



Enabling hydrogen refueling at scale.

PJ Callahan, Director of Operations  
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An accomplished team with **world leading expertise** in hydrogen refueling.



**ANTHONY KU, PhD**  
Co-Founder, CEO

- **20 years** industrial technology R&D and commercialization, including 3 products from lab to market
- **Previously:** CTO, NICE America; Technical staff, GE Research



**JIMMY LI, PhD**  
Co-Founder, CTO

- **30 years** in Hydrogen, with 10 years in hydrogen refueling
- **Previously:** Technology and leadership roles at Air Products, NICE America, and Nikola



**EDWARD YOUN**  
Director of Engineering

- **8 years** in Hydrogen refueling
- **Previously:** Project management of refueling station development with Air Liquide and refueling technology R&D with NICE America



**PJ CALLAHAN**  
Director of Operations

- **5 years** in clean transportation
- **Previously:** Project management of NorCal ZERO, North America's largest commercial deployment of Class 8 FC trucks



**100+**  
Scientific Patents

**4**  
Commercial Pilots

**480**  
days of operations

**1000+**  
fills (37 tH<sub>2</sub> delivered)

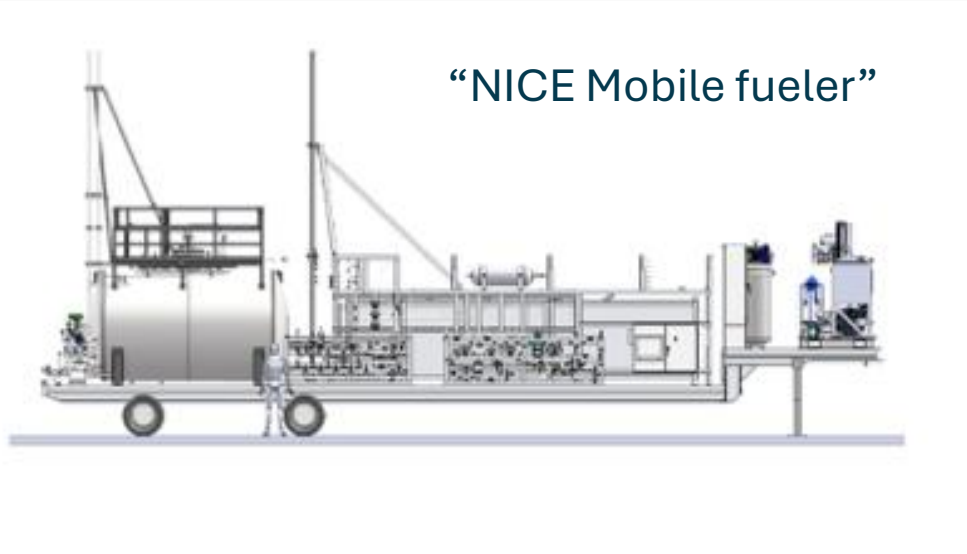
**Zero**  
safety incidents

**World-record**  
back-to-back fill test

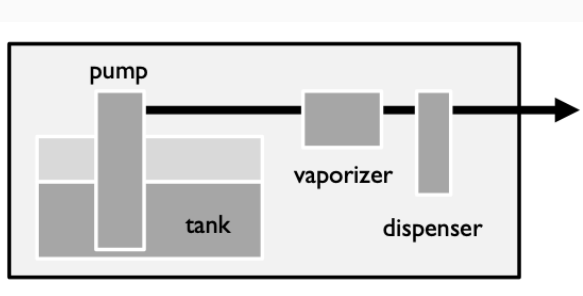
**Largest**  
commercial hydrogen truck station in the US



## Innovative contributions in HDV fueling (2020-2021)

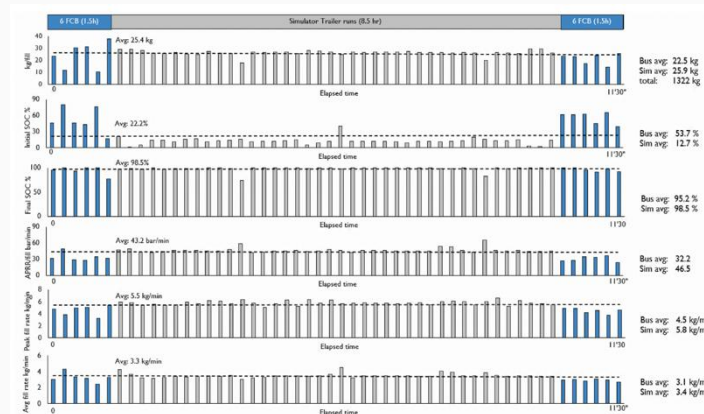


**4 Commercial Pilots  
480 Days Of Operations  
Zero Safety Incidents  
World-record back-to-back fill test**



**Direct fill architecture**

*Extensive testing at Plug Power, SARTA and Sunline Transit*



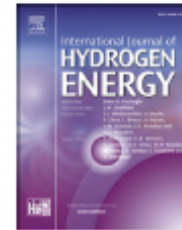
**55 back-to-back fills in 12 hours  
480 days operation**








Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

## International Journal of Hydrogen Energy

journal homepage: [www.elsevier.com/locate/he](http://www.elsevier.com/locate/he)



### Driving towards competitive hydrogen dispensing cost for heavy-duty road transport: Quantifying and mitigating near-term operational penalties

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Alejandra Hormaza-Mejia<sup>e</sup>, Jimmy Li<sup>a</sup>, Sajjad Rezaei<sup>c</sup> , Divyansh Singh<sup>a</sup>, Edward Youn<sup>a</sup> 

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<sup>b</sup> Princeton University, Princeton, NJ, USA

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#### ARTICLE INFO

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Liquid hydrogen  
Operations  
Refueling  
Utilization  
Technoeconomics

#### ABSTRACT

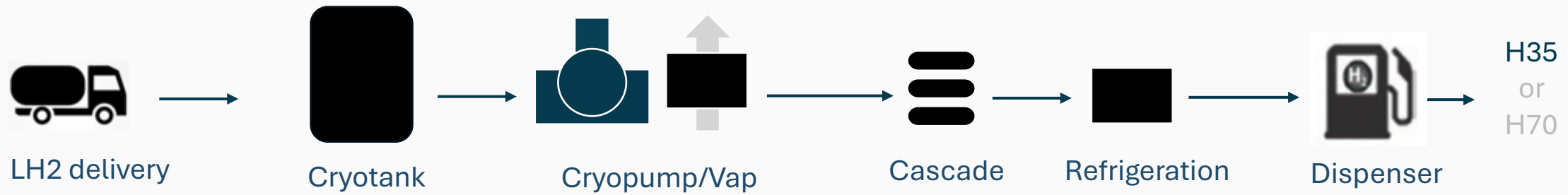
Hydrogen prices at actual refueling stations are commonly higher than projections based on technoeconomic analyses of the underlying station design for a specific vehicle type and hourly load profile. The gap can be understood in terms of several real-world effects that “penalize” economics but are not generally included in idealized analyses. This paper considers penalties arising from low station utilization and boil-off losses at stations using liquid hydrogen delivery. Since dispensing costs are dominated by capital and fixed operating costs, operation of stations at rates significantly below their design capacity increases the cost basis almost inversely proportional to the degree of underutilization. For liquid hydrogen stations, boil-off losses can be as high as 50 % of the delivered liquid hydrogen, resulting in costs from lost fuel due to venting or higher capital costs and station complexity due to equipment for boil-off recovery and use. We describe how to incorporate these effects into cost models to order to close the gap between predicted and actual costs. Proper attribution of penalty effects not only clarifies the inherent potential of fueling station designs, it can guide efforts to improve the economics of hydrogen refueling infrastructure during the design and deployment.

CSH2 analysis in partnership with Argonne National Laboratory, University of California-Irvine, and Cal State Poly - Pomona

- **Real-world costs** of H2 refueling can be higher than predicted by technoeconomic modeling.
- **Low utilization** of station capacity increases the levelized cost of dispensing.
- **Unmitigated boil-off losses** penalize liquid hydrogen station designs and associated dispensing costs.
- **Paths exist for mitigating penalties** to realize long-term competitive H2 dispensing cost potential.

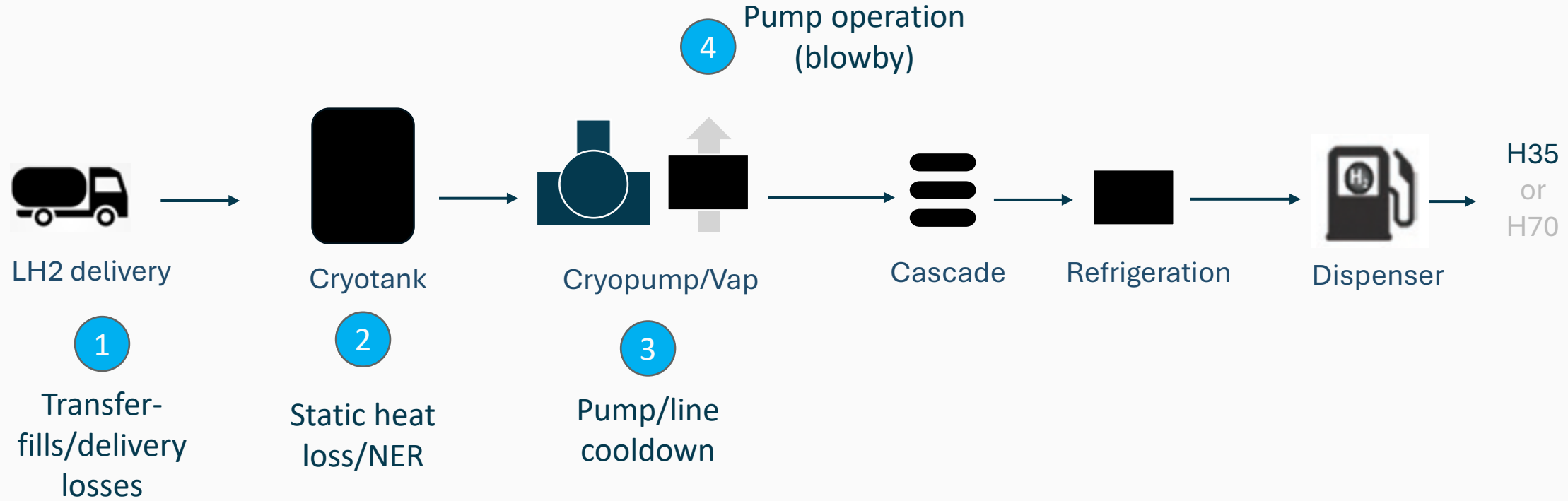


## Typical liquid H2 cryopump station design



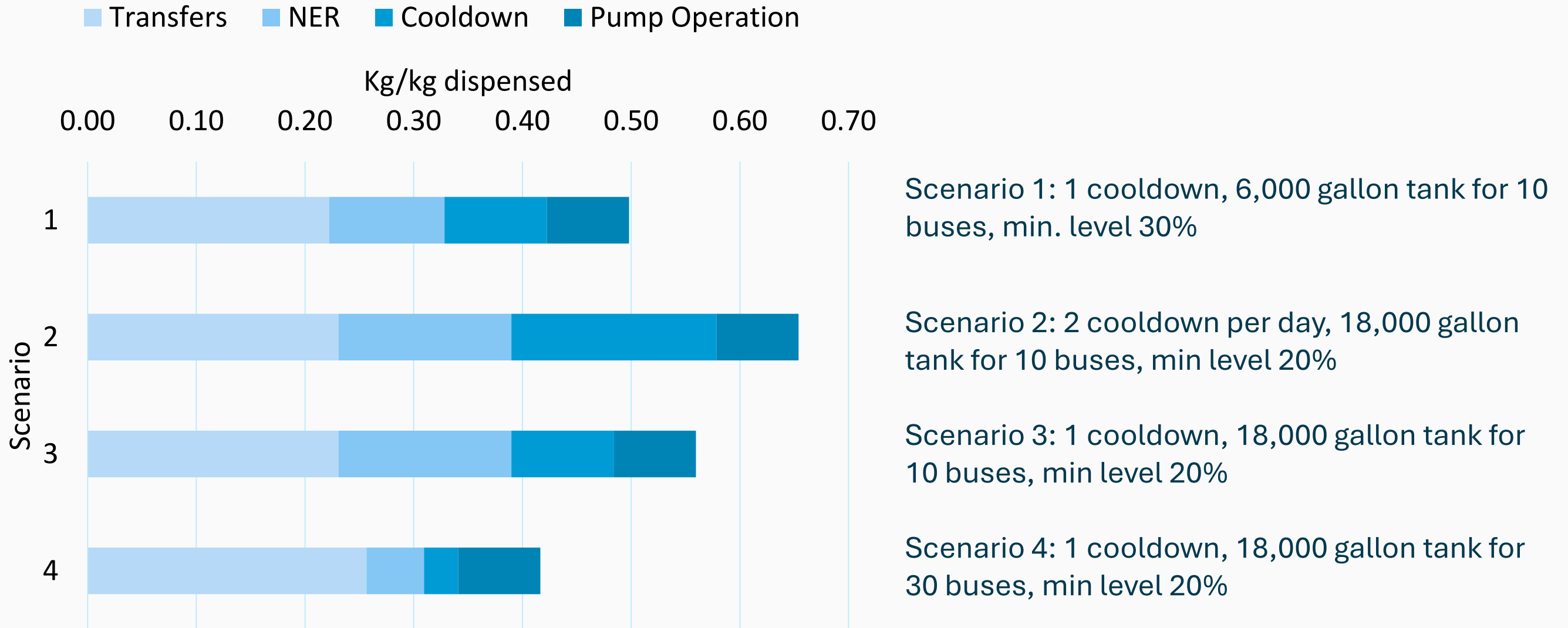


## Boil-off mechanisms



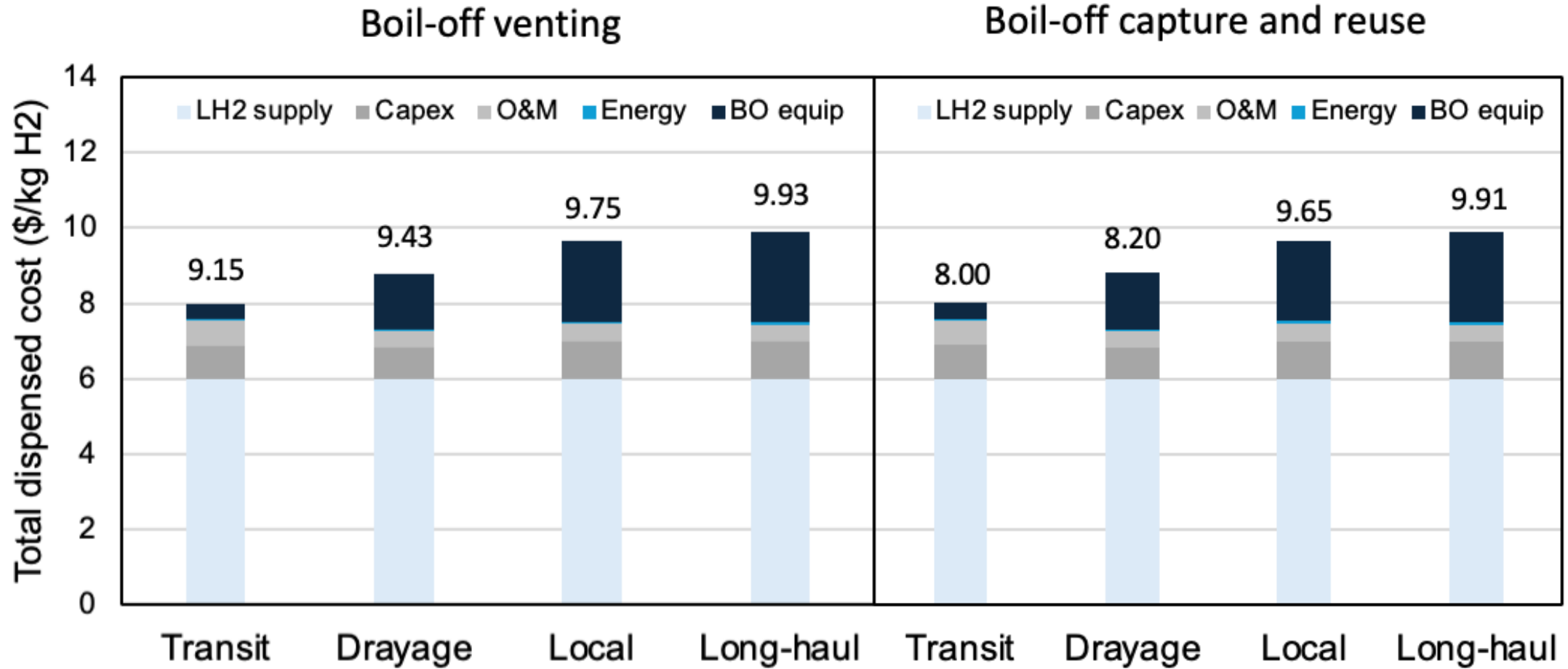


## Right-sized infrastructure & scheduled operations reduce boil-off



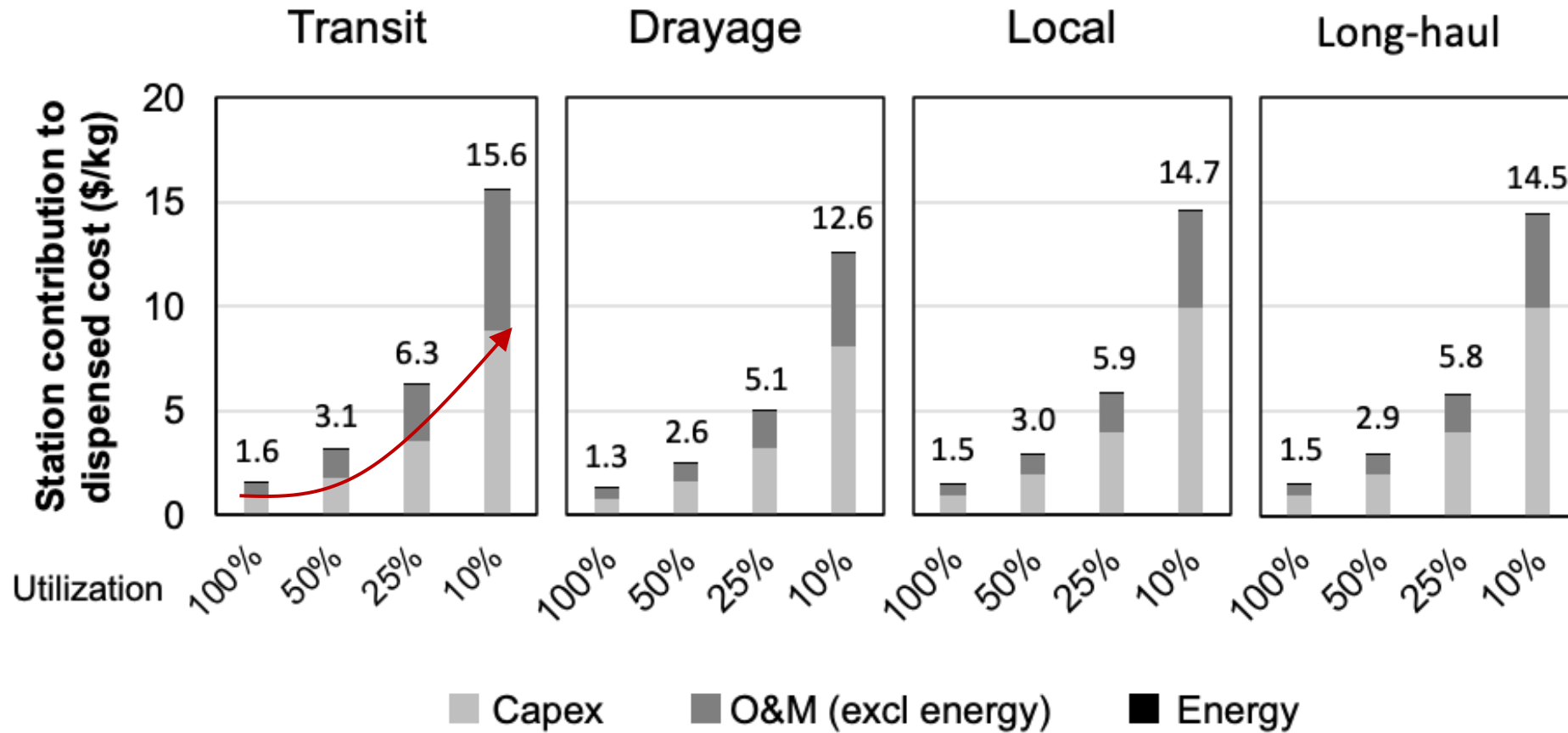


Venting or capture both incur extra cost. **The ideal solution to boil-off is prevention.**





Higher station utilization (more vehicles) leads to lower dispensed costs (\$/kg)





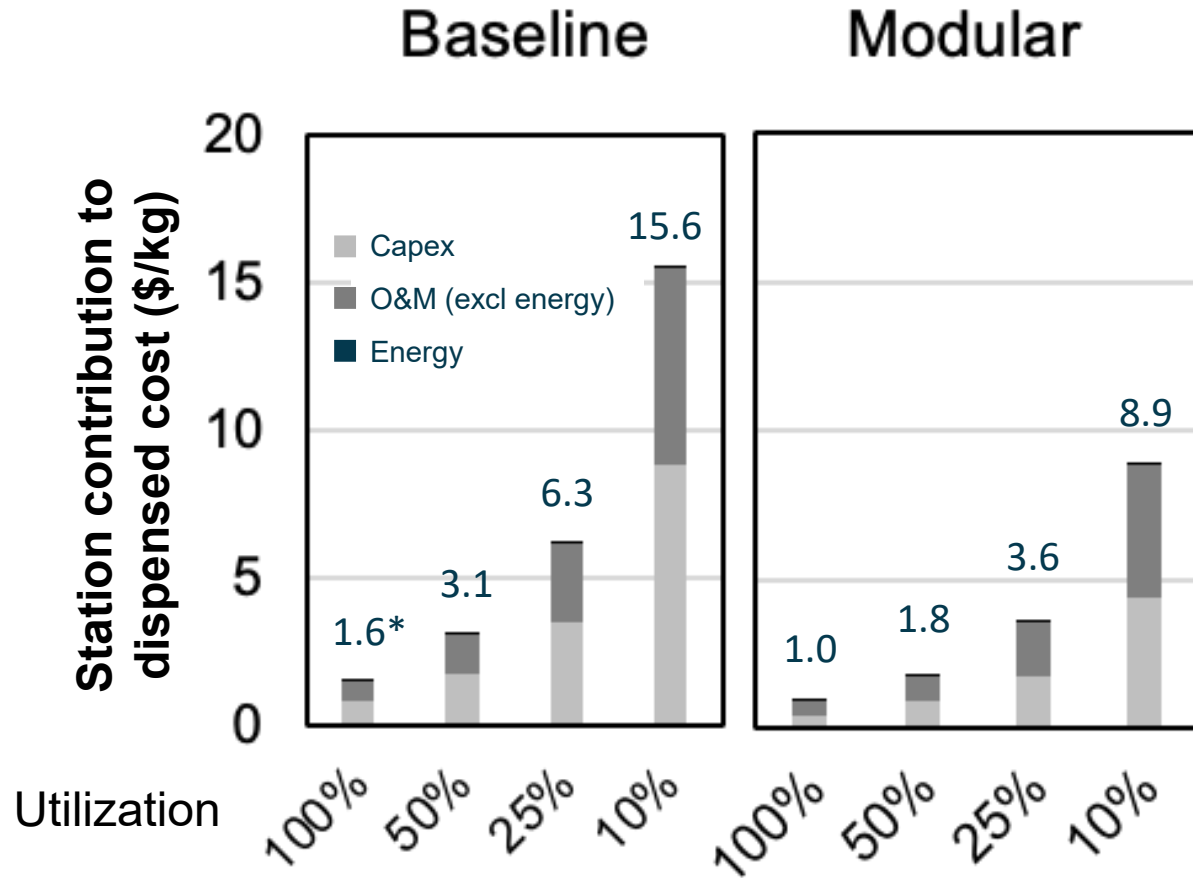
## Fleet adoption schedules can be used to manage utilization penalties.

Case study of utilization penalties for two transit fleet adoption schedules.

Transit	Scenario 1			Scenario 2		
	Year	Fleet size	Utilization	Penalty	Fleet size	Utilization
1	10	20%	4x	10	20%	4x
2	10	20%	4x	20	40%	1.5x
3	50	100%	0	30	60%	0.67x
4	50	100%	0	40	80 %	0.25x
5	50	100%	0	50	100%	0
Average	34	68%			60%	
<b>Total penalty</b>			<b>8x</b>			<b>6.4x</b>



**Modularization (right-sizing) improves capital efficiency and reduces utilization penalties.**



Utilization rate (%)	Baseline cost (\$/kg)	Modular cost (\$/kg)	Relative savings (%)
100%	1.6	1.0	40%
50%	3.1	1.8	42%
25%	6.3	3.6	43%
10%	15.6	8.9	43%

\*HDRSAM estimates for cost : 35 MPa x 20 kg fills x 1 tpd (10 vph)



## Modularity and preventing boil-off can significantly reduce dispensed cost (\$/kg)

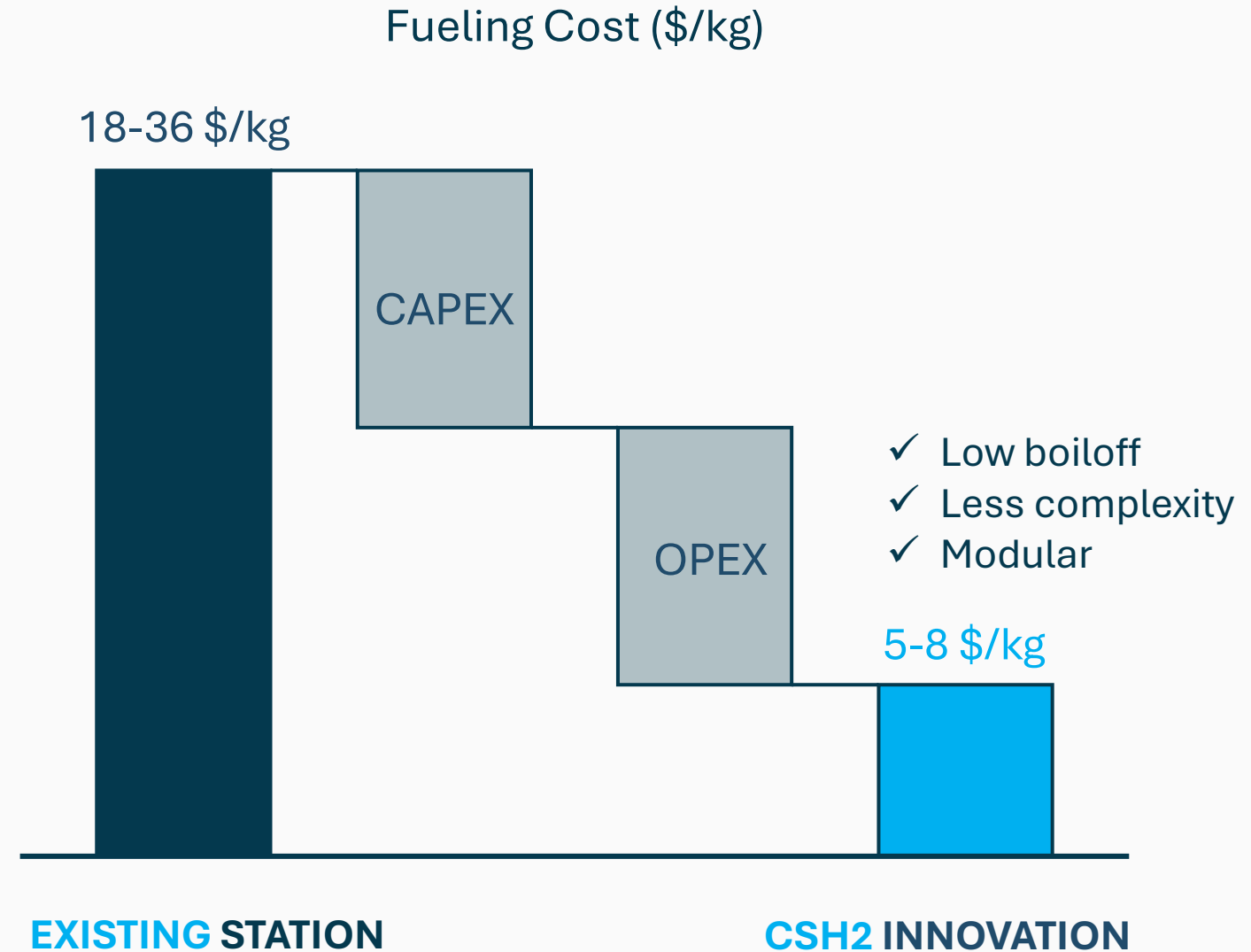
### EXISTING STATION

Capital Cost  
\$15-25 M



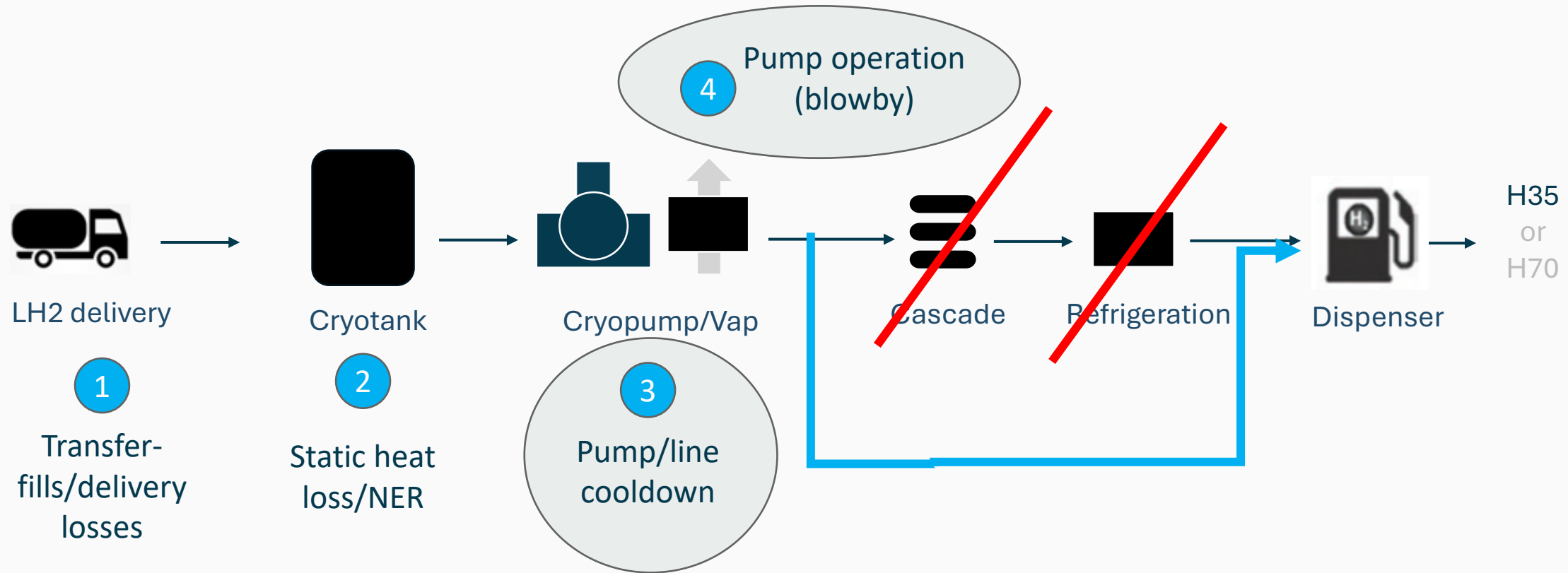
### CSH2 INNOVATION

Capital Cost  
\$5-10M\*





## CSH2s Modular Refuelers Address Key Boil-off Mechanisms, Shrink Station Footprint



**Reduce mechanisms 3&4 up to 90%**

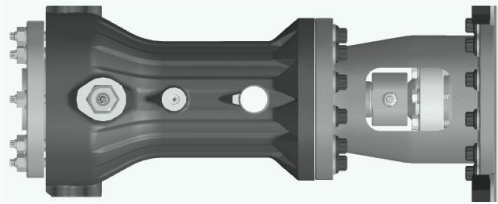


CSH2's technology stack **overcomes the critical limitations** of today's approaches.

## CSH2 Cryopump

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CSH2 cryopump innovations include both design *and* manufacturing.



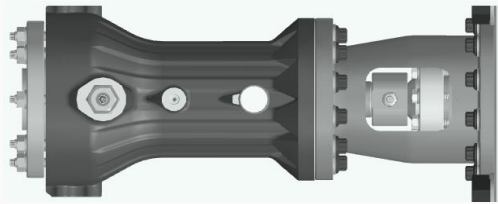
- **3D printing** enables new features reducing costs by up to 90%.
- **CAPEX reductions** up to 50% through production savings and system flowsheet simplification.
- **OPEX reductions** up to 50% from avoided boil-off and reliability.



## CSH2's technology stack **overcomes the critical limitations** of today's approaches.

### CSH2 Cryopump

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### CSH2 Refueler Module

Integrated refueler is fully optimized from earlier innovation by the team



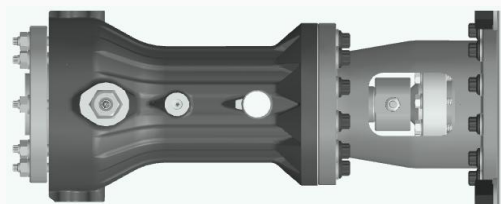
- Full-size station capability with **50% smaller footprint**.
- **Containerized approach** simplifies initial station build and offers simple path to expansion.
- **Modularity offers flexibility** and capital efficiency in network buildout.



## CSH2's technology stack **overcomes the critical limitations** of today's approaches.

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### The full **CSH2 System**

A low-boil-off cryopump enables simplification of the entire system.



Refueler	CSH2 station	Transit station <sup>1</sup>
Price (\$M)	5-10	10-20
Pressure (MPa)	35 or 70	35
Flow (kg/min)	6	4
Size (ft)	20x50	50 x 100



## The first demo is key to market entry. CSH2 is partnering with **Hyundai and Sunline Transit**

### PARTNERS:



#### MOU (July 2025) :

- Commitment of at least 2 Xcient fuel cell trucks

#### MEMORANDUM OF UNDERSTANDING

THIS MEMORANDUM OF UNDERSTANDING ("MOU"), dated as of the 7th day of July, 2025 ("Effective Date"), is entered into by and between Hyundai Motor America, a California corporation with its principal place of business at 10550 Talbert Avenue, Fountain Valley, CA 92708 ("HMA"), Hyundai Motor Company (including its affiliate Kia Corporation), a South-Korean corporation with its principal place of business at Heolleung-ro 12, Seocho-gu, Seoul, Republic of Korea ("H/KMC") and [CSH2 Corp], a [Delaware corporation] with its principal place of business at [92 Nassau St, Princeton, NJ 08542] ("CSH2"). HMA, H/KMC and CSH2 are sometimes referred to individually as a "Party" and collectively as the "Parties".

The Parties are interested in exploring a potential collaborative relationship for the development of CSH2's hydrogen refueler modules to support deployment of HMA and its affiliate's hydrogen fuel cell vehicles (the "Project"). This MOU sets forth the Parties' preliminary mutual understanding with respect to the Project and the principal terms of cooperation as set forth as follows:



#### Formal Negotiations in Progress

- Facility Access & Permitting Support
- Up to 10 buses/day

### OBJECTIVES:

#### *Demonstrate Full end-to-end low boil-off fueling service:*

- ~10 buses/day + ~5 trucks/wk ; Total: 360+ fills ; 8+ weeks

#### *(TRL 5 => TRL 7)*

- Upgrade system capabilities from 2 kg/min to 6 kg/min
- Gather reliability metrics
- Validate low-boil-off performance

### BUDGET

\$2.5M+ Total Project Budget

- Equipment, Facilities, Maintenance

**\$500k Grant Funding Request**

### EXECUTION PLAN

#### March 2025 - Technology Engagement

- Supply of 20 hydrogen storage tanks to support CSH2 tech validation efforts (Hyundai)

#### 4Q 2025 and 1Q 2026 – Demo Planning:

- Selection of host site and definition of commercial KPIs
- Demo logistics and preparation

#### 2Q 2026 – Pilot Contract Signing

- Execute contract with Sunline
- Community impact planning
- Execution of contract co-sponsored by Hyundai North America and Hyundai Kia Motor Company (South Korea)

#### 3Q 2026 – Pilot demonstration/Execution

- Daily fills over 3 months
- Real world reliability and cost data



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## H2 refueling today suffers from a cascade of pain points.

### THERMODYNAMICS

#### **Heat of compression**

(gas-to-gas stations)

- Compensation needed for fast, large, continuous fills
- Multistage compressors
- Chillers to pre-cool

#### **Liquid H2 boil-off**

(liquid-to-gas stations)

- Losses across operations
- Capital cost of BOG recovery equipment

### DESIGN

#### **Flowsheet complexity**

- Higher maintenance from unreliable ops
- Large footprint

#### **Legacy assumptions**

- Bespoke designs
- Limited future-proofing

### ECONOMICS

#### **High capex**

- High base costs
- Penalties at low utilization

#### **High opex**

- Maintenance requirements

### SCALABILITY

#### **Network growth**

- Limited hardware flexibility
- Low capital efficiency



## Unlocking large scale deployment of hydrogen mobility through targeted innovation.

### Fix the cryopump.

#### *Address boil-off*

- Improve insulation
- Eliminate booster
- Optimize seals
- Manage cooldown

#### *Reduce cost*

- Utilize 3D printing

#### *Improve reliability*

- Implement fast swap

CRYOPUMP

### Solve modularity.

#### *Simpler flowsheet*

- No buffer storage
- No chiller

#### *Standardize units*

- Drive cost efficiency.
- Reduce build & deployment time.

MODULE

### Validate system.

#### *Demo core innovations.*

- Multi-mode fueling
- Fast service turnarounds
- Flexible configurations

STATION

### Build fueling networks.

#### *Scale growth using modules.*

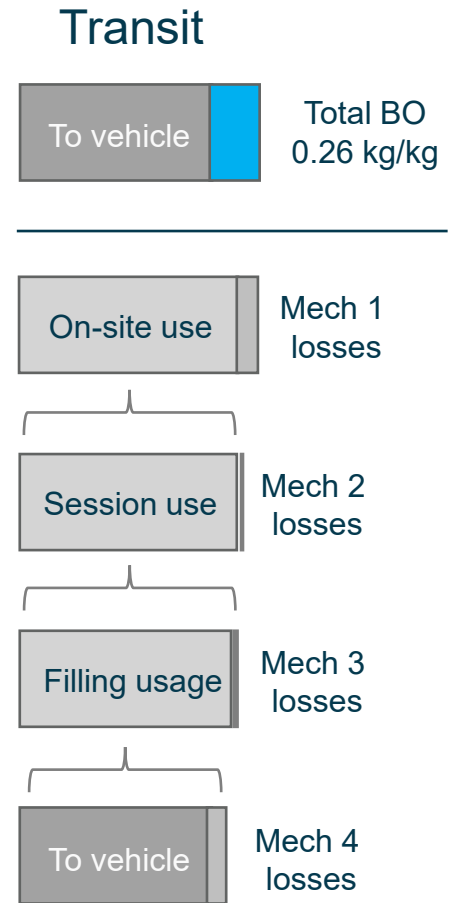
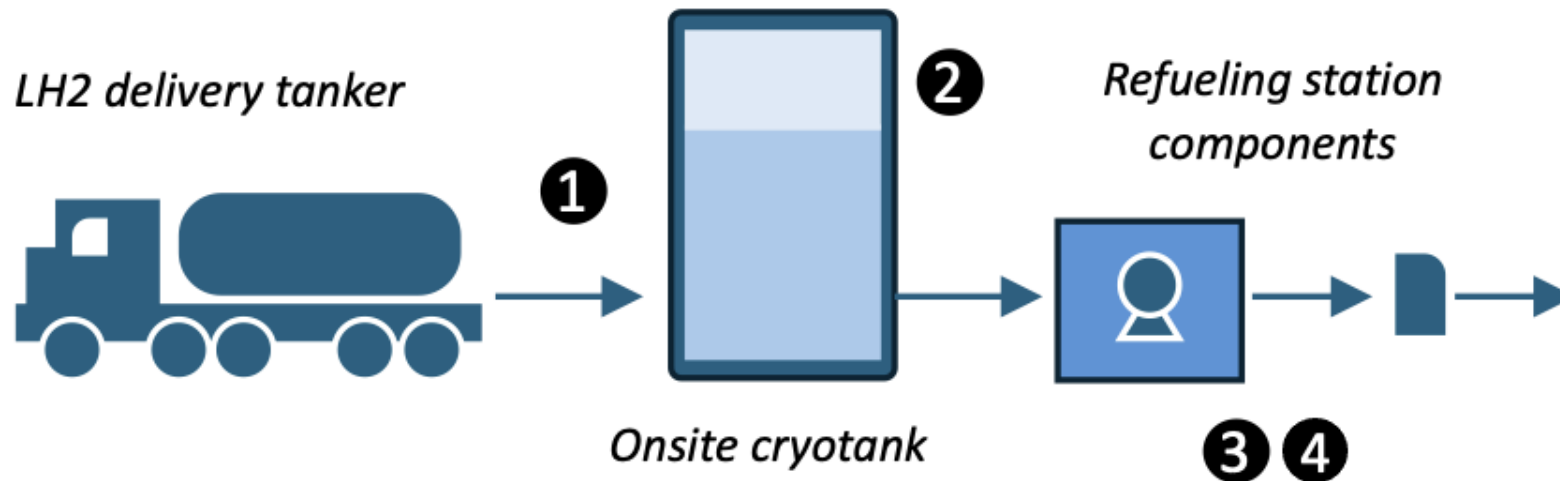
NETWORK

#### **IP POSITION:**

4 trade secrets  
8 patent applications  
Additional dockets in prep

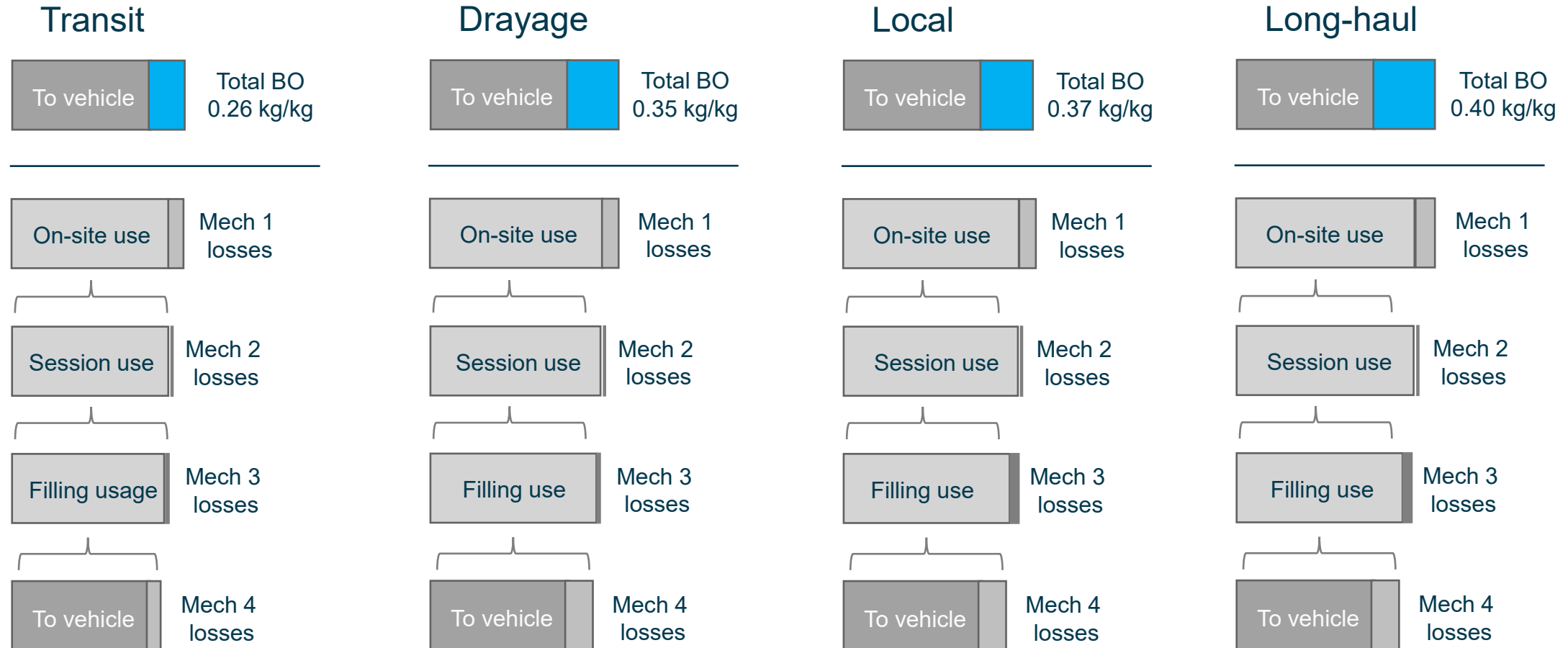


## Boil-off losses are cumulative.



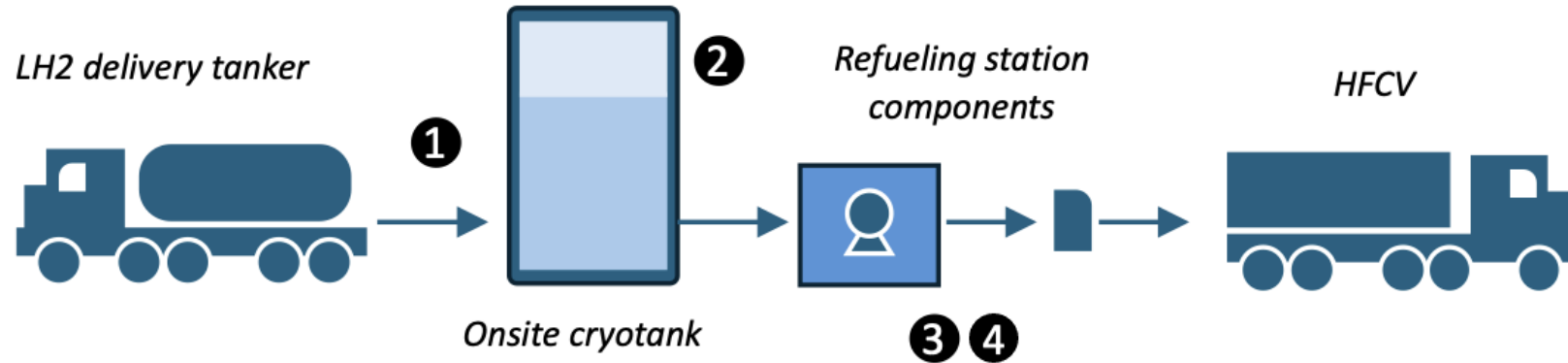


## Boil-off losses are sensitive to station operation details.





## Boil-off can be further mitigated through innovation



Typical boil-off losses range from<sup>1</sup> :  
 23 to 50%  
 of delivered LH<sub>2</sub>

Mechanism	Mitigation
1. Delivery losses	Switch from trans-fill to transfer pump
2. Static heat loss/NER	Improved insulation ; Cryocooler
3. Pump cooldown	Scheduling; Submerged pump ; Heat integration
4. Pump operation	Pump design and operation