Hydrogen Roadmap for the U.S. Midwest Region

Prepared for: Stark Area Regional Transit Authority

In support of the Renewable Hydrogen Fuel Cell Collaborative

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- Renewable Hydrogen Fuel Cell Collaborative
- Midwest Hydrogen Center of Excellence
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EXECUTIVE SUMMARY

This Hydrogen Roadmap for the U.S. Midwest region has been developed for the Renewable Hydrogen Fuel Cell Collaborative (RHFCC) and the Midwest Hydrogen Center of Excellence (MHCoE). The RHFCC was established to propel the Midwest to become a national leader in the adoption of hydrogen fuel cell-powered vehicles through education, advocacy, and research. The RHFCC is a collaboration between the Stark Area Regional Transit Authority (SARTA) and the Ohio State University Center for Automotive Research. A key initiative of the RHFCC is the MHCoE, which supports regional advancement and adoption of hydrogen-powered, zero-emission vehicles (ZEVs) in Midwestern public transit. There is currently a multistate effort underway by these organizations to encourage and support the utilization of hydrogen as the energy source for the states' transportation needs.

The use of hydrogen as the energy source in transportation and other power applications has come a long way. The utilization of fuel cells in transport applications is growing internationally, particularly on a large scale in Asia and Europe. However, here in the U.S., the industry is in its nascent stages, barring the extensive use of hydrogen and fuel cell technology in the material handling sector where forklifts are commonly powered by fuel cells. The Midwest region finds itself well-positioned to coordinate its efforts and collectively become the third corridor, in addition to California and the Northeast, for deployment of fuel cell electric vehicles. Consequently, to maximize the environmental and economic benefits for the region, RHFCC advocates for all zero-emission vehicle solutions - a combination of both battery electric and hydrogen fuel cell vehicles.

Hydrogen stands to contribute to the energy transition currently unfolding. The increasing renewable energy share in today's grid leads to imbalances in power supply and demand. Hydrogen can play a major role as an energy storage medium, as hydrogen can effectively be produced for the transportation sector during times of excess power supply from renewable and other energy sources. The transition into a hydrogen economy poses the additional benefit of creating new high-paying jobs and helping the nation enhance the security of its power supply.

Recent work at SARTA showcases the maturity of fuel cell technology and its application in the transit space. Successfully operating numerous fuel cell buses, SARTA is on a path to becoming the third largest fleet in the nation leveraging this technology. Several bus models and other medium and light duty vehicles are available in the marketplace. Fuel cell lift trucks and various material handling equipment have long been operating on hydrogen due to the fuel cell technology's reliability and cost effectiveness for this application. Over 15,000 fuel cell forklifts have been deployed or are on order as of this year, and over 6 million hydrogen refuelings have taken place to date. In Ohio alone, approximately 1,000 fuel cell forklifts are in operation.

If it successfully aligns its resources and adapts to transit demands both globally and in the U.S., the Midwest region stands on the cusp of becoming a major advanced technology manufacturing leader that provides fuel cell technology to the marketplace. Regions that stay innovative and agile as the energy transition continues should expect strong job growth. The trend of transitioning into more sustainable energy usage will continue with or without the Midwest joining the movement as an original equipment manufacturer and parts supplier. By aligning it resources and building on its leading expertise within manufacturing and related services, the Midwest region is poised to enter the sustainable energy space as a dominant player, enjoying strong job growth in the process. The region already hosts a leading number of companies associated with the fuel cell supply chain. Fuel cell technology careers include the following among others: mechanical, chemical, electrical, and industrial engineers; chemists; material scientists; laboratory technicians; factory workers; power plant operators; power plant maintenance staff; bus, truck and other fleet drivers; vehicle technicians; fueling infrastructure installers; hydrogen production technicians etc.

In this roadmap, it is estimated that **65,000 new jobs** within a timeframe of 15 years could be created in the Midwest as the hydrogen economy continues to grow. Ohio, in particular, stands well-positioned to spearhead this movement as it already hosts a strong supplier network for fuel cell manufacturers. Thus, Ohio serves as the focus and example state for several data points throughout this study.

A different approach to the deployment of fuel cell vehicles than the ones taken in California and the Northeast is suggested for the Midwest region. Instead of focusing on the light-duty sector first, commercial fleet and transit operators could spearhead early infrastructure deployment, overseeing the initial rollout of stations and the station cluster growth. Stations dedicated for fleet usage will ensure that adequate volumes are dispensed early on and that the buildout of the stations are sustainable from a resource and financial perspective. Once these stations are in operation, they could provide public access as well for light-duty customers. Analysis shows that approximately **135,000 FCEVs** and **250 hydrogen refueling stations** could be deployed in the Midwest region during the next 15 years. This assumes a rollout scenario that starts with heavy-duty vehicles in the transit space, followed by medium-duty vehicles in package delivery and transit applications, and an eventual deployment of light-duty vehicles for commercial fleet and public usage. The region, especially, calls for the utilization of renewable hydrogen to attain the utmost social benefits, building a bridge to renewable energy, eliminating emissions, and focusing on developing economically viable methods for the generation of hydrogen. Studies have found that a total of 1 billion metric tons of hydrogen could be produced annually from wind, solar, and other biomass sources in the U.S. Thus, tremendous potential exists for utilization of renewably sourced energy in the nation.

To facilitate the execution of this roadmap, each state (i.e., Michigan, Illinois, Indiana, Ohio and Pennsylvania) is asked to join the RHFCC and the MHCoE in their efforts to take the next step towards a sustainable zero-emission future. Economic and technological barriers related to hydrogen production/distribution and fuel cell technology manufacturing and development exist, however. Therefore, innovative partnerships between the private and public sectors, together with policy support, are crucial to ensuring challenges can be overcome.

1. INTRODUCTION

Hydrogen Facts and Outlook for Midwest and Ohio

Ohio is internationally recognized for its dynamic fuel cell technology industry and plays a critical role in moving the industry from technology advancement to commercialization. With specialty industry resources in place – such as an extensive fuel cell supply chain; an innovative research and development community; a technologically advanced manufacturing base; a skilled workforce; and robust programs that support workforce development – Ohio is a trailblazer in the hydrogen industry economy.

Several stakeholders in Ohio and the Midwest region have joined forces to continue to build on the strengths the region offers and work to introduce fuel cell electric vehicles into the marketplace. Ohio is ready to set the stage for a full rollout of infrastructure and vehicles, continuing on the path towards a more sustainable transportation future. The Midwest region is asked to join Ohio on this path.

This roadmap has been developed to give the reader an introduction to the hydrogen economy, and the current opportunities and barriers the Midwest states are currently facing as they prepare to stay competitive and grow their manufacturing expertise of advanced transportation solutions, innovate, and increase the employment in the region.

New solutions are needed to decarbonize the transportation sector and to eliminate harmful air pollutants at scale. Overall energy use and related emissions have continued to grow, especially for the transportation sector. In fact, 29 % of U.S. energy consumption in 2016 was attributed to the transportation sector, and the carbon emissions from the transportation sector have now surpassed the power sector as measured on a 12-month rolling basis in the U.S. [1]. Measured on a worldwide basis, transportation energy use has doubled in the past 30 years[2].

This roadmap focuses on the transportation sector and, in particular, on having vehicles deployed that emit zero tailpipe emissions. The possibility to leverage hydrogen as the energy source to meet this goal and to position the Midwest to capture the lion's share of the jobs that will be created in this new industry are discussed in detail in this roadmap. Hydrogen is a versatile, clean, safe energy carrier with a high-energy density. Thus, it can help society in the transition into a more sustainable future.

This hydrogen roadmap for the Midwest and with the focus on Ohio, provides a *visionary statement* for what the hydrogen infrastructure and hydrogen vehicle rollout could look like for the greater Midwest/Ohio region. The overarching goals of this roadmap are:

(1) To help create new jobs associated with the hydrogen industry as it relates to transportation;

(2) To help accelerate the deployment of hydrogen in transportation in the region;

(3) To provide strong environmental benefits to the region;

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[1] U.S. Energy Information Administration, 2017

[2] International Energy Agency

(4) To identify barriers for accelerated adoption of hydrogen infrastructure and vehicles and solutions of how to overcome them;

(5) To present a feasible hydrogen infrastructure and vehicle deployment scenario for the region.

According to the U.S. Department of Energy, Hydrogen and Fuel Cells Program, there has been an unprecedented cost reduction and market growth in clean energy technologies during the last ten years. Consequently, new technologies that are viable to serve the transportation space with zero tailpipe emission have emerged. In addition to battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs) are becoming ever more cost competitive as the cost for fuel cell technologies continues to decline, allowing the deployment of fuel cells as power sources in transportation applications. FCEVs all have a battery component, but adding the fuel cell makes the vehicles more versatile. As of date, 1,800 FCEVs[3] have already been sold or leased in the U.S. In fact, a recent Global Automotive Executive Survey[4] showed that 78% of executives believe that FCEVs will be the main mobility solution for the future and more likely than BEVs to succeed in the long term. Within the U.S., California and the Northeast have recognized the benefits of hydrogen and its potential to transform the transportation sector. The Midwest with Ohio's lead, stands to also gain from the current market as it has a vast hydrogen fuel cell supplier network and expertise about the technology with initiatives already underway that have introduced the first stations and FCEVs to the State.

Currently, there are several so-called "forcing factors" at play that will catalyze the transition into sustainable transportation solutions. The finite petroleum resources, climate change, urban air pollution, national energy security, job creation, and fuel independence all comprise these forcing factors, necessitating the transition into more efficient and less polluting transportation technologies that utilize, for example, hydrogen as the energy carrier. Hydrogen is a versatile energy carrier. It does not emit greenhouse gases (GHGs) at the point of its use and can, thus, play a key role in the transition to a low carbon energy economy. Among its advantages, hydrogen can be domestically produced by utilizing various resources, such as natural gas, nuclear power, coal, solar, wind or other bio-sources. As such, great growth potential exists for the utilization of fuel cells in both stationary and portable power applications that are difficult to decarbonize.

This roadmap centers on the transportation sector as it applies to transit buses and other FCEVs in light-duty, medium-duty and heavy-duty applications. Specialty vehicles (e.g., forklifts) are also mentioned as these are considered enablers that can help with the overall sector growth, especially as it relates to the buildout of the initial infrastructure network. Furthermore, needed steps are outlined for widespread commercialization of the technology to take place in Ohio, its neighboring gateway cities, and the overall Midwest area.

The Renewable Hydrogen Fuel Cell Collaborative (RHFCC) has been established to propel the Midwest to become a national leader in the adoption of hydrogen fuel cell-powered vehicles through education, advocacy and research. The RHFCC is a collaboration of the Stark Area Regional Transit Authority (SARTA) and The Ohio State

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[3] Hybridcars.com

[4] KPMG, Global Automotive Executive Survey 2017 (Jan. 2017)

University Center for Automotive Research. A key initiative of the RHFCC is the Midwest Hydrogen Center of Excellence (MHCoE), which supports regional advancement and adoption of hydrogen-powered, zero-emission vehicles (ZEVs) in the Midwestern public transit. The RHFCC and the MHCoE will be the organizations driving the implementation of this roadmap in the region.

Within the Midwest region, Ohio plays a central role in the transition to a hydrogen economy. Ohio has been noted as one of the top fuel cell states[5] as it has a robust supplier network of fuel cell component and material suppliers. Ohio has also supportive policies and incentives in place to encourage industry research, development and business expansion. The Ohio Fuel Cell Coalition (OFCC), a very active industry group, has helped propel the hydrogen sector forward in the State and rather famously remarked that there is not a single fuel cell in the country without a component in it that was manufactured in Ohio. The organization works to build relationships between fuel cell integrators and component suppliers.

Ohio houses one of the four fuel-cell technology exchange centers[6] in the U.S. that has been established to spur communication, standardization, and information sharing between original equipment manufacturers (OEMs) and suppliers. Several business development organizations, as well as community colleges and universities such as Ohio State University, are also involved in making Ohio a nexus for this sector. Recently, organizational partners, such as the RHFCC in Ohio, have been established to further drive market growth and capitalize on the strengths of the region.

CALSTART, Inc. has worked closely with Stark Area Regional Transit Authority (SARTA) in Ohio, through the Federal Transit Administration's National Fuel Cell Bus Program and Low or No Emission Vehicle Deployment Program (LoNo Program), to deploy the first American Fuel Cell Hydrogen Buses in its operational area of Canton, Ohio. In fact, SARTA has emerged as a leader in the hydrogen space as they recently opened the first commercial hydrogen station at their transit site[7]. SARTA is also on track to deploy several more hydrogen fuel cell buses and to operate the third largest fleet of hydrogen fuel cell buses in the country.

As the fuel cell industry expands, growing strongly internationally, the importance of staying competitive and securing future employment in the region is ever more pressing. Innovative steps are needed to align the industry for technology advancement and employee skills advancement. This roadmap describes a very plausible deployment scenario that can take shape even without federal and state subsidies. The deployment starts with the introduction of commercial hydrogen stations for the heavy-duty (HD) vehicle sector (vehicle classes 7-8). The focus here will be on the transit sector first, followed by deployment of HD trucks. Available funding for the transit space, particularly for buses, enables early research and development. Advances in technology can, then, transfer from the bus sector to trucks and other related vehicles. Following the successful rollout of these first vehicles that will allow the build out of the initial hydrogen station clusters, it is envisioned that the medium-duty (MD) vehicles (vehicle classes 3-6) would be deployed. These vehicles would initially be deployed in commercial and municipal applications followed by deployment in other uses. The last vehicles classes to be deployed are in the light-duty (LD) sector (vehicle classes 1-2). The initial focus here would be on the commercial and municipal sectors followed

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[5] U.S Department of Energy: State of the States: Fuel Cells in America 2017, 7th edition

[6] Ohio Fuel Cell Coalition

[7] Air Products

by deployment of private/public vehicles. This proposed deployment schema offers a means to initiate the rollout of hydrogen fuel cell electric vehicles and reach greater vehicle volumes.

While robust fuel cell technology for heavy, medium and light duty vehicles is essential to FCEV adoption, a positive customer refuel experience is also a necessary condition for market acceptance. Federal, state and local agencies need to support early markets to build stakeholder and customer confidence in the vehicles and individual station performance. This initial roadmap sets the stage for stakeholder communication about the vision, drivers, policy and funds which are crucial to the execution of the roadmap.

1.1 FUEL CELLS BACKGROUND AND TECHNOLOGY

The concept of the fuel cell was demonstrated in the 1800's where an electric current was produced by an electrochemical reaction. Modern fuel cells found their way into the U.S. Space program, including the Gemini and Apollo spacecraft. The electrical power systems in the Apollo capsules and lunar modules used alkali fuel cells. Fuel cells also found their way into the automobile industry and, then later, back into space on the Space Shuttle.

Two federal programs helped to jump start fuel cells in transportation applications. In 2003, U.S. President George Bush proposed the Hydrogen Fuel Initiative (HFI). The HFI aimed to further develop hydrogen fuel cells and infrastructure technologies to accelerate the commercial introduction of fuel cell vehicles by contributing $1 billion. In 2006, the Federal Transit Administration (FTA) released a solicitation for projects that would accelerate the adoption of electric drive technologies—battery electric, hybrid electric, and hydrogen fuel cell buses. The President's FreedomCAR and Hydrogen Fuel Initiatives were focused on light-duty vehicles and personal mobility. FTA's expertise and experience implemented a transit program to complement and support the Presidential Initiatives.

While development continued in the auto industry, interest also grew within the transit industry with fuel cell engines being integrated into the mainstay of the transit world: the standard 40 foot transit bus. The buses are now being procured in ever larger quantities worldwide and in the U.S., and the auto industry is now also rolling out several models with a goal to realize commercial quantities of FCEVs. One commercial success to date is the marketing of fuel cell lift trucks, which have found a niche. A barrier to the auto industry is the slow deployment of refueling hydrogen infrastructure.

The hydrogen refuel infrastructure remains a challenge for commercialization of fuel cell cars. As a reference, in mid-July 2016 in California, there were 20 hydrogen refuel stations plus six legacy stations supporting a registered 331 FCEVs. FCEV projections for 2019 and 2022, respectively, are 13,500 and 43,600. By the end of 2017, 50 stations including upgrades are projected to be on-line. The focus of the station deployment in California has been public use (i.e. conventional stations that are not bound to a particular fleet.) Continued co-funding may be needed to build out additional station capacity to avoid a shortfall in total fueling capacity. The California Energy Commission (CEC) funded hydrogen fueling stations in California with $18.7 million, and Governor Jerry Brown signed AB 8 providing funds for building up to 100 stations. The CEC followed with additional funds for station construction.

U.S. Department of Energy (DOE) funded up to $4 million for "continued development of advanced hydrogen storage systems." To address barriers to hydrogen fueling infrastructure enabling the large scale adoption of FCEVs, the DOE and industry partners launched H2USA, a public-private collaboration in 2013, focused on development of hydrogen infrastructure and deployment of FCEVs in the U.S.

From an international perspective, fuel cell vehicles are seen as one of the viable options for the future. Several European countries, as well as Japan and China are planning to roll out significant hydrogen infrastructure and FCEVs in the thousands for the upcoming years. China and Japan have set targets of having 50,000, and respectively 200,000 FCEVs by 2025. Also, specific targets are in place in the transit sector where the overall European target is to deploy up to 1,000 fuel-cell buses by 2020. Furthermore, South Korea has decided to replace all a total of 27,000 compressed natural gas buses with fuel cell buses by 2030.[8]

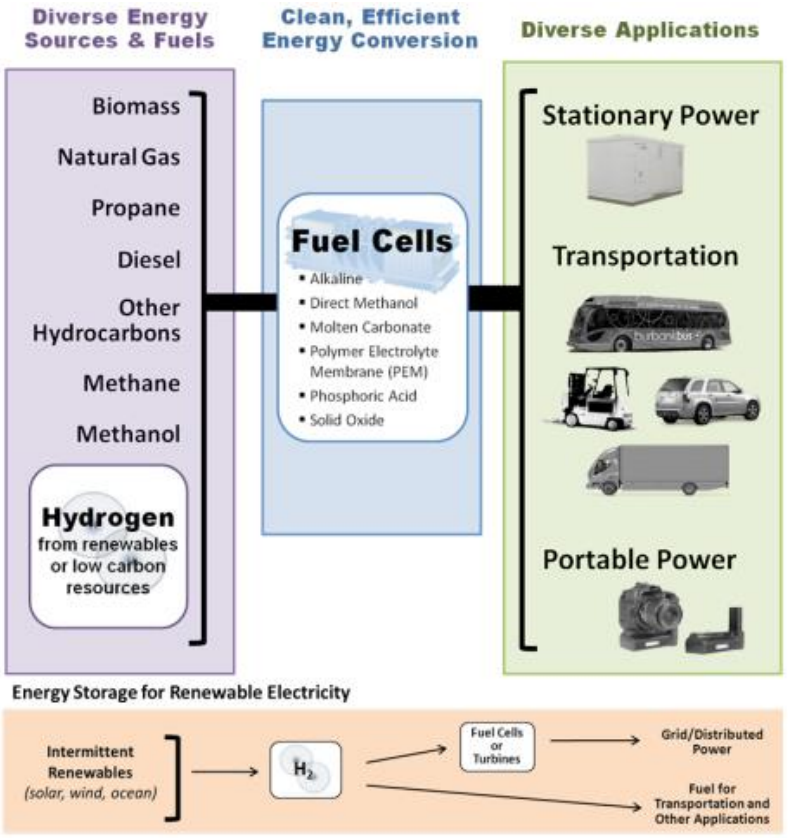

Figure 1: Fuel cell energy sources and applications

Fuel cells can be deployed for various end uses, such as distributed power generation (e.g., backup, primary, and combined-heat-and-power); transportation applications (e.g., passenger cars, buses, forklifts, and other specialty vehicles); and portable power units for smaller electronic devices. Thus, fuel cells can play a significant role in the transition to a clean energy economy. The adjacent figure describes the various fuel cell energy sources and applications[9]. A fuel cell uses the chemical energy of hydrogen, or another fuel, and converts that to electricity through an electrochemical process (i.e., no combustion takes place). If hydrogen is used solely as the fuel for the fuel cell, only water and heat are the byproducts of the energy conversion process.

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[8] How hydrogen empowers the energy transition, Hydrogen Council, January 2017

[9] DOE Fuel Cell Technologies Office

The utilization of fuel cells offers a broad range of environmental benefits for society. Fuel cells enable a highly efficient energy conversion, operate quietly, require little maintenance, and are highly reliable. Hydrogen powered vehicles do not emit any local pollutants such as nitrogen dioxide and particulate matter. As the quantity of renewable energy sources continue to increase globally, the management of these energy sources can present a challenge due to the intermittent nature of solar and wind, for example. Renewable energy producers currently may be financially disincentivized to produce energy at times of oversupply (i.e. surplus solar and wind must be discarded as the grid cannot accept the energy). Therefore, the problem with curtailment of renewable energy sources[10] could be solved in the future if, for example, the excess energy could be used to produce hydrogen. This would naturally also lead to low cost hydrogen.

The use of fuel cells as the power source for the transportation sector has the additional advantage of easily handling the same duty cycle as a conventional vehicle powered by an internal combustion engine. Compared to electric vehicles, the fill-up time for FCEVs is much faster and resembles the process of traditional vehicles. Due to hydrogen's high-energy density, less storage weight is needed on the vehicles, resulting in enhancements in the payload capability of the vehicles. This makes the technology especially well-suited for heavy duty and heavy usage applications. For transportation applications the technology results in zero-local pollutants and CO_2 emissions. Also, the needed durability of fuel cells has been demonstrated in transportation applications. As of today, fuel cells have been extensively tested and are in broad commercial use in the U.S. and globally. Hydrogen fuel cell buses in the U.S. have of June, 2017, exceeded Department of Energy and Department of Transportation durability targets, as the fuel cell engine has operated already for 25,000 hours[11].

For widespread commercialization to take place, however, production volumes must increase, ultimately resulting in decreasing costs, so fuel cell technology can be cost competitive with other energy sources.

2. MIDWEST AND THE FUEL CELL ECONOMY

This section of the roadmap discusses the overall state of the industry and the opportunities and implementation challenges that Ohio and the greater Midwest regions are facing as they aim to deploy hydrogen fueling infrastructure and vehicles on a large scale.

The Midwest area is often termed the auto manufacturing alley since all OEMs are located in the region (i.e. Michigan and Ohio) and the vast supplier networks exists in the region. The Ohio region specifically has a vast fuel cell supplier industry with industry, academic research, and commercialization development activities underway. Among its strengths, the region boasts a well-developed manufacturing base with a focus on the automotive and aerospace industries. There are several OEMs present in the State with second and third tier suppliers supporting them. Even though FCEVs have not yet been deployed in significant quantities, fuel cell powered material handling equipment, such as forklifts, are in heavy use in the various retail outlets, warehouses distributors, and shipping companies in the State. Several of the larger distribution and shipping companies have

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[10] Curtailment is a reduction in the output of a generator from what it could otherwise produce given available resources, typically on an involuntary basis

[11] U.S. Department of Energy, Hydrogen and Fuel Cells Program, 2017 Annual Merit Review and Peer Evaluation Meeting

chosen to use fuel cells as the power source in their forklifts due to the fast fill-up and payback times this technology affords them in comparison to the battery electric forklifts, for example. Preliminary research shows that there are at least 1000 units of material handling equipment/forklifts in use in Ohio that are propelled by hydrogen[12]. The region has the option to evaluate the possibility of sharing hydrogen fueling infrastructure (i.e., dual use of stations between private and public users) during the initial stages of the hydrogen infrastructure rollout. This approach will be explored in more detail in the following chapters.

Academic, industry, and government personnel are working actively to strengthen Ohio's fuel cell industry through various collaborative efforts designed to grow fuel cell technology and hydrogen economy knowledge in the State. The OFCC, together with several prominent academic institutions, has been leading this work. The recently established RHFCC, a regional ambassador for the advancement and adoption of zero-emission vehicles and infrastructure in the Midwest, has founded a Midwestern Hydrogen Center of Excellence devoted to accelerate the use of hydrogen fuel cell technologies for transportation purposes (i.e. transit authorities). These organizations have been formed to spur the market growth, educate various stakeholders about the benefits of fuel cell technologies, and engage in efforts to inform local and state legislators and agencies about relevant policy and code enforcement considerations (e.g., for fire marshals and first responders). Strong partnerships between municipal transit and private fleets are currently being formed to initiate the rollout of the technology and move the industry forward.

Due to this burgeoning network of collaboration, there are great prospects for the Midwest to grow the fuel cell industry with Ohio's lead. The goal is to make the Midwest region a main deployment area for FCEVs in the U.S. As Ohio is already set on a path to be the third largest deployment site for hydrogen buses in the country, potential exists to build on this momentum now. The following sections will take a closer look at the current state and prospects for policy, air quality, jobs and vehicles in Ohio in particular and the surrounding Midwest region.

2.1 REGION POLICY

The Midwest area, including Ohio face a noteworthy challenge: the lack of strong incentive funding to support zero emission vehicles and/or vehicles propelled by alternative fuels, in general. To date, some federal funding has been made available to Clean Fuels Ohio for the development of an electric vehicle readiness plan. However, no state funding directed explicitly towards the use of fuel cells in the transit space has been awarded in Ohio to date. So far, the funding that has been awarded to Ohio stakeholders has come from federal sources. A total of eleven laws and incentives for Ohio related to alternative fuels and advanced vehicles are currently listed at DOE's Alternative Fuels Data Center[13].

The Midwest states are not presently party to the zero emission regulations adopted by ten states in the country. These ten states (California, Oregon, New York, Vermont, Main, Massachusetts, Connecticut, Rhode Island, New Jersey, and Maryland) have adopted vehicle emission standards set by California that are stricter than the federal

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[12] Ohio hydrogen fuel cell material handling equipment: Home Depot, Troy Township – 172 units; Honda, Marysville – 51 units; Ace Hardware, West Jefferson – 76 units; Walmart, Washington Court House – 254 units among others.

[13] Ohio Transportation Data for Alternative Fuels and Vehicles: https://www.afdc.energy.gov/states/oh

vehicles standards. According to section 177 of the Clean Air Act, states can adopt California's standard, but they cannot adopt their own standards. By adopting the stricter standards, these ten states have also effectively required automakers to produce zero emission vehicles (ZEVs) and sell these vehicles in their respective regions in addition to their traditional engine platforms. This regulation specifically requires OEMs to attain ZEV credits that are dependent on the total volume of vehicles each OEM sells in each state. Because of this and other policy support through California's Assembly Bill 8 as well as incentives and the availability of co-funding through the California Energy Commission's Alternative and Renewable Fuel and Vehicle Technology Program[14], initial rollout of FCEV has been possible in California, for example. Moreover, in the Northeast, 12 stations are currently being built through industry partnerships between Toyota and Air Liquide[15]. It is envisioned that FCEV owners soon can drive from New York to Boston by leveraging a cluster of stations.

Thus, a major objective for the stakeholders in Ohio and the general Midwest area is to educate legislators and the public of the possibilities of the hydrogen economy and the energy transition in general. Tremendous possibilities exist for job creation by taking advantage of the transition from petroleum based fuels to hydrogen. To attain the significant industry investment needed, Ohio policymakers must provide the support to guarantee a long-term regulatory framework, a firm dedication to zero emission technologies, and initiatives and incentives to spur early market growth. The Midwest and Ohio, in particular, have already many of the essential building blocks in place, and stand now on the cusp of deploying zero-emission vehicles that are powered by zero-emission technology built and developed in the Midwest. The RHFCC aims to reach the legislators first in Ohio and facilitate the creation of zero emission credits that then can be utilized in the region to spur the market and job growth.

The following listings are potential sources of federal funds that can help fund programs that support compliance with the Environmental Protection Agency's National Ambient Air Quality Standards. By achieving established air quality mandates and GHG emission reduction targets, these funds can help accelerate the deployment and adoption of zero-emission fuel cell electric technologies. Also, many state and federal policy and planning efforts related to achieving established air quality mandates and GHG emission reduction targets highlight the need for a dramatic acceleration in the deployment and adoption of zero- and low-emission transportation technologies.

- U.S. Environmental Protection Agency/NHTSA Heavy-Duty Greenhouse Gas & Fuel Efficiency Standards
- U.S. Congress 2015 "Fixing America's Surface Transportation" Act
- U.S. Department of Energy Hydrogen and Fuel Cells Program
- U.S. Environmental Protection Agency's Diesel Emissions Reduction Act Program
- U.S. Department of Transportation Federal Highway Administration Congestion
- Mitigation Air Quality Program (CMAQ)
- U.S. Department of Agriculture Rural Energy for America Program
- Low or No Emission Vehicle Program - 5339(c)
- Department of Transportation TIGER Discretionary Funds

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[14] 2015 Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development, California Environmental Protection Agency, Air Resources Board

[15] Fuel Cell and Hydrogen Energy Association

- VW Settlement Funds

2.2 OHIO ENERGY CONSUMPTION AND AIR QUALITY

Natural gas production in Ohio has increased by almost 19 times from 2011 to 2016 since the Utica shale gas production began. Ohio has the seventh-largest crude oil refining capacity in the nation and has also a robust ethanol production capacity, producing 550 million gallons of ethanol per year. Energy is predominantly produced from fossil fuel sources in the State; however, during the last decade, wind energy has grown substantially, now representing 43% of the total renewable energy produced in the State[16]. Ohio has a renewable energy portfolio standard in place that requires that 12.5% of the electricity is produced by renewable energy sources by 2027.

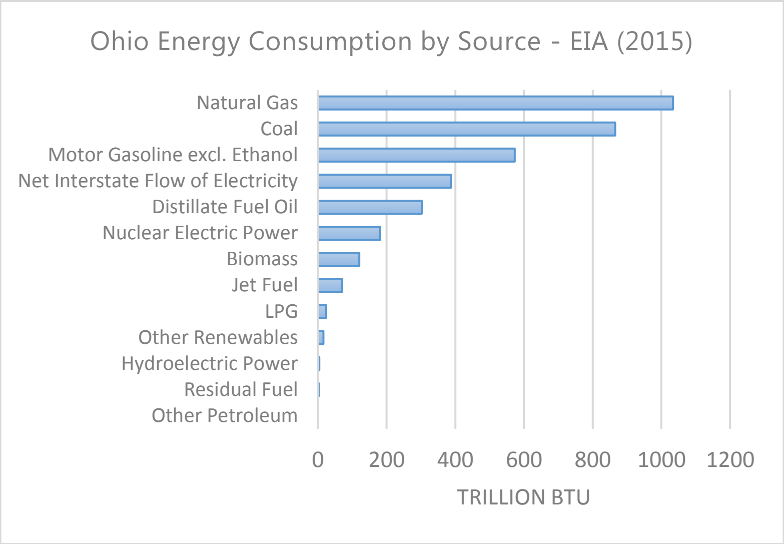

Figure 2: Ohio energy consumption by source

As such, tremendous opportunity exists for Ohio and the Midwest region to move towards a hydrogen economy. As the transportation sector alone accounts for 25% of the total energy consumption in Ohio, the introduction of FCEVs that operate on an overall efficiency of up to 60% can effectively cut the energy consumption and associated pollution levels compared to conventional vehicles that have a 30% efficiency. Hydrogen produced through steam methane reforming for the transportation sector can reduce GHG emissions by 50%, while hydrogen produced by renewable sources can reduce overall GHG emissions associated with the transportation sector by 90%[17].

Ohio is currently ranked fifth in the nation in terms of total carbon emissions, with the carbon emissions from the transportation sector amounting to 63.2 million metric tons[18]. By cutting overall GHG emissions, significant reductions in the six common Criteria Air Pollutants (i.e., Particulate Matter, Carbon Monoxide, Nitrogen Oxides, Sulfur Oxide, Ozone and Lead) can be realized[19]. The introduction of FCEVs offers an efficient means to improving local air quality in Ohio, especially in the major metropolitan areas. Counties such as Butler, Clermont, Cuyahoga, Hamilton, Lorain, and Warren are currently classified as nonattainment counties[20] for the criteria air pollutant

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[16] U.S. Energy Information Administration – Ohio State Profile and Energy Estimates

[17] U.S. Department of Energy, Fuel Cell Technologies Office – Hydrogen Fact Sheet

[18] U.S. Energy Information Administration – Ohio State Profile and Energy Estimates, Ranking 2014

[19] The 1963 Clean Air Act requires U.S. Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards

[20] United States Environmental Protection Agency, February 13th 2017

(Particulate Matter, PM, 2.5) generated by direct emissions from vehicles and secondary formation from precursor gases emitted from engines, such as oxides of nitrogen, volatile organic compounds, and sulfur oxide. The emissions of nitrogen oxides are especially prevalent from diesel engines. Depending on the production method of hydrogen, significant environmental benefits can be attained by the introduction of FCEVs in the State.

2.3 MIDWEST JOBS

Ohio has already become established as a premier location for companies involved in various aspects of the hydrogen and fuel cell industries. The full fuel cell supply chain is represented in Ohio, from cell manufacturers to integrators to end-users. According to the Ohio Fuel Cell Coalition, more than $100 million in fuel cell components were purchased from Ohio supply chain companies in 2015. That same year $150 million was invested in fuel cell development by Ohio companies. More than $93 million has been invested by the State of Ohio for fuel cell R&D and market-readiness projects and was matched with more than $300 million from other state, local, and federal entities. Some of the prime fuel cell supply chain entities in Ohio include Plug Power, Johnson-Matthey Process Technologies, Nexceris, LG Fuel Cell, Crown Equipment, and Stark Area Regional Transit Authority. In addition, the Ohio State University is at the forefront of fuel cell research and development.

With these facts in mind it is easy to forecast that the overall fuel cell industry will play a significant role in Ohio's future economic development and job growth. The exact timeline and job numbers are difficult to predict as they will be partially dependent on the activities of stakeholders based outside of Ohio. However, several organizations have attempted to make forecasts regarding job creation in this industry. In 2008, the United States Department of Energy studied the industry's job creation potential[21]. In 2016 they instigated a process to update this publication based on changes in the market and the industry. This process is ongoing. A preliminary jobs analysis update for 2017 indicates that 16,000 jobs today exist in the fuel cell car sector in the U.S and that over 200,000 potential new jobs (i.e. direct and indirect) can be created in the future[22].

This study predicted that by the year 2050, national employment attributed to the hydrogen fuel cell industry would grow by 361,000 (less aggressive scenario) to 675,000 (Hydrogen Fuel Initiative scenario) jobs. Looking at those numbers regionally, the Department of Energy's study forecasted that under the more aggressive scenario, 105,000 net jobs would be created in the Upper Midwest region which includes Ohio. In this region, the job gains would come from hydrogen production, professional and technical services, and fabricated metals.

Other studies were conducted by Argonne National Laboratory[23]. Their study provided a framework for identifying the jobs impact specifically associated with the mobile fuel cell industry in one state. This methodology has been included in a wider-based forecast that comprised the entire supply chain for mobile and stationary fuel cells, especially those that have been established in Ohio.

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[21] United States Department of Energy. Effects of a Transition to a Hydrogen Economy on Employment in the United States. July 2008.

[22] United States Department of Energy, U.S Energy and Employment Report, January 2017

[23] Argonne National Laboratory. Economic Benefits Associated with Commercializing Fuel Cell Electric Vehicles in California: An Analysis of the California Road Map Using the JOBS H2 Model. ANL/ESD-15/1. December 2014.

Based on these studies and industry factors that have transpired since their publication, an attempt was made to forecast hydrogen fuel cell industry employment specifically for Ohio and the general Midwest area. Some of the factors that were taken into consideration in this forecast included recent federal and state policies for low-emission vehicles, fuel prices, fuel cell component and system price trends, the international fuel cell market, the state of the logistics industry as it applies to the Midwest, and projected fuel cell research needs. Jobs models developed by Argonne National Laboratory were also utilized when making the estimations and evaluating different job growth scenarios. The models let the users differentiate between infrastructure buildout and operation as well as manufacturing of fuel cell engines (i.e. both stationary and mobile).

Based on these factors employment projections for the Midwest hydrogen and fuel cell industry have been made out to the year 2032. There are too many unknown factors in play to project more than 15 years in advance. With that in mind, the gross Midwest job growth in the hydrogen fuel industry to be 65,000 jobs in the year 2032, representing an annual compound annual growth rate of 27%. This growth will occur in an almost-linear fashion between now and 2032. The following chart shows that growth:

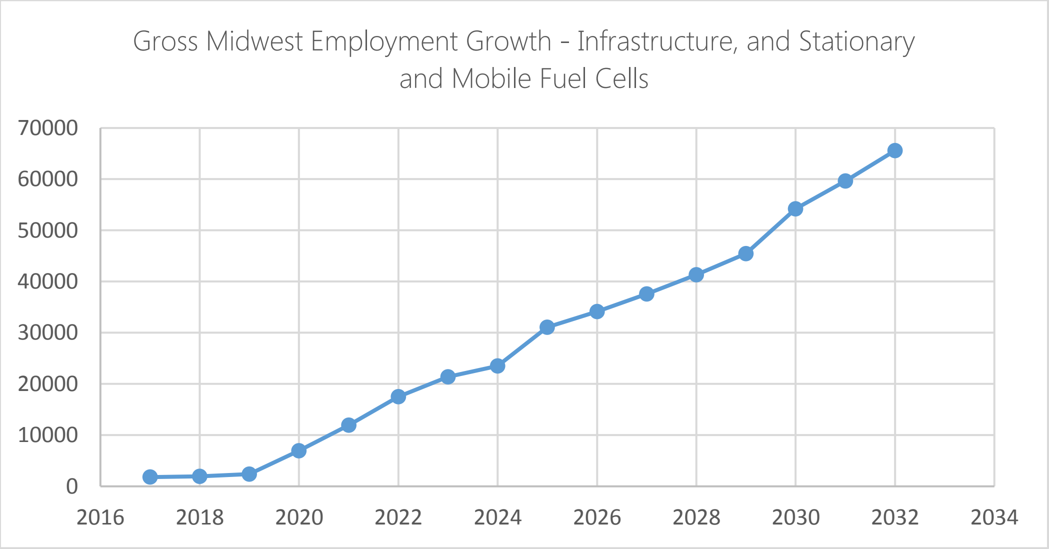

Figure 3: Gross Midwest employment growth related to the hydrogen industry

The accuracy of these predictions will depend on several factors, especially those listed above. However, Ohio has already laid the groundwork for robust growth in this industry through the establishment of a strong industry association, academic support for industry research and development, strong state economic growth policies, manufacturing and innovation infrastructure, and most importantly, a solid logistical situation. All this translates to a positive placement within the hydrogen fuel cell industry. With this in mind, the Midwest region is set for strong employment growth and substantial payback by getting involved with this emerging industry. The continuing rollout of FCEVs nationally and internationally will have an impact on the Midwest job market one way or another. In order to stay competitive, the Midwest has to assure that it is taking the needed steps to adapt, innovate, and create the new jobs needed for the area to stay competitive. The Midwest should do all it can now to make the most of the emerging FCEV market and encourage the growth of jobs in this area.

The supplier network for the vehicle industry is significant in the Midwest. According to the Motor and Equipment Manufacturers Association, the following direct employment numbers are representative for the region: The overall job impact is significant, as well, as these jobs create on average 4.9 additional indirect jobs in the region[24].

- Illinois: 38,394
- Indiana: 88,306
- Michigan: 125,909
- Ohio: 96,238
- Pennsylvania: 27,920

The map below further illustrates the employment concentration for jobs associated with the Motor Vehicle Parts Manufacturing category (NAICS Code 3363). The darker the green shaded areas are the more auto related employment exists in a specific region. The red color indicates states that have at least one OEM assembler[25]. This illustrates the significance of this industry in the Midwest. Suppliers traditionally located themselves close to OEMs, but skills availability, training and state incentives all play a role for supplier location selection. A manufacturing center, the Midwest boasts vast component suppliers. Much is at stake for the region in terms of job creation, technology innovation and advanced transportation solutions.

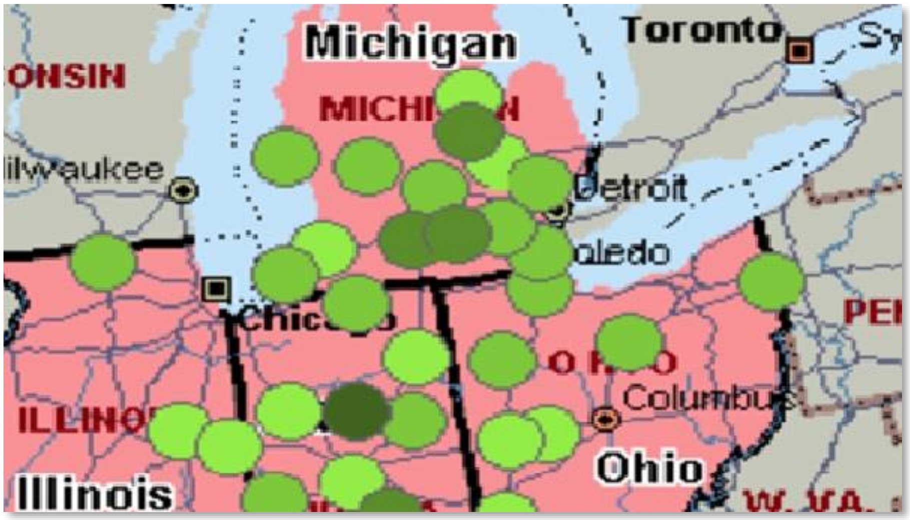

Figure 4: Midwest concentration of auto related employment

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[24] The Employment and Economic Impact of the Vehicle Supplier Industry in the U.S., Motor and Equipment Manufacturers Association, January 2017

[25] Where is the U.S. Automotive Industry Headed? Biggins Lacy Shapiro & Company

2.4 MIDWEST VEHICLES

The rollout of advanced technology vehicles has not been as strong to date across the Midwestern States. The vehicle pool for Ohio is indicative of the general region. Current vehicle statistics for Ohio show that there are 4,751,891 automobiles, 5,143,010 trucks, and 32,232 buses registered in the State[26]. The total number of vehicle registrations issued are 13,038,691[27]. To date, very few of the vehicles are classified as alternative fuel vehicles. The following alternative fuel vehicles have been deployed in the State: natural gas (approximately 1,509 vehicles), propane (1,383 vehicles), biodiesel (4,165 vehicles), and a limited number of ethanol and full electric vehicles[28].

The table[29] below shows the current fueling station quantities for the State and allows for the calculation of the ratio of vehicles to stations, given the vehicle totals above. These numbers can be used as a reference for future planning purposes of hydrogen refueling scenarios that will be discussed in the following sections. The refueling experience for a FCEV resembles closely that of a conventional internal combustion vehicle, as the refueling takes approximately 3-5 minutes (which allows for a range of 300+ miles).

Fueling Stations	Ohio
Motor Gasoline	3,860 stations
Biodiesel (B20 and above)	14 stations
Compressed Natural Gas (CNG)	61 stations
Electric	350 stations
Ethanol (E85)	154 stations
Hydrogen	3 stations
Liquefied Natural Gas (LNG)	6 stations
Propane (LPG)	88 stations

Table 1: Fueling stations in Ohio

Figure 5 provides an indication of the major geographic areas that could be key for the early deployment of fuel cell vehicles. The hybrid-electric and flex-fuel vehicle densities for the Region show that the major metropolitan regions have the most vehicle registrations for these types of vehicle classifications (i.e. red color indicates densities of up to 450 vehicles per square mile. These same metropolitan regions will also be discussed in more detail in the following chapters as they strongly correlate with the early deployment areas that are envisioned for the FCEV.

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[26] Statista.com

[27] Ohio BMV 2015

[28] Clean Fuels Ohio

[29] U.S. Energy Information Administration, Ohio State Energy Profile; DOE Alternative Fuels Data Center, Ohio Transportation Data for Alternative Fuels and Vehicles

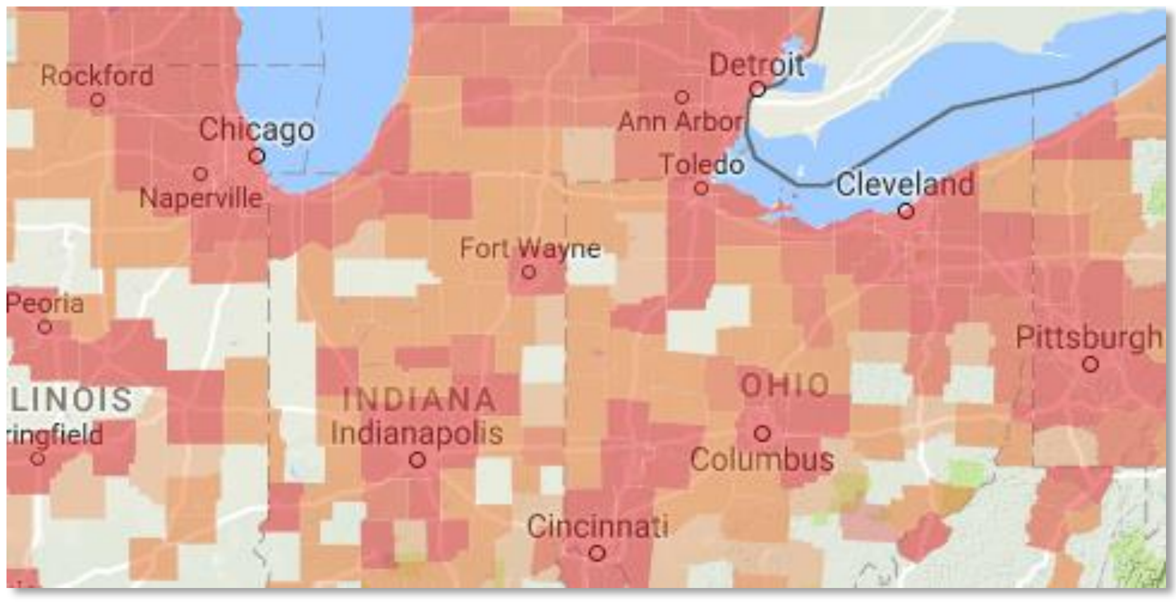

Figure 5: Hybrid-electric and Flex-fuel vehicle densities

3. STATION AND VEHICLE DEPLOYMENT STRATEGY

This Roadmap will describe the hydrogen refueling station and hydrogen vehicle rollout in the State of Ohio and its surrounding gateway cities (Midwest) for the next 15 years (2017-2032). This timeframe has been selected to give stakeholders a long-term view of the deployment strategy, and to allow for adjustments in case the commercialization of the technology takes longer than expected in the region. Moreover, this report functions as a visionary statement of the sequencing and timeline for the rollout of hydrogen infrastructure and vehicles. It is meant to be used as a guiding document for various stakeholders involved with the FCEV deployment and transit development activities for the region.

The overarching goal of this roadmap is to identify early adoption areas where refueling stations can ideally be placed to achieve meaningful volumes of FCEV deployment and market growth. This roadmap, therefore, presents a plausible scenario for the early market hydrogen infrastructure deployment and associated vehicle rollout within the Ohio region. The strategy presented here fosters hydrogen station development in advance of the rollout of light-duty vehicles. For the strategy to be successful, a critical mass of fleets that are willing to be on the forefront of deploying vehicles in the medium and heavy duty vehicle sector need to participate and build out the first clusters of hydrogen stations in the State. Once refueling stations and a functioning hydrogen infrastructure that can support them are in place, the likelihood that light-duty OEMs will bring their models for sale in the State will increase.

This approach varies somewhat from the strategy and the work that has transpired in California. The California Fuel Cell Partnership and its members determined before the buildout of the initial stations in California that the early market for FCEVs would be consumers that use light-duty vehicles and not commercial fleets. It has been commonly acknowledged in California that significant incentive funding is needed to build out the first commercial stations[30]. Due to the lack of current direct incentive funding in Ohio, however, this roadmap will focus on a somewhat different approach that capitalizes on the strengths of FCEVs in the heavy-duty and medium-duty sectors, especially in the transit bus space. This strategy proposes the establishment of clusters of hydrogen stations and associated infrastructure before the introduction of larger volumes of light-duty FCEVs. Initial funding from state/federal sources and foundations is still critical in order to successfully kick start the deployment of stations and vehicles. It is envisioned that the rollout of vehicles will follow a set of four steps as indicated in the figure here below.

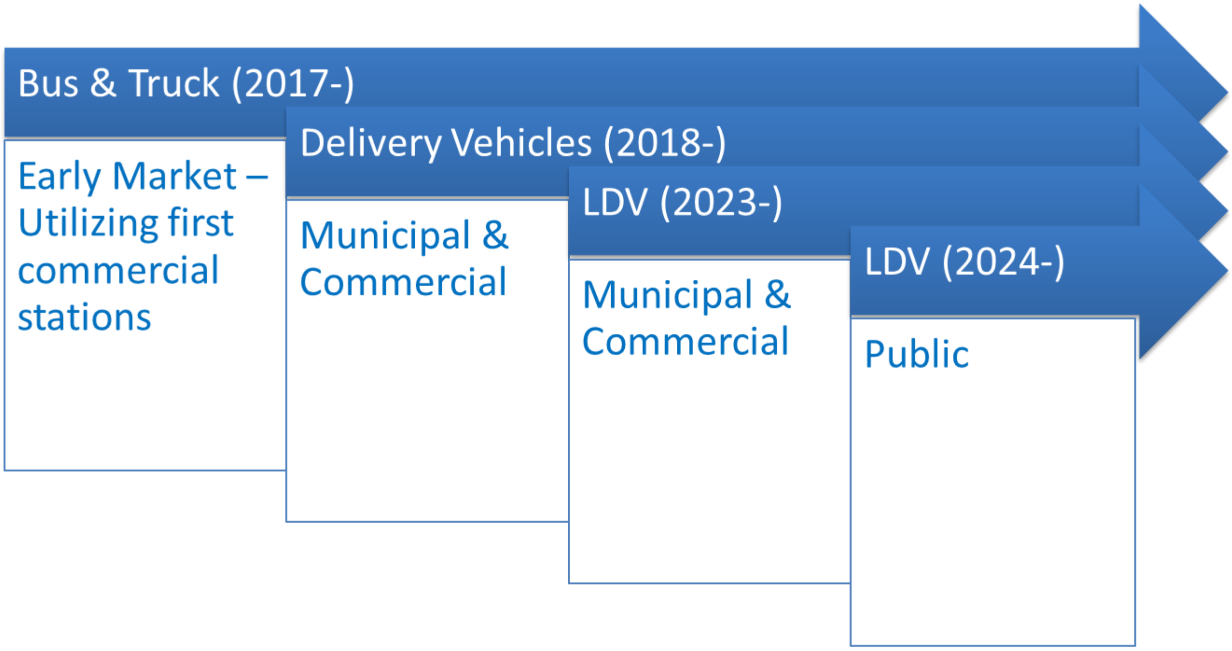

Figure 6: 15-year deployment plan for FCEV in Ohio and Midwest

BUS & TRUCK (2017-)

Fuel cell buses are already in operation in daily service in Ohio at SARTA and Ohio State University. These are the first FCEVs in public operation in the State. Due to available federal funding sources for the transit space, the fuel cell technology has been developed and successfully demonstrated in the transit bus space. Twenty-one fuel cell buses are currently in active service and 44 buses are planned to be put in service in the U.S.[31] These buses and various demonstration projects play a critical role as the first hydrogen refueling stations are deployed. Moreover, the deployment of these buses[32] aids important technology transfer and related learning. Various HD vehicle configurations are possible for the early bus and truck deployments, such as fuel cell dominant and battery

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[30] A California Road Map: The Commercialization of Hydrogen Fuel Cell Vehicles, Technical Version, California Fuel Cell Partnership, 2012

[31] Fuel Cell Buses in U.S. Transit Fleets: Current Status 2016, NREL

[32] The National Renewable Energy Laboratory has evaluated that on a Technology Readiness Level (TRL) the current buses are on a development level that is represented by numbers 6-7 (technology demonstration/commissioning phase) on the commercialization process. This level is the last before full commercial deployment.

dominant configurations where the fuel cell functions as a range extender. Regional delivery vehicles, class 7-8 vehicles, can be deployed adjacent to refueling stations for buses, for example. In addition to transit authorities and campuses, buses can initially be deployed at airports as well.

DELIVERY VEHICLES (2018-)

After the first rollout of the fuel cell buses and other HD vehicles, vehicles used as last mile delivery trucks and shuttle buses (i.e., vehicle classes 4-6) could be deployed. These vehicles can utilize the same stations as the HD vehicles and help increase the utilization and dispensing volumes needed to make the early stations financially feasible. The last mile delivery truck FCEV can serve as a package delivery van, such as those normally operated by UPS and FedEx, for example. For transit applications in this vehicle category, shuttle buses, can serve as a paratransit vehicles or operate at airports or campuses.

LIGHT DUTY VEHICLES (LDV) (2023 & 2024-)

It is envisioned that the light duty vehicles (LDVs) would not enter the Ohio market until meaningful hydrogen refueling infrastructure has been built out in the State. Fleet operators that operate municipal and commercial fleets that might have access to private stations are envisioned to use LD FCEVs first in the State in year 2023, and thereafter the general public would adopt the technology in greater volumes in year 2024. Given that by year 2023 LDVs will have already been sold in markets like California for 7-8 years, more models are expected to be available at that time.

Together the deployment of heavy, medium and light duty vehicles over the *next five years* can be represented by the following numbers. Year 2032 has been added to the table as a projection for year 15 of the rollout. The table represents the deployment in Ohio specifically, but can be extrapolated to represent other Midwest states. The appendix includes a table that shows the projected numbers for years 2017-2032.

Ohio Total	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**…2032**
HD	3	14	19	29	52	73	2106
MD	0	5	17	51	61	92	2647
LD	0	0	0	0	0	0	40500
Total FCEV Count	**3**	**19**	**36**	**80**	**113**	**164**	**45252**

Table 2: Rollout of FCEV in Ohio

3.1 HYDROGEN REFUELING STATIONS

For widespread adoption to take place, it is necessary to establish a reliable network of hydrogen stations. Hydrogen can be produced and delivered by several means to the end users. Infrastructure for production, delivery, and dispensing are all associated with energy consumption and emissions levels. This section gives an introduction to the various production and delivery methods in more detail.

Due to the early stages of technology development and the relatively few stations that have been built, the costs for hydrogen refueling stations are currently high, rendering government support vital at this stage of the commercialization of the technology. Various hydrogen production and delivery pathways exist today. The most common and cost effective method to produce hydrogen today is steam-methane reformation (natural gas reforming). In fact, 95% of the hydrogen produced today in the U.S. is made by this process in large central plants[33]. In California alone, 2.5 million kg per day of hydrogen needs to be generated in order to produce the needed gasoline. For hydrogen stations, the hydrogen fuel can be generated with on-site reformation from natural gas, compression and storage with dispensing on site. If the central industrial location where hydrogen is produced at a larger scale is close to a hydrogen station, then the hydrogen can be delivered through a hydrogen pipeline with purification, compression, and storage on site. The pictures[34] here below gives additional simplified examples of two different delivery methods and an on-site production alternative. Great attention needs to be put on the various production-delivery-distribution scenarios in order to meet the needed life cycle cost, energy use and emission parameters. The costs for the different station types vary depending on location and capacity.

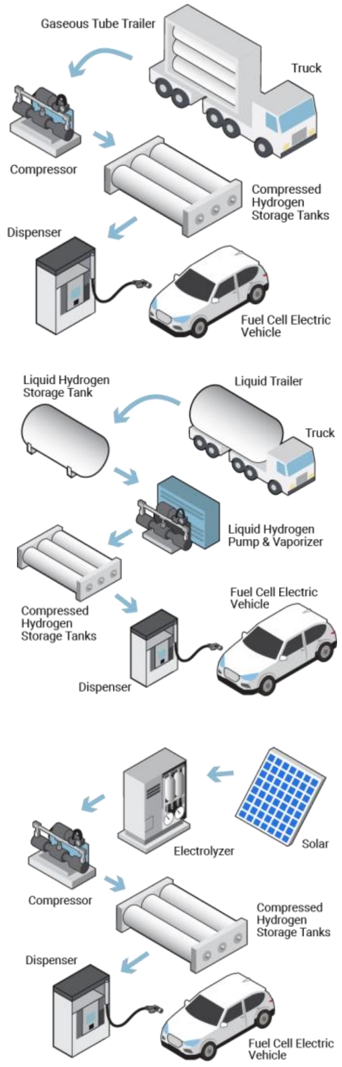

Figure 7: Hydrogen delivery

Gaseous Delivery (Central Production)

The hydrogen is delivered as a gas with a tube trailer to the station. The hydrogen gas is further compressed at the stations and stored in high pressure cascade hydrogen storage tanks from where it is dispensed to the vehicles. Delivery of gaseous hydrogen is not considered an optimal solution for larger fleets, but is sufficient for smaller demonstration projects. An exception would be the use of high-capacity trailers with more than a 500 kg capacity.

Liquid Delivery (Central Production)

The hydrogen is cryogenically cooled at a central location and delivered as a liquid to a liquid storage tank at the station. From there the liquid hydrogen goes through a vaporizer into cascade high pressure hydrogen tanks before it is dispensed to vehicles.

Onsite Production (Forecourt Station)

Hydrogen can be made onsite with an electrolyzer through the use of electricity produced by renewable sources or supplied directly from the grid. After hydrogen gas has been produced it is compressed and stored in high pressure cascade hydrogen tanks from where it is dispensed to the vehicles.

Other onsite production methods in addition to electrolysis are steam-methane reforming and trigeneration that in addition to hydrogen can generate heat and electricity. This innovative station type can be especially appealing in the early station rollout phase, where station investments must be done before FCEV

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[33] DOE Fuel Cell Technologies Office

[34] California Fuel Cell Partnership (CaFCP)

demand. In a tri-generation station hydrogen is only produced when needed. Hydrogen station costs are continuously decreasing as the number of stations deployed continues to increase.

The table here below illustrates the general capacities for a typical hydrogen station.

General Station Type	Typical Capacity (kg/day)
Liquid Delivery	1,000
Onsite Reformation	100-1,000
Pipeline Delivery	>1,000
Onsite Electrolysis	30-100
Mobile Fueler	50
Energy Station (CHP)	100-300

Table 3: Hydrogen station type and typical dispensing capacity[35]

H2USA is a public private partnership focused on encouraging hydrogen infrastructure and deployment of FCEVs across the United States. Released in April 2015 by H2USA and the Department of Energy, a tool designated the Hydrogen Refueling Stations Analysis Model (HRSAM)[36] calculates the cost of hydrogen refueling as a function of various fueling station capacities and design configurations.

Researchers at Argonne National Laboratory (ANL) have developed the Hydrogen Refueling Station Analysis Model (HRSAM), which a user can use to evaluate different refueling options based on selecting various station design parameters. Station design parameters include annual station utilization, the number of dispensing hoses, the number of consecutive fills a station can complete for a given vehicle, and the method of hydrogen delivery to the stations. Economic metrics such as rate of return, capital, operating and maintenance costs as well as the annual and cumulative cash flows. HRSAM also calculates the cost of hydrogen per kilogram.

Also released in 2015, the Hydrogen Financial Analysis Scenario Tool (H2FAST)[37] provides a quick and convenient financial analysis for hydrogen fueling stations. H2FAST complements HRSAM by providing in-depth financial analysis. The focus in the H2FAST model is cash flow and return on investments for hydrogen fueling stations based on key financial inputs such as station capital cost, operating cost, and financing mechanisms. H2FAST is available in two formats: an interactive online tool and a downloadable Excel spreadsheet plus an expert version for advanced analysis. The H2FAST online tool can calculate basic financial performance metrics in response to variations in up to 20 user inputs. By entering input values or adjusting slider bars the performance metrics will change.

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[35] Best Practices in Hydrogen Fueling and Maintenance Facilities for Transit Agencies, CALSTART, 2016

[36] https://www.hydrogen.energy.gov/h2a_delivery.html

[37] H2FAST: http://www.nrel.gov/hydrogen/h2fast/; Hydrogen Financial Analysis Scenario Tool (H2FAST): Web Tool User's Manual" B. Bush, M. Penev, and M. Melaina, National Renewable Energy Laboratory, J. Zuboy Independent Consultant, NREL/TP-5400-64020, May 2015

The spreadsheet version of H2FAST offers basic and advanced user interfaces for modeling individual stations or groups of up to 10 stations. It provides users with detailed annual finance projections such as income statements, cash flow statements, and balance sheet. Outputs of financial performance parameters are available for 65 common metrics and can be presented in graphical presentation.

To date one hydrogen station with dispensing units has been installed at SARTA to serve the American Fuel Cell Buses (AFCB) that the transit authority has deployed. This Air Products station has a 9000-gallon hydrogen storage tank and is currently able to dispense hydrogen at a pressure of 350-bar. The station has been configured in a way that allows future upgrades that can satisfy the demands of FCEVs in the light-duty sector that utilize the 700-bar pressure. This station uses the latest technology in liquid hydrogen pumping that virtually eliminates the need for storing gaseous hydrogen. This innovation allows fast fill-up times as the hydrogen is being vaporized. As of now, the hydrogen to this station is delivered from Sarnia, Ontario in Canada which is approximately 300 miles from Canton, Ohio. SARTA is currently purchasing the hydrogen for $6.50 per kg, which translates into fuel cost of $3.00 per Diesel Gallon Equivalent (DGE). A second station has also recently been opened at Ohio State University for the AFCB that is in use there. The station produces 10kg/day through on-site electrolysis and is built by Millennium Reign Energy of Dayton Ohio. In addition to these two stations, several others smaller stations exist at warehouse locations that utilize hydrogen-fueled material handling equipment. The following sections outline some additional existing approaches to stations.

Figure 8: SARTA hydrogen station and AFCB

AC Transit's hydrogen station[38] in Emeryville, CA started operations in 2011. Planned as a dual-use station, it serves buses at a dedicated dispenser inside the yard and passenger vehicles at a public dispenser outside the yard. A single storage system is used by both. A bus dispenser and back-up bus dispenser provides heavy duty vehicle (bus) fueling inside the fence while a single dispenser provides fuel for light duty vehicles outside the fence.

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[38] MEDIUM- & HEAVY-DUTY FUEL CELL ELECTRIC TRUCK ACTION PLAN FOR CALIFORNIA", October 2016, CaFCP

Figure 9: Emeryville hydrogen fueling station

The Emeryville hydrogen fueling station includes a low-pressure liquid hydrogen storage tank with a capacity of 1800 to 1900 kg delivered every five to ten days with a vaporizer plus an electrolyzer (65 kg/day) which both feed a high-pressure storage tube system as illustrated in Figure 7.

The station has a scalable capacity, with a baseline capacity of 360 kg of 35 MPa fuel per day for buses and 240 kg per day for cars at both 35 and 70 MPa. This provides sufficient fuel for 12 fuel cell buses at 25 kg per fill up and between 40 and 60 cars on a daily basis. Excluding the implementation and capital costs for the hydrogen station equipment, the combined cost of O&M and hydrogen to fuel buses at this station is approximately $8.62/kg (i.e. approximately $4.30 per DGE) dispensed.

The performance of the station to fill multiple buses consecutively at a speed of 6 to 8 minutes per fill—a rate equivalent to diesel bus fueling at AC Transit—is achieved through the use of fast-fuel technology. An increase in the number of FCEBs up to 24 buses, can be accommodated by adding additional compression and gaseous storage equipment. This scalability factor should be considered for the gradual rollout and increase in size of FCEV fleets. AC Transit opened a second station[39] in Oakland in 2014 with a design capacity to fuel 12 buses rapidly and in succession, which can also be expanded to fuel 24 buses. Scheduling and service requirements make it necessary to fuel all buses within a 4-6 hour time slot at night to enable the buses to stay in continuous service from 5 a.m. to 11 p.m. Both AC Transit fueling stations are supplied with hydrogen using liquid hydrogen delivery, with supplemental on-site renewable fuel production at the Emeryville station.

In Oakland, AC Transit is taking an innovative approach to producing hydrogen, as well as to powering AC Transit's largest operating division. On March 27, 2013, AC Transit installed a 420 kW Bloom Energy stationary fuel cell system. Biogas – collected from landfills – feeds the fuel cell, which in turn supplies clean electricity to the entire facility. Electricity from the stationary fuel cell also powers an electrolyzer to produce carbon-neutral hydrogen for the fuel cell buses. Overall, the Oakland station will have the capacity to dispense 360kg of hydrogen per day, with the capability of increasing capacity by adding additional compressors. AC Transit's Stationary Fuel Cells will reduce greenhouse gas emissions by 1,500 tons/year and save over $2 million in energy costs over 10 years.

SunLine Transit's hydrogen station[40] in Thousand Palms opened in April 2000 and is the longest operating hydrogen transit bus fueling station in the United States. The station has on-site production of hydrogen through the use of an auto-thermal reformer, with a capacity of 212 kilograms per day. The five FCEBs currently in service are filled daily with 25-35 kilograms of 35 MPa hydrogen fuel in about 25 minutes per bus. Excluding the capital cost for hydrogen station implementation, the combined cost of O&M and hydrogen is approximately $8.00/kg (i.e. approximately $4.00 per DGE) dispensed.

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[39] AC Transit Many Shades of Green

[40] MEDIUM- & HEAVY-DUTY FUEL CELL ELECTRIC TRUCK ACTION PLAN FOR CALIFORNIA", October 2016, CaFCP

SunLine will be upgrading their existing hydrogen generation station. It will be the largest in the country[41]. The upgrade will allow expansion to produce 800 kilograms of hydrogen a day with renewable electricity; solar, wind and other renewables. The fleet should be able to expand to a fleet of up to 30 buses. Hydrogenics is one of the companies contracted to build the new buses and will upgrade the hydrogen refueling station as well.

3.2 FUEL CELL ELECTRIC VEHICLES

FCEVs offer several advantages compared to traditional vehicles with fossil fueled engines and electric vehicles that are powered solely by batteries. FCEVs are zero emission vehicles where the fuel cell functions as a range extender that allows for tailoring vehicles to specific needs. FCEVs are, in most cases, able to handle the same duty cycle as conventional vehicles with internal combustion engines, while the vehicles' fill-up processes closely resemble one another. Depending on vehicle class, the efficiency of FCEVs are approximately two times better than a traditional internal combustion engine. The main reason for this efficiency gain is that 60% of the available energy content in hydrogen is harnessed to move the vehicle forward, while only approximately 30% of the energy content of gasoline is used due to excessive loss of energy in the form of heat. The significant local attributes for FCEVs include no tail pipe emissions since a fuel cell produces electricity through an electrochemical reaction that only produces water as the byproduct. Dependent on the hydrogen production method, the criteria pollutant and GHG savings can be significant. An added benefit of utilizing hydrogen fueled vehicles is also that there are no direct grid impacts that can result in potentially prohibitive demand charges,[42] especially for fleets that deploy larger volumes of electric vehicles.

The following sections outline some existing fuel cell electric vehicles. Each narrative captures the key "requirements" for each vehicle for hydrogen refueling by illustrating the following metrics: 1) typical daily fill capacity for individual vehicle, 2) station utilization kg/day for a fleet of vehicles of a given size, 3) station design configuration (gaseous or liquid), and 4) station performance dispensing rate kg/min. These metrics can provide a summary by vehicle type e.g. bus, truck, LDV for a discussion on infrastructure required.

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[41] News Release http://www.kesq.com/news/sunline-transit-agency-announces-grant-for-hydrogen-powered-buses/458146574, April 21 2017

[42] Electric Truck & Bus Grid Integration Opportunities, Challenges & Recommendations, CALSTART, 2015

HEAVY DUTY VEHICLES

In the heavy-duty vehicle space, transit buses have been the first to adopt fuel cell technology. The following transit buses are described in more detail below: the American Fuel Cell Bus and the New Flyer battery fuel cell range extended bus.

Figure 10: SARTA American Fuel Cell Bus (SARTA will soon operate ten of these buses)

More than 300 fuel cell electric buses have been deployed around the world. The largest deployment sites to-date in the U.S. have been in California at Alameda-Contra Costa Transit Agency and SunLine Transit Agency in Coachella Valley. Both of these transit properties and other projects throughout the country have successfully demonstrated the technologies and have also surpassed the reliability targets set by the Department of Energy[43]. The fuel cell buses tracked by the National Renewable Energy Laboratory (NREL)[44] have completed hundreds of thousands of miles in service to date and are currently considered to be at Technology Readiness Level (TRL) 7, which is indicative of full-scale validation in a relevant environment. As a reference, diesel buses are currently considered to be at TRL 9 level (mature technology). The benefits of fuel-cell electric buses are that they have low emission, high range, and that the fill-up time only takes minutes. The capital cost for the buses have also drastically decreased. There has been a price reduction of more than 60% for the buses since 2008, as the total capital cost for fuel-cell electric buses are currently around $1.0-1.4 million[45]. Lower prices are achievable with higher volumes. New Flyer has provided a letter to the California Air Resources Board that states that the quoted pricing on an order of 40 buses by 2020 is $900,000 per bus[46].

The American Fuel Cell Bus (AFCB) supplier team includes BAE Systems, Ballard Power Systems and ElDorado National-California. The AFCB is in fleet service at SunLine Transit Agency in the Coachella Valley, California and at the Stark Area Regional Transit Agency (SARTA) in Canton, Ohio. The AFCB features major technology advances and innovations:

- The bus is a purpose-design fuel cell bus by a U.S. manufacturer, ElDorado National - California. The bus is a new production 40 foot bus with numerous bus design improvements aimed at reducing weight, noise, and power consumption.

- The lightweight chassis accommodates a U.S. built hydrogen storage system with 50 kg capacity sufficient for the bus to exceed 350 miles in range. During daily transit service the bus will typically refuel with an average of 23 kg of hydrogen per day of gaseous hydrogen at 5,000 psi delivered at < 2 kg/min.

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[43] CaFCP MD & HD FCET Action Plan (2016)

[44] Fuel Cell Buses in U.S. Transit Fleets: Current Status 2016, NREL

[45] CaFCP and CALSTART

[46] California Air Resources Board – Cost Assumptions and Data Sources; Update 10/3/2016

- The U.S. built traction system is the latest generation of transit-proven BAE Systems Hybridrive® system with an Integrated Motor-Generator and advanced Lithium battery that powers hybrid-electric buses at 3 of the 5 largest transit properties in North America.

- The fuel cell power is delivered via a Buy America compliant Ballard Power Systems /FC/velocity™ HD6 at a gross power level of 150 kW. The /FC/velocity™ fuel cells use a proton-exchange membrane fuel cell stack with a 12,000 hours or 5 year warranty.

- The BAE Systems U.S. built energy storage system (ESS), is a transit proven lithium-ion battery technology which is integrated with the fuel cell stack achieving full hybrid operation with lower weight and improved performance through the latest generation of inverters and controllers.

- Finally, a unique collection of U.S. built high-efficiency accessory electronics achieve higher overall bus efficiency.

The AFCB is described as a fuel cell dominant electric bus because the gross fuel cell power level is 150 kW with the 11 kW-hour ESS which can provide 200 kW peak.

FCEV – American Fuel Cell Bus	
Bus chassis/Model	Eldorado National 40'
Range	350 miles
Hydrogen Fuel Storage (kg H2)	50kg at 350 bar

Table 4: American Fuel Cell Bus

New Flyer Industries, a major American bus Original Equipment Manufacturer (OEM) and bus system integrator, is producing a fuel cell bus by working with an experienced fuel cell provider of Buy America compliant hardware (Ballard Power Systems) to extend the range of a battery electric bus by adding a fuel cell as a "range extender". The result is a "Buy America" Compliant fuel cell bus that, through design simplification and optimized integration, is intended to be more reliable and reduce both purchase and operating costs over other similar class buses.

The current fuel cell buses in demonstration programs have a price premium over other non-zero emission available technologies. The cost of the fuel cell system is a major contributor to that price premium. This bus redesigns the fuel cell by using alternate materials, components and processes that will ease manufacturing, assembly and service as well as increase durability and overall reliability. Ballard Power Systems intends to produce a low-cost, smaller, lighter fuel cell power plant that retains power and performance to charge the batteries periodically. Features of this fuel cell bus are:

- Reduced range extender power plant size

Figure 11: New Flyer fuel cell range extended bus

- Improved power plant life/durability
- Reduced power system cost

New Flyer Industries and Siemens have worked with Ballard Power Systems to develop a fuel cell variant of an electric drive system for the Advanced Generation Fuel Cell Bus (Adv Gen FCB). The electric drive system is scaled-up to power a 60' articulated bus. A key step in the commercialization of the Advanced Generation FC Bus is completion of a full FTA Altoona Durability Bus test which is underway now. On-road fleets continue to be necessary to advance the product development and commercialization process. The 60-foot bus is designated the XHE60 Articulated Bus and is show in the adjacent figure. On board hydrogen 5,000 psi storage is 30 kg with daily fill requirement of average of 25 kg at a nominal fill rate of 6 kg/min. New Flyer is also working with Hydrogenics on another integration project involving the development of a hydrogen fuel cell bus.

FCEV – New Flyer Fuel Cell Range Extended Bus	
Bus chassis/Model	XHE 60'
Range	TBD miles
Hydrogen Fuel Storage (kg H2)	30 kg at 350 bar

Table 5: New Flyer battery range extended FC bus

Other upcoming vehicles in the heavy duty space are also the recently unveiled Toyota HD fuel cell truck and Nikola Motors planned HD truck. Both of these trucks can depending on location utilize the same refueling network as the buses. A HD fueling standardization that allows fast fill-up times (>10kg) has been developed for the HD space (SAE J2601-2)

MEDIUM DUTY VEHICLES

One example of a package delivery truck is the Fuel Cell Extended Range Truck that is currently being developed in California under a grant from the South Coast Air Quality Management District. The project will integrate, validate and demonstrate a commercial-path, optimized fuel cell extended range truck for demonstration out of the UPS Ontario (California) Regional Hub using a nearby hydrogen fueling facility. The vehicle will be deployed for field testing later in 2017.

SARTA and Ohio State University have, among other organizations, recently submitted a proposal for the Department of Energy to deploy 18 package delivery vans in Ohio along with hydrogen fueling infrastructure. Moreover, UPS has voiced an interest to deploy 100 of these trucks together with a large refueling station utilizing steam methane reforming using methane from renewable natural gas.

Figure 12: Extended range delivery truck

FCEV – Extended Range Delivery Truck	
Bus chassis/Model	International / P100D
Range	125 miles
Hydrogen Fuel Storage (kg H2)	20kg at 350 bar
Battery Storage	varies

Table 6: Extended range delivery truck

CALSTART, US Hybrid Corporation, California State University Los Angeles (CSULA), and SunLine Transit Agency (SunLine) have partnered to propose and execute the H2Ride™ Hydrogen Shuttle Bus Demonstration Project. The project partners will build and demonstrate four high-performance hydrogen fuel cell plug-in shuttle buses that will provide pollution-free shuttle service with extended travel ranges of up to 200 miles in Disadvantaged Communities, in eastern Los Angeles and the Coachella Valley.

FCEV – Shuttle Bus	
Bus chassis/Model	H2Ride™ 30' & 32'
Range	125/200 miles
Hydrogen Fuel Storage (kg H2)	10kg/20kg at 350 bar
Battery Storage	varies

Table 7: Fuel cell shuttle bus

Figure 13: H2Ride™ shuttle bus

US Hybrid's advanced, near-commercial H2Ride™ shuttle buses are fully-designed and operational, and have been previously field prototyped and successfully field tested in Hawaii Volcanoes National Park. The shuttle buses will be implemented in two configurations: (a) SunLine will demonstrate two H2Ride™ 32 buses, a 32-foot, 29-seat shuttle with a range of up to 200 miles on 20 kg of H2; (b) CSULA will demonstrate two H2Ride 30 buses, a 25-seat shuttle with a range of up to 125 miles on 10 kg of H2. The buses will also include a plug-in SAE J1772 level II electric charging option, which will support battery assist for transient loads and support regenerative braking. Expanding on prior successful demonstrations, the proposed buses will be updated with improved controls, as well as optional fast charging technology for the CSULA deployment. In addition to this vehicle platform, US Hybrid also offers a paratransit vehicle that is based on the Nissan eNV 200.

LIGHT DUTY VEHICLES

Several OEMs (i.e. Mercedes, Honda, Hyundai, and Toyota) have introduced LD vehicles that are now being rolled out in California. Additional markets will follow, tracking the expansion of a convenient hydrogen refueling infrastructure. In California, the vehicles are awarded with the white sticker that give single occupant HOV access. These vehicles are designed to operate and perform as well or better than traditional vehicles. The refueling process takes approximately 5 minutes. These vehicles are designed to be filled with hydrogen at 700 bar pressure, however, the vehicles can also utilize the lower pressure, 350 bar stations if needed. Some examples of currently available models from Honda, Hyundai, and Toyota can be seen here below.

Figure 14: Examples of LD FCEVs (Honda Clarity, Hyundai Tucson, Toyota Mirai)

FCEV – Example: Honda Clarity	
Range	366 miles
Hydrogen Fuel Storage (kg H2)	5.5 kg at 700 bar

Table 8: Honda Clarity

SPECIAL PURPOSE VEHICLES

As mentioned in earlier sections, there are several other applications that are well suited to be powered by fuel cells. Vehicles in specialty applications such as airport cargo trucks, ground support equipment, and refuse trucks are all good candidates as these vehicles normally operate a set duty cycle and are filled at a designated station.

It is recommended to evaluate the possibility for dual-use stations where the dispenser is shared between the commercial warehouse activity and public/private fleet. To date there are over 7000 fuel cell forklifts in use in various warehouses in the U.S.[47]. The DOE's Fuel Cell Technologies Office has estimated that the earlier funded 700 fuel-cell powered lift truck projects have led to more than 15,000 orders/deployments with no DOE funding[48].

TECHNOLOGY READINESS – HEAVY DUTY AND OFFROAD EQUIPMENT

The technology readiness and the pathway for fuel cell electric drive trucks and buses have been analyzed in the California Air Resources Board's three-year funding plan draft discussion document for the heavy-duty market. As can be seen in the picture below, the forklift market has reached full commercialization, closely followed by the transit buses market. The picture aims to communicate the technology status and the segments that have greatest potential to reach full commercialization with the help of additional investments.

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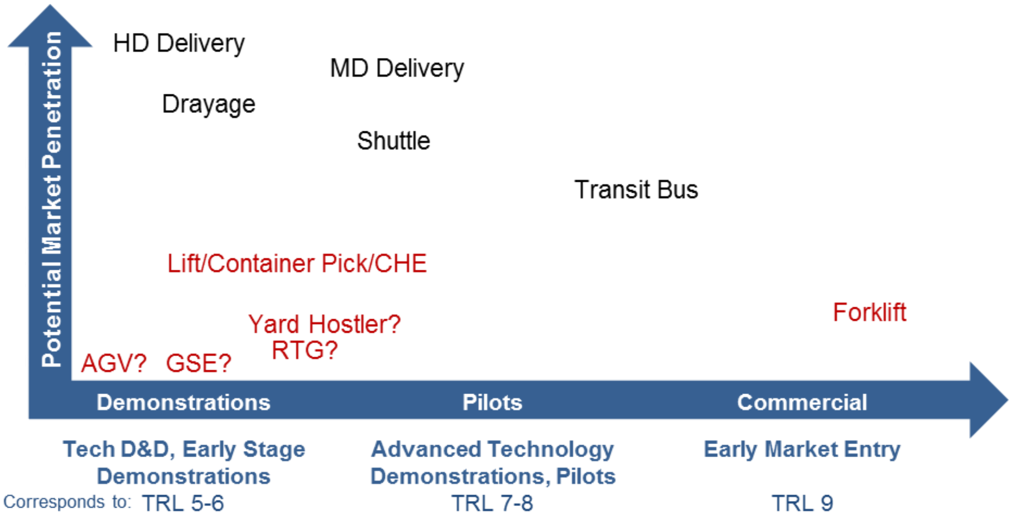
[47] Fuel Cell & Hydrogen Energy Association

[48] DOE Hydrogen and Fuel Cells Program



Key: Off-road shown in Red
AGV = automated guided vehicle
GSE = ground support equipment
RTG = rubber tired gantry crane
CHE = cargo handling equipment

Source: Based on CARB technology assessments, interviews with manufacturers, and other studies and publications. These may be adjusted before being finalized based on further conversations and gathering additional information.

Figure 15: Technology readiness levels of fuel cell electric vehicles and equipment

3.3 PRIORITY REGIONS AND CORRIDORS

It is vital to identify the priority regions and corridors for the region, particularly as the Midwest Hydrogen Center of Excellence is set to achieve a number of goals: (1) educate transit authorities about the benefits of hydrogen fuel cell technology; (2) connect transit authorities and private fleets with funding sources that can enable the transition and adoption of this new technology; (3) serve as a resource to help with the implementation of the new technology; and (4) function as a central hub for support activities in both the policy and R&D spaces.

For this roadmap, specific tools developed by the National Renewable Energy Laboratory (NREL) were utilized to gain an understanding of which urban areas could be the most conducive to deployment of hydrogen refueling infrastructure and vehicles on a larger scale. The map here below identifies a general geographic area of the Midwest region that is the focus of this roadmap. The map's red areas represent major metropolitan regions and corridors, which depict the highest likelihood for vehicle adoption and hydrogen fuel demand. The Hydrogen Demand and Resource Assessment (HyDRA)[49] tool has been utilized to identify the areas that are most likely to

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[49] Several assessment tools exist. For example, in California, the Air Resources Board has developed a tool, California Hydrogen Infrastructure Tool (CHIT) that is a Geographical Information System-based tool that enables the assessment of the coverage provided by stations and the first FCEV adopters.

support successful deployment of FCEVs and their related infrastructure. Among other metrics, hydrogen demand, resource, infrastructure, cost, production, and distribution parameters can be analyzed through the tool. The HyDRA tool integrates data from a wide range of resources, such as the SERA and MSM models among others, to provide spatial and temporal data that can be used when evaluating different hydrogen growth scenarios and strategies. It is a visualization tool that allows for the analysis of complex datasets and a number of future scenarios related to the hydrogen economy.

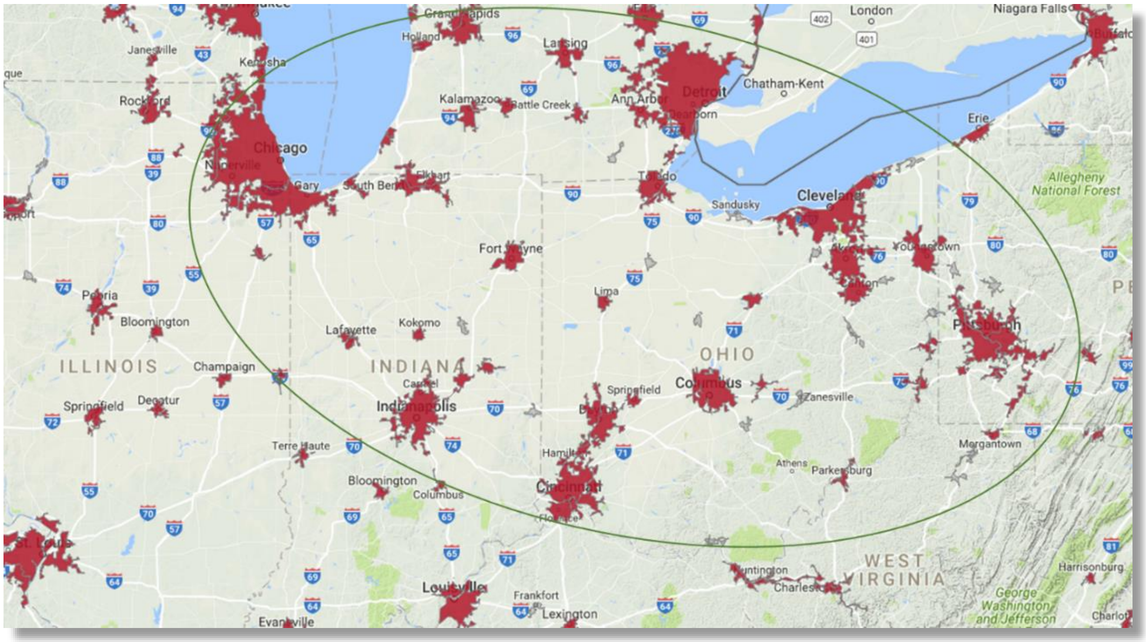
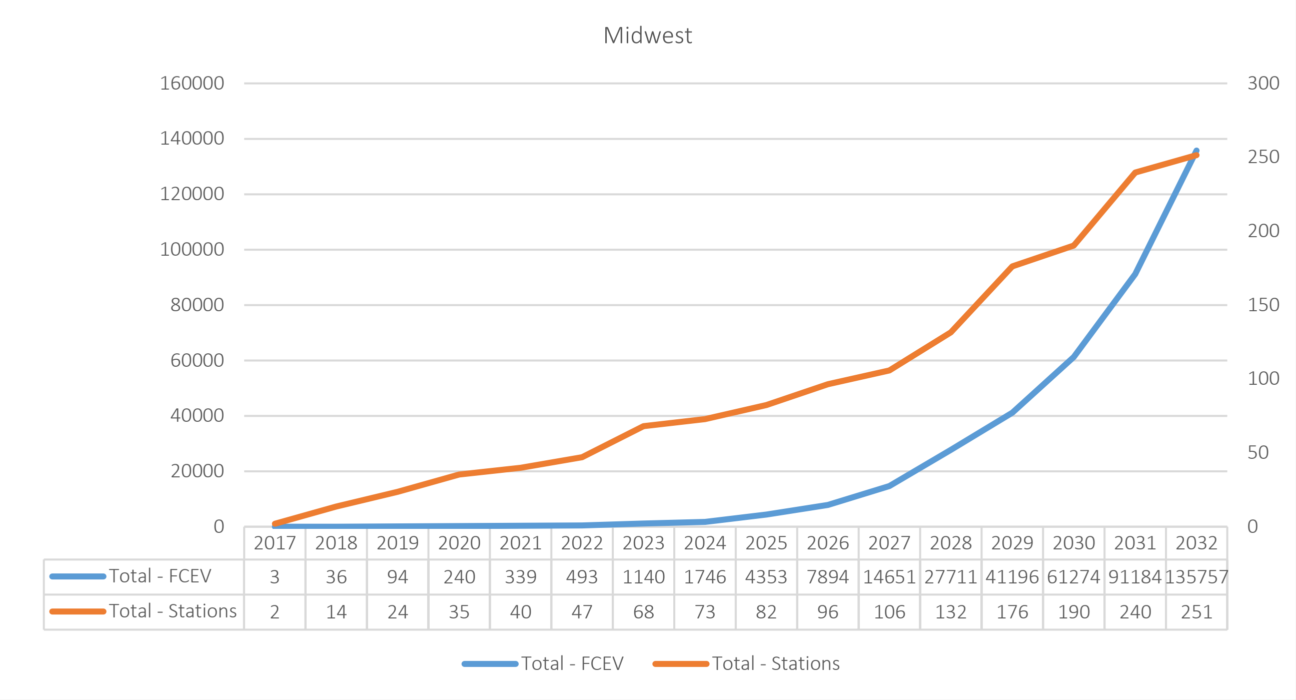


Figure 16: Midwest priority regions for the deployment of hydrogen infrastructure and FCEVs.

For the Midwest the following priority regions have been identified: (1) Ohio, (2) Michigan, (3) Illinois, (4) Indiana, and (5) Western Pennsylvania. As seen in the figure above, the major metropolitan areas within these regions, where the population densities are the highest, should be the priority regions.

For this roadmap, analysis was performed to estimate the total number of vehicles and stations that could be deployed in the region over the next 15 years. As discussed in the previous sections, three different vehicle categories (i.e., HD, MD and LD) were identified and the number of vehicles in each category were counted for each metropolitan area in Ohio, specifically. An earlier deployment of hydrogen stations and vehicles was assumed than the one currently reflected in the HyDRA tool. The number of fueling stations was based on the total vehicle count for a specific region and minimum station capacities were tabulated based on the typical daily filling needs of each vehicle. Average vehicle miles travelled (VMT) and fuel consumption (kg/day) numbers for the vehicles were extracted from the DOE's Alternative Fuels Data Center to gain an understanding of minimum station capacities. The table below illustrates the projections for FCEVs and station growth for the Midwest area. These projections are based on aggregate numbers that are derived from the Ohio projections. As a reference, the National Renewable Energy Laboratory has performed hydrogen station scenario analysis that estimates that the total number of stations deployed by 2050 nationally would be 7,750, in a scenario where FCEVs would have a market share of 20%[50]. This showcases the strong growth prospects and opportunities for the hydrogen transportation sector.



	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Total - FCEV	3	36	94	240	339	493	1140	1746	4353	7894	14651	27711	41196	61274	91184	135757
Total - Stations	2	14	24	35	40	47	68	73	82	96	106	132	176	190	240	251

Figure 17: FCEVs and hydrogen station projections for Midwest

By taking a closer look at Ohio, specifically, and by further utilizing the geospatial and temporal analysis tools, four main clusters for the deployment of early hydrogen infrastructure were identified: **(1) Cleveland – Akron – Canton**, **(2) Columbus, (3) Cincinnati – Dayton**; and **(4) Toledo**. The areas are identified in the figure below.

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[50] Marc Melaina, et al NREL

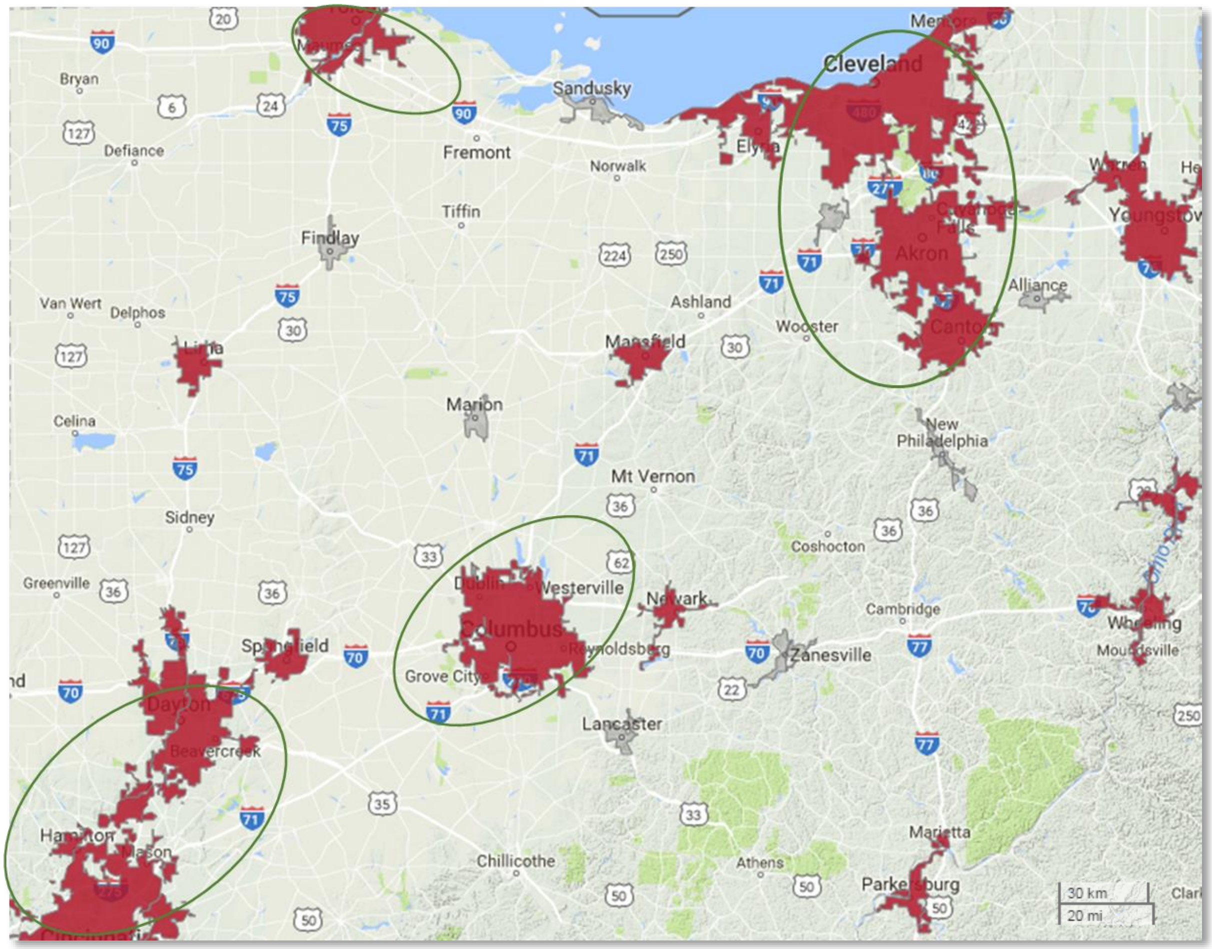
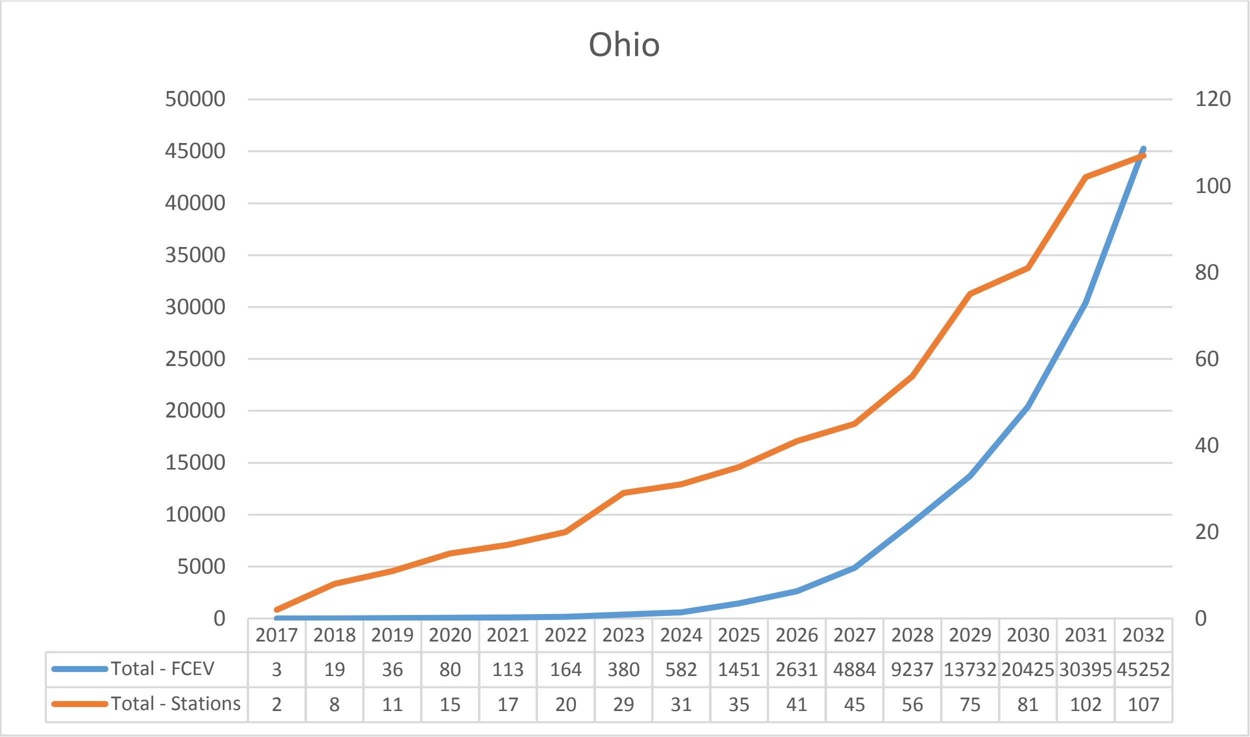


Figure 18: Priority areas for early deployment of hydrogen infrastructure and FCEVs in Ohio

As seen from the map, the metropolitan areas where the population densities are the highest are the most likely to adopt FCEVs first. For the purposes of this roadmap, the focus will be on the four areas identified with a green oval in the figure above. Each of these areas represent a corridor that also can be connected (e.g., the Cincinnati area and Columbus). Gateway cities and regions, as mentioned earlier, that are outside this map but represent the Midwest area, are Detroit to the north, Indianapolis to the west, and Pittsburg to the east. Each of these cities could follow Ohio's lead in the development of the hydrogen economy. The following sections will further analyze each of the areas identified in the map above in more detail.



	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Total - FCEV	3	19	36	80	113	164	380	582	1451	2631	4884	9237	13732	20425	30395	45252
Total - Stations	2	8	11	15	17	20	29	31	35	41	45	56	75	81	102	107

Figure 19: A projection for total FCEVs and stations in Ohio

The figure here above presents the total cumulative FCEVs and station growth projections for Ohio. These numbers represent the combined total for the metropolitan areas identified in the heat map. As seen in the figure, three vehicles and two stations have been listed for 2017. At the writing of this proposal, SARTA and Ohio State University are already operating one bus each, and they both have an operational hydrogen refueling station. The data in the figure does not include material handling equipment. An aggressive compound annual growth rate of 89% is projected as the vehicles are being adopted, and the final FCEV count, represented by all vehicle classes, of approximately 45,000 vehicles is assumed by year 2032. A conservative estimate of the total CO_2 reduction potential from these vehicles is 99,700 metric tons per year, even when the hydrogen is produced from non-renewable sources.

Key questions that need to be solved include which technological pathways will provide the least cost fuel for a specific demand; how the transition from distributed generation to central generation takes place; and how will early low-demand be met. As indicated by the California Fuel Cell Partnership[51], station coverage and capacity utilization are two main criteria for determining the number of stations necessary and their location during the early commercialization phases. It is important to evaluate potential infrastructure deployment scenarios that are dependent on specific timeframes to gain an understanding of how the ideal rollout will take shape. Early stations should not be expected to be profitable before significant utilization by FCEVs. Fleets that operate under a return to base duty cycle can be supported by a limited number of stations, however.

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[51] A California Road Map: The Commercialization of Hydrogen Fuel Cell Vehicles – Technical Version, June 2012, California Fuel Cell Partnership

The following sections will describe the four regions in Ohio in more detail. Early station cluster growth has been projected for each of the four regions. As indicated below, green identifies an existing station, while yellow identifies a proposed station. Furthermore, the Annual Average Daily Traffic (AADT)[52] volumes for U.S. interstate and state highway system routes have been analyzed, as they are listed by Ohio Department of Transportation, to gain a better understanding of optimal station locations. As these station locations are suggestions, further analysis that also identifies fleets is recommended.

🟢 **Existing Station**

🟡 **Proposed Station**

CLEVELAND – AKRON – CANTON AREA

Population: Cleveland – Akron – Canton area that covers counties Cuyahoga (population: 1,249,352), Summit (population: 540,300) and Stark (population: 373,612)[53]

Traffic Volumes: AADT data show that the heaviest traffic volumes (70000-17000 vehicles) for Cuyahoga county are on Interstates 71, 77, 90, 271, and 480; for Summit county, the heaviest traffic volumes (75000-140000 vehicles) are on Interstates 76 and 77; for Stark county the heaviest traffic volumes (80000-100000 vehicles are on Interstate 77 between North Canton and Canton.

Note: I-80 has been identified as an alternative fuels corridor.

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[52] Ohio Department of Transportation, Office of Technical Services, Traffic Monitoring Section, 2013

[53] Ohio Development Services Agency, Office of Research (March 2017)

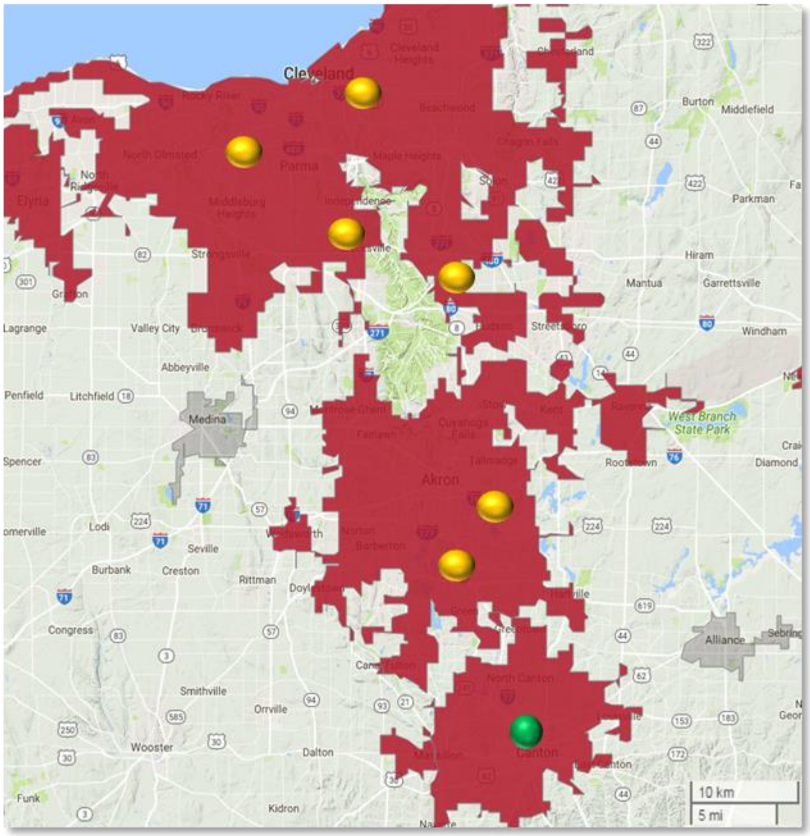

Figure 20: Cleveland-Akron-Canton fuel cell station locations

City	Year					
	2017	2018	2019	2020	2021	2022	…2032
Cleveland-Akron-Canton							
HD	2	8	10	12	22	31	891
MD		2	5	15	20	30	868
LD							14175
Total FCEV Count	**2**	**10**	**15**	**27**	**42**	**61**	**15934**
Hydrogen Station Count	1	2	3	4	5	6	30
Hydrogen Demand (kg/day)	41	197	285	482	767	1106	39255
Hydrogen Station Capacity (kg/day)	41	99	95	121	153	184	1308

Table 9: Cleveland-Akron-Canton FCEVs and hydrogen station projections

COLUMBUS

Population: Columbus and the county of Franklin (population: 1,264,518)

Traffic Volumes: AADT data show that the heaviest traffic volumes (100000-180000 vehicles) are on Interstates 70, 71, 270 and 670.

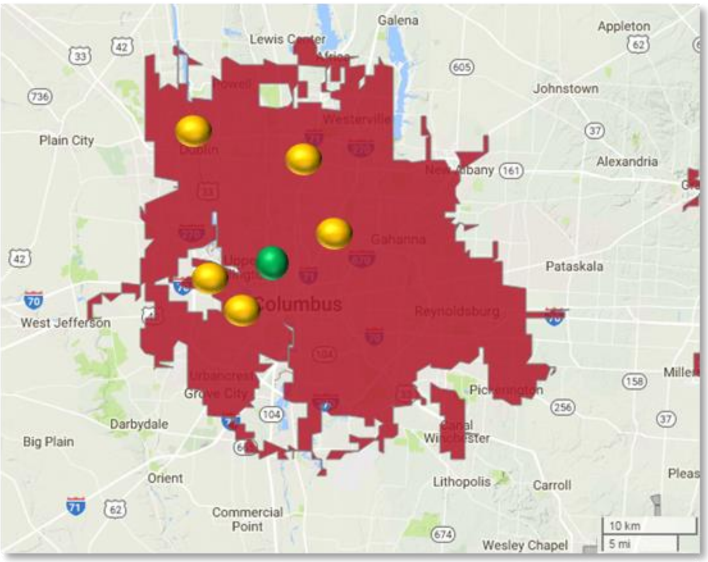

Figure 21: Columbus fuel cell station locations

City	Year 2017	2018	2019	2020	2021	2022	…2032
Columbus							
HD	1	3	4	10	15	21	607
MD		2	5	15	17	26	738
LD							10125
Total FCEV Count	**1**	**5**	**9**	**25**	**32**	**47**	**11470**
Hydrogen Station Count	1	2	2	4	5	6	30
Hydrogen Demand (kg/day)	21	93	161	441	576	832	29270
Hydrogen Station Capacity (kg/day)	21	47	80	110	115	139	976

Table 10: Columbus FCEVs and hydrogen station projections

CINCINNATI – DAYTON AREA

Population: Cincinnati and the counties of Hamilton (809,099), Butler (377,537), Warren (227,063)

Traffic Volumes: AADT data show that the heaviest traffic volumes (50000-19000 vehicles) are on Interstates 71, 74, and 75; for Butler county the heaviest traffic volumes (75000-135000 vehicles) are on Interstate 75; for Warren county the heaviest traffic volumes (35000-91000 vehicles) are on Interstates 71 and 75.

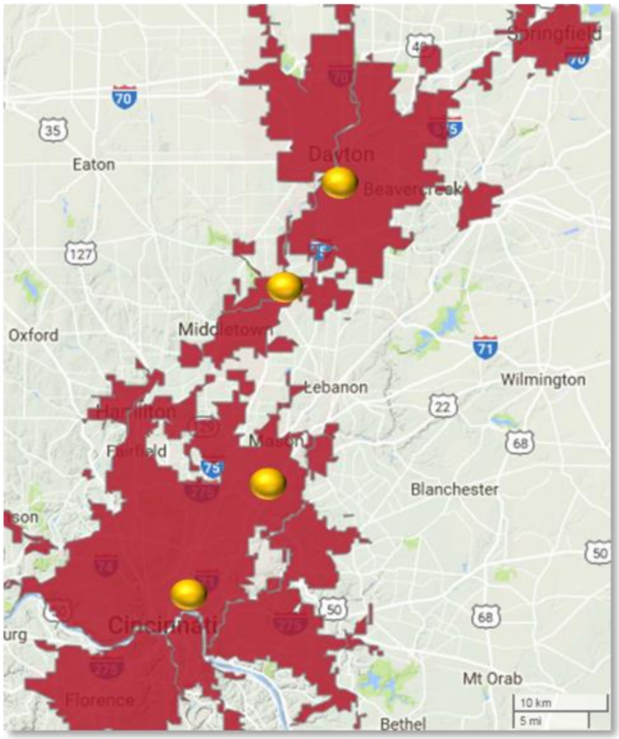

Figure 22: Cincinnati-Dayton fuel cell station locations

City	Year						
	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**…2032**
Cincinnati-Dayton							
HD		2	2	3	7	10	283
MD		1	2	6	8	12	347
LD							8100
Total FCEV Count		**3**	**4**	**9**	**15**	**22**	**8731**
Hydrogen Station Count		2	3	4	4	5	25
Hydrogen Demand (kg/day)		57	73	156	270	390	15437
Hydrogen Station Capacity (kg/day)		29	24	39	67	78	617

Table 11: Cincinnati-Dayton FCEVs and hydrogen station projections

TOLEDO

Population: The Toledo area that is partially covered by Lucas county (population: 432,488)

Traffic Volumes: AADT data show that the heaviest traffic volumes (55000-95000 vehicles) are on Interstates 75, 280 and 475.

Note: The proximity to refineries in Toledo could in the future be evaluated as the hydrogen infrastructure is built out. A direct hydrogen pipeline supply to a station could be a cost-effective solution.

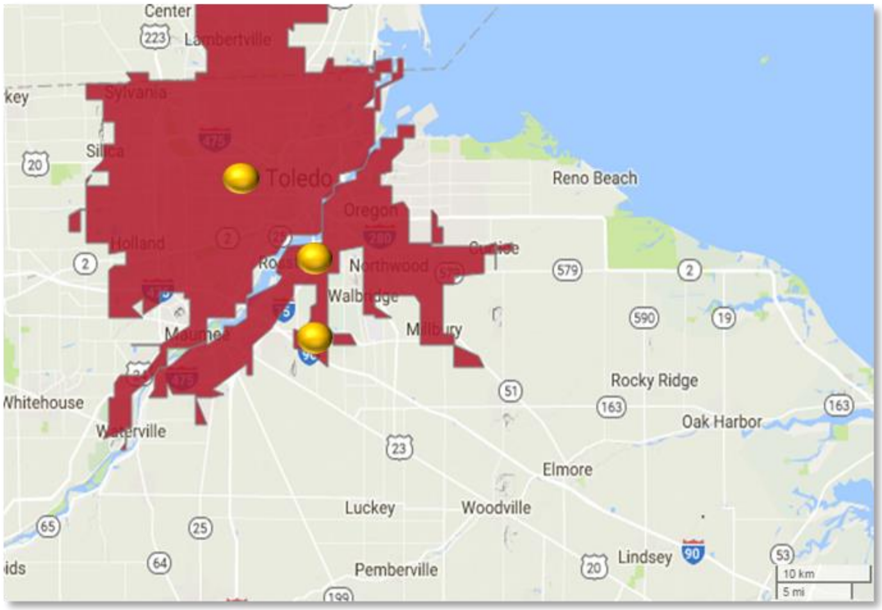

Figure 23: Toledo fuel cell station locations

City	Year						
	2017	2018	2019	2020	2021	2022	...2032
Toledo							
HD		1	3	4	8	11	324
MD			5	15	16	24	694
LD							8100
Total FCEV Count		**1**	**8**	**19**	**24**	**35**	**9118**
Hydrogen Station Count		2	3	3	3	3	22
Hydrogen Demand (kg/day)		21	140	316	415	606	21675
Hydrogen Station Capacity (kg/day)		10	47	105	138	202	985

Table 12: Toledo FCEVs and hydrogen station projections

4. POTENTIAL FOR HYDROGEN PRODUCTION FROM RENEWABLE SOURCES

Today, hydrogen is predominantly produced from fossil fuel sources that do not reduce GHGs as efficiently as possible. Steam-methane reforming, described in the previous chapters, is the most commonly used technology for hydrogen production. In fact, in the U.S. alone, 11 million tons of hydrogen per year is produced for petroleum refining purposes. This amount could support 50 million FCEVs per year, generating significant emissions savings – as one FCEV can displace, depending on the hydrogen pathway, approximately 8,076 pounds of CO_2 per year[54].

Plenty of renewable sources suitable for hydrogen production are, however, available and are especially well-suited for decarbonizing the transportation sector. These renewable sources include solar and wind electrolysis, gasification of biomass, and steam methane reforming of biogas among other innovative solutions such as utilizing biogas for tri-generation of hydrogen, electricity and heat. The DOE supports research and development to discover and optimize technologies that can produce hydrogen economically and sustainably.

As the energy transition continues and the world becomes increasingly dependent on solar power and its derivative wind, the question of how energy storage will be solved will become critical. Hydrogen is a flexible solution for larger scale energy storage and can play a vital role as a storage medium for intermittent renewable sources. Also, biomass has received increasing attention due to the flexibility it offers, its wide range of feedstock, and its broad geographic distribution. Earlier NREL studies have found that a total of 1 billion metric tons of hydrogen could be produced annually from wind, solar, and other biomass sources in the U.S. Thus, tremendous potential exists for utilization of renewably sourced energy.

Currently, the main challenge for hydrogen production is cost. However, as the technology continues to develop, Ohio and the Midwest have an opportunity to incorporate renewable sources in their hydrogen production practices. The adjacent figure indicates the hydrogen production potential from biomass, as an example. The green areas represent this potential of 10 to 15+ thousand kg per sq.km per year[55].

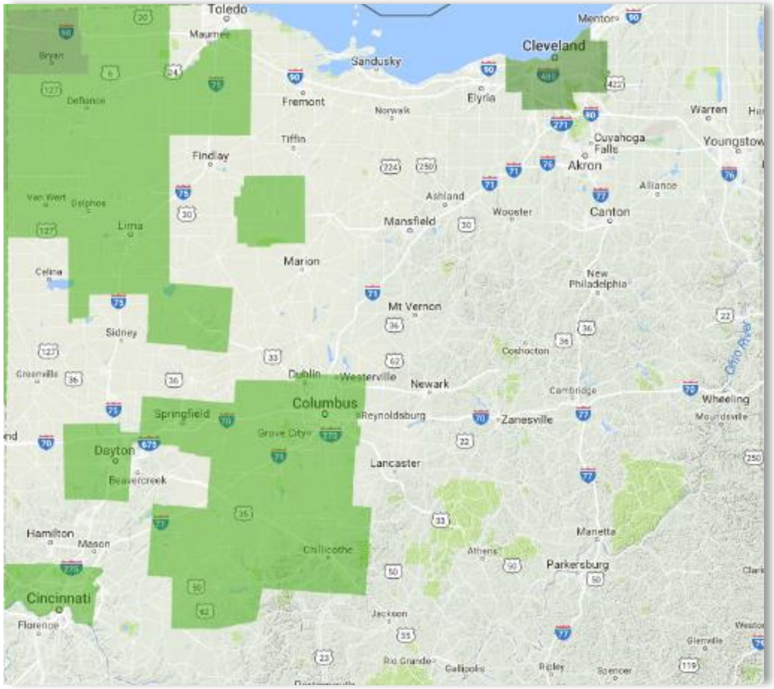

Figure 24: Hydrogen from biomass

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[54] Air Liquide, ICEPAG 2017

[55] Potential for Hydrogen Production from Key Renewable Resources in the United States, A. Milbrandt and M. Mann. February 2007. NREL TP-640-41134

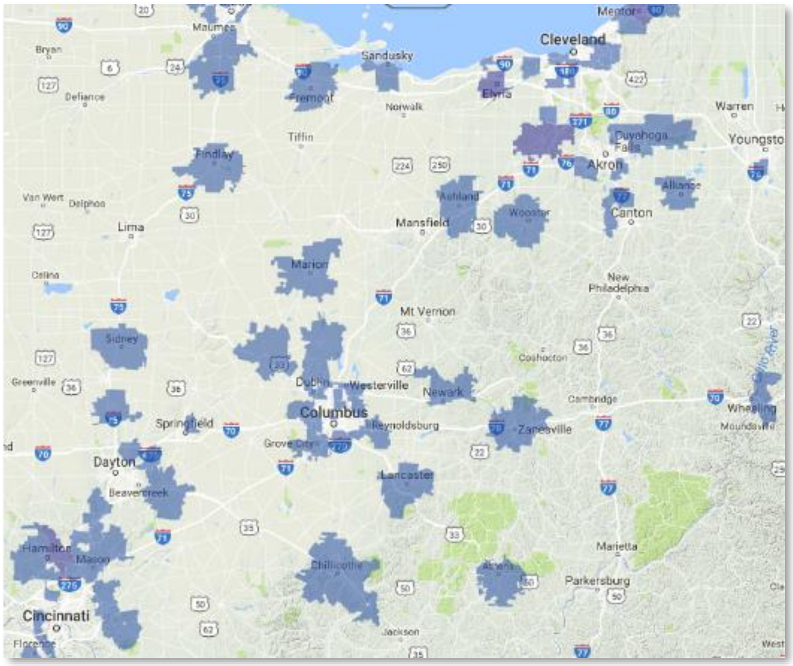

Figure 25: Methane from wastewater (50 to over 100 tons per year)

It is worth noting that methane emissions from landfills are also high, especially within the major metropolitan areas such as Cleveland and Cincinnati. The methane from wastewater is estimated using the methodology from the EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks for years 1990 to 2003[56]. Please see the adjacent figure. Digestion of community green waste, food residue, and municipal sludge offers an effective means for the creation of biogas that can be used for the generation of hydrogen. This process has a negative carbon footprint and also generates a great fertilizer as a side product. Further data on renewable resources for the State has been included in the appendix.

5. HYDROGEN ENERGY SYSTEM ANALYSIS IN TRANSPORTATION

The optimization of the physical build-out of the early hydrogen infrastructure is important not only from a cost perspective, but also from the emissions/environmental impact perspective. The production, delivery, and dispensing elements of hydrogen production all contribute to the overall cost and emissions, playing a role in the optimal deployment scenario. A tool that can help with this analysis is the Macro System Model (MSM) that has been developed under a joint effort between the National Renewable Energy Laboratory and Sandia National Laboratories (SNL). The tool can aid the analysis of the economics, primary energy-source requirements, and emissions of the hydrogen production and delivery pathways. Total cost, energy use, and emissions that incorporates feedstock, conversion, and infrastructure can be simulated.

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[56] A Geographic Perspective on the Current Biomass Resource Availability in the United States, A Milbrant, Technical Report NREL/TP-560-39181, 2005

The following production and delivery methods have been included in the model:

Central Production (involves hydrogen delivery to station)

- Biomass gasification
- Coal gasification (with or without CO_2 sequestration)
- Natural gas reforming (with or without CO_2 sequestration)
- Electrolysis using electricity produced by wind

Distributed Production (hydrogen produced at station location)

- Electrolysis
- Natural gas reforming
- Ethanol reforming

Furthermore, the following delivery methods have been incorporated in the model:

- Pipeline delivery of gaseous hydrogen
- Gaseous hydrogen delivery by tube trucks
- Cryogenic hydrogen delivery by truck

A simulation run where steam-methane reforming is used as the feedstock has been included in the appendix for Cuyahoga County in Ohio. The overall efficiency of the pathway can be reviewed in more detail from the figure.

6. CONCLUSION

This roadmap presents an approach governed by an initial focus on fleet deployment of FCEVs and hydrogen refueling infrastructure. The utilization of fuel cells in transport applications is growing fast, as fuel cell forklifts have already proven their reliability and cost effectiveness, and fuel cell buses are rapidly moving into viability. Boasting a strong manufacturing base, the Midwest region stands poised to continue innovating and creating well-paying jobs that can supply and service the burgeoning advanced transportation sector. Several OEMs have now introduced FCEVs into the marketplace and more models are expected. FCEVs handle the same duty cycle as traditional internal combustion vehicles and are, thus, well positioned to serve the transit space. The Midwest is well situated to utilize and further develop economically viable renewable methods for generating hydrogen that can further eliminate emissions and advance the region's expertise as a hydrogen player.

Of the Midwest states, Ohio already hosts a robust network of fuel cell component and material suppliers. Ohio has also supportive policies and incentives in place to encourage industry research, development, and business expansion. As presented in this roadmap, Ohio has taken the first steps in deploying hydrogen infrastructure for fleet usage and is now on its way to becoming the third largest deployment site for fuel cell electric buses in the nation.

The Midwest states are encouraged to follow the footsteps of Ohio and join the Renewable Hydrogen Fuel Cell Collaborative it spearheads the transition to a hydrogen economy that not only means deployment of infrastructure and vehicles, but also the creation of new jobs for the region. As it is suggested in this roadmap, the Midwest could deploy 135,000 FCEVs supported by 250 hydrogen refueling stations during the next 15 years and create 65,000 new jobs in the process.

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APPENDIX

Renewable Hydrogen Production Sources

Hydrogen from Renewable Resources (million kg)	2002 Gasoline Consumption (million gallons)	2000 Population (thousand people)
9,236	5,295	11,353

Table 13: Renewable Hydrogen Production Potential Relative to Gasoline Consumption and Population - Ohio

Hydrogen from Biomass per km^2 (thousand kg)	Hydrogen from Biomass (million kg)	Hydrogen from Solar per km^2 (thousand kg)	Hydrogen from Solar (million kg)	Hydrogen from Wind per km^2 (thousand kg)	Hydrogen from Wind (million kg)	Total Hydrogen per km^2 (thousand kg)	Total Hydrogen (million kg)
786	934	6,776	8,257	51	44	7,613	9,236

Table 14: Hydrogen Production Potential from Renewable Resources - Ohio

Crop Residues	Switchgrass on CRP Lands	Forest Residues	Methane from Landfills	Methane from Manure Management	Primary Mill	Secondary Mill	Urban Wood	Methane from Domestic Wastewater
5,001	1,587	796	647	41	786	124	1,272	19

Table 15: Total Biomass Resources Available (Thousand ton/year) – Ohio[57]

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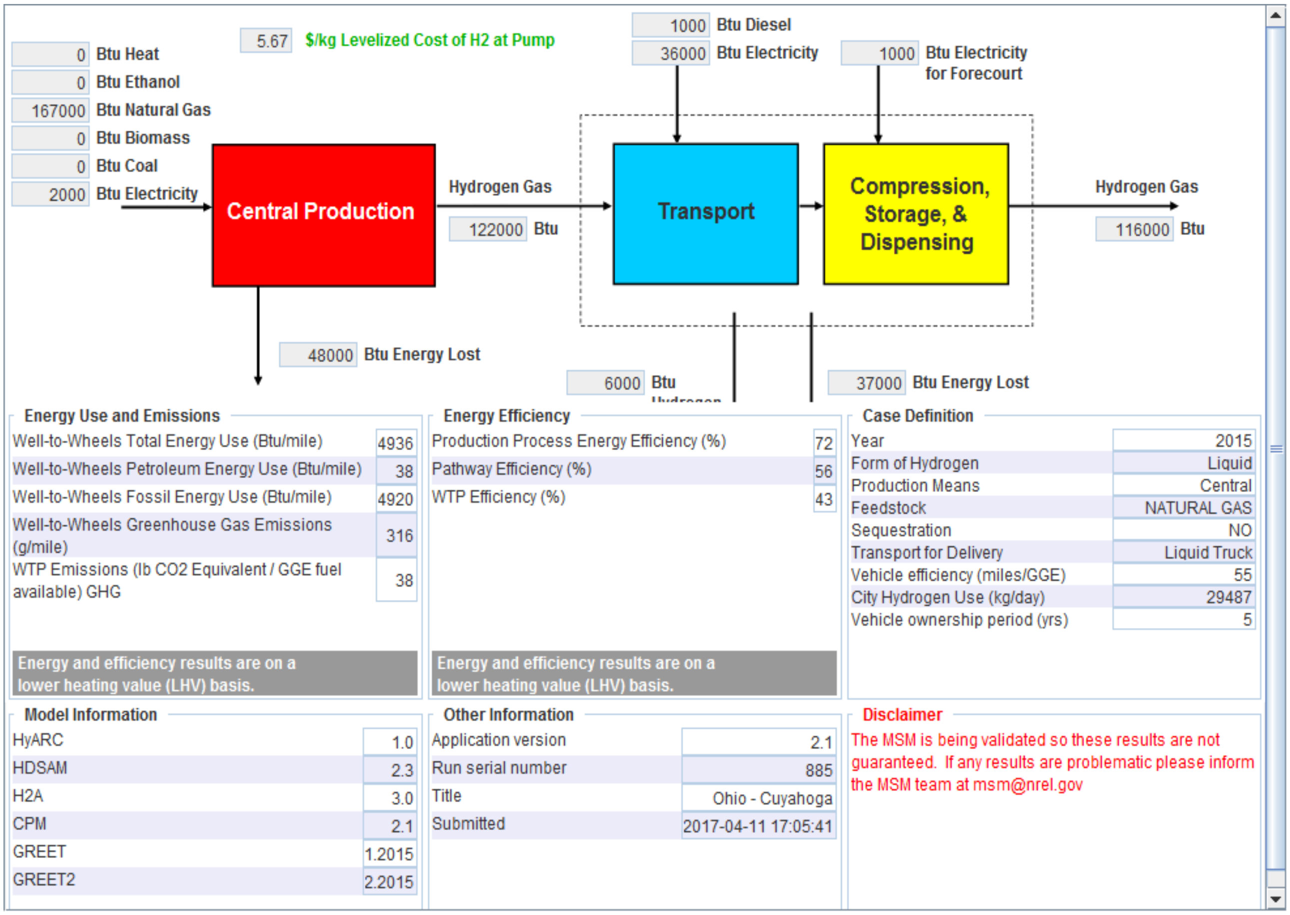
[57] A Geographic Perspective on the Current Biomass Resource Availability in the United States, A Milbrant, Technical Report NREL/TP-560-39181, 2005

Macro System Modeling for Ohio-Cuyahoga (SMR-central production/liquid truck)



0 Btu Heat
0 Btu Ethanol
167000 Btu Natural Gas
0 Btu Biomass
0 Btu Coal
2000 Btu Electricity

5.67 $/kg Levelized Cost of H2 at Pump

1000 Btu Diesel
36000 Btu Electricity
1000 Btu Electricity for Forecourt

122000 Btu
116000 Btu
48000 Btu Energy Lost
6000 Btu
37000 Btu Energy Lost

Energy Use and Emissions

Well-to-Wheels Total Energy Use (Btu/mile)	4936
Well-to-Wheels Petroleum Energy Use (Btu/mile)	38
Well-to-Wheels Fossil Energy Use (Btu/mile)	4920
Well-to-Wheels Greenhouse Gas Emissions (g/mile)	316
WTP Emissions (lb CO2 Equivalent / GGE fuel available) GHG	38

Energy and efficiency results are on a lower heating value (LHV) basis.

Energy Efficiency

Production Process Energy Efficiency (%)	72
Pathway Efficiency (%)	56
WTP Efficiency (%)	43

Energy and efficiency results are on a lower heating value (LHV) basis.

Case Definition

Year	2015
Form of Hydrogen	Liquid
Production Means	Central
Feedstock	NATURAL GAS
Sequestration	NO
Transport for Delivery	Liquid Truck
Vehicle efficiency (miles/GGE)	55
City Hydrogen Use (kg/day)	29487
Vehicle ownership period (yrs)	5

Model Information

HyARC	1.0
HDSAM	2.3
H2A	3.0
CPM	2.1
GREET	1.2015
GREET2	2.2015

Other Information

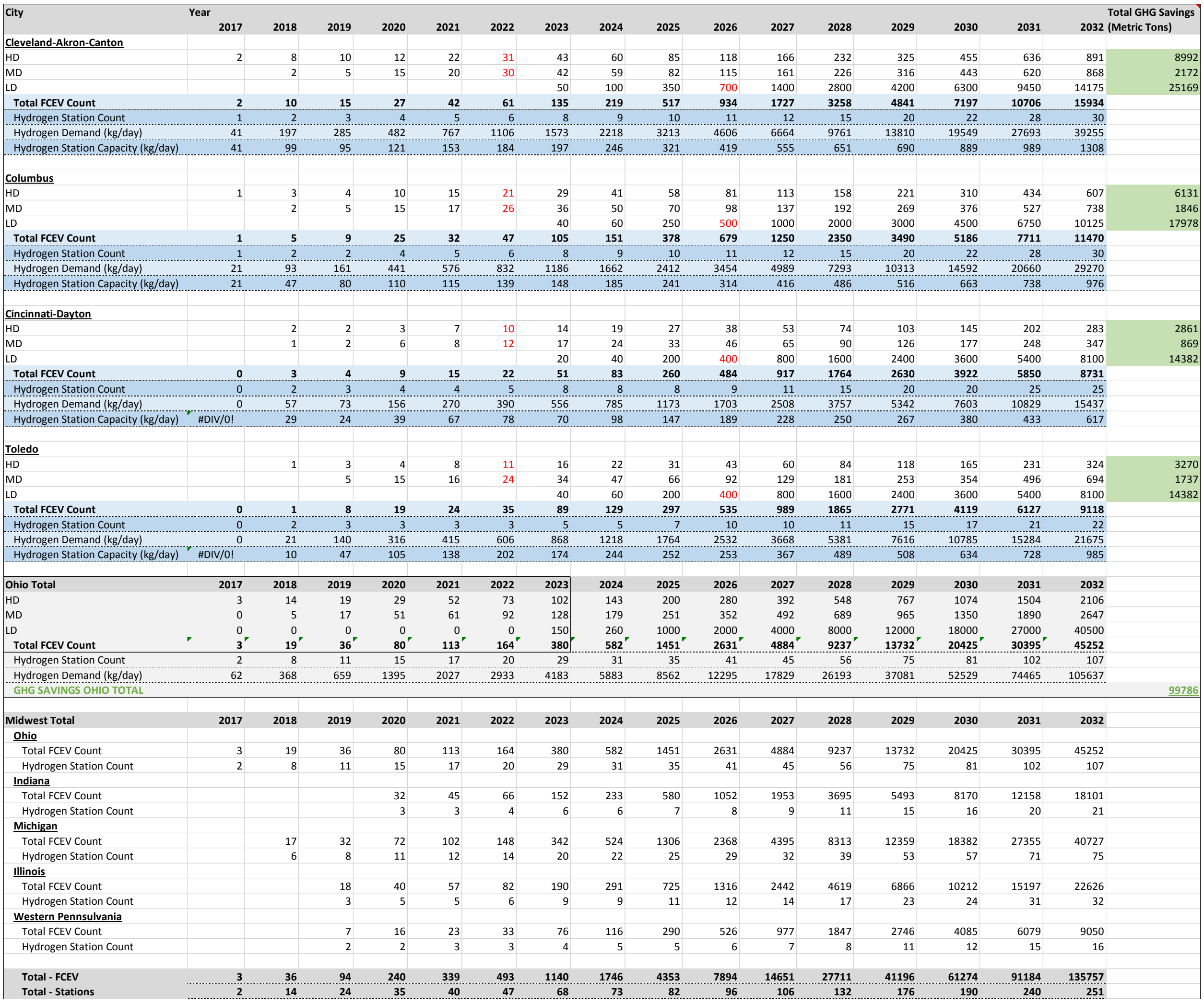
Application version	2.1
Run serial number	885
Title	Ohio - Cuyahoga
Submitted	2017-04-11 17:05:41

Disclaimer

The MSM is being validated so these results are not guaranteed. If any results are problematic please inform the MSM team at msm@nrel.gov

Figure 26: Ohio-Cuyahoga SMR-central production/liquid truck

Hydrogen Infrastructure and Vehicle Deployment Scenario for Ohio/Midwest



City	Year																Total GHG Savings (Metric Tons)
	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	
Cleveland-Akron-Canton																	
HD	2	8	10	12	22	31	43	60	85	118	166	232	325	455	636	891	8992
MD		2	5	15	20	30	42	59	82	115	161	226	316	443	620	868	2172
LD							50	100	350	700	1400	2800	4200	6300	9450	14175	25169
Total FCEV Count	**2**	**10**	**15**	**27**	**42**	**61**	**135**	**219**	**517**	**934**	**1727**	**3258**	**4841**	**7197**	**10706**	**15934**	
Hydrogen Station Count	1	2	3	4	5	6	8	9	10	11	12	15	20	22	28	30	
Hydrogen Demand (kg/day)	41	197	285	482	767	1106	1573	2218	3213	4606	6664	9761	13810	19549	27693	39255	
Hydrogen Station Capacity (kg/day)	41	99	95	121	153	184	197	246	321	419	555	651	690	889	989	1308	
Columbus																	
HD	1	3	4	10	15	21	29	41	58	81	113	158	221	310	434	607	6131
MD		2	5	15	17	26	36	50	70	98	137	192	269	376	527	738	1846
LD							40	60	250	500	1000	2000	3000	4500	6750	10125	17978
Total FCEV Count	**1**	**5**	**9**	**25**	**32**	**47**	**105**	**151**	**378**	**679**	**1250**	**2350**	**3490**	**5186**	**7711**	**11470**	
Hydrogen Station Count	1	2	2	4	5	6	8	9	10	11	12	15	20	22	28	30	
Hydrogen Demand (kg/day)	21	93	161	441	576	832	1186	1662	2412	3454	4989	7293	10313	14592	20660	29270	
Hydrogen Station Capacity (kg/day)	21	47	80	110	115	139	148	185	241	314	416	486	516	663	738	976	
Cincinnati-Dayton																	
HD		2	2	3	7	10	14	19	27	38	53	74	103	145	202	283	2861
MD		1	2	6	8	12	17	24	33	46	65	90	126	177	248	347	869
LD							20	40	200	400	800	1600	2400	3600	5400	8100	14382
Total FCEV Count	**0**	**3**	**4**	**9**	**15**	**22**	**51**	**83**	**260**	**484**	**917**	**1764**	**2630**	**3922**	**5850**	**8731**	
Hydrogen Station Count	0	2	3	4	4	5	8	8	8	9	11	15	20	20	25	25	
Hydrogen Demand (kg/day)	0	57	73	156	270	390	556	785	1173	1703	2508	3757	5342	7603	10829	15437	
Hydrogen Station Capacity (kg/day)	#DIV/0!	29	24	39	67	78	70	98	147	189	228	250	267	380	433	617	
Toledo																	
HD		1	3	4	8	11	16	22	31	43	60	84	118	165	231	324	3270
MD			5	15	16	24	34	47	66	92	129	181	253	354	496	694	1737
LD							40	60	200	400	800	1600	2400	3600	5400	8100	14382
Total FCEV Count	**0**	**1**	**8**	**19**	**24**	**35**	**89**	**129**	**297**	**535**	**989**	**1865**	**2771**	**4119**	**6127**	**9118**	
Hydrogen Station Count	0	2	3	3	3	3	5	5	7	10	10	11	15	17	21	22	
Hydrogen Demand (kg/day)	0	21	140	316	415	606	868	1218	1764	2532	3668	5381	7616	10785	15284	21675	
Hydrogen Station Capacity (kg/day)	#DIV/0!	10	47	105	138	202	174	244	252	253	367	489	508	634	728	985	
Ohio Total	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	
HD	3	14	19	29	52	73	102	143	200	280	392	548	767	1074	1504	2106	
MD	0	5	17	51	61	92	128	179	251	352	492	689	965	1350	1890	2647	
LD	0	0	0	0	0	0	150	260	1000	2000	4000	8000	12000	18000	27000	40500	
Total FCEV Count	**3**	**19**	**36**	**80**	**113**	**164**	**380**	**582**	**1451**	**2631**	**4884**	**9237**	**13732**	**20425**	**30395**	**45252**	
Hydrogen Station Count	2	8	11	15	17	20	29	31	35	41	45	56	75	81	102	107	
Hydrogen Demand (kg/day)	62	368	659	1395	2027	2933	4183	5883	8562	12295	17829	26193	37081	52529	74465	105637	
GHG SAVINGS OHIO TOTAL																	99786
Midwest Total	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	
Ohio																	
Total FCEV Count	3	19	36	80	113	164	380	582	1451	2631	4884	9237	13732	20425	30395	45252	
Hydrogen Station Count	2	8	11	15	17	20	29	31	35	41	45	56	75	81	102	107	
Indiana																	
Total FCEV Count				32	45	66	152	233	580	1052	1953	3695	5493	8170	12158	18101	
Hydrogen Station Count				3	3	4	6	6	7	8	9	11	15	16	20	21	
Michigan																	
Total FCEV Count		17	32	72	102	148	342	524	1306	2368	4395	8313	12359	18382	27355	40727	
Hydrogen Station Count		6	8	11	12	14	20	22	25	29	32	39	53	57	71	75	
Illinois																	
Total FCEV Count			18	40	57	82	190	291	725	1316	2442	4619	6866	10212	15197	22626	
Hydrogen Station Count			3	5	5	6	9	9	11	12	14	17	23	24	31	32	
Western Pennsulvania																	
Total FCEV Count			7	16	23	33	76	116	290	526	977	1847	2746	4085	6079	9050	
Hydrogen Station Count			2	2	3	3	4	5	5	6	7	8	11	12	15	16	
Total - FCEV	**3**	**36**	**94**	**240**	**339**	**493**	**1140**	**1746**	**4353**	**7894**	**14651**	**27711**	**41196**	**61274**	**91184**	**135757**	
Total - Stations	**2**	**14**	**24**	**35**	**40**	**47**	**68**	**73**	**82**	**96**	**106**	**132**	**176**	**190**	**240**	**251**	

Figure 27: Hydrogen infrastructure and vehicle deployment scenario