UNIVERSITY OF CHEMICAL TECHNOLOGY AND METALLURGY
BULGARIA

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Executive Summary

Analysis and Identification of possible hydrogen production and fueling locale

I. Criteria Development

II. Evaluation of possible fueling locales and Hydrogen Sources

Infrastructure Development Timeline

Cost and Economic Plan

Regulations, Codes and Standards

Marketing and Education Plan
EXECUTIVE SUMMARY

Presented with the challenge to design a Hydrogen Fueling infrastructure in Northeastern United States Region, UCTM team has developed a plan.

In our plan we presented three methods for obtaining hydrogen-fermentation, water electrolysis and reforming of natural gas from available sources in the region like a biomass, water and natural gas.

For the needs in the region the production capacities are assumed in the rate of approximately **22 billion tons per 12 years period of time**. The distribution will be secure by liquid tank trucks and pipelines. The **496 numbers of hydrogen stations** are needed to adequately satisfy refueling availability requirements in region NeUSR before the proceeding with the mass production of hydrogen vehicles. However, estimates based upon some general criteria. Three estimation approaches have been explored, based upon: 1) existing populations of gasoline stations, 2) metropolitan land areas, and 3) lengths of principal arterial roads. Comparison of these approaches suggests that the arterial roads approach provides the most consistent analysis of hydrogen station requirements.

Location of the stations depends on factors as availability of hydrogen sources, population and traffic density.

Based on an uncertainty analysis of costs reported in the literature, the **upfront capital costs** associated with establishing this initial threshold of stations by 2025 is estimated to range of **4, 18 billions**. The total cost for Hydrogen production facilities is calculated in amount of **2, 28 billions**.

Under the formulation of levelized per unit costs ($/kg) used in the analysis, **average cost of producing hydrogen is 3,63 $**. We assume that hydrogen will be sold anywhere from $8 - $12/kilogram till end 2020, including sales tax.

The Education and Marketing plan in the analysis present the idea of clear explanation of hydrogen usage by different education programs and advertisement methods.

UCTM’s NeUSR Hydrogen Fuelling Infrastructure provides clean solution for reduction of carbon emissions reduction and full utilization of organic wastes in the region.
ANALYSIS AND IDENTIFICATION OF POSSIBLE HYDROGEN PRODUCTION AND FUELING LOCALES

The current global energy structure is based on fossil fuel resources. About one-third of all fossil fuels are used in the transportation sector. From this perspective, sustainable hydrogen is promoted as it can store clean fossil-based energy to become a ready-to-use transportation fuel. Current views predict that future propulsion systems will probably be hydrogen/fuel cells and electricity, in various proportions, thus using the best of both fuels in various ways. Hydrogen in combination with electricity, will be the main clean and CO\textsubscript{2}-free fuel solution for transportation in the future.

Hydrogen has been used in industry for decades. Industrial experience is now being used to develop the required dedicated technology to use hydrogen in civil situations. Safety aspects are being examined and new regulations are being set up. The development of safe and affordable hydrogen technologies is the key objective for both national and international collaborations.\(^{(1)}\)

The Hydrogen Highway helps to sustain the existing technology cluster and creates links and alliances with other hydrogen highways internationally. It is a ´´touch stone´´ for those seeking information on hydrogen and fuel cell technologies and a portal for information to key audiences to facilitate commercialization process.\(^{(2)}\)

1. CRITERIA DEVELOPMENT

The rapid economic growth of developing nations, together with our own already energy-intensive lifestyles, is placing unprecedented strains on global energy supplies and power generation capacity.

There is growing awareness of the very real consequences associated with the accessibility of oil supplies. Nations across the globe continue to consider and struggle with geo-political tension inherent to importing oil and energy.

Air pollution continues to be a concern in many urban centers (like a New York, Washington DC, Boston and Philadelphia) of the industrialized world and in developing countries. Emissions from industry and motor vehicles release smog, ozone, particles, and nitrogen and sulfur oxides into our environment, all of which can severely affect our health.
There is also growing awareness of the implications of climate change caused by the emission of greenhouse gases, much of which is generated by burning fossil fuels (coal, oil and natural gas). Many consider climate change to be one of the biggest facing humanity over the next century.

<table>
<thead>
<tr>
<th>Criteria Development</th>
<th>Washington DC</th>
<th>Philadelphia</th>
<th>Boston</th>
<th>New York City</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population/Population Density</td>
<td>617.996/3,886$\text{km}^2$</td>
<td>1,528.006/4,405$\text{km}^2$</td>
<td>825.087/4,924$\text{km}^2$</td>
<td>8,244.910/10,518.60$\text{km}^2$</td>
</tr>
<tr>
<td>Amount of Organic wastes per Year</td>
<td>1,110,000 tons</td>
<td>155,867 tons</td>
<td>573,471 tons</td>
<td>1,200,000 tons</td>
</tr>
<tr>
<td>Amount of Green House Gasses per Year</td>
<td>10 500 000 metric tons</td>
<td>4 119,847 metric tons</td>
<td>688,585 metric tons</td>
<td>3 548,688 metric tons</td>
</tr>
<tr>
<td>Annually Trash Collection Taxes per household</td>
<td>240$^{(18)}$</td>
<td>300$^{(13)}$</td>
<td>240$^{(14)}$</td>
<td>700$^{(12)}$</td>
</tr>
</tbody>
</table>

Tabl. 1 A. Some criteria for Development of Northeastern United States Hydrogen Infrastructure

The main criteria for development in this project are Population, Amount of Organic Wastes, Amount of GHG, Trash collection taxes and Auto taxes. Each of these criteria is very important for implementation of Hydrogen Infrastructure in the Northeastern US Region (NeUSR). Between them can be seen strong relation (see Tabl. 1 B).

The growth of population in each city leads to increasing of the amount of organic wastes and vehicles and respectively to increasing in the amount of the GHG in the region. All this reflect of trash collection taxes and auto taxes (by increasing of their amount).

As we can see in Tabl. 1 A the NeUSR have a needs to reduce the amounts of Organic wastes and the GHG emissions. The effective ways for this is usage of

Tabl. 1 B. Connection between the criteria for Development of Northeastern United States Hydrogen Infrastructure
Methods for Bio-hydrogen production for full utilization of organic wastes and replacement of gasoline cars with hydrogen cars. In this way also will be reduce and the trash collection and auto taxes.

To cover the needs of hydrogen in the NeUSR is necessary to use other sources and production technologies. Other existing sources in the region are water and natural gas.

![Fig.1. A Northeast Region Natural Gas Pipeline Network](image1)

![Fig.2. A Biomass Resources of the Northeastern US](image2)

![Fig.2.B National and State lists of landfills and energy projects](image3)

http://www.epa.gov/lmop/projects-candidates/index.html#map-area
These realities are driving the development of new technologies and ideas. In Northeastern United States, the development of hydrogen and fuel cell technologies, products and infrastructure will improve the air we breathe, ensure secure and reliable energy, reduce the emissions that cause climate change and create highly skilled jobs.

**Fig.1.B** Boston and New York’s population density\(^{(45),(46)}\)

**Fig.1.C** Philadelphia and Washington D.C.’s population density\(^{(47),(48)}\)

Advances are also will be made with respect to hydrogen production and distribution. The industry is improving its capability of small-scale, “distributed” hydrogen generation. **Units are becoming smaller, cheaper and more efficient. The vision to move first via predominantly “clean” hydrogen production towards predominantly “green” hydrogen production in 20-30 years is also becoming reality.** It will mean a kick-start of the Northeastern United Stated Infrastructure that can also be used for “clean” hydrogen production from biomass, water and gas.
II. EVALUATION OF POSSIBLE FUELING LOCALES AND HYDROGEN SOURCES

Hydrogen Sources

From Organic Wastes

Biomass as a source of energy is the subject of much attention from researchers. It is of different origin: waste from households, industry, agriculture, the manufacture of dyes, petroleum waste, waste from the wine and spirits. Methods for transformation of biomass are many and varied. (see Fig.2)

The biology provides a wide range of approaches to produce hydrogen, including direct and indirect bio-photolysis as well as photo-fermentation and dark-fermentation. This is not only because of their high efficiency, but also because of their potential to use renewable source of biomass for production. Dark-fermentation is a promising approach to produce hydrogen in a sustainable way and was already examined in lab-scale in many projects. Short hydraulic retention times and high metabolic rates are advantages of the process. The incomplete transformation of the large organic molecules into various organic acids is a disadvantage. So a second process step is required.

Photo-fermentations are processes in which organic compounds, like acetic acid, are converted into hydrogen and CO₂ with sunlight by bacteria. This process takes place under anaerobic conditions and can be combined with the dark hydrogen fermentation. (4)(5)(6)

Fig.4. Used Microorganisms (20)

Fig.3. Process design for biological hydrogen production in two steps (dark and light steps) (4)
From 1, 8 tones CO₂ can be produce 1 ton Biomass using Microorganisms
From 1 tone biomass can be produced 52 kg Hydrogen (20)

Tabl.2. Bio-hydrogen production by Two-stage Dark Fermentation

Electrolysis of Water

Which process is called Electrolysis?

Process for decomposition of water (H₂O) into oxygen (O₂) and hydrogen gas (H₂) due to an electric current being passed through the water.

The photovoltaic driven electrolysis of water (Fig.5) is a subject of technology two.

Fig.5. Photovoltaic-driven electrolysis of water (25) Fig.6. PV-water electrolysis system

The PV-water electrolysis system is a combination of photovoltaic cells (PV) and water electrolysers. This is a quite simple system.

As shown in Fig.6 the electrolysers are connected through DC-AC converters. A DC-AC converters is a solid-state system that convert the voltage level and therefore current level, of alternating current (AC) just like a transformer for direct current (DC). By connecting the PV-system and electrolysers though DC-AC converters as shown in the Fig.5 additional freedom in designing a PV-electrolysis system is acquired. By using DC-
AC converters, PVs and electrolysers can operate different voltage. Therefore both PVs and electrolysers can be designed to operate at their most efficient voltage.\(^{(9)(10)(11)(12)}\)

**Photo-electrochemical (PEC) water splitting**

Photoelectrochemical (PEC) water splitting (fig. ) has attracted significant attention in the past decades as a promising renewable energy source due to their **low production cost and simple manufacturing process.**\(^{(13)}\)

A conventional PEC cell is established with a semiconductor photo-anode and a Pt electrode as the cathode in the electrolyte solution.\(^{(14)}\)

![Fig.7. Electrochemical system for water splitting](image)

\textbf{Fig.7. Electrochemical system for water splitting} \(^{(26)}\)

**Steam Reforming**

Steam reforming of natural gas or syngas sometimes referred to as steam methane reforming (SMR) is the most common method of producing commercial bulk hydrogen as well as the hydrogen used in the industrial synthesis of ammonia. It is also the least expensive method. At high temperatures \((700 - 1100 \, ^\circ\text{C})\) and in the presence of a metal-based catalyst (nickel), steam reacts with methane to yield carbon monoxide \((\text{Fig.8})\) and hydrogen. These two reactions are reversible in nature.

\[
\text{CH}_4 + \text{H}_2\text{O} \rightleftharpoons \text{CO} + 3 \text{H}_2
\]

Additional hydrogen can be recovered by a lower-temperature gas-shift reaction with
the carbon monoxide produced. The reaction is summarized by:

\[ \text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 \]

The first reaction is strongly endothermic (consumes heat), the second reaction is mildly exothermic (produces heat).

This chemical equation illustrates that in the SMR reaction, for every methane molecule (CH\(_4\), the main constituent of natural gas) four hydrogen molecules are produced. Half of this hydrogen comes from water, which is one reason that using hydrogen made from natural gas reduces carbon dioxide emissions by approximately 50 percent compared to using gasoline in a car. Only one carbon dioxide molecule is released for every four hydrogen molecules generated.

**The United States produces nine million tons of hydrogen per year, mostly with steam reforming of natural gas.**

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**Tabl.3. Summary Efficiency of Processes**

<table>
<thead>
<tr>
<th>Process</th>
<th>Two Stage Fermentation</th>
<th>Driven Electrolysis of Water</th>
<th>Steam Reforming</th>
<th>Photoelectrochemical Water Splitting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two Stage Fermentation(4)</td>
<td>70-97%</td>
<td>10-11%</td>
<td>65-75%</td>
<td>&gt;50%</td>
</tr>
</tbody>
</table>

**Tabl.4. Results of the NER, GHG and NRE analysis for hydrogen processes compared with SMR.** Where: Energy Ratio (NER); Non-Renewable Energy (NRE); Energy Efficiency (EE); Greenhouse Gas (GHG); Steam Methane Reforming (SMR)

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**Hydrogen Delivery**

In the United States, more than 20 billion kg of hydrogen were produced in 2008. Corresponding daily production is shown in **Fig.9**.

The method of delivery for merchant hydrogen varies primarily with the volume required by the user. **For the smallest quantities** (individual deliveries of 0.5-50 kg)
Hydrogen is often bought and sold as a compressed gas in cylinders. Larger quantities (50+ kg) are commonly delivered by tube trailers (with gaseous hydrogen that has been compressed after production) and liquid tanker trucks (with cryogenic liquid hydrogen that has been chilled after production). To satisfy extremely large demand, hydrogen can be delivered by pipeline.

The pipeline is nearby and the monthly sales are sufficiently high to justify the connecting costs. In general, while the cost to build a hydrogen pipeline is significant (some estimate costs at $1 million/mile), once built and connected to the customer site, it is by far the cheapest delivery method for hydrogen. (21)
It is very important to be noted that the hydrogen will be produced in big production facilities (but is possible to be build and stations near or infront to them) and after that will be transported to fueling station in the region. That will decrease the levels of investment and will expand coverage.

**Design of Fuel Stations and Infrastructure of Northeastern United States**

The components of Hydrogen stations (Old and New) can be seen in *Tabl.4.*

Hydrogen supplies in „ Early adoption period” till middle of „ Growing market penetration period” will be implemented through liquid truck. However, in the Early adoption period can be starting building a Hydrogen pipeline system connecting the various industries and end-users in the region and satisfying the needs at beginning of „Beginning of mass commercialitation period”.

<table>
<thead>
<tr>
<th>OLD FUEL STATIONS</th>
<th>NEW HYDROGEN STATONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Under or on-ground tank for Hydrogen Fuel Storage</td>
<td>✓ Under or on-ground tank for Hydrogen Fuel Storage</td>
</tr>
<tr>
<td>✓ 2 New Columns for Hydrogen Fuel</td>
<td>✓ 4 Columns for Hydrogen Fuel</td>
</tr>
<tr>
<td>✓ The nozzles (which are combination of handle for existing gas nozzle and typical hydrogen nozzle)</td>
<td>✓ The nozzles (which are combination of handle for existing gas nozzle and typical hydrogen nozzle)</td>
</tr>
<tr>
<td></td>
<td>✓ Convenient Store</td>
</tr>
</tbody>
</table>

*Tabl.4. Components of Fuel Stations*  
*Fig.13. Methods for Hydrogen Storages (27)*

In this project we choose to work whit high pressure storage because the efficiency is more than 99.9%. The efficiency is almost 100% when checked for leaks and only minor energy losses of <0.1% may be expected due to eventual venting and purging of the lines. Availability of the technology may be considered as 99%. This is a rather conservative value, because hydrogen storage tanks may be in service for years between control tests, which are necessary according to the regulations. Unavailability may be attributed to the eventual occurrence of leaks in the piping and fittings connected to the storage, which must be repaired, keeping the storage out of service for some time. The total life period of the technology is 30 years.

The allocation of hydrogen fueling stations in the next part of section was based on factors as traffic and population density (Fig.1.A and B), land availability and
availability of hydrogen sources (Fig.1.A, Fig.2.A and B) in each city in NeUR’s region. That allocation will secure and cover the needs in the region.

Existing fuel stations per each city are presented below.

**NEW YORK**

![New York Location and Possible Hydrogen Production from water (by Water Electrolysis and PEC water splitting) in blue areas](image)

**Fig.14.** New York Location and Possible Hydrogen Production from water (by Water Electrolysis and PEC water splitting) in blue areas

**Fig.15.** Population Density in New York City, 2000

For Possible Hydrogen sources and Locations for production from Biomass See **Fig.2** and Natural Gas-**Fig.12**

For List of addresses see **Appendix 1**
Fig. 17. Boston Location (30)

For Possible Hydrogen sources and Locations for production from Biomass See Fig. 2 and Natural Gas- Fig. 12

For List of addresses see Appendix I

Fig. 18. Location of Possible Hydrogen Fueling Stations in Boston (marked with green spots) and Possible Hydrogen Production from water (by Water Electrolysis and PEC water splitting) in blue areas (30)

Fig. 19. Boston Traffic (30) For Possible Hydrogen sources and Locations for production from Biomass

Fig. 20. Philadelphia Location (30)

Fig. 21. Location of Possible Hydrogen Fueling Stations in Philadelphia (marked with blue spots) and Possible Hydrogen Production from water (by Water Electrolysis and PEC water splitting) in blue areas (30)
Because of lack of information about the exactly location of organic landfills in the region we can't provide information where will be situated the bio-hydrogen production facilities in each city.
The price of fuel is probably at its highest ever across the majority of United States. The consequences of global warming due to carbon dioxide emissions from road use is now hitting home to a wide section of the populace.

The need for infrastructure is based on a number of factors, including driving patterns or traffic flow, geographic coverage of Northeastern region of the country, amount of organic wastes and continuity. Considering these factors, a proposed interstate network for the hydrogen infrastructure analysis was developed. The network is meant to ensure a convenient route and fueling stations between major population centers (e.g., from Washington to Boston -Fig.26).

The hydrogen in the Northeastern region will be produced by the electrolysis of water using electrical power generated by sustainable solar energy, biomass degradation and steam reforming. In 2020 the hydrogen load is zero in each city. In 2020 will be build pipelines between the cities with the largest future hydrogen loads. These pipelines are greatly oversized for 2020, but optimally sized considering the future hydrogen demands. A small steam methane reformation (SMR) plant supplies the cities in the pipeline network, while isolated electrolysis and biomass plants supply the smaller cities. In 2028, near the end of the useful life of the electrolysis plants built in 2013-2014, will be replaced with electrolysis plants with liquid hydrogen truck links from various points in the pipeline network.
Coordinating and co-operating the hydrogen infrastructure with existing natural gas fueling sites is important because these locations have significant experience dealing with the permitting and logistic issues related to gaseous fuels. Additionally, these locations are likely to have several local fleets and customers accustomed to using gaseous fuels and may be likely early adopters of hydrogen fuel cell vehicles. For the purpose of this analysis many existing alternative fueling stations, other fuel and service stations were included. Other interstate and U.S. highways intersecting the proposed interstates are important to this analysis because of the additional traffic they bring to the intersecting point. The Northeastern Hydrogen Highway can be also connected with other Hydrogen Highways like a East-Coast (Fig.27) making network.

This assumes that a fueling station located at an intersection would provide service to more people than a station not at an intersection.

"The Hydrogen Highway is a concept to make it more convenient for road users to use this alternative fuel"

Population data were incorporated. An assumption was made that the greater the population, the more potential customers for a hydrogen station, leading to greater hydrogen demand and a higher likelihood that the station could be economically self sustaining. Because of an assumed vehicle range of about 300 miles, station placement was set to a maximum of 100 miles between stations.

Considering all the factors collected, stations were placed along the selected routes. This was done somewhat subjectively: each station site was manually selected based on proximity to existing infrastructure daily traffic, and local population.

Overall, more than 200 old stations (with 2 hydrogen column are comparable with 100 new) and up to 100 new Hydrogen Stations were identified that could make up a potential transitional hydrogen fueling infrastructure backbone, constructed to meet the needs of 2025.
planning vehicle deployment is a dynamic process. Placing the first wave of stations will impact the locations for the second wave. Vehicles may be more popular in one community than in another. We will survey automakers annually to ensure that the next wave of stations are being constructed at the most desirable locations for the coming customers. Local governments will benefit from becoming a hydrogen community. FCVs and hydrogen stations will bring new jobs and economic opportunities into the community while providing residents with new consumer choices that address environmental and economic concerns. Hydrogen community leaders can coordinate and share resources to maximize their effectiveness. Incentives or other benefits will encourage the community leaders to:
- Identify and develop methods to leverage local and outside resources
- Develop more detailed plans that match their own community’s unique attributes and qualities.
- Lead efforts to inform and prepare their community, develop appropriate policies, and coordinate activities among local stakeholders.

Being connected to the rapidly advancing alternative transportation technology in its early stages will encourage the hydrogen communities to lay the foundations of this new commercial market.

In this chapter we split up a technology’s development to commercialization in different stages. For each stage the different set of activities and (partially) different actors are described. Handing over a technology from one phase to next, might give rise to some specific hurdles. We distinguish between tree development stages. They are related to technology and market developments shown in Fig.30.

**Fig.30 Technology development phases**

Note: In our case the commercialization phase is separated in two parts: Growing market penetration and Beginning of mass commercialization

The creation of national and international hydrogen-fuelling infrastructures will require decades of investment and technological innovation. The latest studies from the US shed light on the commercial challenges – and opportunities – associated with hydrogen generation, distribution and storage.
1. Early market: Early adoption period 2013-2015

The early commercial fuel cell vehicles and hydrogen stations must be placed together in a manner that makes efficient use of limited government and industry resources to support a nascent industry, but also places stations slightly ahead of vehicle rollouts. Communities must be prepared so that permitting becomes routine, and fuel providers must see a path to a viable business plan for investing infrastructure and realizing a profit from selling hydrogen as a retail fuel.


The final phase from the conception of a technology towards commercialization is the commercialization phase itself. In order to enter this phase, the technology needs to be attractive to a different type of customers that have higher demand on matters like costs, user-friendliness and do not necessarily care for novelities. At that stage, the use of old technology might be phased out by prohibiting its use.

There are many clear and valuable linkages between near-term markets and more distant mass markets, like automotive. The growth and maturation of the supply chain, including after sales services, will ultimately benefit the light duty FCV market (Fig. 31).

Applicability of near-term market driven technologies, components and processes will be, dependent on the technologies and design that trigger the commercial launch of FCVs.

If, as many believe, these vehicles are to be heavily hybridized, there may be a high degree of applicability between markets. However, there will also be other areas related to the key elements of the stack system interface, control and monitoring processes, within the complete power train, and other subtleties where the overlap in learning will be more limited. Lastly, the growth in near-term markets will result in a corresponding growth in employment and training. These resources will help position Northeastern America as a source of skilled personnel who can develop, build, test and repair fuel cell products.

Where the need to address energy security, urban pollution and climate change issues are a high priority, hydrogen infrastructure may involve centralized hydrogen and electricity production with carbon capture (Fig. 32). Such facilities could augment
renewable electricity sources for charging plug-in series hybrid fuel cell electric vehicles and provide the hydrogen by pipeline to refueling stations or the home.

**Fig.32 GHG emissions**

In the long term, the generation of hydrogen from natural gas could lead to a greater than 50% reduction in vehicle GHG emissions. Factor in hydrogen generation from renewable resources and it could be possible to eliminate vehicle GHG emissions over the same time frame.\(^{34}\)

The success of hydrogen and fuel cell technologies in the mass markets is dependent on their ability to provide substantially better solutions than the incumbent combustion or battery technologies. What makes for a “better” solution depends on a balance of technical and social benefits.

### 3. Valleys-of-death in between technology phases

Before a technology moves from one phase to the next, it has to be clear that it could ‘survive’ the economic circumstances of the next phase and should address the needs and expectations of actors in the next phase. As the conditions, economic circumstances and actors are not necessarily the same as in the current phase, and the technology might not directly appeal to stakeholders in the next phase, there is a large probability that the technology is not taken up in the next phase. A technology gets sort of lost between to development phases and this barrier is referred to as a ‘valley of death’. For illustration, different end-user technology adopter categories as defined by Rogers (1962) are indicated as well, Valleys of death occur e.g. when a new adopter category is to be addressed. In literature, the valley of death is usually associated with this barrier between the early markets and commercialization. However, using a similar line of reasoning the same type barriers can be found between each development phase, i.e. each transition between development phases has in own valley of death. In **Fig.33** the valleys of death are indicated between the technology phases as mentioned in **Fig.32**. Below, we will elaborate on the specific barrier between technology phases-Early market and Commercialization.

**Early markets → Commercialization**

The main uncertainties for Hydrogen technologies in this phase are the perception of demand with consumers and their demand behavior for the medium to long term.
Actors will compare using H\textsubscript{2} with other options like BEV or vehicles based on ICEs and fuelled with petrol or diesel. The key source of the consumer related uncertainties in this phase are that a different type of consumer needs to be addressed. In the commercialization phase, the early majority, late majority and laggards become the key consumer groups. These customer groups base their choices on a different set of needs and benefits and these types of customers perceive disadvantages differently from innovators and early adopters. If H\textsubscript{2} manages to also fulfill the needs of these customer groups, it may establish itself as a regime technology and autonomously increase and, after stabilization, maintain a market share. Availability of resources as defined in previous sections remains a concern but is now accompanied by for example the ability of suppliers to provide fuel. When the technology starts to become successful, markets for fuel and technology components may become more strained.\textsuperscript{(35)}

4. Fuel Cell Vehicle Deployment and Hydrogen Demand

Automakers’ technical advances and planned deployments are highly confidential, a sure sign that automakers are serious about commercializing fuel cell vehicles. The survey collectively identify where, when and how many FCVs they plan to deploy in the next few years. The results of the survey were aggregated to ensure no individual automaker’s plans could be specifically identified. \textit{Tabl.5} and \textit{Tabl.7} presents an overview of the survey results.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average production/Year</td>
<td>525 600</td>
<td>18 050 400</td>
<td>22 010 927 200</td>
</tr>
<tr>
<td>Average consumption/Year</td>
<td>226 920</td>
<td>8 857 200</td>
<td>20 000 000 183</td>
</tr>
<tr>
<td>Average Number of Vehicles</td>
<td>1 240</td>
<td>484 000</td>
<td>&gt;&gt;2 000 000</td>
</tr>
<tr>
<td>Average Miles Driven/Year</td>
<td>131 254</td>
<td>5 123 140</td>
<td>211 700 000</td>
</tr>
<tr>
<td>Number of Stations</td>
<td>39</td>
<td>240</td>
<td>&gt;227</td>
</tr>
</tbody>
</table>

\textit{Tabl.5} NeUSR’s FCV Deployment Survey Results: Number of Passenger FCVs in operation and Hydrogen Demand\textsuperscript{(36)(37)(38)}

<table>
<thead>
<tr>
<th>2010 Number of Vehicles per Household</th>
<th>Boston, MA</th>
<th>Washington, DC</th>
<th>New York County, NY</th>
<th>Philadelphia, PA</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Vehicle</td>
<td>92 927</td>
<td>32 400</td>
<td>154 549</td>
<td>74 749</td>
</tr>
<tr>
<td>1 Vehicle</td>
<td>132 284</td>
<td>48 743</td>
<td>173 027</td>
<td>74 749</td>
</tr>
<tr>
<td>2 Vehicle</td>
<td>45 263</td>
<td>17 623</td>
<td>49 232</td>
<td>18 623</td>
</tr>
<tr>
<td>3 Vehicle</td>
<td>10 044</td>
<td>3,91%</td>
<td>10 000</td>
<td>3,91%</td>
</tr>
<tr>
<td>4+ Vehicle</td>
<td>3 797</td>
<td>1,93%</td>
<td>5 746</td>
<td>1,93%</td>
</tr>
</tbody>
</table>

\textit{Tabl.6} NeUSR’s Light Duty Vehicles Survey Results till 2010\textsuperscript{(39)(40)(41)(42)}
Tabl.7 NeUSR’s FCV Deployment Survey Results: Number of Passenger FCVs in operation and Hydrogen Demand (per City) (36)(37)

In addition to passenger vehicles, NeUSR’s transit agencies are operating or will soon operate fuel cell buses in demonstration programs. The number of fuel cell buses is projected in Tabl.8.

Tabl.8 Estimated average number of FCBs in NeUSR

Two guiding principles, station coverage and capacity utilization, underlie the process for determining the number of stations necessary during the early commercialization phases. They represent the bookends of building a new transportation infrastructure for light-duty FCEVs. Coverage improves the customer experience, ensures confidence in the technology, increases vehicle utility and enables broad market participation(Fig.34,36).

NeUSR’s scenario for placing stations till 2025 (33)(43)

Note: The capacities of stations can be increased, depends on fuel needs per period (Station Capacity 400 kg/day (in one period) to 1000 kg/day (in another period) or Station Capacity 1000 kg/day to 1500 kg/day). This changes are shown in red color. Here are not presented the stations in the NeUSR’s hydrogen highway.

In short, station coverage establishes a local network by placing adequate fueling outlets in key markets. Capacity utilization supports technology development, minimizes risk to station operators and builds business models to lower overall station costs.

Tabl.9. NeUSR’s highway scenario for stations till 2025

Note: The average distance between each station is 30 miles.
Sufficient utilization ensures station operators have a chance to make their business profitable.
These principles must be systematically reconciled during the commercial launch to ensure automakers, infrastructure equipment providers, station operators and government entities maximize the market’s potential and protect billions of dollars of private and public investment.

7. Fuel Demand

To project the demand for fuel, we assumed that each passenger vehicle will use average 0.5 kg per day, which includes actual projected use plus a small reserve supply. Hydrogen stations for passenger vehicles need to supply fuel at two pressures: 35 MPa (350 bar) and 70 MPa (700 bar). Assuming median numbers of fuel cell buses and 25 kg/day demand for each bus. Hydrogen stations for transit buses need to provide fuel at 35 MPa pressure only. Fig. 39

**Fig.36.** NeUSR’s highway scenario for placing stations till 2025  
*Note:* With Green are shown stations with capacity 100 kg/day, Brown-400 kg/day, Blue – Mixed 400/60 kg/day and Red - 1000 kg/day.

**Fig.37** Types of Hydrogen Production Facilities depends on production size (43)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Central Station (CS) Production</th>
<th>Midsize (MS) Station Production</th>
<th>Distributed (Dist.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Capacity (kg H₂/day)</td>
<td>1,200,000</td>
<td>24,000</td>
<td>480</td>
</tr>
<tr>
<td>Operation Capacity Factor</td>
<td>90% or average 1,080,000</td>
<td>90% or average 21,600</td>
<td>90% or average 432</td>
</tr>
<tr>
<td>Number of support Cars</td>
<td>2,000,000</td>
<td>40,000</td>
<td>800</td>
</tr>
</tbody>
</table>
Fig.38 Hydrogen Production and Distribution Plan in NeUSR

Centralized Hydrogen Production Pathway – This is currently the most common and efficient method to produce hydrogen.

Distributed Hydrogen Production Pathway – Although not as common as the centralized production pathway, distributed hydrogen production has been successfully demonstrated and has the potential to be scalable and economically competitive with alternative pathways. Therefore, this is a priority pathway.

In our project are presented and both pathways for hydrogen production in fig.39. In this way will can be reached low hydrogen price.

---

**Table: Hydrogen Production and Distribution Plan in Northeastern United States Region**

<table>
<thead>
<tr>
<th>City</th>
<th>Centralized Production Method</th>
<th>Distributed Production Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston</td>
<td>40% Water Electrolysis/</td>
<td>35% 80% Reforming of</td>
</tr>
<tr>
<td></td>
<td>Electrochemical Water</td>
<td>Natural gas</td>
</tr>
<tr>
<td></td>
<td>Splitting and 70% Fermentation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>of organic wastes (Biomass)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Truck liquid Tanker and Tube</td>
<td>Pipelines and Truck liquid</td>
</tr>
<tr>
<td></td>
<td>Trailers</td>
<td>Tankers</td>
</tr>
<tr>
<td>New York</td>
<td>50% Water Electrolysis/</td>
<td>20% 60% Reforming of</td>
</tr>
<tr>
<td></td>
<td>Electrochemical Water</td>
<td>Natural gas</td>
</tr>
<tr>
<td></td>
<td>Splitting and 50% Fermentation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>of organic wastes (Biomass)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Truck liquid Tanker and Tube</td>
<td>Pipelines and Truck liquid</td>
</tr>
<tr>
<td></td>
<td>Trailers</td>
<td>Tankers</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>40% Water Electrolysis/</td>
<td>50% 70% Reforming of</td>
</tr>
<tr>
<td></td>
<td>Electrochemical Water</td>
<td>Natural gas</td>
</tr>
<tr>
<td></td>
<td>Splitting and 60% Fermentation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>of organic wastes (Biomass)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Truck liquid Tanker and Tube</td>
<td>Pipelines and Truck liquid</td>
</tr>
<tr>
<td></td>
<td>Trailers</td>
<td>Tankers</td>
</tr>
<tr>
<td>Washington DC</td>
<td>50% Water Electrolysis/</td>
<td>60% 40% Reforming of</td>
</tr>
<tr>
<td></td>
<td>Electrochemical Water</td>
<td>Natural gas</td>
</tr>
<tr>
<td></td>
<td>Splitting and 70% Fermentation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>of organic wastes (Biomass)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Truck liquid Tanker and Tube</td>
<td>Pipelines and Truck liquid</td>
</tr>
<tr>
<td></td>
<td>Trailers</td>
<td>Tankers</td>
</tr>
</tbody>
</table>

**Fig.39 Expected hydrogen demand**

Average hydrogen production 22 010 927 200 kg H₂/year after III Period
Average number of Support Cars in the Period → 100 506 517

**Notes:**
- C = current technology, Y = sequestration (hydrocarbon feedstock in central station);
- F = future technology, PV = photovoltaic driven electrolysis or water splitting, Bio = biohydrogen production
Northeastern United States Region (NeUSR) must meet immediate fuel needs of FCV drivers and plan for the future. In this roll-out scenario, hydrogen supply will temporarily exceed customer demand, but the excess capacity will diminish over time as automakers place more vehicles in the “hydrogen-ready” communities (Fig.40).

Hydrogen stations could be deployed according to a variety of scenarios regarding number of stations per community, station size, timing and location of connector stations between communities and destinations. NeUSR evaluated five scenarios for placing stations to meet demand in 2025 (Fig.41).

1. A scenario that closely matches hydrogen supply with customer demand, which limits excess hydrogen supply and therefore constrains consumer options.

2. A small station approach that maximizes consumer fueling options (more stations), but at a higher cost.

3. A large station approach that maximizes the business case for station providers, but provides fewer fueling options for consumers (fewer stations).

4. An approach that uses mostly portable stations, which could minimize the investment risks.
5. A balanced approach use

The classic “chicken-and-egg” scenario between the development of a hydrogen infrastructure and the commercial maturity of fuel cell technology for automotive transportation applications has played a role in the extending timelines for FCV deployment.

Nevertheless, there are two key obstacles remaining to the adoption of hydrogen as a fuel of the future: The cost of manufacture, storage and transportation relative to conventional fuels, a barrier that is further exacerbated when other methods of hydrogen production (e.g., electrolysis using energy from renewables) are considered.

Infrastructure: today we have a tried and true global distribution system of pipelines for conventional liquid and gaseous fuels. No such system exists for hydrogen.

8. Hydrogen fueling station location by period of time

Cause of the large number of new fueling station we present some of them in the period of time 2013-2025. Location of the stations depends on population and traffic density in each city, hydrogen sources in the region and availability of hydrogen fuel supply. (Fig.1B and C) The Fuel Stations Network covered more than 95% of Northeastern Region Area.

BOSTON

Fig. 40 Boston’s Hydrogen fueling station location in: I phase of Infrastructure Development and in the II phase of Infrastructure Development
NEW YORK

Fig. 41 New York’s Hydrogen fueling station location in: I phase of Infrastructure Development and in the beginning of II phase of Infrastructure Development

PHILADELPHIA

Fig. 42 Philadelphia’s Hydrogen fueling station location in: I phase of Infrastructure Development and in the II phase of Infrastructure Development

WASHINGTON DC
Today's hydrogen stations have been built by the energy companies, Shell, Hess, Agip, Chevron and BP; by industrial gas companies, Air Products, Praxair, Air Liquide and Linde; and by governments and universities. As stations transition to retail, it’s likely that the energy companies and industrial gas companies will remain strongly involved and that new companies will become interested in providing alternative fuel stations.

COST AND ECONOMIC PLAN

There is no one clear business model for the hydrogen infrastructure market at present. Currently, the major players in hydrogen fueling are large multinationals: the industrial gas companies, and the energy and gas companies, both those that operate retail gas stations and those that provide fuels for the grid. This project part analyzes the dynamics of the Northeastern US demand for hydrogen fuel and the infrastructure investments that will support fueling stations for fuel cell light duty vehicles, buses, forklifts, scooters, and stationary power applications. The study includes an examination of market issues, technology issues, and the competitive landscape within the hydrogen infrastructure industry. Market forecasts for hydrogen demand and fueling infrastructure, segmented by application and geography, are provided through 2025. 

It is too early to know exactly which types of vehicles customers will be driving in 2025. But we do know that to meet the 2025 goal, advanced technology must be in virtually every vehicle produced and sold by 2030, allowing 20 years to fully turn over the vehicle population. By 2020, automakers must begin introducing commercially viable technology into multiple production vehicle platforms.

Hydrogen stations for light-duty vehicles range in cost from $1.5-5.5 million, including equipment, site preparation, engineering and permitting. The type of station, station capacity and number of dispensers directly affect costs.

Despite the many variations on station design, most stations contain the following pieces of hardware: Hydrogen production equipment (e.g. electrolyzer, steam reformer) (if hydrogen is produced on-site); Purification system: purifies gas to acceptable purity for use in hydrogen vehicles; Compressor: compresses hydrogen gas to achieve high-pressure 5,000-10,000 psi fueling and minimize storage volume; Storage vessels (liquid
<table>
<thead>
<tr>
<th>Station Type</th>
<th>Capacity (kg/day)</th>
<th>2013-2015</th>
<th>2015-2020</th>
<th>2020-2025</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New Stations</td>
<td>Old Stations</td>
<td>New Stations</td>
<td>Old Stations</td>
</tr>
<tr>
<td>50</td>
<td>Permanent</td>
<td>$1.5 m</td>
<td>-</td>
<td>$310 k</td>
</tr>
<tr>
<td>100</td>
<td>Permanent</td>
<td>$2.0 m</td>
<td>$1.0 m</td>
<td>$418 k</td>
</tr>
<tr>
<td>400</td>
<td>Permanent</td>
<td>$3.0 m</td>
<td>$1.5 m</td>
<td>$714 k</td>
</tr>
<tr>
<td>1000</td>
<td>Permanent</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>Permanent</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>400/60</td>
<td>Permanent</td>
<td>$4.0 m</td>
<td>-</td>
<td>$900 k</td>
</tr>
<tr>
<td>1000/400</td>
<td>Permanent</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table 10 Capital Investment in Hydrogen Fuel Stations in NeUSRs by periods of time (Yellow-2013-2015, Orange-2015-2020 and Red 2020-2025)* (49,50,51,52,53,54,55)
or gaseous); **Safety equipment** (e.g. vent stack, fencing, bollards); **Mechanical equipment** (e.g. underground piping, valves); **Electrical equipment** (e.g. control panels, high-voltage connections)

**Total station construction costs** also include the following: engineering and design, site preparation, permitting, installation, and commissioning (i.e. ensuring the station works properly) (see **Tabl.11**).

Actual **operating and maintenance (O&M) costs** vary depending on the size and type of station. This analysis assumes annual **average O&M costs are 12 percent of the station capital costs, including maintenance, insurance and taxes**. Land costs for hydrogen stations in the Southern California area are assumed to be $130,000-$430,000 per year, depending on station size (In the case of NeUSR for only 30% of stations will be paid land cost because they will be new). (59)

Our analysis uses 2011 costs for infrastructure capital and operating expenditures based on industry cost data together with costs for government-funded hydrogen station deployments in California to calculate the dispensed hydrogen cost for the centralized and distributed hydrogen production approaches (**Tabl.10**). Where appropriate, NREL’s H2A Production Analysis tool (“H2A”), together with default H2A assumptions, was used to convert available cost data to a $/kg basis. 60 H2A is a well-known and widely used techno-economic modeling tool within the hydrogen industry and DOE. It calculates the dispensed hydrogen costs based on operating and capital inputs with transparency and consistency among multiple pathways. Steam methane reforming of natural gas was assumed for both the centralized and distributed approach because this is commonly regarded as the most economical method for hydrogen production.

We assumed some reduction of fuel station cost caused hydrogen production. In the case of California, hydrogen is on-site produced.

**Tabl.11 Installation cost categories**

<table>
<thead>
<tr>
<th>Installation Cost Categories</th>
<th>% of Capital Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Facilities</td>
<td>20%</td>
</tr>
<tr>
<td>Eng.permitting &amp; Startup</td>
<td>10%</td>
</tr>
<tr>
<td>Contingencies</td>
<td>10%</td>
</tr>
<tr>
<td>Working Capital, Land Misc</td>
<td>5%</td>
</tr>
</tbody>
</table>

The most expensive outcome illustrated by the error bars pair high capital costs with a $2 retail margin and “Slow Growth” FCEV deployment. Conversely, the least cost outcomes benefit from low capital costs, a $4 retail margin, and “Medium Growth” FCEV deployment, allowing a station to become profitable sooner (**fig.44**).

The cash flow support approach demonstrates greater variability primarily because the stations are 100 percent debt financed, which allows hydrogen fuel sale revenues to be used to pay off station debt. If cars are rapidly adopted, the amount of incentive needed to support cash flow shortfalls decreases.

In terms of cash flow support, two factors dictate the amount of incentive money needed each year: number of stations and hydrogen fuel sales. The early years require increasing cash flow support as more stations come on line. As hydrogen sales increase,
the need for cash flow support decreases as stations begin to pay for themselves. In contrast, the capital cost buy-down requires substantial upfront investment.

Fig. 44. A) Total Cost of Hydrogen Fuel Stations in NeUSR (With Blue is noted New Stations (Cash Flow Support); Light blue line is noted Existing Stations (O&M Support); Red line is noted Existing Stations (O&M Support)

B) NeUSRs Hydrogen Production facilities Investment by periods of time

Note: Calculations are made on the basis of information taken from Fig.39, Tabl.11 and Fig.45

A. CENTRALIZED HYDROGEN PRODUCTION COST ESTIMATES

The cost analysis for each centralized production technology is based on a benchmark capacity of 150,000 kg/day, as utilized by SFA (SFA Pacific, Inc. 2002). SFA presented cost elements that would allow the costs for plants of various sizes to be estimated, but we chose to assume the same plant size for all centralized production technologies (fig.45). Energy cost projections to 2025 for electricity and natural gas used in both the centralized and distributed production cost analysis are from EIA’s AEO 2003 documentation (EIA 2003a) (Tabl.12).

Biomass resource costs were derived from biomass supply curves developed by ORNL and available by state (ORNL 2003). Regional estimates were calculated by weighting the state-level volume and price estimates (The AEO and ORNL price estimates are treated as costs in the production of H2) (Tabl.13).

<table>
<thead>
<tr>
<th>Sector and Source</th>
<th>2010</th>
<th>2020</th>
<th>2025</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas Price, $/mmBTU</td>
<td>5.03</td>
<td>5.35</td>
<td>5.60</td>
<td>Extrapolated from 2021-2025</td>
</tr>
<tr>
<td>Electricity Price, $/kWh</td>
<td>0.063</td>
<td>0.066</td>
<td>0.67</td>
<td>Extrapolated from 2021-2025</td>
</tr>
</tbody>
</table>
Tabl. 12 Cost of Input energy (Natural Gas and Electricity) to produce Hydrogen, National Averages

Tabl. 13 Costs of Input Energy (Biomass) to Produce Hydrogen

<table>
<thead>
<tr>
<th>Region</th>
<th>Median Price ($/dry ton) in 2010</th>
<th>Median Price ($/dry ton) in 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>New England (include Boston)</td>
<td>30.03</td>
<td>23.78</td>
</tr>
<tr>
<td>Middle Atlantic (include New York and Philadelphia)</td>
<td>31.53</td>
<td>30.02</td>
</tr>
<tr>
<td>Pacific (include Washington)</td>
<td>29.08</td>
<td>23.03</td>
</tr>
</tbody>
</table>

*Median prices gradually decrease from 2010 to 2050 values

Tabl. 14 Price of Transportation and Capital Cost of H2 Pipelines

In our analysis, we assumed that only liquefied H2 tankers and pipelines would be used to deliver H2. We assumed that liquefied H2 tankers would be used initially (or for very low demand), and then, as production volume grows, a shift would occur from liquefied H2 tanker to pipeline (Tabl. 14).

We reduced the delivery and dispensing cost of both pathways, assuming technological improvement over time. For pipelines, we also reduced SFA’s estimates to account for the following: The assumed transport distance of 600 km and 18% capital charges appeared high; As production volume grows, it was assumed that capital costs for old pipelines would be amortized, existing lines would be converted, and transport distances would decline as shipments increased. Therefore, transport and dispensing cost on a per-unit basis decreases with time. We also evaluates the near term total cost of hydrogen (“dispensed hydrogen”) based on cost data from recent government-funded hydrogen infrastructure deployments in 2008 dollars unless otherwise stated. Dispensed hydrogen cost is evaluated on a $/kg basis where,

\[
\text{Dispensed Hydrogen Cost} = \text{Cost of (Production + Distribution + Compression + Storage + Dispensing)}
\]
Fig. 45 Centralized Hydrogen Production Cost Estimates (58)
B. LEVELIZED COST OF HYDROGEN

We cannot predict the retail price of hydrogen fuel. For the purposes of this analysis, we assume that hydrogen will be sold anywhere from $8 - $12/kilogram till end 2020, including sales tax. These costs include approximately $6/kg wholesale cost, sales tax of 9% ($0.72 to $0.90/kg) and retail margins of $2-5/kg. After second period the price of hydrogen can be reduced with till 30%. Given that one kilogram of hydrogen holds approximately the same energy content as one gallon of gasoline, and that fuel cell electric vehicles (FCEVs) are about 2.5 times as efficient as conventional gasoline engine vehicles, $8-12/kg hydrogen is comparable to gasoline priced between $3.20 and $4.40 per gallon. Consumers will be required to understand the efficiency of their vehicle as they compare $8-12/kg hydrogen to the current price of gasoline. As gasoline prices rise, educated FCEV drivers will view hydrogen priced at $8-12/kg as a competitive fuel. The assumptions are made on the basis of calculations presented on Tabl.15. (the information was taken from Fig.39, Tabl.10, Fig.44 A and B).

Tabl.15. Price calculations

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital costs per kg basis (Ccap)</td>
<td>11,59</td>
<td>0,17</td>
<td></td>
</tr>
<tr>
<td>Levelized Cost of Hydrogen (LCH)</td>
<td>20,42</td>
<td>15,22</td>
<td>3,48</td>
</tr>
</tbody>
</table>

* avg.CRF (Capital Recovery Factor) is 12% and average variable cost of hydrogen is 3,63 $. The resulting capital recovery factors are 13 percent for mini and small stations, and 11 percent for medium and large stations. These assumptions are similar to those reported in a preliminary version of the H2A study, which assumed an internal rate of return of 10 percent for onsite SMR stations (H2A 2004). The avg.LCH per all 12 years period of time is 13,14 $. (60)

Note: The aggregate LCH values indicated in Tabl.15 represent the cost of hydrogen delivered from the entire network of early and new stations. However, the LCH for small and remotely located stations is higher than the aggregate network LCH, due to diseconomies of scale and underutilization.

Discrepancies in the LCH between stations of different sizes and stations introduced at different time periods have important implications for expected patterns of investment and potential policies to encourage stakeholder engagement in the initiation process. For example, high-volume stations in metropolitan areas will see more rapid returns on investment than those located along interstates, but both types of stations would be needed to assure consumer confidence.
Widespread market acceptance and penetration of vehicles that use hydrogen for fuel—whether fuel cell vehicles or vehicles with internal combustion engines—will eventually require hydrogen fueling stations. Just as there currently are corner gasoline stations, there will be a need for corner hydrogen fueling stations (or stations that provide both gasoline and hydrogen).

In the United States, only a small number of hydrogen fueling stations currently exist.

Most were established to support demonstration or experimental hydrogen-powered vehicle projects. Because these stations are first-of-a-kind, they generally are overdesigned with respect to human health, safety, and fire prevention issues.\(^{(3)}\)

As of winter 2008, there are more than 60 hydrogen fueling stations in the United States, with 30 more stations planned or in the process of obtaining permits. Enough stations have been built that local jurisdictions do not have to reinvent the wheel.\(^{(1)}\)

As of June 2012, the United States safely produces and uses over 9 million tons of hydrogen per year. Standards and regulations have been set to ensure the safe production, storage, handling, and use of hydrogen. All hydrogen components undergo strict third-party testing for safety and structural integrity.\(^{(2)}\)

I. PURPOSE

The purpose of this module is to guide us in approving and implementing of hydrogen motor fuel dispensing facilities. The module facilitates the identification of the:

- issues to be addressed in the permitting of a project as it progresses through the approval process
- specific requirements associated with those issues
- applicable (or potentially applicable) codes and standards by which to determine whether the specific requirements have been met.

A typical set of building and construction codes might include the following:
- **Building Code** – including seismic and structural standards
- **Mechanical Code** – including ventilation requirements
- **Plumbing Code** – including fuel piping, water and waste piping and process piping
- **Energy Code** – including energy efficiency and insulation
- **Fire Code** – including ventilation and fire protection requirements
- **Electrical Code** – including wiring, hazardous locations and fire protection requirements
- **Administrative Requirements** – including the requirements to obtain permits, mitigate environmental impacts, fees and inspection requirements
- **Air Quality Regulations** – including gaseous and particulate emissions \(^{(4,5)}\)
In this module, a hydrogen motor fuel dispensing facility is a service station for: 1) receiving hydrogen produced offsite and delivered to the station; 2) long-term storage of liquid hydrogen or compressed hydrogen gas or both; and 3) dispensing hydrogen (as a gas or liquid) to fuel cell vehicles and vehicles with hydrogen-powered internal combustion engines. Such a facility is analogous to a gasoline service station but stores and dispenses hydrogen (instead of gasoline and diesel fuel) to cars, buses, and trucks.

The module attempts to identify all applicable codes and standards relevant to the permitting requirements, regardless of the organizations that formulated them. Consequently, the codes and standards articulated include those formulated by the organizations such as the: International Code Council (ICC); National Fire Protection Association (NFPA); American Society of Mechanical Engineers (ASME); Compressed Gas Association (CGA).[3]

**II. Hydrogen Motor Fuel Dispensing Facility BASICS**

**Fig. 46. Hydrogen dispensing facility overview**

**Fig. 46** shows the basic installation of a stationary hydrogen motor fuel dispensing facility that receives and stores liquid hydrogen, vaporizes the hydrogen and compresses it, and then dispenses hydrogen gas into vehicles at 3,600 to 5,000 psi. The basic elements of the installation include liquid hydrogen storage tanks (liquid hydrogen delivered to the site); cryogenic hydrogen compressors for high-pressure hydrogen supply; vaporizers; and gaseous high-pressure storage tanks.

**Fig. 47. Hydrogen Motor Fuel Dispensing Facility Requirements**

The storage system consists of five types of components: storage container; connectors; piping; vents; controlling devices. Examples of controlling devices include regulators to control volumetric flow rate in piping and ventilation for systems located inside buildings. All five of these component types are addressed in the International Fire Code (IFC), International Fuel Gas Code (IFGC), and NFPA 50A.

**Dispensing System**

The hydrogen fueling system must be accessible and safe for use with hydrogen, and any equipment in the dispensing area must meet the requirements of the National Electric Code. Safety interlocks are an important part of the dispensing system. The system must be constructed so that it will shut down.
For hydrogen fueling to take place, several steps are required:

1. The hydrogen must be transported to the fueling station. Although hydrogen could be produced onsite, this module does not deal with onsite production. Fuel cell sites covered by this manual will have the fuel delivered to the site in some manner (truck, train or pipeline).

2. The hydrogen is stored onsite. The hydrogen can be stored as either a gas or liquid on the dispensing facility site.

3. The hydrogen is converted to its final form. The storage of the hydrogen may be in a different form than required for the final distribution and may be converted onsite. In the case study (included in this module), the fuel is converted from liquid to gas for final distribution to the vehicles.

4. The hydrogen is distributed to vehicles.

III. Codes and Standards Affecting Design, Installation, and Operation of a Hydrogen Motor Fuel Dispensing Facility

This section focuses on codes and standards (building regulations) that affect the design, installation, and operation of a hydrogen production and motor fuel dispensing facilities and will therefore have an impact on its suitability for service to the public.

The Failure Mode and Effect Analysis (FMEA) and the Codes and Standards associated with Northeastern US Hydrogen Infra-structure are briefly reviewed to give an overview of the safety needed for these systems.

**Fig.48** shows the scale of both the Failure Magnitude (FM) and Frequency (F) of each failure mode/safety concern. When the FM and F are combined, the level of risk associated with each failure mode can be determined. Table 1 shows a list of the FMEA and the steps needed to mitigate the effects of the situation. **It should be noted that there are many failure modes associated with each component, although**
for the conciseness of this paper we are only mentioning the higher risk modes.\(^6\)

The applicable codes and standards identified in „The Case Study“ provide a general guide to the regulations affecting the design of hydrogen production and motor fuel dispensing stations. More detail on the exact provisions for specific issues is provided in Appendix II. Appendix 2 provides a list of the codes and standards that affect the design, installation, and operation of a hydrogen production and motor fuel dispensing facility for service to the public (the direct connection between standards and project design is marked with red color). This table is designed as a reference for enforcement personnel to determine the codes and/or standards that govern the design, testing, and certification of the fuel dispensing and storage equipment itself, as well as the codes and standards that cover the installation and siting of the facility and its fuel dispensing and storage equipment. It should be noted that there are many codes and standards associated with each component in the Hydrogen Infrastructure, although for the conciseness of this paper we are only mentioning the Main of them. This data can be used also by the design and engineering community to determine how to document compliance with the various codes and standards.

\[\text{Fig.48. Failure Mode and Effect Analysis of Systems}\]

<table>
<thead>
<tr>
<th>System Components</th>
<th>Failure Mode</th>
<th>Causes</th>
<th>Effects</th>
<th>Mitigation of Failure/Concern</th>
<th>F</th>
<th>M</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anaerobic Digester (Bio-Reactor)</td>
<td>Gas Leakage</td>
<td>Mechanical Failure</td>
<td>Cause Injury or Death</td>
<td>Gas Detectors, Infrared sensors</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Changing of Products</td>
<td>Environmental Factors Failure</td>
<td>Release of harmful gases, Potential fire or Explosion</td>
<td>pH and Temperature sensors</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Syngas Cleanup</td>
<td>Toxic Chemicals and Solids</td>
<td>Mechanical Failure</td>
<td>Cause Poisoning, Illness, Injury or Death</td>
<td>Toxic Chemicals/Solid signs, Control plan of contaminated</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Electrolysis Unit</td>
<td>Unit Failure</td>
<td>Lack of Water Feeding</td>
<td>Loss in end use production</td>
<td>Flow Sensors</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Category</td>
<td>Failure Mode</td>
<td>Potential Event</td>
<td>Safety Measures</td>
<td></td>
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<tr>
<td><strong>Photovoltaic Unit</strong></td>
<td>Unit Failure</td>
<td>Lack of Energy supply</td>
<td>Potential fire or Explosion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mechanical Failure</td>
<td></td>
<td>Electrical switches</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Steam Methane Reforming Unit</strong></td>
<td>Unit Failure or Natural gas feed valve leaks</td>
<td>Mechanical Failure</td>
<td>Loss in end use Production; Potential Fire or Explosion; Cause Injury or Death</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Mechanical Failure</td>
<td></td>
<td>Gas Detectors and Infrared and Temperature Sensors</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Gas Leakage</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>H₂ Compressor</strong></td>
<td>Unit Failure</td>
<td>Reduction in amount of H₂ supply from PSA H₂ separator</td>
<td>Vacuum large enough to break seals and let in air, potential fire or explosion</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Mechanical Failure</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>H₂ Storage</strong></td>
<td>Storage Tank failure</td>
<td>Mechanical Failure, Corrosion, H₂ embrittlement</td>
<td>Release harmful gases to atm., Potential fire or Explosion</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Instrument Failure</td>
<td></td>
<td>System contains redundant relief devices, H₂ sensor</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Storage Tank overfill</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Vehicle impact to H₂ tank</td>
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</tr>
<tr>
<td><strong>Hydrogen Fueling Station</strong></td>
<td>Leak in Connection</td>
<td>O-ring damaged or nozzle damaged</td>
<td>Potential fire or Explosion</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Drive away while connected to dispenser</td>
<td>Human Error</td>
<td>Dispenser conducts leak check prior each fill</td>
<td></td>
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<tr>
<td></td>
<td>Piping Failure</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Vehicle impact to H₂ fueling station</td>
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</tr>
<tr>
<td><strong>Piping</strong></td>
<td>High pressure H₂ supply line failure</td>
<td>Mechanical Failure</td>
<td>Release H₂ and Potential fire</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>H₂ sensor, area electrical classification</td>
<td></td>
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<tr>
<td></td>
<td>Piping Leak</td>
<td>Mechanical Failure</td>
<td>Release harmful gases to atm.</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Depending on type of gas: sensor, MI of piping</td>
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<tr>
<td><strong>Valves-Seals</strong></td>
<td>Unit Failure</td>
<td>Mechanical Failure</td>
<td>Potential fire or Explosion</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Mechanical Failure</td>
<td></td>
<td>MI of valves and Seals</td>
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</tr>
</tbody>
</table>
MARKETING AND EDUCATION PLAN

The design of hydrogen community at **Northeastern US Region** (Boston, New York, Philadelphia and Washington D.C.) has to be environmentally sustainable and economically viable in the long term. A successful marketing strategy and an intensive education program would go a long way in popularizing the concept of hydrogen and its applications to the citizens of region in particular and the country as a whole. The initiatives that will be taken up by the UCTM team to promote and educate the people of Northeastern US Region are explained below and in fig.49: 1. UCTM’s team would like to conduct **public workshops** regarding the benefits of hydrogen as a fuel and applications of hydrogen (at **Auto shows and Visits of Hydrogen production facilities**), science fairs and other public events. This would also include real-time demonstrations of some of the applications of hydrogen, thus helping in the better understanding among the general public of NeUSR acting as an eye-opener to foreign visitors to the cities. 2. Through **collaboration with the university participants (Fig.50)** and partnerships with other stakeholder organizations, the NeUSR will develop hydrogen curriculum efforts targeted at students throughout the states.

We are currently identifying existing hydrogen learning material and resources for the college and university participants to use as a base in developing their initial hydrogen education modules. We envision that each of the education modules developed by the participants will contain initial introductory in-class activities for students regarding hydrogen and fuel cell basics.

This would be followed by a tour of the NeUSR’s participant’s fuel cell facility with a hands-on demonstration activity. For example, the activity may include sample data collection of some aspect of

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**Goal**: To help increase the fuel cell vehicle customer base in the Northeast, dispel myths about hydrogen, and promote a hydrogen fuel cell vehicle culture.

**For Students and Educators**:
- A compilation of lesson plans and classroom activities, as well as information about workshops, competitions, scholarships, and internships.

  - Grades 5-12
    - Lesson plans
    - Visual aids
    - Lab and experimental videos
    - Teacher workshops

  - Higher Education
    - College-level textbooks, programs
    - Scholarships, internships, and competitions
    - Seminars, Exhibitions, Conferences

**For Early Adopters**:
- Resources like seminars and demonstrations for “early adopters” of hydrogen technologies.
  - Possible seminar topics are:
    - "Hydrogen and Fuel Cells Properties"
    - "Hydrogen FAQ’s"
    - "Hydrogen Applications"
    - "Hydrogen Production"
    - "Hydrogen Safety", etc.

**For State and Local Governments**
- Initiatives, policies, programs, and partnerships that advance the use of hydrogen and fuel cell technologies.

**Career in Hydrogen and Fuel Cells**
- Resources for people interested in pursuing careers related to hydrogen and fuel cells.
the fuel cell’s operation. This would then be followed by further activities in the classroom to tie together the initial introductory lesson with the real world experience at the facility that they gathered. Opportunities for students to further explore hydrogen and fuel cells through class or student team projects should also be offered. The developed instructional modules may be tested on selected students with methods including targeted seminars and independent study projects.

3. **Establish a public education centers** at each city (2 in Boston, Washington and Philadelphia and 4 in New York) and **building of „Green and Sustainable “City Network** between cities with existing Hydrogen Infrastructure with aim experience transfer. The project can reached **some technical barriers as:** Lack of Readily Available, Objective, and Technically Accurate Information; Mixed Messages; Disconnect Between Hydrogen Information and Dissemination Networks; Lack of Educated Trainers and Training Opportunities; Regional Differences; Difficulty of Measuring Success

We will market hydrogen community in the same manner and expect to receive the same enthusiastic response from NeUR’s residents. To allay the public fears we will provide a clear explanation of the benefits of hydrogen residential fueling infrastructure. The main public fear concerns the safety related with hydrogen handling under high pressure. We will report that our design is focused on the safest way to operate with hydrogen. This will help in convincing the public that hydrogen energy can indeed be used to power the future. The media will act as an interface between the government and general public, thus informing the public about the latest updates regarding the government’s view on hydrogen energy. It can also give an update on the various hydrogen programs undertaken in different parts of the world. Part of this campaign will be based on educating the masses and help alleviating the public safety fears to integrate the H₂ based technology with maximum acceptance in the community. The company will invest time and money on assessing the knowledge of the public about renewable energy, fuel cells, safe usage of H₂ and recycling organic wastes. For successful completion of the plan it is necessary to be made surveys to students and general public.

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**Fig.51. NeUSRs Education campaign**

This will help in convincing the public that hydrogen energy can indeed be used to power the future. The media will act as an interface between the government and general public, thus informing the public about the latest updates regarding the government’s view on hydrogen energy. It can also give an update on the various hydrogen programs undertaken in different parts of the world. Part of this campaign will be based on educating the masses and help alleviating the public safety fears to integrate the H₂ based technology with maximum acceptance in the community. The company will invest time and money on assessing the knowledge of the public about renewable energy, fuel cells, safe usage of H₂ and recycling organic wastes. For successful completion of the plan it is necessary to be made surveys to students and general public.
For successful completion of the plan it is necessary to be made surveys to students and general public.
# APPENDIX II

## Applicable Codes and Standards in The Northwestern US Hydrogen Infrastructure

### Generators

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSA International Requirements No. 568</td>
<td>Applicable to design, manufacture, testing, inspection, operation, and maintenance of hydrogen generation facilities</td>
</tr>
</tbody>
</table>

### Storage and Transport

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFPA 1</td>
<td>For the storage, handling, and transportation of hydrogen, including storage, transport, and dispensing of hydrogen in vehicles</td>
</tr>
</tbody>
</table>

### Performance

- **Safety**: Refers to the safe operation and maintenance of hydrogen systems, ensuring they do not pose a risk to public safety or the environment.
- **Environment**: This includes the protection of the environment from hydrogen leaks and improper handling.
- **Economics**: Focuses on the cost-effectiveness of hydrogen systems, including the cost of materials, installation, and operation.

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**Note**: The codes and standards listed are not exhaustive, and there may be additional requirements specific to local regulations and the specific application of hydrogen infrastructure.
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