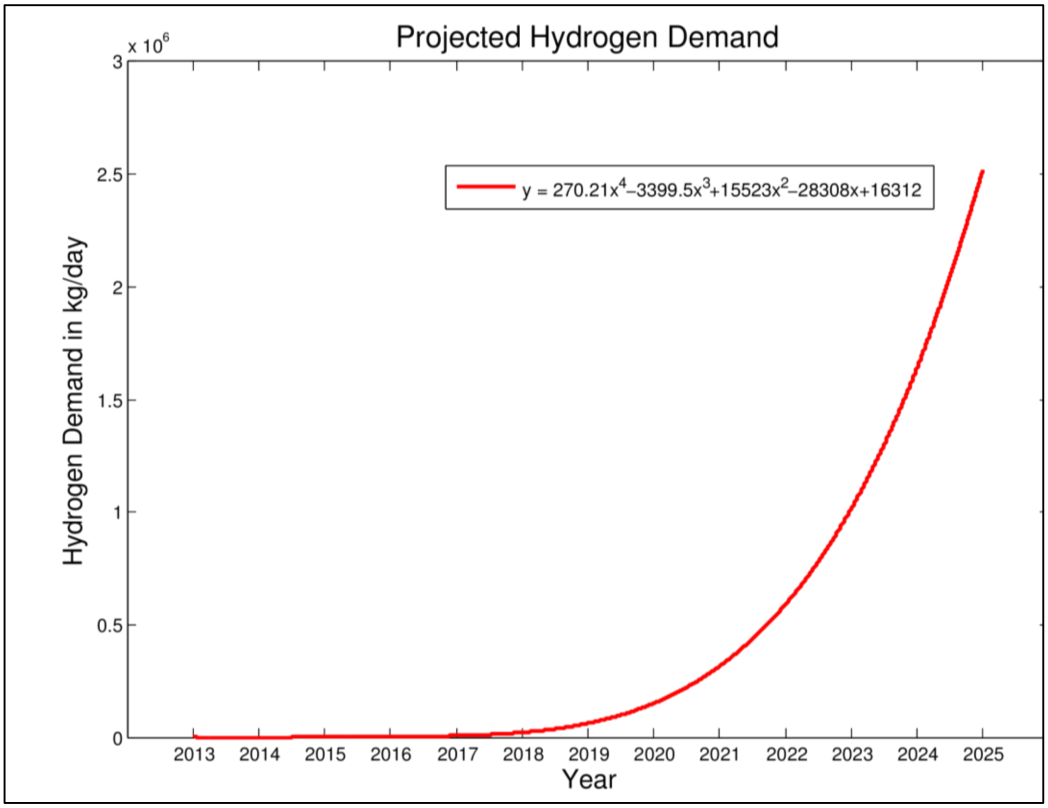


Figure 4 – Performing curve-fit of the expected demand for extrapolation.

In an attempt to optimize the model, in terms of *safety stock*, the variable of cumulative daily excess, that is the difference between the supply and demand of hydrogen, is fixed at 1,000 kg per day. This means, that regardless of the year, the plant in Waterloo will attempt to keep a daily excess of 1,000kg of hydrogen to account for fluctuations. This model yields the following table:

Table 15 – Cumulative stock for needed reserve.

Year	Needed reserve (kg/day)	Demand (kg/day)	Units needed	Daily feedstock required (tons)	Daily feed stock available (tons)	Yearly surplus feedstock (tons)	Cumulative feedstock (tons)
2016	1000	2,000	13	493	3,951	1,262,104	4,975,578
2017	1000	7,500	29	1,126	4,148	1,103,072	6,078,650
2018	1000	22,500	76	2,995	4,355	496,393	6,575,042
2019	1000	60,000	205	8,031	4,573	-1,262,148	5,312,895
2020	1000	150,000	529	20,756	4,802	-5,823,283	-510,389

In this model, letting the required number of units be a function of safety stock (SS), results in the following equation:

$$\mathrm{Units_i} = \frac{\mathrm{SS} + (\mathrm{Demand_i} + \mathrm{Demand_{i-1}})}{\text{Daily Production of Unit}}$$

Now, the concerns that accompany this model are:

1. Availability of Feedstock
2. Storage Capacity for daily excess

In order to address the first concern, the last column of the table for the optimized model indicates that the required production capacity is exceeded at year 2019, and the demand is exceeded by the supply in year 2020. This essentially results in a critical response period wherein decisions need to be made in order to meet future demand requirements. Moving to additional locations such as Keystone Sanitary Landfill in Dunmore, PA will aid in meeting demand past the period of the study.

This secondary location could support additional production to supplement demand through the end of 2023. After this period of time further data would be required to make a better assessment of future works. A simple consideration may be to upgrade the second facility to using DFC 3000 units which would produce hydrogen at a much higher rate on a day-to-day basis, but overall decrease the amount of time this facility could support demand.

Construction work-layout and time estimation

Creating a Hydrogen Fueling Infrastructure will need development of the following:

- Hydrogen production and storage
- Hydrogen transport
- Hydrogen dispensing (combined gasoline and hydrogen fuel stations)

Each of the above categories will have a number of tasks to be performed. These are listed below:

Hydrogen production and storage: **(**Typical for each landfill locations)

- Sourcing of raw material (material already available in landfills)
    - Use trucks or machines
- Storage of raw material (the typical list of tasks for installation of equipment are)
    - Design the equipment
    - Manufacture the equipment
    - Ship the equipment
    - Install the equipment
    - Build foundation
    - Install the equipment
    - Put anchor bolts to finish the installation
- Processing to convert to biogas
    - Filtering (manual filtering or automated)
    - Install crusher
    - Install digester
- Separation of methane and carbon di-oxide
    - Install PSA units
- Conversion of methane to hydrogen, heat, and electricity
    - Install fuel cell (DFC1500 or DFC300)

- Hydrogen separation unit
    - Install PSA units
    - Install heat exchanger
    - Install piping, valves and fittings
- Processing hydrogen for storage
    - Install equipment to convert gaseous hydrogen to liquid hydrogen
    - Install equipment to reduce temperature of liquid hydrogen to cryogenic temperatures
    - Install piping, valves and fittings
- Storing hydrogen for transport
    - Install pump
    - Install cryogenic tanks
    - Install piping, valves and fittings

Hydrogen transport:

- Transferring hydrogen from storage to transport vehicles
    - Install pumps
    - Install piping, valves and fittings
- Transport to fueling locales or fueling stations
    - Use liquid hydrogen transport tankers

Hydrogen dispensing (fuel station):

- Transfer hydrogen from tankers to storage
    - Install pumps
    - Install piping, valves and fittings
    - Install cryogenic storage tanks
- Store some of the liquid hydrogen to fuel liquid dispensers (install a storage tank)
    - Install piping, valve and fittings
    - Install liquid hydrogen dispensing stations
- Vaporize to convert liquid hydrogen to gaseous hydrogen
    - Install vaporizer
    - Install piping, valves and fittings

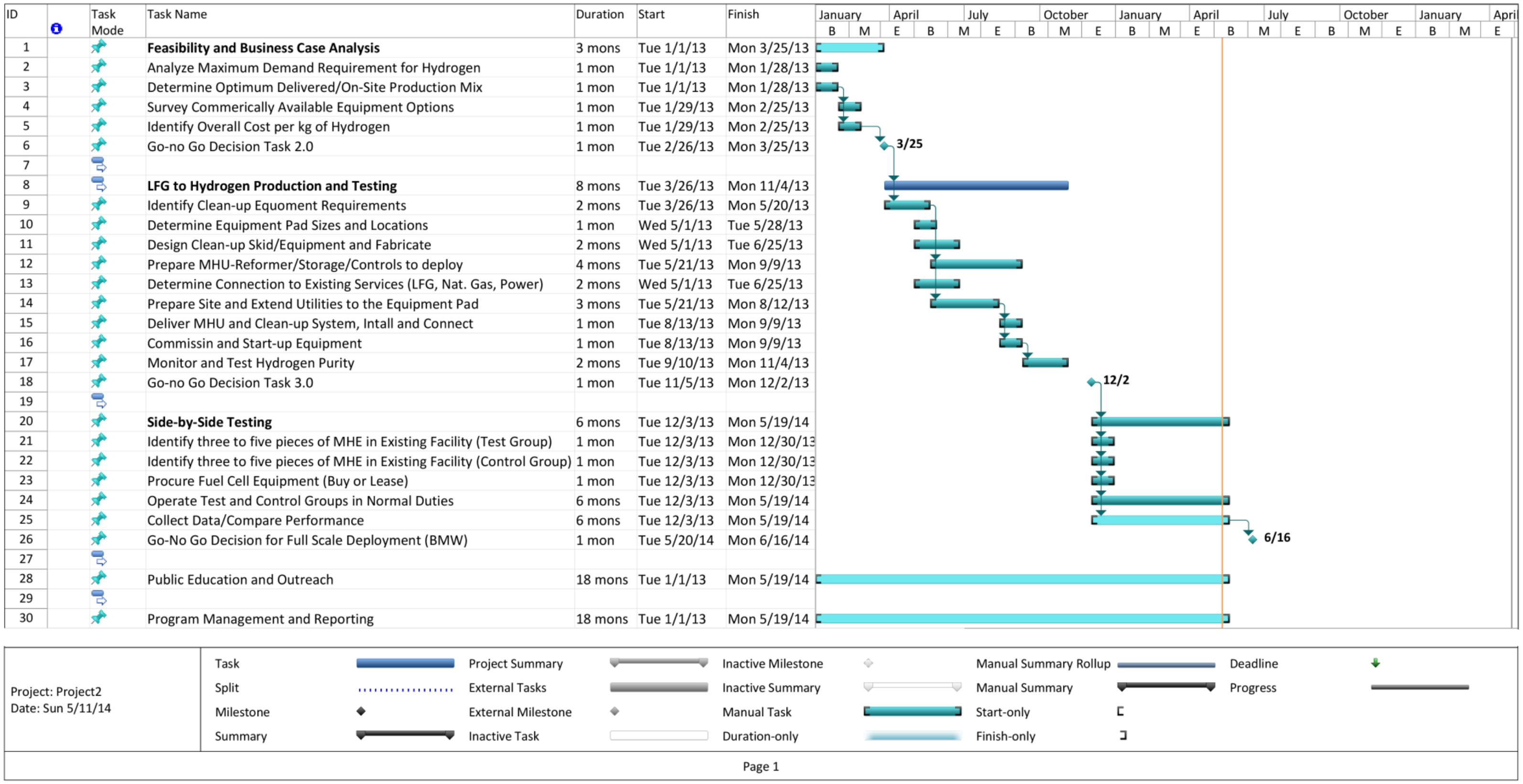
- First stage of compression (up to 5000 psi or 350 bar)
  - Install compressor
  - Install piping, valves and fittings
- Store pressurized hydrogen (install storage tank)
  - Install pressure vessels
  - Install piping, valves and fittings
- Provide an outlet for low pressure hydrogen dispensing (install necessary equipment)
  - Install piping, valve and fittings
  - Install hydrogen dispensing stations
- Second stage of compression (up to 10,000 psi or 700 bar)
- Provide an outlet for high pressure hydrogen dispensing (install necessary equipment)
  - Install piping, valve and fittings
- Install necessary fire safety equipment (as per codes and standards)

Further inferences

Since there exist no reliable data for the construction timeline of a large-scale production facility for BTH production on a true-commercial scale, we begin with a model based off of the 2012 study conducted for the SCRA, which would likely be essential in order to gain public support and aid in the outreach for the uptake of hydrogen fuel as a viable replacement for petroleum based vehicles, Fig. 5.

Regulations, Codes and Standards

Safety is of paramount importance when we are attempting to introduce such a significant change in the energy sector. Resistance from the community is a natural process and was also observed during the transition to fossil fuel. The operators, personnel and the community as a whole should be provided with adequate assurance about the safety of this new hydrogen fueling infrastructure. Authors have performed an extensive search of the applicable regulations, codes and standards, which are detailed in Table 16, [42]. The wide range of guidelines available suggests that hydrogen safety has been studied in great detail and the world is now ready to install a hydrogen fueling infrastructure.



ID	Task Mode	Task Name	Duration	Start	Finish
1		**Feasibility and Business Case Analysis**	3 mons	Tue 1/1/13	Mon 3/25/13
2		Analyze Maximum Demand Requirement for Hydrogen	1 mon	Tue 1/1/13	Mon 1/28/13
3		Determine Optimum Delivered/On-Site Production Mix	1 mon	Tue 1/1/13	Mon 1/28/13
4		Survey Commerically Available Equipment Options	1 mon	Tue 1/29/13	Mon 2/25/13
5		Identify Overall Cost per kg of Hydrogen	1 mon	Tue 1/29/13	Mon 2/25/13
6		Go-no Go Decision Task 2.0	1 mon	Tue 2/26/13	Mon 3/25/13
7					
8		**LFG to Hydrogen Production and Testing**	8 mons	Tue 3/26/13	Mon 11/4/13
9		Identify Clean-up Equoment Requirements	2 mons	Tue 3/26/13	Mon 5/20/13
10		Determine Equipment Pad Sizes and Locations	1 mon	Wed 5/1/13	Tue 5/28/13
11		Design Clean-up Skid/Equipment and Fabricate	2 mons	Wed 5/1/13	Tue 6/25/13
12		Prepare MHU-Reformer/Storage/Controls to deploy	4 mons	Tue 5/21/13	Mon 9/9/13
13		Determine Connection to Existing Services (LFG, Nat. Gas, Power)	2 mons	Wed 5/1/13	Tue 6/25/13
14		Prepare Site and Extend Utilities to the Equipment Pad	3 mons	Tue 5/21/13	Mon 8/12/13
15		Deliver MHU and Clean-up System, Intall and Connect	1 mon	Tue 8/13/13	Mon 9/9/13
16		Commission and Start-up Equipment	1 mon	Tue 8/13/13	Mon 9/9/13
17		Monitor and Test Hydrogen Purity	2 mons	Tue 9/10/13	Mon 11/4/13
18		Go-no Go Decision Task 3.0	1 mon	Tue 11/5/13	Mon 12/2/13
19					
20		**Side-by-Side Testing**	6 mons	Tue 12/3/13	Mon 5/19/14
21		Identify three to five pieces of MHE in Existing Facility (Test Group)	1 mon	Tue 12/3/13	Mon 12/30/1
22		Identify three to five pieces of MHE in Existing Facility (Control Group)	1 mon	Tue 12/3/13	Mon 12/30/1
23		Procure Fuel Cell Equipment (Buy or Lease)	1 mon	Tue 12/3/13	Mon 12/30/1
24		Operate Test and Control Groups in Normal Duties	6 mons	Tue 12/3/13	Mon 5/19/14
25		Collect Data/Compare Performance	6 mons	Tue 12/3/13	Mon 5/19/14
26		Go-No Go Decision for Full Scale Deployment (BMW)	1 mon	Tue 5/20/14	Mon 6/16/14
27					
28		Public Education and Outreach	18 mons	Tue 1/1/13	Mon 5/19/14
29					
30		Program Management and Reporting	18 mons	Tue 1/1/13	Mon 5/19/14

Project: Project2
Date: Sun 5/11/14

Page 1

Figure 5 – Project Schedule.

Table 16 – Summary of recommended regulations, codes and standards.	
Sr. No.	**Codes and standards**
	Codes and standards for hydrogen production locales
	Facility Standards Manual (FSM)
1	FSM Division 10.03 Fire Apparatus Accessibility includes NFPA1 Fire Prevention Code, NFPA241
2	FSM Division 2.13 Site standards: C Bollards non-removable. Dumpster pad design.
3	FSM Division 2.18 Trash Dumpster and Compactor Pads: includes placement to reduce aromatic nuisances
4	FSM Division 13.01 Fire Alarm Systems
5	FSM Division 13.02 Fire-suppression and protection system
6	FSM Division 13.03 Fuel Storage Tanks
7	FSM Division 13.04 Wet Chemical Fire Extinguishing Systems
8	FSM Division 15.06 Plumbing – Gas Lines and Piping
9	FSM Division 15.09 Scub Concept
10	FSM Division 16.03 Outdoor Power Transmission and Distribution
11	FSM Division 16.04 Basic Electrical Materials and Methods
12	FSM Division 16.05 Emergency Power
13	FSM Division 16.06 Fire Protection System
14	FSM Division 16.10 Security Guidelines – Office of Public Safety, Building Security Systems
15	FSM Division 16.12 Uninterruptible Power System
16	FSM Division 17.01 Central Control and Monitoring System CCMS
17	Maryland Department of the Environment COMAR (Code of Maryland Regulations) Title 26
18	MOSH (Maryland Occupational Safety and Health
19	EPA Title 40 CFR parts 260-268 includes hazardous waste management systems.
	National Fire Protection Association Codes
20	NFPA 101 Life Safety Code
21	NFPA 70 National Electric Code, Article 692 Fuel Cell Systems
22	NFPA 72 National Fire Alarm Code
23	NFPA 110 Standard for Standby Power Systems
24	NFPA 170 Fire Safety Symbols
	Fuel Cell Safety Standards
25	IEC 62282-3-100 – Stationary Fuel Cells - Safety
26	ANSI/CSA America FC1-2400 Fuel Cell Power Systems
27	IEC (International Electro-technical Commission) 62282-3-1 (2007-04)

Table 16 – Summary of recommended regulations, codes and standards (cont.)

28	IEC 62282-2-200 (2011-10) Test Method for the Performance of Stationary Fuel Cell Power Plants
29	ANSI/INFPA 853 Installation of Stationary Fuel Cell Power Plant
	Hydrogen Safety Standards
30	OSHA 1910.103 Subpart H Hazardous Materials
	Electrical Standards
31	ANSI/IEEE 1547-2003 Standard for Interconnecting Distributed Resources with Electric Power Systems
32	IEC/PAS 63547
33	IEEE 1547.1-3 Standard for Conformance Test Procedures for Equipment
	Hydrogen Recovery
34	ISO 9001: 2000 – Water Gas Shift Reactor Adjustable valve at inlet
35	ISO 9001: 2000 – Water Gas Shift Reactor Routine checking of coolant level
36	ISO 9001: 2000 – Vapor-Liquid Separator Adjustable valves at inlet and outlet
37	ISO 9001: 2000 – Plate-and-Fin Heat Exchanger routine checking of mechanical stress
38	ISO 9001: 2000 – Pressure Swing Adsorption Unit routine checking of valve function
39	NFPA 55, ISO-TC 58 – Compressors temperature sensors
40	NFPA 55, ISO-TC 58 – Compressors routine checking of inflow and outflow
41	NFPA 55, ISO-TC – Compressors routine checking of inflow
42	NFPA 55, ISO-TC 58 – Compressors adjustable valve at outlet
43	NFPA 55, ISO-TC 58 – Compressors routine checking of mechanical stress
44	NFPA 55, ISO-TC 58 – Hydrogen Storage routine checking of mechanical stress
45	NFPA 55, ISO-TC 58 – Hydrogen Storage maintain safe external conditions
46	NFPA 55, ISO-TC 58 – Hydrogen Storage adjustable valve at outlet; temperature sensor
47	NFPA 55, ISO-TC 58 – Hydrogen Storage utilize tanks with high pressure capacities
48	NFPA 55, ISO-TC 58 – Compressed Gas Cylinders extra tank connected to others
49	NFPA 55, ISO-TC 58 – Compressed Gas Cylinders routine checking of mechanical stress
50	ISO 9001: 2000 – Hot Water Storage pressure gauge on system
51	ISO 9001: 2000 – Hot Water Storage temperature sensor for liquid inflow
52	ASME B31.1, B31.3, B31.9 – Piping/Valves routine checking of mechanical stress
53	ASME B31.1, B31.3, B31.9 – Piping/Valves routine checking of mechanical stress
54	ASME B31.1, B31.3, B31.9 – Piping/Valves proper and gradual closing of valves

Table 16 – Summary of recommended regulations, codes and standards (cont.)

55	ASME PTC 50 Test procedures, methods and definitions for the performance characterization of fuel cell power systems.
56	Underwriters Laboratories, UL Subject 1741 Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources
57	US Department of Energy Hydrogen and Fuel Cells Permitting Guide Regulating Hydrogen technologies, permitting Fuel Cell installations, and Hydrogen motor fuel dispensing facilities.
58	The Federal Energy Regulatory Commission (FERC) FERC Order No. 2006, FERC Order No. 2006-A, FERC Order No. 2006-B "Small generator" interconnection standards for distributed energy resources up to 20 megawatts (MW)
59	NFPA 54 – National Fuel Cell Code
60	IEC 62282-3-1: Fuel Cell Power Systems – Safety
61	IEC 62282-3-2 (2006-03): Fuel Cell Power System - Performance
	Codes and Standards for Fueling Locales
62	International Fire Code – 2000 edition
63	International Building Code – 2000 edition
64	DCMR Title 20, Chapter’s 55-70- Environmental Law Requirements for Fuel Cell Storage Tanks
65	NFPA 2: Hydrogen Technologies Code
66	NFPA 30 – Flammable and Combustible Liquid Standards
67	NFPA 30 – Motor Fuel Dispensing Standards
68	NFPA 50A – Standard for Gaseous Hydrogen Systems at Consumer Sites
69	NFPA 50B – Standard for Liquid Hydrogen Systems at Consumer Sites
70	NFPA 52 – Compressed Natural Gas (CNG) Vehicular Fueling System Standard
71	NFPA 57 – Liquefied Natural Gas (LNG) Vehicular Fueling System Standard
72	NFPA 59A – Standard for the Production, Storage, and Handling of Liquefied Natural Gas
73	ASME BPV Code, Section VIII, Division I – Rules for Constructions of Pressure Vessels
74	ASME BPV Code, Section IX – Welding and Brazing Qualifications
75	ASME/ ANSI B31.3 – Piping Design Standards
76	SAEJ2600 – Hydrogen Dispensers
77	SAEJ2601 – Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles

Authors have carried out a detailed failure modes and effects analysis (FMEA) for the various parts involved, which is presented in Table 17. The FMEA identifies various risks associated with the hydrogen fueling infrastructure and provides mitigation strategies for risk aversion. An event tree analysis (ETA) for a typical initiating event has also been carried out, shown in Fig. 6.

By considering the results presented in the FMEA and ETA authors have developed representative layouts for the hydrogen production facility, shown in Fig. 7 and hydrogen dispensing facilities, shown in Fig. 3. OSHA 1910.103(b) (ii) should be followed to identify the minimum required separation between equipment in hydrogen service. Hydrogen transport through the liquid containers should be carried out as per the guidelines stated in OSHA 1910.103(a) (1) (v). Authors recommend carrying out detailed FMEA for each component. Risk in early design (RED) should also be used to determine all possible failure modes [43]. The failure modes identified using the RED analysis should be then studied with a fault tree analysis (FTA) [44] to determine the fundamental reason for failure. Efforts should be made to reduce the likelihood of these failures.

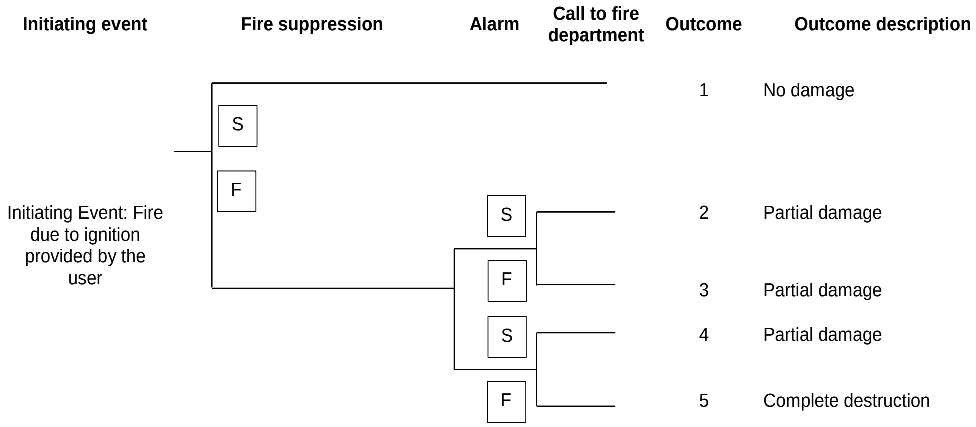


Figure 6 – Event Tree Analysis.

Table 17. Failure Modes and Effects Analysis.

Part	Function	Failure Mode	Effect	Causes	Severity	Occurrence	Detection	Recommended Action	RPN
Pressure Vessels	Storage liquid and gaseous hydrogen under pressure	Ductile Fracture	Release of hydrogen leading to loss of revenue and a potential fire hazard	Supply hydrogen at a pressure higher than design pressure	10	3	8	Install pressure safety valve to avoid overpressure situations. Follow ASME BPV Sec. VIII and ISO 9001:2000	240
		Leakage	Release of hydrogen leading to loss of revenue and a potential fire hazard	Low clamping force in the nozzle flanges	10	3	8	Design nozzles as per ASME B31.3. Install the piping and nozzles as per ASME B31.3	240
		Hydrogen damage	Reduces strength of the metal causing rupture	Hydrogen environment	10	6	10	Design for hydrogen environment	600
		Stress Corrosion	Reduces strength of the metal causing rupture	Hydrogen environment	10	6	10	Design for hydrogen environment	600

Table 17. Failure Modes and Effects Analysis (cont.)

Pressure Vessels	Storage liquid and gaseous hydrogen under pressure	Force induced deformation	May rupture the vessel leading to loss of revenue and a potential fire hazard	Vehicle hitting the vessel	10	8	4	Add barriers to restrict vehicle access to storage areas. Introduce speed breakers to reduce vehicle impact	320
Hydrogen dispensing islands	To transfer hydrogen to the vehicles	Leakage	Potential fire hazard	Operator error, faulty equipment	10	8	4	Include hydrogen detectors near dispensing stations. Design the dispensing nozzles as per SAEJ2600	320
		Fire	Destruction of property and personnel	Ignition source provided by the operator	10	8	10	Include fire suppression system, surveillance cameras, educate the operators by displaying warning signs	800
		Fire	Destruction of property and personnel	Hydrogen air cloud	10	8	10	Design the roof to avoid hydrogen accumulation. Provide vent	800
		Fire	Destruction of property and personnel	Due to sabotage	10	1	10	Include fire suppression system, surveillance cameras, educate the operators by displaying warning signs	100

Table 17. Failure Modes and Effects Analysis (cont.)

Piping, Valves and Fittings	Transfer hydrogen	Ductile fracture	Release of hydrogen leading to loss of revenue and a potential fire hazard	Supply hydrogen at a pressure higher than design pressure	10	3	8	Install pressure safety valve to avoid overpressure situations. Follow ASME BPV Sec. VIII and ISO 9001:2000	240
		Leakage	Release of hydrogen leading to loss of revenue and a potential fire hazard	Low clamping force in the pipe flanges	10	3	8	Install the piping and nozzles as per ASME B31.3	240
		Hydrogen damage	Reduces strength of the metal causing rupture	Hydrogen environment	10	6	10	Design for hydrogen environment	600
		Stress Corrosion	Reduces strength of the metal causing rupture	Hydrogen environment	10	6	10	Design for hydrogen environment	600

Table 17. Failure Modes and Effects Analysis (cont.)

Piping, Valves and Fittings	Transfer hydrogen	Force induced deformation	Rupture the vessel leading to loss of revenue and a potential fire hazard	Vehicle hitting the vessel	10	8	4	Add barriers to restrict vehicle access to storage areas. Introduce speed breakers to reduce vehicle impact	320
		Water Hammer	Rupture the valve leading to loss of revenue and a potential fire hazard	Error in start-up	10	1	2	Define commissioning procedures. Design as per ASME B31.1, B31.3 and B31.9	20
Compressor stations	Pressurize hydrogen	Ductile fracture	Release of hydrogen leading to loss of revenue and a potential fire hazard	Supply hydrogen at a pressure higher than design pressure	10	3	8	Install pressure safety valve to avoid overpressure situations. Follow ASME BPV Sec. VIII and ISO 9001:2000	240

Table 17. Failure Modes and Effects Analysis (cont.)

Compressor stations	Pressurize hydrogen	Leakage	Release of hydrogen leading to loss of revenue and a potential fire hazard	Low clamping force in the pipe flanges	10	3	8	Design nozzles as per ASME B31.3. Install the piping and nozzles as per ASME B31.3	240
		Hydrogen damage	Reduces strength of the metal causing rupture	Hydrogen environment	10	6	10	Design for hydrogen environment	600
		Stress Corrosion	Reduces strength of the metal causing rupture	Hydrogen environment	10	6	10	Design for hydrogen environment	600
		Force induced deformation	May rupture the vessel leading to loss of revenue and a potential fire hazard	Vehicle hitting the vessel	10	8	4	Add barriers to restrict vehicle access to storage areas. Introduce speed breakers to reduce vehicle impact	320

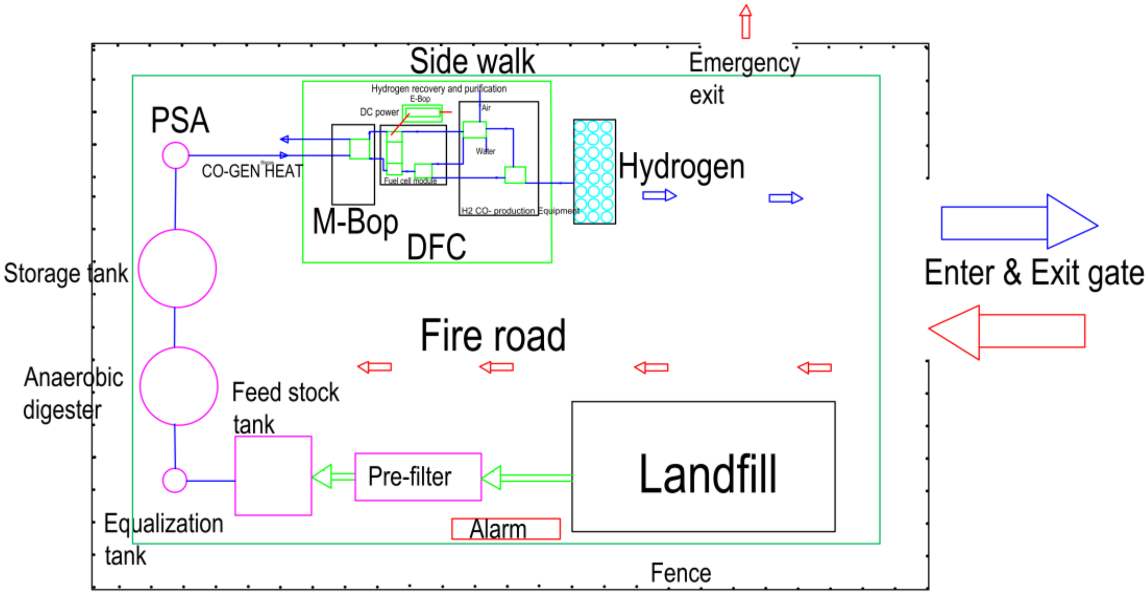


Figure 7 – A representative layout of the hydrogen production site.

Conclusions and Future Work

The paper presented an infrastructure development plan for the hydrogen fueling stations in the Northeastern United States. Analysis of various hydrogen production, storage and transportation technologies allowed the design to present a combination that would be a best-fit for the geographic location. The design utilizes SMR during the introductory phase and constructs the combined heat, hydrogen, and power centralized facilities during the same period; to be used in the market penetration and commercialization phase. The infrastructure development time line considers the surges in the supply and demand and therefore provides secondary and tertiary locations to meet it. Although the design satisfies the technical constraints, the business side of it remains to be explored. A detailed cost analysis will be performed, which will compare government, small-business and large-business methods of introduction of the hydrogen fueling infrastructure. Because of the variations in the tax models, and profit margins, this study is considered as a future work.

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SECTION

2. CONCLUSION

This dissertation examines different alternative energy technologies that can help decrease the impact of fossil fuel and increase energy security. Reducing the use of fossil fuels will also lead to lower greenhouse gas emissions. Energy security can alleviate economic disruptions, increase health and safety, and reduce potential environmental effects of energy security disruptions. The papers in the dissertation provide a collection of solutions to the problems related to energy consumption and greenhouse gas emissions.

The Molten Carbonate Fuel Cell Combined Heat, Hydrogen and Power System: Feedstock Analysis was identified. Based on the design system, this study was focused on concerning energy flow and resource availability to ascertain both the type and source of feedstock to run a fuel cell system unceasingly while maintaining maximum capacity. The results of this study were used to identify a FuelCell Energy 1500 unit (a molten carbonate fuel cell) that can meet 91% of the fuel requirements on campus. This particular fuel cell will provide electric power, thermal energy to heat the anaerobic digester, hydrogen for transportation, auxiliary power to the campus, and myriad possibilities for more applications.

A design for hydrogen production and dispensing for northeastern United States, along with its infrastructural development timeline was identified. This work was conducted in an effort to provide an introductory feasibility study that addressed the implementation of a hydrogen fueling infrastructure in the northeast quadrant of the United States. It was a collaborative effort between the H_2 Design Solution Team at Missouri University of Science and Technology (Missouri S&T). The research was focused on the mass production of hydrogen. The research utilized the naturally occurring methane from biomass waste that is commonly referred to as the Landfill Gas-Hydrogen. Several hydrogen processes were identified. Various strategies are provided here for the implementation of a sustainable hydrogen energy supply in the northeast quadrant of the United States.

This paper also includes discussions that are focused on desirable production facility characteristics, potential locations, and optimum fueling station sites. A discussion on transportation, storage and dispensing equipment, and imperative codes and standards is also included. A detailed infrastructural developmental timeline is provided to ensure a continuous supply of hydrogen that meets expected demand for a period of 13 years (from 2013 through 2025). Finally, illustrative design layouts are provided for nonspecific hydrogen production and fueling facilities. The design presented herein prioritizes customer convenience and minimizes capital expenses.

In conclusion, the research presented the implementation of hydrogen energy infrastructure in the transportation and commercial sector. The result also investigated methods to integrate hydrogen fueling infrastructure with existing technologies. The results demonstrate a significant reduction in the fossil fuel usage and greenhouse gas emissions. In order to successfully achieve the design targets, energy policies need to be implemented. Alternative energy technologies are expensive compared to the traditional energy sources. Therefore, a detailed cost analysis should be performed on the presented designs.

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VITA

Yousif Hamad was born on November 30, 1974 in Albyda, Libya. In December 1997, he received his B.E. in Mechanical Engineering from Bright Star University of Technology, Marsa al-Brega, Libya. Later, he continued his graduate study at Tabbin Institute for Metallurgical Studies, Cairo, Egypt, and received his M.S. degree in Mechanical Engineering in 2005. He worked at Omer Al-Mokhtar University, Libya as a lecturer in mechanical engineering department from January 2006 to June 2008. Since June 2010, he has been enrolled in the Ph.D. Program in Mechanical Engineering at Missouri University of Science and Technology, Rolla. He has been an active participant in The Missouri S&T Hydrogen Design Team that involved in Hydrogen Student Design Contest through 2010 and 2014. He has been the Team Leader of The Missouri S&T Hydrogen Design Team through 2012 and 2014 and received his Ph.D. Degree in Mechanical Engineering in May 2015.