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Hydrogen Storage in Wind Turbine Towers: Cost Analysis and Conceptual Design

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Abstract

Low-cost hydrogen storage is recognized as a cornerstone of a renewables-hydrogen economy. Modern utility-scale wind turbine towers are typically conical steel structures that, in addition to supporting the rotor, could be used to store hydrogen. The most cost-effective hydrogen tower design would use substantially all of its volume for hydrogen storage and be designed at its crossover pressure. An 84-m tall hydrogen tower for a 1.5-MW turbine would cost an additional $84,000 (beyond the cost of the conventional tower) and would store 950 kg of hydrogen. The resulting incremental storage cost of $88/kg is approximately 30% of that for conventional pressure vessels.

Introduction

Low-cost hydrogen storage is recognized as a cornerstone of a renewables-hydrogen economy. Modern utility-scale wind turbine towers are typically conical steel structures that, in addition to supporting the rotor, could be used to store hydrogen. This capacity for energy storage could significantly mitigate the drawbacks to wind's intermittent nature and provide a cost-effective means of meeting peak demand.

Hydrogen towers have a "crossover pressure" at which their critical mode of failure crosses over from fatigue to bursting. The crossover pressure for many turbine towers is between 10 and 15 atmospheres. The cost of hydrogen storage per unit of storage capacity is lowest near the crossover pressure. Above the crossover pressure, however, storage costs rise quickly.

Storing hydrogen in a turbine tower appears to be an idea first suggested by Lee Jay Fingersh at the National Renewable Energy Laboratory (NREL) (Fingersh 2003). As outlined above, this technology could play an important role in the hydrogen economy and is, therefore, worth exploring. The objectives of this paper are to propose and analyze a cost-effective design for a hydrogen-storing tower and to compare the cost of hydrogen storage in turbine towers to the cost of hydrogen storage in conventional pressure vessels. This paper summarizes work presented earlier in an NREL technical report (Kottenstette and Cotrell 2003).

Benchmarks and Assumptions

Information regarding conventional wind turbine towers and conventional pressure vessels formed the starting point of our analysis. We based our analysis on a 1.5-MW tubular steel tower designed to withstand peak and fatigue bending moments at the base and top. It has a linear taper of diameter and wall thickness, a constant tower diameter/wall thickness (d/t) ratio of 320, and the top diameter equal to ½ of the base diameter. We assume the construction material to be structural steel with a yield strength of 350 MPa. The cost of the tower is estimated by multiplying the tower mass by $1.50/kg (Malcolm and Hansen 2002).

Industrial pressure vessels are often built of carbon steel similar to that used in turbine tower construction. Although the most economical pressure vessel geometry is long and slender, vessels have a practical length limitation of about 25 meters because of shipping constraints on length and weight. This length limitation results in vessels that are designed to high pressure ratings to better distribute fixed costs. Although higher pressures reduce the cost per kg of stored gas, higher pressures require additional compression costs.

In this paper, storage device comparisons are often based on a cost/mass ratio. This ratio is the cost (in dollars) of a storage device divided by the mass of deliverable hydrogen gas stored. It should also be mentioned that where the mass of pressurized hydrogen is computed, hydrogen is modeled as an ideal gas.

Design of a Hydrogen Tower

This section outlines a cost and uses it to evaluate subsequent conceptual designs.

Cost Analysis

The primary cost increases for a hydrogen tower result from reinforcing the tower walls and installing pressure vessel heads (also called end caps). Wall reinforcement is conservatively estimated to cost \$1.50/kg (Malcolm and Hansen 2002). End caps are estimated to cost \$2.66/kg. The estimate for end cap cost was created by fitting a linear regression to data obtained from industry:

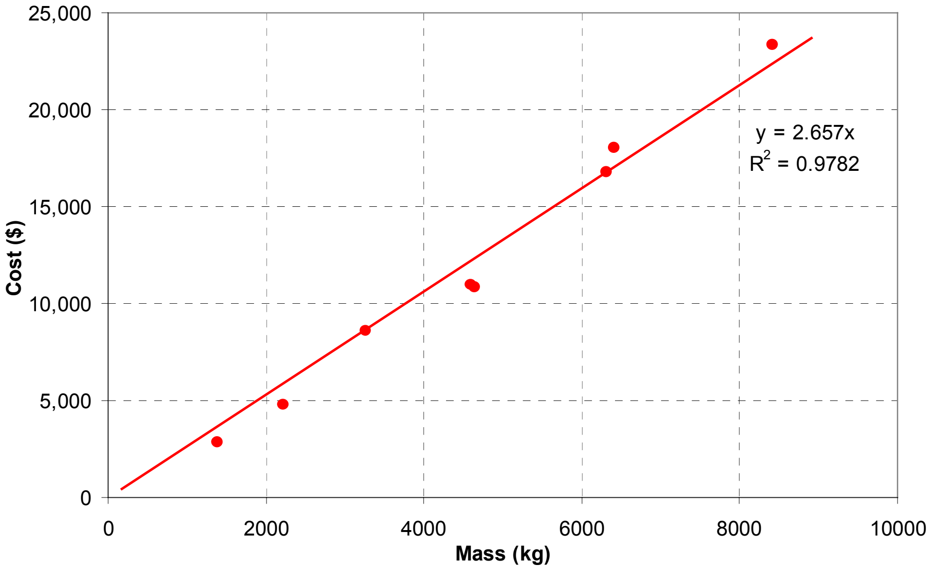

Figure 1: Mass-based model for cost of end caps.

Certain conceptual designs may require additional costs. For example, storage near the top of the tower would require an external emergency ladder. This choice necessitates an extended mainframe to keep the rotor from striking the ladder. As another example, power cable routed down the outside of the tower requires weather-resistant conduit. The secondary costs that were considered are outlined in Table 1. These estimates are based on a survey of industry and a comparison to similar components.

Table 1: Secondary Hydrogen Storage Costs

Additional Door	$	2,000
Mainframe Extension	$	6,300
Ladder Cost	$/m	32.80
Nozzles and Manway	$	16,000
Conduit	$/m	35

Cost Based on Storage Volume

The most cost-effective storage volume would be created using as much wall surface and as little cap surface as possible. The storage solution with the lowest cost/mass ratio will, therefore, have end caps spaced out as far as possible. Fig. 2 shows how the cost/mass ratio ($/kg of H_2 stored) varies with storage volume.

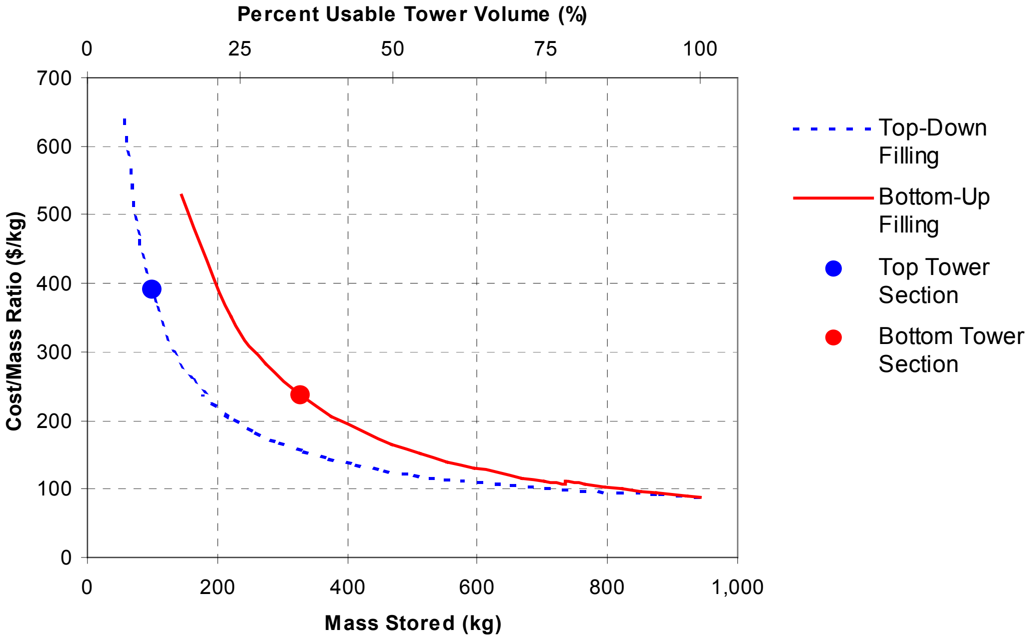

Figure 2: Effect of storage volume on cost/mass ratio.

The dashed line represents a tower with storage beginning near the top; as extra capacity is required, the bottom cap is moved lower in the tower. This design will be known as top-down filling. The solid line represents a tower designed with its storage volume near the base. As extra volume is needed, the upper cap is moved higher in the tower (bottom-up filling). Both of these lines take into account the appropriate fixed costs associated with their storage design. Storage above 50 m in the tower requires a $6300 extension of the mainframe. This study assumes that such towers would use an exterior personnel ladder for the entire height of the tower. Towers without storage above this height are assumed to bring the personnel ladder and power cables into the tower via a $2000 reinforced doorway midway up the tower. The discontinuity in the solid line at 735 kg reflects the fact that above this capacity, bottom-up filling requires a costly extension of the mainframe. Both of these curves demonstrate that the cost/mass ratio drops off steeply as storage volume is increased. This figure suggests that for a given volume capacity, storage is less expensive if the top of the tower is used.

Modern wind turbine towers are usually divided into 25-m-long sections because of transportation constraints. This study assumes the tower is divided into four sections. In some situations, one may wish to use only one tower section for hydrogen storage. In this case, storage may be cheaper near the base of the tower. In Fig. 2, the dot on the solid line shows the volume and cost/mass ratio corresponding to hydrogen storage in the bottom section of the tower. The dot on the dashed line shows the volume and cost/mass ratio corresponding to hydrogen storage in the top section of the tower. Although the top of the tower offers less expensive storage on a volumetric basis, the bottom of the tower provides a sufficiently large volume to make it the less expensive option on a height basis. This means that if one desires to use only a certain vertical height of the tower as storage, it would be less expensive to store hydrogen close to the base of the tower.

Cost Based on Storage Pressure

Fig. 3 illustrates the influence of pressure on cost/mass ratio.

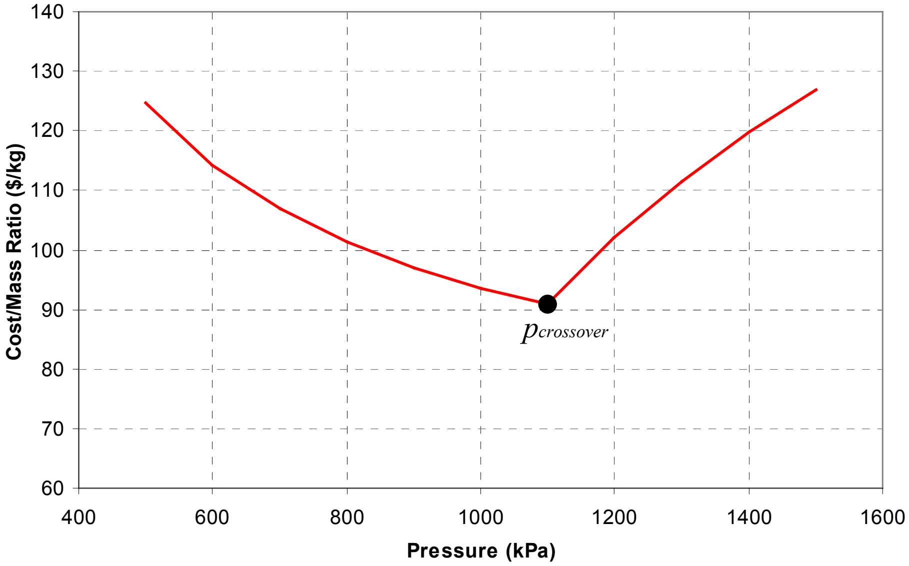

Figure 3: Cost/mass ratio as a function of pressure.

Fig. 3 demonstrates that the crossover pressure actually corresponds to a minimum cost/mass ratio when all costs (walls, end caps, and fixed costs such as a ladder and access hatch) are considered. The cost/mass ratio is higher at pressures below the crossover pressure because fixed costs (such as an extended mainframe) are distributed over a smaller storage capacity. This figure also suggests that hydrogen towers are particularly well suited for use with electrolyzers because PEM and high-pressure alkaline electrolyzers can produce hydrogen above the crossover pressure without a compressor.

Conceptual Designs

Several alternate hydrogen tower designs were evaluated based on the preceding cost analysis, the most promising of which is illustrated in Fig. 4.

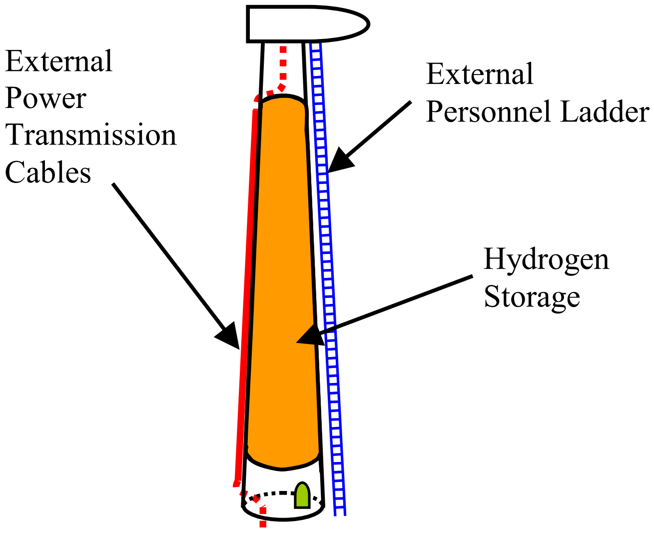

Figure 4: **Full hydrogen tower.**

This design places pressure head weldments near the top and bottom of the tower and moves the access ladder and power transmission lines to the exterior of the tower. If the power transmission lines are moved to the outside, then they must be protected by conduit. This prevents standard droop-cable design and requires that 9 m of space be left in the tower above the upper pressure head to allow for installation of cable with torsional flexibility (Poore and Lettenmaier 2002). The bottom end cap allows the equipment that is normally stored in the base of a tower to remain there. These pressure heads also contain the pressure vessel loads, which allow the foundation and nacelle design to be unaffected by hydrogen storage. This concept is appealing because it offers a great amount of hydrogen storage with relatively simple design modifications. For these reasons, this idea stands out as a cost-effective option.

Costs for a full hydrogen tower designed at the crossover pressure are detailed in Fig. 5.

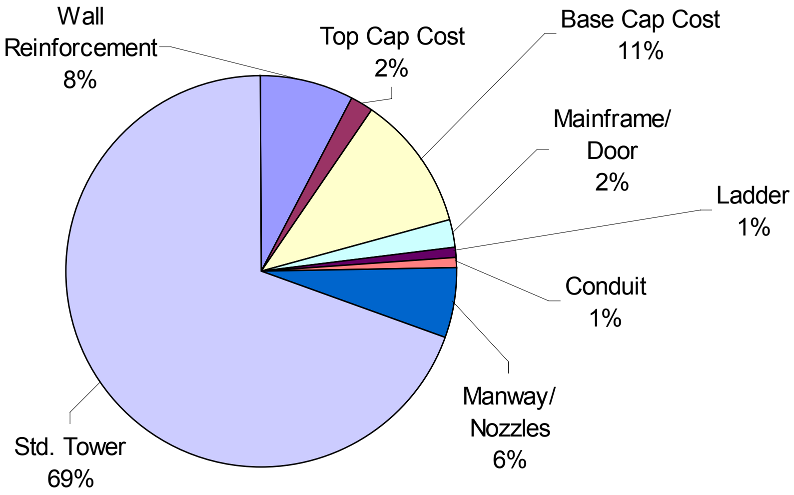

Figure 5: **Hydrogen tower cost summary.**

A full hydrogen tower designed with a storage capacity of 940 kg can offer storage at a rate of less than $90/kg. The total costs associated with outfitting a full tower for hydrogen storage would be $83,000.

Comparison: Towers, H_2 Towers, Pressure Vessels

The full hydrogen tower design represents a 44% increase in cost over a conventional tower. Although this is a significant premium for a turbine tower, it is far below the costs of similar storage capacities in conventional pressure vessels.

Fig. 6 displays the costs associated with several tower and pressure vessel configurations.

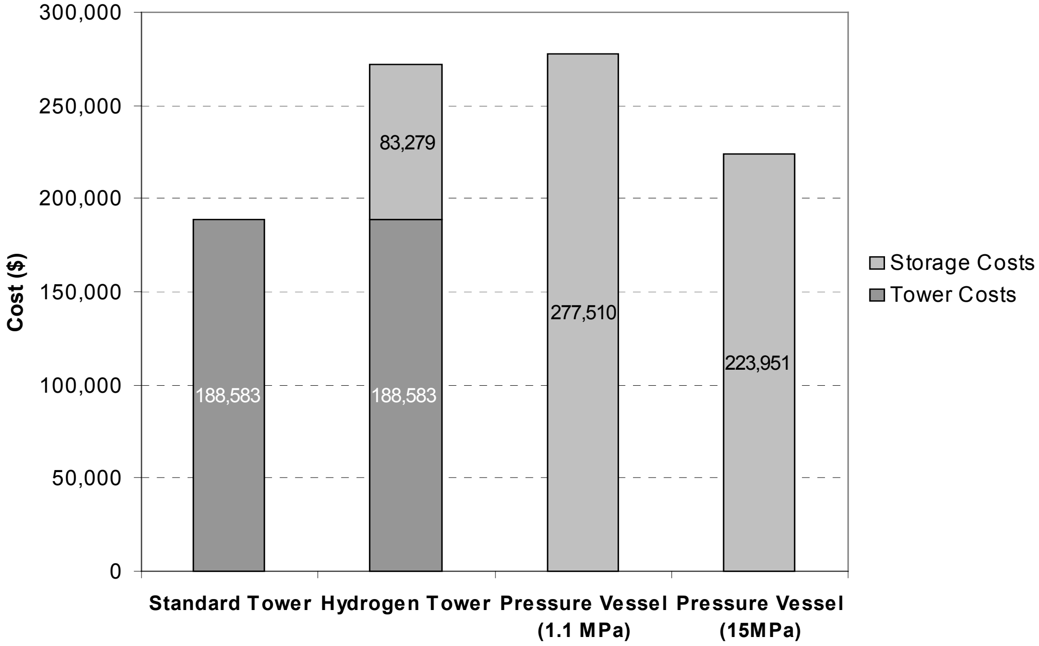

Figure 6: Cost comparison: a standard tower, an H_2 tower, and pressure vessels.

In conventional pressure vessels, which are limited to about 25 m in length, higher pressures better distribute the fixed costs. Fig. 7 shows the cost of a 15-MPa (150 atm) vessel in order to compare a single storage vessel to a hydrogen tower of the same capacity. However, using pressures higher than 1.5 MPa (15 atm) requires additional compression costs. For this reason, Fig. 7 also shows a 1.1-MPa (11 atm) pressure vessel for comparison with the hydrogen tower. Pressure vessel storage at this lower pressure is more expensive because three vessels are necessary to achieve the same capacity; this triples the fixed costs of nozzles and manways.

Conclusions

This study describes general design guidelines for a cost-effective hydrogen tower:

1) Fatigue-driven towers have a crossover pressure at which they offer the most cost-effective storage capacity. For most utility-scale towers, this crossover pressure is expected to be between 1.0 and 1.5 MPa (10–15 atm).

2) A hydrogen tower should utilize as much of the tower's volume as possible to minimize the cost/mass ratio of hydrogen storage.
3) In general, storage should be located as high in the tower as possible to minimize the cost of hydrogen storage. However, if only one section of the tower is used for storage, the storage should be placed as low in the tower as possible to take advantage of increased volume.

As a result of this study, we concluded that a hydrogen tower offers storage at approximately 30% of the cost for a conventional pressure vessel.

Future Work

A review of the literature reveals a lack of reliable information regarding the cost of above-ground pressure vessel storage. The industry quotes we collected on pressure vessel costs were 2 to 5 times lower than the costs most commonly cited in the literature. Discrepancies of this magnitude could severely handicap the future of the hydrogen energy economy.

An additional consideration for the construction of a hydrogen tower is whether or not the value of hydrogen stored at the turbine tower justifies the storage cost. NREL is currently evaluating the value of storing hydrogen in turbine towers as part of its WindSTORM study.

References

Fingersh, L. J. (2003). *Optimized Hydrogen and Electricity Generation from Wind*. NREL/TP-500-34364. Golden, CO: National Renewable Energy Laboratory.

Malcolm, D.J.; Hansen, A.C. (2002), *WindPACT Turbine Rotor Design Study*. NREL/SR-500-32495. Work performed by Global Energy Concepts, LLC, Kirkland, Washington. Golden, CO: National Renewable Energy Laboratory.

Kottenstette, R.; Cotrell, J. *Hydrogen Storage in Wind Turbine Towers.* NREL/TP-500-34656. Golden, CO: National Renewable Energy Laboratory, 2003.

Poore, R.; Lettenmaier, T. (2002). *Alternative Design Study Report: WindPACT Advanced Wind Turbine Drive Train Designs Study*. NREL/SR-500-33196. Work performed by Global Energy Concepts, LLC, Kirkland, Washington. Golden, CO: National Renewable Energy Laboratory.

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