Is the Utility Scale Hydrogen Energy Storage of Solar (PV) Electricity Ready for Prime Time on the North American Grid? A Guide for Bankers and Investors

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Summary— A **bulk electric** (**utility scale**[1]) energy storage plant can be used on the North American electric grid for the daily, weekly or seasonal storage of **solar (PV) electricity (energy)** and/or to provide ancillary services. The goal of this paper is to help bankers and investors determine whether hydrogen (H_2) energy storage is ready for prime time[2] on the North American grid.

To determine this, the author has developed a H_2 storage plant (HSP) levelized cost of storage (LCOS)[3] financial algorithm for a model HSP. To compute the LCOS, the paper's HSP LCOS financial algorithm[4] requires 22 HSP specifications (specs) [metrics]. The 22 HSP specs (metrics) [independent variables] and the 76 dependent variables are all defined using a standard set of SI H_2 energy units. This HSP LCOS algorithm is used by the author for sensitivity analysis and to confirm published HSP specifications (specs). This algorithm is presented on the paper's Excel[5] HSP LCOS Financial Algorithm Workbook. The paper discusses H_2 storage (HS) technology, focusing on the three phases of all HSP; one, the production of the H_2 using solar electricity, two, the storage of the solar electricity as H_2, three, the use of the stored H_2 as the fuel to regenerate the solar electricity. The HSP LCOS algorithm uses "project accounting" to compute a separate "partial LCOS" for each HSP phase; charging, storage and discharging. As the three HSP phases are discussed in this paper, the reader should study how the solar electricity "absorbs" the cost of storage.

The author used the paper's HSP LCOS algorithm and a base case "dataset" of compiled HSP specs to do sensitivity analysis. The author

[1] in the range of 100-3,500/MWh/day
[2] is currently commercially viable
[3] not to be confused with the levelized cost of energy (LCOE). See reference [1]
[4] hereafter referred to as the HSP LCOS algorithm
[5] a fully functioning Excel Workbook

[a]Michael's family name, STAVY, is in capital letters on this paper because French was the host language for the 2015 Paris Climate Change Accord. In French, the family name is CAPITALIZED. This is Michael's story and he is sticking to it. Version: 07/01/20

has found that both low round trip HSP efficiency (η) and high Total HSP CapEx do not allow a HSP to operate commercially on the North American gird. The cost of capital[6] was not a factor. This is confirmed by the fact that currently there are no commercial HSP operating on the North American grid.

I. THIS PAPER WAS WRITTEN UNDER "SHELTER-IN - PLACE" ORDERS BY THE GOVERNORS OF THE STATES OF ILLINOIS[7] AND COLORADO[8]

The author lives in Chicago, Illinois. He was in Georgetown, Colorado planning to ski when he heard about these "two shelter-in-place" orders. He followed both orders. He has continued to stay in Georgetown and to write this paper without his regular office files. He has not updated certain of the algorithm's 22 spec values and certain of the paper's References.

See Section VIII. Three Examples of Spec Values That Need to be Updated.

The paper, itself, is complete. It is technically and grammatically correct although certain statements and references may not be up to date and then, of course, there may be certain of those pesky undetected "typos".

II. THE PRESENTATION OF A PUBLIC DATA BASE OF HSP SPECS IS NOT THE GOAL OF THIS PAPER

The actual presentation of a public data base of HSP specs for use by a banker (investor, financial analyst) is not the primary goal of this paper [2] [3] [4]. This author has the much more modest goal of presenting a recognized standard methodology, a model HSP, and an accurate "back of the envelope" LCOS financial algorithm.

III. THE PAPER'S HSP LCOS FINANCIAL ALGORITHM AND ITS EXCEL WORKBOOK

For the reader to follow this paper's narrative, the reader must download[9] (@ no cost) the paper's Excel[4] HSP LCOS Financial Algorithm
Workbook. Go to:

https://tinyurl.com/StavyPapers2020

If you attended the SOLAR 20/20 Virtual Convention, you were able to download copies of this paper and the paper's Excel[5] HSP LCOS Financial Algorithm Workbook.

This paper refers to worksheet (WS) lines on the four WS of the Excel HSP LCOS Financial Algorithm Workbook[10].

References are on page 8. Table 1, *The 22 Specs (Metrics) of the LCOS HSP Algorithm*, is on page 10.

Putting the algorithm on an Excel Workbook allows the reader to quickly do sensitivity analysis. By selecting different realistic values for the 22 HSP specs of a model HSP, it has become 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[11] HSP CapEx.

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[6] discount rate
[7] J. B. Pritzker
[8] Jared Polis
[9] available to those that did not attend the Virtual Conference on 07/01/20. Clients can get it earlier.
[10] Hereafter, referred to as the Excel HSP LCOS Workbook
[11] Total CapEx refers to the sum of the CapEx of each of the three phases (HE, H_2 "Tank", FC)

A H_2 Electrolyzer (HE) is used in the HSP charging phase; a H_2 "Tank" in the HSP storage phase and a Fuel Cell (FC) in the HSP 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.

WS # 4 is the Summary Page. WS # 4 is on pages 11-13 and is a summary of the model HSP base case. Fig. 1, *Schematic of a H_2 Storage Plant*, is on page 10. The HSP LCOS Financial Algorithm uses "project accounting" to "fine tune" sensitivity studies. This also allows the Workbook user to do a sensitivity study of each phase separately. For each HSP phase (charging, storage and discharging), a separate "partial LCOS" is computed.

The lines and values for the 22 HSP spec values (the independent variables) and for the 79 computed dependent variable values [lines A→VVV]) that are referred to in this paper are listed on WS # 1, HE, WS # 2, H_2 "Tank", and WS # 3, FC, and are summarized on WS # 4.
The data flow is

WS # 1 → WS # 2 → WS # 3 → WS # 4

Each WS has notes to explain, when necessary, the 22 specs and the 79 dependent variables.

The LCOS algorithm equations are available to clients.

The reader who has the paper's Excel[5] HSP LCOS Workbook can enter their own 22 HSP spec values in their Excel Workbook and check their results. While this paper discusses the 22 HSP specs, there is no case study to discuss how to compile[12] datasets of the 22 HSP specs from the current authoritative data sources. The author was unable to locate any commercial bulk HSP on the North American gird. Readers who want to learn how to compile datasets of the 22 HSP specs should read the Cabin Creek Pumped Storage Plant spec compilation case study that is found in the author's Wind Europe 2018 Paper [5] [6].

A HSP can be designed for a daily, weekly (seven days) or seasonal (180 days) storage cycle. The paper's model HSP is basic. It is designed to have a daily energy storage cycle.

The paper's LCOS HSP algorithm only computes the LCOS (US$/MWh; €/MWh) for the daily storage of solar electricity. Two of the 22 HSP specs (metrics) specify how many hours a day are used in the daily charging and discharging phases. The remaining hours of each day are automatically assigned to the storage phase. The three phases of the model HSP do not operate at the same time. A HSP can be designed to have all three phases operate at the same time.

A HSP 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.

The Excel HSP LCOS Workbook also requires a FX value (US$1.14610/€) {13/01/19} [d/m/yr] [7] to convert the US$ LCOS values into € LCOS values for virtual attendees from the € zone.

[12] assemble, organize, gather, create

IV. STANDARD (SI) HYDROGEN ENERGY UNITS

The 22 HSP specs (metrics) are defined using standard SI H_2 energy units. HSP specs can be presented using any of these standard SI units: (MJ_{H2}; kg_{H2}; Nm^3_{H2}; MWh_{H2}). There are standard conversion factors for converting[13] [14], MJ_{H2} into kg_{H2}; into Nm^3_{H2} and into MWh_{H2}. [8] [9] [10]

The key conversion factor in the HSP LCOS algorithm is

$1\ MWh_{ELECT} \equiv 1\ MWh_{H2}$

MWh_{ELECT} and MWh_{H2} are equal SI energy units regardless of the type of energy or the authoritative SI source[15] cited for the standard conversion factors. This is because they are both the same quantity of energy.

The model HSP's energy flow, using SI units, is as follows:

First, during HPS charging phase, MWh_{ELECT} of solar (PV) energy from the grid powers the HE. The HE produces MWh_{H2} that is then put into H_2 Tank. Second, during the HSP storage phase, MWh_{H2} are stored in the H_2 Tank. Third, during the HSP discharging phase, MWh_{H2} from the H_2 Tank powers the FC. The FC consumes the MWh_{H2} to regenerate MWh_{ELECT} of solar energy that are then put back on the grid.

Here are some other key energy units for the reader to have:

$1\ MWh_{ELECT} = 1\ MWh_{H2} = 3.1420\ mmBtu_{ELECT}$

$1\ MWh_{ELECT} = 1\ MWh_{H2} = 3{,}600\ MJ$

$1\ MWh_{ELECT} = 1\ MWh_{H2} = 333.3\ Nm^3$

$33.33\ kWh_{ELECT} = 1\ kg_{H2}$

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

V. THE THREE PHASES OF THE HSP

This paper discusses H_2 storage technology focusing on the three phases of all HSP; one, the production of the H_2 with solar electricity, two, the storage of the H_2, three, the use of the stored H_2 as the fuel to regenerate the solar electricity. In a HSP, H_2 is used as the energy carrier[16]. There is no carbon released [11]

In the base case, the HE spec values, WS # 1, Lines 4, 6, 7, 8 & 9, have also been used as the H_2 Tank spec values, WS # 2, Lines 11, 12, 13, 14 & 15, and as the FC spec values WS # 3, Lines 18, 19, 20, 21 & 22. A specific example is WS # 1, Line 9, cost of capital, interest rate/ROE [WACC] which is 6%, so are WS # 2, Line 15 and WS # 3, Line 22. Another example is, Line 8, HE Life-yrs, is set at 20, a typical "life" for power projects, so are WS # 2, Line 14 and WS # 3, Line 21. This is done to have a straightforward base case. The Excel HSP LCOS Workbook allows the reader to use different spec values for each HSP phase.

In the paper's model HSP, solar electricity from the North American grid powers a HE. The HE uses the solar electricity to separate H_20 into H_2 and O_2. When the HE is producing H_2 with solar electricity, the HSP is charging. Currently no H_2 electrolyzer format is the most mature technology. The paper's LCOS algorithm measures the "financial maturity" of HE with

[13] or for the reverse conversion

[14] and for the conversion into US "English" standard energy units (i.e. $mmBtu_{H2}$; lbs_{H2}; scf_{H2})

[15] examples, IEA or EIA

[16] PV electricity is kinetic energy; H_2 is potential energy

different technologies. The most important 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 (η).

In the paper's model HSP, the solar 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 solar electricity. There are various technologies for storing H_2. These include pressurized 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. NH_3, metal hydrides, chemical 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 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 (η).

In the paper's model HSP, the H_2 is taken out of the H_2 Tank and is consumed as the fuel to power a FC that regenerates the solar electricity which is then put back on the North American grid. When the FC is generating electricity with the stored H_2 as the fuel, the HSP is discharging the solar electricity from storage. There are various technologies for using the stored H_2 as the fuel to regenerate the solar energy as electricity. These include FC of various technologies 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 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 algorithm 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, FC efficiency (η).

VI. Sensitivity Analysis

WS # 1, Line 5, Cost of the Solar Electricity to be Stored, US$50.16/MWh (€43.77), is the cost[17] of solar electricity from a model PV plant sold wholesale to a load serving entity. The retail price could be higher.

On WS # 3, Line LLL, the LCOS in the base case is US$142.21 /MWh (€124.08). This 183.5% 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 to US$60.19 (€52.46) for stored solar electricity but not much higher.

If the physical life of the HE (WS # 1, Line 8), H_2 Tank (WS # 2, Line 14) and FC (WS # 3, Line 21) are each set at 25 years instead of 20 years[18], the LCOS would be US$134.79/MWh (€117.61). This is a 5.2% LCOS reduction from the base case of US$142.21 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/ROE [WACC] of the HE (WS # 1, Line 9), H_2 Tank (WS # 2, Line 15) and

[17] it could be the PV plant's LCOE [1]

[18] and if all 19 of the other 22 specs remain the same

FC (WS # 3, Line 22) are each set at 4% instead of 6%[18], then the LCOS would be US$130.95/MWh (€114.26). This is a 7.9% LCOS reduction from the base case US$142.21/MWh for a 33.3% decrease in the WACC. It is doubtful, however, that bankers or investors would risk funding a HSP at even 6% with the current state of HSP technical development.

To get "hands on experience" in LCOS sensitivity analysis, the reader should enter their own 22 spec values for the HE, H_2 Tank and FC phases.

Sensitivity analysis shows that currently the two key HSP specs (metrics) in determining the HSP LCOS are the HSP Round Trip Efficiency (η) (not low enough) and the Total HSP Total CapEx (too high).

On WS # 4, HSP Round Trip 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% (WS # 3, Line 18, FC-η). This is a very optimistic HSP Round Trip η because HE and FC do not actually operate at η = 90%. If the bulk H_2 storage tank were, in 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, H_2 Tank and FC are now each set at 80% instead of 90%[18] (an 11.1% reduction), the HSP Round Trip η would decline from 72.9% to 51.2% (a 29.8% decrease) while the LCOS would increase from the base case US$142.21 to US$187.37/MWh (€116.22), an 31.8% increase.

WS # 4, Total[11] HSP CapEx, US$660,600,000 (€576,389,435) is the sum of US$171,900,000/HE [WS # 1, Line D, HE CapEx] plus US$270,000,000/$H_2$ Tank [WS # 2, Line BB, H_2 Tank CapEx] plus US$218,700,000/FC [WS # 3, Line AAA, Total FC CapEx].

The HE CapEx (WS # 1, Line D) is computed by multiplying the 300 $MW_{ELECTin}$ of HE capacity (WS # 1, Line A) times 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[19]. The 300 MW_{ELECT} (WS # 1, Line A) is computed by dividing the 3,000 MWh_{ELECT} of solar electricity that charges the HSP each day (WS # 1, Line 2) with the 10 hrs. per day that the HE operates (WS # 1, Line 1).

The H_2 Tank CapEx (WS # 2, Line BB) is computed by multiplying the 2,700 MWh_{H2} H_2 Tank size (WS # 2, Line I) times the H_2 Tank CapEx of US$100,000/$MWh_{H2}$[20] (WS #2, Line 10)

The FC CapEx (WS # 3, Line AAA) is computed by multiplying the 219 $MW_{ELECTout}$ of FC capacity (WS #3, Line XX) times the FC CapEx of US$1,000,000/$MW_{ELECTout}$[21] (WS # 3, Line 17). The 219 MW_{ELECT} (WS # 3, Line XX) is computed by dividing the 2,187 MWh_{ELECT} (WS # 3, Line YY) discharged by the HSP each day with the 10 hours per day that the FC operates (WS #3, Line 16).

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%[18], the Total[10] HSP CapEx would be $528,420,000 (€461,059,244), a 20% reduction from the base case Total HSP

[19] the published value was €500/kWh (US$573/kWh) [12]

[20] the H_2 Storage "Tank" CapEx is based on a projected US$100/kWh for the Tesla Li-ion battery

[21] this is equal to a FC CapEx of US$1,000/kW

CapEx of US$660,600,000. The LCOS would be US$127.69/MWh (€111.41), a 10.3% LCOS reduction from the base case of US$142.21 (€124.08). This result is caused by the 20% decrease in the CapEx of each HSP phase. The author estimates that the Total CapEx will have to go down by more than 60% for the model HSP to become commercially viable.

VII. Conclusion

If you are a banker or investor asking the author, is hydrogen energy storage ready for prime time on the North American grid?

Based on the research that the author did to assemble the following facts; the author's answer is NO!

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

2. HSP specs (metrics) for a commercial North American HSP were not found in any current authoritative data source.

3. The author complied specs for a model HSP. With the paper's LCOS algorithm, the author computed the LCOS but it was too high for the current development of a commercial North American 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 solar electricity being stored but too low to reflect current HSP CapEx values.

6. Readers might want to compare the LCOS for current pumped storage plants as a benchmark for future HSP [5,6].

VIII. Three Examples of Spec Values That Need to be updated

Refer to your copy of the paper's Excel HSP LCOS Workbook.

1. WS # 1, Line 5, Cost of the Solar Electricity (COE)-US$/MWh, to be stored, should be changed from US$50.16/MWh to US$40.00/MWh. This is the author's current estimate of the cost of solar (PV) electricity (COE) currently sold wholesale to load serving entities (utilities) under a long-term contract (PPA) from a new utility-scale solar plant.

2. WS #1, Line 2, Daily MWh_{ELECT} Solar Electricity that charges HSP is 3,000 MWh. This is the value that the author used to test the LCOS algorithm. The algorithm works. 300 MWh/day is a more realistic value. A 75 MW utility scale PV plant that operated at 4 sun hours a day, would generate 300 MWh a day.

There is no economy of scale equation in the algorithm. Economies of scale, when they exist, would show up in CapEx of the HE (WS #1, Line 3, H_2 Storage Tank (WS # 2, Line 10) and in the FC (WS # 3, Line 17) and in the WS #4 Total HSP CapEx.

3. US$1.140/€ FX rate of 13 January 2019 should be updated on the worksheet to the current FX rate. On 05 May 2020 the FX value was $1.09243/€.

The reader can put their spec values for the Cost of Solar Electricity, the MWh/day that charges the HSP and the US$/€ FX value.

The paper's Excel LCOS Workbook, itself, is complete and works as designed.

There are no errors in the equations. The equations are available to clients.

The reader can, with confidence, update their Workbook with their own complied 22 specs.

There may still be certain of those pesky undetected "typos" in the Workbook labels and notes.

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Acronym Glossary

acronym	Definition
CH_3 =	ammonia
CCGT =	combined cycle gas turbine
η =	efficiency
EIA =	Energy Information Administration (USA)
FC =	fuel cell
FX =	foreign exchange
HE =	H_2 electrolyzer
HS =	H_2 storage
H_2 =	hydrogen
HSP =	hydrogen storage plant
IEA =	International Energy Agency (OECD)
Kg_{H2} =	Kilogram-H_2
LCOE =	levelized cost of energy
LCOS =	levelized cost of storage
MJ_{H2} =	megajoule-H_2
lbs_{H2} =	pounds-H_2
MW =	megawatt
MWh	megawatt hour
$mmBtu_{H2}$ =	million British thermal units-H_2
NG =	natural gas
Nm^3_{H2} =	nominal cubic meter-H_2
O_2 =	oxygen
PV =	photovoltaic
ROE =	return on owner's equity
scf_{H2} =	standard cubic foot-H_2
SI =	Système International d'Unités
H_2O =	water
WACC =	weighted average cost of capital
WS =	worksheet

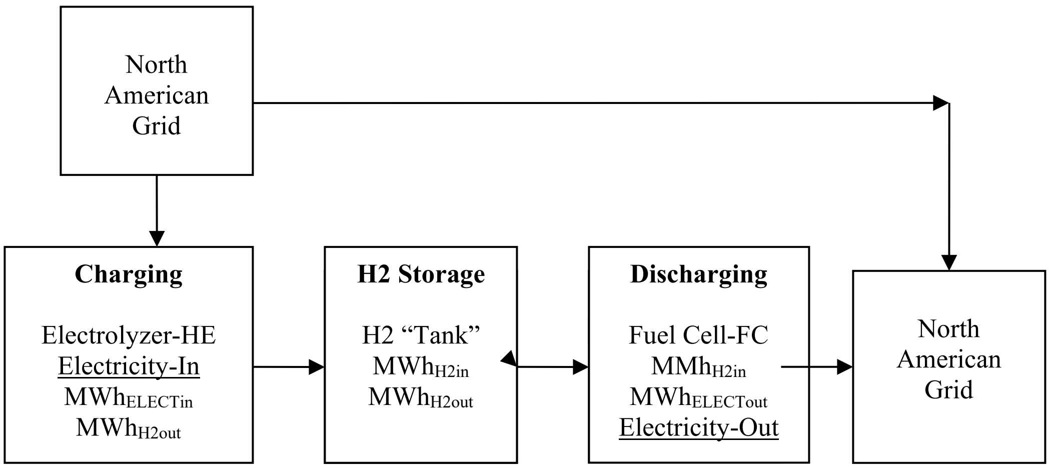

Fig. 1 Schematic of H_2 Storage Plant

spec #	Charging HE	spec #	Storage H2 Tank	spec #	Discharging Fuel Cell
1	HE hrs/Day Operating	10	H_2 Tank CapEx-US$/MWh$_{H2in}$	16	FC hrs/Day Discharging
2	Solar Energy to be Stored MWh/Day	11	H_2 Tank Efficiency-η	17	FC CapEx-US$/MW$_{ELECTout}$
			Annual Fixed O & M-%		
3	HE CapEx-US$[22]/MW$_{ELECTin}$	12	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$/FC
5	Cost of the Solar Energy Stored-MWh$_{ELECTin}$	14	H_2 Tank life-yrs	20	FC Variable O & M-US$/MWh$_{ELECTout}$
6	Annual Fixed O & M-% HE total CapEx-US$/HE	15	H_2 Tank Interest/ROE rate-%	21	FC Life-yrs
7	HE Variable O & M-US$/MWh$_{H2out}$			22	FC Interest/ROE rate-%
8	HE Life-yrs				
9	HE Interest/ROE rate-%				

Table 1 The 22 Specs (Metrics) of the LCOS HSP Algorithm

[22] Excel LCOS Financial Algorithm Workbook converts US$ into € with the user selected FX rate

WS # 4

		d/m/y		Color Coding
US$/€	US$1.14610	13/01/19		From WS # 1
				From WS # 2
	WS # 1	WS # 2	WS # 3	From WS # 3
	HE	H_2 Tank	FC	Result
				Side Column Result
quick key to HPS energy flow→	HE produces H_2	H_2 Tank stores H_2	FC consumes H_2	In €
Phase→	Charging	Storage	Discharging	HSP-η-%
HSP Phase-η-%	90%	90%	90%	72.9%
MWh_{ELECT}/day	3,000.00	←MWh_{ELECT}/day solar energy stored		
MWh_{H2}/day	2,700.00	←MWh_{H2}/day produced by HE		
MWh_{H2}/day		2,700.00	←MWh_{H2}/day stored	
MWh_{H2}/day		2,430.00	←MWh_{H2}/day released	
MWh_{H2}/day			2,430.00	←MWh_{H2}/day consumed by FC
MWh_{ELECT}/day			2,187.00	←MWh_{ELECT}/day solar energy regenerated
		proof ↓	72.9%	←HSP round trip η-%
MWh_{ELECT}/yr of solar energy stored→	1,095,000	72.9%	798,255	←MWh_{ELECT}/yr of solar energy put back on the grid

WS # 4

	WS # 1 HE Charging	WS # 2 H_2 Tank Storage	WS # 3 H_2 FC Discharging	
Phase →				
Phase Operating hrs/day	10	4.00	10	24
	Only one phase operates at a time; HSP operates 24 hr/day; 365/yr			
US$/MWh$_{ELECT}$	$50.16	←US$/MWh$_{ELECT}$ cost (LCOE) of the solar energy to be stored		
US$/MWh$_{H2}$	$71.28	←US$/MWh$_{H2}$ HE LC to produce H_2		
US$/MWh$_{H2}$		$71.28	←US$/MWh$_{H2}$ LC of H_2 stored	
US$/MWh$_{H2}$		$106.14	←US$/MWh$_{H2}$ LC of H_2 released	
US$/MWh$_{H2}$			106.14	←US$/MWh$_{H2}$ LC H_2 FC consumed
US$/MWh$_{ELECT}$			$142.21	← US$/MWh$_{ELECT}$ LCOS for solar energy
			183.5%	←% LCOS increased cost

WS # 4	WS # 1	WS # 2	WS # 3			
	HE	H_2 Tank	H_2 FC			
Phase→	Charging	Storage	Discharging			
	HE Power $MW_{ELECTin}$ ↓ 300	Tank Size MWh_{H2} ↓	FC Power $MW_{ELECTout}$ ↓	€/$MW_{ELECTin}$ ↓	€/MWh_{H2} ↓	€/$MW_{ELECTout}$ ↓
HE CapEx-US$/$MW_{ELECTin}$	$573,000	2,700		€ 499,956		
Tank CapEx-US$/$MWh_{H2}$		$100,000	219		€ 87,252	
FC CapEx-US$/$MW_{ELECTout}$			$1,000,000			€ 872,524
CapEx -US$/$kw_{ELECTin}$; US$/kWh_{H2}; US$/$Kw_{ELECTout}$	$573	$100	$1,000			
CapEx -€/$kw_{ELECTin}$; €/kWh_{H2}; €/$Kw_{ELECTout}$	€ 500	€ 87	€ 873			
				Total[7] HSP CapEx ↓		
HSP CapEx-US$/Phase	$171,900,000	$270,000,000	$218,700,000	$660,600,000		
HSP CapEx-€/Phase	€ 149,986,912	€ 235,581,537	€ 190,821,045	€ 576,389,495		
Fixed O&M Cost-% Phase CapEx	0.05%	0.05%	0.05%			
Variable O & M Cost-US$/Phase MWh	$0.25	$0.25	$0.25			
Phase Physical Life -Years	20	20	20			
Phase Interest/ROE Rate [WACC]-%	6.00%	6.00%	6.00%			