Life-cycle cost and storage pressure of hydrogen

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Abstract

As storage pressure increases, so does compression work and cost, but tank cost may not. To find out whether there might be an optimal pressure to achieve minimum storage cost, we determined the cyfe-cycle compression energy cost and tank cost vs. H2 storage peak pressure.

A 2009 report by TIAX and Argonne National Labs concluded that local or central production of compressed H2 from natural gas via steam reforming leads to retail LHV prices of 20 $/GJ-H2 or We wanted to determine whether there are optimal (i.e. minimum cost) conditions in terms of tank size and storage pressure.

Discussion

We determined tank, compressor and compression electricity costs to arrive at life-cycle storage costs per unit weight of hydrogen, e.g. in $/kg-H2. The capital costs were averaged over the assumed life cycle of 30 years, tank capacity and once daily compressions of H2 from p1 to p2.

1. **Tank costs** -- Reference [2] lists prices of air tanks, which can also be used to store H2, natural gas and other gases, up to 250 psig. We plotted those data in Fig. 1 as $/kg-H2 vs. tank capacity and pressure to get an overview. A minimum price of 500-600 $/kg-H2 shows at ~20-30,000 gallons. Their 6-10-ft diameters are larger than the tube-trailer tanks mentioned in ref.[1], with maximum pressures of 5000-10,000 psi (350-700 bar), but close to the above minimum cost of 500-600 $/kg-H2. Scuba tanks for up to 3442 psi were of higher cost with ranges in the 1000-1500 $/kg-H2[3]; both were included and labeled in Fig.1. We concluded that for this analysis we can start with storage at 250 psi and 600 $/kg-H2. In the unlikely case that compressor and/or compression costs are lower at higher pressures, we would need to revise this conclusion.

2. **Compressor costs** – Reference [3] also lists prices for SCUBA tank compressors up to 5000 psi, which were plotted, together with the prices for Ingersoll-Rand compressors[4] for up to 175 psi, in Fig.2. One would expect that the compressors' cost, Cc, to rise as their rated pressure, p, increases, so that, despite the lack of data between ~200 and 5000 psi, we settled for an exponential fit between the above data, which resulted in:

   $$Cc = 0.146577 \cdot \exp(0.000422 \cdot p), \text{ with p in psig and Cc in \$/W.} \qquad (1)$$

   Because many of the Ingersoll-Rand compressors included tanks of 60-120 gal, we subtracted their estimated cost to arrive at the $/W values

3. **Compression costs** – As pressure increases the compression energy and electricity cost rise. We based such costs on the input electricity cost of 4-5 ¢/kWh and the mean (a = 0.5) of the isothermal and adiabatic energy, E, to compress each kg of H2:

   $$E = a \cdot n \cdot 1.9876 \cdot (T1+273.15) \cdot LN(p2/p1) \cdot 4.184\ (J/cal)\ /(3.6e6\ (J/kWh)) \cdot 500 (mol\text{-}H2/kg\text{-}H2) + \\ + (1-a) \cdot n \cdot cp \cdot (T1 \cdot ((p2/p1)^{(2/7)} - 1) \cdot 4.184/3.6e6 \cdot 500 \quad \text{in kWh/kg-H2} \qquad (2)$$

   where n = 1 mol; T1 = intake temperature in °C; 1.9876 = Universal gas constant in cal/(mol.K); p1 and p2 = input and output pressures; and cp = specific heat of 7 cal/(mol.K) for H2.

   Figure 3 shows plots of those isothermal (bottom), adiabatic (top) and mean compression energies as a tank is filled with H2 from 30 to increasing pressures up to 250 psia. Assuming that most or average H2 compression operations would proceed at pressures below the maximum tank pressure of 250 psi, we chose the H2-weight-average compression work pressure* of 150 psi as the representative one for this life-cycle storage cost determination. But because such compression cost could well be charged to the fuel processing cost, we may keep this cost as a separate contribution, rather than charge it as extra "storage cost"

* By spending an equal amount of H2-compression cost with each element of an array of 22 pressure-range elements from 30 to 250 psia, we determined that for a max. pressure of 250 psi, the (kWh/kg-H2)-weighted average pressure is 150 psi, as indicated in Fig.3, at a cost of 0.58 kWh/kg-H2

4. **Life-cycle H2 storage costs –** Both tank and compressor costs were assumed to be debt-financed and amortized over 7.5 years at 6 %/y interest. Because we:
   a. Did not regard storage space as an issue in this analysis,
   b. Found the 250-psi tank costs in $/kg-H2 to be about equal to those of 5000 and 10,000 psi tube-tank trailers, and concluded that the tank cost in $/kg-H2 is about pressure-independent
   c. Approximated the compression cost by assuming a 50-50 combination of isothermal and adiabatic compression steps,
   d. Assumed that the compressor power and cost is determined by the needed peak and
   e. Spread the compressor and tank cost ($/kg-H2) over their 10- and 30-year daily life cycle use, we could represent the total life-cycle cost as

   C_L = 0.5*Isoth.compression + (1-0.5)*Adiab.compression +
   + (1+interest)*(tank $/kg-H2/L-cycles + compressor $/kg-H2/Lc-cycles).

   With the (1+interest) factor = 1.2717; the tank capex = 600 $/kg-H2 (independent of pressure), and from eq.(2) above:
   Isothermal compression = n*1.9876*(T+273.15)*LN(p2/p1)*4.184/3.6e6*1000/2 in kWh/kg-H2
   Adiabatic compression = n*cp*(T1*((p2/p1)^(2/7) -1)*4.184/3.6e6*1000/2 in kWh/kg-H2;
   and from eq.(1) above, with an assumed 12-hour daily compressor operating time, a compressor efficiency of 80%, and Cc = 0.17 $/W for 250 psi and 1.6 $/W for 5075 psi, we get::
   Compressor cost per kg/H2, Ck = Cc*(Gas compression work/12 hours)/Compr.efficiency =
   = 0.118 and 0.385 $/kg-H2 for 250 and 5075 psi, respectively

Conclusions

By levelizing tank and compressor costs and deriving H2 compression energy cost from 30 to 100 and up to10,000 psia, this analysis found that:

- Tank costs of 600 $/kg-H2 were remarkably similar, when comparing
  (a) the minimum tank cost of 250-psi tanks vs. size holding between 12,000 and 45,000 gallons,
  (b) 3441-psi/3-4-gal SCUBA tanks (after removing a likely 2x retail mark-up) and
  (c) 5000-10,000-psi/ 60-80-gal tube-trailer tanks
- While tank costs stood out as the highest contributor to life-cycle cost at low-pressure tanks (59%), compressor cost was the highest contributor (44 %), with high-pressure storage, as indicated in the table below. Not included were tank shipping & installation cost, which could well double the total tank cost, but be partly offset by not charging compression energy to storage.

Pressure psia	**Compression Energy** %	**Tank Cost** %	**Compressor Cost** %	**Total Life-Cycle Cost $/kg-H2**
250	37.0	59.1	4.6	0.1185
5075	37.9	18.2	44.0	0.3855

- Because 3.2 kg-H2 are needed to synthesize 1 GGE, fractional H2 storage should be minimized
- Overall life-cycle cost storage was over 3x more costly with the high-pressure tanks, as shown in above table: 0.118 and 0.385 $/kg-H2 for low and high-pressure tanks, respectively
- The 10,000-psi tank topped all life-cycle costs with 0.48 $/kg-H2
- Separate from capital tank and compressor costs, actual compression energy cost for H2 storage may be zero, if later H2 use requires 250 psi H2 anyway.
- If later use of H2 only requires 250 psia pressure, actual storage compression energy storage cost share may only be ~30% because the pressure-averaged compressor energy needed to fill a nearly empty tank from 30 to 250 psia is only 150 psia, rather than continuously working against a 250 psia pressure

Comparing the above results with data and DOE goals reported by ANL [1], see Table 1, it appears that our optimal storage tank cost of 600 $/kg-H2 is consistent with the listed values of 13.4 and 20 $/kWh, by using the conversion of 33.32 kWh/kg-H2, which would result in 446 and 664 $/kg-H2. However, the ANL study does not seem to have gotten into the detail of considering compressor cost and compression energy as part of the whole life-cycle cost of H2 storage.

References

[1] Stephen Lasher, Kurtis McKenney, and Jayanti Sinha (TIAX LLC, Cambridge, MA, Ref.No.: D0268) and Rajesh Ahluwalia, Thanh Hua, and J-K Peng (Argonne National Laboratory, Argonne, IL), "Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications," Report to DOE, Office of Energy Efficiency and Renewable Energy, Grant No.: DE-FC36-04GO14283, 10 December 2009, http://www.tiaxllc.com/reports/TIAX_Compressed%20H2%20Storage_Combined%20Report_final2.pdf

[2] Roy E. Hanson Jr. Manufacturing., www.ammoniatanks.com, mfg. rep.:steve@asmepressuretanks.com, 213-798-0903. Air tanks, which can be used for other gases like hydrogen, natural gas or others.

[3] Scuba.com, Irvine, CA, 800-347-2822, info@scuba.com, www.scuba.com

[4] Tools USA 800-451-2425, http://www.toolsusa.com/Compressors/index.htm

[5] DOE Hydrogen Energy Center,"Lower and Higher Heating Values of Fuels," website calc. http://hydrogen.pnl.gov/cocoon/morf/hydrogen/site_specific/fuel_heating_calculator?canprint=false and http://hydrogen.pnl.gov/cocoon/morf/projects/hydrogen/datasheets/lower_and_higher_heating_values.xls

[6] R.K. Ahluwalia, X. Wang, A.Rousseau, and R.Kumar, "Fuel Economy of Hydrogen Fuel Cell Vehicles," Journal of Power Sources, 130, 192-201, 2004.

Table 1. Summary results of the assessment for compressed hydrogen storage systems compared to DOE targets[1]

Performance and Cost Metric	Units	350-bar	700-bar	2010 Targets	2015 Targets	Ultimate Targets
System Gravimetric Capacity	wt%	6.0	4.8	4.5	5.5	7.5
System Volumetric Capacity	kg-H_2/m^3	17.8	25.6	28	40	70
Storage System Cost	$/kWh	13.4	20.0	4	2	TBD
Fuel Cost	$/gge	4.22	4.33	2-3	2-3	2-3
WTT Efficiency	%	57.4	55.0	60	60	60

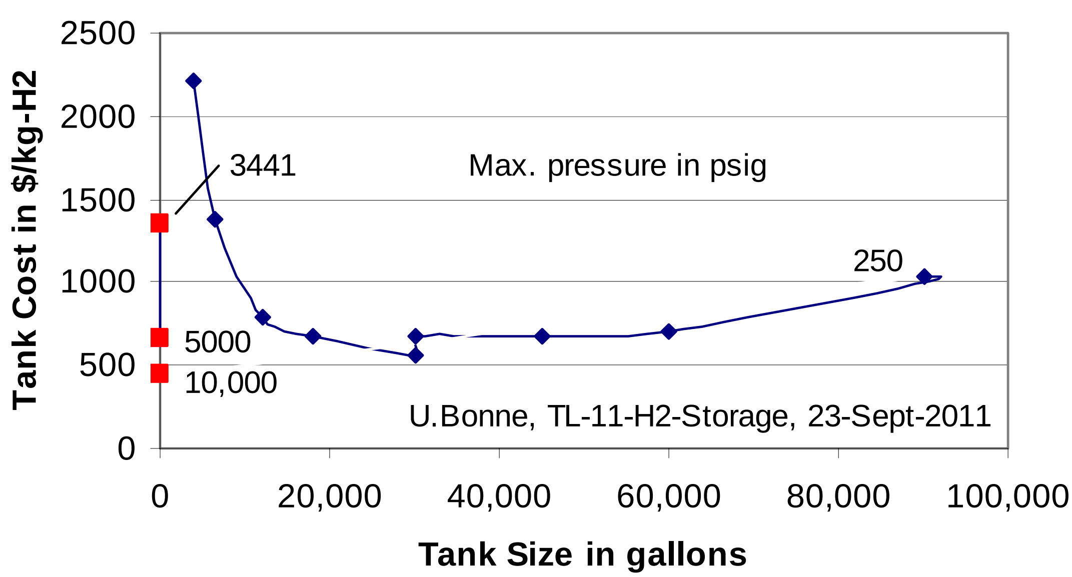

Fig. 1. Storage cost vs. tank size, mostly for 250 psi

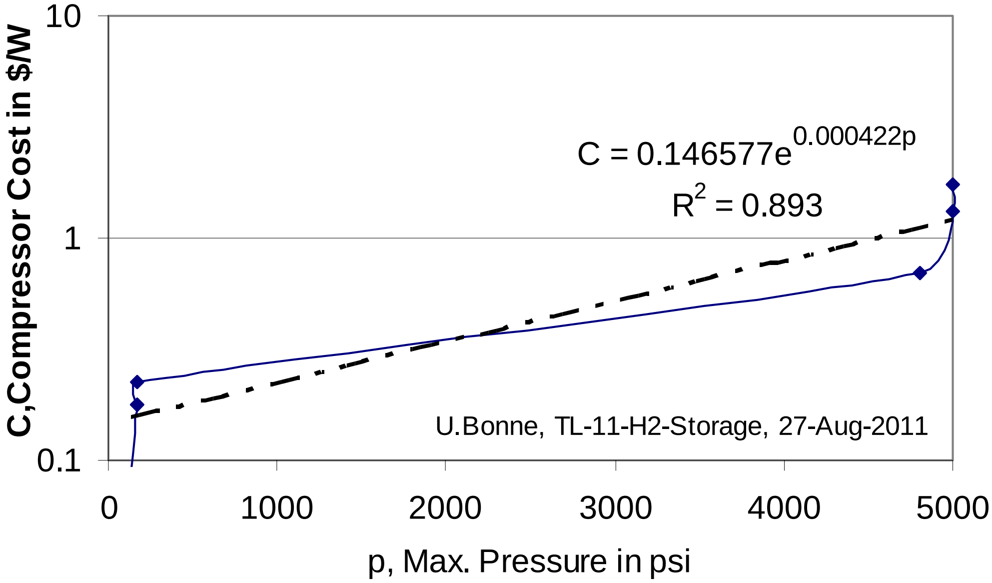

Fig. 2. Compressor costs vs. max. pressure rating

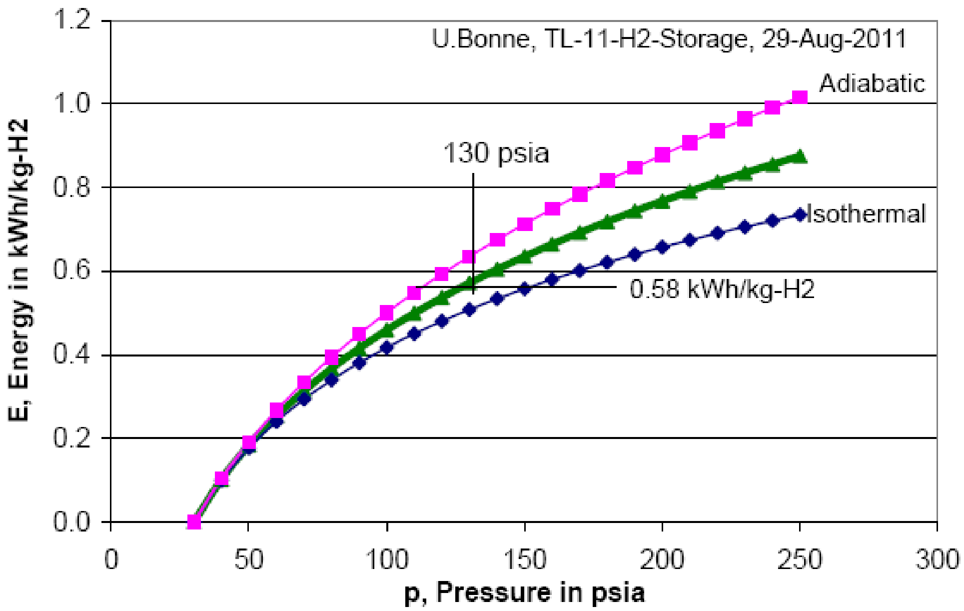

Fig. 3. Compression energy of hydrogen pumped into a tank of rising pressure, versus that rising tank pressure