# Is Hydrogen Energy Storage Ready for Prime Time on the North American Grid?

AUTHOR

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### Summary

A bulk electric energy storage plant can be used on the North American electric grid for the daily, weekly or seasonal storage of wind electricity (energy) and/or to provide ancillary services. The goal of this paper is to determine whether hydrogen ($H_2$) energy storage is ready for prime time[1] on the North American grid.

To determine this, the author has developed a $H_2$ storage plant (HSP) levelized cost of storage (LCOS) financial algorithm for a model HSP. This LCOS algorithm is used for sensitivity analysis and to confirm published HSP specifications (specs). This paper discusses $H_2$ storage (HS) technology, focusing on the three phases of all HSP; one, the production of the $H_2$, two, the storage of the $H_2$, three, the use of the stored $H_2$ as the fuel to regenerate the wind electricity. The LCOS Algorithm uses "project accounting" to compute a separate LCOS for each HSP phase; charging, storage and discharging. To compute the LCOS, the paper's HSP LCOS Algorithm requires 22 HSP specifications (specs) [metrics]. These 22 HSP specs (metrics) [independent variables] are defined using a standard set of $H_2$ SI units.

The author used the paper's HSP LCOS and "datasets" of compiled HSP specs to do sensitivity analysis. The author found that both high round trip HSP efficiency (η) and high Total HSP CapEx do not allow the HSP to operate commercially. The cost of capital[2] was not a factor. This is

[1] is currently commercially viable
[2] the discount rate

confirmed by the fact that currently there are no commercial HSP operating on the North American grid.

## 1. THE HSP LCOS ALGORTHUM AND ITS EXCEL WORKBOOK

For the reader to follow the paper's narrative, the reader must download (@ no charge) the paper's Excel[3] HSP LCOS Financial Algorithm Workbook. https://tinyurl.com/WP19StavyPAPER . This paper refers to worksheet (WS) lines for the 22 specs and for the computed values on the four WS of the Excel HSP LCOS Financial Algorithm Workbook[4]. A Glossary is on page 10. Table # 1 with the 22 specs defined and a List of References are on page 11.

Putting the algorithm on an Excel workbook allows the author (reader) to quickly do a sensitivity analysis. By selecting different realistic values for the 22 specs, it became clear to the author that there are two key values that determine whether a HSP is ready for commercial development. These are the HSP Round Trip efficiency (η) and the Total[5] HSP CapEx.

A $H_2$ Electrolyzer (HE) is used in the charging phase; a $H_2$ "Tank" in the storage phase and a Fuel Cell (FC) in the discharging phase. The Excel HSP LCOS Workbook has four WS: three WS are for the three HSP phases: WS # 1, Charging-$H_2$ Electrolyzer (HE); WS # 2, Storage-$H_2$ Storage "Tank"; WS #3, Discharging-Fuel Cell (FC) and WS # 4, is the Summary Worksheet (WS # 4 is on pages 8 & 9). Fig. 1 (Page 11) is a schematic of the model HSP. The HSP LCOS Financial Algorithm uses "project accounting" to "fine tune" sensitivity studies. This also allows the user to do a sensitivity study of each phase separately. For each HSP phase (charging, storage and discharging), a separate partial LCOS is computed. Each WS in the Excel HSP LCOS Workbook has notes to explain each of the 22 specs and each of the computed values.

The lines and values (22 spec independent variable values and the computed dependent variable values [lines A→VVV]) referred to in the paper are listed on WS # 1 (HE), WS # 2 ($H_2$ "Tank") and WS # 3 (FC) and are summarized on WS # 4.

The reader who has downloaded the paper's Excel[3] HSP LCOS Workbook can enter their own 22 spec values on the LCOS workbook and check their results. While this paper discusses the 22 HSP specs (metrics), there is no case study to discuss how to compile the 22 specs from current authoritative data sources. The author was unable to locate any commercial bulk HSP on the North American gird. Interested readers should check the Cabin Creek Pumped Storage Plant compilation case study that is found in the author's Wind Europe 2018 Paper [1].

[3] a functioning Excel Workbook
[4] hereafter referred to as the Excel HSP LCOS Workbook
[5] Total CapEx refers to the sum of the CapEx of the three phases

The paper's LCOS HSP Algorithm only computes the LCOS (US$/MWh; €/MWh) for the daily storage of wind electricity. The paper's model HSP is basic. It is designed to have one daily energy storage cycle. Two of the 22 specs (metrics) specify how many hours a day are used in the daily charging and discharging phases. The remaining 24 hours are automatically assigned to the storage phase. The three phases do not operate at the same time. A model HSP can also be designed for weekly (seven days) or seasonal (180 days) storage. In another model HSP, the three phases could operate at the same time.

The Excel HSP LCOS Workbook also requires a FX value (US$1.14610/€) {13/01/19} [2] to convert the US$ LCOS values into €.

A bulk energy storage plant (ESP) can be engineered to provide energy storage and/or ancillary grid services (voltage and frequency control and reactive power [var]) for the grid. This paper's model HSP is not designed to provide ancillary services.

## 2. STANDARD (SI) HYDROGEN UNITS

The 22 HSP specs (metrics) are defined using standard SI $H_2$ units. $H_2$ specs can be presented with these standard SI units: ($MJ_{H2}$; $kg_{H2}$; $Nm^3{}_{H2}$; $MWh_{H2}$). There are standard conversion factors for converting[6] $MJ_{H2}$ into $kg_{H2}$; into $Nm^3{}_{H2}$ and into $MWh_{H2}$.

The key conversion factor in the HSP LCOS algorithm is

$1\ MWh_{elect} \equiv 1\ MWh_{H2}$.

In the energy flows of the HSP financial algorithm, the $MWh_{elect}$ are first converted into $MWh_{H2}$. Then the $MWh_{H2}$ are then converted back into $MWh_{elect}$. This makes sense since wind electricity is being stored as $H_2$. This does not mean that the HSP is 100% efficient.

1. Charging--$MWh_{ELECTin}$ into the HE and in $MWh_{H2out}$ out of the HE and into $H_2$ Tank

2. Storage--$MWh_{H2in}$ put into $H_2$ Tank and in $MWh_{H2out}$ taken out of $H_2$ Tank

3. Discharging--$MWh_{H2out}$ take out of the $H_2$ Tank to fuel the FC and in $MWh_{ELECTout}$ generated by the FC.

$1\ MWh_{elect} = 1\ MWh_{H2} = 3.1420\ mmBtu_{elect}$ [3]

$1\ MWh_{elect} = 1\ MWh_{H2} = 3{,}600\ MJ$ [3]

$1\ MWh_{elect} = 1\ MWh_{H2} = 333.3\ Nm^3$ [4]

[6] And for a reverse conversion

33.33 $kWh_{elect}$ = 1 $kg_{H2}$ [4]

1 $MWh_{elect}$ = 1 $MWh_{H2}$ = 30.3 $kg_{H2}$ [author's unit analysis]

## 3. THE THREE PHASES OF THE HSP

This paper discusses the HS technology focusing on the three phases of all HSP; one, the production of the $H_2$, two, the storage of the $H_2$, three, the use of stored $H_2$ as the fuel to regenerate the wind electricity. In the paper's model HSP, $H_2$ is used as the energy carrier.

The HE specs (WS #1) Lines 6, 7, 8 & 9 have been set the same for the $H_2$ Tank (WS # 2), Lines 12, 13, 14, 15 and for the FC (WS # 3) [Lines 19, 20, 21, 22] phases. One example is, WS # 1, Line 8, HE Life-yrs., is 20 years, so are WS # 2, Line 14 and WS # 3, Line 21. Another example is WS # 1, Line 9, cost of capital (interest rate/ROE [WACC] is 6%, so are WS # 2, Line 15 and WS # 3, Line 22.

In the paper's model HSP, wind electricity powers a HE. The HE uses the wind electricity to separate $H_20$ into $H_2$ and $O_2$. When the HE is producing $H_2$ with wind electricity, the HSP is charging. Currently no $H_2$ electrolyser format is the most mature technology. The paper's LCOS algorithm measures the "financial maturity" of HE with different technologies. The most important HSP LCOS Algorithm HE values are WS # 1 Line A, HE capacity ($MW_{ELECTin}$), WS # 1 Line 3, HE CapEx-US$/$MW_{ELECTin}$ (€/$MW_{ELECTin}$) and WS # 1 Line 4, HE efficiency ($\eta$) .

In the paper's model HSP, the wind electricity is stored as $H_2$ in a generic $H_2$ "Tank". When the $H_2$ is in the storage "$H_2$ Tank", the HSP is storing the wind electricity. There are various technologies for storing $H_2$. These include pressured $H_2$ storage tanks, liquefied $H_2$ storage tanks, $H_2$ salt caverns (another type of $H_2$ storage tank), as ammonia ($NH_3$), with other $H_2$ rich chemicals or in metal hydrides. Metal hydrides, ammonia, other types of material storage, and $H_2$ in salt caverns are not yet mature enough technologies for a commercial HSP. High pressure and liquefied $H_2$ storage tanks are currently the most technically mature and most widely used technologies for industrial $H_2$ storage. The HSP LCOS Algorithm measures the "financial maturity" of different $H_2$ "Tanks" (technologies). The most important HSP LCOS Algorithm $H_2$ Tank values are WS # 2 Line I, $H_2$ Tank size ($MWh_{H2}$), WS # 2 Line 10, $H_2$ Tank CapEx-US$/$MWh_{H2}$ (€/$MWh_{H2}$), and WS # 2 Line 11, $H_2$ Tank efficiency ($\eta$).

In the paper's model HSP, the $H_2$ is taken out of the $H_2$ Tank and used as the fuel to power a FC that regenerates the wind electricity which is then put back on the grid. When the $H_2$ FC is generating electricity with the stored $H_2$ as the fuel, the HSP is discharging the wind electricity from storage. There are various technologies for using the stored $H_2$ as the fuel to regenerate the wind energy as electricity. These include FC of various types and $H_2$ powered electric turbines in various formats ($H_2$ peaker turbine ≈ NG peaker turbine; combined cycle $H_2$ turbine ≈ combined cycle NG turbine [CCGT]). For a daily storage cycle, only a $H_2$ peaker turbine can be considered, but the $H_2$ peaker turbine is not a mature technology. This leaves the FC of various technologies with different technical and financial maturities. The paper's HSP LCOS Algorithm measures the "financial maturity" of different types of FC. The most important HSP LCOS Algorithm $H_2$ FC values are WS # 3 Line XX, FC capacity ($MW_{ELECTout}$), WS # 3 Line 17, FC CapEx-US$/$MW_{ELECTout}$ (€/$MW_{ELECTout}$), and WS # 3 Line 18, $H_2$ FC efficiency (η).

## 4. CONCLUSIONS

WS # 1, Line 5, Cost of the Wind Electricity to be Stored, US$50.16/MWh (€43.77), is wind's LCOE[7]. On WS # 3, Line LLL, the LCOS is US$144.88[8] (€126.41). This 188.8% increase from US$50.16 is too high for the market. Perhaps a carbon constrained North American grid would accept a time of day 20% increase (US$60.19 [€52.46]) for storing wind electricity but not much higher.

If the physical life of the HE, $H_2$ Tank and FC are each set at 25 years instead of 20 years, the LCOS would be US$137.19/MWh (€119.70), a 5.3% LCOS reduction from US$144.88 (€126.41) for a 25% increase in the physical life of the HSP. It is doubtful that a HSP would have a physical life of 25 years.

If the interest rate (WACC) of the HE, $H_2$ Tank and FC are each set at 4% instead of 6%, the LCOS would be US$133.20/MWh (€116.22), an 8.1% LCOS reduction from US$144.88 for a 33.3% decrease in the WACC. It is doubtful, however, that investors would fund a HSP at even 6% with the current state of HSP technical development.

Sensitivity analysis shows that currently the two key specs (metrics) in determining the HSP LCOS are the HSP Round Trip Efficiency (η) and the Total HSP Total CapEx.

On WS # 4, Round Trip HSP η-%, 72.9% is the product of 90% [WS # 1, Line 4, HE-η] X 90% [WS # 2, Line 11, $H_2$ Tank-η] X 90%[10] [WS # 3, Line 18, FC-η]. This is a very optimistic Round Trip HSP η because HE and FC do not actually operate at η = 90%. If the bulk $H_2$ storage tank were, in

[7] it can also be a solar plant's LCOE [5]
[8] On WS # 4, the LCOS is also US$144.88

actuality, a high pressure $H_2$ storage tank or a liquefied $H_2$ storage tank, the storage phase η would be, at most, in the 70% range. If the phase η of the HE, H2 Tank and FC are each set at 80% instead of 90% (an 11.1% per phase reduction) Round Trip HSP η would decline from 72.9% to 57.6% (a 21% decrease) while the LCOS would increase to US$193.37/MWh (€116.22), an 35.5% increase from US$144.88.

WS # 4, Total[5] HSP CapEx, US$684,900,000 is the sum of US$171,900,000 [WS # 1, Line D, Total HE CapEx] + US$270,000,000 [WS # 2, Line BB, Total $H_2$ Tank CapEx] + US$243,000,000 [WS # 3, Line AAA, Total FC CapEx].

The Total HE CapEx (WS # 1, Line D) is determined by the 300 $MW_{ELECTin}$ of HE capacity (WS # 1, Line A) and the HE CapEx of US$573,000/$MW_{ELECTin}$ (WS # 1, Line 3). The HE CapEx value was published by a prominent European HE manufacturer[9]. Line A is determined by the 10 hrs per day that the HE operates (WS # 1, Line 1) and by the 3,000 $MWh_{ELECTin}$ of Wind Electricity that charges the HSP each day (WS # 1, Line 2).

The Total $H_2$ Tank CapEx (WS # 2, Line BB) is determined by the 2,700 $MWh_{H2}$ $H_2$ Tank size (WS # 2, Line I) and by a $H_2$ Tank CapEx of US$100,000[10]/$MWh_{H2}$ (WS #2, Line 10)

The Total FC CapEx (WS # 3, Line AAA) is determined by the FC power output 243 $MW_{ELECTout}$ (WS #3, Line XX) and by the FC CapEx of US$1,000,000[11] /$MW_{ELCTout}$ (WS # 3, Line 17). WS # 3, Line XX is determined by the 10 hours per day that the FC operates (WS #3, Line 16) and by the 2,430 $MWH_{H2}$ (WS # 3, Line III.) taken out of the $H_2$ Tank to power the FC.

If the CapEx of the HE (WS # 1, Line 3), $H_2$ Tank (WS #2, Line 10) and the FC (WS # 3, Line 17) are each reduced by 20%, the Total[5] HSP CapEx would be $547,800,000, a 20% reduction from the original Total HSP CapEx of US$684,900,000. The LCOS would be US$129.82/MWh (€113.27), a 10.4% LCOS reduction from US$144.88 (€126.41) for a 20% decrease in the CapEx of each HSP phase. The Total CapEx will have to go down by more than 40% for the HSP to be commercially viable.

Is hydrogen energy storage ready for prime time on the North American grid? Based on the following facts, the answer is NO.

1. There are no commercial HSP on the North American grid.

2. HSP specs (metrics) for commercial HSP were not found in the literature.

[9] the published value was €500/kWh (US$573/kWh) [6]
[10] The H2 Storage "Tank" CapEx is based on the projected US$100/kWh CapEx for the Tesla Li-ion battery
[11] this is equal to FC CapEx of US$1,000/kWh

3. The author complied specs for a HSP. With the paper's LCOS algorithm, the author computed the LCOS but it was too high for the current development of a commercial HSP

4. Sensitivity analysis showed that the HSP Round Trip η is not realistically presented by the author. He is too optimistic. HSP Round Trip η should currently be in the 60% range; not the computed 72.9%.

5. Sensitivity analysis showed that the Total HSP CapEx is also not realistically presented by the author. He is again too optimistic. Total HSP CapEx was too high for the LCOS to be less than 20% more than the cost of the wind electricity being stored but too low to reflect current HSP CapEx estimates.

6. Readers might want to compare the LCOS for current pumped storage plants as a benchmark for future HSP.

## WORKSHEET # 4, EXCEL HSP LCOS ALGORITHM SUMMARY WORKSHEET

| | | | | | |
|---|---|---|---|---|---|
| US$/€ | $1.14610 | 13/01/19 | | | |
| | WS # 1 | WS # 2 | WS # 3 | | |
| | HE | $H_2$ Tank | $H_2$ FC | | |
| Phase→ | Charge | Storage | Discharge | HSP-η-% | |
| HSP Phase-η-% | 90% | 90% | 90% | 72.9% | |
| MWh/day-in | 3,000.00 | | | | ←MWh/day wind energy stored |
| MWh/day-out | 2,700.00 | | | | ←MWh/day $H_2$ produced by HE |
| MWh/day-in | | 2,700.00 | | | ←MWh/day $H_2$ stored |
| MWh/day-out | | 2,430.00 | | | ←MWh/day $H_2$ released |
| MWh/day-in | | | 2,430.00 | | ←MWh/day FC $H_2$ fuel |
| MWh/day-out | | | 2,187.00 | | ←MWh/day FC electricity |
| | | | 72.9% | | ←% round trip HSP η |
| Phase Operating hrs/day | 10 | 4.00 | 10 | 24 | |
| | Only one phase operates at a time; HSP operates 24 hr/day; 365/yr | | | | |
| $/MWh-in | $50.16 | | | | ←US$/MWh cost of stored wind energy |
| $/MWh-out | $71.28 | | | | ←US$/MWh HE LC to produce $H_2$ |
| $/MWh-in | | $71.28 | | | ←US$/MWh LC of $H_2$ stored |
| $/MWh-out | | $106.14 | | | ←US$/MWh LC of $H_2$ released |
| $/MWh-in | | | 106.14 | | ←US$/MWh LC FC $H_2$ fuel |
| $/MWh-out | | | $144.88 | | ← US$/MWh LCOS wind energy |
| | | | 188.8% | | ←% LCOS increased cost |

| | WS # 1 | WS # 2 | WS # 3 | |
|---|---|---|---|---|
| | HE | $H_2$ Tank | $H_2$ FC | |
| Phase→ | Charge | Storage | Discharge | |
| | | | | €/MWh ↓ |
| HE CapEx-US$/$MW_{in}$ | $573,000 | | | € 499,956 |
| Tank CapEx-US$/MWh | | $100,000 | | € 87,252 |
| FC CapEx-US$/$MW_{in}$ | | | $1,000,000 | € 872,524 |
| CapEx -US$/kWh | $573 | $100 | $1,000 | |
| CapEx -€/kWh | € 500 | € 87 | € 873 | |
| | | | | Total HSP CapEx |
| HSP CapEx-US$/Phase | $171,900,000 | $270,000,000 | $243,000,000 | $684,900,000 |
| HSP CapEx-€/Phase | € 149,986,912 | € 235,581,537 | € 212,023,384 | € 597,591,833 |
| | | | | |
| Fixed O&M Cost-% Phase CapEx | 0.05% | 0.05% | 0.05% | |
| Variable O & M Cost-US$/MWh | $0.25 | $0.25 | $0.25 | |
| Physical Life -Years | 20 | 20 | 20 | |
| Interest/ROE Rate-% | 6.00% | 6.00% | 6.00% | |

## Glossary

| | | | |
|---|---|---|---|
| CAES = | compressed air energy storage | mmBtu = | million British thermal units |
| CCGT = | combined cycle gas turbine | MW = | megawatts |
| CCHT = | combined cycle $H_2$ turbine | MWh = | megawatt hour |
| CHES = | compressed $H_2$ energy storage | NG = | Natural gas |
| ES = | energy storage | $Nm^3$ = | nominal cubic meter-$H_2$ |
| ESP = | energy storage plant | $O_2$ = | oxygen |
| FC = | fuel cell | PSP = | pumped storage plant |
| gal = | US gallon-$H_2$ | ROE = | return on owner's equity |
| $H_2$ = | Hydrogen | scf = | standard cubic foot-$H_2$ |
| HSP = | hydrogen storage plant | SI = | Système International d'Unités |
| Kg = | kilogram-$H_2$ | SMR = | steam methane reformation |
| LC = | levelized cost | WACC = | weighted average cost of capital |
| LCOE = | levelized cost of energy | WS = | worksheet |
| LCOS = | levelized cost of storage | $\eta$ = | efficiency |
| MJ = | megajoules | | |

FIGURE # 1 Schematic of the MODEL HSP

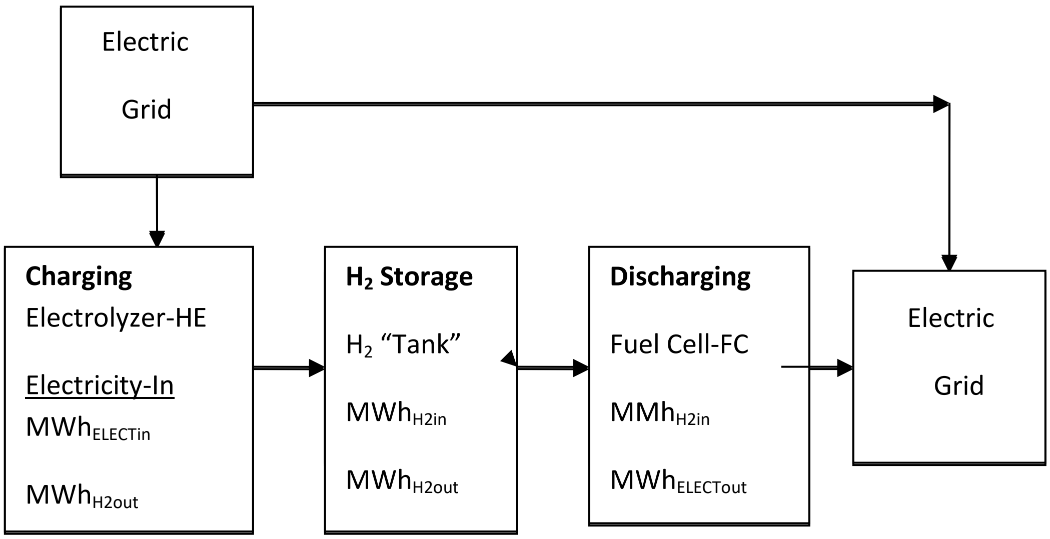


Table # 1 THE 22 SPECIFICATIONS (METRICS) OF THE HSP LCOS ALGORITHM

| spec # | Charging HE | spec # | Storage $H_2$ Tank | spec # | Discharging Fuel Cell |
|---|---|---|---|---|---|
| 1 | HE hrs/Day Operating | 10 | $H_2$ Tank CapEx-US$/$MWh_{H2in}$ | 16 | FC hrs/Day Discharging |
| 2 | Wind Energy to be Stored MWh/Day | 11 | H2 Tank Efficiency-η | 17 | FC CapEx-US$/$MW_{ELECTout}$ |
| 3 | HE CapEx-US$/$MW_{ELECTin}$ | 12 | Annual Fixed O & M-% $H_2$ Tank total CapEx-US$/$H_2$ Tank | 18 | FC Efficiency-η |
| 4 | HE Efficiency-η | 13 | Variable O & M-US$/$MWh_{H2out}$ | 19 | Annual fixed O & M-% FC Total CapEx-US$/FC |
| 5 | Cost of the Wind Energy Stored-$MWh_{ELECTin}$ | 14 | $H_2$ Tank life-yrs | 20 | FC Variable O & M-US$/$MWh_{ELECTout}$ |
| 6 | Annual Fixed O & M-% HE | 15 | $H_2$ Tank | 21 | FC Life-yrs |

| spec # | Charging<br>HE | spec # | Storage<br>$H_2$ Tank | spec # | Discharging<br>Fuel Cell |
|---|---|---|---|---|---|
| | total CapEx-US$/FC | | Interest/ROE rate-% | | |
| 7 | HE Variable O & M-€/$MWh_{H2out}$ | | | 22 | FC Interest/ROE rate-% |
| 8 | HE Life-yrs | | | | |
| 9 | HE Interest/ROE rate-% | | | | |

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