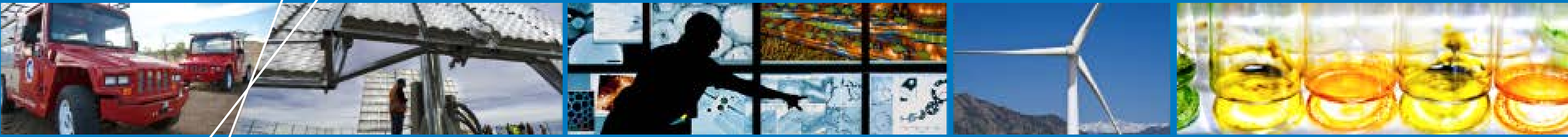
Hydrogen Refueling Infrastructure Cost Analysis



M.W. Melaina, M. Penev
National Renewable Energy Laboratory

2012 Department of Energy Fuel Cell Technologies Program Annual Merit Review

Arlington, VA
May 15, 2012

Project ID:
AN020

Overview

Timeline

Project Start Date: October 2010

Project End Date: September 2012

Percent Complete: 80%

Barriers

Future Market Behavior [4.5.A]

Inconsistent Data, Assumptions, and Guidelines [4.5.C]

Unplanned Studies and Analysis [4.5.E]

Budget

Total project funding

- DOE share: $200,000
- Contractor share: none

Funding received in FY11: $150k

Funding for FY12: $50k

Partners

Formal Collaborators

- IDC Energy Insights (collected input from multiple industry, academic and government stakeholders)

Interactions

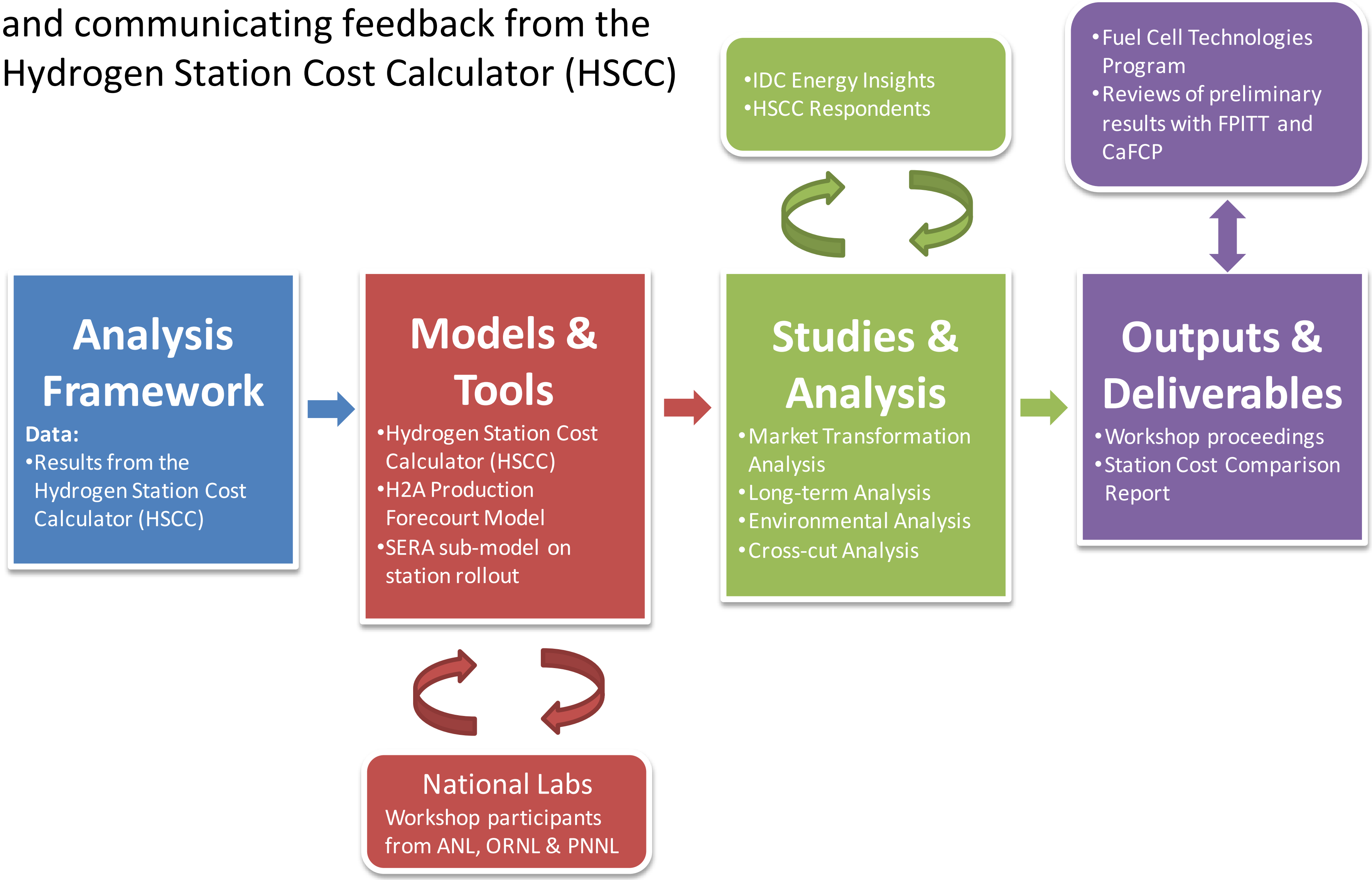
- Multiple reviews
- Workshop Participant Reviews

NREL Project Team

- M. Melaina, M. Penev, D. Steward

Hydrogen Refueling Infrastructure Cost Analysis

Analysis involves collecting, organizing and communicating feedback from the Hydrogen Station Cost Calculator (HSCC)



Analysis Framework

Data:

- Results from the Hydrogen Station Cost Calculator (HSCC)

Models & Tools

- Hydrogen Station Cost Calculator (HSCC)
- H2A Production Forecourt Model
- SERA sub-model on station rollout

National Labs

Workshop participants from ANL, ORNL & PNNL

Studies & Analysis

- Market Transformation Analysis
- Long-term Analysis
- Environmental Analysis
- Cross-cut Analysis

- IDC Energy Insights
- HSCC Respondents

Outputs & Deliverables

- Workshop proceedings
- Station Cost Comparison Report

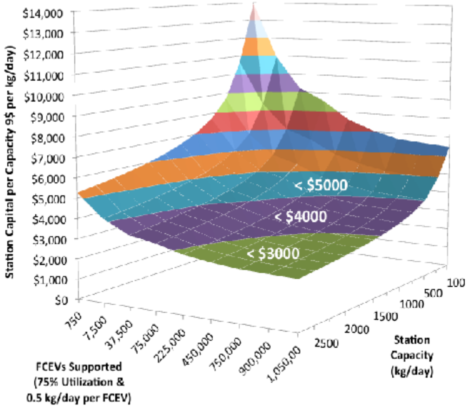
- Fuel Cell Technologies Program
- Reviews of preliminary results with FPITT and CaFCP

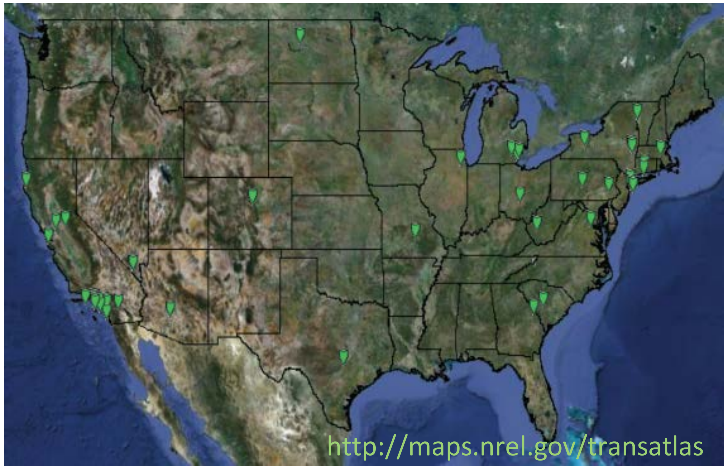
Early Infrastructure Costs are Key to Understanding Investment Options

Relevance [1]

Technology innovation and growing demand from emerging markets are driving down hydrogen infrastructure costs

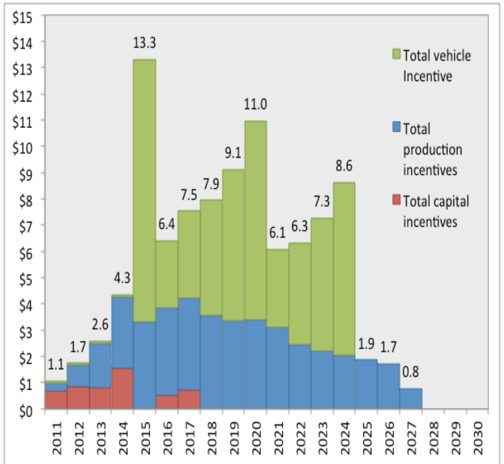
- Near-term cost estimates must be updated to reflect recent progress
- Cost analysis can guide infrastructure investment and deployment decisions
- Understanding overall investment cash flow requires more extensive and systemic business case analysis




http://maps.nrel.gov/transatlas

http://fuelcellsworks.com

What is the cost of moving from where we are today to a high-volume network with 100-1000s of stations?



Analysis of opportunities from the 2011 Early Markets Workshop

Relevance [2]

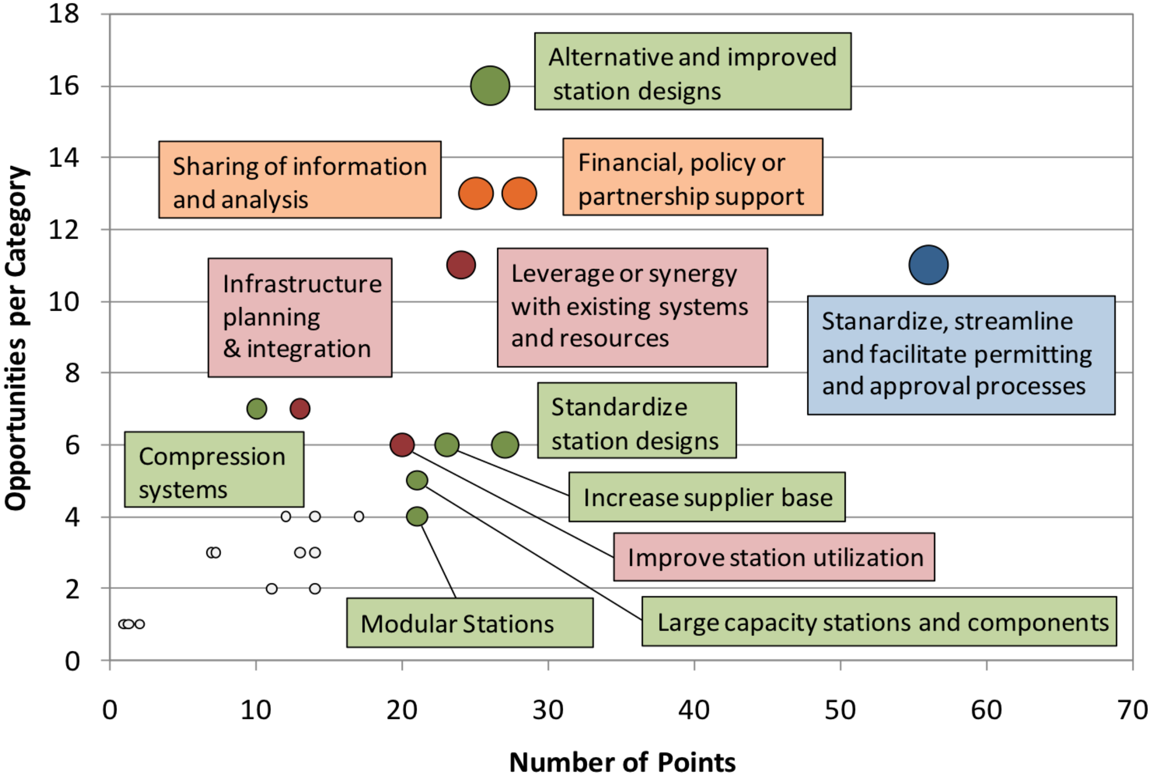
Station cost analysis is the quantitative follow-up activity to the feedback collected at the 2011 Market Readiness Workshop

Four Opportunity Types

- TECHNOLOGICAL
- INSTITUTIONAL, FINANCIAL & POLICY
- STREAMLINE PERMITTING; CODES & STANDARDS
- ANALYSIS, PLANNING AND INTEGRATION

Vertical axis shows the number of opportunities per category, and the horizontal axis shows the total points within each category. Opportunities from panels received 2 points, those from breakout groups received one point plus one for each dot allocated during the participant voting process.

137 cost reduction opportunities identified by panels and break out groups were prioritized by participants. They are categorized below.



Objectives #1 & #2: Identify Station Cost Metrics for Near-term Markets

Relevance [4]

Which cost metrics are most useful for understanding the near-term business case for hydrogen infrastructure investments?

OBJECTIVE #1: Identify the capacity (kg/d) and capital costs associated with "Early Commercial" hydrogen stations

- The value and financial viability of early stations will depend upon a number of factors, including location, size, capital cost and utilization
- Stations supporting early markets may require subsidies – but how long will this market status endure? When will Early Commercial stations be installed and how large will they be?

OBJECTIVE #2: Identify cost metrics for larger numbers of stations (More Stations) and larger capacities (Larger Stations)

- After achieving Early Commercial status, what additional cost reductions can be achieved through economies of scale and volume?
- Experience and learning

Analysis responds to qualitative stakeholder workshop feedback

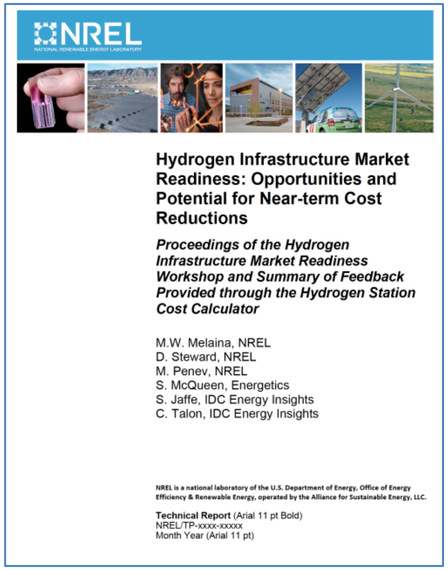
Approach [1]

Stakeholder engagement and feedback provided concrete guidance on cost reduction opportunities

KEY STATION COST REDUCTION OPPORTUNITIES

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
4. Develop "Standard" station designs
5. Harmonize/Standardize dispensing equipment specifications
6. Develop "Type Approvals" for use in permitting
7. Improve information and training available to safety and code officials
8. Develop mechanisms for planning station rollouts and sharing early market information

Workshop proceedings summarize feedback from over 60 participants from a diverse mix of stakeholder groups



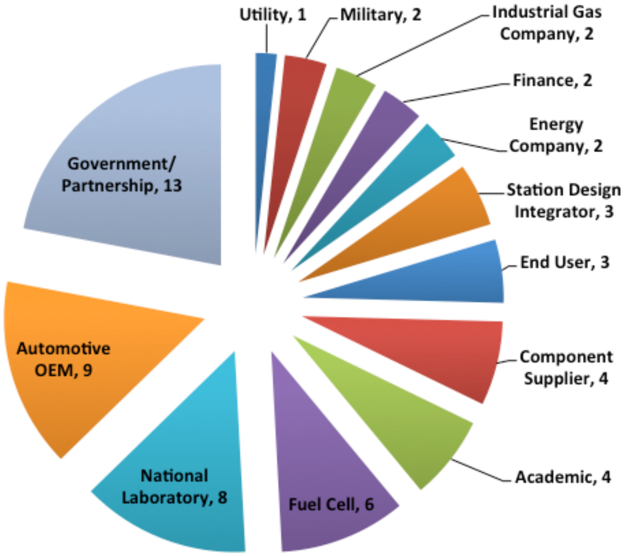
Hydrogen Infrastructure Market Readiness: Opportunities and Potential for Near-term Cost Reductions

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

M.W. Melaina, NREL
D. Steward, NREL
M. Penev, NREL
S. McQueen, Energetics
S. Jaffe, IDC Energy Insights
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 (Arial 11 pt Bold)
NREL/TP-xxxx-xxxxx
Month Year (Arial 11 pt)



Hydrogen Station Cost Calculator (HSCC)

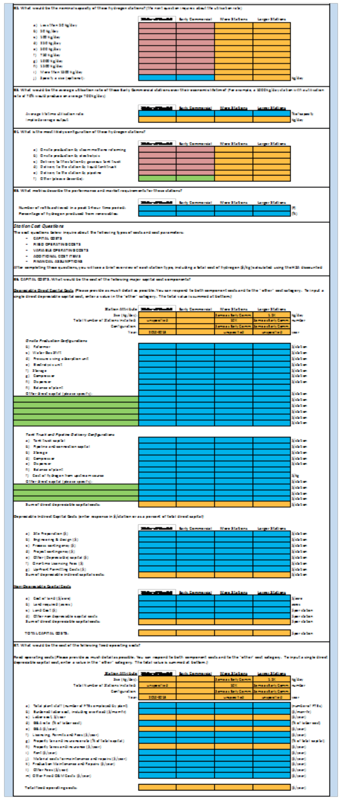
Approach [2]

The HSCC was design to quantify particular cost trends

- The HSCC defines 4 station types:
  - State-of-the-art (SOTA)
  - Early Commercial (EC)
  - More Stations (MS)
  - Larger Stations (LS)
- Respondents were asked to provide input on any station type (or pathway) applicable to their expertise (gaseous truck, onsite production, etc.)
- At the bottom of the HSCC is a “calculate” button that determines the $/kg result based upon respondent’s inputs. Calculation is consistent with H2A.
- Respondents were able to respond to multiple levels of detail in terms of costs and station characteristics. Respondents are also able to provide more aggregate information and still perform the summary $/kg calculations
- Section C is separate from the cost calculation section, and allows respondents to prioritize research funding across the Research, Development, Demonstration and Deployment (RD^3) innovation spectrum.

Types are defined to isolate cost reductions due to scale, volume and experience

HSCC is designed to shows all four types side-by-side



Screenshot shows 33% of total HSCC

Station types defined in the HSCC

Approach [3]

The deployment year, size and cost of "Early Commercial" stations were all posed as open questions within the HSCC

State-of-the-Art Stations (SOTA). Newly installed hydrogen stations with the following attributes: 1) Installed and operational within the 2011-2012 timeframe, 2) include the most recent generations of major components; but not necessarily include novel or "demonstration" components.

Early Commercial Stations (EC). Installed within the next 5-20 years with the following attributes: 1) The stations are financially viable with little government support, 2) The stations are sized to support growing demand in a promising market region, and to ensure adequate ROI, 3) The station design enables cost reductions because it is replicable.

More Stations (MS). Identical to Early Commercial stations, but deployed in larger numbers. Additional cost reductions are achieved through standardization, mass production, streamlining of installation processes and learning by doing.

Larger Stations (LS). Identical to Early Commercial stations, but designed for higher volume output. Default value is a 1.5 increase in size over the Early Commercial stations, with 2000 kg/day as an upper limit.

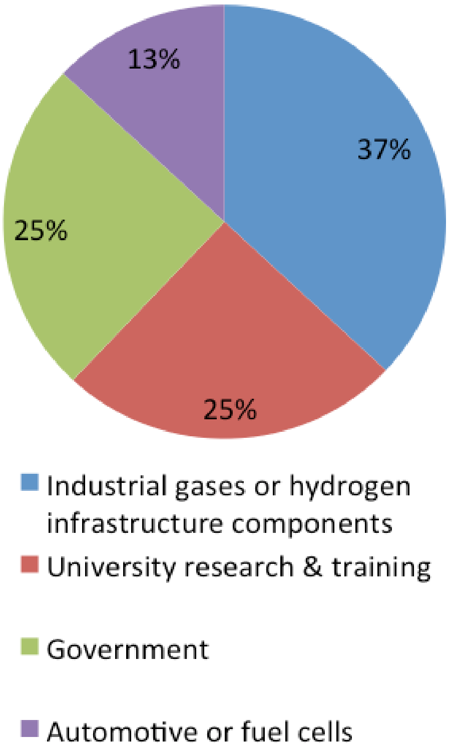
Complete station definitions, as provided in the HSCC, are shown in backup slides

Interpretation, articulation and analysis of HSCC Responses

Accomplishments and Progress [1]

HSCC responses were weighted and aggregated to develop a generic representation of hydrogen station costs and rollout timeframes

- The HSCC was distributed to a select group of experts
- 11 responses were received from a diverse set of stakeholders (see pie chart)
- Responses were weighted based upon industry experience metrics developed by IDC Energy Insights
    - Responses from stakeholders with more historical experience installing hydrogen stations were weighted more heavily
- Respondent anonymity was maintained throughout the data collection and articulation process
- Given that the HSCC allowed for detailed and varied types of responses, some challenges were posed in synthesizing responses into an aggregate and representative whole
    - Different respondents filled out different parts of the HSCC
    - Aggregated results could not be reported for all cost items



HSCC Respondents by Stakeholder Type

Workshop attendees agreed up a range of high priority opportunities

Accomplishments and Progress [2]

Numbers indicate points allocated to each opportunity

STATION DESIGN. (15): Type approval approach – once you're approve to install the station, able to install anywhere, to reduce the administrative costs; streamline codes and standards and permitting. **(11):** Standardize station designs (where possible across applications) and don't "gold plate" it. **(12):** Use a modular approach to building stations (small/medium/large).

PLANNING & PERMITTING. (9): Educate fire marshals and municipalities to ease permitting process. **(7):** Need for more uniform permitting process (uninformed permitting officials). **(8):** Dispensing standards optimization. **(6):** Better educate officials and public on codes and standards. Standardize information directed at local fire marshals.

STRATEGY, POLICY. (10): Provide awards for a network of stations rather than one-off projects. **(8):** Need to address market risk and attract private capital. **(7):** Be willing to sacrifice the number of stations to obtain larger stations, even early on. **(6):** Commitment by Government to support hydrogen in the long term.

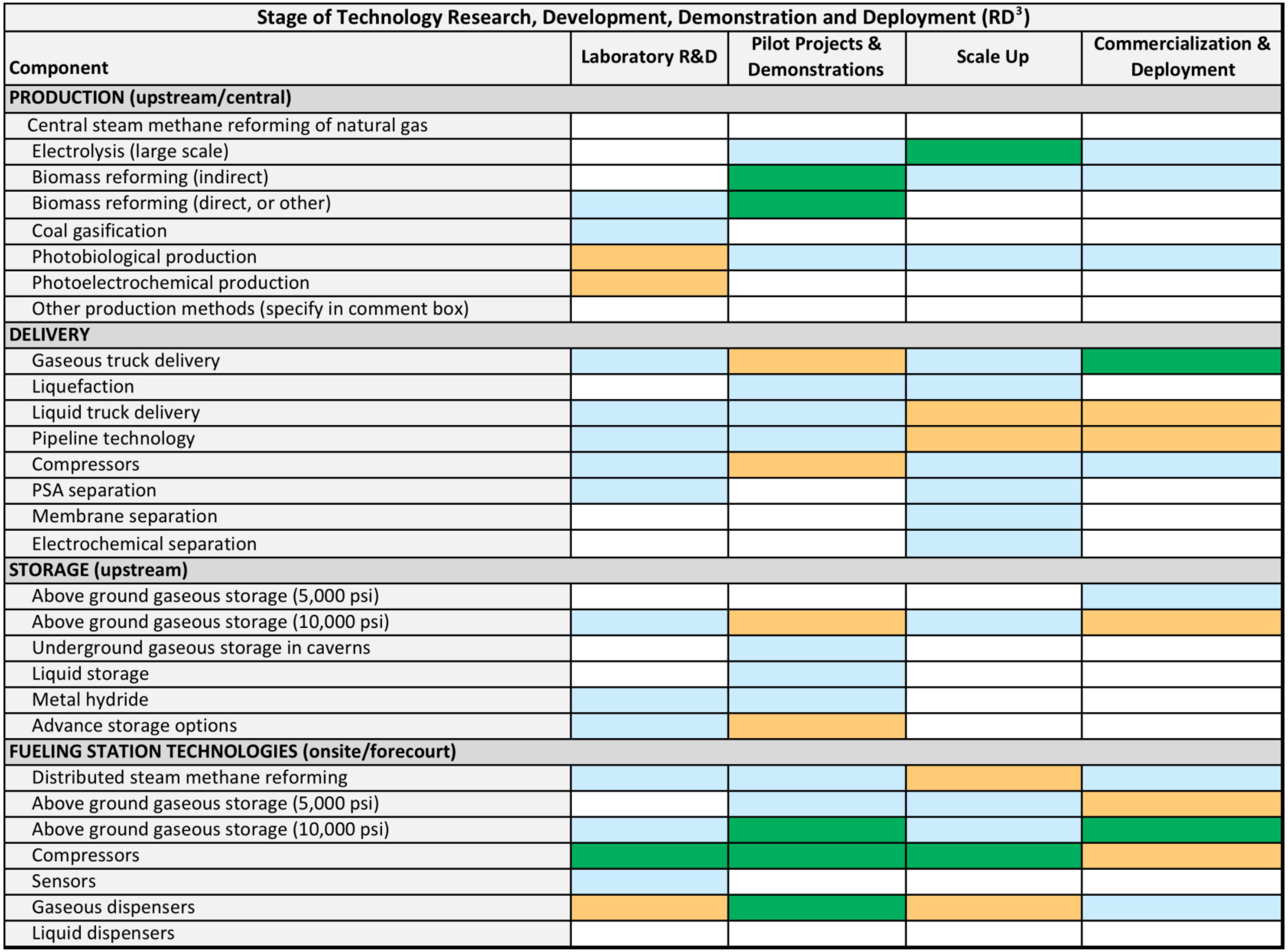
COMPONENTS. (9): Target processes and components (e.g., O-rings) that cause station reliability problems for improvement. **(7):** Cost of 70 MPa hoses (# of suppliers)/ More component manufacturers, a la DOD. **(7):** Large scale compression.

The 14 opportunities show above received the greatest number of points. Note that each STATION DESIGN opportunity has a "standardization" theme.

Priorities for Research, Development Demonstration and Deployment (RD^3)

Accomplishments and Progress [3]

Respondents had 100 points to allocate across topics



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	⬜	⬜	⬜	⬜

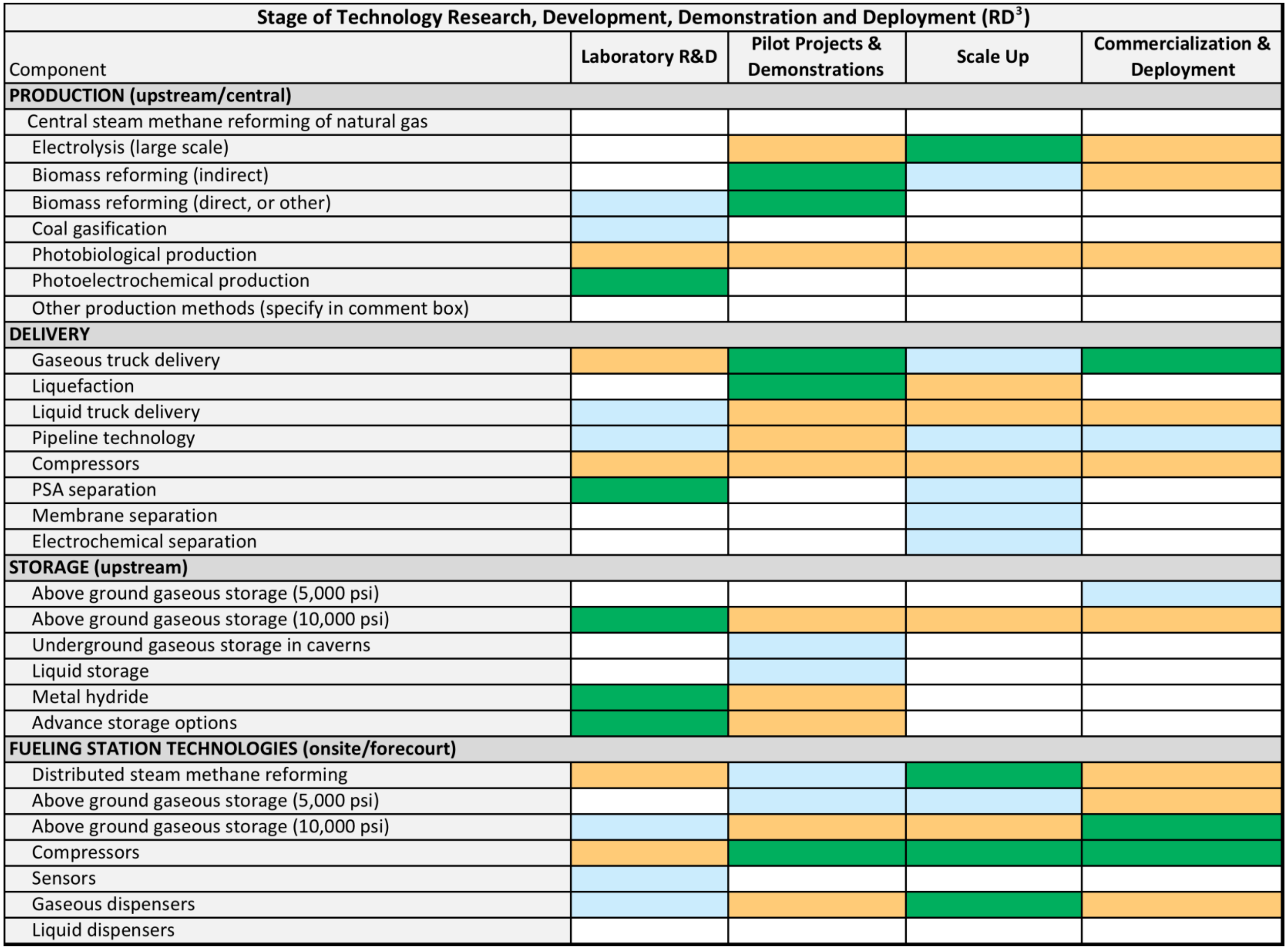
# of Responses	
⬜	0
🟦	1
🟧	2
🟩	3+

- Responses were distributed broadly across topics
- Several items received responses/points across all RD^3 phases
- See backup slide for details

Multiple priorities were identified, stations compressors stand out

Accomplishments and Progress [4]

Respondents had 100 points to allocate across RD^3 topics



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%+

- 100 points total, so average investment as a percent is the same as average number of points allocated
- Station compressors received a large percentage of points across multiple phases

Early station sizes and capital costs

Accomplishments and Progress [5]

HSCC results suggest the following general conclusion:

"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."

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%

Actual station capacities reported by ICD Energy Insights varied slightly from those shown above. A scaling factor (0.51) was used to match capital costs to the nominal values indicated in Table 1 above. The scaling factor fit the EC, MS and LS stations, and a linear function fit the SOTA and EC station capital costs. Each function generated values within 3% of the original values when using the original capacities.

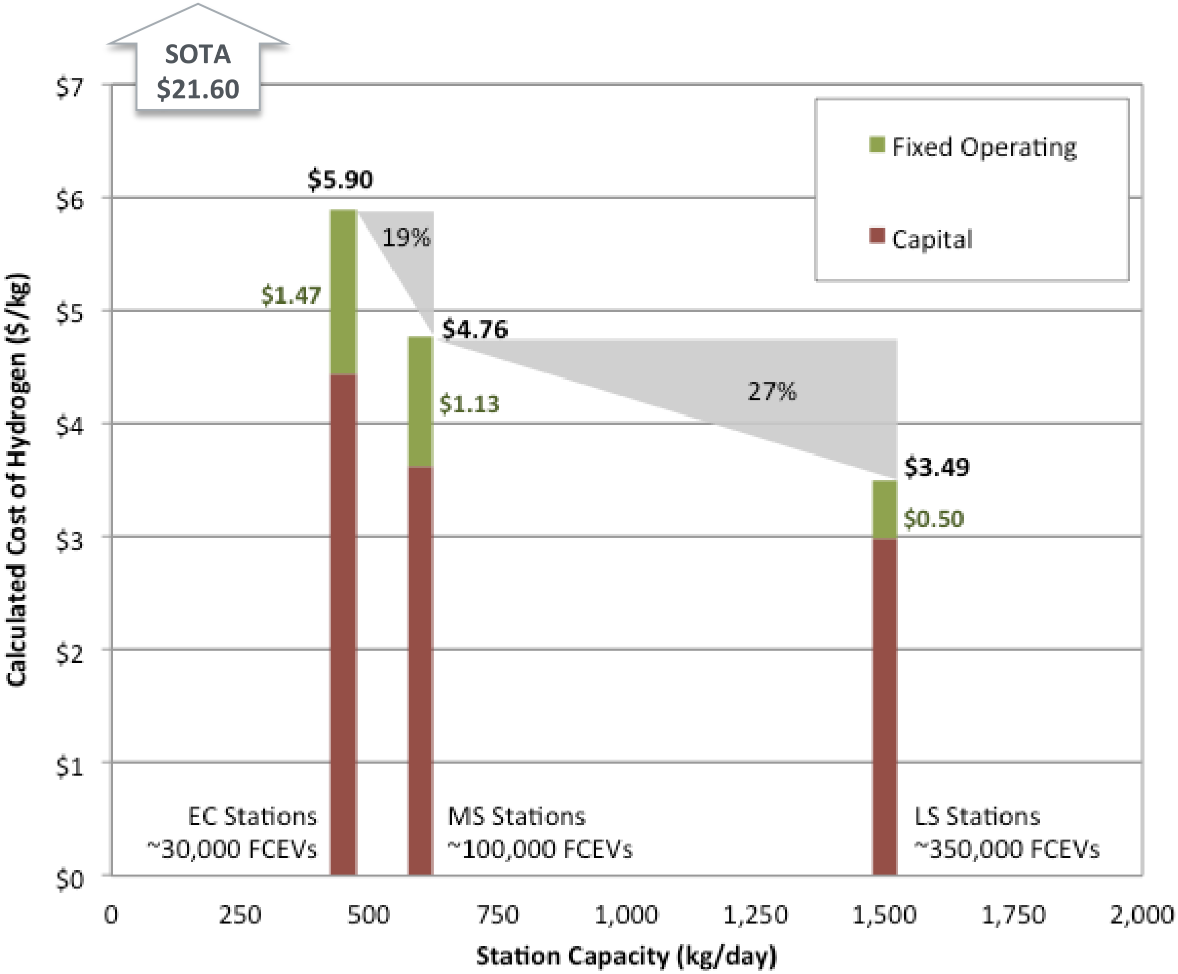
Results suggest an 80% reduction in capital cost per capacity [$/(kg/day)] between SOTA and LS stations. This cost reduction would due to a number of different factors.

Capital and Fixed Operating Costs

Accomplishments and Progress [6]

Capital and fixed operating costs decline by 41% between EC and LS Stations. Variable costs are more station-specific.

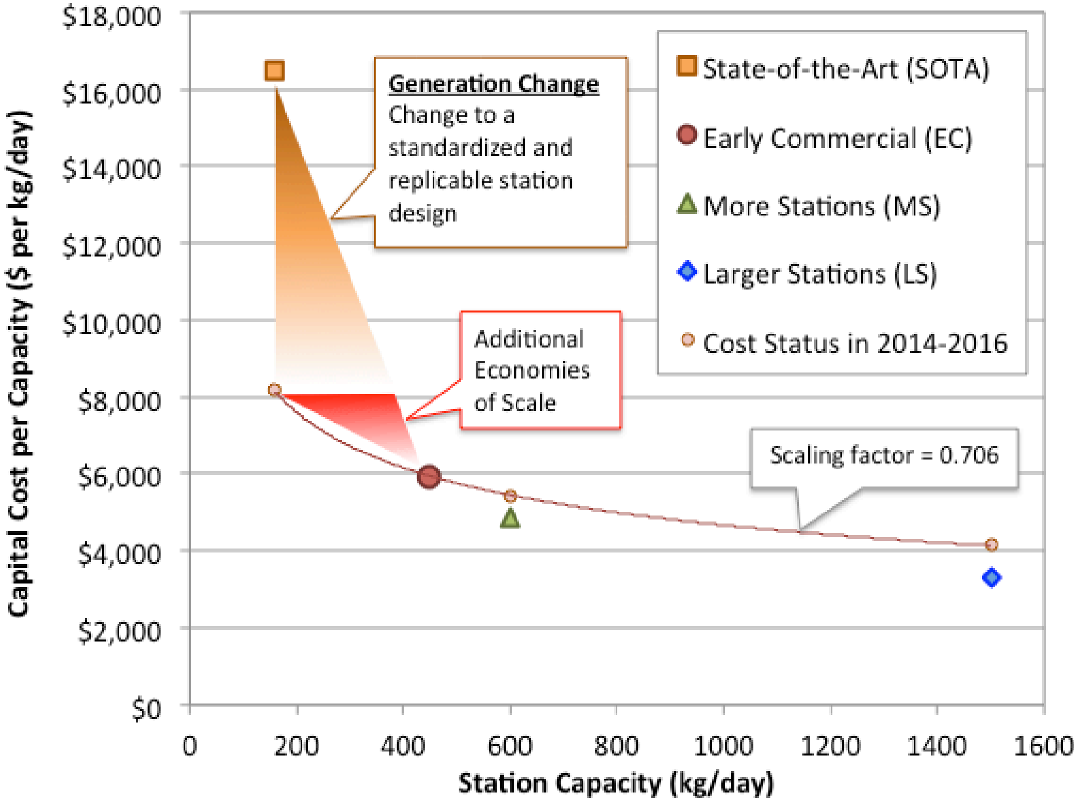
- Taking the weighted, aggregated capital and fixed operating costs results from IDC Energy Insights and plugging them back into the HSCC gives the $/kg results shown at right
- Variable costs are more station specific, especially with regard to electricity consumption being onsite or upstream
- Future analyses will incorporate variable costs based upon performance



Capital Cost Reductions: SOTA-EC

Accomplishments and Progress [8]

HSCC results suggest that significant capital cost reductions can be attained by 2014-1016



Cost Reduction Opportunities Suggested by the Definition of Early Commercial Stations

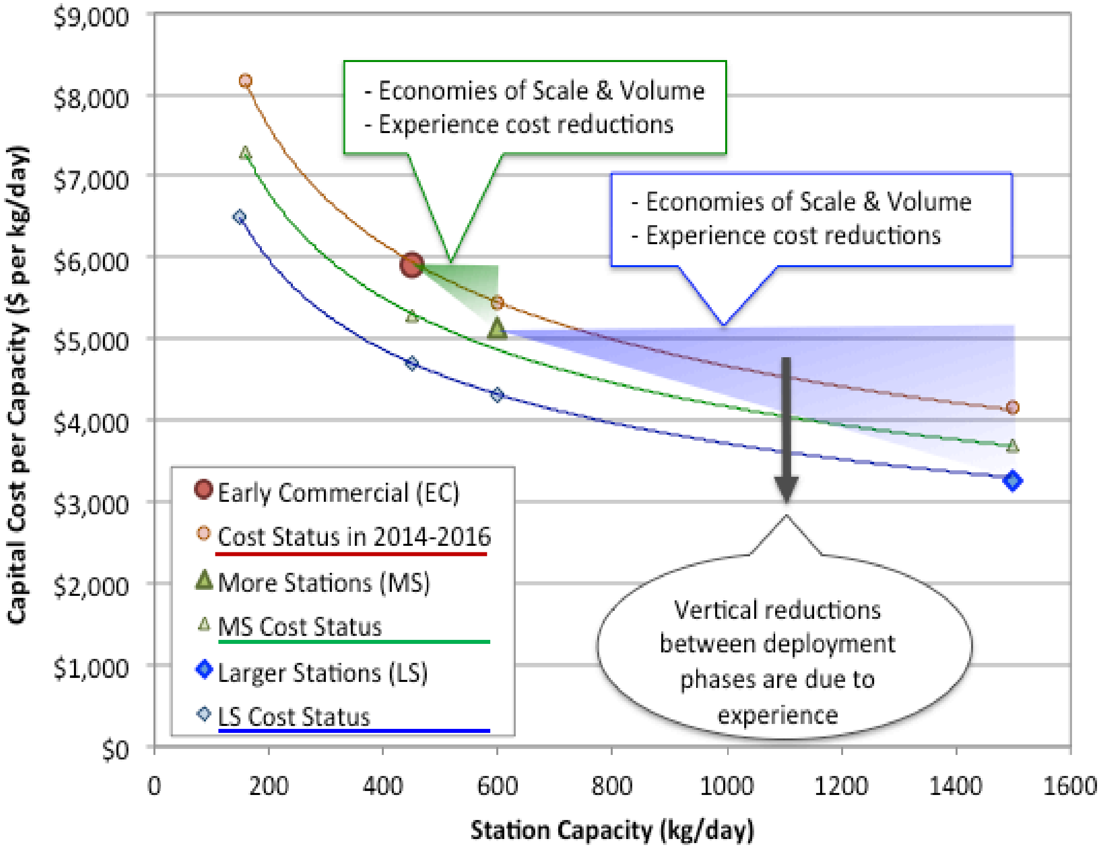
- Develop “Standard” station designs
- Harmonize/Standardize dispensing equipment specifications
- Develop “Type Approvals” for use in permitting
- Encourage station buyers to design RFPs that incentivize standard, scalable designs or networks of stations (rather than one-off, custom-built projects)

The EC Definition in the HSCC was developed based upon workshop feedback.

Capital Cost Reductions: EC-MS-LS

Accomplishments and Progress [9]

Longer-term cost reductions are due to economies of scale and volume, as well as increased experience and learning



A Broader Set of Cost Reduction Opportunities Applies to EC-MS-LS Stations

- Expand and enhance supply chains for production of high-performing, lower-cost parts
- Reduce cost of hydrogen compression
- Develop high-pressure hydrogen delivery and storage components
- Facilitate development of codes and standards for high pressure equipment

High Capital Utilization Rates

- Develop mechanisms for planning station rollouts and sharing early market information

Projecting early station capital investment requirements

A function for early station capital has been developed for size and experience

$$C' = C^{o}\left[\left(\frac{Q'}{Q^{o}}\right)^{\alpha} \Big/ \left(\frac{V'}{V^{o}}\right)^{\beta}\right]$$

C' = Station Capital Cost (\$/stn)

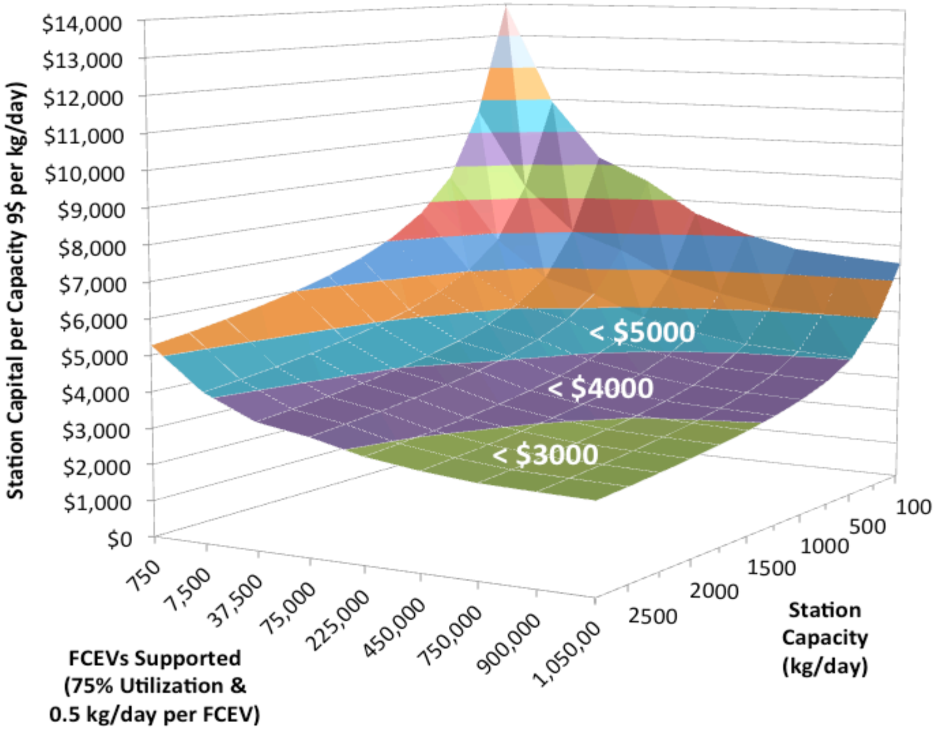
C^{o} = Base Station Capital Cost (\$/stn)

Q' = Station Capacity (kg/d)

Q^{o} = Base Station Capacity (kg/day)

V' = Cumulative Capacity (kg/day)

V^{o} = Cumulative Capacity at Cost Status of Base Station (kg/day)



HSCC Results Suggest:[A]
Scaling Factor ($a = 0.707$)
Learning Factor ($b = -0.106$)
C^{o} (EC) = \$2.65M (see Table 1)
$V^{o} = 25{,}000$ kg/d

Given HSCC responses, a reasonable range for this general equation is probably less than ~750,000 FCEVs, or 500,000 kg/day. Additional empirical data on station costs is needed before establishing a more robust learning function, ideally articulated by station type.

Collaboration

Collaborations [1]

HSCC was a follow-up activity to the 2011 Market Readiness Workshop

- Design of the HSCC was based upon feedback received during and after the Market Readiness workshop
- HSCC results were received from a select group of technology experts
- Significant work was involved in clarifying and articulating results received by IDC Energy Insights and subsequently provided to NREL staff

Additional reviews

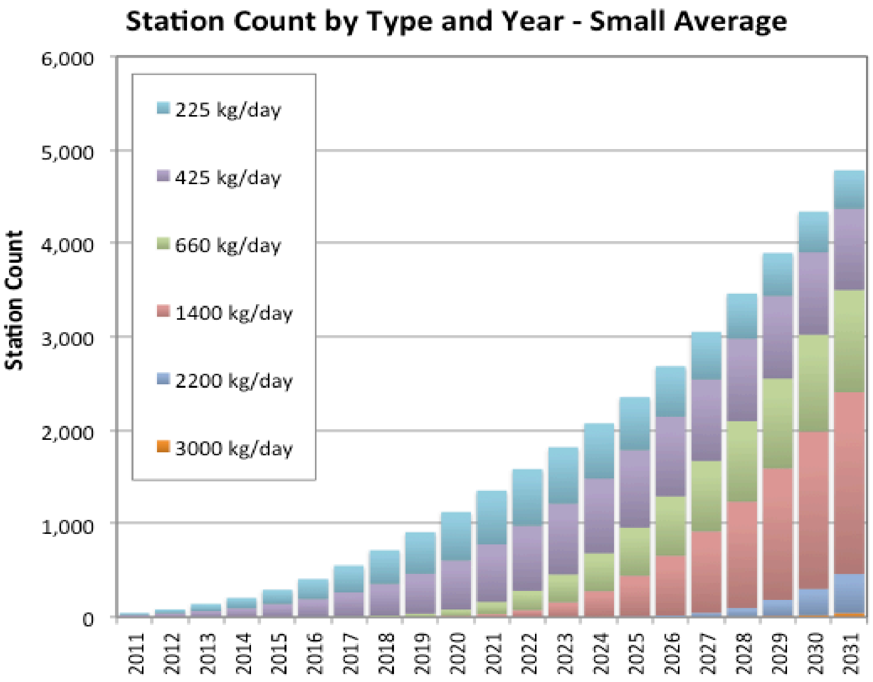
- Preliminary results reviewed with California Fuel Cell Partnership stakeholders
- Multiple reviews with the USDRIVE Fuel Pathways Integration Tech Team (ExxonMobil, Chevron, Shell Oil Products, ConocoPhillips and Air Products and Chemicals, Inc.)
- Cost results were compared to recent hydrogen stations awards from the California Energy Commission

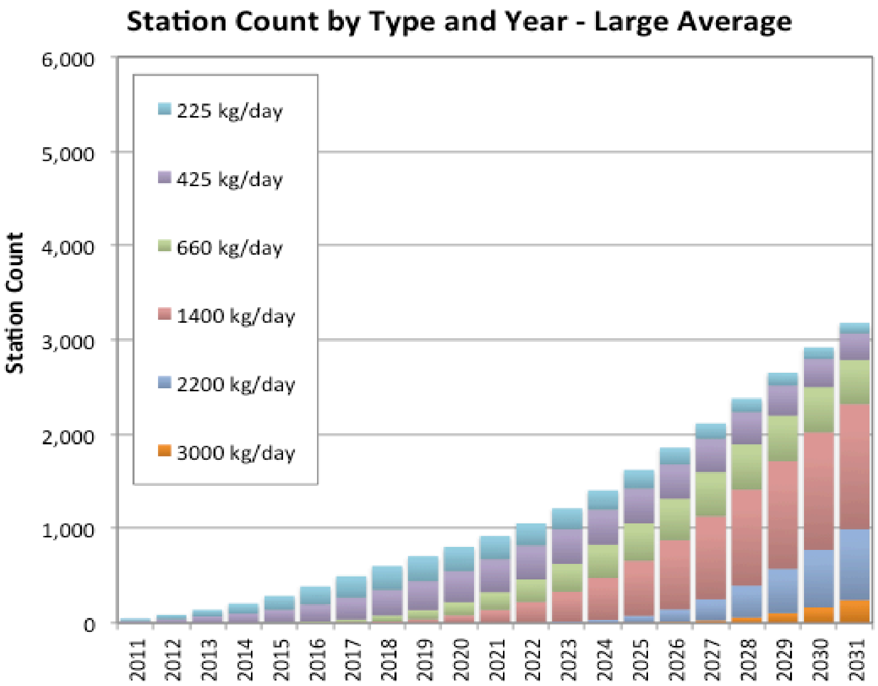
Station Size Distribution: Station Coverage vs. Capacity

Proposed Future Work [1]

Retail markets (and other phenomena) tend to have size distributions with long tails. Will future hydrogen station networks mimic gasoline?

- The long-term average station size will depend upon rollout dynamics, market entry and competition, and urban form
- The distributions below are a generic example of balancing size and number


Station Count by Type and Year - Small Average


Station Count by Type and Year - Large Average

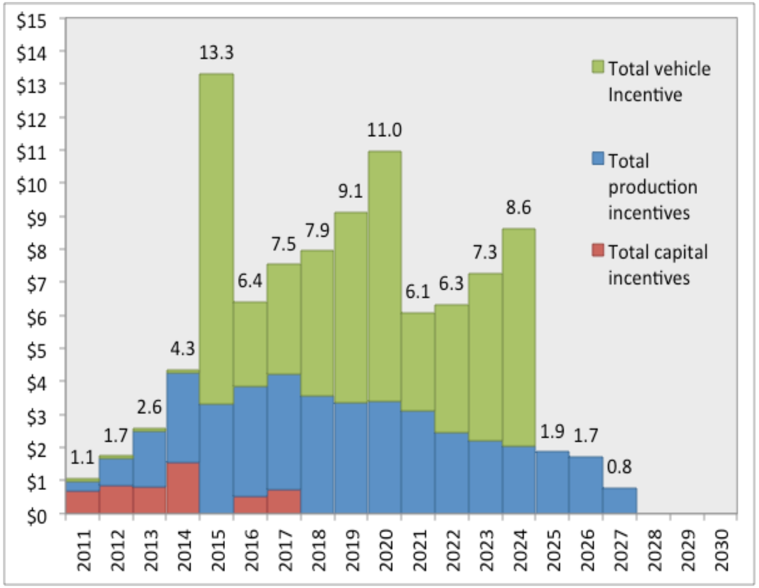
System and Station Business Cases

Proposed Future Work [2]

More realistic business metrics must be included in cost analyses to inform future infrastructure investment decisions and strategies

- The dynamic cost model for early stations must be supplemented with a more detailed cost model for vehicles to understand transition dynamics
- Investment decisions may depend upon multi-party agreements, and therefore cost models must account for different sources of capital and risk tolerance levels
- Subsidies will likely be needed, but where should they be placed, to what degree, and for how long?
- Understanding infrastructure investment opportunities implicates vehicle adoption speed and geographic concentration

NREL's involvement in ongoing roadmap and deployment activities, especially in California and Hawaii, is contributing to more realistic analytic representations of the business case for infrastructure investment.



Project Summary

Relevance

- Station costs have changed due to technology innovation and growth in early markets
- Understanding the business case for 100s-1000s of stations requires updated cost and cash flow analysis

Approach

- Market Readiness workshop identified qualitative cost reduction opportunities
- Hydrogen Station Cost Calculator (HSCC) collective quantitative feedback anonymously, and several cost components were generalized through weighting and aggregation

Technical Accomplishments and Progress

- Quantification of capital and fixed costs by station size and timeframe
- Based upon specific definition of an “Early Commercial” station

Collaboration

- IDC Energy Insights administered the HSCC, collecting feedback from multiple stakeholders

Proposed Future Research

- Integrate results into infrastructure rollout cash flow (via the SERA model)

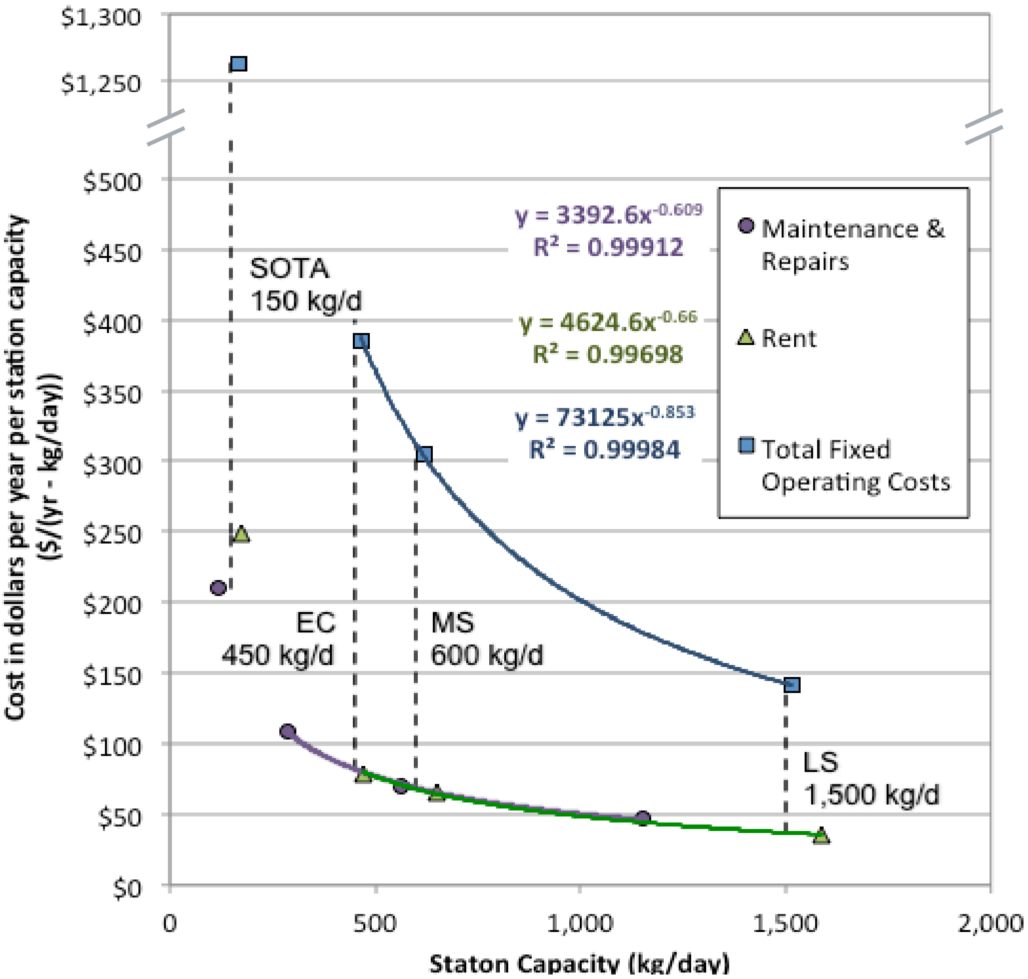
Technical Backup Slides

Fixed Operating Cost Estimates

Accomplishments and Progress

Parametric fits were made for the forward-looking station types ES, MS, & LS

- The curves developed do not approximate aggregate results for SOTA stations
- This suggests a step-change or “generation” improvement in Fixed Operating Costs between SOTA and EC
- These costs are based upon a unique subset of HSCC results (and are higher than the fixed operating values below)
- Reported variable costs, such as cost of hydrogen delivered or feedstock costs, were removed from the final data



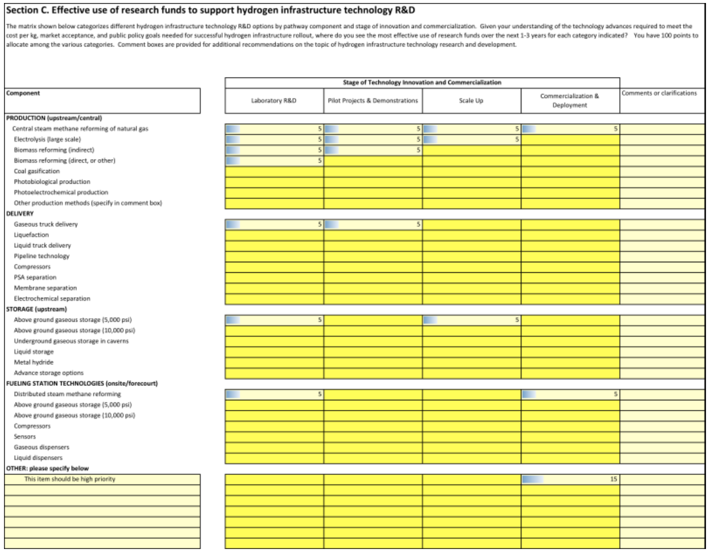
NOTES: 1) The parametric fit to Total Fixed Operating Costs for a station size of 150 kg/day is $915 $/(yr–kg/day), which is 28% less than the corresponding data point indicated above. 2) Rent and Maintenance & Repair cost curves above are nearly identical.

HSCC: Text accompanying section where RD3 phases were allocated 100 points

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.

Screen shot of Section C. Respondents where shown how many points they had allocated, and blank spaces were given at bottom to add additional items.



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	Stage of Technology Innovation and Commercialization				
Component	Laboratory R&D	Pilot Projects & Demonstrations	Scale Up	Commercialization & Deployment	Comments or clarifications
PRODUCTION (upstream/central)					
Central steam methane reforming of natural gas	5	5	5	5	
Electrolysis (large scale)	5	5	5		
Biomass reforming (indirect)	5	5			
Biomass reforming (direct, or other)	5				
Coal gasification					
Photobiological production					
Photoelectrochemical production					
Other production methods (specify in comment box)					
DELIVERY					
Gaseous truck delivery	5	5			
Liquefaction					
Liquid truck delivery					
Pipeline technology					
Compressors					
PSA separation					
Membrane separation					
Electrochemical separation					
STORAGE (upstream)					
Above ground gaseous storage (5,000 psi)	5		5		
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	5			5	
Above ground gaseous storage (5,000 psi)					
Above ground gaseous storage (10,000 psi)					
Compressors					
Sensors					
Gaseous dispensers					
Liquid dispensers					
OTHER: please specify below					
This item should be high priority				15	

Station definitions included in the HSCC

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), 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.** 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.

References and Additional Notes

McDonald, A. and L. Schrattenholzer (2001). "Learning rates for energy technologies." Energy Policy 29: 255-261.

Wene, C.-O. (2000). Experience curves for energy technology policy. Paris, Organisation for Economic Co-operation and Development, International Energy Agency.

[A] This general capital cost equation does not necessarily apply beyond a cumulative installed capacity of approximately 500,000 kg per day. The HSCC results suggest that most respondents were not projecting costs beyond this level of infrastructure expansion, which, assuming an average station size of 1000 kg/d, is about 500 stations total. The experience curve Progress Ratio is 95.8 (2^-0.062), which is relatively conservative for new energy technologies (Wene 2000; McDonald, Schrattenholzer 2001). However, sufficient historical experience with hydrogen station costs has not be achieved to justify a truly general and empirical learning rate. Therefore, if available, design and technology-specific cost estimates should be employed beyond approximately 100,000 - 500,000 kg per day of cumulative installed capacity. As discussed above, the HSCC results are generic for all station types anticipated by respondents within the time frames reported.