DOE/NASA Advances in Liquid Hydrogen Storage Workshop

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Economics of Energy-Efficient, Large-Scale LH_2 Storage Using IRAS & Glass Bubble Insulation

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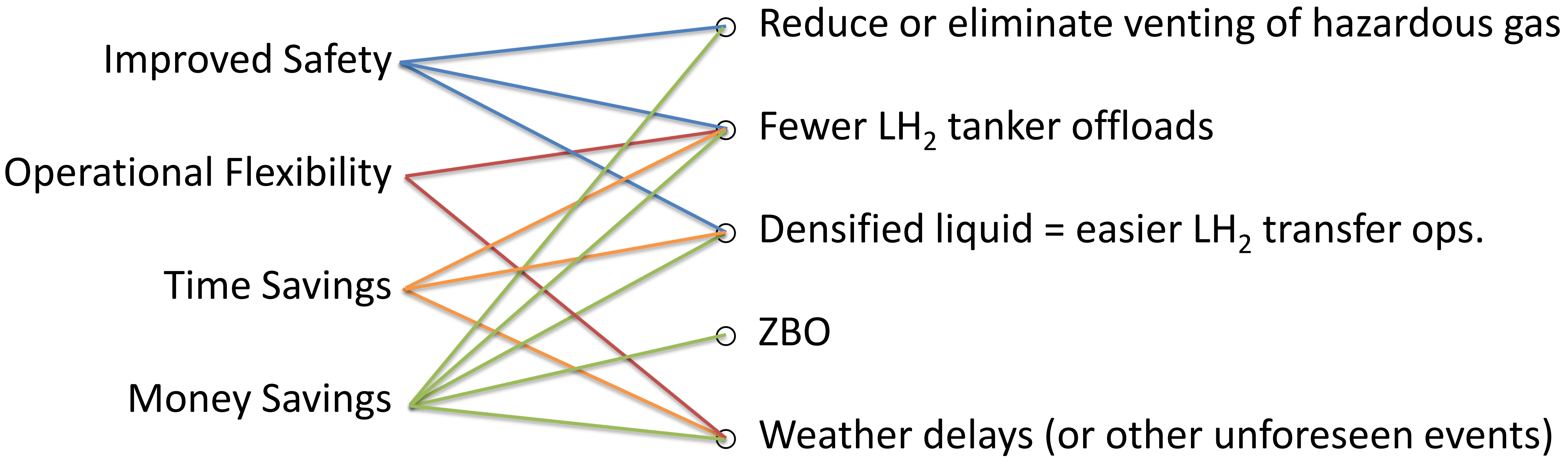
Contents

Significance of IRAS

- IRAS is more than just zero boiloff (ZBO)—It is a about gaining control!
- Benefits of <u>Full Control Storage </u>via IRAS:



Should I implement an IRAS system?

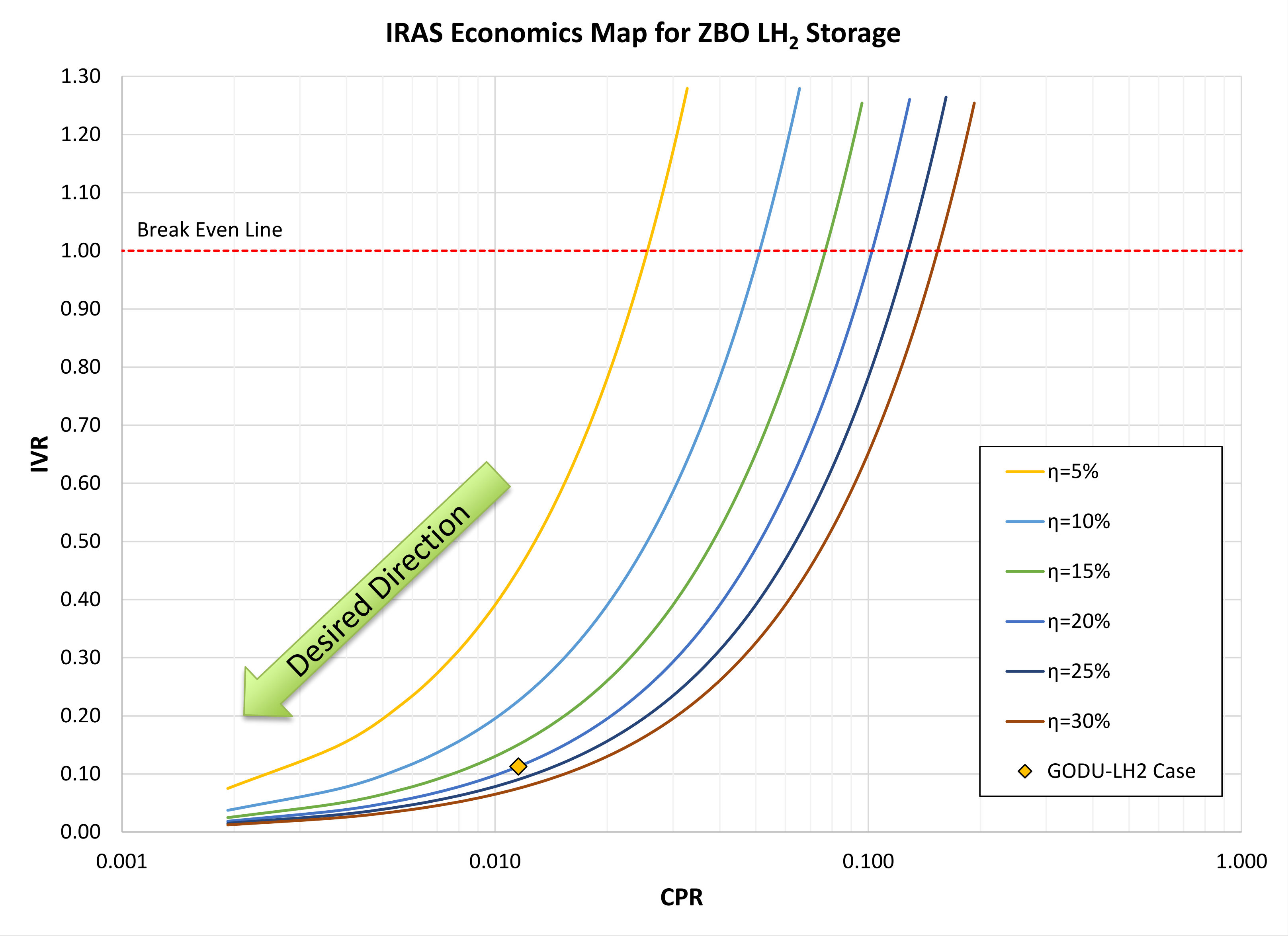
IRAS Value Ratio (IVR): $\frac{\$_e}{\$_{LH2}}$

- Money spent on electricity to power the IRAS system for ZBO vs. LH_2 savings

Commodity Price Ratio (CPR): $\frac{C_e}{C_{LH2}}$

- Price of electricity vs. price of LH_2
- $C_e = \frac{\$}{kWh}$ $C_{LH2} = \frac{\$}{kg}$

η = Refrigerator efficiency {%Carnot}

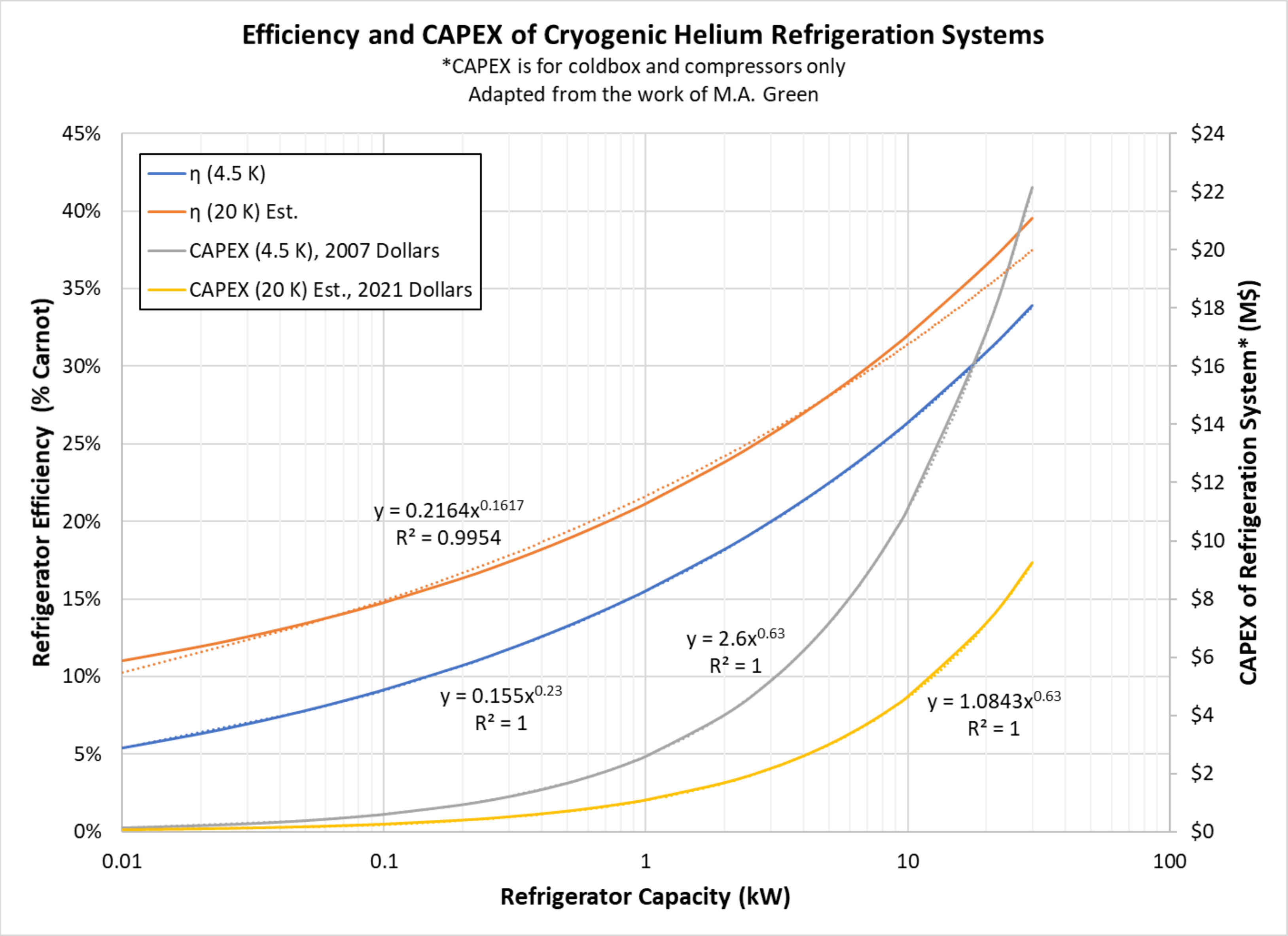


Should I implement an IRAS system?

- M. A. Green of Lawrence Berkeley National Laboratory, published work in 2007 surveying CAPEX & efficiencies of 4.5 K helium refrigeration systems [2]

- CAPEX is for coldboxes and compressors only
  - Roughly half of the total system cost

- Efficiency and CAPEX estimated for 20 K using difference in Carnot efficiency between 4.5 K and 20 K



Why care about tank thermal performance?

Monetary cost of boiloff

$$\$_{boiloff} = \frac{Q_{liq} C_{LH2} t}{\rho h_{fg}}$$

$\$_{boiloff}$ = Total cost of LH_2 boiloff losses

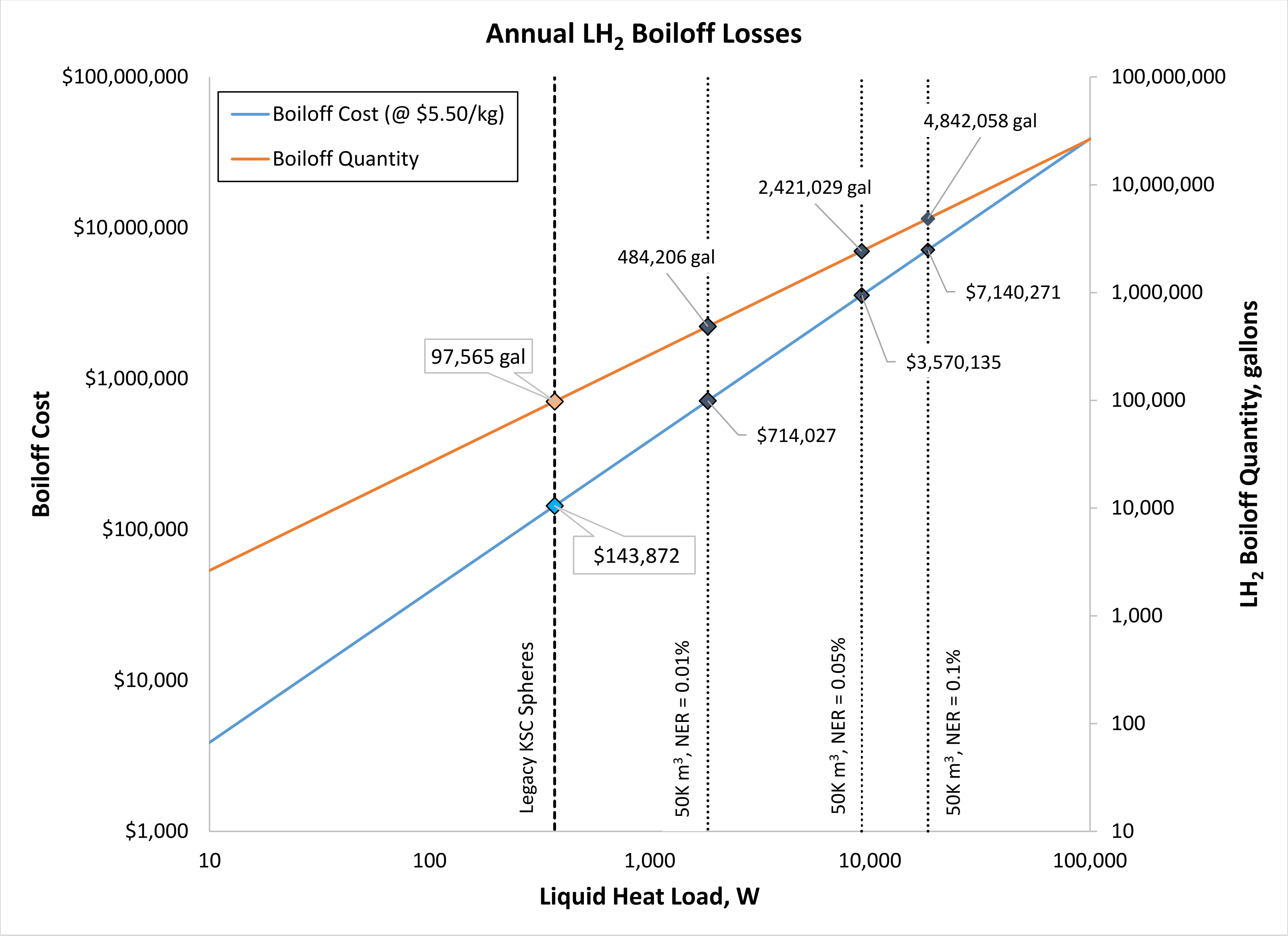
Q_{liq} = Heat load on the liquid {W}

C_{LH2} = Price of LH_2 {\$/m³}

t = Time {s}

ρ = Density of LH_2 {kg/m³}

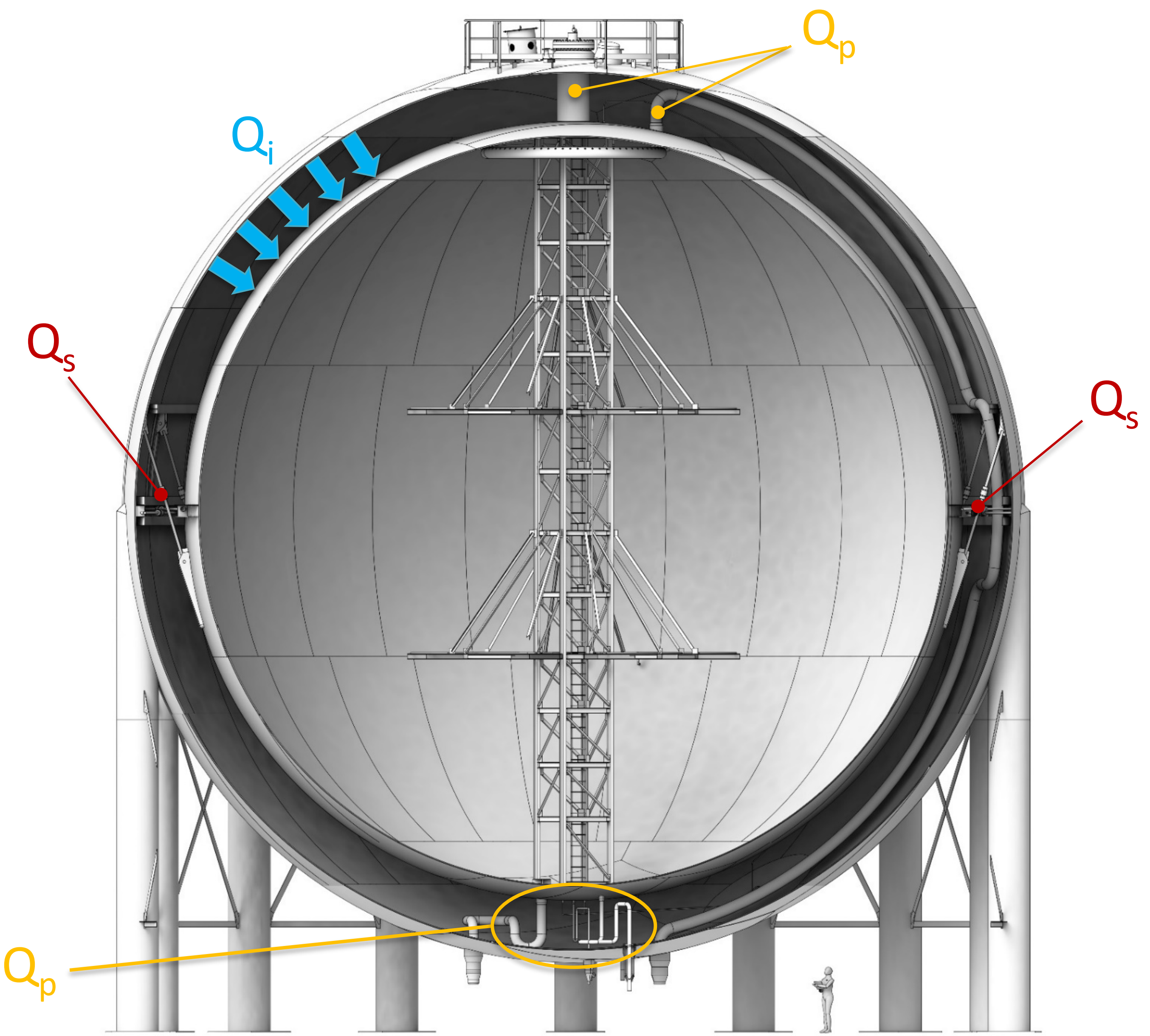
h_{fg} = Heat of Vaporization of LH_2 {J/kg}



Why care about tank thermal performance?

- Q_{liq} driven by tank design
- **Cold Triangle Approach** [3]
    1. Insulation (Q_i)
    2. Supports (Q_s)
    3. Piping (Q_p)
    4. Insulation Quality Factor (Q_{IQF})

$$Q_{total} = Q_i + Q_s + Q_p + Q_{IQF}$$



Why care about tank thermal performance?

<u>Example</u>

50,000 m^3 tank, 0.1%/day NER w/Perlite, replacing Perlite with Glass Bubbles

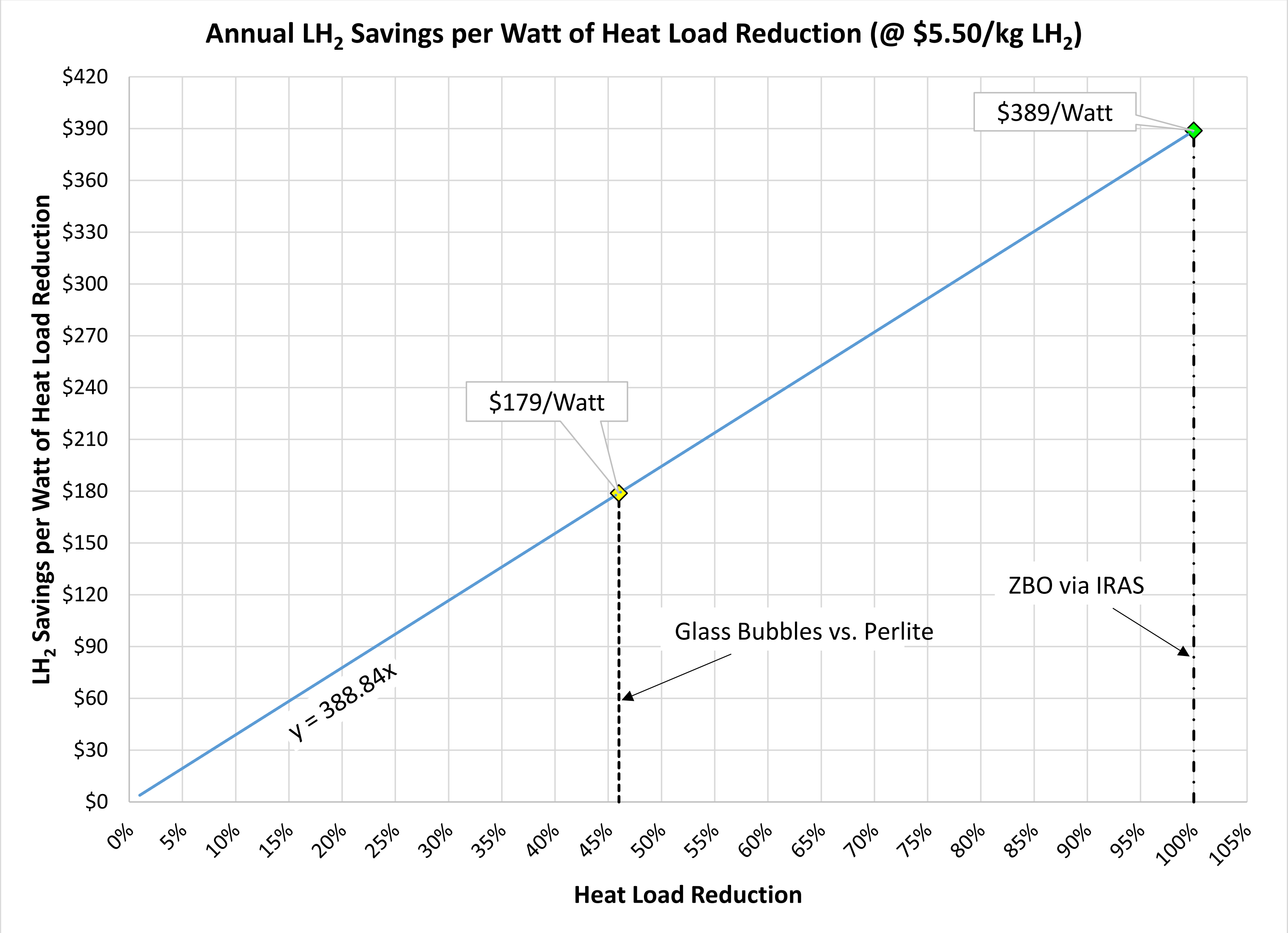
$Q_{liq,perlite}$ = 18.4 kW

$Q_{liq,GB} = 0.54 Q_{liq,perlite}$ = 9.9 kW

Total heat load reduction = 8.5 kW

Annual LH_2 cost savings

(8500 W)($179/W) = **$1.52M**



Passive-Active Synergy

IRAS and tank thermal performance are not mutually exclusive, they are synergetic!

Baseline Case

Baseline design:

- 40,000 m^3 LH_2 tank
- NER = 0.06%/day
- No IRAS

Assumptions:

- LH_2 price = $6.25/kg
- Electricity Price = $0.12/kWh
  - ➢ Commodity Price Ratio = 0.019

Baseline Analysis:

- Heat Load = 8.8 kW
- Annual Boiloff = 8,800 m^3 (2.32Mgal)
- Annual Boiloff Cost **= $3.9M**

Case 1

✓ 20% improvement in tank thermal performance

X No IRAS

Case 2

X Baseline tank thermal performance

✓ ZBO with IRAS

Case 3

✓ 20% improvement in tank thermal performance

✓ ZBO with IRAS

Passive-Active Synergy

Baseline Case
- 40,000 m^3 LH_2 tank
- NER = 0.06%/day
- No IRAS

Case 1
- ✓ 20% improvement in tank thermal performance
- X No IRAS

Case 2
- X Baseline tank thermal performance
- ✓ ZBO with IRAS

Case 3
- ✓ 20% improvement in tank thermal performance
- ✓ ZBO with IRAS

	Units	Baseline	Case 1	Case 2	Case 3
Heat Load	kW	8.8	7.1	8.8	7.1
Annual Boiloff	m^3 (Mgal)	8,800 (2.32)	7,000 (1.86)	0	0
Annual Boiloff Cost	USD	**$3.9M**	$3.1M	$0	$0
Annual Boiloff Savings	USD	---	**$800k**	**$3.9M**	**$3.1M**
Est. Refrigerator CAPEX†	USD	---	---	$4.2M	$3.6M
Est. Refrigerator Efficiency	% Carnot	---	---	31%	30%
IRAS Value Ratio (IVR)	dimless	---	---	0.121	0.125
Annual IRAS Electricity Cost	USD	---	---	$473k	$391k
Est. CAPEX Payback Period	Months	---	---	11.5	12.4

† Assuming zero margin on the heat load, and including 50% margin for additional cost beyond the coldbox and compressor

★ CAPEX savings of $600k between Cases 2 & 3

Additional Impacts of Boiloff

- Obtaining and liquefying hydrogen is energy intensive, so we need to preserve that investment!
- Eliminating boiloff, even a small amount, can have a large positive impact!

Back to our case study….

	Units	Baseline	Case 1	Case 2	Case 3	Notes
Annual Liquefaction Energy Required to Replenish Boiloff Losses	GWh	6.9	5.5	N/A	N/A	Combination of the SMR process and liquefaction power required
Annual Energy Savings By Reducing/Eliminating Boiloff	GWh	N/A	1.4	3.0	3.6	
Annual CO_2 Production to Replenish Boiloff Losses	MT	8,671	6,937	N/A	N/A	Case 1: SMR + Liquefaction power
Annual Reduction in CO_2 by Reducing/Eliminating Boiloff	MT	N/A	1,734	7,031	7,315	Case 1: SMR + Liquefaction power Cases 2 & 3: Liquefaction power only

Roughly 1 MT of CO_2 is created per Watt of heat load on an LH_2 tank

References

1. Barron R. F., 1985, *Cryogenic Systems,* 2nd Ed., Scurlock R. G., New York, NY, Oxford University Press, p 242
2. Green M. A., THE COST OF HELIUM REFRIGERATORS AND COOLERS FOR SUPERCONDUCTING DEVICES AS A FUNCTION OF COOLING AT 4 K, AIP Conference Proceedings 985, 872 (2008); https://doi.org/10.1063/1.2908683
3. Fesmire J. E., and Swanger A. M, Advanced cryogenic insulation systems, Proceeding of the 25th International Congress of Refrigeration, Montreal, Canada, (2019)

Links used as references for the analysis presented on slide 10

CO2 and Electricity Production

CO2 and the Steam Methane Reformation (SMR) Process

CO2 Produced by Passenger Cars

Thank you for your attention!

Questions?

Backup Slides

Calculation for curves in IRAS economics map, slide 4

$$\mathrm{IVR} = \mathrm{CPR}\frac{\mathrm{h_{fg}}\left[\mathrm{T_o}\ln\left(\frac{\mathrm{T_2}}{\mathrm{T_1}}\right) + \mathrm{T_1} - \mathrm{T_2}\right]}{\eta(\mathrm{T_2} - \mathrm{T_1})}$$

h_{fg} = Heat of Vaporization of LH_2 {J/kg}

η = Refrigerator Efficiency {% Carnot}

T_o = Sink Temperature (Ambient) {K}

T_1 = Helium Supply Temp. {K}

T_2 = Helium Return Temp. {K}

See reference [1]

New KSC LH_2 Sphere Analysis

New 4,700 m³ KSC Sphere

Spec. design:

- 4,700 m^3 LH_2 tank
- NER = 0.048%/day
- No IRAS

Assumptions:

- LH_2 price = $5.50/kg
- Electricity Price = $0.06/kWh
  - ➢ Commodity Price Ratio = 0.011

Case 1

✓ Glass Bubbles

X No IRAS

Case 2

X Glass Bubbles

✓ ZBO with IRAS

Case 3

✓ Glass Bubbles

✓ ZBO with IRAS

	Units	Tank Specification	Case 1	Case 2	Case 3
Heat Load	W	829	525	829	525
Annual Boiloff	m^3 (kgal)	827 (219)	524 (138)	0	0
Annual Boiloff Cost	USD	$322k	$204k	$0	$0
Annual Boiloff Savings	USD	---	$118k	$322k	$204k
Est. Refrigerator CAPEX†	USD	---	---	$900k	$700k
Est. Refrigerator Efficiency	% Carnot	---	---	21%	19%
IRAS Value Ratio (IVR)	dimless	---	---	0.102	0.112
Annual IRAS Electricity Cost	USD	---	---	$33k	$23k
Est. CAPEX Payback Period	Years	---	---	2.7	3.3

† Assuming zero margin on the heat load, and includes 50% margin for additional cost beyond the coldbox and compressor

New KSC LH_2 Sphere Analysis

	Units	Tank Specification	Case 1	Case 2	Case 3	Notes
Annual Liquefaction Energy Required to Replenish Boiloff Losses	MWh	652	413	N/A	N/A	Combination of the SMR process and liquefaction power required
Annual Energy Savings By Reducing/Eliminating Boiloff	MWh	N/A	239	105	269	
Annual CO_2 Production to Replenish Boiloff Losses	MT	815	516	N/A	N/A	Case 1: SMR + Liquefaction power
Annual Reduction in CO_2 by Reducing/Eliminating Boiloff	MT	N/A	299	587	656	Case 1: SMR + Liquefaction power Cases 2 & 3: Liquefaction power only