Is Hydrogen Energy Storage Ready for Prime Time on the North American Grid? A Guide for Bankers and Their Engineers

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Abstract

A utility scale[1] energy storage plant can be used on the North American (NA) grid for the storage of solar (PV) electricity and/or to provide ancillary services. To help bankers and their engineers determine whether hydrogen (H_2) energy storage is ready for prime time[2], this paper presents a H_2 storage plant (HSP) levelized cost of storage (LCOS)[3] financial algorithm for a model HSP. The LCOS algorithm is based on engineering economics and financial accounting principles. The algorithm only uses S. I. energy units for both the HSP's kinetic (electricity) energy and its potential energy (H_2). It converts US$ values into € values. The paper discusses HSP technology focusing on the three phases of all HSP; <u>charging</u> the HSP by using a H_2 electrolyzer (HE) to produce H_2, <u>storage</u> of the PV electricity as H_2 in a "H_2 "Tank", and <u>discharging</u> the PV electricity from the HSP by using the stored H_2 as the fuel for a fuel cell (FC) to regenerate the PV electricity. The LCOS algorithm uses "project accounting" to compute a separate "LCOS" for each HSP phase. The LCOS algorithm is presented in the paper's Excel[4] HSP LCOS Financial Algorithm Workbook. Based on the paper's LCOS algorithm and on the HSP specifications (specs, metrics) complied for a base case "data set" for the model HSP, H_2 energy storage is not yet ready for commercial development on the North American grid. Low round trip HSP efficiency (η) and a high HSP CapEx do not allow a HSP to operate commercially on the North American grid.

Keywords: levelized cost of storage, LCOS, LCOE, hydrogen energy storage, North American grid, PV electricity, S.I. units, hydrogen electrolyzer, fuel cell, commercial energy storage, financial algorithm, engineering economics

1. The Levelized Cost of Storage (LCOS) Algorithm and its Excel Workbook

The goal of this paper is to determine if H_2 energy storage is ready for commercial development. To reach this goal, the author developed a HSP LCOS algorithm with a recognized uniform set of HSP specs that is based on generally accepted financial and engineering principles. Both "back of the envelope" simplicity and an accurate first approximation of the cost (US$/MWh; €/MWh) of storing PV electric energy in a HSP are the two criteria for choosing a computational method. The paper's levelized cost (LC) algorithm meets both criteria.

The paper's HSP LCOS algorithm requires 22 HSP specifications (specs) [metrics]. The 22 HSP specs [independent variables] and the 76 dependent variables are all defined[5] using the standard S.I. power (MW_{ELECT}) and energy (MWh_{ELECT}, MWh_{H2}) units.

The actual compilation[6] of a public data base of the HSP specs for use by bankers (and their engineers) is not the primary goal of this paper (Electric Power Research Institute, Inc. (EPRI); Lazard; US DOE). The author has the much more modest goal of first presenting a recognized standard LC financial algorithm, second, using a base case for a model HSP to demonstrate to the reader how the LCOS algorithm works and third, using these base case specs and the LCOS algorithm to compare the PV electricity's LCOS with the grid's wholesale PV price for electricity.

While the paper discusses the 22 specs for a model HSP, there is also no case study to discuss how to compile[6] the 22 HSP base case specs from the current authoritative data sources. Readers who want learn how to compile[6] the 22 HSP specs for either their own base case (or to compile a public data base of HSP specs) should read the author's Cabin Creek Pumped Storage Plant spec compilation case study that is found in the author's Wind Europe 2018 paper (Task Committee…, Stavy, 2018).

[1] 100-2,500/MWh/day
[2] is currently ready for commercial development
[3] not to be confused with the levelized cost of energy (LCOE) [Stavy, 2002)
[4] a fully functioning Excel Workbook
[5] required in these SOLAR 20/20 Conference Proceedings, but this is not the conventional practice in either the North American H_2 industrial gas industry or North American H_2 electrolyzer industry
[6] assemble, organize, gather, create, publish

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Putting the paper's LCOS algorithm in an Excel Workbook allows the reader (author, banker, engineer) to quickly do sensitivity analysis. For the reader to follow this paper, the reader must download this paper's Excel HSP LCOS Financial Algorithm Workbook from this paper's Additional Material Section[7] at SOLAR 20/20 Conference Proceedings Website: *[Link].* This is because the paper refers to the worksheet (WS) lines on the four WS of the Excel HSP LCOS Financial Algorithm Workbook[8].

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.

At the end of this paper is Fig. 1. *A Schematic of a H_2 Storage Plant*; Table 1. *Acronym Meanings*; Table 2. *The 22 Specs of the HSP LCOS Algorithm* and for those readers who cannot access this paper's "Additional Material Section", Table 3, *WS # 4 Summary of the HSP Specs and the Key Computed Values.*

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. By selecting different realistic values for the 22 specs of the model HSP, it has become clear to the author that there are two key dependent variables that determine whether a HSP is ready for commercial development; the HSP round trip efficiency (η) which is set too high in the base case to be realistic and the Total[9] HSP CapEx which is set too low in the base case to be realistic. The reader can enter their own 22 HSP spec values in their Excel HSP LCOS Workbook and check their results.

In addition to the 22 HSP specs, the Excel HSP LCOS Workbook also requires a FX value. The base case uses US$1.12987/€. (OANDA, 7 July 12, 2020) to convert the US$ spec and dependent variable values into € values for readers in the € zone.

A HSP can be designed for the 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 financial 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 algorithm assigns the remaining hours of each day 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 also 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. S. I. Energy Units and the H2 Energy Units in the North American (NA) Industrial Gas and H2 Electrolyzer (HE) Industries

The NA electric utility industry already measures production and prices electric power and electric energy in the S. I. units of the MW and the MWh. The NA industrial gas industry, however, measures the production and pricing of industrial H_2 in Kg_{H2} (mass) or in Nm^3_{H2} (volume). The NA HE industry sizes and prices HE in $MW_{ELECTin}$ of electric power into the HE and measures and prices the production of H_2 in Kg_{H2} or in Nm^3_{H2}. These are the correct units for H_2 as an industrial gas but not for H_2 as an energy carrier in a HSP. Since $MWh_{ELECTin}$ are charging the HSP and since $MWh_{ELECTout}$ are discharged from the HSP, the paper's HSP LCOS financial algorithm measures the production and price of the H_2 gas that is used to store the electricity in MWh_{H2}. [H-TEC Systems; Universal Industrial Gases, Inc; US EIA). Even though the editors of these proceedings require S. I. units, the author considers the consistent[10] use of the S. I. MW power unit and the MWh energy unit to be a major contribution to the "H_2 Economy" literature.

$$MWh_{ELECT} = MWh_{H2}$$

3. The Three Phases of the HSP and the Algorithm's LC Method Explained

[7] **Editor,** I just checked some other journals that I am familiar with (i.e. the American Economics Review) and they allow additional material to be presented with the paper. I assume that the Solar 20/20 Proceedings also allow "additional material" to be downloaded by the reader from the Solar 20/20 Proceedings website

[8] hereafter, referred to as the Excel HSP LCOS Workbook

[9] Total CapEx refers to the sum of the CapEx of each of the three HSP phases (HE; H_2 "Tank"; FC)

[10] without first converting to Kg_{H2} (Nm^3_{H2}) for H_2 coming out of the HE and stored in the H_2 "Tank" and then converting the Kg_{H2} (Nm^3_{H2}) back into MWh_{H2} for the FC

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. There is no carbon released (Stavy, 2005).

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[11]. A specific example is WS # 1, Line 9, Cost of Capital, interest rate/ROE [WACC] is set at 6%, which is the author's base case estimate. So are WS # 2, Line 15 and WS # 3, Line 22. Another example is, Line 8, HE Life-yrs, is set at 20, which is the author's base case estimate for the typical "life" for power projects. So are WS # 2, Line 14 and WS # 3, Line 21. WS # 1, Line 1, HE hours/day operating and WS #3, FC hours/day operating are both eight hours. The algorithm assigns the remaining 8 hours/day to the H_2 "Tank". This is done to have a straightforward base case. The paper's Excel HSP LCOS Workbook allows the user to use different spec values for each HSP phase.

In the paper's model HSP, solar electricity from the North America grid powers a HE. The HE uses the solar power 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 different technologies. The most important algorithm HE specs are WS # 1, Line A, HE Power Input ($MW_{ELECTin}$), WS # 1, Line 3, HE CapEx-US\$/$MW_{ELECTin}$ (€/$MW_{ELECTin}$) and WS # 1, Line 4, HE efficiency (η).

The algorithm's levelized cost method will now be explained using WS # 1, the HE phase.

WS #1 Line 9, Interest/ROE [WACC] is set at 6%. This is the cost (as a %) to invest the capital in the HE, WS # 1 Line D, Total HE CapEx. The HSP owner either provides the capital (equity) or borrows (debt) the capital to in order to own the HE phase. WS # 1 Line 8, HE Life-yrs is 20 years. During its physical life, as the HE phase operates the Total HE CapEx (WS # 1 Line D) must be recovered (depreciated) and the cost of capital (WS #1, Line 9) for using the invested capital must be paid. If borrowed money is used to construct the HE phase, the cost of borrowing the money is called the lender's interest. If the HSP plant owner uses their own capital to construct the HSP, the cost of using the owner's money is called the return on owner's equity (ROE). The cost of capital (Line 9) is a weighted average percent for both the lender's interest and for the owner's ROE. Let us hypothesize that the HSP debt/owner's equity ratio is 1:1; the interest on the debt is 4% and the required ROE is 8%; then the weighted average cost of capital (WACC), Interest/ROE Rate is 6%.

WS # 1, Line I is the capital amortization factor-CAF. It is computed to be 0.08720. This is the end of year annual payment computed for a financial annuity having US\$1.00 as the principal borrowed, a loan period of 20 years (WS # 1, Line 8) and an interest rate of 6% (WS #1, Line 9).

WS # 1, Line L is the annual capital amortization (ACA) in US\$/year. This computed to be US\$1,847,202/yr (€1,634,710/yr). Line L is the product of Line D multiplied by Line I.

The levelized cost (LC) method uses a financial annuity to compute Line L. The ACA-US\$/yr is one constant yearly payment for both the depreciation of Line B and for the payment of Interest/ROE (Line 9) over the physical life of the HE phase. This level (constant) capital amortization payment gives the method its name. The first year's payment is almost all Interest/ROE, while the last year's payment is almost all depreciation.

The algorithm's LC method is the same in the H_2 "Tank" phase (WS # 2) and in the FC phase (WS #3).

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 specs 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

[11] Table 2 on page 7 makes the relationships between the 22 HSP specs clear

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 electro-chemistries and H_2 powered electric gas 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 yet 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 specs 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).

4. Sensitivity Analysis

WS # 1, Line 5, Cost of the Solar Electricity to be Stored, US$40.00/MWh (€35.40), is the cost of solar electricity generated a model PV plant. US$40/MWh is the author's estimate of a model utility scale PV plant's LCOE (Stavy, 2002).

On WS # 3, Line LLL, the LCOS in the base case is US$138.67/MWh (€120.99). This 246.7% increase from US$40.00/MWh is too high for the market. Perhaps a carbon constrained North American grid would accept a time of day 20% increase to US$48.00 (€42.48) 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[12], the LCOS would be US$130.19/MWh (€115.23). This is a 6.1% LCOS reduction from the base case of US$138.67/MWh 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 FC (WS # 3, Line 22) are each set at 4% instead of 6%[12], then the LCOS would be US$125.80/MWh (€111.34). This is a 9.3% LCOS reduction from the base case US$138.67/MWh for a 33.3% decrease in the WACC. It is doubtful, however, that bankers or their engineers would risk funding a HSP at even 6% with the current state of HSP technical development.

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

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 the HE, H_2 "Tank" and FC do not actually operate at η = 90%. If the H_2 "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%[12] (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$138.67 to US$179.78/MWh (€159.12), an 26.9% increase.

On WS # 4, Total[9] HSP CapEx, US$75,524,756 (€66,838,836) is the sum of US$21,187,256/HE [WS # 1, Line D, HE CapEx] plus US$27,000,000/$H_2$ "Tank" [WS # 2, Line BB, H_2 "Tank" CapEx] plus US$27,337,500[13]/FC [WS # 3, Line AAA, Total FC CapEx].

The HE CapEx (WS # 1, Line D) is computed by multiplying the 38 $MW_{ELECTin}$ of HE capacity (WS # 1, Line A) times the HE CapEx of US$564,994/$MW_{ELECTin}$ (WS # 1, Line 3). €500/$kW_{ELECTin}$ (US$573/kW) is the author's estimated cost of a modern commercial European MW scaled HE. The 38 $MW_{ELECTin}$ (WS # 1, Line A) is computed by dividing the 300 $MWh_{ELECTin}$ of solar electricity that charges the HSP each day (WS # 1, Line 2) with the 8 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 270 MWh_{H2} H_2 "Tank" size (WS # 2, Line L) times the H_2 "Tank" CapEx of US$100,000/$MWh_{H2}$ (WS #2, Line 10). US$100,000/MWh is equal to US$100/kWh which is the projected cost of a Tesla utility scale Li-ion battery. The H_2 "Tank" size is equal to the daily H_2 produced (WS #1, Line B) by the HE. What is produced by the HE is stored in the H_2 "Tank".

The FC CapEx (WS # 3, Line AAA) is computed by multiplying the 27 $MW_{ELECTout}$ of FC capacity (WS #3, Line XX) times the FC CapEx of US$1,000,000/$MW_{ELECTout}$ (WS # 3, Line 17). The 27 $MW_{ELECTout}$ (WS # 3, Line XX)

[12] and if all 19 of the other 22 specs remain the same
[13] rounding errors appear in certain of the Workbook results

is computed by dividing the 219 $MWh_{ELECTout}$ (WS # 3, Line YY) discharged by the HSP each day with the 8 hours per day that the FC operates (WS #3, Line 16). US$1,000,000/$MW_{ELECTout}$ is the author's estimate of the current cost of a utility scale 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%[12], the Total[9] HSP CapEx would be $60,419,813 (€53,575,013), a 20% reduction from the base case Total HSP CapEx of US$75,524,756. The LCOS would be US$122.07/MWh (€108.04), a 10.3% LCOS reduction from the base case of US$138.67. This reduced Total HSP CapEx 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.

To get "hands on experience" in LCOS sensitivity analysis, the Workbook user should enter their own 22 HSP spec values on the paper's Excel HSP LCOS Workbook.

5. Conclusion

If you are a banker, or a banker's engineer, 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 for commercial North American HSP were not found in any current authoritative data source.

3. The author complied the 22 base case specs for a model HSP. With the paper's LCOS financial 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. His HSP Round Trip η is too <u>high</u> to be realistic. HSP Round Trip η should actually be about 60%; 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. His HSP CapEx is too <u>low</u> to be realistic. 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 (Task Committee…, Stavy, 2018).

6. Acknowledgements

The author took (1960) the Physical Science Study Committee (PSSC) Course at Niles Township High School, Skokie, IL US where he learned how to do the S. I. Unit Analysis used in this paper. (MIT Institute Archives & Special Collections, 1956).

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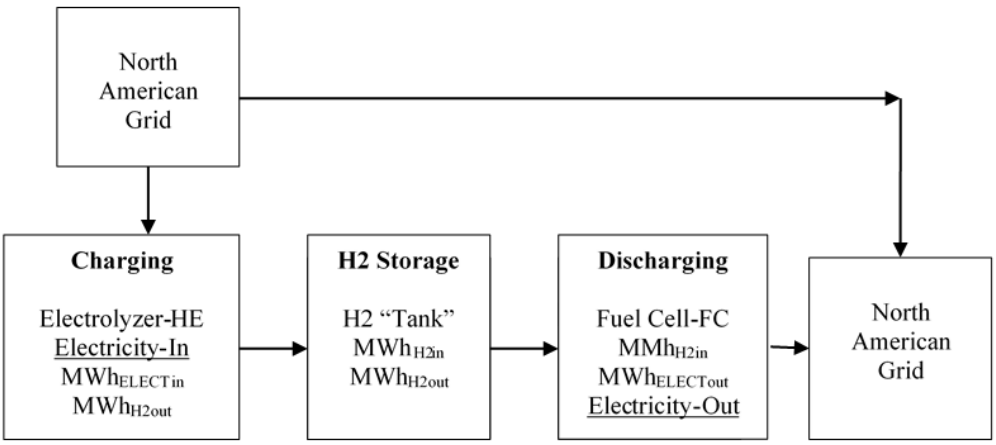

Fig. 1: Schematic of a H_2 Storage Plant (HSP)

Table 1: Acronym Meanings

Acronym	Meaning
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

Table 2: The 22 Specs of the HSP LCOS Algorithm

spec #	Charging HE	spec #	Storage H_2 "Tank"	spec #	Discharging Fuel Cell
1	HE hrs/Day Operating			16	FC hrs/Day Operating
2	Solar Energy to be Stored MWh/Day				
3	HE CapEx-US$[1]/MW$_{ELECTin}$	10	H_2 "Tank" CapEx-US$/MWh$_{H2in}$	17	FC CapEx-US$/MW$_{ELECTout}$
4	HE Efficiency-η	11	H_2 "Tank" Efficiency-η	18	FC Efficiency-η
5	Cost of the Solar Energy Stored-MWh$_{ELECTin}$				
6	Annual Fixed O & M-% HE Total HE CapEx-US$	12	Annual Fixed O&M-% H_2 "Tank" Total CapEx-US$	19	Annual fixed O&M-% FC Total CapEx-US$
7	HE Variable O&M-US$/MWh$_{H2out}$	13	H_2 "Tank" Variable O&M-US$/MWh$_{H2out}$	20	FC Variable O&M-US$/MWh$_{ELECTout}$
8	HE Life-yrs	14	H_2 "Tank" Life-yrs	21	FC Life-yrs
9	HE Interest/ROE rate-%	15	H_2 "Tank" Interest/ROE rate-%	22	FC Interest/ROE rate-%

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

Table 3: WS # 4 Summary of the HSP Specs and the Key Computed Values

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	300.00	←MWh_{ELECT}/day solar energy stored		
MWh_{H2}/day	270.00	←MWh_{H2}/day produced by HE		
MWh_{H2}/day		270.00	←MWh_{H2}/day stored	
MWh_{H2}/day		243.00	←MWh_{H2}/day released	
MWh_{H2}/day			243.00	←MWh_{H2}/day consumed by FC
MWh_{ELECT}/day			218.00	←MWh_{ELECT}/day solar energy regenerated
		proof ↓	72.9%	←HSP round trip η-%
MWh_{ELECT}/yr of solar energy stored→	109,500	72.9%	79,826	←MWh_{ELECT}/yr of solar energy put back on the grid

continued on next page

Table 3: WS # 4 Summary of the HSP Specs and the Key Computed Values

WS # 4

	WS # 1 HE Charging	WS # 2 H_2 Tank Storage	WS # 3 H_2 FC Discharging	
Phase →				Total hrs/day
Phase Operating hrs/day	8	8	8	24
	Only one phase operates at a time; HSP operates 24 hr/day; 365/yr			
US$/MWh$_{ELECT}$	$50.00	←US$/MWh$_{ELECT}$ cost (LCOE) of the solar energy to be stored		
US$/MWh$_{H2}$	$63.55	←US$/MWh$_{H2}$ HE LC to produce H_2		
US$/MWh$_{H2}$		$63.55	←US$/MWh$_{H2}$ LC of H_2 stored	
US$/MWh$_{H2}$		$97.55	←US$/MWh$_{H2}$ LC of H_2 released	
US$/MWh$_{H2}$			$97.55	←US$/MWh$_{H2}$ LC H_2 FC consumed
US$/MWh$_{ELECT}$			$138.67	← US$/MWh$_{ELECT}$ LCOS for solar energy
			246.7%	←% LCOS increased cost

continued on next page

Table 3: WS # 4 Summary of the HSP Specs and the Key Computed Values

WS # 4	WS # 1	WS # 2	WS # 3			
	HE	H_2 Tank	H_2 FC			
Phase→	Charging	Storage	Discharging			
	HE Power MW$_{ELECTin}$ ↓ 38	Tank Size MWh$_{H2}$ ↓ 270	FC Power MW$_{ELECTout}$ ↓ 27	€/MW$_{ELECTin}$ ↓	€/MWh$_{H2}$ ↓	€/MW$_{ELECTout}$ ↓
HE CapEx-US$/MW$_{ELECTin}$	$64,994			€ 499,956		
Tank CapEx-US$/MWh$_{H2}$		$100,000			€ 87,252	
FC CapEx-US$/MW$_{ELECTout}$			$1,000,000			€ 872,524
CapEx -US$/kw$_{ELECTin}$; US$/kWh$_{H2}$; US$/Kw$_{ELECTout}$	$565	$100	$1,000			
CapEx -€/kw$_{ELECTin}$; €/kWh$_{H2}$; €/Kw$_{ELECTout}$	€ 500	€ 88	€ 885			
				Total[9] HSP CapEx ↓		
HSP CapEx-US$/Phase	$21,187,256	$27,000,000	$27,337,500	$75,524,756		
HSP CapEx-€/Phase	€ 18,750,000	€ 23,894,080	€ 24,192,756	€ 66,836,836		
Fixed O&M Cost-% Phase CapEx	0.05%	0.05%	0.05%			
Variable O & M Cost-US$/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%			