Inexpensive delivery of compressed hydrogen with advanced vessel technology

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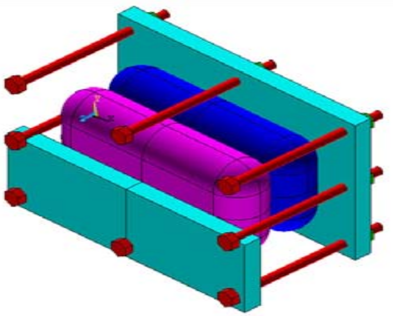
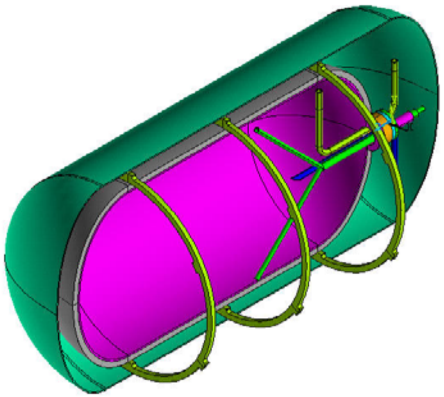
LLNL is developing innovative concepts for efficient containment of hydrogen in light duty vehicles concepts may offer advantages for hydrogen delivery

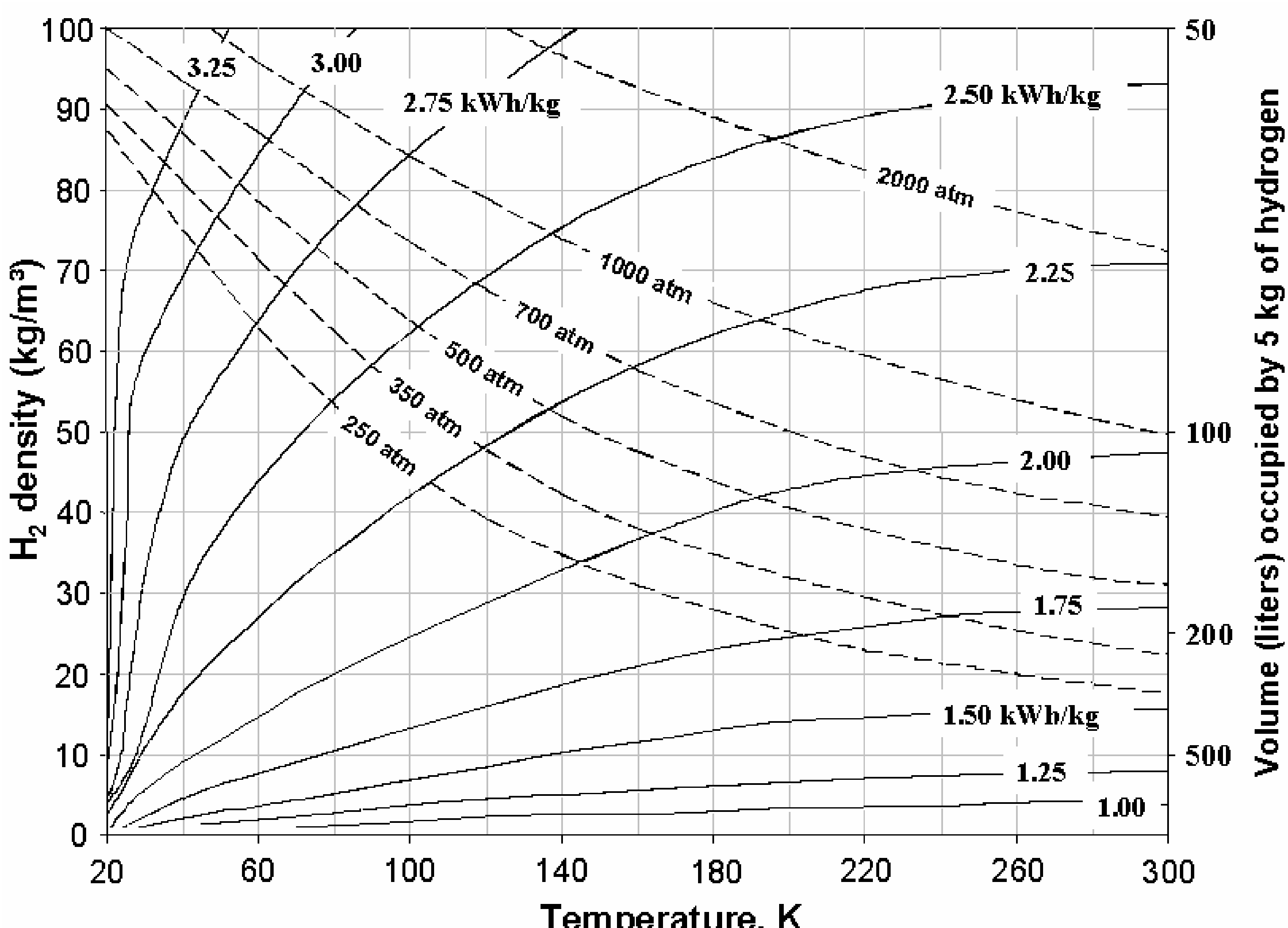




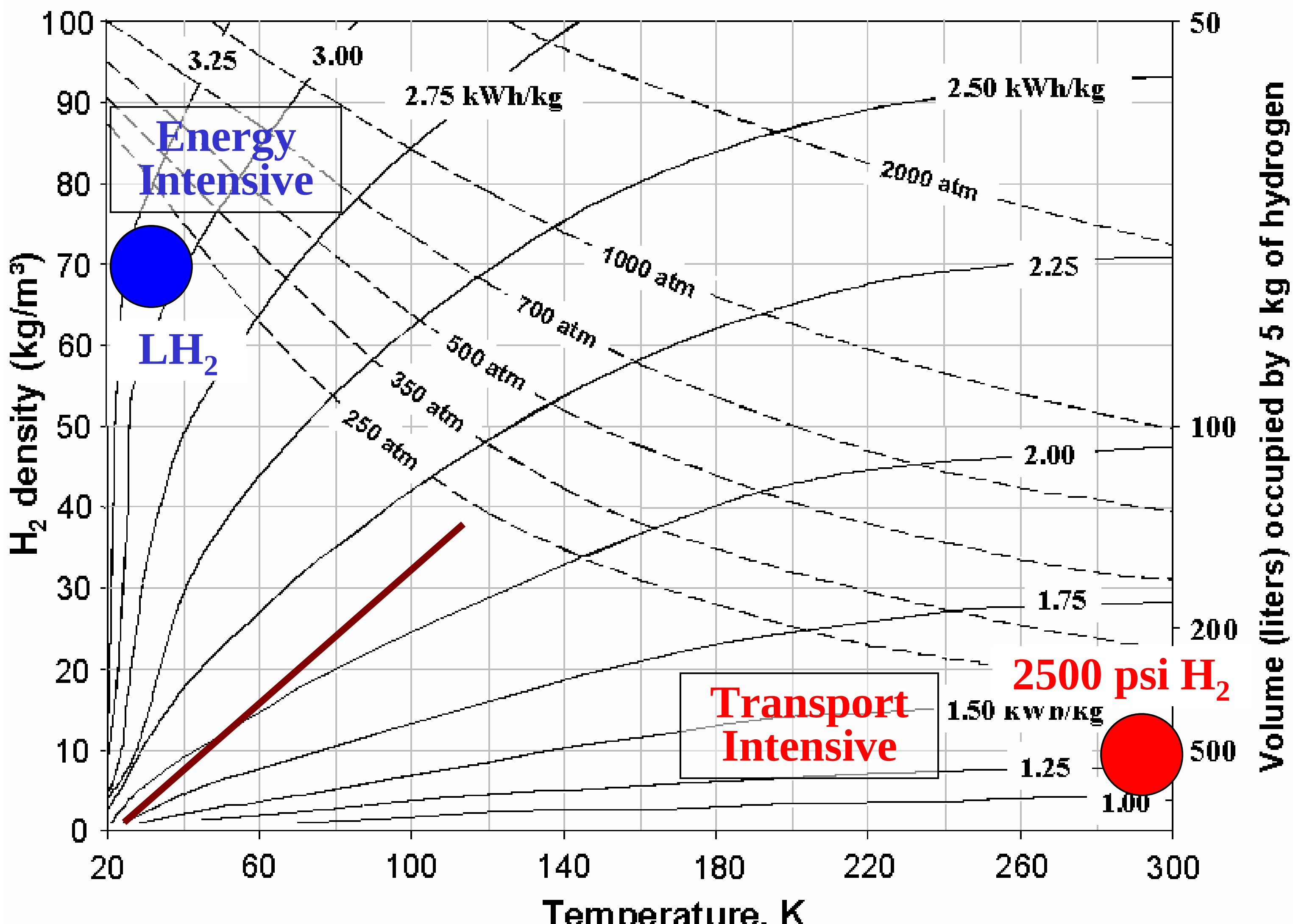
Conformable containers efficiently use available space in the vehicle. We are pursuing multiple approaches to conformability

High Strength **insulated pressure vessels** extend LH_2 dormancy 10x, eliminate boiloff, and enable efficiencies of flexible refueling (compressed/cryogenic H_2/(L)H_2)

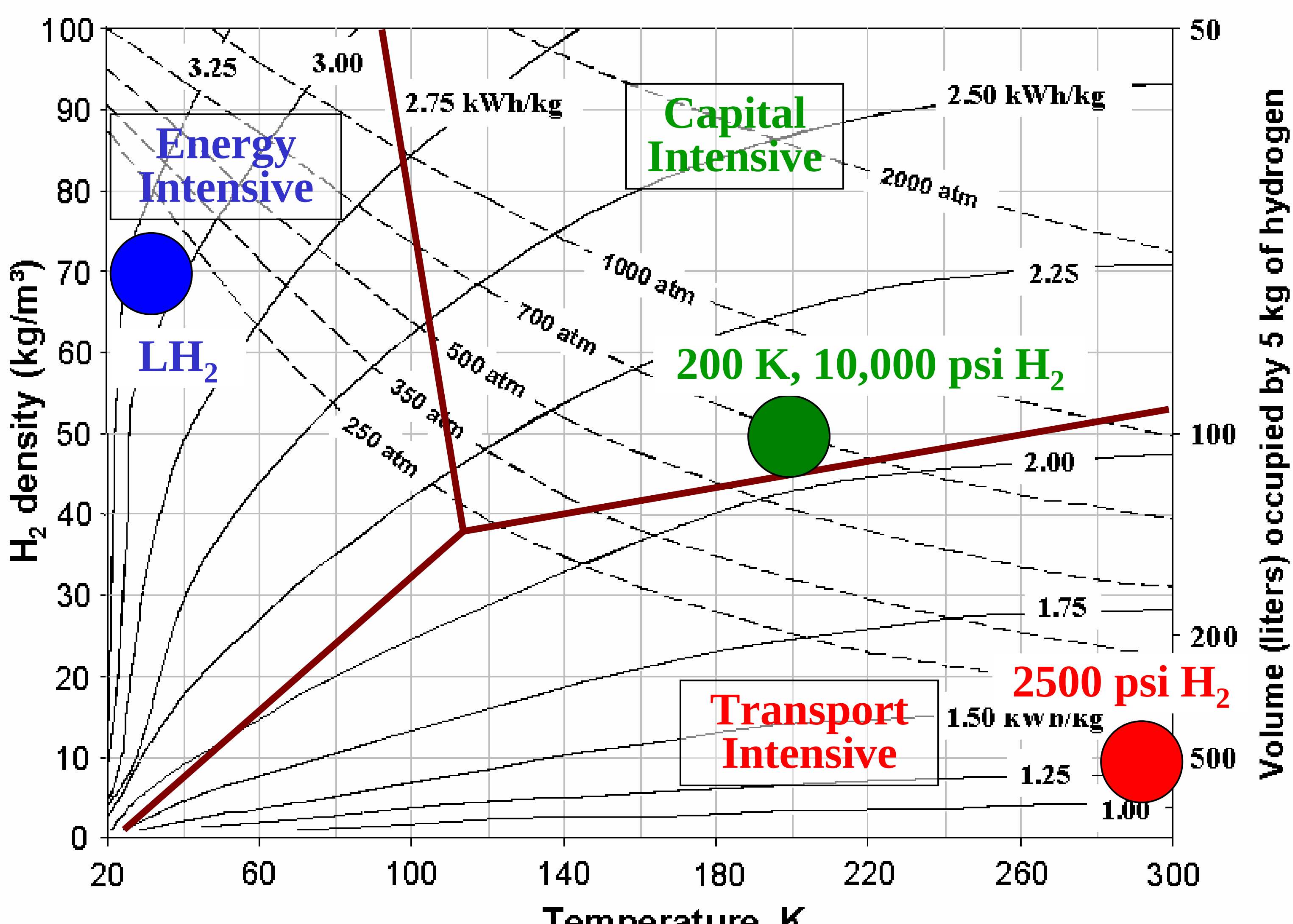
The PVT properties of H_2 drive storage and delivery costs (capital, energy, and transport)



Today's commercial hydrogen delivery approaches occupy extreme delivery strategy spaces



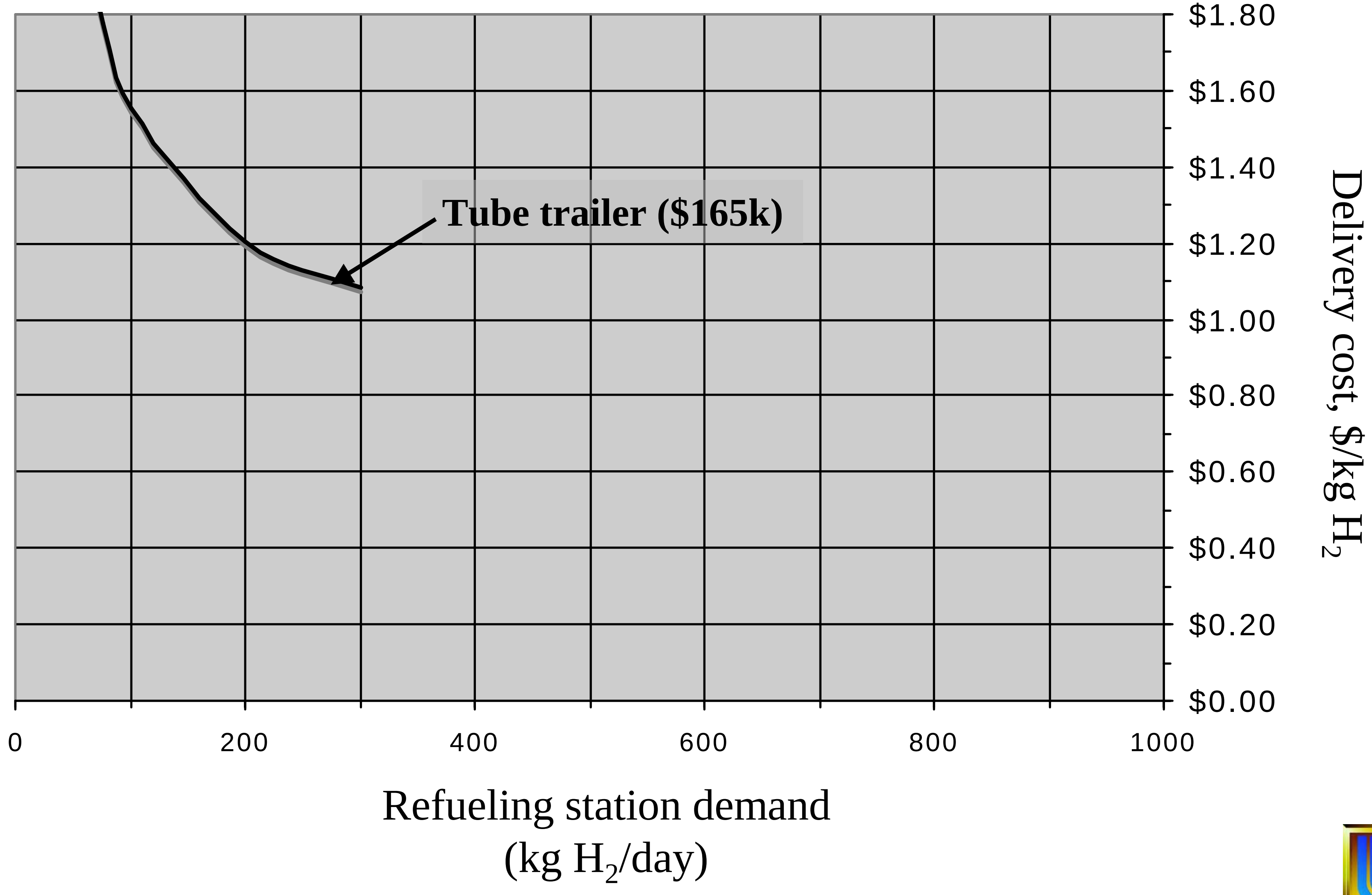
In principle, higher capital intensity could better balance energy and transport costs



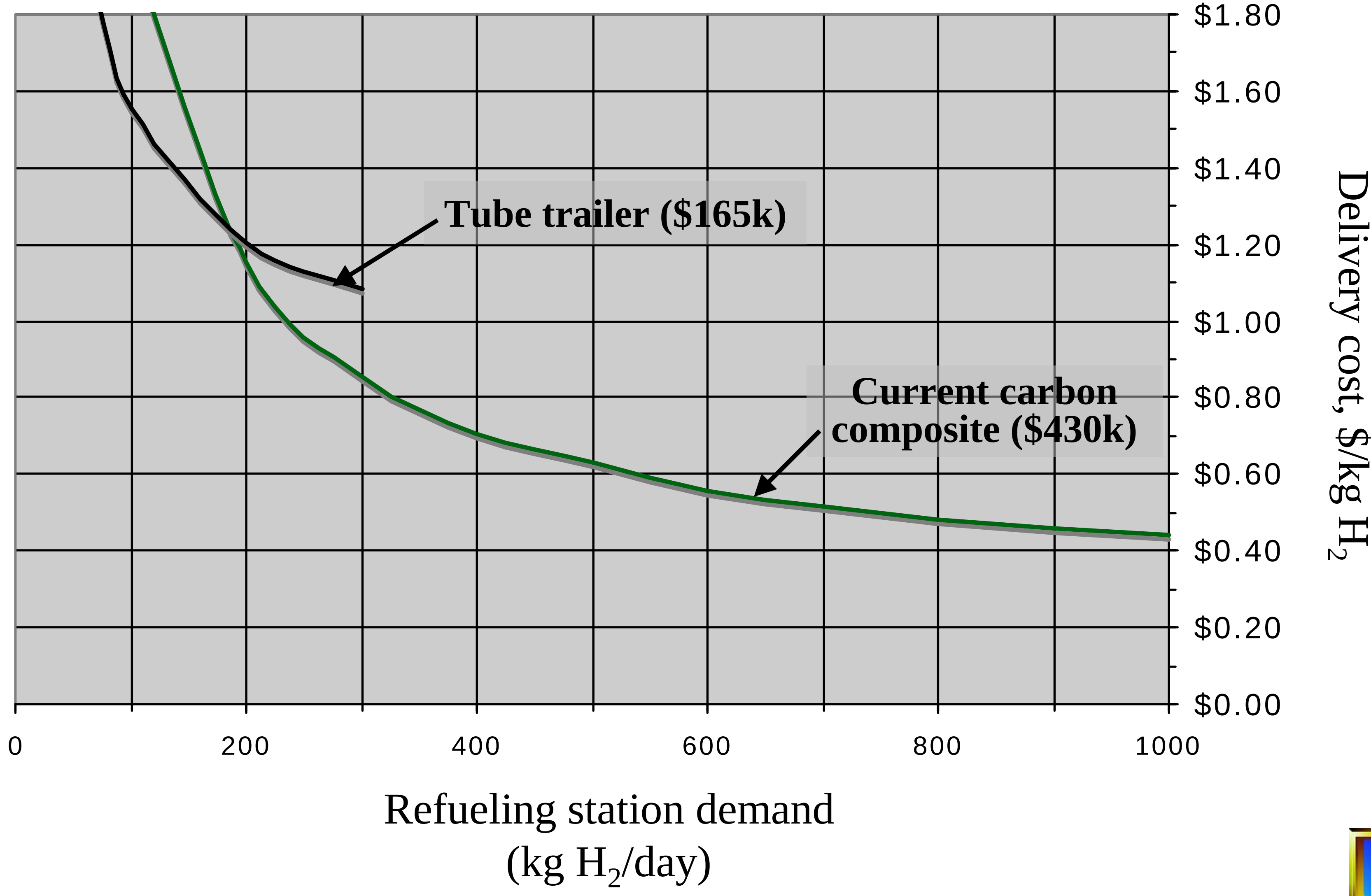
Preliminary economic analysis for hydrogen trailers

- **Benchmark to tube trailer drop-off scenario**
  - **100 km round trip**
  - **Trailer drop-off time determined by capacity and station scale**
  - **All trailers sized to 1300 kg H_2 capacity (1150 kg deliverable)**
  - **Explore station demand from 70 kg H_2/day to 1000 kg H_2/day**
- **Real hydrogen thermodynamic and PVT properties**
  - **All trailers store hydrogen at 10,000 psi**
    - **trailers designed for burst pressure of 2.25x MOP**
    - **300 Kelvin ambient assumed**
- **Consistent with H2A methodology**
  - **H2A financial parameters for everything except trailer cost**
  - **$0.08/kWh electricity**

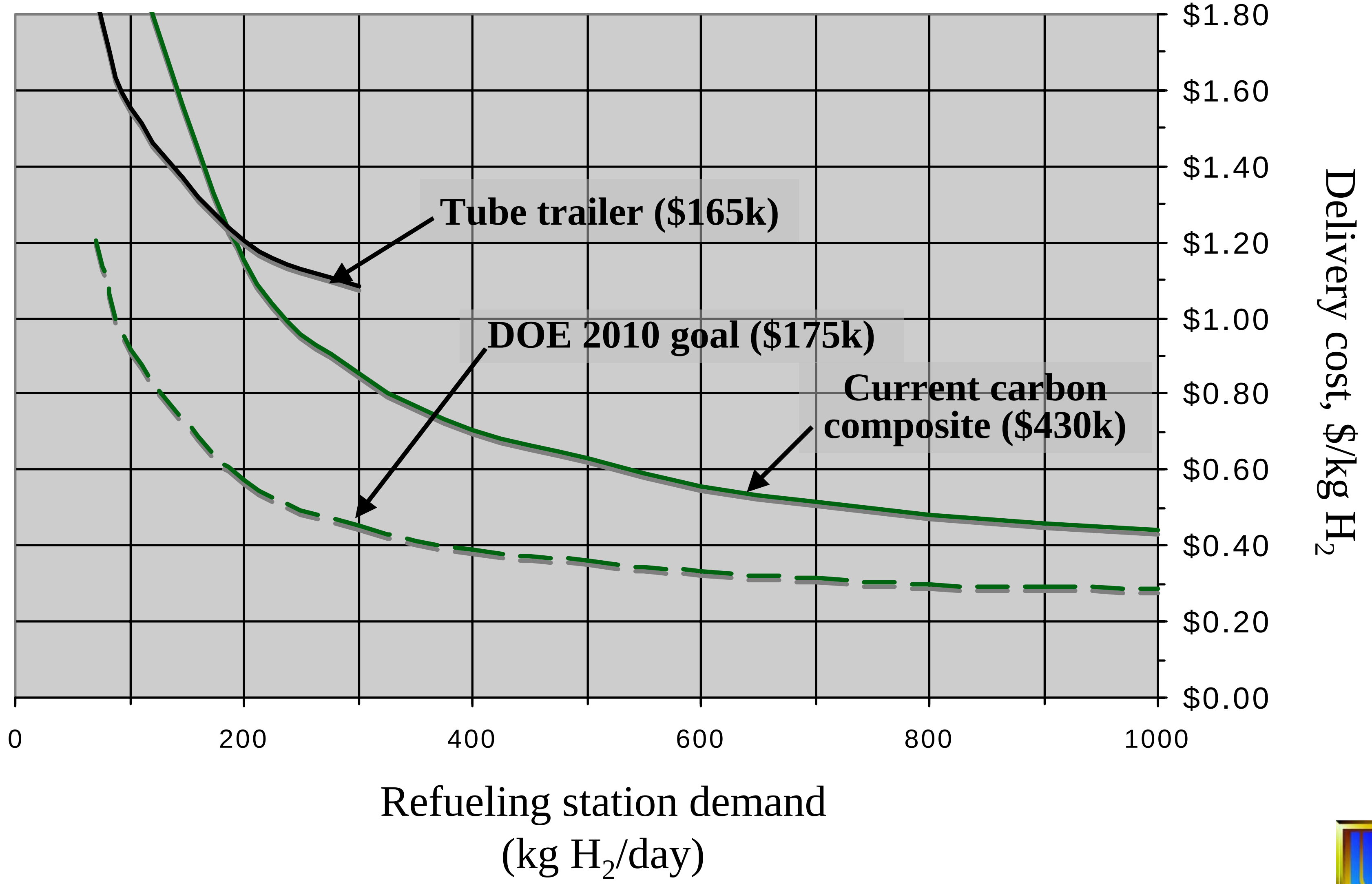
Conventional metallic tube trailers (2640 psi) have low H_2 capacity (~300 kg H_2) leading to high estimated delivery costs



Raising trailer pressure (10,000 psi) increases H_2 capacity 4x but requires composites to minimize trailer weight



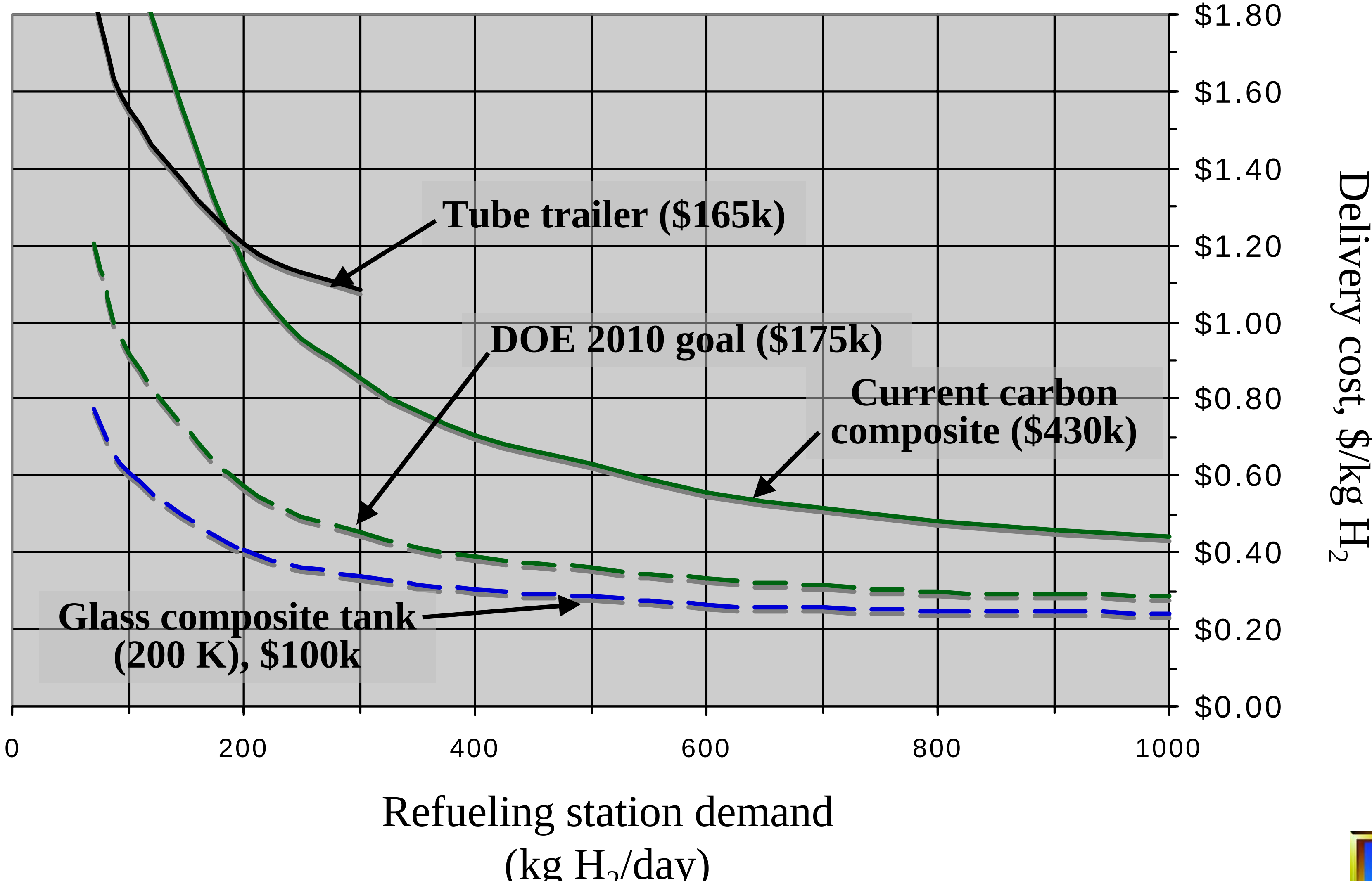
Delivering H_2 below \$0.30/kg
Implies trailer costs below \$4/kWh (2010 onboard goal)
(corresponds to \$6/kg of vessel for a 6 wt% H_2 trailer)



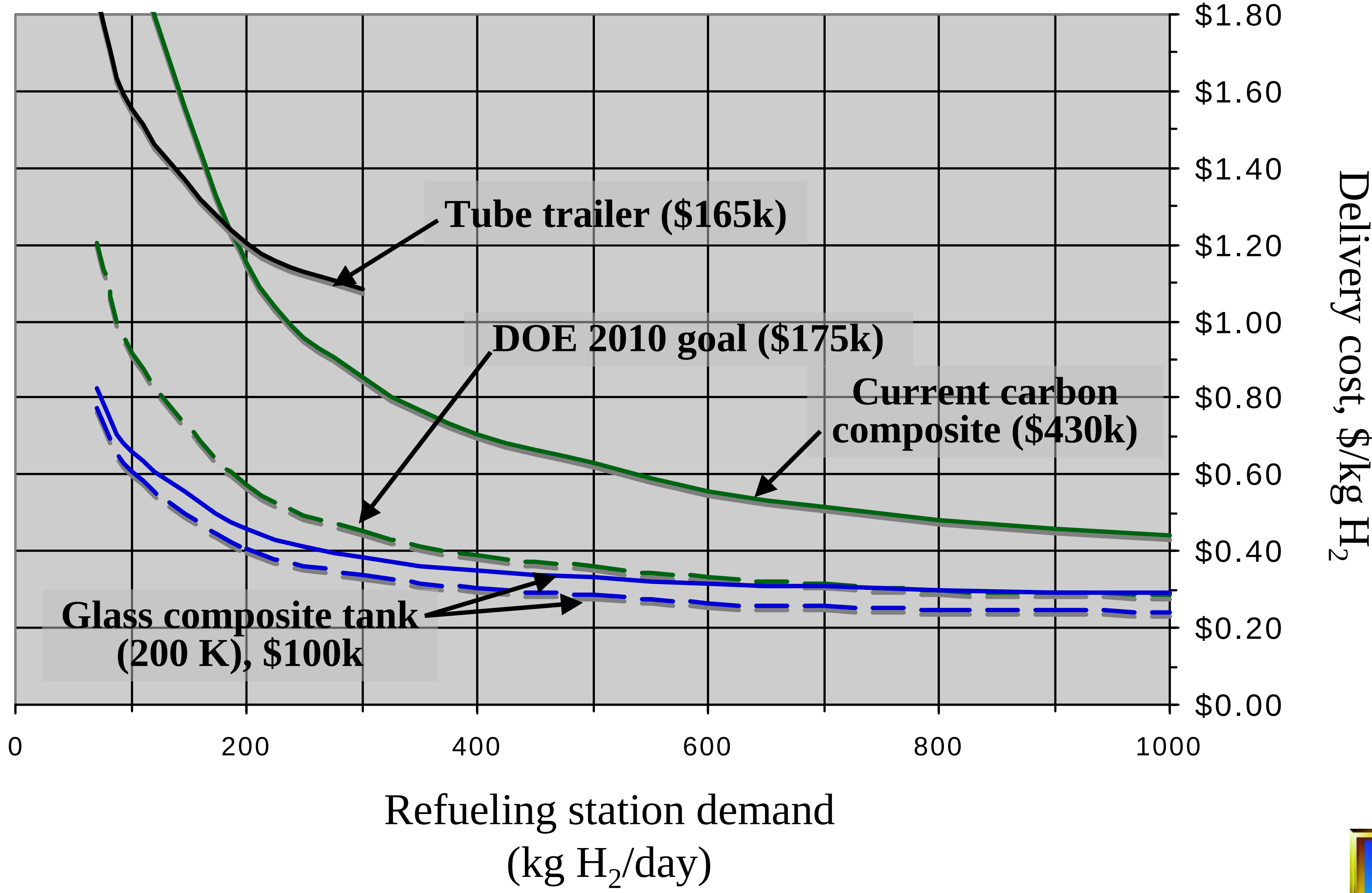
Our approach exploits the hydrogen phase diagram and vessel characteristics to minimize delivery cost

- **Hydrogen and material properties**
  - **Increased pressure (10,000 psi) saves per trip costs**
  - **Colder temperatures (~200 K) increase density ~35% with small increases in theoretical storage energy requirements**
  - **Low temperatures are synergistic with glass fiber composites**
    - **glass fiber strengthens 50% at 200 Kelvin (vs. 300 K)**
    - **expands weight limited trailer capacity**
- **Design custom vessels with optimum characteristics**
  - **Replicant vessels are good candidates**
    - **cost advantages with respect to winding at large sizes**
    - **glass composite (~$1.50/kg) minimizes material cost**
- **Trailer Utilization**
  - **1-2 day delivery cycle minimizes idle capital and insulation**
  - **Insulated trailer retains cold from flow work (~ 220 kWh_{th})**

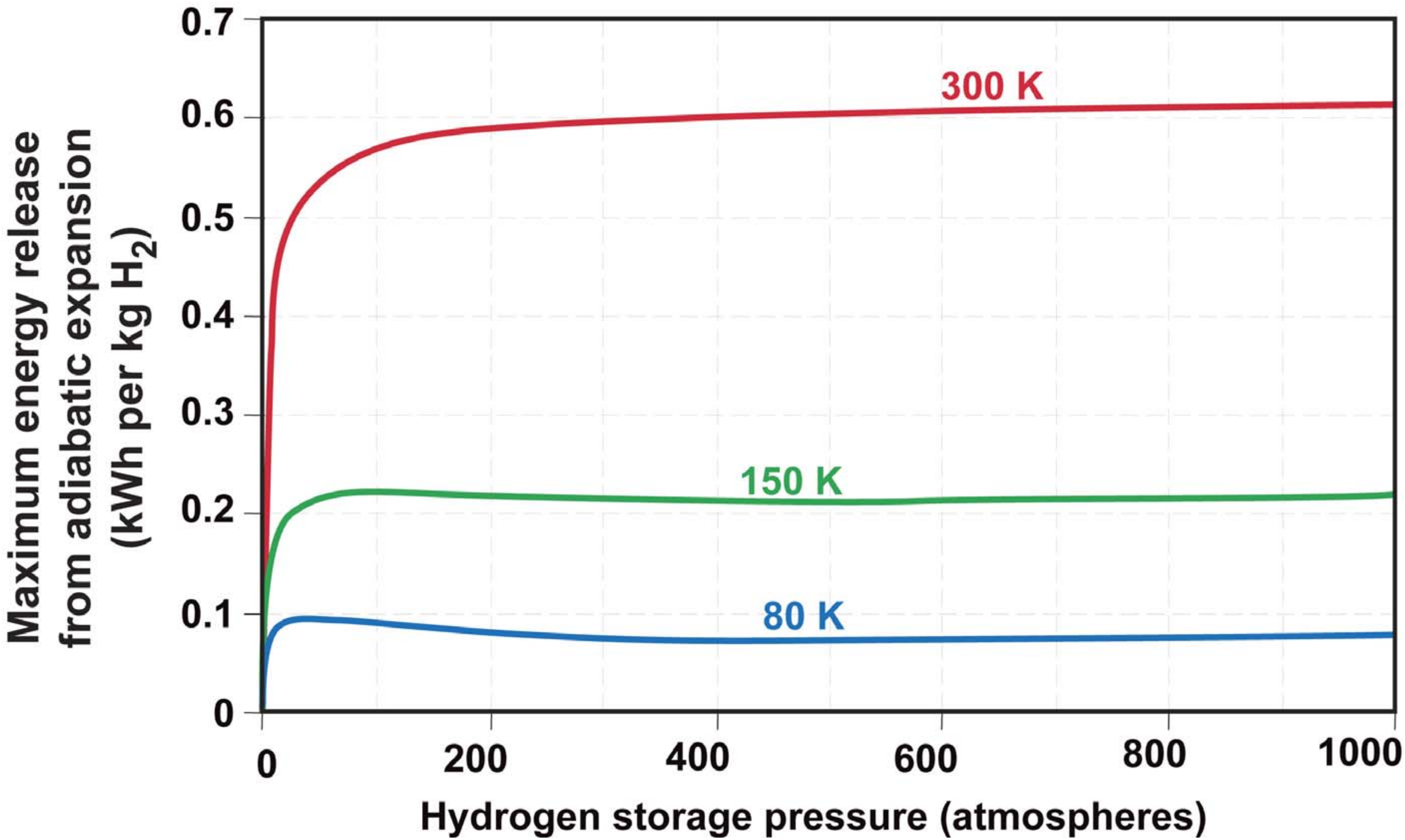
We estimate a glass composite trailer designed for 10,000 psi at 200 Kelvin can deliver H_2 for ~ $0.30/kg H_2



Assuming 30% efficient refrigeration from 300 K to 200 K with equal capital and energy refrigeration cost components would add ~ \$0.05/kg H_2 to delivery cost



Cooling hydrogen removes expansion energy from the gas - offering intrinsic potential safety advantages



Delivery of cold (200 K) high pressure (10,000 psi) hydrogen in glass fiber trailers can reduce delivery cost to ~$0.30/kg

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Desirable features of macrolattice containers for hydrogen delivery

- **Make best use of the best structural material for this application (S-Glass) :**
  - **Conventional winding processes for composite pressure vessels capture some of the economic performance advantages of S-Glass**
  - ***Wound* composite tanks are unlikely to achieve manufacturing costs below $1/kg - this is necessary to achieve vessel costs below $4/kWh H2**
  - **Structures (e.g. pressure vessels) are very costly to develop at larger than human scale. Macrolattices have far smaller scales (0.3m) than tanker trucks (10m), enabling rapid evolution**
- **One macrolattice solution can be proven on a scale smaller than a phone booth, and assembled into nearly-arbitrarily-larger rectangular containers. No new tooling costs or qualification of manufacturing procedures are required to build larger or tailored shapes**
- **Proof of technical feasibility implies collection of statistical component failure data, qualifying real failure modes exhaustively**
- **Radical geometries will likely result in novel properties enabling new features (crashworthiness)**

Closing thoughts on impact of delivery to onboard storage

- **H_2 stored at 300 K (10,000 psi) -----> 380 K when fast-filled**
- **H_2 stored at 200 K (10,000 psi) -----> 313 K when fast filled**

- **This represents a 15% capacity difference, or ~ $100 in capital cost (given $660 for 5 kg H_2 storage at $4/kWh)**
- **Discounted at 10% over 12 years this cost is $15/yr**

- **~$0.10/kg H_2 for 80 mpg equiv. H_2 auto @ 12,000 mi/yr**
- **Scales with onboard storage investment (range or cost driven)**