2015 DOE Hydrogen and Fuel Cells Program Annual Merit Review

Hydrogen Fueling Station Pre-Cooling Analysis

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Overview

Timeline

- Start: FY 2015
- End: Determined by DOE
- % complete (FY15): 70%

Barriers/Challenges

- Lack of Hydrogen Infrastructure Options Analysis
- Evaluate energy and emission benefits of H_2 FC technologies
- Overcome inconsistent data, assumptions, and guidelines
- Conduct unplanned studies and analyses

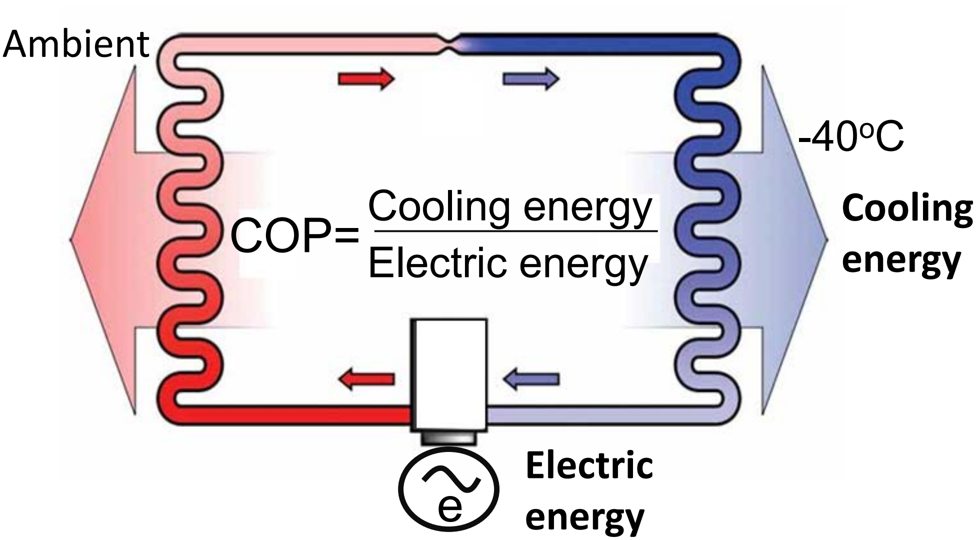
Budget

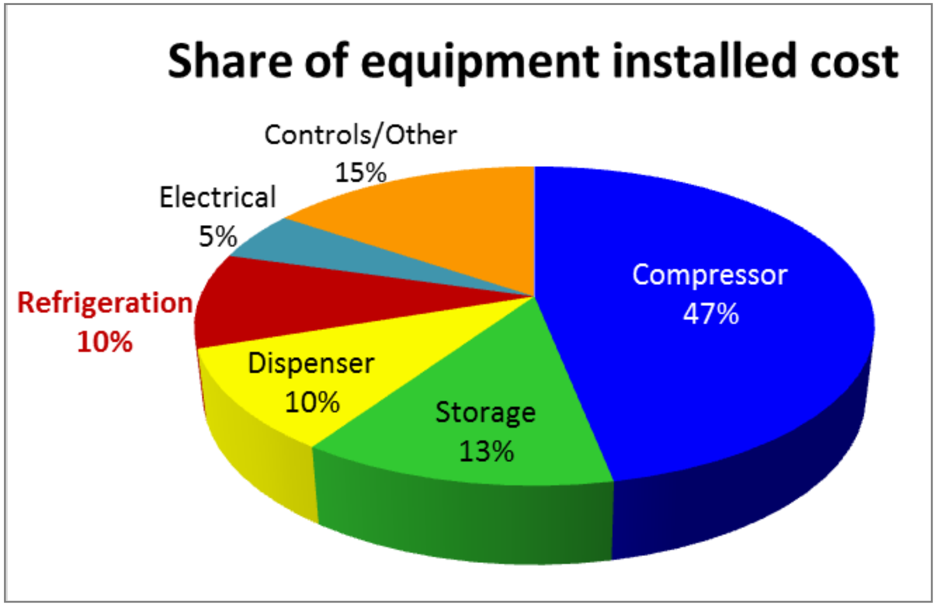
- FY15 Funding: $100K
- 100% DOE funding

Partners/Collaborators

- PNNL
- Boyd Hydrogen
- Linde Americas
- H2 Frontier
- Honda R&D Americas
- Hydrogen station operators

Refrigeration is a major contributor to refueling cost – Relevance/Motivation





- Equipment cost of pre-cooler plus heat exchanger (HX) is significant
  - SAE J2601 hydrogen fueling protocol for T40 stations requires at least -33°C cooling at the dispenser within 30 seconds
  - Joule-Thomson (J-T) effect by variable area control device (VACD) at beginning of fill may increase temperature of H_2 ahead of HX by up to 40°C
- Operating energy cost is a concern with less frequent fueling
  - 50-60 kWhe/kg_{H2} for cooling is reported from EU early station operations
    - ~\$5-\$7/kg_{H2} cost of cooling energy (@ \$0.10-\$0.12/kWhe)

> Research Question: What is the energy penalty and cost of precooling per kg of dispensed hydrogen? Can it be reduced?

International stakeholders identified several areas of research to reduce cooling cost – Relevance

- 2nd international workshop on hydrogen refueling infrastructure (May 8-9, 2014 CA) identified pre-cooling energy consumption as a challenge and recommended the following activities:
  - ✓ Optimize pre-cooler and heat exchanger operation
  - ✓ Perform study on costs, temperature, rates and utilization
  - ✓ Review other fueling protocols
  - ✓ Examine impact of semi-continuous cooling to meet SAE J2601
  - ✓ Develop an on-demand hydrogen chiller

European Commission

NOW National Organisation Hydrogen and Fuel Cell Technology

Scandinavian Hydrogen Highway Partnership

NEDO New Energy and Industrial Technology Development Organization

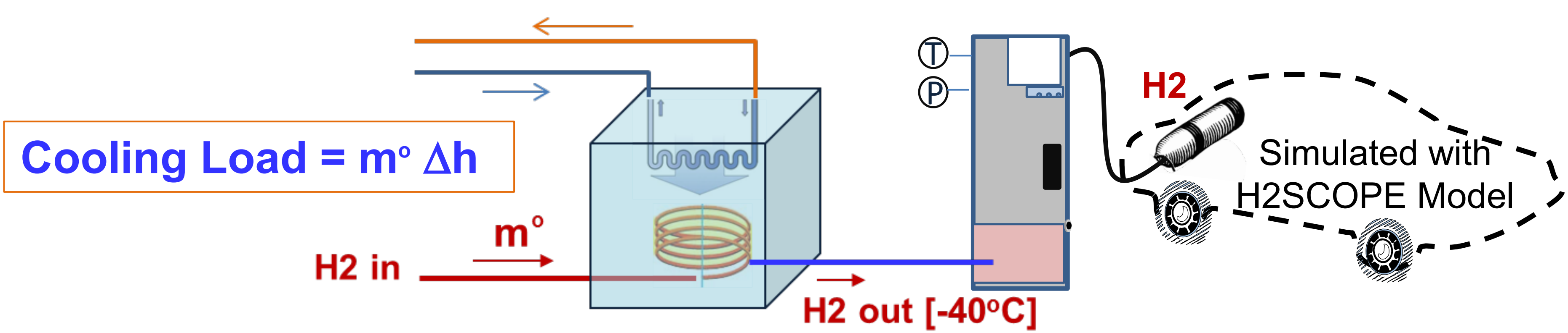
U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy

http://energy.gov/sites/prod/files/2015/03/f20/fcto_webinarslides_2nd_international_h2_infrastructure_challenges_031015.pdf

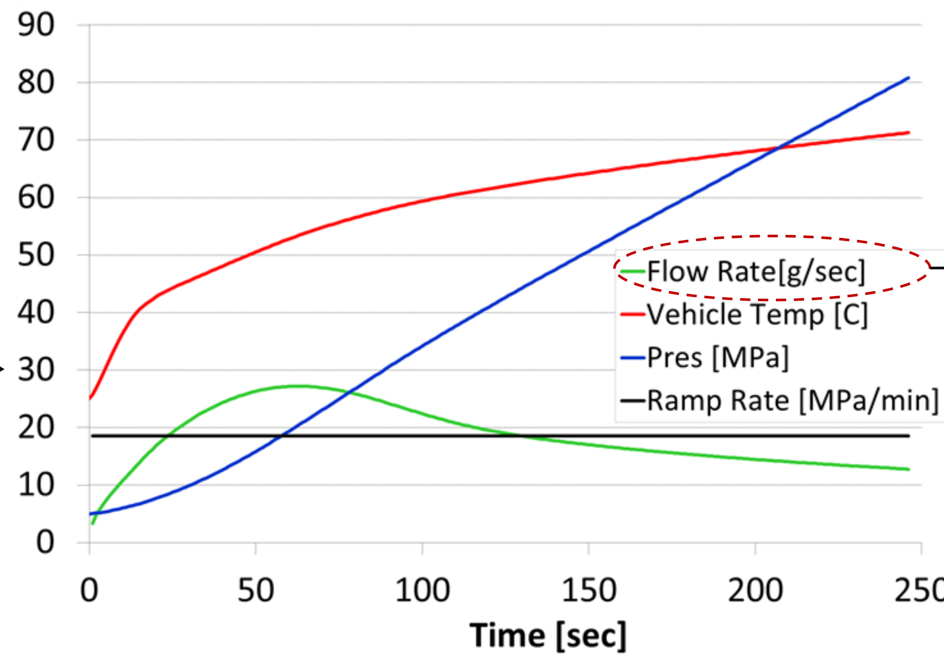
Theoretical analysis combined with real-world validation – Approach

- **Evaluate** theoretical precooling requirement at hydrogen refueling stations (HRS)
  - With respect to SAE J2601 refueling protocol
  - Determine size of precooling equipment and heat exchanger
- **Collaborate** to acquire information on refueling operation, and to examine/review results
- **Examine** current pre-cooling equipment design and cost
- **Identify** major drivers for precooling cost and energy consumption
  - Impact of HRS utilization and frequency of fills
  - Impact of number of back-to-back fills
  - Impact of SAE J2601 30-sec window to reach precooling temperature
- **Analyze** tradeoff between different design concepts
- **Vet** analysis results and findings
  - Internally via partners
  - Externally, via collaborators, interacting with US DRIVE Tech Teams, and reaching out to experts from industry

Simulated transient vehicle fill rate – Approach

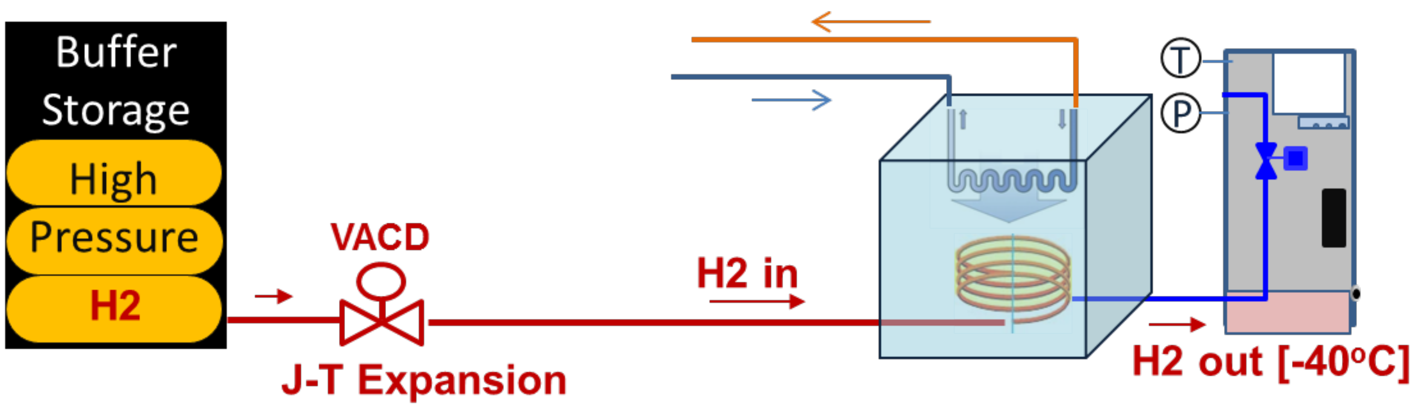


Fill rate can reach 30 g/sec during fueling



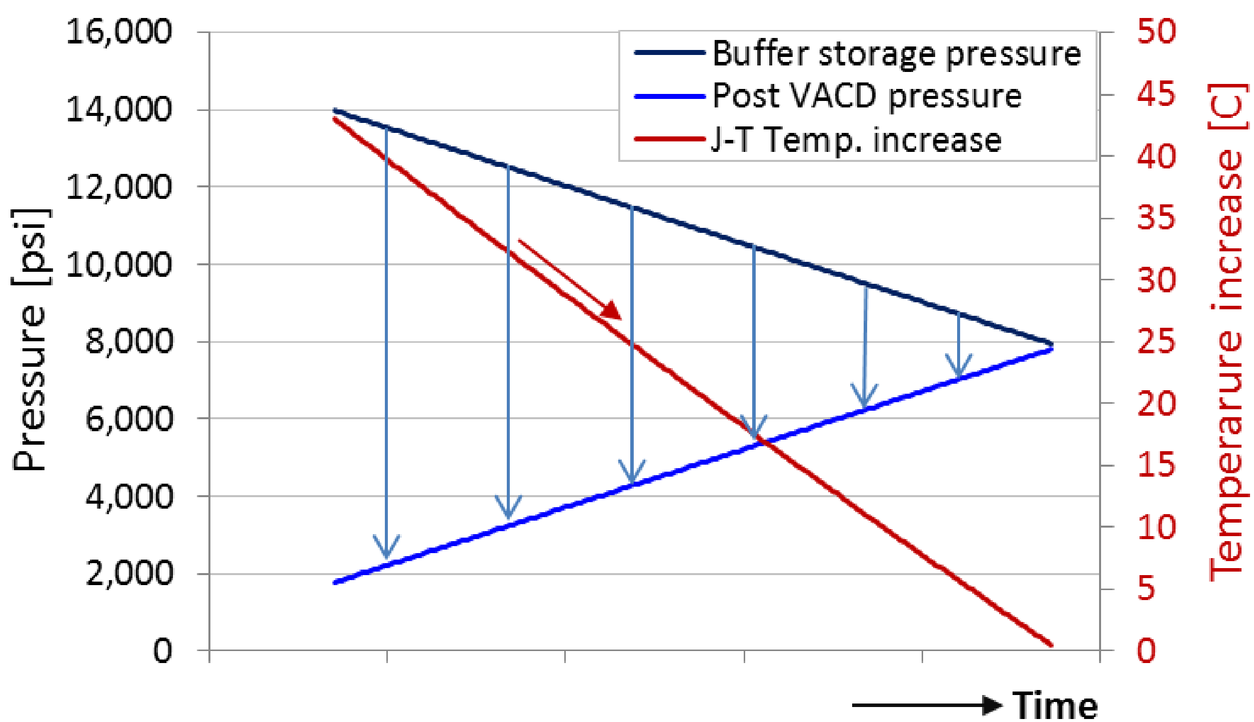
Design consideration for on-demand cooling

Evaluated impact of J-T expansion at VACD – Approach

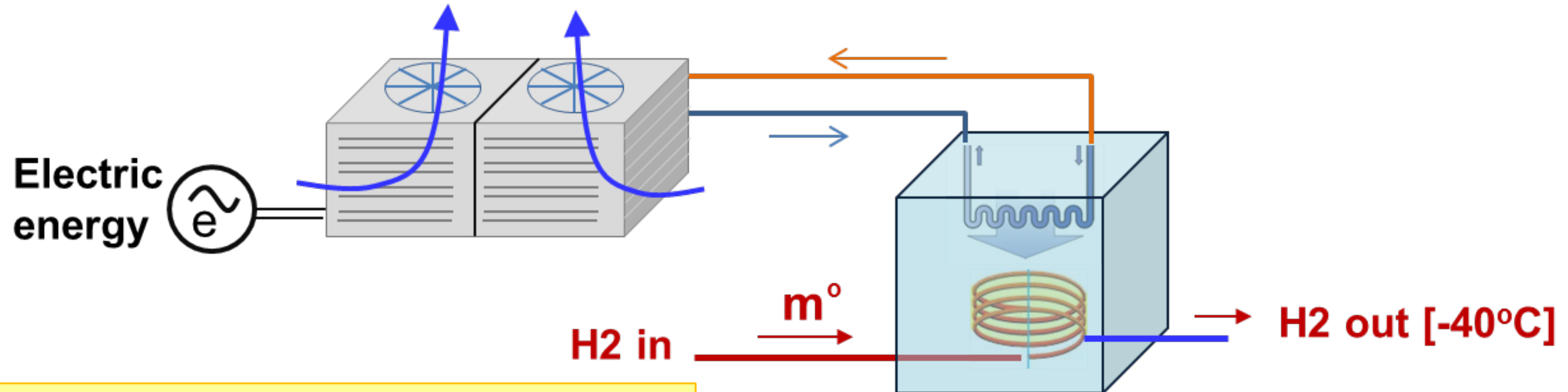


HX capacity = UA $\Delta T_{log\text{-}mean}$

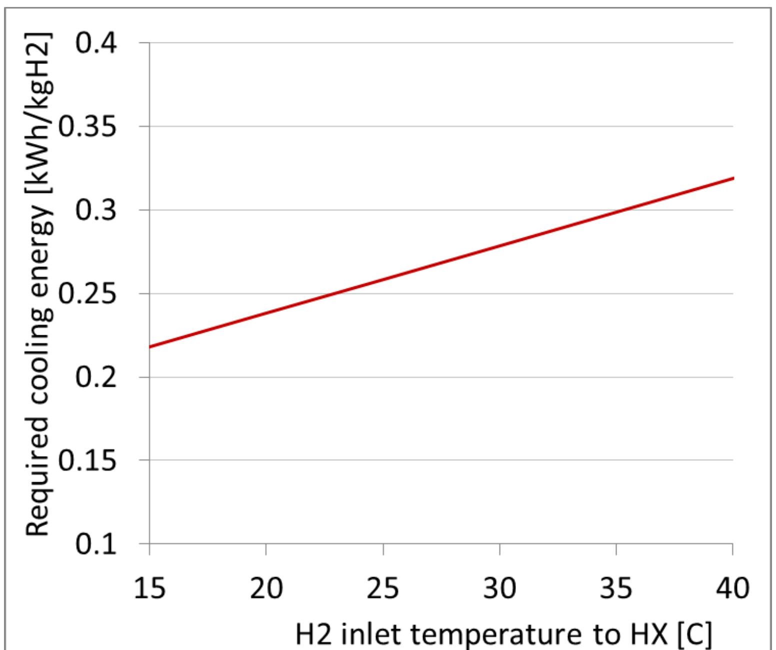
Temperature rise could be as high as 40°C at beginning of fill

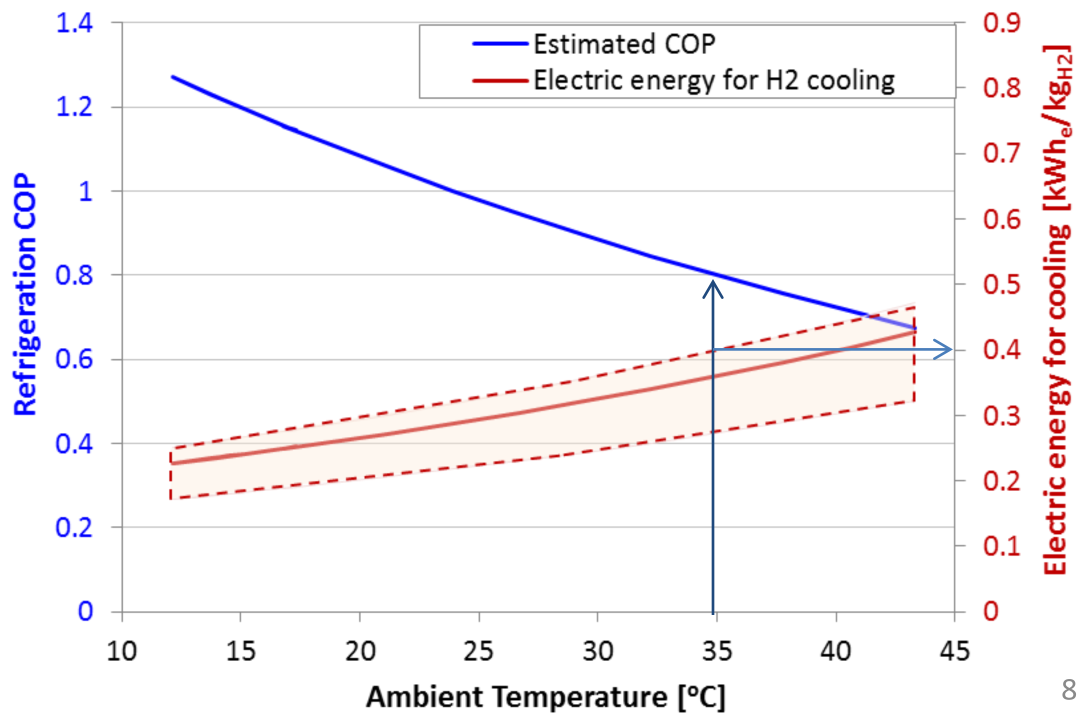


Electricity consumption required for cooling H_2 is small – Accomplishment

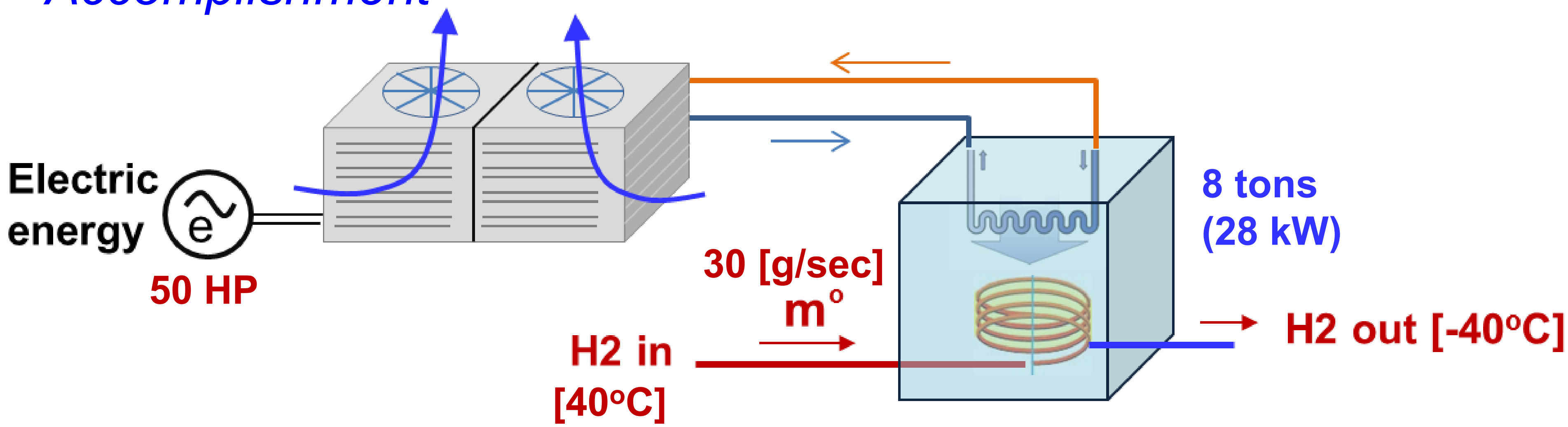


Electric energy for cooling H_2 < 0.5 kWhe/kg_{H2}
<< reported 50-60 kWhe/kg_{H2}





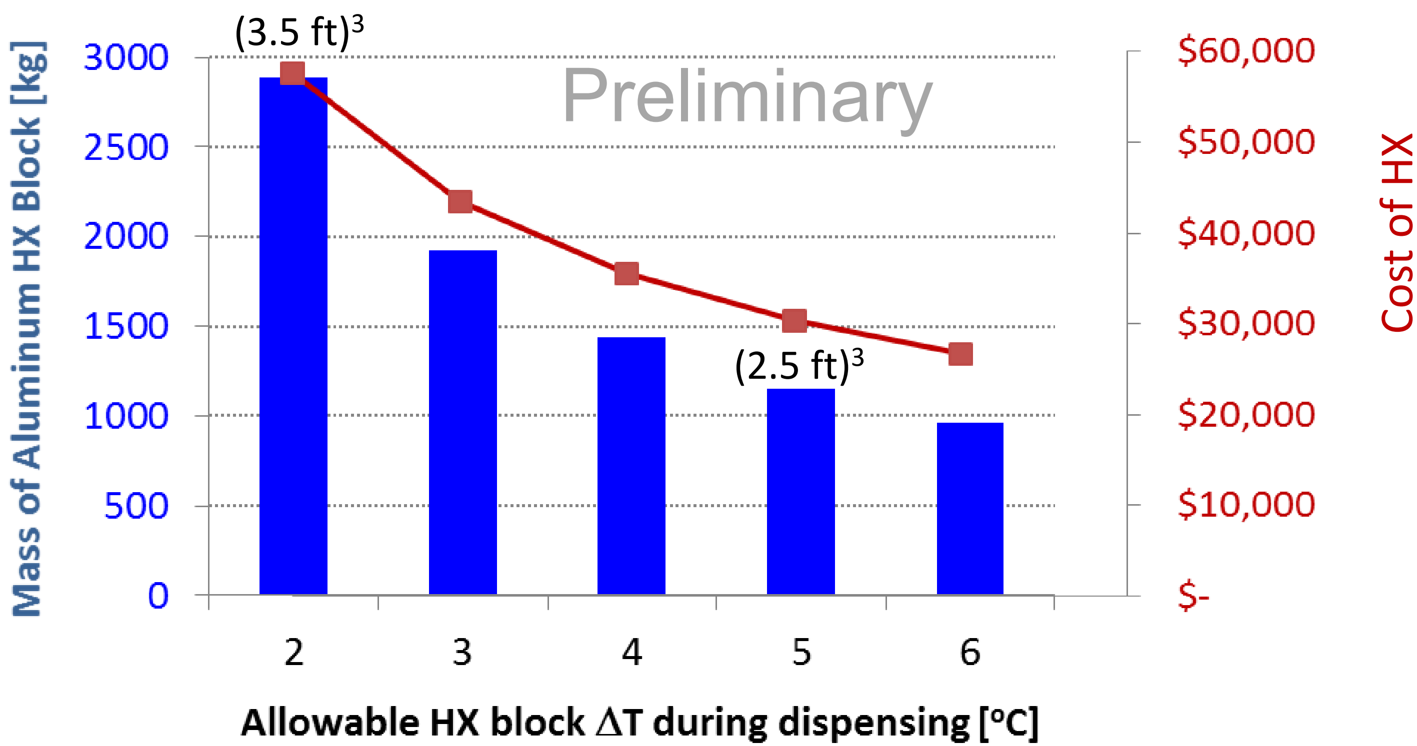
Cooling capacity is large for on-demand cooling – Accomplishment



- ~28 kW (8 ton) of cooling capacity per hose
  - ✓ at T_{H2_in} = 25°C and max flow rate of 30 g/sec
  - ✓ ~ 38 kWe (~50 HP) electric power @40°C ambient
- Requires fast transient ramp-up of cooling within 30 sec
  - ✓ Requires high UA, low thermal mass, compact HX
- Subject to temperature fluctuation supplied to dispenser

On-demand cooling represents the upper bound on refrigeration capacity

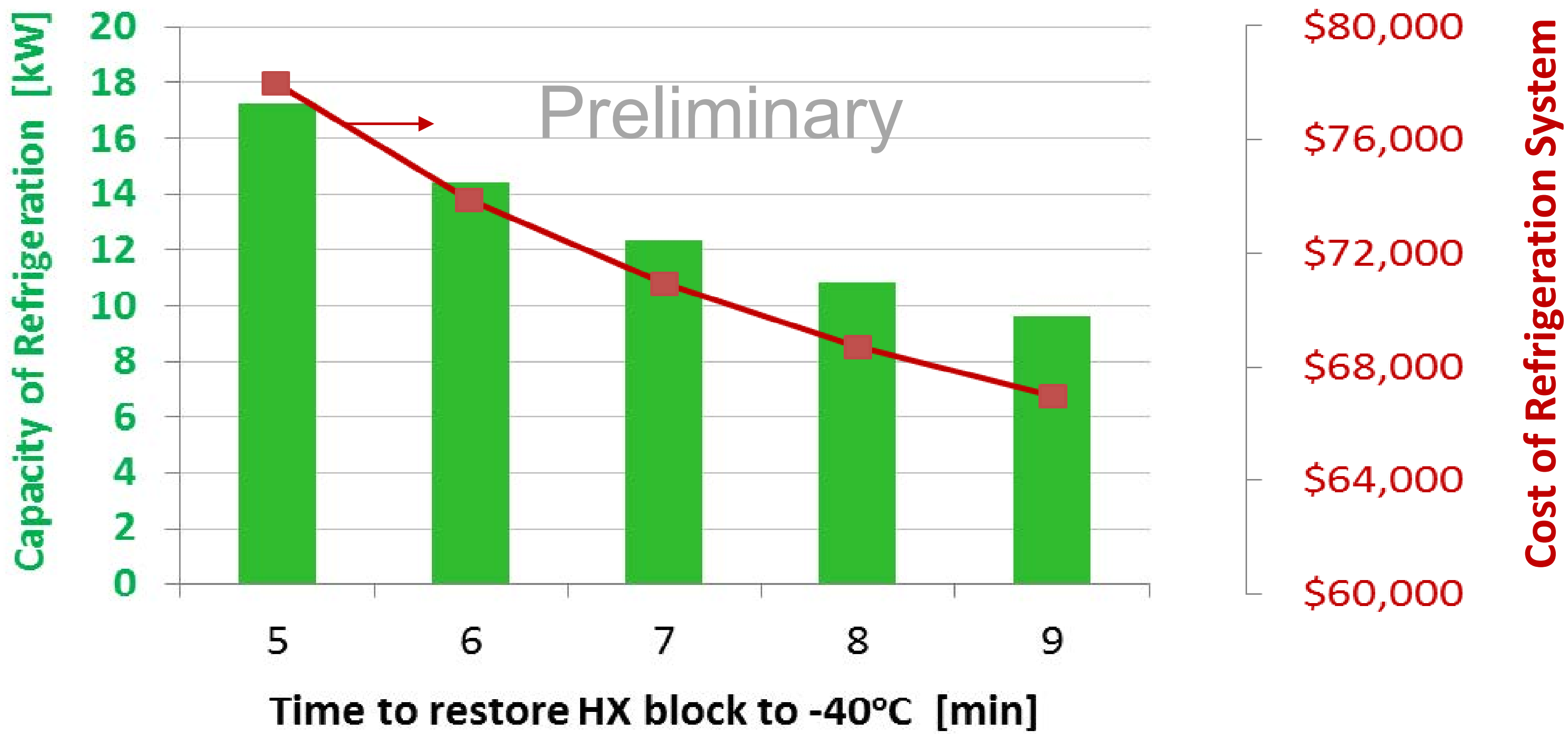
Impact of HX thermal mass – Accomplishment



- HX block can buffer refrigeration system during peak cooling demand and reduce refrigeration design capacity
  - ✓ ~ 12 kW (or 3.5 ton) per hose
- Block must be sized so that its ΔT between fills is sufficiently low (~2:4 °C) in order to meet -33°C cooling at the dispenser within 30 seconds for next fill

A large thermal mass HX provides reliable and near steady precooling at the dispenser during fueling

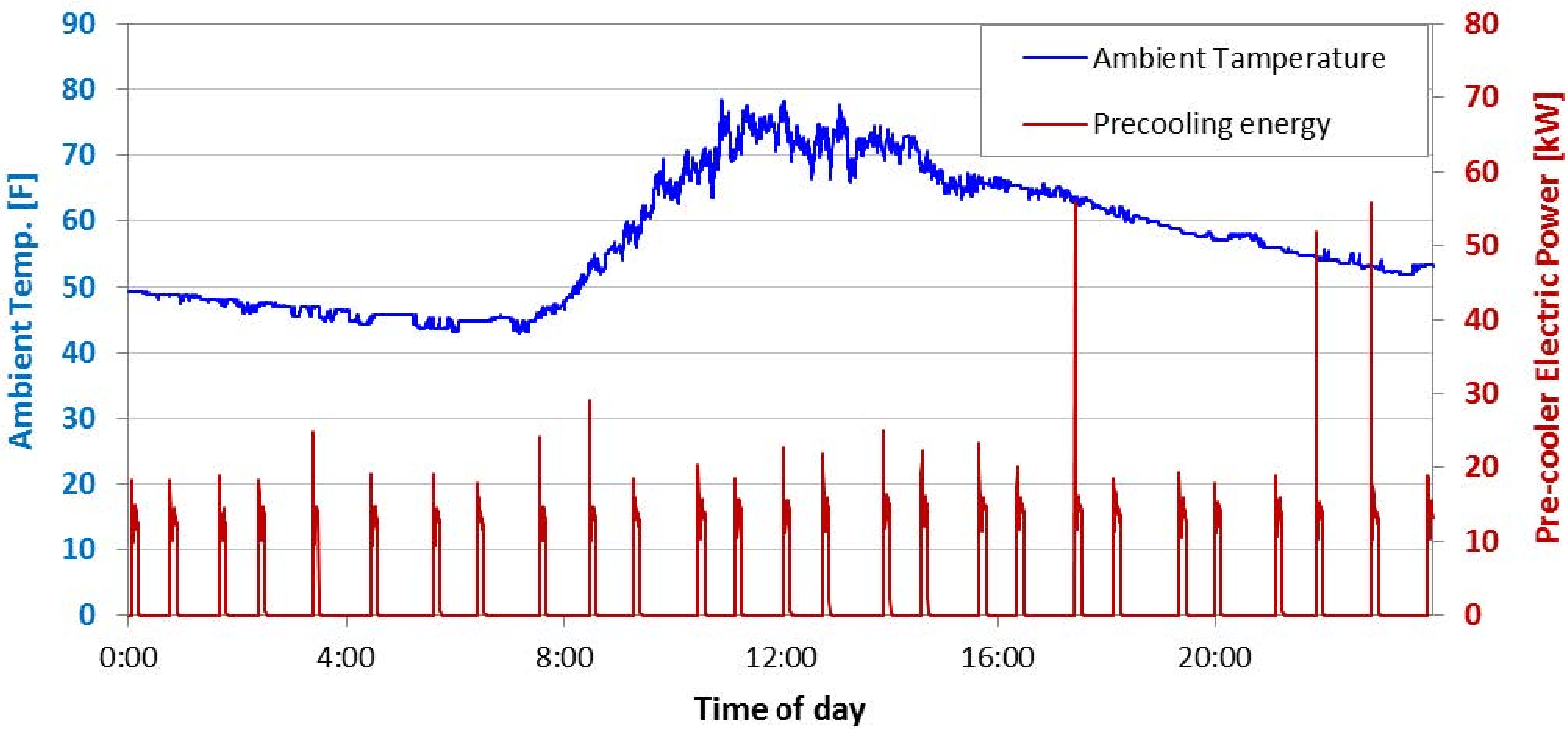
Refrigeration capacity requirement is decided by desired frequency of back-to-back fills – Accomplishment



- Time to restore HX block to -40°C is important for back-to-back fills
  - ✓ For 5 kg_{H2} fill in 5 min (+2 min lingering) → 12 kW (3.5 ton) of cooling

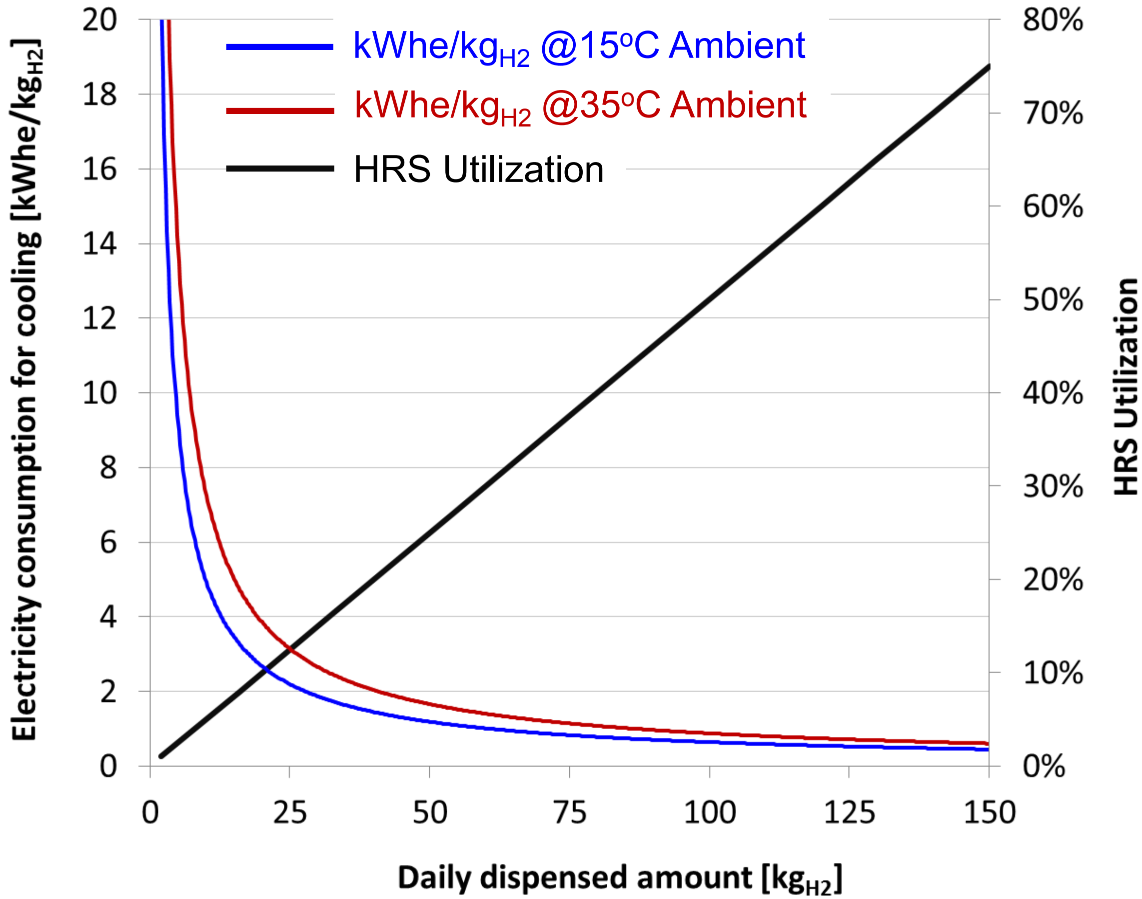
Energy consumption to maintain HX low temperature – Accomplishment

- Daily energy consumption (@58^{o}F ambient temp.) is 45 kWhe with no vehicle fills
- Heat gain rate by HX block is < 100 W → < 2.4 kWh/day (i.e., < 2 kWhe/day of the total daily 45 kWhe)



Field data shows that the overhead to keep the HX block cold is ~40 to 60 KWh/day, or only \$4-\$7/day cost to station; thermal parasitics can be minimized

Electricity consumption for cooling H_2 depends strongly on refueling station utilization – Accomplishment



$$\textit{Cooling Electricity Consumption}\ [kWh/kg_{H2}] \approx \frac{\left[0.3 + \dfrac{54}{\textit{Daily dispensed } kg_{H2}}\right]}{\textit{System COP}}$$

At high refueling station capacity utilization, the electricity consumption for H_2 precooling is < 1 [kWhe/kg$_{H2}$]

Summary – Progress and Accomplishment

- Evaluated theoretical precooling energy and electricity consumption at hydrogen refueling stations (< 1 kWhe/kg$_{H2}$)
- Developed a methodology to size precooling equipment and heat exchanger
  - ✓ On-demand cooling vs. large thermal mass HX
  - ✓ Impact of SAE J2601 30-sec window
  - ✓ Impact of number of back-to-back fills
- Collaborated with experts and examined current pre-cooling equipment design and cost
- Identified major drivers for precooling energy consumption
- Demonstrated the critical impact of HRS utilization on precooling energy consumption per kg of dispensed hydrogen
- Developed a formula for estimating cooling kWhe/kg$_{H2}$

Collaborations and Acknowledgments

Collaborators and Partners:

– PNNL: Daryl Brown provided cost of refrigeration and heat exchanger equipment

– Boyd Hydrogen: Bob Boyd provided specific data on refueling equipment required for modeling flow and thermal behavior of hydrogen between refueling components

– Linde Americas ATZ: Kyle McKeown provided data on precooling operation at a hydrogen refueling station and valuable input for verifying modeling and analysis

– H2 Frontier: Dan Poppe provided critical input for vetting model and analysis outcomes

– Honda R&D Americas: Steve Mathison provided input critical for the understanding of various fill methods

Future Work

- Develop and evaluate new design concepts
  - ✓ Various refrigeration systems (CO2, R507, others)
  - ✓ Impact of relaxing SAE J2601 30-sec window (e.g., MC Default fill)
- Acquire cost data on refrigeration and HX designs and concepts (current and future)
- Evaluate trade off between different design concepts
  - ✓ Optimize refrigeration capacity /HX size for various station capacities and demand profiles
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- Update Hydrogen Refueling Station Analysis Model (HRSAM) with modeling results and analysis
- Continue to provide technical support to FCT Office and industry stakeholders

Project Summary

- **Relevance:** Equipment cost of pre-cooler plus heat exchanger (HX) is significant (~ 10% of station equipment cost). Electricity consumption of 50-60 kWhe/kg_H2 for cooling hydrogen is reported from EU early station operations. Second international workshop on hydrogen refueling infrastructure identified pre-cooling energy consumption as a challenge and recommended detailed station precooling analysis.
- **Approach:** Evaluate theoretical precooling requirement at hydrogen refueling stations (HRS) with respect to SAE J2601 refueling protocol. Determine size of precooling equipment and heat exchanger. Collaborate to acquire information and examine current pre-cooling equipment design and cost. Identify major drivers for precooling cost and energy consumption.
- **Collaborations**: Collaborated with experts from industry and examined current pre-cooling equipment design and cost. Acquired information needed for modeling and simulations, and received valuable input to complete /review modeling results and analysis.
- **Technical accomplishments and progress:**
  - Determined theoretical precooling electricity consumption at hydrogen refueling stations
  - Examined the impact of different design concepts on energy consumption and cost
  - Developed a methodology to size precooling equipment and heat exchanger
  - Identified station utilization as the major drivers for precooling energy consumption per kg_{H2}
  - Developed a formula for estimating cooling electric energy consumption [$kWhe/kg_{H2}$]
- **Future Research**: Evaluate trade off between different design concepts. Optimize refrigeration capacity /HX size for various station capacities and demand profiles. Update Hydrogen Refueling Station Analysis Model (HRSAM) with modeling results and analysis.

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