Is Hydrogen Energy Storage Ready for Prime Time on the European Grid?

AUTHOR

Michael STAVY MBA-Kellogg, Illinois-CPA (inactive), Senior Advisor on Renewable Energy Finance, USA

michael@michaelstavy.com www.michaelstavy.com M: 1-312-523-8328

Version 1.1

NATIONAL PARTNER: AEE Spanish Wind Energy Associaton

REGIONAL PARTNERS: ENERGIAREN EUSKAL ERAKUNDEA ENTE VASCO DE LA ENERGÍA; EUSKO JAURLARITZA GOBIERNO VASCO

WindEurope CONFERENCE & EXHIBITION 2019 2-4 APRIL BILBAO

SUMMARY

A bulk electric energy storage plant can be used on the European 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 help bankers and investors determine whether hydrogen (H_2) energy storage is ready for prime time[1] on the European grid.

To determine this, the author has developed a H_2 storage plant (HSP) levelized cost of storage (LCOS)[2] financial algorithm for a model HSP. To compute the LCOS, the paper's HSP LCOS financial algorithm[3] requires 22 HSP specifications (specs) [metrics]. These 22 HSP specs (metrics) [independent variables] are 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[4] 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 wind electricity, two, the storage of the wind electricity as H_2, three, the use of the stored H_2 as the fuel to regenerate the wind electricity. The HSP LCOS algorithm uses "project accounting" to compute a separate LCOS for each HSP phase; charging, storage and discharging.

The author used the paper's HSP LCOS algorithm and "datasets" of compiled HSP specs to do sensitivity analysis. The author has found that both low round trip HSP efficiency (η) and high Total HSP CapEx do not allow a HSP to operate commercially in Europe. The cost of capital[5] was not a factor. This is confirmed by the fact that currently there are no commercial HSP operating on the European grid.

[1] Is currently commercially viable
[2] not to be confused with the levelized cost of energy (LCOE). See reference [5]
[3] hereafter referred to as the HSP LCOS algorithm
[4] a fully functioning Excel Workbook
[5] discount rate

1. THE HSP LCOS FINANCIAL ALGORTHUM AND ITS EXCEL WORKBOOK

For the reader to follow this paper's narrative, the reader must download (@ **no cost**) the paper's Excel[4] HSP LCOS Financial Algorithm Workbook. https://tinyurl.com/WEU19-Stavy-Paper . This paper refers to worksheet (WS) lines on the four WS of the Excel HSP LCOS Financial Algorithm Workbook[6]. A Glossary is on page 10. Table # 1 with the 22 clearly defined HSP specs and a List of References are both on page 11.

Putting the algorithm on an Excel workbook allows the author (and the reader) to quickly do sensitivity analysis. By selecting different realistic values for the 22 HSP specs, 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[7] HSP CapEx.

A H_2 Electrolyser (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 Electrolyser, 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 8 & 9 and is a summary of the model HSP base case. Fig. 1 (page 10) is a Schematic of the Model HSP. 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. 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 for the 22 HSP spec values (the independent variables) and for the 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 reader who has downloaded the paper's Excel[4] HSP LCOS Workbook can enter their own 22 HSP spec values on the Excel 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 HSP specs from the current authoritative data sources. The author was unable to locate any commercial bulk HSP on the European gird. Readers who want to learn how to compile the 22 HSP specs should read the Cabin Creek Pumped Storage Plant compilation case study that is found in the author's Wind Europe 2018 Paper [1].

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 wind 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 24 hours 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 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

[6] hereafter referred to as the Excel HSP LCOS Workbook

[7] Total CapEx refers to the sum of the CapEx of each of the three phases

not designed to provide ancillary services.

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

2. 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[8,9] MJ_{H2} into kg_{H2}; into Nm^3_{H2} and into MWh_{H2}.

The key conversion factor in the HSP LCOS algorithm is

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

MWh_{ELECT} and MWh_{H2} are equal SI energy units regardless of the type of energy[10] or the authoritative SI source cited[11] for the standard conversion factors. This is because they are both the same quantity of energy.

The model HSP's energy flow[12,13] using SI units is as follows:

First, during HPS charging phase, MWh_{ELECT} of wind energy from the grid go into the HE. The HE produces MWh_{H2} that are 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 power the FC. The FC consumes the MWh_{H2} to regenerate MWh_{ELECT} of wind energy that are then put back on the grid.

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

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

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

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

$33.33\ kWh_{ELECT} = 1\ kg_{H2}$ [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 H_2 storage technology focusing on the three phases of all HSP; one, the production of the H_2 with wind electricity, two, the storage of the H_2, three, the use of the stored H_2 as the fuel to regenerate the wind electricity. In a HSP, H_2 is used as the energy carrier[14].

[8] or for the reverse conversion
[9] and for the conversion into US "English" standard units and for the reserve conversion
[10] here kinetic energy such as wind electricity or potential energy such as H_2
[11] examples, the IEA or EIA
[12] HE produces H_2; H_2 Tank stores H_2; FC consumes H_2
[13] a Schematic of the Model HSP is on page 10

In the base case, the HE spec values, WS #1, Lines 6, 7, 8 & 9, have also been used as the H_2 Tank spec values, WS # 2, Lines 12, 13, 14 & 15, and as the FC spec values WS # 3, Lines 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. 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, wind electricity from the European grid 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 algorithm HE values are WS # 1, Line A, HE capacity (MW_{ELECT}), WS # 1, Line 3, HE CapEx-US$/$MW_{ELECT}$ (€/MW_{ELECT}) and WS # 1, Line 4, HE efficiency (η) .

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 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, 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 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 wind electricity which is then put back on the European grid. When the 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 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_{ELECT}), WS # 3, Line 17, FC CapEx-US$/$MW_{ELECT}$ (€/MW_{ELECT}), and WS # 3, Line 18, FC efficiency (η).

4. CONCLUSIONS

WS # 1, Line 5, Cost of the Wind Electricity to be Stored, US$50.16/MWh (€43.77), is a model wind plant's LCOE[15]. On WS # 3, Line LLL, the LCOS in the base case is US$142.21[16]/MWh (€124.08). This 183.5% increase from US$50.16 is too high for the market. Perhaps a carbon constrained European grid

[14] potential energy
[15] it can also be a solar plant's LCOE [5]
[16] on WS # 4, the LCOS is also US$142.21

would accept a time of day 20% increase to US$60.19 (€52.46) for stored wind 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[17], 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 FC (WS # 3, Line 22) are each set at 4% instead of 6%[17], 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 fund a HSP at even 6% with the current state of HSP technical development.

Sensitivity analysis shows that currently the two key HSP specs (metrics) in determining the HSP LCOS are the HSP Round Trip Efficiency (η) (too low) 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%[17] (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[7] HSP CapEx, US$660,600,000 (€576,389,435) is the sum of US$171,900,000 [WS # 1, Line D, Total HE CapEx] plus US$270,000,000 [WS # 2, Line BB, Total H_2 Tank CapEx] plus US$218,700,000 [WS # 3, Line AAA, Total FC CapEx].

The Total HE CapEx (WS # 1, Line D) is computed by multiplying the 300 MW_{ELECT} of HE capacity (WS # 1, Line A) times the HE CapEx of US$573,000/$MW_{ELECT}$ (WS # 1, Line 3). The HE CapEx value was published by a prominent European HE manufacturer[18]. The 300 MW_{ELECT} (WS # 1, Line A) is computed by dividing the 3,000 MWh_{ELECT} of wind 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 Total 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$100,000[19]/$MWh_{H2}$ (WS #2, Line 10)

The Total FC CapEx (WS # 3, Line AAA) is computed by multiplying the 219 MW_{ELECT} of FC capacity (WS #3, Line XX) times the FC CapEx of US$1,000,000[20] /$MW_{ELCT}$ (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).

[17] and if all 19 of the other 22 specs remain the same
[18] the published value is €500/kWh (US$573/kWh) [6]
[19] The H_2 Storage "Tank" CapEx based on a projected US$100/kWh CapEx for the Tesla Li-ion battery
[20] this is equal to a FC CapEx of US$1,000/kW

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%[17], the Total[7] HSP CapEx would be $528,420,000 (€461,059,244), a 20% reduction from the base case Total HSP 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 Total CapEx will have to go down by more than 60% for the model HSP to become commercially viable.

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

The author's answer is NO!

He bases his answer on the following facts.

1. There are no commercial HSP on the European grid.
2. HSP specs (metrics) for commercial 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 European 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 values.
6. Readers might want to compare the LCOS for current pumped storage plants as a benchmark for future HSP [1].

Version 1.1

WORKSHEET # 4, HSP LCOS ALGORITHM SUMMARY NUMBERS

		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 wind 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 wind energy regenerated
			72.9%	←HSP round trip η-%

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 wind 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 wind energy
			183.5%	←% LCOS increased cost

Phase→	WS # 1 HE Charging	WS # 2 H_2 Tank Storage	WS # 3 H_2 FC Discharging	€/MW_{ELECT} ↓	€/MWh_{H2} ↓	€/MW_{ELECT} ↓
	HE Power MW_{ELECT} ↓ 300	Tank Size MWh_{H2} ↓ 2,700	FC Power MW_{ELECT} ↓ 219			
HE CapEx-US$/$MW_{ELECT}$	$573,000			€ 499,956		
Tank CapEx-US$/$MWh_{H2}$		$100,000			€ 87,252	
FC CapEx-US$/$MW_{ELECT}$			$1,000,000			€ 872,524
CapEx -US$/$kw_{ELECT}$; US$/kWh_{H2}; US$/Kw_{ELECT}	$573	$100	$1,000			
CapEx -€/Kw_{ELECT} ; €/kWh_{H2}; €/Kw_{ELECT}	€ 500	€ 87	€ 873			
				Total[7] HSP CapEx		
HSP CapEx-US$/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%			

GLOSSARY

CCGT =	combined cycle gas turbine	mmBtu =	million British thermal unit
EIA =	US Energy Information Administration	MW =	megawatt
ES =	energy storage	MWh =	megawatt hour
ESP =	energy storage plant	NG =	Natural gas
FC =	fuel cell	Nm^3 =	nominal cubic meter-H_2
H_2 =	hydrogen	O_2 =	oxygen
HSP =	hydrogen storage plant	ROE =	return on owner's equity
IEA =	OECD International Energy Agency	scf =	standard cubic foot-H_2
Kg =	kilogram-H_2	SI =	Système International d'Unités
LC =	levelized cost	WACC =	weighted average cost of capital
LCOE =	levelized cost of energy	WS =	worksheet
LCOS =	levelized cost of storage	η =	efficiency
MJ =	megajoule		

FIGURE # 1 A SCHEMATIC OF THE MODEL HSP

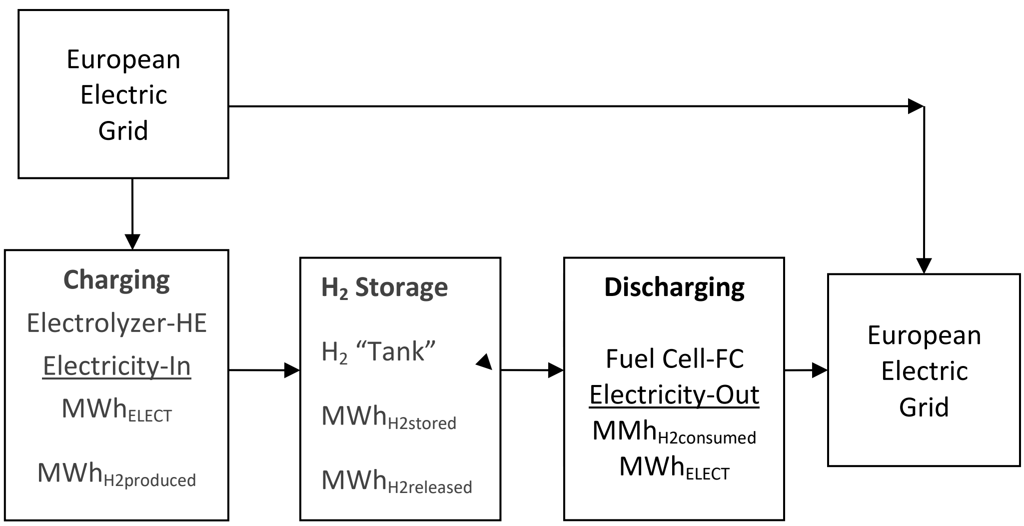

TABLE # 1 THE 22 SPECIFICATIONS (METRICS) OF THE HSP LCOS ALGORITHM

spec #	Charging HE	spec #	Storage H_2 Tank	spec #	Discharging Fuel Cell
1	HE hrs/Day Operating	10	H_2 Tank CapEx-US$/MWh$_{H2stored}$	16	FC hrs/Day Operating
2	Wind Energy to be Stored MWh/Day	11	H2 Tank Efficiency-η	17	FC CapEx-US$/MW$_{ELECT}$
3	HE CapEx-US$/MW$_{ELECT}$	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$/MWh$_{H2released}$	19	Annual fixed O & M-% FC Total CapEx-US$/FC
5	Cost of the Wind Energy to be Stored-MWh$_{ELECT}$	14	H_2 Tank life-yrs	20	FC Variable O & M-US$/MWh$_{ELECT}$
6	Annual Fixed O & M-% HE total CapEx-US$/HE	15	H_2 Tank Interest/ROE rate-%	21	FC Life-yrs
7	HE Variable O & M-€/MWh$_{H2}$			22	FC Interest/ROE rate-%
8	HE Life-yrs				
9	HE Interest/ROE rate-%				

REFERENCES

[1]. Stavy, M, "A Financial Algorithm for Computing the Levelized Cost (US$/MWh; €/MWh) of the Bulk Storage of Wind Electricity (LCOS)", WindEurope 2018 Conference, 25-28 September, Hamburg, Germany.

[2]. OANDA Corporation, "Web Currency Converter", http://www.oanda.com/ visited: 13 January 2019

[3]. US Energy Information Agency (EIA), "Energy Units and Calculators Explained: Energy Conversion Calculators" http://tinyurl.com/y4dptl6f visited; 25 January 2019

[4]. H-TEC Systems, "Hydrogen Data Card" Lübeck Germany, undated paper handout www.h-tec-systems.com

[5]. Stavy, M, "A Financial Worksheet for Computing the Cost (¢/kWh) of Solar Electricity Generated at Grid Connected Photovoltaic (PV) Generating Plants", Journal of Solar Energy Engineering, 2002, **Vol. 124**, Page 319-321. https://tinyurl.com/yatsour7

[6]. Nel Hydrogen Electrolyser, "The World's Most Efficient and Reliable Electrolyser", undated brochure, https://nelhydrogen.com/ downloaded: 16 January 2019