Cryo-Compressed Pathway Analysis

Project ID: PD134

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2016 Annual Merit Review
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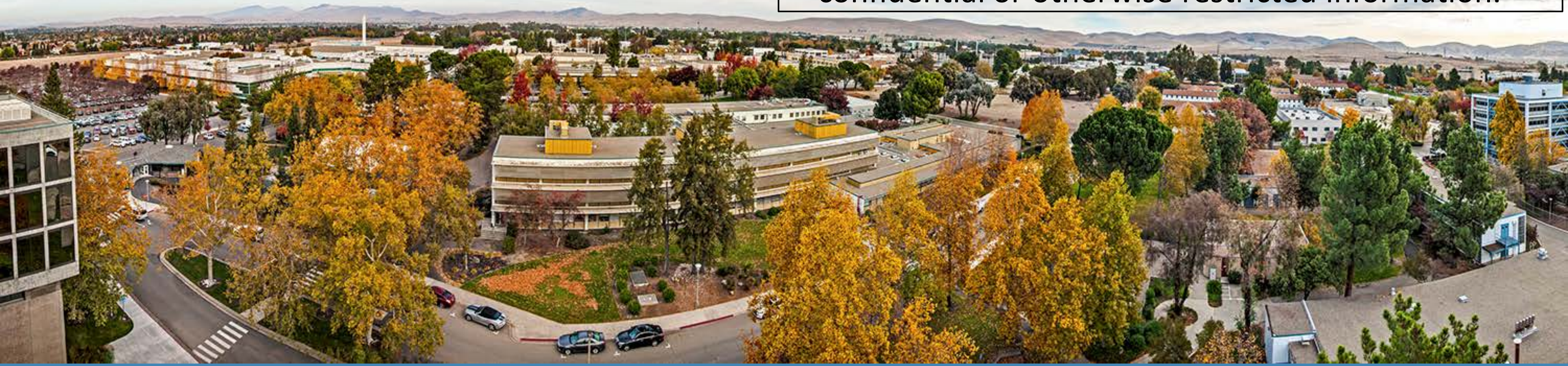

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Overview

Timeline

Start: October, 2015
End: October, 2016
% Complete: 80%

Barriers

A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis
C. Reliability and Costs of Liquid Hydrogen Pumping

Budget

FY 2015: N/A
FY 2016: $50k
Total to Date: $50k

Partners/Collaborators

- **LLNL (Lead)**
- Argonne National Lab
- Linde
- BMW

Relevance

Objective: Develop well-to-wheels cost and emissions estimates for cryo-compressed hydrogen (ccH2) pathways.

- This supports the Hydrogen Delivery team's ability to ***identify the cost-effective options for hydrogen delivery.***
- Specifically, it enables the ***analysis of infrastructure trade-offs*** through an investigation of key parameters associated with liquid hydrogen such as:
  - Cost of ccH2- and LH2-compressed-gas-relevant components (on-vehicle tank, cryopump)
  - Bulk leakage and boil-off from the Liquid Hydrogen (LH2) delivery chain
  - Distributed boil-off across the ccH2 vehicle fleet
- This foundational work will help FCTO ***set technical targets*** for components such as LH2 pumps and dispensers, as well as to ***establish best practices*** across the LH2 delivery chain.

Analysis has identified and bounded observed loss mechanisms in LLNL's LH2 delivery chain. ***Optimized delivery logistics*** could eliminate these losses in commercial operation.

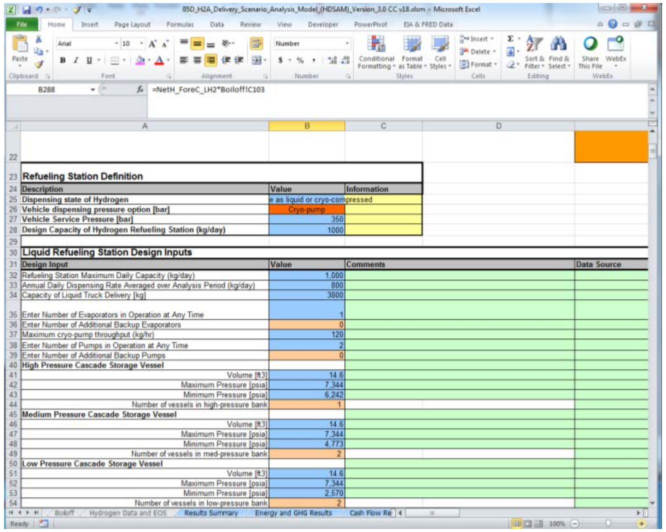
Approach to estimating ccH2 Pathway cost and performance

Modifications to Hydrogen Delivery Systems Analysis Model (HDSAM) include:

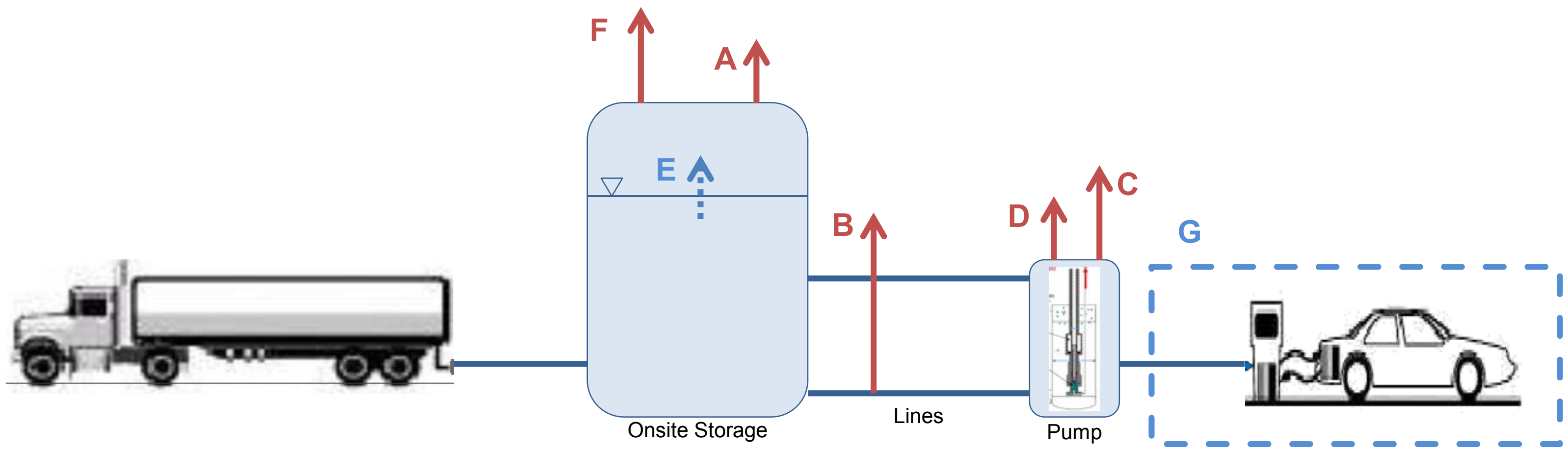
- Improved estimates of H_2 losses at terminal, in transit, ***during delivery*** and ***from station***
- Improved, parameterized estimates of high pressure cryopump cost and energy consumption

Cost of Ownership [$/mi] and **GHG Emissions** [gCO2-e/mi] are calculated in scenarios that vary:

- Cryopump and on-vehicle tank cost and performance
- Station size
- Heat transfer parameters
- Delivery Method



Approach to estimating *potential* station boil-off and net losses



[A]* Dewar: 5.5 kg/day for a 725 kg tank.

[B]* Lines : 0.3 kg/day per line.

[C]** Pump: 1.1 kg/day per pump.

[D]** Pumping: 0.06 kg/kg-dispensed at 700 bar.

[E] Avoided losses: 0.073 kg H_2 must be evaporated per kg H_2 dispensed.

[F]* Delivery losses (cold vapor displacement, bottom-fill): ***up to*** 0.07 kg vented per kg-LH_2 delivered.

[G] Station-related losses from the high pressure section are assumed to be zero.

* Consistent with LLNL's non-optimized tank operation and delivery experience

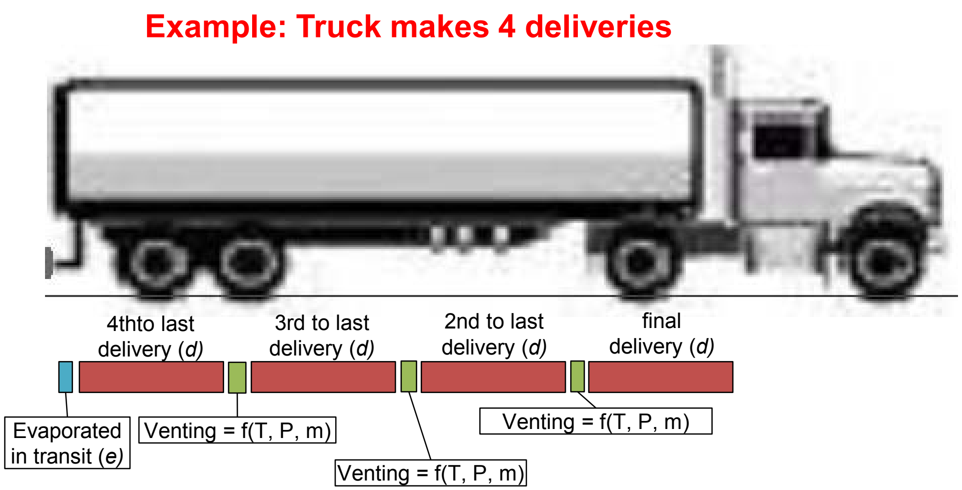
** Consistent with anticipated industrial technology developments

Parameters are adjustable for sensitivity analysis in a modified version of HDSAM

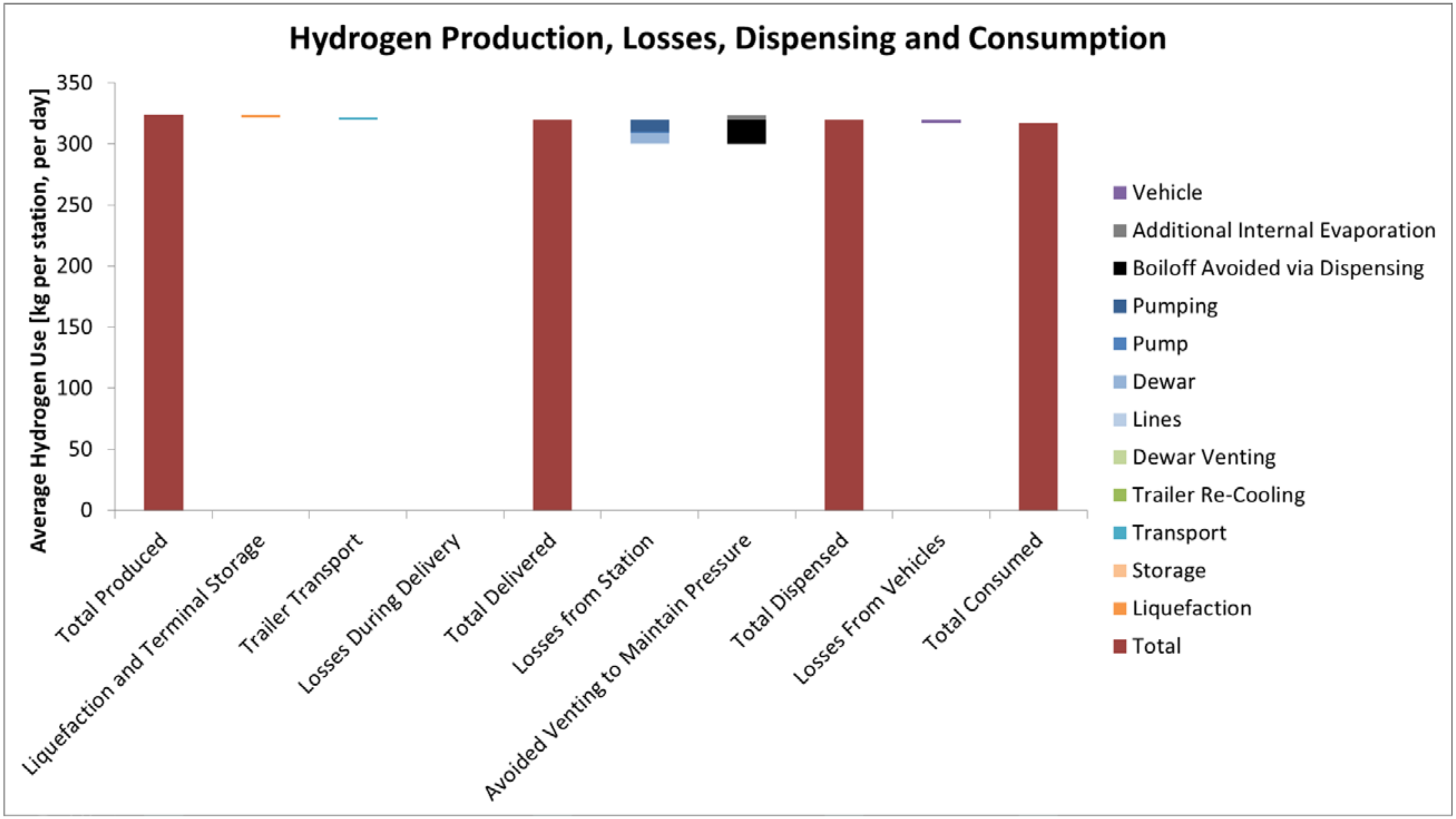
Approach to estimating delivery losses

After delivery, the trailer may be depressurized by venting hydrogen. The quantity of hydrogen vented is a function of the delivery conditions (quantities, temperatures and pressure of liquid and vapor remaining).

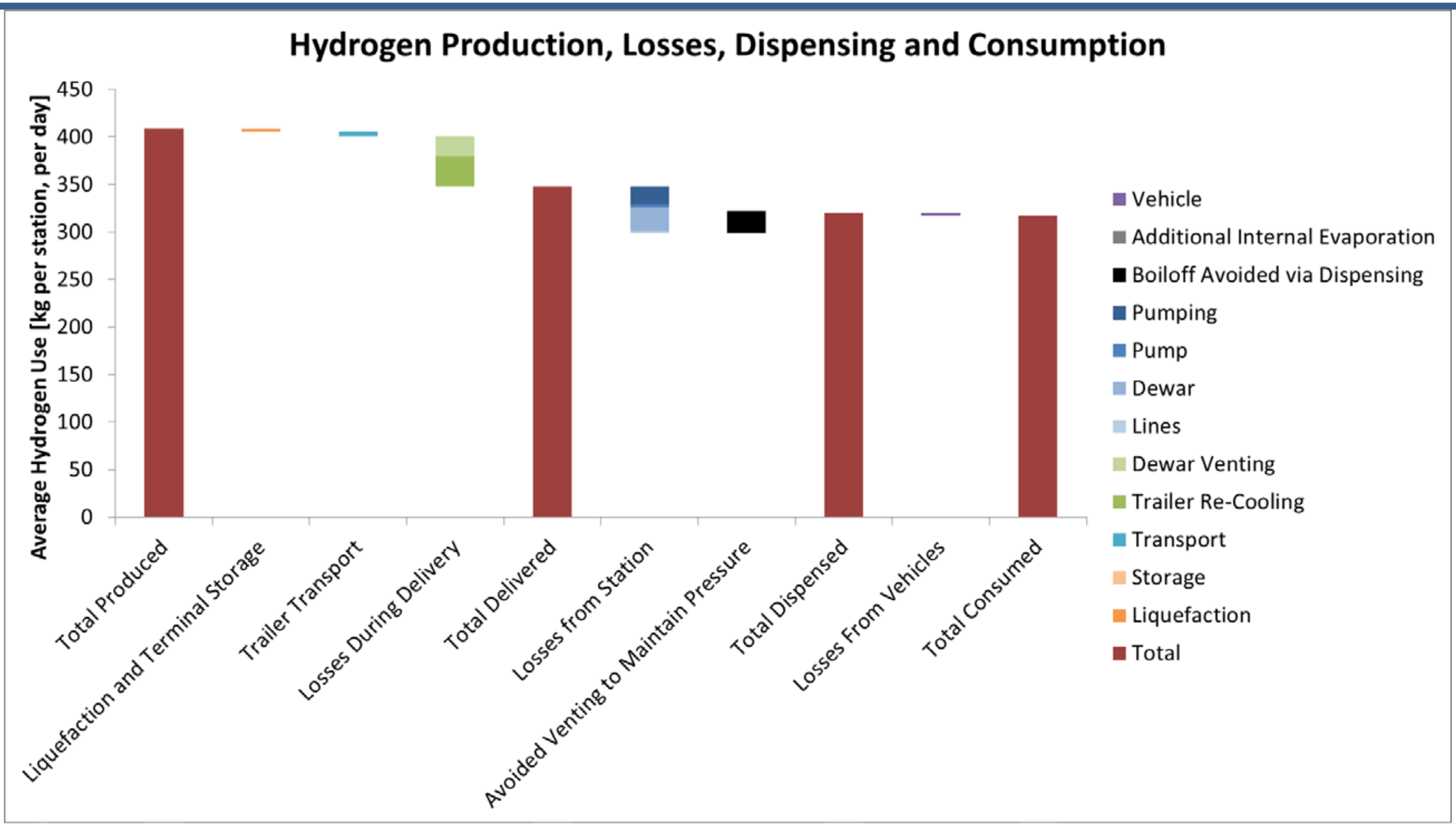
Venting could be avoided when trailer is empty, or if final pressure can meet over-the-road requirements.



Accomplishment: Analysis of potential boil-off losses under future delivery scenarios



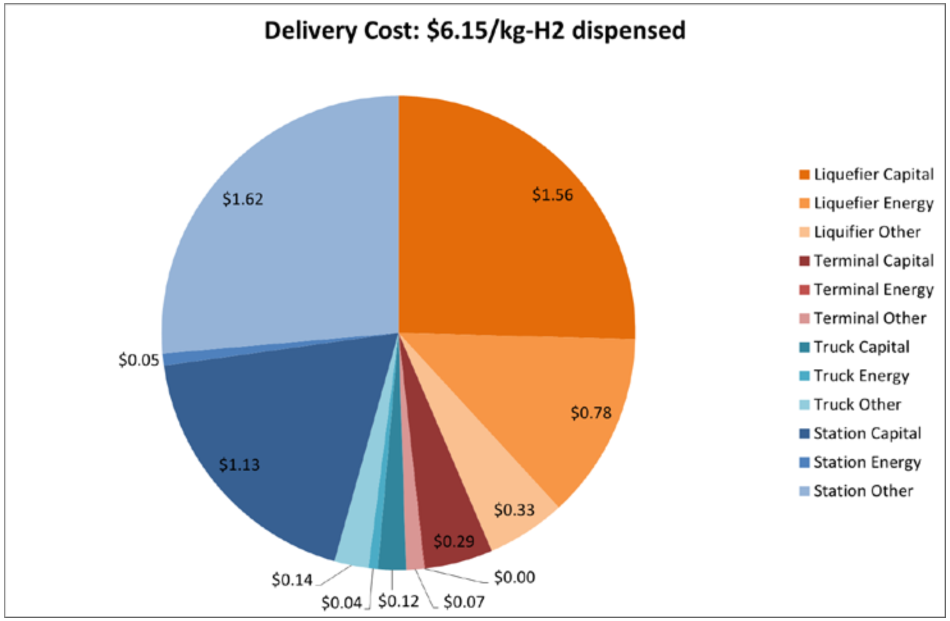
Accomplishment: Illustrate all potential boil-off losses

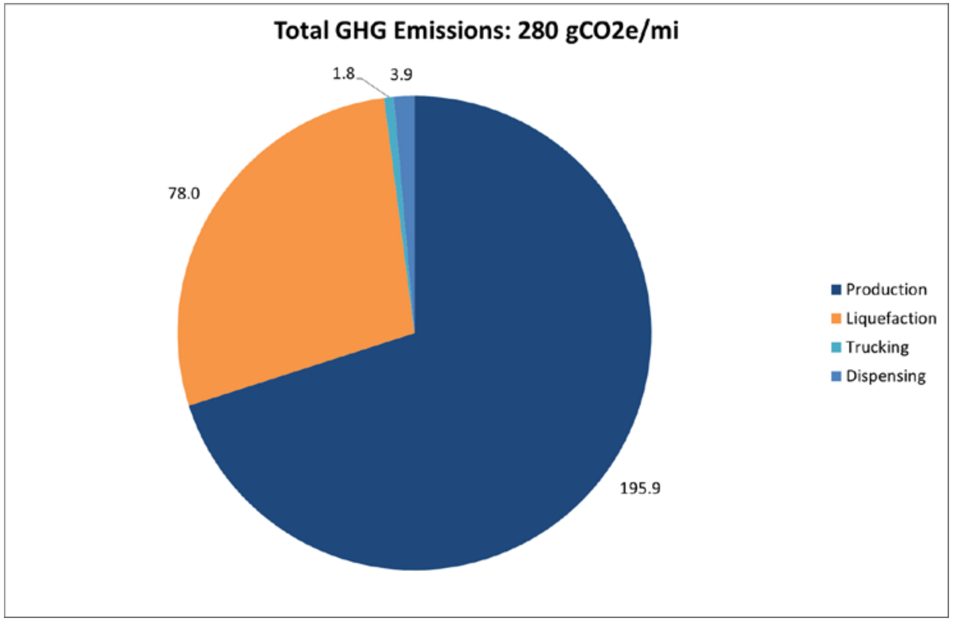


Illustrative case shows all loss mechanisms at small station size (320 kg/day), poor heat transfer characteristics, and observed “thermal” trailer unloading.

Accomplishment: Cost and Emissions Analysis

- For the analysis depicted below (320 kg/day station), the cost of hydrogen is **$7.85/kg** and the cost of ownership is **$0.44/mi**.



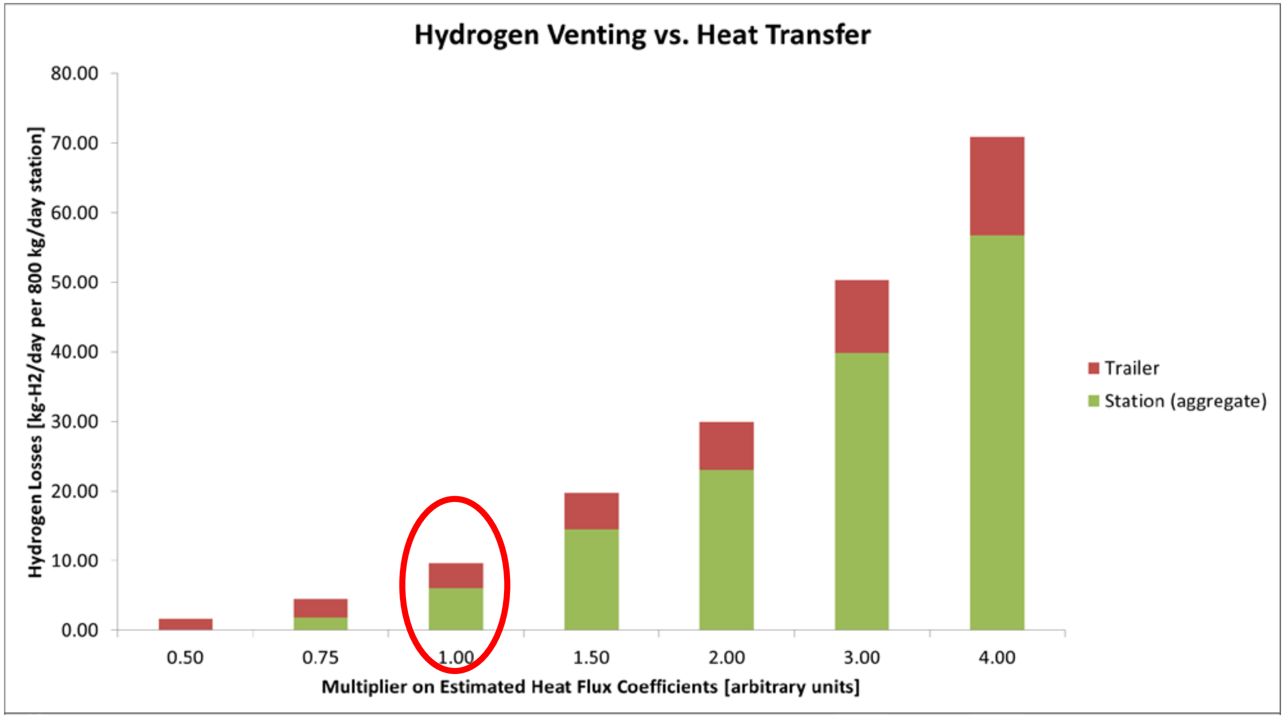


Hydrogen lost in the delivery chain increases Production and Liquefaction costs and emissions. Comparisons to the 700 bar Compressed Gas pathway will be performed soon.

Accomplishment: Single Parameter Sensitivity Analyses (vary heat transfer)

- Increasing heat transfer into the dewar, lines, pump and trailer increases the amount of hydrogen lost. The station does not begin to vent hydrogen until the "avoided losses" from dispensing are exceeded.

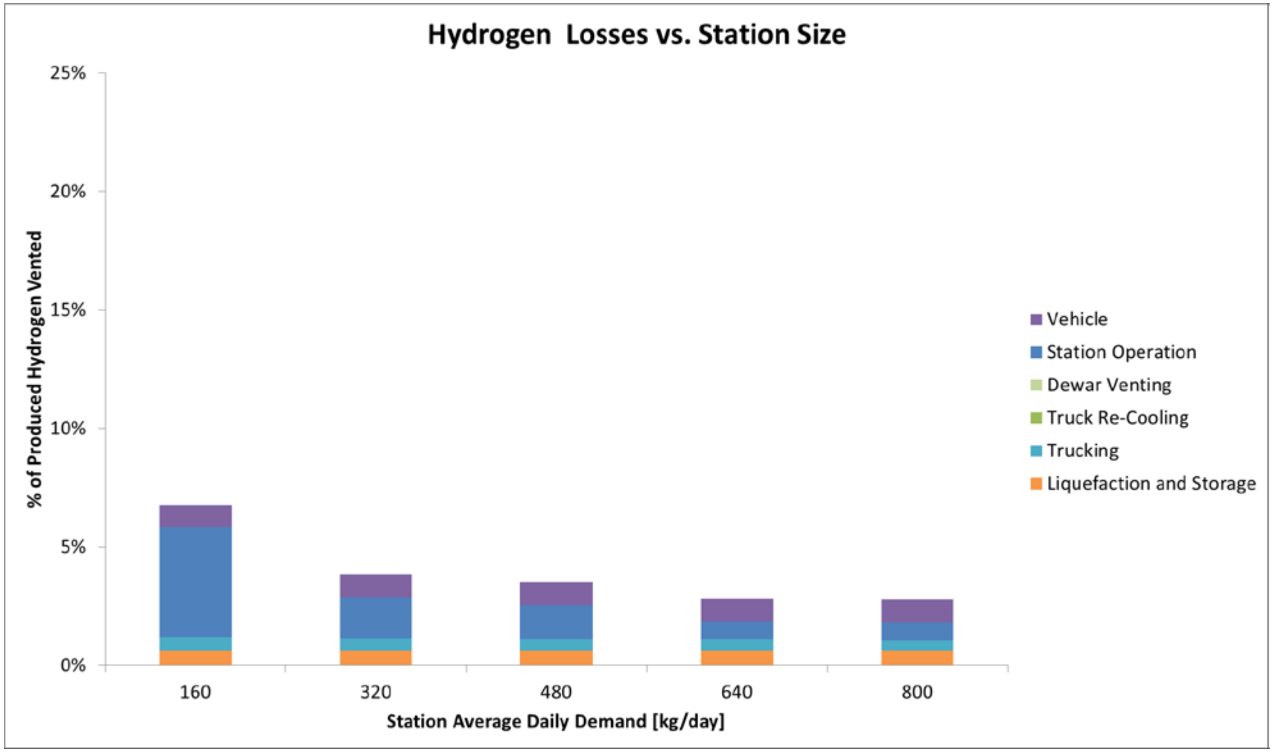
- This analysis was performed on an 800 kg/day station with all other parameters held fixed.



"Steady state" boiloff is not a major loss factor until heat transfer exceeds LLNL experience.

Accomplishment: Single Parameter Sensitivity varying Station Size

- Largest remaining losses are in station operation (pumping, heat transfer at observed/reported performance) for small stations.



At commercial station sizes and adopting best delivery practices, station losses are comparable to other losses throughout the delivery chain.

Accomplishment: Single Parameter Sensitivity Analyses (pump cost and performance)

- Hydraulically driven 700-bar crypoumps are estimated to require > 0.8 kWh/kg. Next-generation cryopumps may be 2x as efficient. All pumps are assumed to draw 1 kW at standby (24x7).
- At large station sizes (800 kg/day), current delivery methods and low heat transfer, each 1% change in installed cryopump price (nominally $225k) causes a 0.07% change in delivery costs and a 0.01% change in the cost of driving.
- Deposition of heat in the low-pressure LH2 reservoir was also analyzed and found to contribute to station-based losses when >2.5% of minimum cryo-compression energy ends up in the pumping dewar.

High Pressure Cryopumping electricity use could be reduced by up to 2x, but that is a very small component of system cost and GHG.

Responses to Previous Year Reviewers' Comments

- This project was not reviewed last year

Collaborations

Collaborator	Role
ANL	Developed HDSAM, Provided Inputs and Feedback, Provided technical assistance with HDSAM operation
Linde	Provided guidance on estimating existing and future cryopump cost and performance. Advised on future supply chain logistics. Reviewed analysis.
BMW	Described experience with existing cryopump operation. Reviewed analysis.

Remaining Barriers and Challenges

- Incorporation of boiloff analysis into production version of HDSAM.
- Further validation of estimates using LLNL experience
  - Dewar losses
  - Line losses
  - **Pump losses**
- Evaluate sensitivity of ownership costs to variations in ccH2 tank price
- Estimates of on-vehicle losses using simulated drive/dormancy cycles (extremely large parameter space)

Proposed Future Work

- Measure actual hydrogen losses during LLNL trailer deliveries

- Estimate heating and losses from LH2 delivery chain in optimized delivery scenarios (top-fill, non-equilibrium pressurization)

- Estimate energy and financial costs (and benefits) of low-pressure LH2 pumping (***transfer cryo-pumping***) to avoid delivery losses from “thermal” transfers

Summary

Objective: Develop well-to-wheels cost and emissions estimates for liquid hydrogen delivery pathways.

Relevance: Helps define infrastructure trade-offs between the cryocompressed delivery pathway and other pathways such as liquid hydrogen delivery and compressed gas on-vehicle storage; and compressed gas delivery.

Approach: Build physics-based and industry-guided estimates of system and cryopump performance and cost into HDSAM.

Accomplishments: Full-pathway assessment of loss mechanisms (trailer boiloff, delivery venting, station heat infiltration, etc.) completed. Multiple single-parameter sensitivity studies (station size, heat transfer, pump price, pump efficiency, pump performance) completed. Total cost and GHG of driving can be estimated under a wide variety of assumptions.

Collaboration: ANL, Linde and BMW all contributed to the completion and review of this work.

Technical Back-Up Slides

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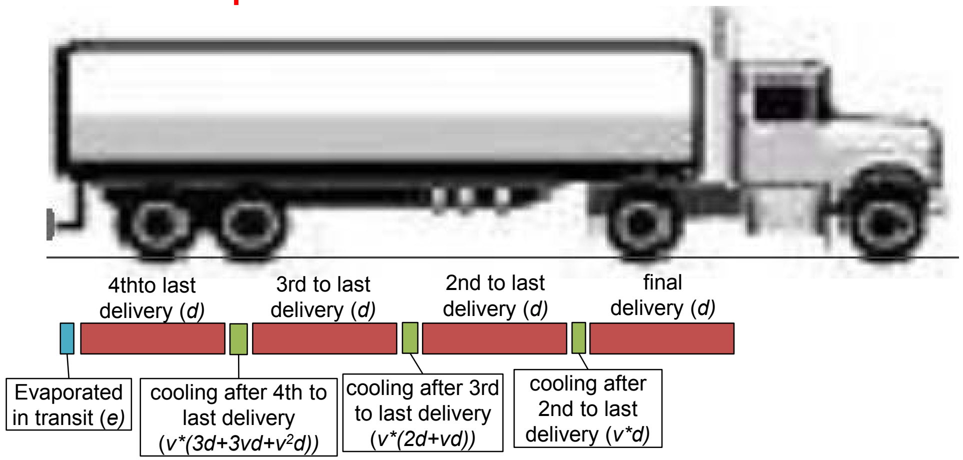
Maximum delivery losses (full liquid-vapor equilibrium)

After delivery, the trailer is depressurized by evaporating hydrogen with latent heat of vaporization [$h_{fg} = 403$ kJ/kg] to cool the remaining hydrogen from 26.6K (4.7 bar-a) to 23.6K (2.3 bar-a) [Δh=38 kJ/kg].

At each equal delivery of ***d*** kg-H_2, the truck loses ~9% (***v***) of the liquid that remains in the tank for subsequent deliveries and cooling.

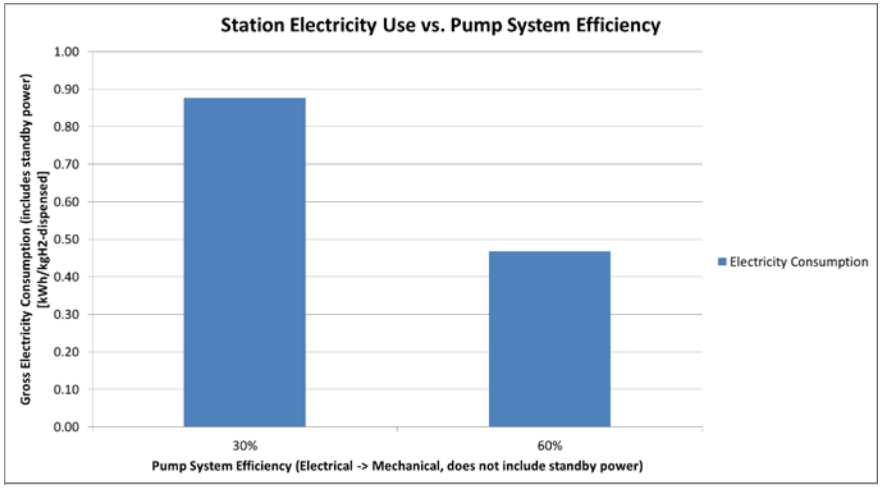
Example: Truck makes 4 deliveries

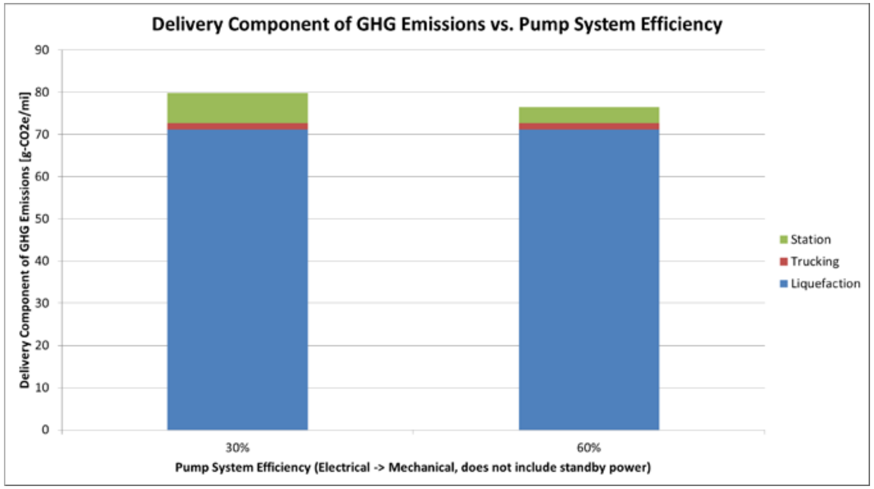


Estimated losses are consistent with LLNL's experience: 6% and 37% of delivered quantity. ***Top-filling of dewar*** and ***non-equilibrium pressurization of trailer*** can reduce these losses to zero.

Accomplishment: Single Parameter Sensitivity Analyses (pump cost and performance)

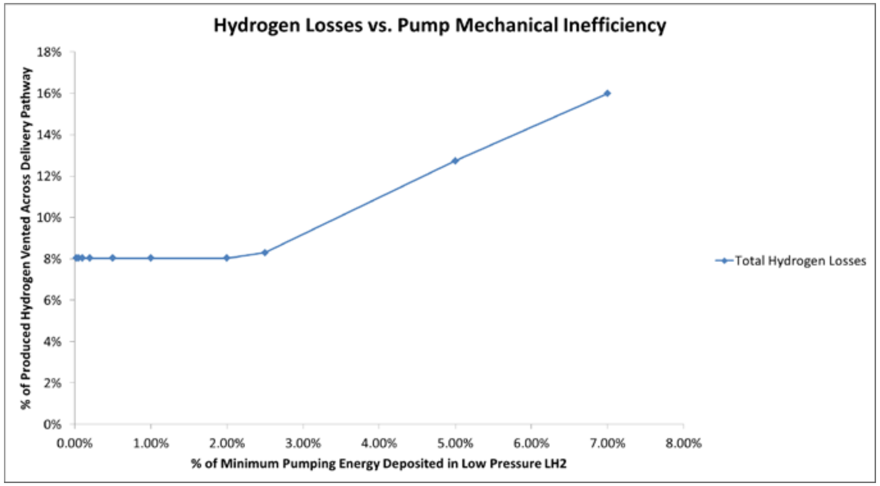
- Hydraulically driven 700-bar crypoumps are estimated to require > 0.8 kWh/kg. Next-generation cryopumps may be 2x as efficient. All pumps are assumed to draw 1 kW at standby (24x7).
- At large station sizes (800 kg/day), current delivery methods and low heat transfer, each 1% change in installed cryopump price (nominally $225k) causes a 0.07% change in delivery costs and a 0.01% change in the cost of driving.





Accomplishment: Single Parameter Sensitivity Analyses (pumping heat deposition)

- The whole pump system, including electric or hydraulic drive, is estimated to be 30% - 60% efficient with respect to the minimum energy required to pressurize LH_2 to 700 bar.

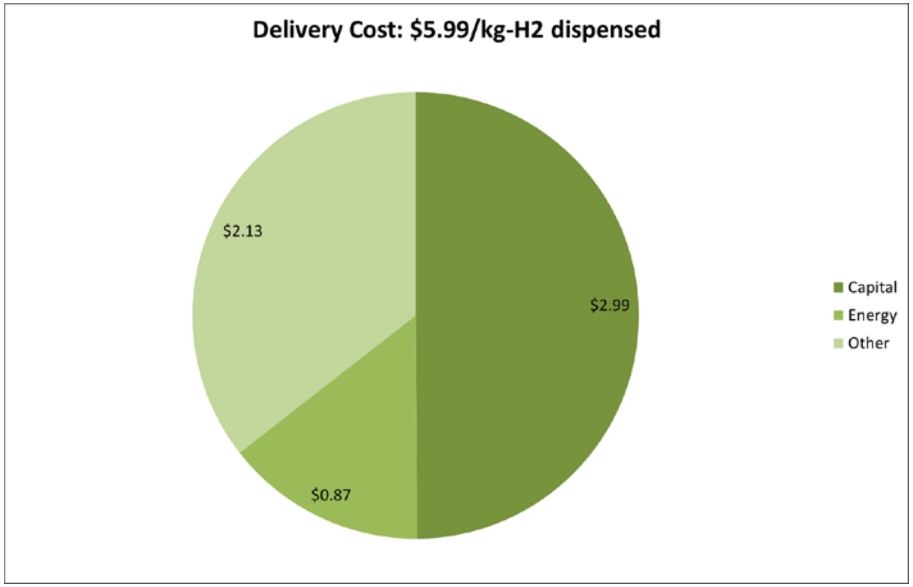


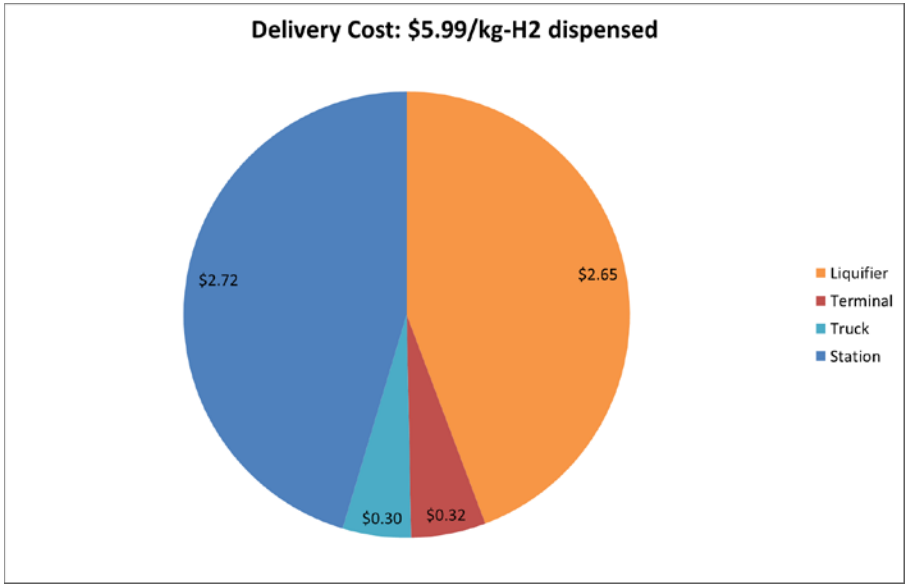
- The mechanical portion of the pump is likely to be 80% - 95% efficient (typical liquid pump isentropic efficiency), and most heat deposited by the pump will likely end up in the fluid on the high pressure side. This will manifest in higher temperature ccH2 delivered to the vehicle.

- Any heat deposited by the pump on the low pressure side could contribute to hydrogen boil-off at the station after the avoided losses due to dispensing are exceeded.

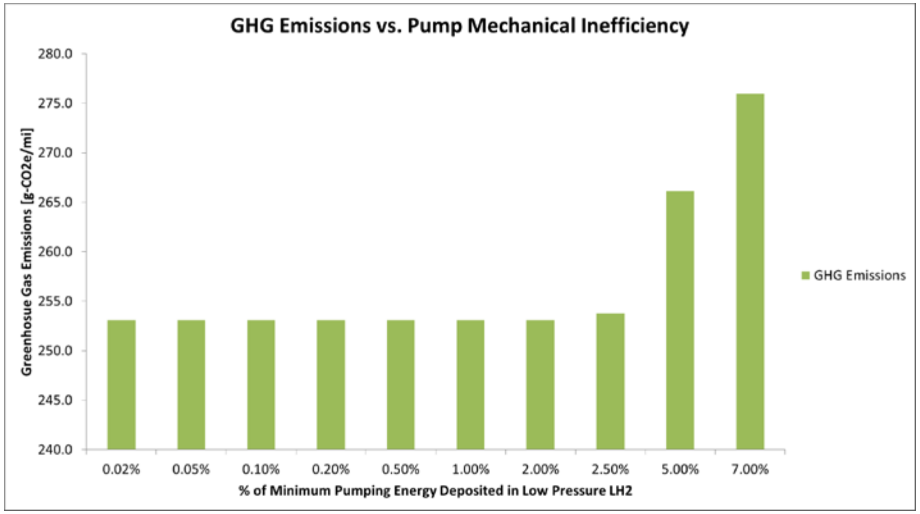
Accomplishment: Delivery Cost Breakdowns

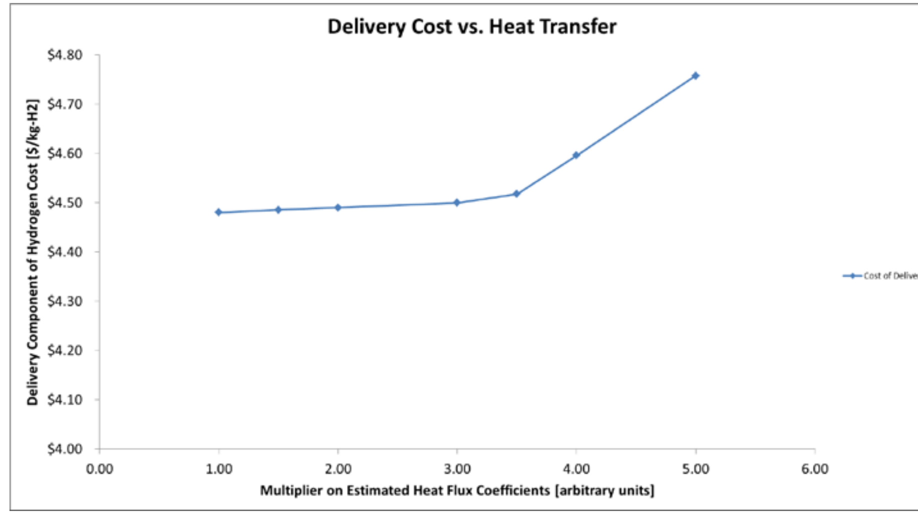
- 320 kg/day station, medium heat transfer. Nominal pump price, high pump performance. Thermal delivery

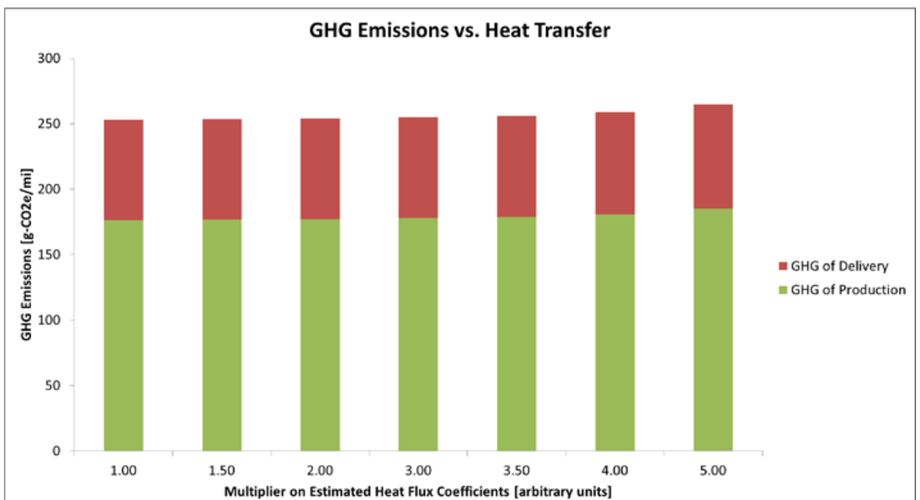


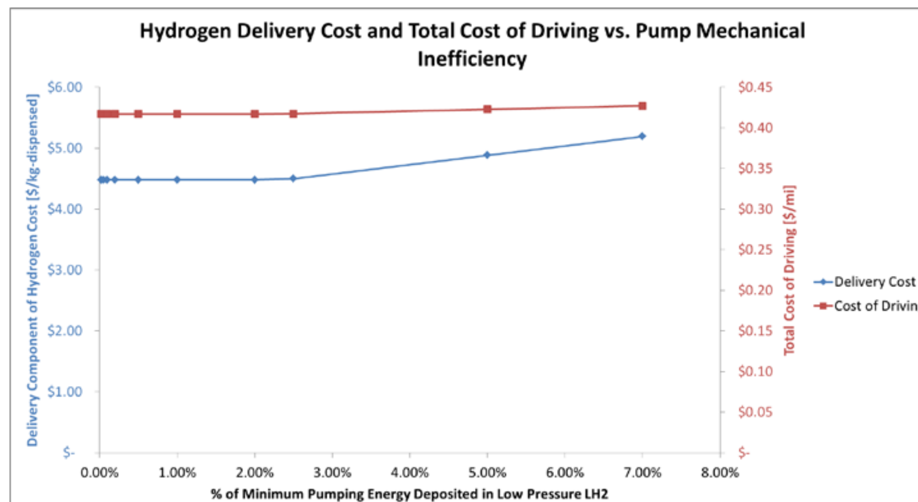


Accomplishment: Sensitivity Analyses









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