Hydrogen Infrastructure Market Readiness: Opportunities and Potential for Near-term Cost Reductions

Proceedings of the Hydrogen Infrastructure Market Readiness Workshop and Summary of Feedback Provided through the Hydrogen Station Cost Calculator

M.W. Melaina, D. Steward, and M. Penev
National Renewable Energy Laboratory

S. McQueen
Energetics

S. Jaffe and C. Talon
IDC Energy Insights

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/BK-5600-55961
August 2012

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

Hydrogen Infrastructure Market Readiness: Opportunities and Potential for Near-term Cost Reductions

Proceedings of the Hydrogen Infrastructure Market Readiness Workshop and Summary of Feedback Provided through the Hydrogen Station Cost Calculator

M.W. Melaina, D. Steward, and M. Penev
National Renewable Energy Laboratory

S. McQueen
Energetics

S. Jaffe and C. Talon
IDC Energy Insights

Prepared under Task No. HT12.2010

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

Technical Report
NREL/BK-5600-55961
August 2012

Contract No. DE-AC36-08GO28308

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Acknowledgements

The authors would like to acknowledge the U.S. Department of Energy's Fuel Cell Technologies Program in the Office of Energy Efficiency and Renewable Energy (EERE) for funding this project. We would also like to thank the workshop participants and speakers for volunteering their time and expertise to prepare for and attend the workshop. Many of these participants also spent a significant amount of time providing feedback through the Hydrogen Station Cost Calculator, providing valuable quantitative information on station cost estimates. We would also like to acknowledge: members of the workshop Planning Committee (Adrian Corless, James Cross, Catherine Dunwoody, John Garbak, Fred Joseck, and Alex Keros), workshop facilitators from Energetics (Shawna McQueen, Jeanette Brinch and Matt Antes), NREL analysts for developing the Hydrogen Station Cost Calculator (Darlene Steward, Michael Penev, and Marc Melaina), staff from TTCorp for providing logistical and technical support for the workshop, and IDC Energy Insights staff for helping to design and implement the Hydrogen Station Cost Calculator (Sam Jaffe and Casey Talon). Finally, this report had been improved due to comments and suggestions from several individuals who reviewed an early version.

Acronyms and Abbreviations

CaFCP	California Fuel Cell Partnership
CEC	California Energy Commission
DOE	U.S. Department of Energy
EC	Early Commercial
FCEV	Fuel Cell Electric Vehicle
FCHEA	Fuel Cell and Hydrogen Energy Association
FCTP	Fuel Cell Technologies Program
GGE	Gasoline gallon equivalent
H2I	Hawaii Hydrogen Initiative
HSCC	Hydrogen Station Cost Calculator
ICE	Internal combustion engine
LDV	Light-duty vehicle
LS	Larger Stations
MHE	Material handling equipment
MS	More Stations
NOW	Nationale Organisation Wasserstoff (National Organization for Hydrogen)
NREL	National Renewable Energy Laboratory
O&M	Operation and maintenance
OEM	Original equipment manufacturer
R&D	Research and development
RD^3	Research, development, demonstration, and deployment
SMR	Steam methane reformer
SOTA	State-of-the-Art

Executive Summary

Recent progress with fuel cell electric vehicles (FCEVs) has focused attention on hydrogen infrastructure as a critical commercialization barrier. With major automakers focused on 2015 as a target timeframe for global FCEV commercialization, the window of opportunity is short for establishing a sufficient network of hydrogen stations to support large-volume vehicle deployments. This report describes expert feedback on the market readiness of hydrogen infrastructure technology from two activities: 1) the Hydrogen Infrastructure Market Readiness workshop held February 16-17, 2011, at the Gaylord National Hotel, National Harbor, Maryland; and 2) collection of cost data from the Hydrogen Station Cost Calculator (HSCC), administered by IDC Energy Insights and providing anonymous, weighted, aggregate cost results from 11 stakeholders on four types of hydrogen stations.

The feedback received from both activities is consistent, suggesting that major cost reductions can be achieved within the 2015 timeframe, with relatively small hydrogen stations (about 430 kg per day in nominal capacity) contributing approximately $6.00 per gallon gasoline equivalent (gge) to the total cost of hydrogen. This is a significant reduction from the estimated cost associated with stations installed today, more than $20.00 per gge, and additional reductions are expected as greater numbers of the same station type are installed (down to $4.80 per gge) and even more reductions if the same station type is designed at a larger capacity (to $3.50 per gge).

More than 60 attendees participated in the Market Readiness workshop, providing detailed descriptions of station cost-reduction opportunities and suggesting action items to achieve these cost reductions. Eight general cost-reduction opportunities identified at the workshop are summarized within four categories:

REDUCE STATION COMPONENT COSTS

1. Expand and enhance supply chains for production of high-performance, lower-cost parts
2. Reduce cost of hydrogen compression
3. Develop high-pressure hydrogen delivery and storage components

STATION DESIGNS

4. Develop "standard" station designs
5. Harmonize/standardize dispensing equipment specifications

PERMITTING PROCESS

6. Develop "type approvals" for use in permitting
7. Improve information and training available to safety and code officials

ANALYSIS AND INFORMATION SHARING

8. Develop mechanisms for planning station rollouts and sharing early market information

Additional recommendations synthesized from workshop feedback include three high-priority cost-reduction topics to be pursued through future workshops or other activities: 1) Innovation and Standardization of Station Designs, 2) Streamlining and Facilitation of Station Permitting and Approval Processes, and 3) Focus on the End-User Experience. Finally, in addition to providing quantitative cost estimates for near-term hydrogen stations, respondents to the HSCC identified a relatively broad range of research, development, demonstration, and deployment

(RD^3) topics as being high priority. Priority RD^3 items identified include: scale-up of electrolysis systems, pilot and demonstration projects for biomass reforming, commercialization and deployment of gaseous delivery trucks, commercialization and deployment of aboveground high-pressure storage (10,000 psi) at stations, and piloting, demonstration, and scale-up of station compressors.

Contents

List of Figures

List of Tables

1 Introduction and Background

Interest in hydrogen as a fuel for fuel cell electric vehicles (FCEVs) has a long history. The concept and first demonstration of a fuel cell emerged in the 1800s, and the first demonstration of a mobile application was a 15 kW tractor built in 1959. This demonstration was quickly followed by NASA's use of alkaline fuel cells in the Gemini and Apollo capsules in the 1960s (Hoffman 1981). The contemporary idea of a "hydrogen economy" developed within the automotive industry in the 1970s, and with continued research and development, especially by Canada's Ballard Power, the first demonstrations of fuel cell buses and passenger vehicles occurred in the 1990s (Vaitheeswaran and Carson 2008). Enthusiasm for vehicular applications continued to build into the early 2000s, and the first demonstration projects releasing several hundreds of vehicles to the public began in 2007. Recently, most major automakers have adhered to a planned commercial launch of FCEVs in the 2014-2016 timeframe (FCT 2011; GCC 2011). In September 2009, nine major automakers signed a Letter of Understanding suggesting that a few hundred thousand vehicles may be deployed within this timeframe (REF 2009).

Concurrent with these automotive developments, fuel cells have taken hold in several smaller emerging markets, including material handling equipment (MHE) such as forklifts, stationary or remote power applications for telecommunications and data centers, and combined heat and power in buildings. Some of these applications are novel, such as a molten carbonate fuel cell demonstrated in "tri-generation" mode, consuming biogas from a wastewater treatment plant and producing heat, power, and hydrogen for vehicle applications (EERE 2011). But most deployments have been in basic applications, often replacing battery systems. Though smaller and lower-profile than light-duty vehicles (LDVs), these emerging market applications have carried fuel cells from demonstration towards real-world commercialization, as revealed by the adoption trends of major corporations (BTI 2011; FCT 2011; cf. Kurtz, Wipke et al. 2011).

In addition to these fuel cell successes in emerging markets, recent LDV market and technology studies have claimed that a shift from demonstration to commercial status is also imminent for FCEVs (McKinsey 2010; PikeResearch 2011). Optimistic announcements have been made on multiple past occasions, typically by automotive companies, stating that FCEVs would be commercialized at high volumes within very short timeframes. Some of these announcements were made in the wake of the California Zero Emission Vehicle mandate adopted in 1990, requiring 10% of all new vehicles sold to be electric vehicles by 2003 (Collantes 2006). However, with continued accumulation of real-world experience through the Department of Energy's Hydrogen Learning Demonstration Program,[1] experience with vehicle rollout projects in other countries, and continued unveilings of newer next-generation prototype fuel cell vehicles (GCC 2010; GCC 2011a; GCC 2011d), the industry focus on a 2015 launch date for FCEVs is more compelling today than when individual automakers made previous announcements. Significant progress has been made on vehicle performance, including enabling more than 400 miles of range with 10,000 psi gaseous tanks, and continued progress on fuel cell stack durability is promising (DOE 2011). There has been significant discussion of a $50,000 price point for early vehicles from one major automaker (Bloomberg 2010).

---

[1] See the program website at http://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/fleet_demonstration.html

This progress towards vehicle market readiness has resulted in an increased focus on infrastructure availability as a market barrier. California continues to provide significant government support for hydrogen infrastructure, and ambitious plans have been proposed in the European Union and Japan, but, with 2015 approaching quickly, station rollout may prove to be a limiting factor. This concern is summarized in a recent quote from a 2011 Pike Research report (GCC 2011; PikeResearch 2011):

> *The limiting factor for the FCV market will be the availability of hydrogen infrastructure. If current plans for station construction are delayed or abandoned, the rollout of FCVs will be similarly pushed back.*

There are at least three major links between emerging markets for non-LDV fuel cell applications and market barriers associated with the 2015 launch date for LDVs. The first link is the cost reductions anticipated due to high-volume production of fuel cell units for stationary and MHE markets. A recent Oak Ridge National Laboratory report examined this topic, concluding that significant cost reductions have been achieved over the last 2-5 years, on the order of 50%, but that continued government support must be maintained to achieve further reductions through economies of scale and to reach competitive status by 2015-2020 (Greene, Duleep et al. 2011). A second link is how the expansion of hydrogen supply chains to support emerging markets may result in cost reductions spilling over to reduce the cost of hydrogen for LDVs, especially for hydrogen delivery and retail station equipment. This infrastructure-expansion and cost-reduction link—resulting from growth in emerging markets and the associated economies of scale, scope, volume, learning, and technological innovation—is an important theme within this report and was a major topic of discussion at the Hydrogen Infrastructure Market Readiness workshop held on February 16-17, 2011. A third link, closely related to the second, is how hydrogen fuel supply infrastructure for emerging markets may be leveraged to increase the availability of hydrogen for LDVs as the 2015 launch date approaches. While fuel availability for LDVs can be procured more easily if infrastructure costs are reduced, the implications of this third and more direct link are not explicitly addressed in the present study.

This report includes proceedings from the 2011 Hydrogen Infrastructure Market Readiness workshop (Section 2) as well as preliminary results from an effort to collect consistent data from key stakeholders on near-term hydrogen station costs using the Hydrogen Station Cost Calculator (HSCC) (Section 3). The descriptive and qualitative information provided through deliberation and discussion among workshop participants, combined with the quantitative results from key stakeholders through the HSCC, provide an update on the market readiness of hydrogen infrastructure technology. This update can serve as a reference point for future scenario analyses, roadmap exercises, and other stakeholder coordination activities supporting the transition to expanded use of hydrogen in mobile and other applications.

2 Hydrogen Infrastructure Market Readiness Workshop

The Hydrogen Infrastructure Market Readiness workshop was held for 1.5 days in conjunction with the 2011 Fuel Cell and Hydrogen Energy Association (FCHEA) Conference at the Gaylord National Hotel, National Harbor, Maryland, February 16-17, 2011. This was the seventh major workshop in a series of stakeholder workshops held under Systems Analysis within the U.S. Department of Energy's Fuel Cell Technologies Program (FCTP). Proceedings from this and previous Systems Analysis workshops can be found on the FCTP Workshop and Meeting Proceedings website.[2]

The workshop attendees provided valuable feedback during the workshop, discussing issues openly, engaging in dialogue with colleagues during open and facilitated discussion sessions, and providing detailed feedback on specific issues. More than 260 experts were invited, and more than 60 people attended the panel discussions and breakout groups, representing a diverse mix of stakeholder types and viewpoints. One workshop goal, as determined by DOE and the workshop Planning Team (see below), was to collect feedback from emerging non-LDV market end users, such as stakeholders related to MHE, telecommunications, backup power, and transit agencies. The aim was to identify potential cost-reduction opportunities based on synergies or linkages between these emerging markets and infrastructure needed to support LDV markets.

Though valuable information was received on early hydrogen infrastructure costs in general, the goal of collecting a large amount of feedback from emerging market end users was only partially fulfilled. Figure 1 indicates the percentage of invitees from various stakeholder groups, with 8% of invitees from the end-user group. Of the approximately 60 attendees who participated in both the panels and the breakout groups (additional attendees participated in one or the other), only two were clearly identified as end users (Figure 2). However, several participants in the fuel cell, consultant, and component-supplier groups had direct experience with hydrogen infrastructure systems installed for end users and offered their perspectives on the end-user experience. Another remarkable trend in Figure 2 is the large number of participants from the automotive, national laboratory and partnership stakeholder groups, such as the National Organization for Hydrogen (NOW 2011), the California Fuel Cell Partnership (CaFCP 2011), and the Hawaii Hydrogen Initiative.[3] One interpretation of the high level of participation from these groups is their traditional involvement in infrastructure issues for the LDV market, especially with the recent emphasis by automotive OEMs on the need for additional infrastructure to support near-term and 2015 vehicle rollouts. In Planning Team discussion following the workshop, it was proposed that a future workshop limited to primarily emerging market stakeholders, rather than a more diverse mix of hydrogen and fuel cell stakeholders, would be more successful in collecting detailed feedback on the end-user experience.

The sections below describe the focus of the workshop, the format and approach as conceived by the Planning Team, and feedback received during panel sessions and facilitated breakout groups.

---

[2] See the proceedings website at http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_proceedings.html

[3] See the Hawaii Hydrogen Initiative website at http://www.hydrogen2hawaii.com

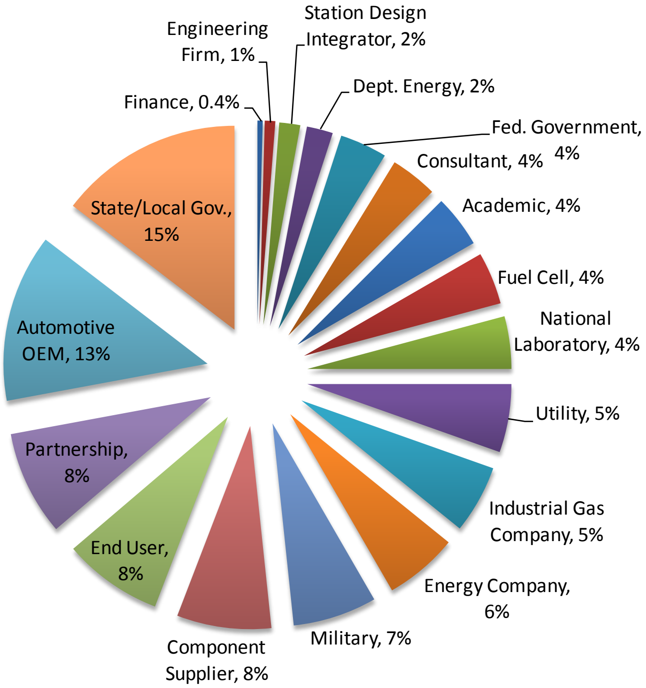


Figure 1. Percentage of workshop invitees by stakeholder type.

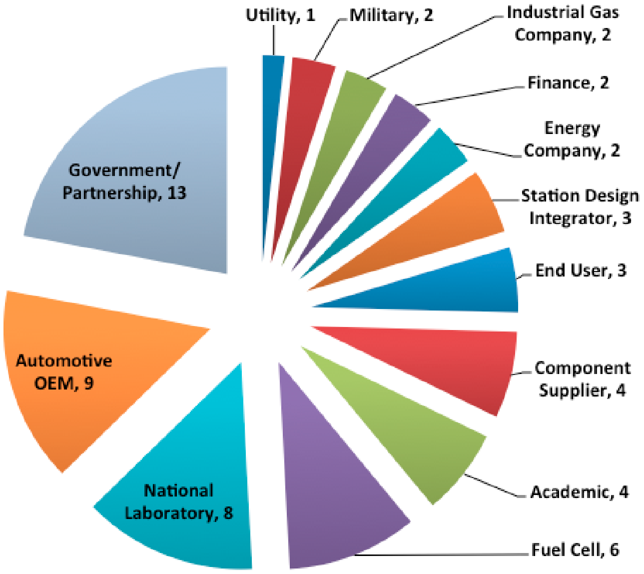


Figure 2. Number of workshop breakout group participants by stakeholder type.

2.1 Workshop Focus, Format, and Approach

The workshop focused on identifying near-term opportunities to reduce the cost of hydrogen fueling stations while increasing hydrogen availability for market readiness. The goal was to collect feedback from key stakeholders (those who have been involved directly in the planning, funding, and installation of hydrogen stations) on the following:

- Cost-reduction opportunities from economies of scale (e.g., station standardization, number and size of installations) and learning-by-doing resulting from growth in MHE, backup power, transit bus, and LDV markets.
- Cost-reduction opportunities from focused R&D areas and related priorities.
- Specific examples through which early markets—such as MHE, backup power, and transit buses—can increase hydrogen demand and reduce infrastructure costs.

This focus was communicated in the workshop invitation sent to invitees, and was reviewed in the opening remarks made by Dr. Sunita Satyapal, manager of the Fuel Cell Technologies Program, on the afternoon of February 16. Dr. Satyapal also reviewed the status of hydrogen and fuel cell technologies (Figure 3), recent ARRA funding supporting companies that previously received DOE R&D funds, and the track record to date for FCEVs, fuel cell buses, backup power units, and MHE units such as forklifts. Following this opening presentation, two panel discussions addressed end-user experiences and forward-looking perspectives on cost-reduction opportunities. Day two began with three overview presentations, which were followed by facilitated breakout groups and then closing remarks and a discussion session. Table 1 shows the agenda. The workshop was planned with input from the Planning Team, which included members from the U.S. Department of Energy, National Renewable Energy Laboratory, California Fuel Cell Partnership, General Motors, Plug Power, Nuvera, and Energetics Incorporated. To increase discussion and feedback during breakout groups, facilitators worked with relatively small groups of participants, with each group having a balance of different stakeholder perspectives. The following sections review feedback received during the panel sessions and breakout groups.

Fuel Cells for Stationary Power, Auxiliary Power, and Specialty Vehicles

The largest markets for fuel cells today are in stationary power, portable power, auxiliary power units, and forklifts.

~75,000 *fuel cells have been shipped worldwide.*

> 15,000 *fuel cells shipped in 2009 (> 40% increase over 2008).*

Fuel cells can be a cost-competitive option for critical-load facilities, backup power, and forklifts.

Production & Delivery of Hydrogen

In the U.S., there are currently:

~9 million metric tons *of H_2 produced annually*

> 1200 miles *of H_2 pipelines*

Source: US DOE 09/2010

Fuel Cells for Transportation

In the U.S., there are currently:

> 200 fuel cell vehicles

~ 20 active fuel cell buses

~ 60 fueling stations

Sept. 2009: Auto manufacturers from around the world signed a letter of understanding supporting fuel cell vehicles in anticipation of widespread commercialization, beginning in 2015.

Figure 3. Current status of hydrogen and fuel cell technologies (Satyapal 2011).

Table 1. Agenda for the Hydrogen Infrastructure Market Readiness Workshop, Gaylord National Hotel, National Harbor, Maryland, February 16-17, 2011

February 16: Infrastructure Developments and Market Readiness Issues	
2:00 – 2:15 PM	*Opening Remarks, Dr. Sunita Satyapal , DOE*
2:15 – 3:15 PM	*Discussion Panel: Early Market End User Experiences* *Moderator: Pete Devlin, U.S. Department of Energy* • Roberto Cordaro, Nuvera • Jamie Levin, AC Transit • Alex Keros, General Motors • Kevin Kelly, Sprint
3:30 – 4:30 PM	*Discussion Panel: Outlook for Infrastructure Cost Reductions* *Moderator: Matt Fronk, Matt Fronk & Associates LLC* • Nikunj Gputa, Shell • Steve Eckhardt, Linde • Joan Ogden, University of California, Davis • Ed Heydorn, Air Products • James Cross, Nuvera
4:45 - 5:00 PM	*Closing Remarks, Fred Joseck, DOE*
February 17: Expert Workshop on Cost Reduction Issues	
8:30 – 8:45 AM	*Welcome Remarks and Hydrogen Cost Overview, Fred Joseck, DOE*
8:45 – 9:30 AM	*Station Costs and Vehicle Deployments* California Station Deployment, Gerhard Achtelik, CARB Early Station Cost Calculator, Marc Melaina, NREL
9:30 – 9:45 AM	*Goals and Agenda for Breakout Groups, Shawna McQueen, Energetics*
10:00 – 12:15 PM	*Breakout Session #1: Cost Reduction Opportunities*
12:15 – 1:15 PM	Lunch
1:15 – 3:30 PM	*Breakout Session #2: Actions Needed to Achieve Cost Reduction Opportunities*
3:45 – 4:15 PM	*Report Back from Breakout Groups*
4:15 – 4:30 PM	*Closing Remarks and Discussion, Fred Joseck, DOE*

2.2 Workshop Results: Panel Discussions

This section summarizes the February 16 panel discussions. The panel moderators, speakers, and key questions proposed to guide each panel discussion are summarized in Table 2. The first panel focused on cost-reduction opportunities and trends associated with end-user experiences in emerging markets, including onsite production for MHE applications, transit buses, LDVs and backup power for telecommunications. The second panel focused on future market barriers and cost projections for the next 2-5 years. Speakers were provided with the discussion questions prior to the discussion, and though moderators modified their questions to follow the flow of the discussion, each panel addressed the general topics shown in Table 2.

Table 2. Panel Discussion Sessions: Day One (February 16, 2011)

Panel 1: Early Market End User Experiences	**Panel 2: Outlook for Infrastructure Cost**
Moderator: *Pete Devlin, U.S. Department of Energy*	***Moderator****: Matt Fronk, Matt Fronk & Associates LLC*
• Roberto Cordaro, Nuvera • Jamie Levin, AC Transit • Alex Keros, General Motors • Kevin Kelly, Sprint	• Nikunj Gputa, Shell • Steve Eckhardt, Linde • Joan Ogden, University of California Davis • Ed Heydorn, Air Products • James Cross, Nuvera
Panel Questions	***Panel Questions***
1. Based upon your experience with recent projects, what are the biggest costs and the biggest cost-reduction opportunities for hydrogen stations? 2. What "hidden" costs emerged in your projects? What unexpected benefits did you achieve? 3. In hindsight, what could you have done to reduce costs incurred during the installation process? For example: contracting, planning, permitting, etc. 4. What government support mechanisms were most effective or would have been most effective in your project?	1. What is the most significant cost driver for hydrogen stations today, and what needs to be done to overcome it? 2. How can improved technology bring down the cost of delivered hydrogen in the next 2-5 years? What's needed to achieve these technology advancements? 3. What are the major institutional or contractual barriers to deploying low-cost production technologies, delivery methods and adequately sized hydrogen stations in the next 2-5 years? 4. What are the major barriers to realizing a business case for hydrogen stations within the next 2-5 years?

Major topics and key points raised during the first panel discussion are summarized and paraphrased below. Actual questions posed by the moderator are reviewed to provide context.

- What are the biggest costs, cost-reduction opportunities, and "hidden" costs that have emerged in your projects?
    - Installation costs are highly variable among stations and can range from 50%-200% of total capital costs.
    - Elimination of unnecessary and excessively conservative design requirements for stations could lead to significant cost savings.
    - Current costs for fuel cell transit buses are 2-3 times higher than diesel bus costs, largely due to O&M costs.
    - Many problems with station installations are due to relatively simple and non-novel components, such as O-rings, nozzles, valves, etc. One panelist described these as "50% of all hassles." The resulting costs are tangible and could be reduced by increasing the number of suppliers that have achieved third-party certification or by improving standardization.
    - Mobile systems can reduce costs associated with smaller fueling stations.
    - High-voltage electricity requirements, which require trenching, can be an unexpected or additional cost.
- In hindsight, what could you have done to reduce installation costs?

    - Permitting can be a significant additional cost, and is often unexpected. Early discussions with fire marshals can lead to significant cost savings later on during the station-installation process.
- Additional comments from open discussion:
    - Increased utilization of hydrogen for LDVs, "every kg," contributes to a stronger business case. Building this business case will require both larger, robust stations on the order of 1,000 kg/day and smaller stations on the order of 100 kg/day.
    - The next step for providing hydrogen to MHE markets is to increase the scale of capacity up to 250 or 500 kg per day.
    - Cell phone towers number in the tens of thousands, and market growth in similar backup power applications has the potential to expand to other stationary markets such as hospitals.

Major topics and key points raised during the second panel discussion are summarized and paraphrased below. Questions posed by the moderator are indicated to provide context.

- What are key cost drivers and opportunities to reduce costs today?
    - Site-preparation costs can be significant, as high as $2 million before equipment is put in place.
    - Total installed hydrogen capacity is not the only measure of progress on hydrogen infrastructure. Coverage and geographic availability is also very important to market success for LDVs.
    - Standardization of station designs and components (compressors, storage, etc.) can lead to significant cost savings. This can also facilitate codes and standards, which leads to cost savings, and reduce costs for component suppliers.
    - Onsite steam methane reforming systems can offer promising cost savings, especially when stations are installed at higher volumes.
    - Cost savings can be achieved at the station network level through better planning, resulting in co-locating cars and new stations in high-priority areas.
    - Scale economies are key to reducing costs. This is especially true with 700 bar pressure systems. Technologies that are high cost today will come down in cost as more stations are installed.
    - Novel station designs that reduce high electricity and O&M costs are promising.
    - There is a need to demonstrate that high-volume stations are viable.
- What are promising options to reduce costs within the next 2-5 years?
    - Increasing the scale of onsite production up to 1,000 kg/day, with improved efficiency, purification, and compressors.
    - Home refueling by way of SMR would be costly and could only be justified if combined with heating and electricity for a building.
    - Onsite SMR systems are the best option today and will be for some time.

  - Low costs are key to market success in 2015; simplified systems and reduced siting costs are needed to achieve cost goals.
  - Higher-pressure delivery trucks will be an important option over the next 2-5 years.
  - Combined heat and power units at the neighborhood scale could prove to be an important option.
  - Stations need to be in place ahead of vehicles so that automotive OEMs are confident, and large stations will be needed to handle large volumes of vehicles when commercialization takes off.
  - Central SMR will be a viable pathway for low-cost hydrogen over the next 2-5 years, but production from multiple sources will also be needed.
- If automakers are guided by regulations, what are fuel providers being guided by?
  - Markets guide infrastructure development; if FCEVs are no-compromise vehicles, they will also require support from a no-compromise infrastructure.
  - Climate change and need for cleaner fuels are significant considerations.
- How quickly could infrastructure be put in place?
  - There is currently excess production capacity to support the LDV sector in the near term.
  - The first 5-6 million FCEVs would require about 4,000 stations at an expense of about $8 billion over approximately 12 years. This cost is small when compared to other energy-sector expenses.[4]
- What is an adequately sized station, and how is station size a barrier to cost reductions?
  - Risk is associated with the balance between geographic coverage and volume. By managing the coverage aspect, the California Energy Commissions AB118 program has removed the volume risk.
- Would fuel providers consider “not being whole” as the auto companies have with vehicles?
  - One provider commented that they are already in that position; they already “have skin in the game.”
  - One means of managing that situation is a longer-term partnership model. This is possible in the United States, especially since there is already an example to follow.
  - Planning can reduce risks, showing the “light at the end of the tunnel.”
- Will investments be easier for owners of multiple or many retail outlets?
  - Business plan needs to exist for small, individual station owners as well. They need a good proposition and will not necessarily put up the capital.

---

[4] This comment was a reference to results from a National Academies of Sciences study (NAS 2004).

    - Lack of a longer-term vision is a significant market barrier. Having a vision in place can increase the number of players (e.g., buses), improving market growth.
- What is the vision for a business case? Who will need help?
    - The perception of risk has increased in recent years but is lower in other parts of the world.
    - The business case is easy: "volume, volume, volume." But the tentative period needs a funding mechanism.
    - After market ramp-up, new stations will reach a business case quickly. It is the legacy stations that will struggle.
    - A transition period could last for 2-5 years; a long-lasting partnership is needed to get through this transition period.
    - Perceived risk is important, and this is challenging in the United States due to the lack of a longer-term commitment. There are three relevant social cost drivers—energy security, climate change, and economic growth—but it is difficult for an individual actor to put an effective cost on these. Having a climate change policy would make this social cost tangible.
    - Having a large, high-volume station in place within the next few years would send a strong signal that the business case is viable and would counter claims by naysayers that the case does not exist; then show how ramp-up can meet demand.
    - Having 25-30 new stations in place and performing would build confidence.

In general, there was significant agreement among panelists on most key points. The end-user experience panel tended to concur that significant cost reductions were possible—from relatively minor modifications in the installation process, sharing of lessons learned, or enhancements to the technology supply base—and did not necessarily require major technology breakthroughs. They also tended to agree that even greater reductions were possible with improved and streamlined station designs and permitting and that increased market growth would lead to additional cost reductions due to economies of scale, standardization, and learning. The second panel covered a more diverse set of topics and tended to offer somewhat more conflicting responses, but they also exhibited general agreement that significant cost reductions were possible within the next 2-5 years. Panelist views diverged on the topics of market forces vs. partnerships and perhaps on the relative importance of large vs. small vs. onsite-production stations. Panelists concurred that the next 2-5 years would be part of a transition period requiring some type of policy support but appeared to agree that with continued market growth a business case would materialize for new stations, given expected cost, market, and technology trends.

2.3 Workshop Results: Overview Presentations and Facilitated Breakout Sessions

Three presentations were given in preparation for the facilitated breakout groups on day two. Each is summarized below, followed by a summary of results from the breakout groups. The full presentations are available on the DOE Fuel Cell Technologies Program website for workshop and meeting proceedings.[5]

Hydrogen and Infrastructure Cost Overview

Fred Joseck, of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy's Fuel Cell Technologies Program (FCTP), gave an overview of the FCTP and progress on reducing hydrogen infrastructure costs. The FCTP is developing infrastructure technologies to achieve efficient and low-cost delivery of hydrogen and has made significant progress in reducing costs for stations with tube trailer, pipeline, and liquid-truck hydrogen delivery. Figure 4 shows and example of this progress, with a 30% reduction in the cost of hydrogen stations with tube trailer delivery between 2005 and 2009, largely due to reduction in the cost of the tube trailer, and a trajectory to meet a $1/gge goal by 2019. Complementing FCTP efforts to accelerate fuel cell deployments, more than $40 million in American Recovery and Reinvestment Act funding has supported 12 projects that seek to deploy up to 1,000 fuel cells in multiple applications, including material handling (forklifts), backup power, auxiliary power, portable power, and combined heat and power for residential and small commercial buildings. Additional government support includes a number of tax credits that promote fuel cell deployment, some of which have been expanded. The Hydrogen Infrastructure Market Readiness Workshop will help the FCTP and others identify important cost drivers for hydrogen supply infrastructure, identify and quantify key cost-reduction opportunities, and identify actions necessary to realize the cost reductions.

---

[5] See the FCTP website at http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_proceedings.html

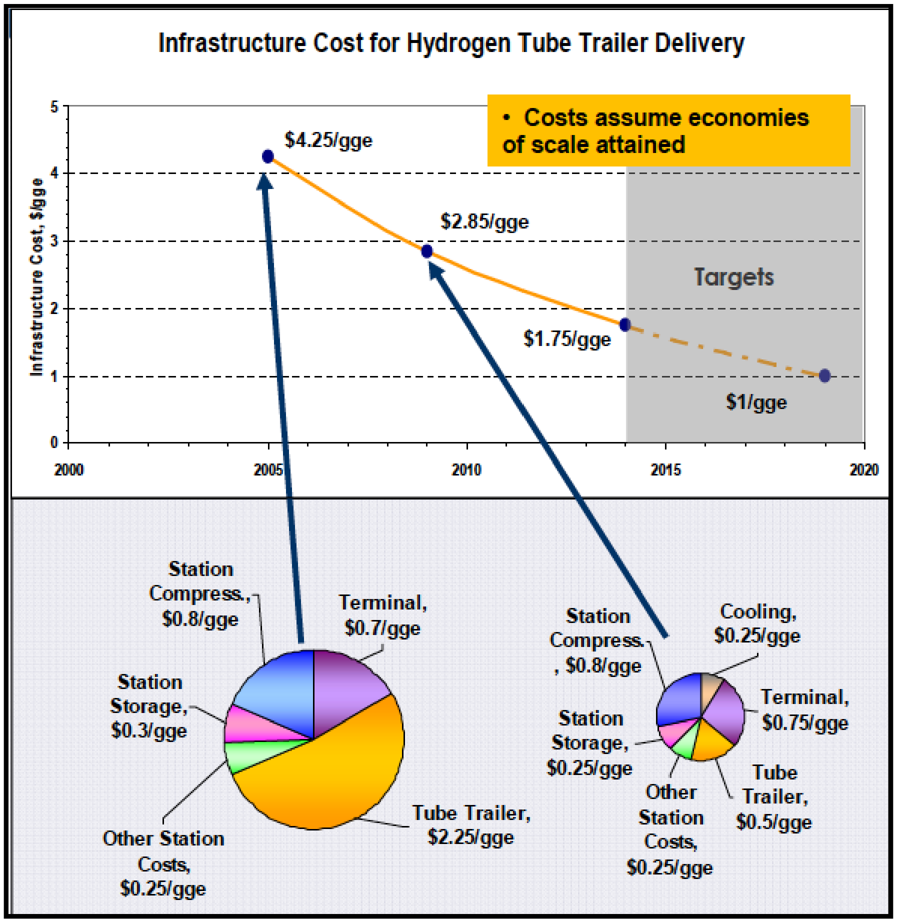


Figure 4. Costs for hydrogen station with tube trailer delivery, based on high-volume delivery. Does not include cost of the hydrogen delivered to the station (Joseck 2011). These costs were developed using an earlier version of the H2A model instead of the new H2A Version 3, which has been updated to a baseline of $2007.

State Experience in Hydrogen Infrastructure in California

Gerhard H. Achtelik Jr. of the California Air Resources Board presented on the status and future of hydrogen infrastructure in California. In southern California, there are currently five public-access and 10 private-access stations in operation, with six more public-access stations under construction and eight stations planned, pending funding (Figure 5). California's approach to introducing hydrogen infrastructure includes first focusing on the major population centers of Los Angeles, the Bay Area, and Sacramento. During this first phase, California seeks to match hydrogen infrastructure to the size of vehicle and bus fleets; meet customer expectations; and provide outreach to permitting officials, first responders, and the public. Solicitation considerations for refueling stations in California include meeting renewable and environmental requirements and operating in a traditional retail manner. An overview of recent awards for hydrogen stations, provided through the California Energy Commission, is provided in Table 3.

Hydrogen Station Cost Calculator

Dr. Marc Melaina, of the Hydrogen Technologies and Systems Center at the National Renewable Energy Laboratory (NREL), discussed NREL's Hydrogen Station Cost Calculator (HSCC), which enables organizations with experience with hydrogen station costs (system integrators and component suppliers) to offer anonymous feedback on current costs, near-term costs, research and development priorities, and economies of scale. The feedback will be used to help government agencies and the hydrogen community better understand the status and potential future trajectory of refueling infrastructure costs and will serve as a reference for updated infrastructure cost models. The presentation reviewed the basic structure of the HSCC and the types of cost elements to be included and requested feedback from workshop participants on the Beta version. HSCC participants will be asked to provide feedback on hydrogen markets and infrastructure costs at four different "levels" of station infrastructure development, reflecting increasing market demand and technological maturity: 1) state-of-the-art (stations deployed in 2011-2012 timeframe), 2) "early commercial," 3) "more stations," and 4) "larger stations." Based on responses to a series of questions about timing, volume, and detailed costs, the "cost calculator" embedded in the spreadsheet will develop a cost ($) per kilogram of hydrogen for each station type, allowing participants to see how their responses affect the cost results. IDC Energy Insights will administer collection of data through the HSCC and compile aggregated, anonymous results.

Table 3. Continued California Energy Commission Awards for New Hydrogen Stations
Additional awards were provided for upgrades for stations at U.C. Irvine, Diamond Bar, and San Francisco International Airport (Achtelik 2011).

Applicant	Location	Award	% Eligible cost share
APCI	N. Irvine	$1.4M	70
APCI	Santa Monica	$1.5M	76
APCI	Beverly Hills	$1.3M	65
APCI	West Los Angeles	$1.3M	65
APCI	Hermosa Beach	$1.5M	76
APCI	Hawthorne	$1.2M	60
Linde	W. Sacramento	$1.9M	76
Linde	Laguna Nigel	$2.0M	76

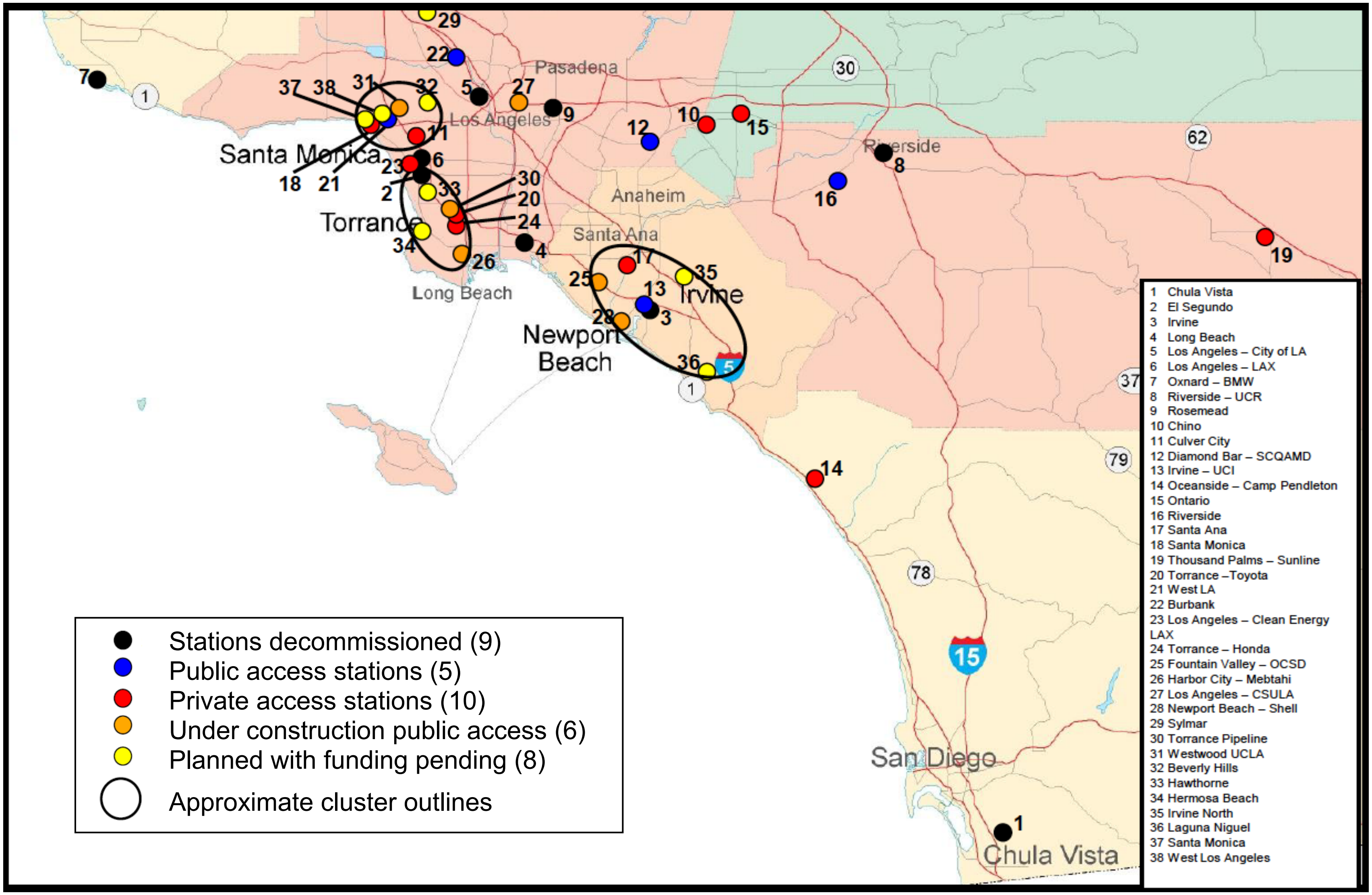


Figure 5. Southern California Hydrogen Highway network historical region/cluster station development (Achtelik 2011).

Facilitated Breakout Sessions

Following the presentations, participants broke into three predetermined groups to discuss cost-reduction opportunities in greater detail. Each facilitated group organized feedback to key discussion questions into categories and then underwent a prioritization voting process after discussing all responses as a group. The following key questions were posed during the facilitated breakout sessions:

1) What are the biggest opportunities to reduce the costs of hydrogen fueling stations over the next 2-5 years?
2) What can we do to achieve the high-priority cost-reduction opportunities?
3) Drill down on high-priority opportunities (identified through a group voting process): Who needs to do what when? What kind of help is needed? Is information sharing or coordination needed?

Appendix A provides detailed feedback collected within each group in response to these and other follow-up questions within the same themes. Colored dots indicate the number of votes each opportunity received when participants prioritized their responses. Breakout groups 1 and 3 did not complete the prioritization of their responses to key question 2 above, while group 2 continued on to outline an action plan responding to the questions: “How, Who, and When?” Table 4 summarizes the high-priority cost-reduction opportunities identified during the panel and breakout group discussions as well as suggested actions or next steps needed to achieve the opportunities, grouped into four main areas: 1) component costs, 2) station designs, 3) permitting processes, and 4) analysis and information sharing. While the summary results were agreed upon as being high priority, these priorities reflect the expertise and backgrounds of the workshop participants; a different set of attendees may have emphasized a different set of priorities. The importance of crosscutting issues may also be obscured. For example, actions on station standardization could cut across multiple topic areas and, therefore, may not be highlighted to the degree justified.

Some participants offered quantitative feedback on achieving cost reductions through economies of scale and learning-by-doing, including the following:

- Modular station design approaches and standardized manufacturing of station components can lead to as much as 50% cost reduction
- More uniform permitting processes could reduce total station costs by 20-30%
- Using validated components could cut O&M equipment costs by 75%

To organize the prioritized cost-reduction opportunities identified during the workshop, each opportunity has been placed in one of the four general categories shown in Figure 6. The vertical axis indicates the number of opportunities proposed within each category, and the horizontal axis is the number of points allocated during the breakout sessions. The point system includes one point for the person proposing the opportunity within a breakout group and two points for each opportunity proposed (and not widely contested) during the panel sessions. Circle sizes are proportional to values for both metrics. Opportunities within the category of Technology are the most numerous and highest priority. Opportunities within the category of Institutional, Financial & Policy are more numerous but lower priority than those in Streamline Permitting/Codes and Standards. Opportunities within the category of Analysis, Planning, and Integration are least numerous and lower priority.

Table 4. High-Priority Cost-Reduction Needs and Suggested Actions

High-Priority Need	Suggested Actions
COMPONENT COSTS	
1. Expand and Enhance Supply Chains for Production of High-Performing, Lower-Cost Parts • Achieve third-party certification (preferably UL) for parts in hydrogen service • Develop specific performance requirements that manufacturers can understand • Incentivize suppliers to produce certified parts for hydrogen service ***Desired Outcome***: Improve the durability and reliability of parts, reduce station operation and maintenance costs, increase the availability of parts, and reduce downtime.	• Generate transparent record of operation and maintenance issues for DOE-sponsored projects • Target components that cause station reliability problems (e.g., O-rings, IR nozzles, high-pressure equipment valves, etc.) • Task an industry association like FCHEA to work with industry players on performance/certification requirements • Provide government support for equipment testing and certification • Provide green job credits to suppliers • Create a "design and build" challenge • Provide information to suppliers on what the demand curves look like
2. Reduce Cost of Hydrogen Compression • Develop high-volume, high-reliability hydrogen compressors • Develop standard targets for compression ***Desired Outcome:*** Lower compressor capital costs and enable more interchangeable components.	• Conduct DOE R&D program on compressor development
3. Develop High-Pressure Hydrogen Delivery and Storage Components • Develop cost-effective high-pressure hydrogen storage technologies • Develop low-cost cooling and dispensing systems for high-pressure service ***Desired Outcome:*** Reduce costs for hydrogen compression, reduce capital and O&M costs for high-pressure equipment, lower system footprint.	• Conduct R&D to develop, test, and validate use of composite tanks for hydrogen storage • Conduct R&D to develop, test, and validate low-cost cooling and dispensing technology • Conduct high-pressure part testing • Facilitate development of codes and standards for high-pressure equipment
STATION DESIGNS	
4. Develop "Standard" Station Designs • Harmonize design requirements for small/medium/large stations • Eliminate overly conservative station design/installation requirements ***Desired Outcome:*** Reduce station design, site preparation, installation, and capital costs by enabling modular station expansion as demand grows, scalable designs for different footprints, and repeatable deployments; increasing manufacturing volume of component parts; and facilitating streamlined permitting processes.	• Create a "design and build" challenge • Encourage station buyers to design RFPs that incentivize standard, scalable designs or networks of stations (rather than one-off, custom-built projects) • Foster state collaboration on solicitations or station design requirements • Test specific components for overly conservative station design specifications (e.g., equipment for leak checking, heat detection)

5. Harmonize/Standardize Dispensing Equipment Specifications ***Desired Outcome:*** Reduce capital and operating costs for hydrogen dispensers and facilitated permitting.	• Task an industry association like FCHEA to work with industry players on standardized designs for hydrogen dispensing equipment ○ Encourage players from different end-use areas (e.g., forklift and LDV fueling) to work together to develop common needs or solutions • Complete and execute the SAE hydrogen filling protocol (SAE J6201)
PERMITTING PROCESSES	
6. Develop “Type Approvals” for Use in Permitting • Develop information to support a “type approval” approach for hydrogen station or component permitting ***Desired Outcome:*** Simplify and streamline the permitting process, to expedite the process and lower associated labor costs for the site/station design, engineering, and permitting process.	• Work with code and standard development organizations (CDOs and SDOs) to consider type approval approaches
7. Improve Information and Training Available to Safety and Code Officials • Develop targeted, plain-language materials for fire marshals and permitting officials • Update language in codes so that it correctly applies to today’s systems and is easily understood and interpreted ***Desired Outcome:*** Reduce the time and cost required for permitting by better informing permitting officials and eliminating problems caused by confusion over interpretation of the codes.	• Work with station developers, CDOs, and SDOs to identify language in codes that is out of date, or commonly misinterpreted and develop plan to update the language. • Develop simple-to-use-and-understand information products with references to codes, including targeted presentations, models, examples, and workshops; distribute information through trade associations and DOE • Obtain letters from EPA and/or DHS approving the use of hydrogen technology in “critical infrastructure” applications • Continue DOE workshops for first responders and code officials
ANALYSIS & INFORMATION SHARING	
8. Develop mechanisms for planning station rollouts and sharing early market information ***Desired Outcome:*** *Achieve cost reductions by providing decision-support tools for multiple interested parties.*	• Conduct planning to develop clustered station-rollout strategies with a 5-10 year outlook. Consider ways to cluster multiple hydrogen users around a single hydrogen generator, with cost sharing of hydrogen production and storage among users. • Create an early-market hydrogen users group. The users group would include webinar series, conferences, and briefings to be posted on a website, codes & standards database, AMR-like exchange of information across industries.

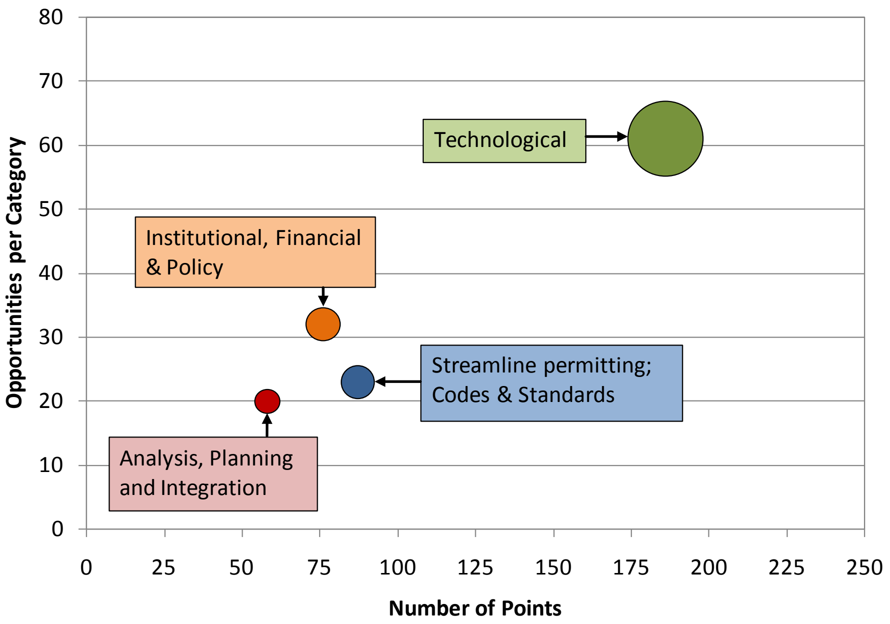
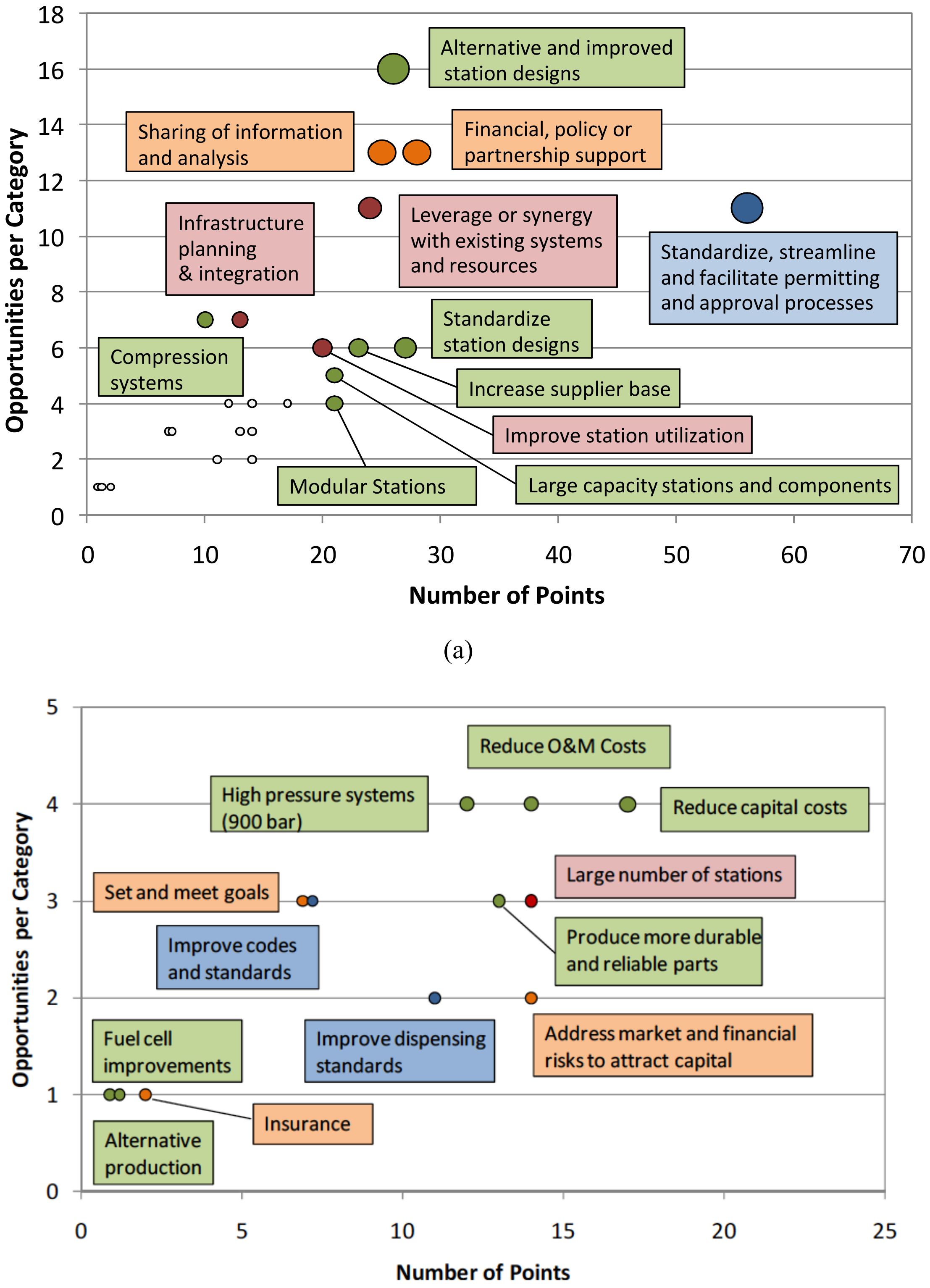


Figure 6. High-level aggregation of cost-reduction opportunities collected from the workshop.

The cost-reduction opportunities identified can be further broken down into subcategories within each of the four high-level categories (Figure 7). This image indicates the diversity of opportunities discussed during the workshop as well as the perceived levels of priority. Figure 7b is a detailed view of opportunities in the lower left-hand corner of Figure 7a. This figure shows that, even though technological cost-reduction opportunities are the most numerous and highest priority as a single category, they consist of a diverse set of distinct opportunities with different priority levels. Some of these opportunities may involve relatively minor technological challenges (e.g., O-rings), while others, such as standardized station designs, would require significant technological innovation as well as contributions from activities in the Institutional or Streamlining categories.

One interpretation of this aggregate view of feedback from the workshop is that technological cost-reduction opportunities represent "low hanging fruit" in terms of effort and payback. However, it should not be concluded that these technological opportunities can be pursued effectively independent of activities or processes that fall within the other categories. Institutional, policy, or code and standards issues may have important influences on technological opportunities. As mentioned previously, many cost-reduction opportunities are crosscutting and difficult to categorize. The most useful interpretation of this aggregate perspective may be simply that multiple types of cost-reduction opportunities exist and that different approaches or action items may be appropriate means of pursuing different opportunities. Follow-up activities worth pursuing, such as future workshops, could be organized around one or more of these main categories, involving participants concentrated within one or more fields of expertise and with distinct workshop goals in terms of anticipated outcomes.



(a)

(b)

Figure 7. Characterization of cost-reduction opportunities by subcategory. Figure (b) shows the subset of opportunities in the lower left-hand corner of Figure (a).

Two recommendations for future workshop topics that follow from this aggregate view of cost-reduction opportunities:

Innovation and Standardization of Station Designs. This topic may encompass a broad range of technological cost-reduction opportunities as well as issues from other categories. Focusing on the crosscutting issues of standardized design could lead to integration of many other technological opportunities, including supplier base, modular designs, large-capacity stations, alternative or novel designs, more durable and reliable parts, reducing O&M costs, and reducing capital costs. The workshop scope could also include topics from codes and standards and the permitting process and may also address (perhaps indirectly) the issue of station network planning.

Streamlining and Facilitating Station Permitting and Approval Processes. This is clearly identified in Figure 7a as a very high-priority cost-reduction opportunity, and it appears to be much more self-contained than the technological opportunities. In contrast to the many valuable and ongoing workshops conducted to address codes and standards issues (see http://www.hydrogenandfuelcellsafety.info), this workshop would be explicitly focused on the goal of reducing costs incurred during the installation process, and accelerating timelines for installation.

In addition, given the perceived value of end-user experiences in emerging non-LDV markets, a third follow-on activity, possibly a workshop, would convene a more select group of end-user stakeholders from the MHE or forklift, backup power, telecommunications, transit bus, and micro-combined heat and power markets to focus on cost-reduction lessons learned. This workshop may also explore leveraging infrastructure supply systems serving these emerging fuel cell markets to support LDV markets as they expand.

3 Feedback from the Hydrogen Station Cost Calculator (HSCC)

As a follow-up activity to the Market Readiness Workshop, the HSCC was developed and used to collect quantitative information on the current and near-term status of hydrogen station costs. An independent third party, IDC Energy Insights (IDC), administered the collection of data from stakeholders using the HSCC. The collection process served as a clean room mechanism; with IDC interfaced with stakeholders and delivered aggregated, anonymous results to NREL after all data were collected. IDC, therefore, played an intermediary role by collecting and interpreting the data, fielding respondents' questions about the HSCC posed by respondents, and clarifying the significance of results to NREL staff. IDC also assisted in the initial design of the HSCC, though the tool has been developed, refined based upon reviewer comments, and ultimately maintained by NREL. The HSCC is based on the same discounted cash flow cost framework and financial assumptions employed in the Production and Delivery H2A models (DOE 2011). Section 3.1 below describes the HSCC and Section 3.2 presents summary results derived from HSCC data.

3.1 HSCC Design and Administration

A conceptual overview of the HSCC was presented at the Market Readiness Workshop on February 17, 2011, and suggestions to revise the tool were received from workshop participants. On March 11, 2011, a review version of the HSCC was circulated to potential respondents, and suggestions for improving the tool were collected (by email) and incorporated into a final version that was circulated on April 11, 2011. Many respondents provided quantitative feedback through the HSCC by the initial target response date of May 13, 2011. However, more than one respondent requested multiple extensions after this date due to both the complexity of the tool and the level of detail at which they had volunteered to provide data. One respondent also identified an isolated error in the HSCC, which NREL staff fixed. IDC worked with NREL staff and HSCC respondents through a data-validation phase extending from September 2011 through February 2012. This process included determination of the level at which itemized station cost data would be reported as well as multiple internal reviews of preliminary results at distinct venues with experts from NREL, DOE, and the CaFCP. In addition, IDC distributed an earlier draft of this report to stakeholders who had provided input using the HSCC. Various issues raised by these reviews were resolved during the data-validation phase. Completing this validation process ensured that meaningful cost data would be reported without jeopardizing the anonymity of HSCC respondents. The first public presentation of HSCC results was given at the DOE Annual Merit Review meeting on May 15, 2012, in Washington, DC.[6] After an additional review by DOE, a draft of this report was distributed by NREL for broader, open review to members of the Workshop Planning Team, key participants in the Market Readiness workshop, and other reviewers.

A key contribution to the study from IDC was the weighting system employed to aggregate data received through the HSCC. Based on discussions with NREL staff about historical developments in the hydrogen station and station sub-component industry, as well as an internal technology-sector assessment, IDC established the weighting system based (primarily) on past cumulative experience with hydrogen delivery and station technology, as well as experience with the station installation process. This system gives greater weight to data provided from stakeholders with more experience with hydrogen stations. Responses to questions A5 and A6 (Table 5) were also considered as inputs to the weighting system. The system enables consistent communication of results at both the total aggregated data level and for specific cost items, while maintaining the anonymity of individual respondents.

The HSCC was designed to allow respondents to provide either very detailed, bottom-up data on individual cost components (such as compressor capital costs, rent or conversion efficiencies) or higher-level, top-down cost data (such as total station capital costs or total annual variable costs). The weighted, aggregated data delivered by IDC to NREL is a mixture of both top-down and bottom-up data, with bottom-up data provided on only a subset of detailed cost items. This subset is necessarily limited due to the quantity and type of feedback received and due to the requirement to maintain the anonymity of HSCC respondents. This limitation clarifies the scope and implications of the results presented below.

The HSCC has three sections:

1. Introduction and preface to questions
2. Hydrogen market and infrastructure cost attributes
3. Effective use of research funds to support hydrogen infrastructure technology RD^3

---

[6] See the presentation at http://www.hydrogen.energy.gov/pdfs/review12/an020_melaina_2012_o.pdf

Questions posed in each section of the HSCC are summarized in Table 5. Appendix B provides screenshots of the HSCC.

In total, 11 respondents provided IDC with feedback using the HSCC. Key results from Section A include respondent type and strategic market interests. The breakdown of respondents by type is shown in Figure 8 and reflects respondents self-identifying their organization's core expertise in response to the question: "Which of the following categories best matches the core expertise of your organization?" No respondents identified their organization's core expertise in the category of "petroleum production, refining or marketing." In addition to core expertise, when given an opportunity to identify one or more markets in which their organization has a strategic interest, seven respondents chose "fuel cell electric or hydrogen ICE vehicles," four chose "hydrogen fuel cell material handling equipment," and six chose "fuel cell electric or hydrogen ICE buses."

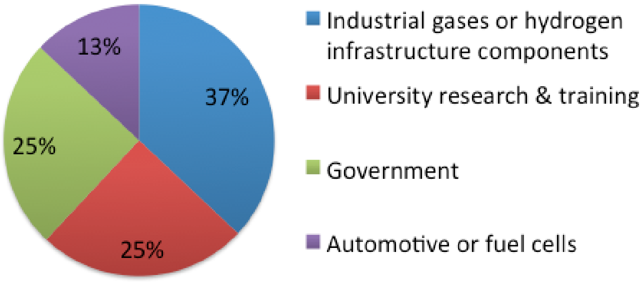


Figure 8. Percentage of Hydrogen Station Cost Calculator respondents by type.

Section B introduces definitions for four distinct types of hydrogen stations:

1) State-of-the-Art (SOTA)
2) Early Commercial (EC)
3) More Stations (MS)
4) Larger Stations (LS)

The definitions of each station type, as provided within the HSCC, are shown in Table 6. NREL developed these definitions with input from multiple stakeholders, including various Market Readiness Workshop participants and DOE representatives. The first station type, SOTA, is limited to stations installed and operational within the 2011-2012 timeframe. The EC station type has a more subjective and forward-looking definition: "financially viable with little government support," "sized to meet growing demand in a promising market region," and having a station design that "enables cost reductions because it is replicable." The remaining two station types are variations on the EC station type. MS stations are identical to EC stations but produced in larger numbers, and LS stations are also identical to EC stations but designed at a larger station capacity (measured in kg of hydrogen per day).

Due to the design of the HSCC, the high-level cost results presented below are generic with regard to station design and configuration, encompassing gaseous truck delivery, liquid truck delivery, onsite SMR or electrolysis production, and pipeline stations. In addition, one design constraint of the HSCC is that MS and LS station types are forced to be the same type as the EC station type. This design constraint was one of several design tradeoffs between greater complexity and flexibility and the need to pose more targeted questions to highlight the influences of volume (number of stations) and station size on costs. Therefore, the cost results are interpreted as corresponding to expected station sizes and deployment years rather than particular station designs; they represent an aggregate mixture of station types expected to be deployed by respondents. That said, the HSCC results suggest that liquid hydrogen delivery stations represent the majority of responses for EC, MS, and LS station types.

Section C allows respondents to prioritize how they would allocate funds towards different RD^3 activities associated with hydrogen delivery and station technologies. A matrix of options was presented (see Appendix B), and respondents were given 100 points to distribute across cells within the matrix. Respondents were notified when all 100 points were allocated, and they were allowed an opportunity to provide text comments to accompany or qualify their responses.

Results from Section A of the HSCC have been reviewed above. The following section reviews feedback from Sections B and C.

3.2 Summary of Results from the HSCC

As show in Table 5, four key questions from Section B inquire about the following:

1) The year in which EC stations are anticipated to be installed
2) The anticipated capacity of these stations (in kg per day)
3) The anticipated average utilization rate of these stations over their lifetime
4) Total capital and operating costs associated with each station type

Aggregate results from all respondents for each of these questions are summarized in Table 7. This table indicates the following unique quantitative profile for early commercial hydrogen stations, representative of the weighted, aggregate results of all HSCC respondents:

> ***Early Commercial*** **stations will be installed in the 2014-2016 timeframe, with a nominal capacity of 450 kg/day, a lifetime average utilization rate of 74%, and a total capital cost of $2.8 million.**[7]

Another significant result in Table 7 is the total reduction in capital costs across station types, which can be compared in a simplified manner on a per-capacity basis ($ per kg/day). As shown at the bottom of Table 7, HSCC results suggests that EC stations would be 62% less capital intensive per capacity than SOTA stations and that MS and LS stations would be 69% and 80% less capital intensive per capacity than SOTA stations, respectively. This reduction in capital intensity does include learning-by-doing and economies of scale, and provides a first approximation of general capital cost reductions anticipated for early market hydrogen stations.

---

[7] Of all HSCC respondents, 73% reported EC station installations anticipated in the 2014-2016 timeframe. The original aggregate, weighted EC station size from IDC Energy Insights was 430 kg/day before scaling to the nominal capacity of 450 kg/day.

Table 5. Summary of Questions Included in the HSCC

Section A. Introduction and preface to questions

A1. Which of the following categories best matches the core expertise of your organization?
Note: To maintain anonymity, responses to this question will not be reported if fewer than 3 responses are received within each category. Responses in the "other" category can be fewer than 3, and will be reported as "other."

A2. In which of the following hydrogen markets does your organization have a strategic interest? (choose all that apply)

A3. Which of the following best characterize your organization's expertise in relation to hydrogen infrastructure development?

A4. Which of the following best describes your job responsibilities within your organization?

A5. How many hydrogen fueling installations has your organization helped to develop over the past 10 years?
Note: to maintain anonymity, responses to this question will not be reported by organization "type" (organization types are identified in question A1).

A6. How many hydrogen fueling installations has your organization led over the past 10 years? Please do not include stations where your organization has partnered but has not been familiar with the technical and financial details. Note: to maintain anonymity, responses to this question will not be reported by organization "type" (organization types are identified in question A1).

Section B. Hydrogen market and infrastructure cost attributes

B1. When does your organization anticipate that hydrogen stations could begin to be installed that meet the attributes for Early Commercial hydrogen stations?

B2. What would be the nominal capacity of these hydrogen stations? Notes: 1) the next question inquires about the utilization rate, and 2) More Stations are by definition the same nominal capacity as Early Commercial stations.

B3. What would be the average utilization rate of these early commercial stations over their lifetime?
(For example, a 1000 kg/day station with a utilization rate of 70% would produce or dispense on average 700 kg/day)

B4. What is the most likely configuration of these hydrogen stations? Note: More Stations and Larger Stations are by definition the same configuration as Early Commercial stations.

B5. How many cumulative stations will be installed of each type for which years?

B6. What metrics describe the performance and market requirements for these stations? Note: these questions are informational only and do not influence the cost calculations.

B7. CAPITAL COSTS. What would be the cost of the following major capital cost components?

B8. What would be the cost of the following fixed operating costs?

B9. What would be the cost of the following variable operating costs?

B10. The following financial parameters are H2A default values.
Please change any of the following financial parameters to best reflect assumptions that should be used to calculate the delivered cost of hydrogen ($/gge) for each station type.

Section C. Effective use of research funds to support hydrogen infrastructure technology R&D
The matrix shown below categorizes different hydrogen infrastructure technology R&D options by pathway component and stage of innovation and commercialization. Given your understanding of the technology advances required to meet the cost per kg, market acceptance, and public policy goals needed for successful hydrogen infrastructure rollout, where do you see the most effective use of research funds over the next 1-3 years for each category indicated? You have 100 points to allocate among the various categories. Comment boxes are provided for additional recommendations on the topic of hydrogen infrastructure technology research and development.

Figure 9 plots the total station capital costs from Table 7 as a function of nominal station size and therefore gives some indication of cost reductions associated with increased station size for stations built after 2016. A power function fitting the EC, MS and LS stations provides a relatively consistent representation of the cost trend, but the 160 kg/day SOTA station does not scale with the other three estimates. This suggests a discontinuity, as might be expected, between the cost factors underlying SOTA stations and those influencing EC, MS, and LS station sizes. While some cost reductions between EC stations and MS and LS stations are due to experience and learning-by-doing, as is apparent from feedback on the timelines for installing numbers of stations over time (see question B5 in Table 5), the equation indicated by the solid black line is generally representative of the scaling implied by the EC, MS, and LS station costs reported in Table 7. This correlation was used to derive the nominal station sizes in Table 7 based on results originally received from IDC. Note that though EC and MS stations were defined as being identical in size, the resulting MS capacity is larger after applying the weighting factors.

Additional cost results from the HSCC are provided in Table 8 and Table 9. One result of providing respondents with multiple levels of detail to provide cost data is that some respondents provided detailed cost data for specific items and others did not. In terms of aggregating final results, this heterogeneous data results in specific costs being relevant for certain station sizes, rather than the aggregate HSCC nominal sizes. The cost data in Table 8 and Table 9 therefore represent the weighted, aggregate results from a particular subset of all HSCC respondents. Moreover, these values have been scaled to the nominal station sizes reported in Table 7. As shown, a sufficient number of respondents provided detailed information to allow IDC to report aggregate results for the three types of indirect capital costs: project contingency, site preparation and upfront permitting costs. For annual operating costs, detailed data were reported for total fixed costs, and then for rent and maintenance and repair costs, as shown in Figure 10.

Table 6. Station Definitions from the Hydrogen Station Cost Calculator (HSCC)

1. State-of-the-Art Stations (SOTA). Newly installed hydrogen stations with the following attributes:

- The stations would be installed and operational within the 2011-2012 timeframe.
- The stations would include the most recent generations of major components, but would not necessarily include novel or "demonstration" components that have not been previously tested in the field.
- The stations would be sized to meet hydrogen demands in a geographic region with promising future market demand.

2. Early Commercial Stations (EC). Based upon your organization's understanding of the growth in demand for hydrogen in the near future (next 5-20 years from the fuel cell electric vehicle, transit bus and material handling equipment markets), consider hydrogen stations to be "Early Commercial" stations if they have the following attributes:

- The stations are financially viable with little government support. Based on financial criteria, such as ROI, and requiring far less financial support or subsidy than the average support offered to all previous hydrogen stations in the same area or region (70-90% less). Disregard ongoing support offered to all types of alternative or low carbon fuels, such as a LCFS, alternative fuel credits, or carbon credits.
- The stations are sized to support growing demand in a promising market region and to ensure adequate ROI. This size could vary from station to station and neighborhood to neighborhood, but consider what might be a typical size for new Early Commercial stations.
- The station design enables cost reductions because it is replicable. The same station design may be used for other stations, reducing the cost of subsequent stations through standardization and economies of production.

3. More Stations (MS). Identical to Early Commercial stations, but deployed in larger numbers. Default value is 10 times more stations being deployed than anticipated in the time period identified for Early Commercial stations. Additional cost reductions are achieved through standardization, mass production, streamlining of installation processes, and learning by doing.

4. Larger Stations (LS). Identical to Early Commercial stations, but designed for higher volume output. The number deployed is assumed to be similar to Early Commercial stations, but growth in market demand warrants larger station sizes. Default value is a 1.5 increase in size over the Early Commercial stations, with 2,000 kg/day as an upper limit.

Table 7. Summary Results by Station Type

Station Attribute	Units	Station Type			
		State-of-the-Art	Early Commercial	More Stations	Larger Stations
Introduction timeframe	years	2011-2012	2014-2016	after 2016	after 2016
Capacity	kg/day	160	450	600	1,500
Utilization	%	57%	74%	76%	80%
Average output	kg/day	91	333	456	1,200
Total Capital	\$M	\$2.65	\$2.80	\$3.09	\$5.05
Capital Cost per capacity	\$1000 per kg/d	\$16.57	\$6.22	\$5.15	\$3.37
reduction from SOTA	%	na	62%	69%	80%

Notes: These results reflect the weighting factors applied by IDC, and some respondents did not complete HSCC sections for all station types.

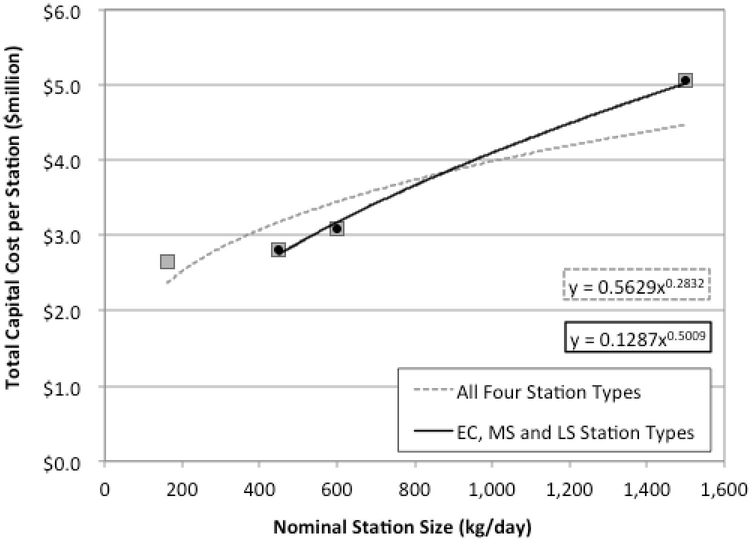


Figure 9. Total station capital costs as power functions. The curve fit to the EC, MS and LS station types is more representative than the fit to all four types.

When providing input data to the HSCC, respondents received feedback on the implications of their inputs for the cost of hydrogen. This feedback was provided through a "calculate" button at the bottom of the HSCC, which reports the levelized cost of hydrogen on a per-gge basis for each of the four station types. Respondents are directed to review these cost-per-gge results, which are shown for four types of costs (capital, fixed, variable, and other), and to revise their inputs if the values are not consistent with their expected cost-per-gge estimates. While respondents were given the opportunity to alter the financial variables used to calculate the cost-per-gge values, default H2A financial assumptions, few chose to change these assumptions. The resulting weighted, aggregate cost of hydrogen results from the HSCC for retail stations are shown by cost category and station type in Figure 11. As indicated, hydrogen costs for EC stations are anticipated to be $5.90 per gge and are anticipated to decline by 19% to $4.76 per gge when EC stations are installed in larger numbers (MS Station results). As the EC stations are designed for larger capacities, an additional reduction of 27% is anticipated, resulting in a hydrogen cost of $3.49 per gge. These costs do not include variable costs, such as electricity for compression or the cost of hydrogen delivered to stations, but do include upstream capital costs directly associated with the retail stations. The number of FCEVs supported is based upon weighted, aggregate responses to the number of stations required by type, assuming 70% utilization.

Table 8. Itemized Indirect Capital and Annual Operating Costs per Station

		Station Type and Capacity			
Cost Item	**Units**	**State-of-the-Art**	**Early Commercial**	**More Stations**	**Larger Stations**
		160 kg/day	450 kg/day	600 kg/day	1,500 kg/day
Depreciable Indirect Capital Costs					
Select cost items					
Project Contingency	$/stn	$72,100	$29,100	$34,700	$60,900
Site Preparation	$/stn	$424,000	$468,000	$504,000	$640,000
Upfront Permitting Costs	$/stn	$43,500	$11,300	$12,400	$16,900
Annual Operating Costs					
Select cost items					
Total Fixed Costs	$/year/stn	$202,000	$180,000	$187,000	$214,000
Rent	$/year/stn	$39,900	$36,900	$40,700	$55,600
Maintenance & repairs	$/year/stn	$33,600	$37,000	$41,400	$59,200

Notes: Costs have been rounded. Annual operating costs are based upon the scaling factors indicated in Figure 11.

Table 9. Itemized Indirect Capital and Annual Operating Costs by Station Type and per Capacity

		Station Type and Capacity			
Cost Item	**Units**	**State-of-the-Art**	**Early Commercial**	**More Stations**	**Larger Stations**
		160 kg/day	450 kg/day	600 kg/day	1,500 kg/day
Depreciable Indirect Capital Costs					
Select cost items					
Project Contingency	$ per kg/d	$451	$65	$58	$41
Site Preparation	$ per kg/d	$2,650	$1,039	$840	$427
Upfront Permitting Costs	$ per kg/d	$272	$25	$21	$11
Annual Operating Costs					
Select cost items					
Total Fixed	$/(yr-kg/d)	$1,263	$399	$312	$143
Rent	$/(yr-kg/d)	$250	$82	$68	$37
Maintenance & repairs	$/(yr-kg/d)	$210	$82	$69	$39

Notes: Total Fixed Annual Operating costs include rent, maintenance and repairs, labor costs, and other annual operating costs that could not be itemized due to limited data. Fixed Annual Operating costs do not include the cost of hydrogen delivered to the station.

The $3.49 per gge result for LS stations is an aggregate, weighted result from all HSCC responses for the LS station cost type. Unfortunately, sufficient data were not available to allow for a breakdown or comparison of variable and fixed operating costs among respondents and station types. As a result, the degree to which these cost estimates rely upon either low feedstock processes or higher conversion efficiencies cannot be determined. The data therefore do not allow for direct, detailed comparisons to other estimates of future hydrogen costs. They should be considered standalone estimates unique to HSCC respondent expectations of future cost-reduction opportunities.

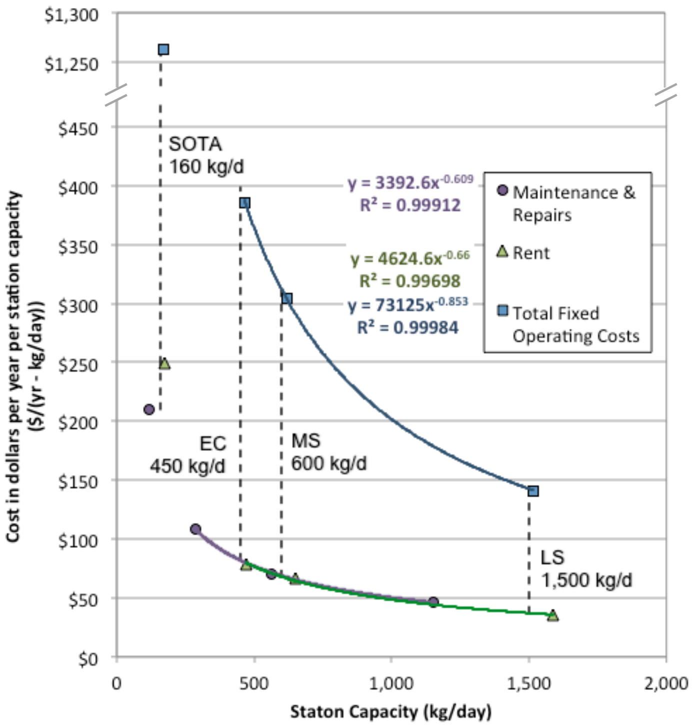


Figure 10. Parametric representation of annual operating costs. Capacities indicated for the four stations types: State-of-the-Art (SOTA), Early Commercial (EC), More Stations (MS) and Larger Stations (LS). Functions for Rent and Maintenance & Repair overlap in the figure and are nearly identical. Fixed operating costs for SOTA stations are higher than the scale shown.

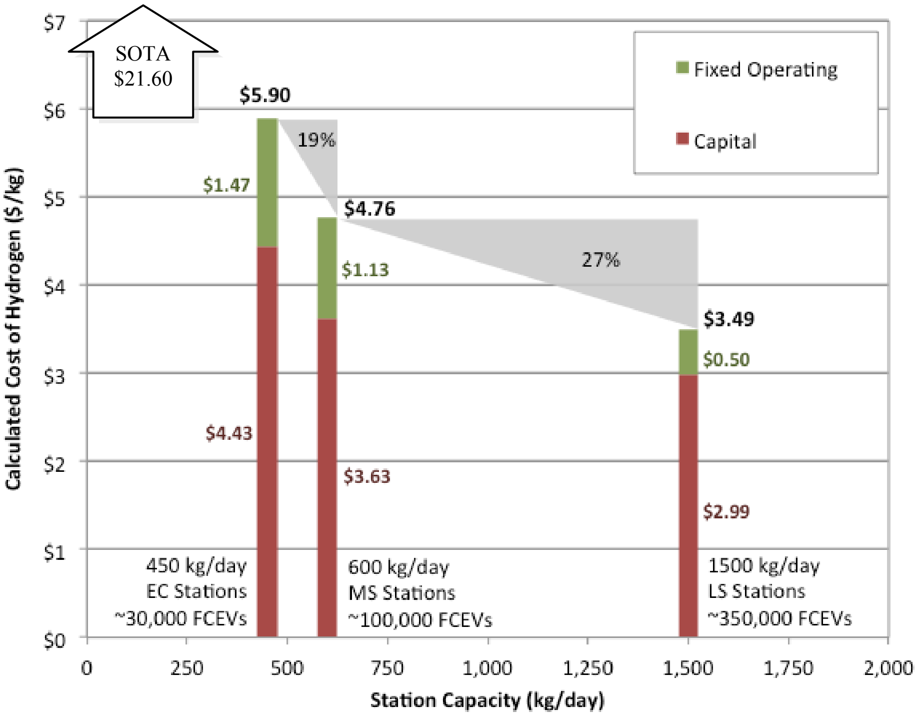


Figure 11. Fixed operating and capital costs by hydrogen station type, capacity and approximate level of nationwide FCEV deployment.

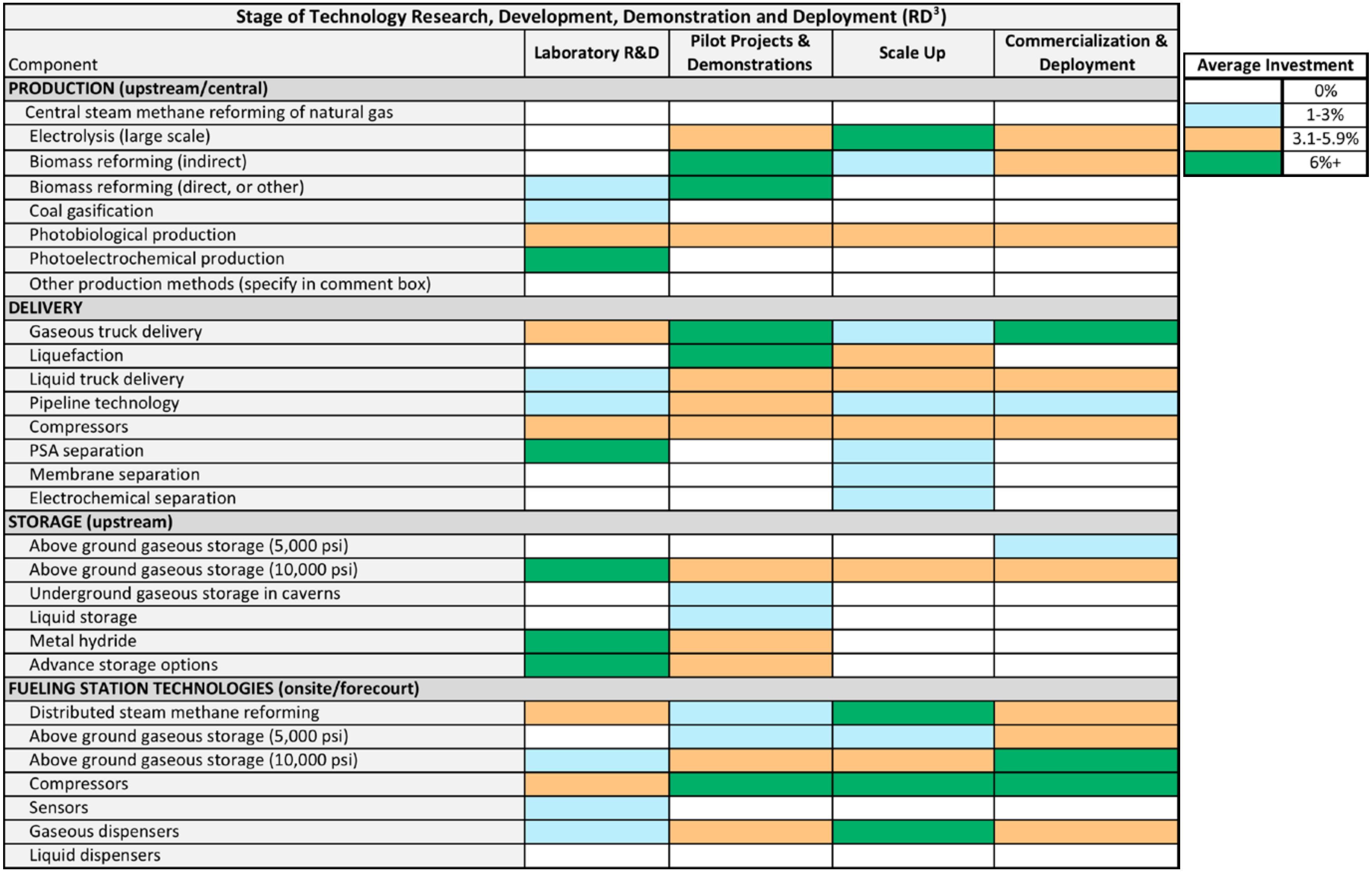
3.3 Research, Development, Demonstration and Deployment (RD^3) priorities

Within the HSCC, a matrix of RD^3 topics was presented, and respondents were allowed to prioritize these topics (see Section C of the HSCC, in Appendix B.). Results from this section of the HSCC, which were not weighted using the same system as costs, are indicated by color-coding in Figure 13 to indicate the total points allocated by respondents to each RD^3 item. It is apparent from these results that a wide breadth of topics were identified as priority items across multiple RD^3 phases. An important obersvation from IDC is that no item received more than 10% of total investment points allocated by all respondents, so respondents tended to prioritize a relatively broad portfolio of RD^3 options. Items shown in dark green received more than 6% of all investment points, and some of these also had responses from more than three respondents: scale-up of electrolysis systems, pilot and demonstration projects for biomass reforming, commercialization and deployment of gaseous delivery trucks, commercializaton and deployment of above-ground high-pressure storage (10,000 psi) at stations, and pilot, demonstration, and scale-up of station compressors. Items that received a larger number of total investment points (greater than 6%) but also had a smaller number of responses tended to be in the Laboratory R&D category. These included photoelectrochemical production, PSA separation, and upstream storage applications for aboveground 10,000 psi, hydride and advanced storage options. In addition to these trends, there was a greater emphasis on earlier RD^3 phases for storage items and later RD^3 phases for delivery and station items.

3.4 Limitations and Interpretation of HSCC Results

The results presented in Section 3.2 are weighted, aggregate representations of the data provided to IDC Energy Insights from the 11 stakeholders who responded to distribution of the HSCC. An important caveat to accompany the costs reported here is that the HSCC was only designed to collect some of the information that must be taken into account to project the future cost of hydrogen from early stations. Though the HSCC has collected key stakeholder data on cost estimates, other factors that may influence costs are beyond its scope. These include the following factors:

1. **Station size and age distribution**. The HSCC data provide cost estimates for stations of different sizes, but how rapidly larger stations become the dominant source of most hydrogen supplied in any given urban area is an issue that must be addressed with additional analysis. As larger and potentially more appealing stations are installed in a given network, costs must still be covered at the smaller stations. In addition, HSCC results suggest that earlier stations will cost more, but costs for these older stations must also be covered by revenue from hydrogen fuel sales as newer and larger stations are installed. Both of these effects can be captured in a dynamic model that explicitly tracks size and age distributions across the evolution of a station network.



	Stage of Technology Research, Development, Demonstration and Deployment (RD^3)			
Component	Laboratory R&D	Pilot Projects & Demonstrations	Scale Up	Commercialization & Deployment
PRODUCTION (upstream/central)				
Central steam methane reforming of natural gas	⬜	⬜	⬜	⬜
Electrolysis (large scale)	⬜	🟧	🟩	🟧
Biomass reforming (indirect)	⬜	🟩	🟦	🟧
Biomass reforming (direct, or other)	🟦	🟩	⬜	⬜
Coal gasification	🟦	⬜	⬜	⬜
Photobiological production	🟧	🟧	🟧	🟧
Photoelectrochemical production	🟩	⬜	⬜	⬜
Other production methods (specify in comment box)	⬜	⬜	⬜	⬜
DELIVERY				
Gaseous truck delivery	🟧	🟩	🟦	🟩
Liquefaction	⬜	🟩	🟧	⬜
Liquid truck delivery	🟦	🟧	🟧	🟧
Pipeline technology	🟦	🟧	🟦	🟦
Compressors	🟧	🟧	🟧	🟧
PSA separation	🟩	⬜	🟦	⬜
Membrane separation	⬜	⬜	🟦	⬜
Electrochemical separation	⬜	⬜	🟦	⬜
STORAGE (upstream)				
Above ground gaseous storage (5,000 psi)	⬜	⬜	⬜	🟦
Above ground gaseous storage (10,000 psi)	🟩	🟧	🟧	🟧
Underground gaseous storage in caverns	⬜	🟦	⬜	⬜
Liquid storage	⬜	🟦	⬜	⬜
Metal hydride	🟩	🟧	⬜	⬜
Advance storage options	🟩	🟧	⬜	⬜
FUELING STATION TECHNOLOGIES (onsite/forecourt)				
Distributed steam methane reforming	🟧	🟦	🟩	🟧
Above ground gaseous storage (5,000 psi)	⬜	🟦	🟦	🟧
Above ground gaseous storage (10,000 psi)	🟦	🟧	🟧	🟩
Compressors	🟧	🟩	🟩	🟩
Sensors	🟦	⬜	⬜	⬜
Gaseous dispensers	🟦	🟧	🟩	🟧
Liquid dispensers	⬜	⬜	⬜	⬜

Average Investment	
⬜	0%
🟦	1-3%
🟧	3.1-5.9%
🟩	6%+

Figure 12. Research, development, demonstration and deployment (RD^3) responses coded for interest level by share of total investment. Note that there was a broad dispersion of interest in research focus, and no single area received greater than 10% of funding in this exercise.

2. **Underutilization**. Respondents to the HSCC provided an average utilization rate over the life of a station. These utilization rates reflect a lower rate for SOTA stations (57%) than for EC (74%), MS (76%), or LS (80%) stations. However, as a network of stations expands over time to provide coverage to a given urban area, it is probable that the average utilization across all stations will remain well below these ideal rates. Eventually, average utilization rates will level out as supply and demand approach a steady state, but understanding how quickly this may happen and how it may vary between stations requires additional analysis. The economics of retail hydrogen dispensing during early ramp-up periods are critical to understanding market entry criteria for early station owners and investors, such as return on investment. In addition, connector stations linking urban areas may face other unique underutilization dynamics during the early market development phase.

3. **Unanticipated site-preparation costs**. Given how the HSCC solicited responses, it is likely that data provided on site-preparation costs were based on an ideal conceptualization of adequate locations for new hydrogen fueling stations. Within a broader systems context, higher site-preparation costs may be incurred for some stations in order to satisfy demands for station coverage made by automakers (or funding agencies), and potential competition for prime locations may also drive up site-preparation costs. This issue requires additional inquiry and analysis but is likely to add to the average cost of hydrogen in a given urban area.

4 Summary and Recommendations

The two parts of this report include the proceedings from the Hydrogen Infrastructure Market Readiness workshop and an overview of results collected through the HSCC. Both activities are described briefly below, followed by recommendations to the U.S. Department of Energy that follow directly from the feedback received through each activity.

The Market Readiness workshop was held on February 16-17, 2011, at the Gaylord National Hotel in National Harbor, Maryland. More than 60 attendees participated in panel discussions on the first day and breakout groups on the second day. The focus of the workshop was to collect feedback from attendees—who were invited based on their direct expert experience with the planning, funding, and installation of hydrogen stations—on the following:

- Cost-reduction opportunities from economies of scale (e.g., station standardization, number and size of installations) and learning-by-doing resulting from growth in MHE, backup power, transit bus, and LDV markets.
- Cost-reduction opportunities from focused R&D areas and related priorities.
- Specific examples through which early markets—such as MHE, backup power, and transit buses—can provide increased hydrogen demand and reduce infrastructure costs.

Recommendations from the Market Readiness Workshop have been categorized into two types: 1) recommendations to achieve station cost reductions, and 2) recommendations for follow-up activities to better understand high-priority cost-reduction opportunities. The list below shows eight station cost reduction opportunities, within four topical groups, synthesized from all feedback collected during the workshop (detailed action items and desired outcomes are reviewed in Table 4):

REDUCE STATION COMPONENT COSTS

1. Expand and enhance supply chains for production of high-performing, lower-cost parts
2. Reduce cost of hydrogen compression
3. Develop high-pressure hydrogen delivery and storage components

STATION DESIGNS

4. Develop "standard" station designs
5. Harmonize/standardize dispensing equipment specifications

PERMITTING PROCESS

6. Develop "type approvals" for use in permitting
7. Improve information and training available to safety and code officials

ANALYSIS AND INFORMATION SHARING

8. Develop mechanisms for planning station rollouts and sharing early market information

Three breakout group participants discussed opportunities and then voted on the highest priority opportunities. The results were collected into four categories, which are summarized in Figure 13, with opportunities included in the Technological category being, as a category, both the most numerous (vertical axis) and the highest-priority items (horizontal axis). A more detailed view of these opportunities reveals diversity within the Technological group, as well as interconnections between each of the four groups.

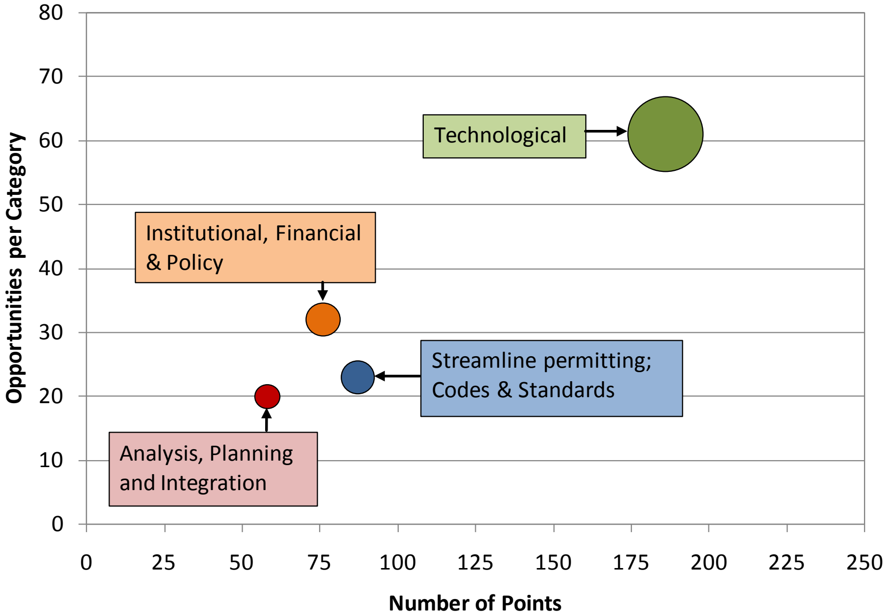


Figure 13. High-level aggregation of cost reduction opportunities collected from the workshop.

Considering a high-level perspective on all feedback received, as well as both the full list of recommendations (Appendix A) and the composition of the stakeholder types (Figure 2), three recommendations for follow-up workshop topics become apparent:

1. **Innovation and Standardization of Station Designs.** Focusing on the crosscutting issues of standardized design could lead to integration of many other technological opportunities, including supplier base, modular designs, large-capacity stations, alternative or novel designs, more durable and reliable parts, reducing O&M costs, and reducing capital costs.
2. **Streamlining and Facilitating Station Permitting and Approval Processes.** This workshop would be explicitly focused on the goal of reducing costs incurred during the installation process, as well as accelerating timelines for installation.
3. **Focus on the End-User Experience.** This workshop would convene a more select group of end-user stakeholders from the MHE, backup power, telecommunications, transit bus and micro-combined heat and power markets to focus on cost-reduction lessons from their experiences. This workshop may also be an appropriate venue to pursue the possibility of leveraging infrastructure supply systems serving these emerging fuel cell markets to also support LDV markets as they expand.

The feedback collected from the Market Readiness Workshop is primarily descriptive and qualitative. In contrast, feedback received through the HSCC is quantitative and focuses on cost associated with four hydrogen station types (defined in Table 6):

1) State-of-the-Art (SOTA)

2) Early Commercial (EC)

3) More Stations (MS)

4) Larger Stations (LS)

One of the key results from the HSCC is a weighted, aggregate, and quantitative description of the EC station type:

> ***Early Commercial*** **stations, as defined in Table 6, are expected to be installed in the 2014-2016 timeframe, with a nominal capacity of 450 kg/day, a lifetime average utilization rate of 74%, and a total capital cost of $2.8 million.**

Another significant result is the total reduction in capital across station types, which can be compared in a simplified manner on a per-capacity basis ($ per kg/day). As shown at the bottom of Table 10, HSCC results suggest that EC stations would be 62% less capital intensive per capacity than SOTA stations, and that MS and LS stations would be 69% and 80% less capital intensive per capacity than SOTA stations, respectively. This comparison of capital intensity does not explicitly distinguish between learning-by-doing or economies of scale, but it does give a first approximation of general capital cost reductions anticipated for early market hydrogen stations.

Table 10. Summary Results by Station Type

Station Attribute	Units	Station Type			
		State-of-the-Art	Early Commercial	More Stations	Larger Stations
Introduction timeframe	years	2011-2012	2014-2016	after 2016	after 2016
Capacity	kg/day	160	450	600	1,500
Utilization	%	57%	74%	76%	80%
Average output	kg/day	91	333	456	1,200
Total Capital	$M	$2.65	$2.80	$3.09	$5.05
Capital Cost per capacity	$1000 per kg/d	$16.57	$6.22	$5.15	$3.37
reduction from SOTA	%	na	62%	69%	80%

The HSCC also generates a levelized cost of hydrogen ($/gge) for each station type based on stakeholder inputs, utilizing the discounted cash flow framework and default financial assumptions from the H2A model (DOE 2011). These cost of hydrogen results are summarized in Figure 14 for two types of costs (fixed operating and capital costs) in $/gge as a function of the capacity of each station type. The 19% reduction from EC to MS stations would be associated with producing a larger number of stations, while the 27% reduction from MS to LS station types would be associated with economies of scale. Some cost reductions associated with learning and experience would also be included

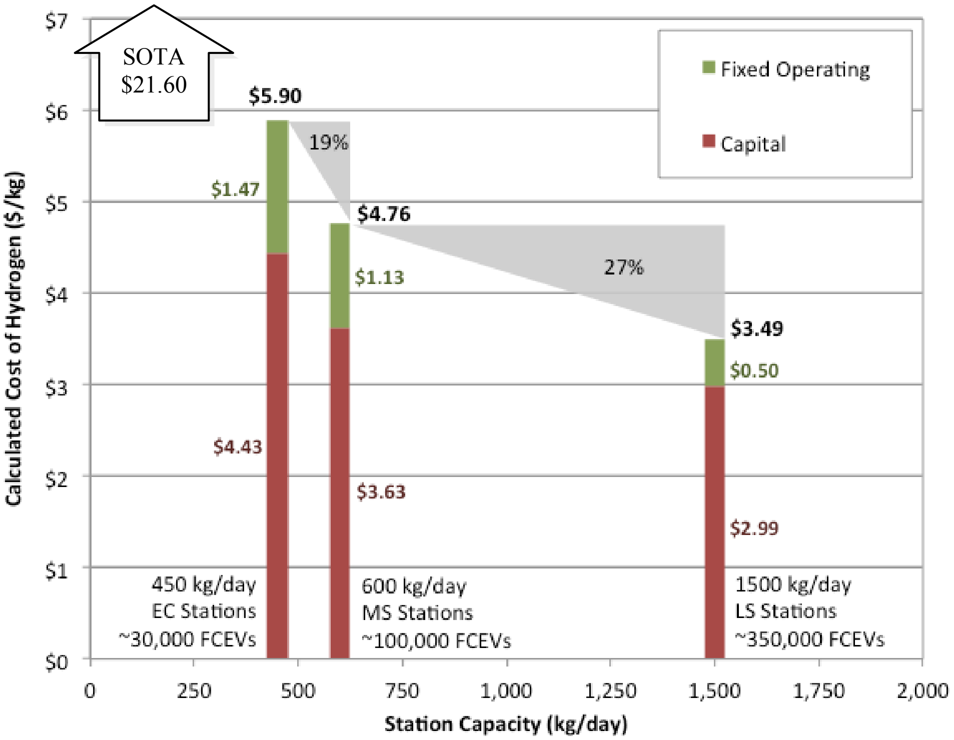


Figure 14. Fixed operating and capital costs by hydrogen station type, capacity and approximate level of nationwide FCEV deployment. The results are generic for a mix of station types expected for early markets, and variable costs would depend on station type (SOTA: State-of-the-Art; EC: Early Commercial; MS: More Stations; LS: Larger Stations; FCEV: Fuel Cell Electric Vehicle).

In summary, feedback provided from participants in the Market Readiness workshop suggests that significant cost-reduction opportunities exist for near-term hydrogen stations. This feedback included relatively detailed descriptions of these opportunities as well as suggestions for action items needed to pursue each opportunity. Feedback provided from the HSCC is consistent with these qualitative assertions, suggesting that hydrogen capital and fixed operating costs per gge for EC stations would be 70% lower than those from today's hydrogen stations. Moreover, these stations are anticipated to be installed in the 2014-2016 timeframe and have a nominal capacity of about 450 kg per day. The capital and fixed operating costs for hydrogen associated with these EC stations would be $5.90 per gge over the lifetime of the station. Deploying more of these same stations could reduce the cost to $4.76 per gge, and designing the same station type for larger capacity, about 1,500 kg/day, would reduce the cost to $3.49 per gge. Upstream and variable costs would have to be added to these capital and fixed operating station costs to develop a total cost estimate for hydrogen delivered to vehicles. These additional costs will be addressed in future studies of early hydrogen station costs, infrastructure rollout logistics, consumer fueling convenience, and integration of renewable hydrogen supply options.

APPENDIX A: Summary of Breakout Group Results

Hydrogen Infrastructure Market Readiness Workshop—Breakout Group 1

Guiding question #1: What are the Biggest Opportunities to Reduce the Costs of Hydrogen Fueling Stations Over the Next 2–5 Years?
Voting Criteria: Which of these represents the LARGEST OPPORTUNITY to reduce the cost of hydrogen fueling stations of the next 2–5 years?

Component-Level Costs (cost to produce)	**System Station Costs (design, performance requirements)**	**Planning and Permitting (siting, cost of compliance)**	**Business Operations (station utilization/ revenue, investment, finance, coordination, etc.)**	**Policy**	**Best Practices**
• Design, develop, validate, and manufacture for high-volume production (50 kg) to reduce capital and O&M costs ●	• No more science experiments (In favor of standardized commercial products) ●●●●	• Small setbacks: engineer systems to be safer with a small footprint; underground? ●●	• Expand the supply chain to include volume-minded suppliers versus project-oriented suppliers	• Tax credits for renewable H2 to level the playing field with alternative fuels with NO renewables requirement; reduce capital costs (e.g., cost of electricity) through supportive government legislation, renewable tax credits, etc. ●●●●	• Cost reduction/ learning by doing: Capture all of the learnings from the existing station installations; don't repeat the same problems ●
• Use a modular approach to building stations (small/medium/large) ●●●●●●●●●●●	• Liquid-large stations: delivery, storage; gas dispensing—lower compressor cost, distribution cost, and public anxiety ●●●	• Certify high-pressure storage (ASTM, DOT, CHP) ~14,000 psi	• Increasing the number of stations matures the supply chain and reduces costs of capital equipment ●	• Be willing to sacrifice the number of stations to obtain larger stations, even early on ●●●●●●	• Use a "target-costing" process; 50%–60% reduction goal; set practical targets under the business case, both short and long terms ●●
• Develop more replicates (Follow a Starbucks/ McDonalds model)	• On-site liquefaction with pumping to replace compressor and power requirements (storage/ dispensing)	• Increase H2 safety knowledge of experts; reduce redundant safety factors/footprint	• Increase H2 throughput; Corollary: Guarantee a minimum throughput for deployed stations ●●●	• Demonstrate value to drive demand; cars/ applications, fuel costs, efficiency	• Worldwide benchmarks/ best practices ●●

Component-Level Costs (cost to produce)	**System Station Costs (design, performance requirements)**	**Planning and Permitting (siting, cost of compliance)**	**Business Operations (station utilization/ revenue, investment, finance, coordination, etc.)**	**Policy**	**Best Practices**
- Re-evaluate the 3.3x safety factor on composite cylinders used for delivery●●	- Model CO2 & H2 energy use (well-to-wheels) of various distribution models and better distribute the information	- Educate fire marshals and municipalities to ease permitting process ●●●●●●●●	- Liquid H2 transfer: Understand/improve to reduce clearance and effort	- Provide awards for a network of stations rather than one-off projects ●●●●●●●●●	
- Cost of 70 MPA hoses (# of suppliers)/ More component manufacturers, a la DoD ●●●●●●		- Type approval approach—once you're approved to install the station, able to install anywhere, to reduce the administrative costs; streamline codes and standards and permitting ●●●●●●●●●●●●●●	- Add more stations to existing H2 pipelines (e.g., Torrance) ●●●●	- DOE or FERC or DOS standards to overrule NFPA/ASME and local fire marshals ●●	
- On-site storage (underground systems, high-volume storage) ●				- Address conflicts with local building requirements/ codes and H2 safety codes ●	
- 900 bar storage cost reduction/ more suppliers ●				- Grid Management; tie to H2	
- Forecourt distribution model (similar to gasoline stations) ●●				- Commitment by Government to support H2 in the long term ●●●●●	
- Support new concepts for compressing at the IS and electrolyzer ●				- 3rd-party reinforcement of H2 policy for mobility	
- Increase vendor base for station construction and operation ●●●					

Hydrogen Infrastructure Market Readiness Workshop—Breakout Group 1

Guiding question #2: What can we do to achieve these high-priority opportunities to reduce hydrogen station costs?

Cost Reduction Opportunity	Economics of Scale/learning by doing	R&D	Installation & Permitting	Collaborative Actions	Other
Type Approval Approach; Standardize Process for Permitting; Codes and Standards/ Educate Fire Marshals and Municipalities	• Labor costs dealing with permitting would drop by an order of magnitude if process is standardized, accepted across the country, and shortened to 1/10 the time; also recommended that labor costs could be reduced from 20% to 8%; time from 18 months to 1 month, or from 1 year to 1.5 months; and total costs by 3%–5%	• Clear understanding of each state's permitting requirements; **Action:** database or other information repository; **How:** Coordinate with state fire marshals; **Who:** DOE or Federal partnerships • W-T-E for renewable H2, CNG, electricity; **Who:** DOE • Safety research, flaws proposition; gather, summarize, and distribute correctly interpreted H2 information; Develop and deliver educational campaign for fire marshals and permitting officials **Who:** DOE, Trade associations • Fire marshal testing grounds; **Who:** AQMD in CA, training grounds in HI, DOE (?) • Worldwide standard and disseminated information sharing; **Who:** IPHE (emulate international standards for use in the United States) • Standardize risk management (safety, financial, insurance); **Who:** Central body • Federal funding for component and equipment certification	• At a state level, develop an approved, streamlined permitting process • Agree on reduced setback distances as code improvement (Rely on science-based data for support); **How:** modeling • Develop a codes and standards "swat team" for education and training; use as H2 proponents; **Who:** Federal central body, or collaboration by cities • Open a federal office to help companies in facilitating and permitting	• Share the timeline of implementation of hydrogen/ codes and standard of stations	• Include H2 training in standard U.S. Fire Department training; **Who:** FCF (?) • Continue current codes and standards online courses (keep updating) **Who**: NREL
Use Modular Approach (Harmonize Requirements); small/medium/large (complete system, design, determined by manufacturer)	• Cut O&M costs for equipment by 75% through using validated components • Modular approach allows for standardized manufacturing, which can lead to significant cost reductions (as much as 50%)	• Fund R&D for high-volume, high-reliability H2 compressor development • Lower compression costs through new technology, electrochemical pump synergistic with PENFC; Who: DOE, industry • Cylinder performance evaluation; storage evaluation; HP part testing and evaluation • Fund development of component requirement/ test program	• DOE funding of new stations; develop a roll out plan		• Funding from agencies and supportive policies

COST REDUCTION OPPORTUNITY	ECONOMICS OF SCALE/LEARNING BY DOING	R&D	INSTALLATION & PERMITTING	COLLABORATIVE ACTIONS	OTHER
		• Ensure end-of-life costs are included in analysis: longevity of materials; scaling requirements; fundamentals			
Provide Awards for Networks of Stations Rather Than One-Off Projects	• Yes; (consensus was that this could be helpful, but the group did not come to a consensus regarding what actions should be taken)		• DOE funding for new stations • Creative ways to reduce capital carrying costs, from 20% to 5% • Evaluation of previous awards for H2 stations	• Collaborate among states to provide awards	• Value capacity, not just $/gge sold
Increase Number of Suppliers	• 5%–6% capital equity cost reduction for doubling the volume of manufacturers, keeping existing technology	• DOE testing of 700 bar components for hoses and materials leading to new ideas for the design of materials		• Detailed station and deployment plan: include all OEMs, focused markets, potentially contractual, provides a 5–10 year outlook	• Federal support for suppliers of components
Sacrifice the Number of Stations for Larger Stations, Fully Utilized	• Maybe (participants felt that this warranted further discussion)		• In at least 1 upcoming station solicitation require min. daily capacity of >500 kg/day		

Hydrogen Infrastructure Market Readiness Workshop—Breakout Group 2

Guiding question #1: What are the Biggest Opportunities to Reduce the Costs of Hydrogen Fueling Stations Over the Next 2–5 Years?

Voting Criteria: Which of these represents the LARGEST OPPORTUNITY to reduce the cost of hydrogen fueling stations of the next 2–5 years?

Component-Level Costs (cost to produce)	**System Station Costs (design, performance requirements)**	**Planning and Permitting (siting, cost of compliance)**	**Business Operations (station utilization/ revenue, investment, finance, coordination, etc.)**	**Other**
• Large-scale compression ●●●●●● • High-pressure hydrogen storage—14,000 psi ●●●● • Compression for renewables (from 1 psi) ● • Compressor cost and reliability (eliminate need for redundancy) ● • Expand supply chain ● • Station components (O-rings, valves, etc.) • Pursue other methods of pre-cooling	• Reduce capital equipment costs, especially for high pressure ●●●●● • High-pressure hydrogen delivery—14,000 psi ●●● • Station design (especially dispenser) optimized for low cost ●● • Need to reduce station footprint ●● • Standardized designs to support series production of stations (EOS) learn break points ● • HFC TCI must reach diesel ? parity ● • Low-cost station design for low-utilized stations (destination) • Need to increase volume—economy of size	• Dispensing standards optimization ●●●●●●● • Need for more uniform permitting process (un-informed permitting officials) ●●●●●● • Station scaling adaption to growth ●● • Roaming mobile re-fuelers to provide backup supply/refueling ● • Need to revisit codes— issues of interpretation ● • Locate equipment underground • Lower install $ market coordination (area help) • Cost of rooftop installations	• Need to address market risk and attract private capital ●●●●●●● • Capital utilization cost spread over too few kgs; risk not attracting investment ●●●● • Development entity that can use both financial and other assets to offset capital and O&M ●●● • Permit $ market coordination ●● • Need for other financial ROI models • Need to give business consistent long-term message • Cost of capital—rates too high, period too short, methods to improve • Match daily demand to station "status" or availability • Mobile refueling	• Need for shared information ●●●● • Opportunity for coordination and convergence on a single storage process (vehicle) ●●●● • Economic impact analysis of H2 cost parity with gasoline ● • Need for stricter environmental policies/ regulations ● • Station location optimized

Hydrogen Infrastructure Market Readiness Workshop—Breakout Group 2

Guiding question #2: What can we do to achieve these high-priority opportunities to reduce hydrogen station costs?

Cost Reduction Opportunity	**Economics of Scale/Learning by Doing**	**R&D**	**Installation & Planning**	**Operations & Maintenance**	**Collaborative Actions**	**Policy Actions**	**Codes and Standards**	**Other**
Capital utilization -cost spread over too few customers risk not attracting investors	• 20%–30%/kg through clusters	• Design modular expansion stations ●●	• Plan for multiple potential users	• Clustering allows focused support (equipment and personnel)	• OEM communications	• Funding criteria; clustering, multi-use ●●	• NA	• Vehicle to stations communication to shift demand in time
High-pressure hydrogen storage 14,000 psi	• 10% of overall station costs up to 40% for component	• Develop codes cost share for development	• AHJ - support training efforts	• Fund program to extend service life ●	• National labs, DOT	• Federal/state local AHS meetings	• ASME, DOT codes followed ●	•
Need for shared information	• 1%–5%, light duty; 20–40% new markets = larger number of locations & lower number of replications	• Set up a universal web-based database	• Expand existing vehicle education/ outreach/ training to other H2 uses. Create typical model or deployment example ●●	• Workforce training of service operators, certification process, community college, train the trainer	• Early market hydrogen users group—webinar series, conferences, briefings to be posted on website, codes and standards database, AMR like exchange of information across industries ●●●	• Consistent long-term policy directions; give a program sufficient time to mature or die ●●●●●●	• Feedback loop from government to industry; what works, what doesn't, or other	• Industry funded "in part" to help self and all
Reduce capital equipment costs, especially for high-pressure	• 20%–50%; Look for opportunities to eliminate costs through eng./R&D	• Fund large-scale infrastructure roll out ●●●●●	• NA	• Consider O&M during design & development	• State and local stakeholders, industrial participants ●	• NA	• Refer to permitting topic	• Clear fuel outlet (CA)
Need to address	• NA	• Near-term R&D— mfg.,	• Harmonization of installation	• NA	• Stakeholder agreements and	• Long-term roadmaps with	• Streamline testing and	•

Cost Reduction Opportunity	Economics of Scale/Learning by Doing	R&D	Installation & Planning	Operations & Maintenance	Collaborative Actions	Policy Actions	Codes and Standards	Other
market risk and attract private capital		component reliability	process (e.g., statewide)		communication	policy goals ●	certification requirements ●●●	
Need for more uniform permitting process	• 20%–30% of station costs	• Set up a universal web-based database ●●●	• Expand existing website education, outreach and training to early market H2 users; create models and examples, workshops ●	• Workforce training of service operators, certification process, community colleges, train the trainers	• See 4	• NA	• Code body summary (real words, plain English) of C&S; national or state uniform code on permitting ●●●●●	•
Large-scale compression	• Mostly learned by doing—10% of the capital	• DOE program targeted	• NA	• Support demonstration program	• Coordinate energy and gas suppliers	• NA	• NA	•
Dispensing standards optimization - standards - protocol-station costs	• 0%	• Develop low-cost cooling system/ dispensing, validate boundary conditions of operation, validate alternative fuel products ●●	• NA	• Study key dispensing cost drivers for operation & maintenance	• Common funding for data study of optimization ●	• NA	• Complete SAE J2601 with optimization ●●●●	• Complete study and standardization of HVAs ●

Hydrogen Infrastructure Market Readiness Workshop—Breakout Group 2

Action Plan

COMPLETE SAE J2601 WITH OPTIMIZATION	**HOW**	**WHO**	**WHEN**
	- Continue meetings	- SAE members	- 24 months
Create a national or state code standard with plain language	- “mimic” ASHRAE and IEEE code process—consistent, understandable	- Collaborative federal leadership	- 24 months
Fund and execute large-scale infrastructure roll out	- Collaborative planning - Create list of criteria (punch list) - Run assets through development entities - Identify incentives, put in place	- Task force leads - All stakeholders and agencies - Government co-fund	- In parallel with policy direction, ASAP within 12 months
Consistent long-term policy direction	- Develop U.S. state energy policy that includes H2	- Government with industry collaboration	- ASAP—within 12 months

Hydrogen Infrastructure Market Readiness Workshop—Breakout Group 3

Guiding question #1: What are the Biggest Opportunities to Reduce the Costs of Hydrogen Fueling Stations Over the Next 2–5 Years?

Voting Criteria: Which of these represents the LARGEST OPPORTUNITY to reduce the cost of hydrogen fueling stations of the next 2–5 years?

COMPONENT-LEVEL COSTS (COST TO PRODUCE)	**SYSTEM STATION COSTS (DESIGN, PERFORMANCE REQUIREMENTS)**	**PLANNING AND PERMITTING (SITING, COST OF COMPLIANCE)**	**BUSINESS OPERATIONS (STATION UTILIZATION/REVENUE, INVESTMENT, FINANCE, COORDINATION, ETC.)**	**OTHER**
• Get more suppliers into the market supply chain; access to multiple suppliers ●●●●● • Station compressor costs: capital (tied to reliability and need for redundancy) • Operating/Maintenance (ties to not ?, e.g., cost, but station downtime) ●●●●● • Reduce cost of H2 storage, (e.g., utilization of composite tank storage) ●●●● • New, improved core technology fuel cells • Compressor (H35) overhaul costs ~$40K) • Low-life-cycle cost compression technology, (e.g., electrochemical) • Ionic liquid compressors	• Standardize station designs (where possible across applications) and don't "gold plate" it ●●●●●●●●●● • Target processes and components (e.g., O-rings) that cause station reliability problems for improvement ●●●●●●●● • Optimize forecourt design with scale-up in mind ●● • Better match supply and demand (from multiple sources) to reduce redundancy and storage at stations ●● • O&M expenses reducing labor associated with maintenance ● • Identify less rigorous design (overly conservative) specifications (step below "gold" standard • Design/information-sharing database for federal/state funding • Utilize excess H2 from CHHP • Siting electrical requirements and system design • Develop "portfolio" of H2 delivery solution	• Better educate officials and public on codes and standards. Standardize information directed at local fire marshal ●●●●● • Providing 3rd-party certification of equipment ●●●● • Smart network growth ● • "Scale economics" in permitting, build on learnings network of experts • Planning and permitting "fast track" permit process for H2 stations; like SC AQMD does for FC BUP	• Overlap early markets with 2015 auto markets. Find synergy for stations. Government help for reserve capacity ●●● • Load up the infrastructure with multiple apps (e.g., ?vehicles and MHE and buses) ●● • Liability insurance ($50K/yr) costs too much ● • Cost to get government financial help (too high) • Leverage hydrogen supplies that aren't being fully utilized • Utilize H2 supply from excess H2 capacity (e.g., NASA operations) • Utilize waste H2 from industrial H2-intensive processes; localized H2 station, lower delivery • Increased station volume—reduction in amortized costs • Gas station integration (co-locate with gas stations) ●●● • Short pipelines for H2 delivery • Lower fuel costs—increase supply options (delivered cost of H2 is too high) – Why do we pay for H2 molecules and input energy costs • Siting—take land costs out of the equation where possible by using brownfields, EUL at federal sites, etc. • Partner to reduce land/site costs	• Common data collection and reporting (ala TechVal) ●●●● • Intensive (high-utilization) demonstrations outside of California (renewables mandate impedes H2 roll out and is a cost barrier) ●●● • Cooperation among players ●●● • Reduce cost of "money" to finance stations ●●● • Government incentives for new applications for hydrogen ●● • Consistent H2/energy vision for the United States ● • Transparent cost analysis from historic programs (data is fuzzy regarding pricing) • Adopt a collective responsibility to bring H2 to market • Government challenges/awards regarding feasibility • Motivation of political will to "win the future" (clear government commitment and carbon policy) • Include H2 infrastructure (and PHEV) in administrations "infrastructure fund" (road, bridges) proposal • Develop an updated H2/fuel cell roadmap

Hydrogen Infrastructure Market Readiness Workshop—Breakout Group 3

Guiding question #2: What can we do to achieve these high-priority opportunities to reduce hydrogen station costs?

- **Provide better education to officials and the public and insurance industry on codes and standards**
  - Continue C&S workshops
  - Target outreach one-on-one meetings with opinion leaders
    - Seminars to NECA, SIGMA, labor
    - Insurers (NAIC), building inspectors, public works divisions
  - Model the outreach done on vehicle HEVs
  - Set up a network of official that could be resource to others
  - Develop technical validation report on station reliability

- **Standardize station designs (and don't "gold plate")**
  - 30%–50% cost reduction through economies of scale
  - Incentivize smaller-scale suppliers to test and verify reliability of designs
    - Accelerate life testing, testing protocols
  - Station buyers design RFPs incentivize a standard design
  - Forklift and OEM work together to develop both station needs and solutions
  - Integration of compression and storage and dispensing
  - Execute SAEJ......filling protocol
  - Identify which components or station design/installation requirements suffer from over design, e.g., "fire eyes" at stations - heat or H2 defector cheaper

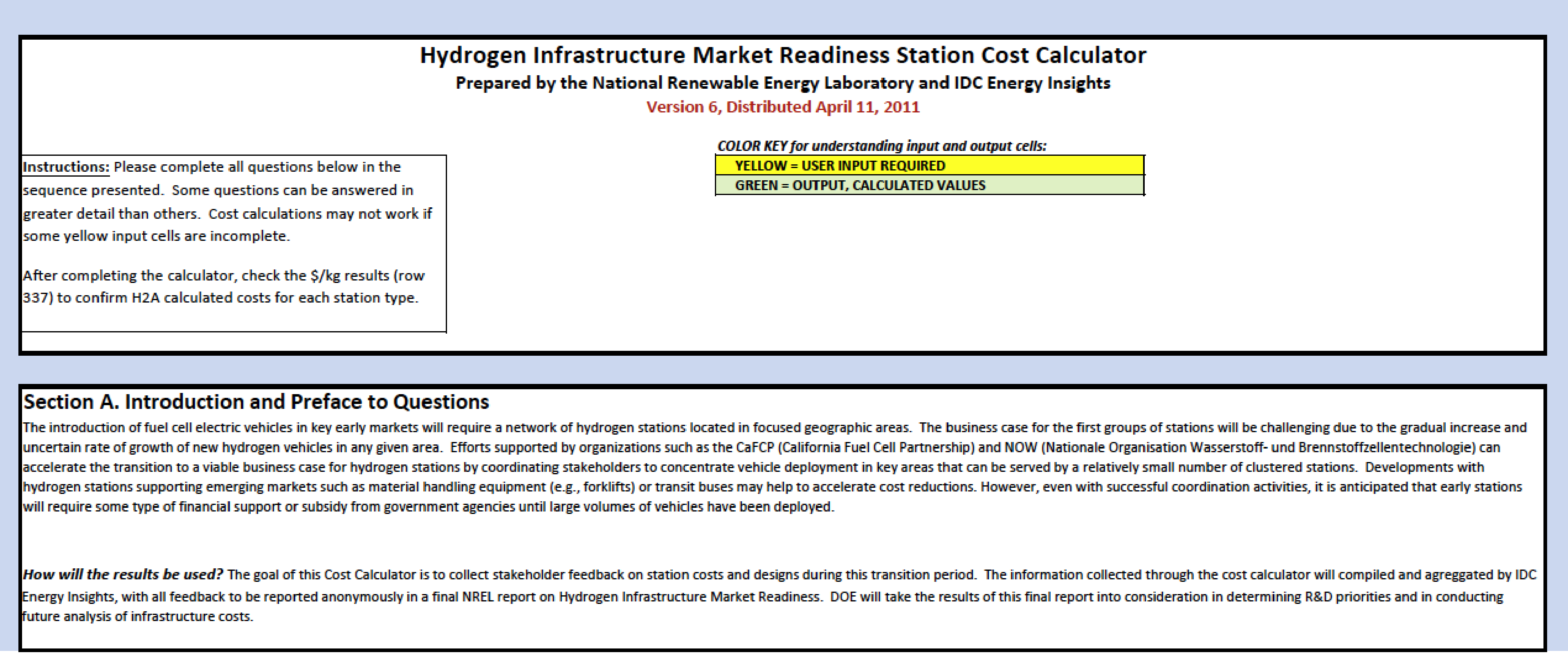
- **Increase station volume (Increase synergy with multiple markets)**
  - Incentivize combining fleet operations with public refueling, e.g., at Fed Ex site)
  - RFPs that require that station be publicly available
  - Survey and database of where this makes sense around the country
  - Co-locate H2 dispensers at gas stations
  - R&D into station designs that link nearby applications with one H2 "generator," (e.g., thru short pipelines, tubes, etc.)
  - Conduct H2A level understanding about volume scaling on infrastructure costs
  - Build learning curves on costs of different components to give guidance
  - Provide common data collection and reporting

- **Target processes and components that cause station reliability problems (e.g., O-rings), Work toward making certified equipment for H2 use / provide 3rd-party certification of equipment**
  - O-rings/ball valves, IR nozzles, compressors (O&M), diaphragm (O&M), fire sensors, pressure sensors, check valves on compressors, pressure release valves
  - Get industry players to work together for common certification—task to FCHEA or industry association
  - Provide government funding support to get testing and certification done (suppliers can't/won't on their own)

  - Get suppliers (U.S.) together to talk about how to lower costs/ruggedize
  - Potential for cost $50,000–$100,000 reduction in annual cost
- **Get more suppliers into the market**
  - Provide clear design specs that they can respond to
  - Create “challenge” for design/build
  - Provide information on what demand curve looks like (with error bars); more market analysis
  - Target information toward the T-3 suppliers; their pubs, conferences, associations
  - Are there testing needs that are low risk to them

- **Reduce cost of storage (e.g., utilize composite tank storage)**
  - Evaluate ability to use composite tank storage
  - Develop permitting requirements, etc.

APPENDIX B: Screenshots of the Hydrogen Station Cost Calculator



Hydrogen Infrastructure Market Readiness Station Cost Calculator

Prepared by the National Renewable Energy Laboratory and IDC Energy Insights

Version 6, Distributed April 11, 2011

Instructions: Please complete all questions below in the sequence presented. Some questions can be answered in greater detail than others. Cost calculations may not work if some yellow input cells are incomplete.

After completing the calculator, check the $/kg results (row 337) to confirm H2A calculated costs for each station type.

COLOR KEY for understanding input and output cells:

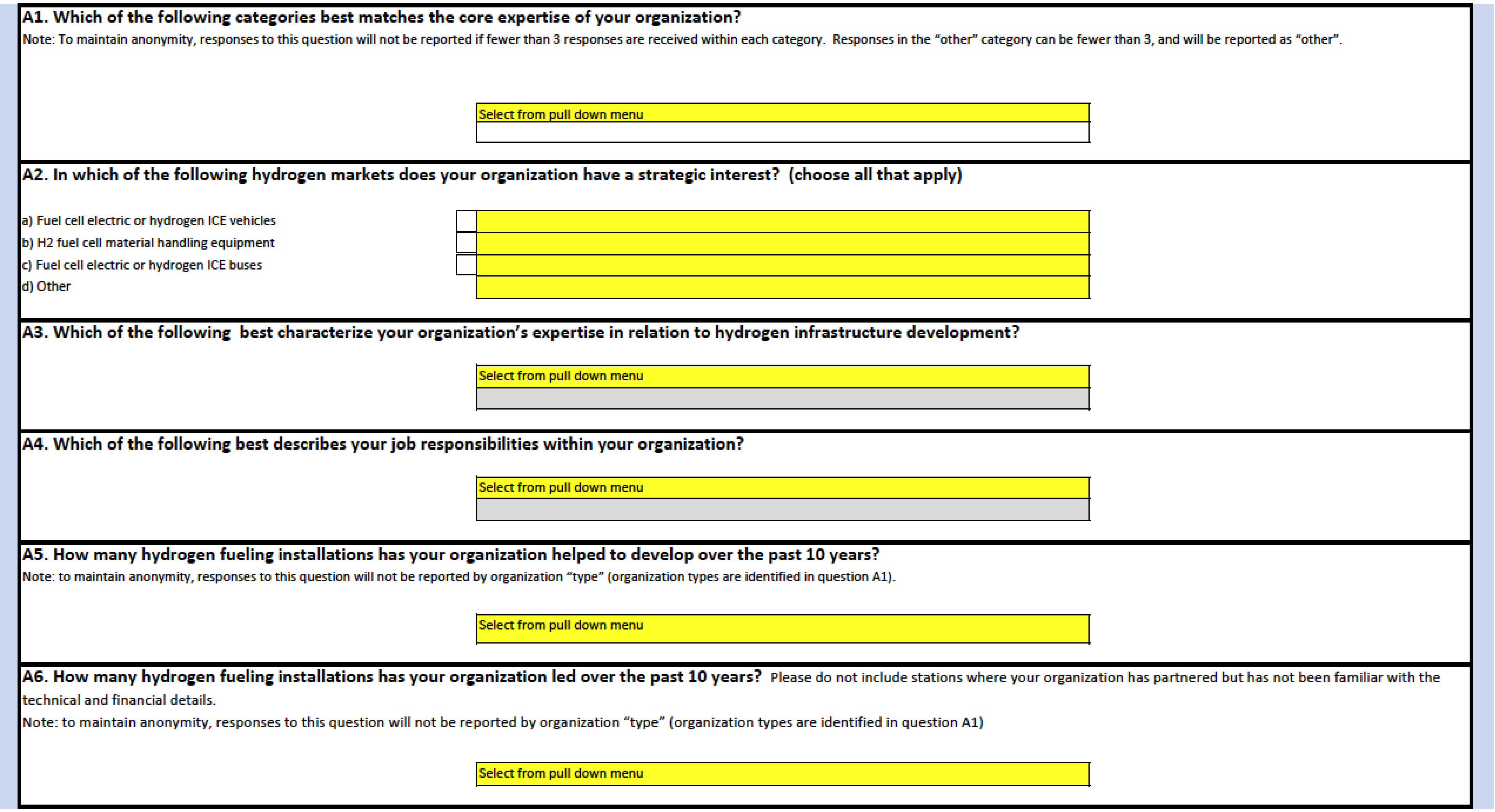
YELLOW = USER INPUT REQUIRED

GREEN = OUTPUT, CALCULATED VALUES

Section A. Introduction and Preface to Questions

The introduction of fuel cell electric vehicles in key early markets will require a network of hydrogen stations located in focused geographic areas. The business case for the first groups of stations will be challenging due to the gradual increase and uncertain rate of growth of new hydrogen vehicles in any given area. Efforts supported by organizations such as the CaFCP (California Fuel Cell Partnership) and NOW (Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie) can accelerate the transition to a viable business case for hydrogen stations by coordinating stakeholders to concentrate vehicle deployment in key areas that can be served by a relatively small number of clustered stations. Developments with hydrogen stations supporting emerging markets such as material handling equipment (e.g., forklifts) or transit buses may help to accelerate cost reductions. However, even with successful coordination activities, it is anticipated that early stations will require some type of financial support or subsidy from government agencies until large volumes of vehicles have been deployed.

How will the results be used? The goal of this Cost Calculator is to collect stakeholder feedback on station costs and designs during this transition period. The information collected through the cost calculator will compiled and agreggated by IDC Energy Insights, with all feedback to be reported anonymously in a final NREL report on Hydrogen Infrastructure Market Readiness. DOE will take the results of this final report into consideration in determining R&D priorities and in conducting future analysis of infrastructure costs.



A1. Which of the following categories best matches the core expertise of your organization?

Note: To maintain anonymity, responses to this question will not be reported if fewer than 3 responses are received within each category. Responses in the “other” category can be fewer than 3, and will be reported as “other”.

Select from pull down menu

A2. In which of the following hydrogen markets does your organization have a strategic interest? (choose all that apply)

a) Fuel cell electric or hydrogen ICE vehicles ☐

b) H2 fuel cell material handling equipment ☐

c) Fuel cell electric or hydrogen ICE buses ☐

d) Other

A3. Which of the following best characterize your organization’s expertise in relation to hydrogen infrastructure development?

Select from pull down menu

A4. Which of the following best describes your job responsibilities within your organization?

Select from pull down menu

A5. How many hydrogen fueling installations has your organization helped to develop over the past 10 years?

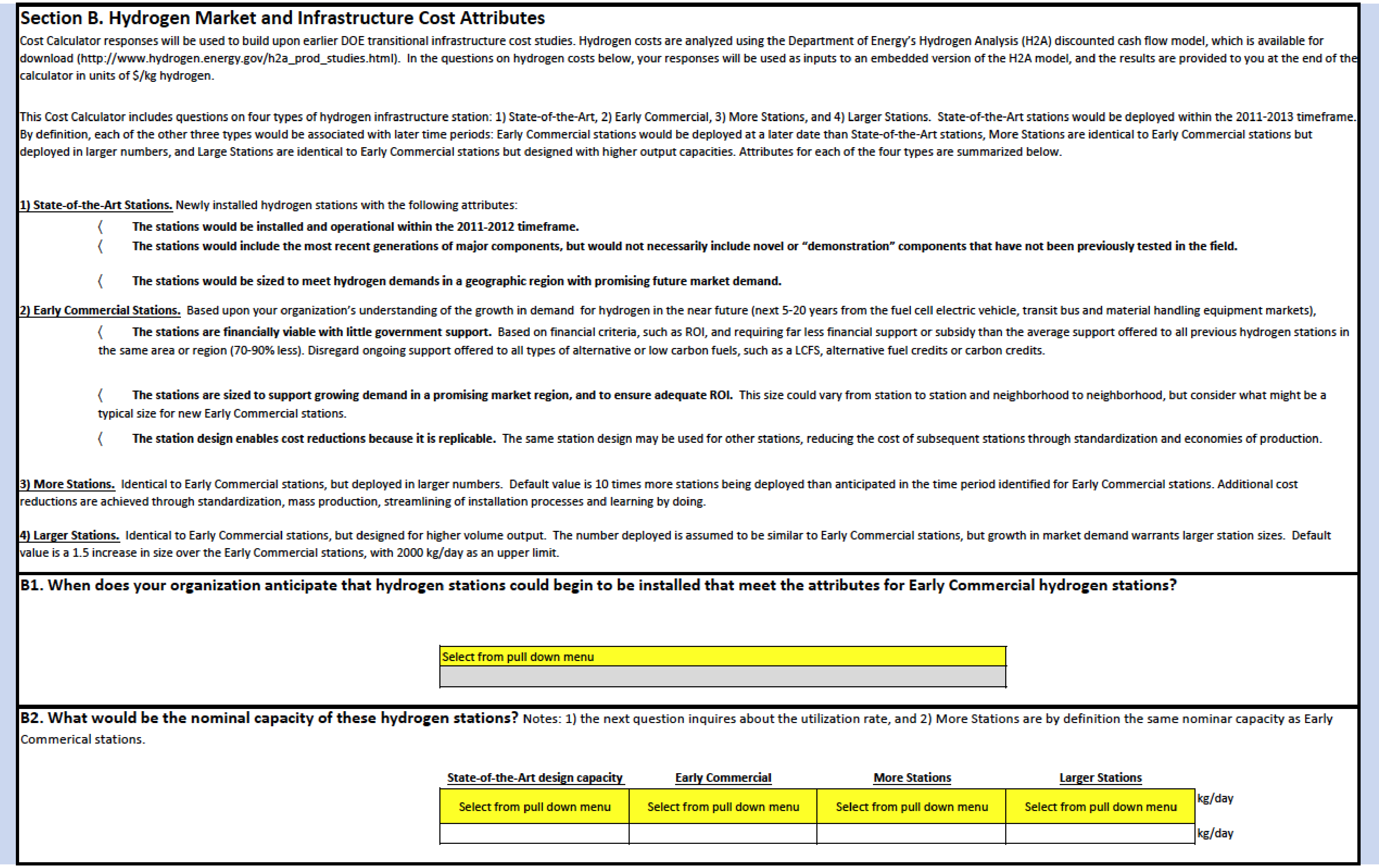
Note: to maintain anonymity, responses to this question will not be reported by organization “type” (organization types are identified in question A1).

Select from pull down menu

A6. How many hydrogen fueling installations has your organization led over the past 10 years? Please do not include stations where your organization has partnered but has not been familiar with the technical and financial details.

Note: to maintain anonymity, responses to this question will not be reported by organization “type” (organization types are identified in question A1)

Select from pull down menu



Section B. Hydrogen Market and Infrastructure Cost Attributes

Cost Calculator responses will be used to build upon earlier DOE transitional infrastructure cost studies. Hydrogen costs are analyzed using the Department of Energy's Hydrogen Analysis (H2A) discounted cash flow model, which is available for download (http://www.hydrogen.energy.gov/h2a_prod_studies.html). In the questions on hydrogen costs below, your responses will be used as inputs to an embedded version of the H2A model, and the results are provided to you at the end of the calculator in units of $/kg hydrogen.

This Cost Calculator includes questions on four types of hydrogen infrastructure station: 1) State-of-the-Art, 2) Early Commercial, 3) More Stations, and 4) Larger Stations. State-of-the-Art stations would be deployed within the 2011-2013 timeframe. By definition, each of the other three types would be associated with later time periods: Early Commercial stations would be deployed at a later date than State-of-the-Art stations, More Stations are identical to Early Commercial stations but deployed in larger numbers, and Large Stations are identical to Early Commercial stations but designed with higher output capacities. Attributes for each of the four types are summarized below.

1) State-of-the-Art Stations. Newly installed hydrogen stations with the following attributes:

- **The stations would be installed and operational within the 2011-2012 timeframe.**
- **The stations would include the most recent generations of major components, but would not necessarily include novel or "demonstration" components that have not been previously tested in the field.**
- **The stations would be sized to meet hydrogen demands in a geographic region with promising future market demand.**

2) Early Commercial Stations. Based upon your organization's understanding of the growth in demand for hydrogen in the near future (next 5-20 years from the fuel cell electric vehicle, transit bus and material handling equipment markets),

- **The stations are financially viable with little government support.** Based on financial criteria, such as ROI, and requiring far less financial support or subsidy than the average support offered to all previous hydrogen stations in the same area or region (70-90% less). Disregard ongoing support offered to all types of alternative or low carbon fuels, such as a LCFS, alternative fuel credits or carbon credits.
- **The stations are sized to support growing demand in a promising market region, and to ensure adequate ROI.** This size could vary from station to station and neighborhood to neighborhood, but consider what might be a typical size for new Early Commercial stations.
- **The station design enables cost reductions because it is replicable.** The same station design may be used for other stations, reducing the cost of subsequent stations through standardization and economies of production.

3) More Stations. Identical to Early Commercial stations, but deployed in larger numbers. Default value is 10 times more stations being deployed than anticipated in the time period identified for Early Commercial stations. Additional cost reductions are achieved through standardization, mass production, streamlining of installation processes and learning by doing.

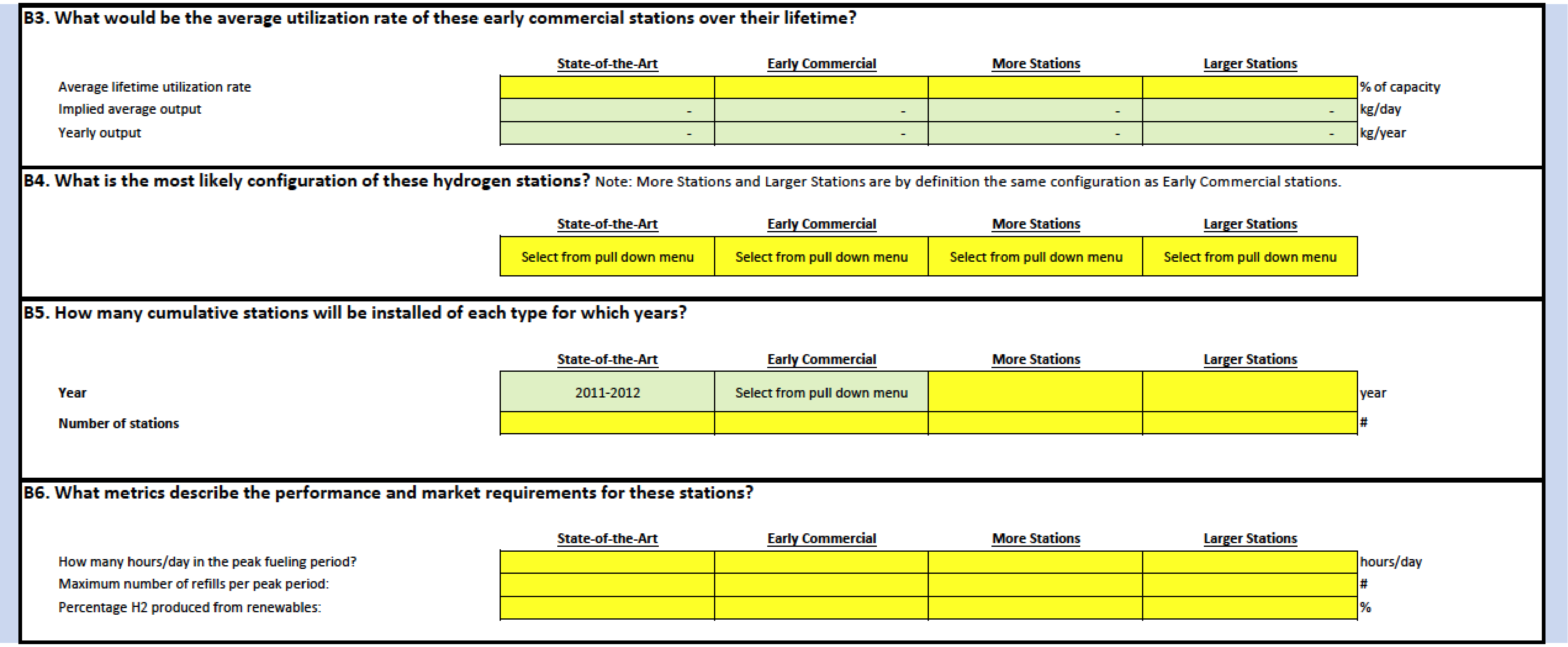
4) Larger Stations. Identical to Early Commercial stations, but designed for higher volume output. The number deployed is assumed to be similar to Early Commercial stations, but growth in market demand warrants larger station sizes. Default value is a 1.5 increase in size over the Early Commercial stations, with 2000 kg/day as an upper limit.

B1. When does your organization anticipate that hydrogen stations could begin to be installed that meet the attributes for Early Commercial hydrogen stations?

Select from pull down menu

B2. What would be the nominal capacity of these hydrogen stations? Notes: 1) the next question inquires about the utilization rate, and 2) More Stations are by definition the same nominar capacity as Early Commerical stations.

State-of-the-Art design capacity	Early Commercial	More Stations	Larger Stations	
Select from pull down menu	Select from pull down menu	Select from pull down menu	Select from pull down menu	kg/day
				kg/day



B3. What would be the average utilization rate of these early commercial stations over their lifetime?

	State-of-the-Art	Early Commercial	More Stations	Larger Stations	
Average lifetime utilization rate					% of capacity
Implied average output	-	-	-	-	kg/day
Yearly output	-	-	-	-	kg/year

B4. What is the most likely configuration of these hydrogen stations? Note: More Stations and Larger Stations are by definition the same configuration as Early Commercial stations.

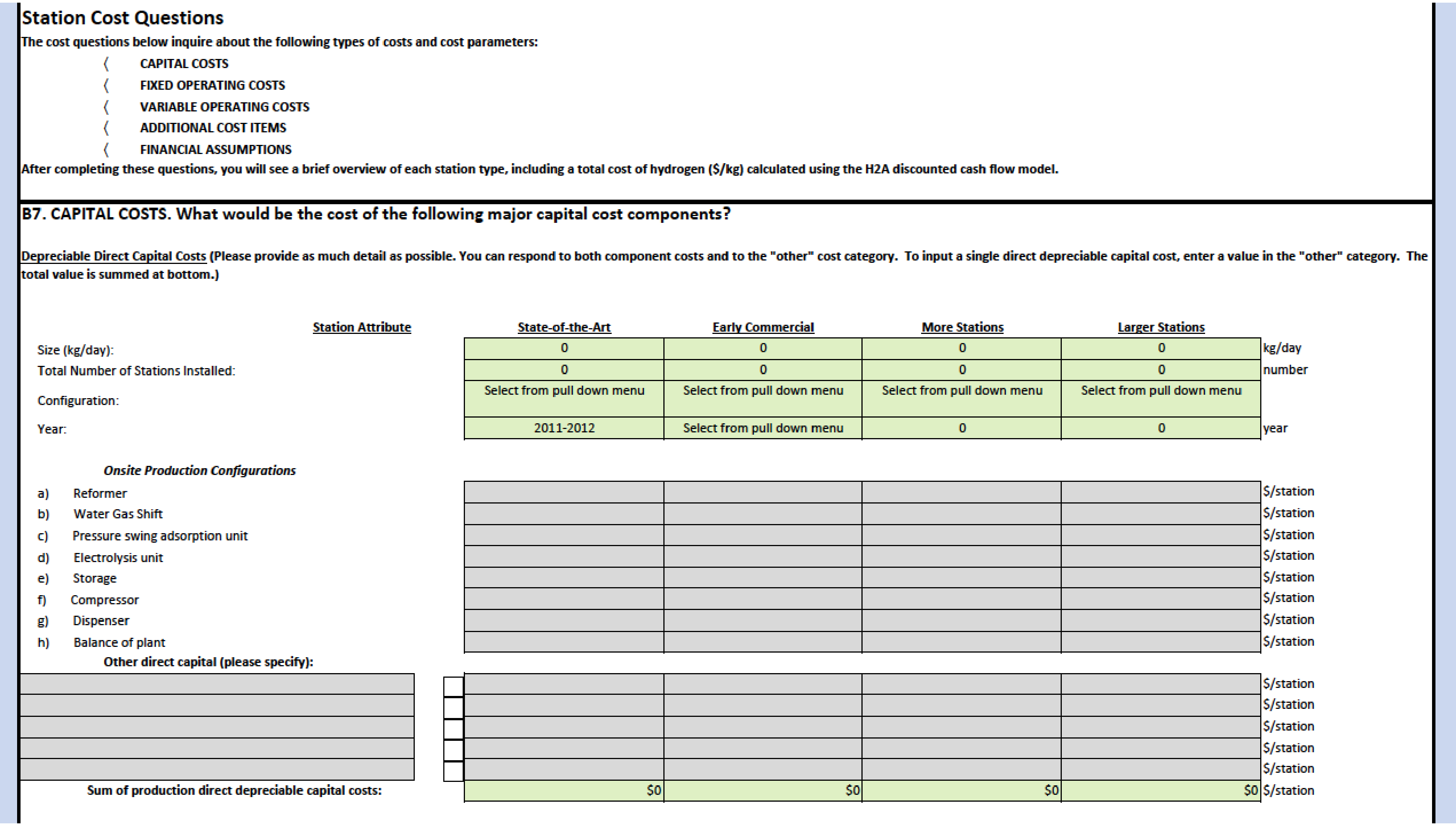
State-of-the-Art	Early Commercial	More Stations	Larger Stations
Select from pull down menu	Select from pull down menu	Select from pull down menu	Select from pull down menu

B5. How many cumulative stations will be installed of each type for which years?

	State-of-the-Art	Early Commercial	More Stations	Larger Stations	
Year	2011-2012	Select from pull down menu			year
Number of stations					#

B6. What metrics describe the performance and market requirements for these stations?

	State-of-the-Art	Early Commercial	More Stations	Larger Stations	
How many hours/day in the peak fueling period?					hours/day
Maximum number of refills per peak period:					#
Percentage H2 produced from renewables:					%



Station Cost Questions

The cost questions below inquire about the following types of costs and cost parameters:

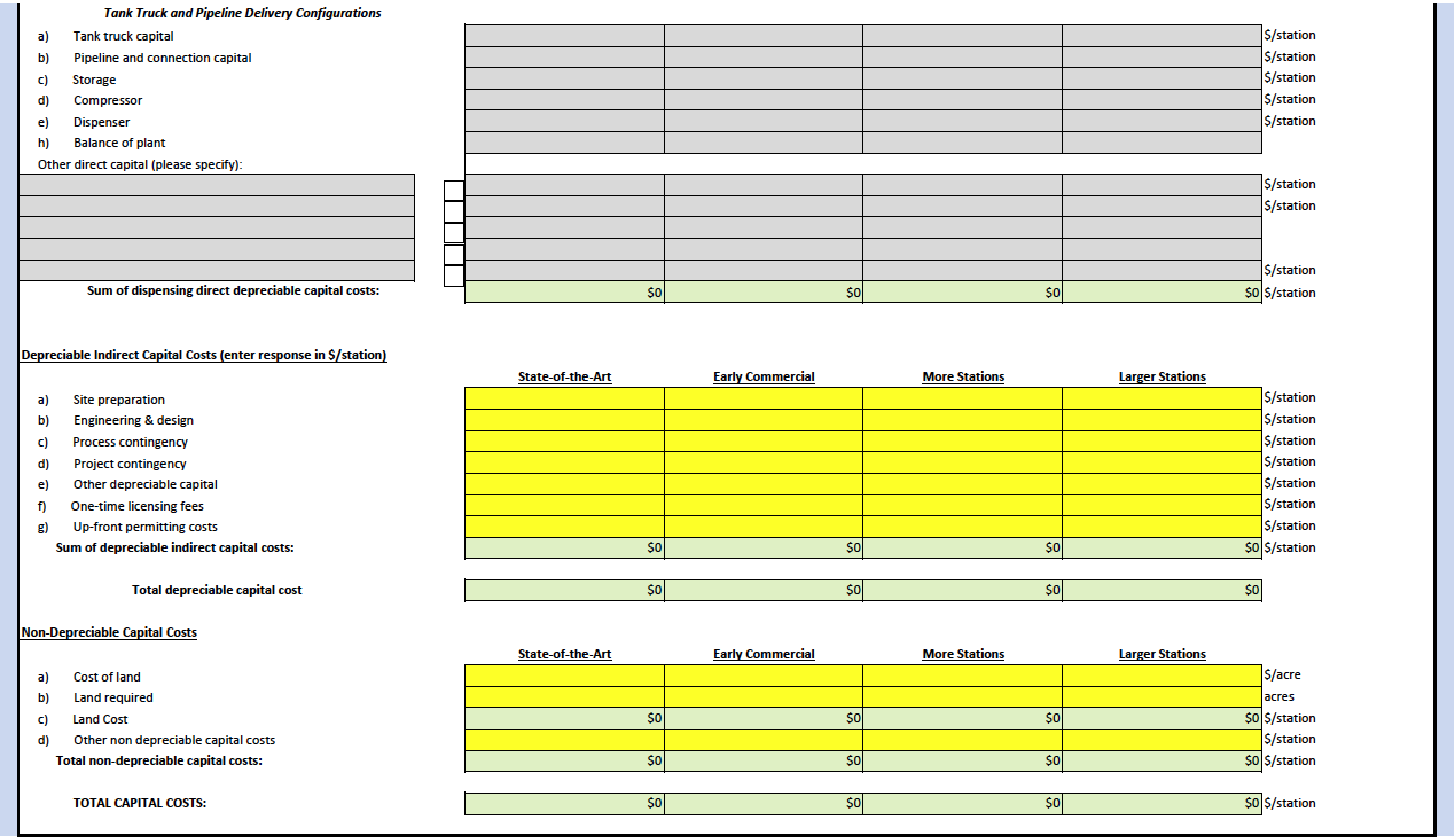
- **CAPITAL COSTS**
- **FIXED OPERATING COSTS**
- **VARIABLE OPERATING COSTS**
- **ADDITIONAL COST ITEMS**
- **FINANCIAL ASSUMPTIONS**

After completing these questions, you will see a brief overview of each station type, including a total cost of hydrogen ($/kg) calculated using the H2A discounted cash flow model.

B7. CAPITAL COSTS. What would be the cost of the following major capital cost components?

Depreciable Direct Capital Costs (Please provide as much detail as possible. You can respond to both component costs and to the "other" cost category. To input a single direct depreciable capital cost, enter a value in the "other" category. The total value is summed at bottom.)

Station Attribute		**State-of-the-Art**	**Early Commercial**	**More Stations**	**Larger Stations**	
Size (kg/day):		0	0	0	0	kg/day
Total Number of Stations Installed:		0	0	0	0	number
Configuration:		Select from pull down menu	Select from pull down menu	Select from pull down menu	Select from pull down menu	
Year:		2011-2012	Select from pull down menu	0	0	year
Onsite Production Configurations						
a) Reformer						$/station
b) Water Gas Shift						$/station
c) Pressure swing adsorption unit						$/station
d) Electrolysis unit						$/station
e) Storage						$/station
f) Compressor						$/station
g) Dispenser						$/station
h) Balance of plant						$/station
Other direct capital (please specify):						
	☐					$/station
	☐					$/station
	☐					$/station
	☐					$/station
	☐					$/station
Sum of production direct depreciable capital costs:		$0	$0	$0	$0	$/station



Tank Truck and Pipeline Delivery Configurations

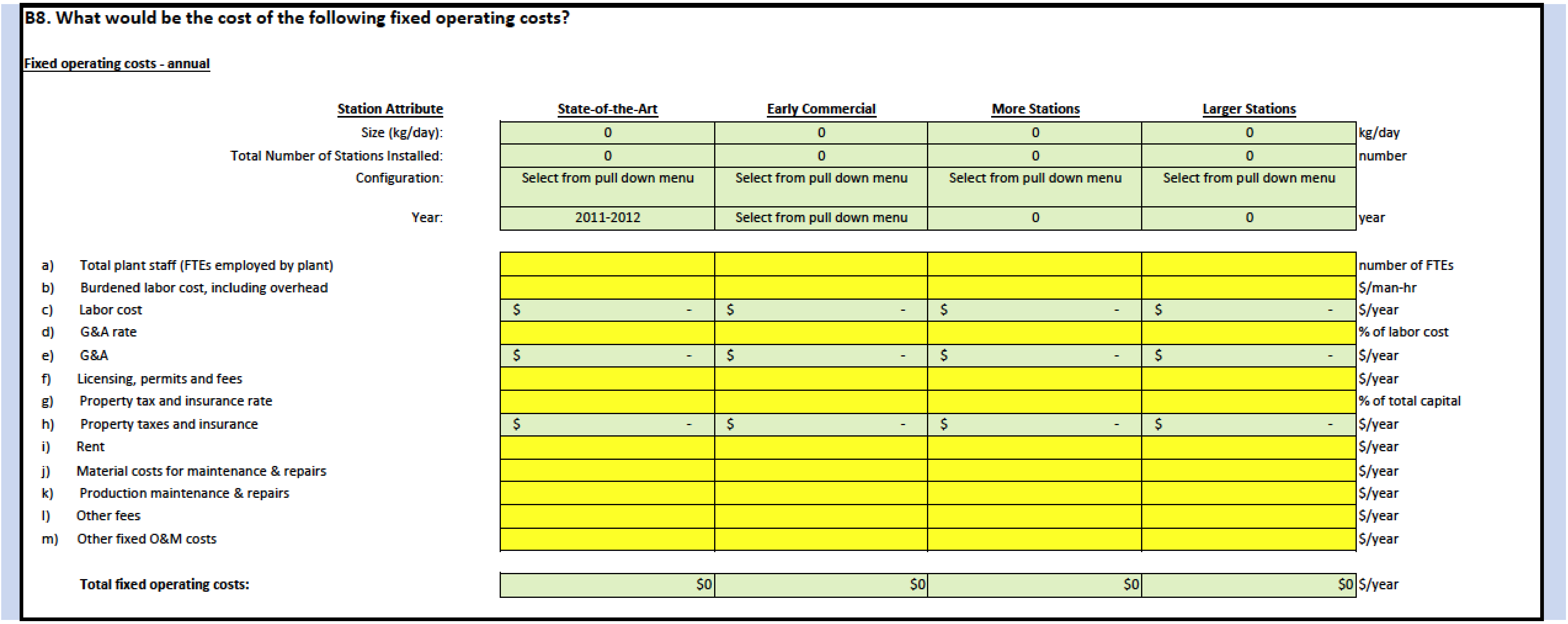
a) Tank truck capital					$/station
b) Pipeline and connection capital					$/station
c) Storage					$/station
d) Compressor					$/station
e) Dispenser					$/station
h) Balance of plant					
Other direct capital (please specify):					
☐					$/station
☐					$/station
☐					
☐					
☐					$/station
Sum of dispensing direct depreciable capital costs:	$0	$0	$0	$0	$/station

Depreciable Indirect Capital Costs (enter response in $/station)

	State-of-the-Art	**Early Commercial**	**More Stations**	**Larger Stations**	
a) Site preparation					$/station
b) Engineering & design					$/station
c) Process contingency					$/station
d) Project contingency					$/station
e) Other depreciable capital					$/station
f) One-time licensing fees					$/station
g) Up-front permitting costs					$/station
Sum of depreciable indirect capital costs:	$0	$0	$0	$0	$/station
Total depreciable capital cost	$0	$0	$0	$0	

Non-Depreciable Capital Costs

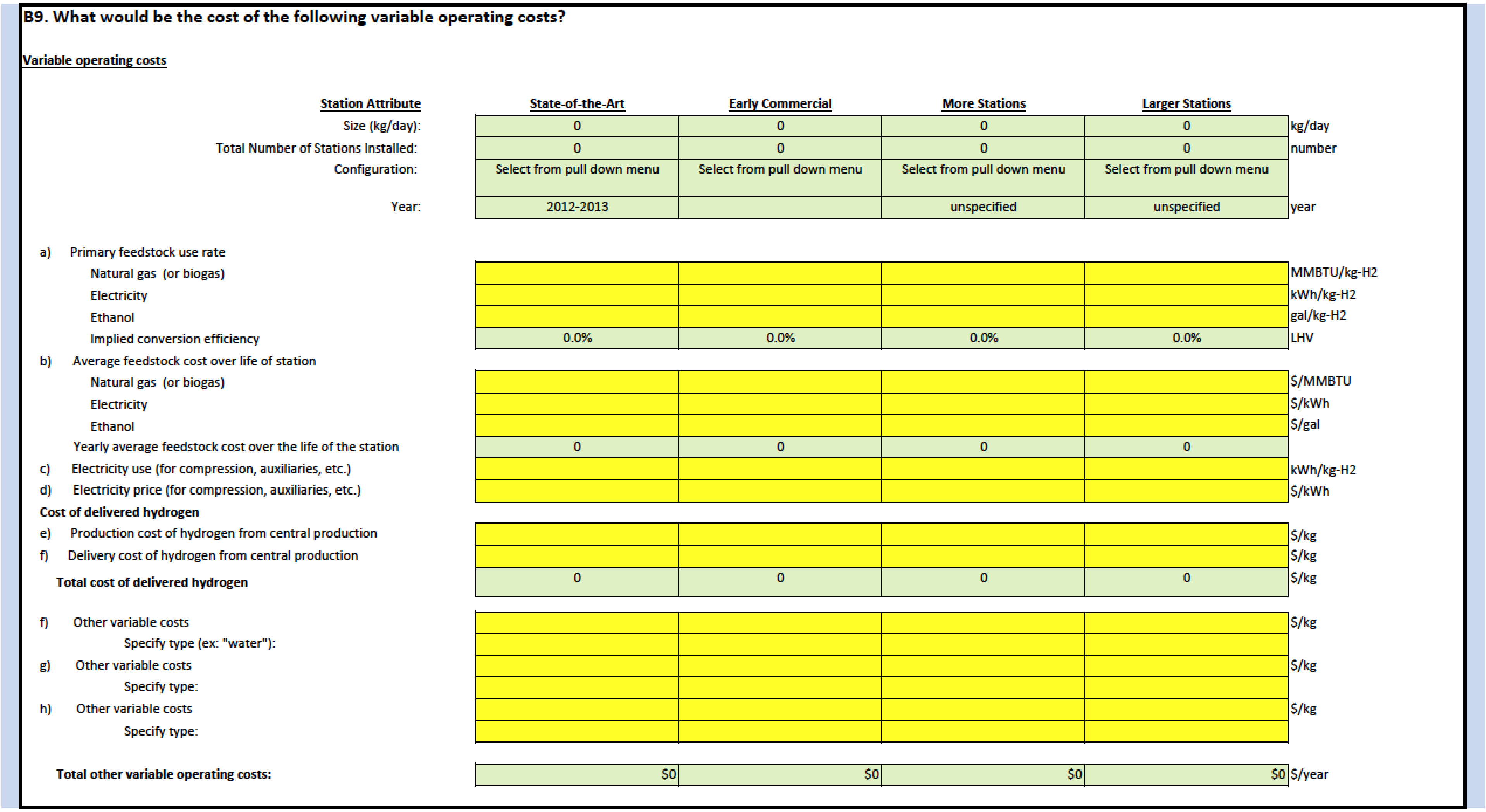
	State-of-the-Art	**Early Commercial**	**More Stations**	**Larger Stations**	
a) Cost of land					$/acre
b) Land required					acres
c) Land Cost	$0	$0	$0	$0	$/station
d) Other non depreciable capital costs					$/station
Total non-depreciable capital costs:	$0	$0	$0	$0	$/station
TOTAL CAPITAL COSTS:	$0	$0	$0	$0	$/station



B8. What would be the cost of the following fixed operating costs?

Fixed operating costs - annual

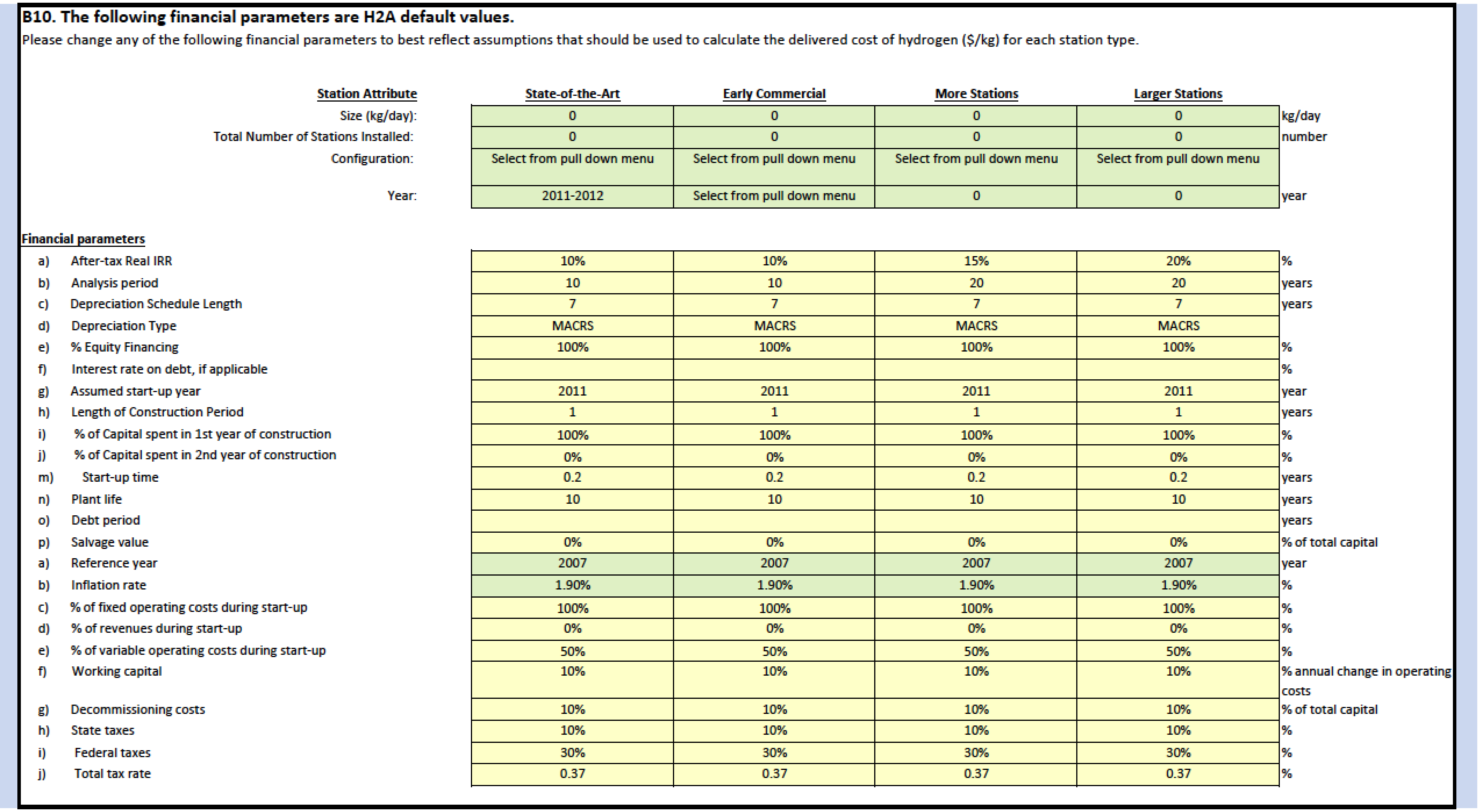
	Station Attribute	**State-of-the-Art**	**Early Commercial**	**More Stations**	**Larger Stations**	
	Size (kg/day):	0	0	0	0	kg/day
	Total Number of Stations Installed:	0	0	0	0	number
	Configuration:	Select from pull down menu	Select from pull down menu	Select from pull down menu	Select from pull down menu	
	Year:	2011-2012	Select from pull down menu	0	0	year
a)	Total plant staff (FTEs employed by plant)					number of FTEs
b)	Burdened labor cost, including overhead					$/man-hr
c)	Labor cost	$ -	$ -	$ -	$ -	$/year
d)	G&A rate					% of labor cost
e)	G&A	$ -	$ -	$ -	$ -	$/year
f)	Licensing, permits and fees					$/year
g)	Property tax and insurance rate					% of total capital
h)	Property taxes and insurance	$ -	$ -	$ -	$ -	$/year
i)	Rent					$/year
j)	Material costs for maintenance & repairs					$/year
k)	Production maintenance & repairs					$/year
l)	Other fees					$/year
m)	Other fixed O&M costs					$/year
	Total fixed operating costs:	$0	$0	$0	$0	$/year



B9. What would be the cost of the following variable operating costs?

Variable operating costs

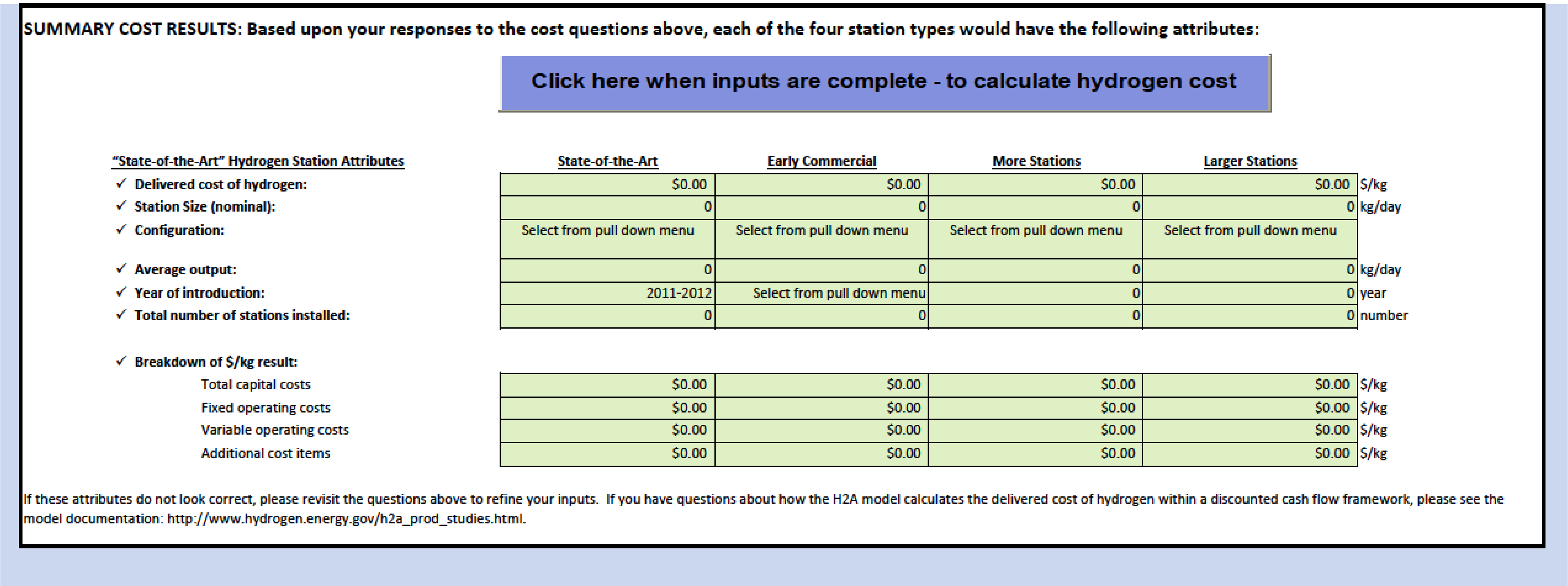
Station Attribute	State-of-the-Art	Early Commercial	More Stations	Larger Stations	
Size (kg/day):	0	0	0	0	kg/day
Total Number of Stations Installed:	0	0	0	0	number
Configuration:	Select from pull down menu	Select from pull down menu	Select from pull down menu	Select from pull down menu	
Year:	2012-2013		unspecified	unspecified	year
a) Primary feedstock use rate					
Natural gas (or biogas)					MMBTU/kg-H2
Electricity					kWh/kg-H2
Ethanol					gal/kg-H2
Implied conversion efficiency	0.0%	0.0%	0.0%	0.0%	LHV
b) Average feedstock cost over life of station					
Natural gas (or biogas)					$/MMBTU
Electricity					$/kWh
Ethanol					$/gal
Yearly average feedstock cost over the life of the station	0	0	0	0	
c) Electricity use (for compression, auxiliaries, etc.)					kWh/kg-H2
d) Electricity price (for compression, auxiliaries, etc.)					$/kWh
Cost of delivered hydrogen					
e) Production cost of hydrogen from central production					$/kg
f) Delivery cost of hydrogen from central production					$/kg
Total cost of delivered hydrogen	0	0	0	0	$/kg
f) Other variable costs					$/kg
Specify type (ex: "water"):					
g) Other variable costs					$/kg
Specify type:					
h) Other variable costs					$/kg
Specify type:					
Total other variable operating costs:	$0	$0	$0	$0	$/year



B10. The following financial parameters are H2A default values.

Please change any of the following financial parameters to best reflect assumptions that should be used to calculate the delivered cost of hydrogen ($/kg) for each station type.

Station Attribute	State-of-the-Art	Early Commercial	More Stations	Larger Stations	
Size (kg/day):	0	0	0	0	kg/day
Total Number of Stations Installed:	0	0	0	0	number
Configuration:	Select from pull down menu	Select from pull down menu	Select from pull down menu	Select from pull down menu	
Year:	2011-2012	Select from pull down menu	0	0	year
Financial parameters					
a) After-tax Real IRR	10%	10%	15%	20%	%
b) Analysis period	10	10	20	20	years
c) Depreciation Schedule Length	7	7	7	7	years
d) Depreciation Type	MACRS	MACRS	MACRS	MACRS	
e) % Equity Financing	100%	100%	100%	100%	%
f) Interest rate on debt, if applicable					%
g) Assumed start-up year	2011	2011	2011	2011	year
h) Length of Construction Period	1	1	1	1	years
i) % of Capital spent in 1st year of construction	100%	100%	100%	100%	%
j) % of Capital spent in 2nd year of construction	0%	0%	0%	0%	%
m) Start-up time	0.2	0.2	0.2	0.2	years
n) Plant life	10	10	10	10	years
o) Debt period					years
p) Salvage value	0%	0%	0%	0%	% of total capital
a) Reference year	2007	2007	2007	2007	year
b) Inflation rate	1.90%	1.90%	1.90%	1.90%	%
c) % of fixed operating costs during start-up	100%	100%	100%	100%	%
d) % of revenues during start-up	0%	0%	0%	0%	%
e) % of variable operating costs during start-up	50%	50%	50%	50%	%
f) Working capital	10%	10%	10%	10%	% annual change in operating costs
g) Decommissioning costs	10%	10%	10%	10%	% of total capital
h) State taxes	10%	10%	10%	10%	%
i) Federal taxes	30%	30%	30%	30%	%
j) Total tax rate	0.37	0.37	0.37	0.37	%



SUMMARY COST RESULTS: Based upon your responses to the cost questions above, each of the four station types would have the following attributes:

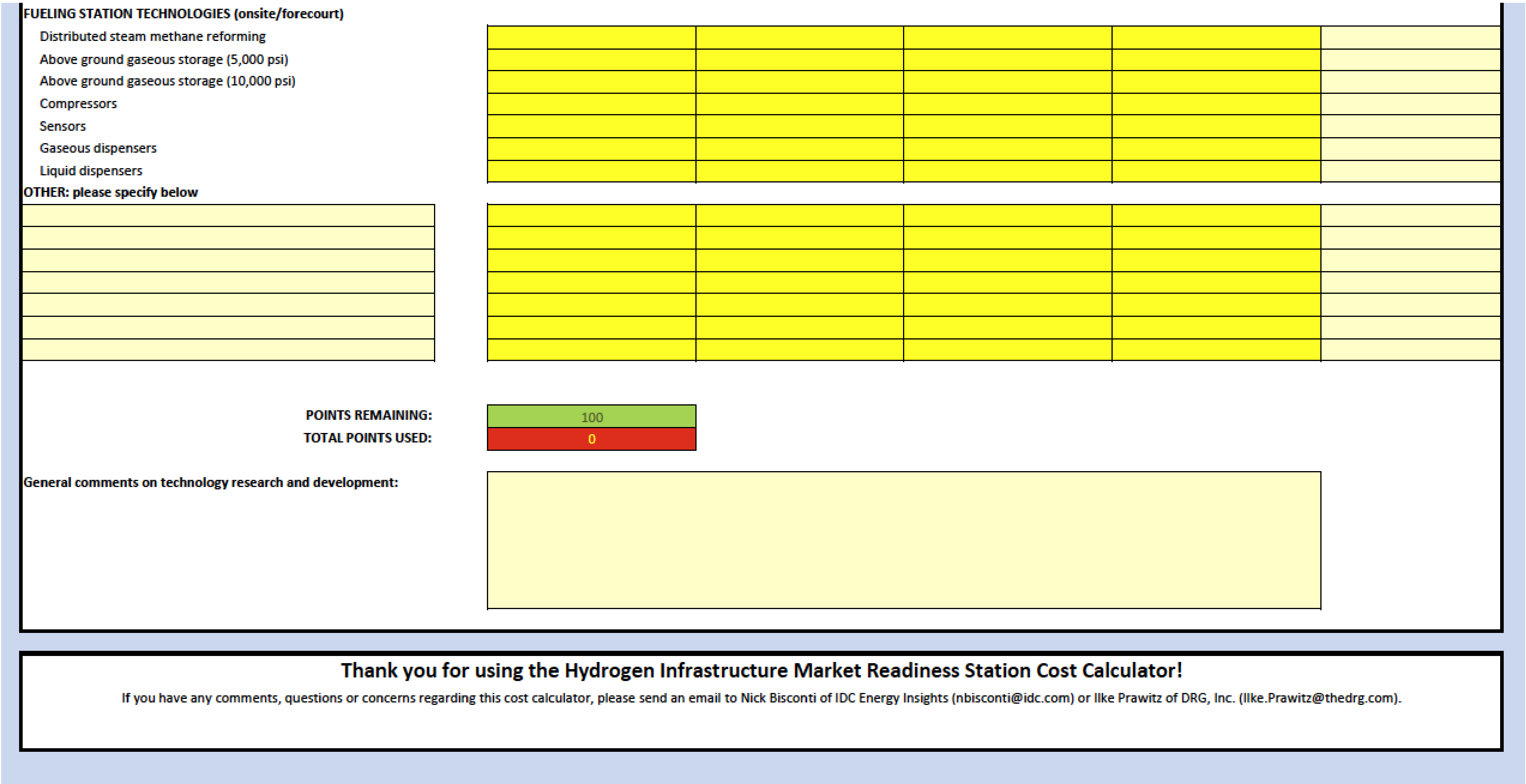
“State-of-the-Art” Hydrogen Station Attributes	State-of-the-Art	Early Commercial	More Stations	Larger Stations	
✓ **Delivered cost of hydrogen:**	$0.00	$0.00	$0.00	$0.00	$/kg
✓ **Station Size (nominal):**	0	0	0	0	kg/day
✓ **Configuration:**	Select from pull down menu	Select from pull down menu	Select from pull down menu	Select from pull down menu	
✓ **Average output:**	0	0	0	0	kg/day
✓ **Year of introduction:**	2011-2012	Select from pull down menu	0	0	year
✓ **Total number of stations installed:**	0	0	0	0	number
✓ **Breakdown of $/kg result:**					
Total capital costs	$0.00	$0.00	$0.00	$0.00	$/kg
Fixed operating costs	$0.00	$0.00	$0.00	$0.00	$/kg
Variable operating costs	$0.00	$0.00	$0.00	$0.00	$/kg
Additional cost items	$0.00	$0.00	$0.00	$0.00	$/kg

If these attributes do not look correct, please revisit the questions above to refine your inputs. If you have questions about how the H2A model calculates the delivered cost of hydrogen within a discounted cash flow framework, please see the model documentation: http://www.hydrogen.energy.gov/h2a_prod_studies.html.

Section C. Effective use of research funds to support hydrogen infrastructure technology R&D

The matrix shown below categorizes different hydrogen infrastructure technology R&D options by pathway component and stage of innovation and commercialization. Given your understanding of the technology advances required to meet the cost per kg, market acceptance, and public policy goals needed for successful hydrogen infrastructure rollout, where do you see the most effective use of research funds over the next 1-3 years for each category indicated? You have 100 points to allocate among the various categories. Comment boxes are provided for additional recommendations on the topic of hydrogen infrastructure technology research and development.

Component	Stage of Technology Innovation and Commercialization				Comments or clarifications
	Laboratory R&D	Pilot Projects & Demonstrations	Scale Up	Commercialization & Deployment	
PRODUCTION (upstream/central)					
Central steam methane reforming of natural gas					
Electrolysis (large scale)					
Biomass reforming (indirect)					
Biomass reforming (direct, or other)					
Coal gasification					
Photobiological production					
Photoelectrochemical production					
Other production methods (specify in comment box)					
DELIVERY					
Gaseous truck delivery					
Liquefaction					
Liquid truck delivery					
Pipeline technology					
Compressors					
PSA separation					
Membrane separation					
Electrochemical separation					
STORAGE (upstream)					
Above ground gaseous storage (5,000 psi)					
Above ground gaseous storage (10,000 psi)					
Underground gaseous storage in caverns					
Liquid storage					
Metal hydride					
Advance storage options					



FUELING STATION TECHNOLOGIES (onsite/forecourt)					
Distributed steam methane reforming					
Above ground gaseous storage (5,000 psi)					
Above ground gaseous storage (10,000 psi)					
Compressors					
Sensors					
Gaseous dispensers					
Liquid dispensers					
OTHER: please specify below					

POINTS REMAINING:	100
TOTAL POINTS USED:	0

General comments on technology research and development:

Thank you for using the Hydrogen Infrastructure Market Readiness Station Cost Calculator!

If you have any comments, questions or concerns regarding this cost calculator, please send an email to Nick Bisconti of IDC Energy Insights (nbisconti@idc.com) or Ilke Prawitz of DRG, Inc. (Ilke.Prawitz@thedrg.com).

References

Bloomberg. (2010). "Toyota Plans $50,000 Hydrogen Fuel-Cell Sedan by 2015." Retrieved December 30, 2011, from http://mobile.bloomberg.com/news/2010-05-06/toyota-targets-50-000-range-for-hydrogen-powered-sedan-planned-by-2015.

BTI. (2011). *2010 Fuel Cell Technologies Market Report, June 2011*. Breakthrough Technologies Institute, Inc., Washington, DC. DOE/GO-102011-3296. Retrieved December 28, 2011, from http://www.nrel.gov/docs/fy11osti/51551.pdf.

CaFCP. (2011). "Homepage." California Fuel Cell Partnership, from http://cafcp.org/.

Collantes, G. (2006). *The California Zero-Emission Vehicle Mandate: A Study of the Policy Process, 1990-2004*. University of California at Davis, Ph.D. Dissertation. UCD-ITS-RR-06-09. Retrieved December 30, 2011, from http://pubs.its.ucdavis.edu/publication_detail.php?id=1038.

DOE. (2011). "Fuel Cell Technologies Program: Durability Working Group." Retrieved December 30, 2011, from http://www1.eere.energy.gov/hydrogenandfuelcells/durability_group.html.

DOE. (2011). *H2A Analysis*. Department of Energy Hydrogen and Fuel Cells Program, Retrieved December 28, 2011, from http://www.hydrogen.energy.gov/h2a_analysis.html.

EERE. (2011). *Energy Department Applauds World's First Fuel Cell and Hydrogen Energy Station in Orange County*. U.S. Department of Energy, Energy Effiicency & Renewable Energy: EERE News, Retrieved December 28, 2011, from http://apps1.eere.energy.gov/news/progress_alerts.cfm/pa_id=600.

FCT. (2011). *The Fuel Cell Today Industry Review 2011*. Fuel Cell Today, Royston, UK. Retrieved December 28, 2011, from http://www.fuelcelltoday.com/media/1351623/industry_review_2011.pdf.

GCC. (2010). "BMW Research and Technology Showcases Hydrogen Fuel Cell Hybrid, On-Board Reformer." Green Car Congress Retrieved December 30, 2011, from http://www.greencarcongress.com/2010/03/bmw-research-and-technology-showcases-hydrogen-fuel-cell-hybrid-onboard-reformer.html.

GCC. (2011a). "Hyundai unveils next-gen FCEV sedan concept Blue2 at Seoul Motor Show." Green Car Congress Retrieved December 30, 2011, from http://www.greencarcongress.com/2011/03/blue2-2-11-331.html.

GCC. (2011b). "Pike Research forecasts fuel cell vehicle cumulative sales to cross the 1M mark in 2020 with $16.9B in annual revenue." Green Car Congress Retrieved December 30, 2011, from http://www.greencarcongress.com/2011/10/pikefcv-20111007.html.

GCC. (2011c). "Topic Area: Fuel Cells." Green Car Congress Retrieved December 28, 2011, from http://www.greencarcongress.com/fuel_cells/.

GCC. (2011d). "Toyota unveiling new hydrogen fuel cell concept vehicle indicative of 2015 production model at Tokyo Motor Show; Aqua hybrid and FT-EV III." Green Car Congress Retrieved December 30, 2011, from http://www.greencarcongress.com/2011/11/tmc-20111115.html - more.

Greene, D., K. G. Duleep, et al. (2011). *Status and Outlook for the U.S. Non-Automotive Fuel Cell Industry: Impacts of Government Policies and Assessment of Future Opportunities*. Oak Ridge National Laboratory, Oakridge, TN. ORNL/TM-2011/101. Retrieved December 28, 2011, from http://info.ornl.gov/sites/publications/files/Pub29486.pdf.

Hoffman, P. (1981) The Forever Fuel: The Story of Hydrogen. Boulder, CO. Westview Press.

Kurtz, J., K. Wipke, et al. (2011). *Fall 2010 Composite Data Products ARRA Material Handling Equipment: Quarter 3 of 2010, Final Version September 30, 2010*. National Renewable Energy Laboratory, Golden, CO. Retrieved Dec 28, 2011, from http://www.nrel.gov/docs/fy11osti/49603.pdf.

McKinsey. (2010). *A portfolio of power-trains for Europe: a fact-based analysis*. McKinsey & Company, Retrieved December 28, 2011, from http://www.iphe.net/docs/Resources/Power_trains_for_Europe.pdf.

NAS. (2004). *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. National Academy of Sciences / National Research Council, National Academies Press, Washington, D.C.

NOW. (2011). "Homepage." Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie, from http://www.now-gmbh.de/de/.

PikeResearch. (2011). *Fuel Cell Vehicles*. Pike Research, Washington, DC. Retrieved December 28, 2011, from http://www.pikeresearch.com/research/fuel-cell-vehicles.

REF. (2009). "Automakers pull together to support fuel cell vehicles." Retrieved December 28, 2011, from http://www.renewableenergyfocus.com/view/4067/automakers-pull-together-to-support-fuel-cell-vehicles/.

Vaitheeswaran, V. and I. Carson (2008). ZOOM: The Global Race to Fuel the Car of the Future, Twelve.