Is Wind Power to Gas (P2G) Technology Ready for Prime Time on the North American Grid? A Guide for Bankers and Their Engineers

AUTHOR

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Abstract--
This white paper discusses the finances of power to gas (P2G) technology. The power is wind (or solar) power, the gas is green methane (CH_4), the grids are the North American (NA) electric and natural gas (NG) grids. The paper discusses the two phases of a model wind power to gas plant (P2GP). First, wind (solar) power from the grid is converted into green hydrogen (H_2) gas using a H_2 electrolyzer (HE). Second, a Sabatier Reactor (SR) is used to convert the green H_2 into green methane (CH_4). CH_4 is green natural gas (GNG). The GNG is then injected into the NA NG grid. The HE H_2 has to be converted into CH_4 because the NA NG grid cannot accept significant quantities (>20%) of even green H_2. The model P2GP is a continuous flow plant. The paper discusses both the HE and SR technologies.

[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.

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The goal of this white paper is to determine whether P2G technology is ready for prime time[1] on the North American grid.

To determine this, the author has developed a levelized cost of gas ($LCOG_{H2}$; $LCOG_{CH4}$) financial algorithm for a model wind (solar) P2GP. This algorithm is presented to the reader in an Excel[2] P2G LCOG Financial Algorithm Workbook. The LC financial principles are discussed. This P2G LCOG algorithm is used for sensitivity analysis and to confirm "published" P2G plant specifications (specs). The P2GP LCOG Algorithm uses "project accounting" to compute a partial "LCOG" for each P2G plant phases: one, $LCOG_{H2}$-H_2 production-HE and two, $LCOG_{CH4}$-CH_4 production-SR. To compute the $LCOG_{H2}$, the algorithm's P2G HE Phase requires nine HE specifications (specs) [independent variables]; two foreign exchange values, one energy unit conversion factor and 35 dependent variables. Both the HE and the SR specs (metrics) and dependent variables are defined using a standard set of SI and US "English" energy units.

The author used the paper's P2GP LCOG Financial Algorithm and a "dataset" of compiled HE specs to do sensitivity analysis. He found that the low HE efficiency (η), the high cost of wind electricity and the high HE CapEx were sufficient[3] to <u>not</u> allow the model P2G plant to operate commercially on the North America electric and NG grids. The HE $LCOG_{H2}$ was computed to be US$24.25/mmBtu which is 88% greater than the US Henry Hub 05/04/21 spot price for NG [1]. The HE $LCOG_{H2}$ was computed to be €0.06430/kWh which is 27% greater than the 05/05/21 average price of NG (average 2nd half year NG price) as reported by Eurostat [2]. Both the H_2 and the NG were priced in €/kWh.. The low SR η as well as the high SR CapEx would further preclude a P2G plant from operating commercially on the NA electric and NG grids. The cost of capital[4] was not a factor. This is confirmed by the fact that currently there are no commercial P2GP operating (or planned) on the North American grid.

[1] is currently commercially viable
[2] a fully functioning Excel Workbook
[3] even before computing the $LCOG_{CH4}$ using a SR to convert the green H_2 into green CH_4
[4] the discount rate or return on assets

1. THE LCOG ALGORTHUM AND ITS EXCEL WORKBOOK

For the reader to follow the paper's narrative and to do rapid computations, the reader must download (www.michaelstavy.com) the 06/07/21 version of the paper's Excel P2GP LCOG Financial Algorithm Workbook[5]. The current version of the paper's Workbook only has the HE WS. The complete Excel P2G LCOG Financial Algorithm Workbook will have three worksheets (WS); WS #1, HE WS; # 2, SR and WS # 3, the Summary WS. Each WS will have explanation notes. A printed copy of WS # 1, HE is on pages 12-14. Fig. 1 (page 17) is the Schematic of the Model P2G Plant. The P2GP LCOG Financial Algorithm uses "project accounting" to "fine tune" sensitivity studies. This also allows the user to do a separate sensitivity study for each (HE, SR) phase of the P2GP. For each P2GP phase, a separate partial LCOG is computed.

This white paper only discusses the HE $LCOG_{H2}$ algorithm. It does this by referring to the HE WS lines for the nine HE specs, the two foreign exchange values, the one energy conversion factor and for the HE LCOH algorithm's 35 dependent computed values. An Acronym Glossary is on pages 15-16. Table # 1, The Nine HE Specs (Specifications) and two NG Market Prices, is on page 18. The References are on page 19. The author expects revise this white paper and add the SR $LCOG_{CH4}$ WS after the HE becomes "commercially viable".

The paper's model P2G plant is basic. The model P2G plant is a continuous flow plant. One of the HE specs specifies how many hours a day the HE operates. The SR operates the same number of hours a day and at the same time. There is no storage of the wind electricity at the P2G plant before powering the HE. There is no storage of the green H_2 during the plant operation nor is there any plant storage of the green CH_4 (GNG) before its injection into NA NG grid. The two phases operate continuously at the same time. A model P2G plant can also be designed to have storage. If there were storage, the two phases would not have to operate at the same time. The paper's P2GP LCOG Algorithm only computes the LCOG (US$/mmBtu$_{NG}$; €/kWh$_{NG}$[6]) for the continuous production of first the H_2 and then the CH_4.

For this paper, both "back of the envelope" simplicity and an accurate first approximation of the cost (US$/mmBtu$_{NG}$; €/kWh$_{NG}$) to produce green methane (GNG) using wind (solar) P2G technology are the two criteria for choosing a computational method. This paper's levelized cost (LC) algorithm

[5] Hereafter referred to as the Excel P2G LCOG. Workbook

[6] In the Euro Zone, retail NG is priced in €/kWh$_{NG}$ (€/MJ$_{NG}$)

meets both criteria. The goal of this paper is to present a LCOG algorithm based on generally accepted financial and engineering principles with a recognized uniform set of P2G Plant specs.

Putting the P2GP LCOG algorithm on an Excel workbook allows the reader (author) to quickly do a sensitivity analysis. By selecting different realistic values for the nine HE specs, it became clear to the author that that there are three HE key specs that determine whether the P2G technology is ready for commercial development. These are the HE Round Trip Efficiency (η); the Cost of the Wind Electricity to be converted into H_2 and the HE CapEx US$/$MW_{ELECT}$.

After the banker (other reader) has downloaded the HE WS of the paper's Excel[2] W2G LCOG Workbook, they can enter their own nine HE spec values and their own two NG market price values and check their results with their engineer. While this paper discusses the nine HE specs and will, in a future version of this paper, also discuss the SR specs, this paper does not have a database of P2G plant specs (HE or SR) for use by the banker and their engineer. Creating a database is not the primary goal of this paper. This author has the much more modest goal of first, presenting a recognized standard levelized cost (LC) methodology, (i.e. an accurate "back of the envelope" P2G LCOG financial algorithm), second, using one case study to demonstrate to the reader how the P2G LCOG algorithm works and three, comparing the HE $LCOG_{H2}$ with the current US Henry Hub NG spot price for the US and the Eurostat NG price for the Euro Zone countries. The author was unable to locate any commercial P2GP on the North American gird. The paper does not have a case study to discuss how to compile a database of the nine HE specs from current authoritative sources. Instead, interested readers who want to learn how to compile a database of P2GP specs should review the Cabin Creek Pumped Storage Plant compilation case study that is found in the author's Wind Europe 2018 Paper [3].

2. STANDARD (SI) AND AMERICAN "ENGLISH" ENERGY UNITS

This paper defines P2GP specs and dependent variables using the standard SI and US "English" energy units for electricity, NG, H_2, and CH_4. The H_2 industry uses the kg_{H2}, and sometimes, the Nm^3_{H2} (standard SI mass and volume units) for measuring the physical production and the pricing of industrial H_2. This paper adds the kWh_{H2} and the US "English" energy unit; $mmBtu_{H2}$. The North American NG industry uses the $mmBtu_{NG}$ (the standard US "English" energy unit) for measuring the production[7] and the pricing of NG. For Euro Zone readers, this paper adds the €/kWh_{NG}. There are published authoritative standard conversion factors [4][8].

[7] In the US, NG production and storage are first measured in ft^3

[8] from both the US EIA and the OECD IEA

The key conversion factors in the P2GP LCOG algorithm are

1 MWh_{ELECT} = 3.4120 $mmBtu_{ELECT}$ = 1 MWh_{H2} = 1 MWh_{NG} = 3.4120 $mmBtu_{NG}$

1 kWh_{ELECT} = 3.412 Btu_{ELECT} = 1 kWh_{H2} = 1 kWh_{NG} = 3.4120 Btu_{NG}

CH_4 ≡ NG ≡ SNG ≡ GNG

In the P2GP LCOG financial algorithm energy flow, first, the HE converts the MWh_{ELECT} into $mmBtu_{H2}$. Second, the $mmBtu_{H2}$ are converted by the SR into $mmBtu_{Ch4}$ which are then injected into the North American NG grid. This does not mean that the P2G plant is 100% efficient.

1. H_2 Production--$MWh_{ELECTin}$ from the NA electric grid go into the HE and $mmBtu_{H2out}$ come out of the HE and go into SR
2. CH_4 Production-- $mmBtu_{H2in}$ come into the SR and $mmBtu_{CH4out}$ come out of the SR and go onto the North American NG grid

3. THE TWO PHASES OF THE POWER TO GAS PLANT

This paper discusses the two phases of all P2G plants; one, the production of the H_2, and two, the conversion of the H_2 into methane (CH_4).

In the paper's model P2GP, wind (solar) electricity powers a HE. While this technology is called P2G it is actually wind energy (electricity[9]) to gas. The HE uses the wind energy to separate H_20 into H_2 and O_2. The equation is:

$$2H_2O \rightarrow 2H_2 + O_2.$$

Currently there is no H_2 electrolyzer technology that is the most "financial mature" technology. The paper's $LCOG_{H2}$ algorithm measures the "financial maturity" of HE with different technologies. The four most important P2GP LCOG Algorithm HE specs are Line 1, HE Efficiency (η), Line 2, P2G Plant-hrs/day Operating, Line 4, HE CapEx-US$/$MW_{ELECTin}$ (€/$MW_{ELECTin}$) and Line 5, Cost of the Wind Electricity-US$/MWh (€/MWh).

In the paper's model P2GP, the H_2 is used as one of the feed stocks for the Sabatier Reactor (SR). The other feed stock is CO_2, which to produce green CH_4, must be taken out of the atmosphere. The

[9] electricity is kinetic energy while H_2 and CH_4 gases are both potential energy

SR also requires wind (solar) electric energy. In the Sabatier Reactor, CO_2 reacts with the H_2 in the presence of catalysts to produce methane, water and heat. The SR equation is:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

A SR is used in the American space program to recycle the atmospheric CO_2 of manned space vehicles. Back on earth, and unlike the serial production of HE, wind turbines and PV panels, there is no serial production of SR. The SR technology is also currently not "commercially mature". Purpose-specific construction of a SR is possible but its CapEx is not currently "commercially mature". The P2GP LCOG Algorithm measures the "financial maturity" of different SR. If the SR were in commercial serial production, the most important P2GP LCOG Algorithm SR spec values would be: SR Capacity ($mmBtu_{CH4out}$; MWh_{CH4out}), SR Capacity factor; SR electric energy consumed (MWh/yr); SR CO_2 consumed (ton_{CO2}/yr; US$/$ton_m$; €/$ton_m$) SR CapEx-US$/$mmBtu_{CH4out}$ (€/MWh_{CH4out}), SR efficiency (η).

4. THE HE WORKSHEET OF THE EXCEL P2G PLANT LCOG FINANCIAL WORKBOOK

The author stated above that four HE spec values are sufficient to not allow the model P2G plant to operate commercially on the North American electric and NG grids. The HE algorithm computed the $LCOG_{H2}$ to be US$21.25/$mmBtu_{H2}$ (€0.0688/kWh) which is 88% greater than the 05/04/21 US Henry Hub NG spot price of US$2.91/mmBtu [1]. The low SR η as well as the very high SR CapEx would further preclude a P2G plant from operating commercially on the NA electric and NG grids.

The paper will now go over the HE worksheet Line by Line to show how the $LCOG_{H2}$ is computed. This section also explains the levelized cost method. The Excel HE WS #1 is printed on pages 12-14.

All the lines referred to are on HE WS. Below are the author's comments on the nine HE specs, the two foreign exchange values, the one energy unit conversion factor and for the HE LCOH algorithm's 35 dependent computed values that are used to compute the $LCOG_{H2}$ (LCOH).

1. <u>Foreign Exchange</u>

Line FX has the FX value (US$1.20188/€ and US$1.3811/£) on 05/05/21 [5] that is used to convert the $LCOG_{H2}$ Worksheet US$ values into € values and to convert the one £ value into a US$ value.

2. P2G Plant Specifications

Line 1, P2G Plant HE Efficiency is 70%. This is the base case spec (which is an optimistic value). Published HE efficiency values from authoritative source are difficult to find. Once source that I referred to is the Extended Data on Fig 10, Literature Review, Electrolysis Data, in Ueckerdt, F et al, [6]

Line 2, P2G Plant hours/day operating is 22. This equals as a 92% capacity factor. This is also a P2G Plant base case spec. Two hours are for maintenance of the model P2G plant. Other P2GP can operate on different schedules. During the 22 hours both the HE and the SR work in continuous series production. Since the wind does not blow all the time and since the sun does not shin all the time, it is difficult to get a 92% capacity factor when only using wind and solar power. The lower the capacity factor, the higher the LCOH.

Line 3, P2G Plant Power Input is 300 MWh_{ELECT}. HE are sized and priced by their power input. This is the base case spec.

Line A, the MWh_{ELECT} of wind electricity to be converted in H_2 is 6,000, which is the product of Line 2 times Line 3.

Line B, the daily H_2 produced is 4,200 MWh_{H2} which is the product of Line 1 times Line A.

Line C is 3.4120 mmBtu/MWh. This the standard conversion factor [4][8] for converting a MWh of energy into a mmBtu of energy. This done because the spot price of NG at the US Henry Hub is quoted in US$/$mmBtu_{NG}$ not in kWh or in MJ.

Line D, the daily P2G Plant HE H_2 produced is 15,763 mmBtu/day which is the product of Line B times Line C.

Line E, the yearly P2G Plant HE H_2 produced is 5,753,656 mmBtu/yr which is the product of Line D times 365.

Line 4, the P2G Plant HE CapEx, is US$1,104,000/MW. This US$ value was converted from the £800,000/MW electrolyzer CapEx value that was reported in an 20-Jan-21 Recharge article [7]. Published HE CapEx values (US$/MW; €/MW; £/MW) from authoritative source are difficult to find.

Line F, Total P2G Plant CapEx, is US$331,454,200 (€275,783,938; £240,000,000). This is the product of Line 3 times Line 4.

3. Cost of the Wind Electricity that is First Being Converted into $mmBtu_{H2}$

Line 5, the cost of the wind electricity that is first being converted into H_2, is US$40/MWh (€33.28/MWh). This US$40.00/MWh value is the author's estimate of a utility scale wind plant's LCOE [8].

Line G is the same cost of this wind electricity after it is converted from $US\$/MWh_{ELECT}$ into $US\$/mmBtu_{ELECT}$. Line F is $US\$11.7233/mmBtu_{ELECT}$ which is the quotient of Line 5 divided by Line C.

4. After Efficiency (η) Loss Cost of the Wind Electricity that is Being Converted in $mmBtu_{H2}$

Line H is the after efficiency (η) loss cost of the wind electricity that is being converted into H_2 AELCOE-$US\$/mmBtu_{ELECT}$. The computed value of $US\$16.75/mmBtu_{H2}$ is quotient of Line G divided by Line 1.

Line I is the extra cost (AELCOE-COE) of the wind electricity because of the η loss. The computed value is $US\$5.02/mmBtu_{ELECT}$ which is Line H minus Line G.

Line J is the % increase in the cost of the wind electricity from the η loss when it is converted into H_2. The 43% increase in the cost is computed by dividing Line H by Line G.

5. P2G Plant HE CapEx, OpEx and the LC Method Explanation

Line 6 is the HE annual fixed O&M cost as a % of the total HE CapEx (Line F). 3% is the base case value.

Line K, the HE annual Fixed O&M cost is US$9,943,776/year (€8,273,518/yr). This is the product of Line 6 multiplied by Line F.

Line 7 is the HE variable O&M cost is $US\$0.75/mmBtu_{H2}$ (€0.0026/kWh) which is the base case value.

Line 8 is the physical life of the HE. 20 years is the base case.

Line 9 is the Interest/ROE Rate or the cost of capital. The author's estimate is 6%. This is the cost (as a %) to invest the amount of capital on Line F, Total P2G Plant HE, CapEx. The P2GP owner either provides the capital (equity) or borrows (debt) the capital to in order to own the HE of the P2G plant. This spec is also known as the return on assets (ROA) or as the internal rate of return (IRR). An P2GP HE has a physical life (Line 8). During its physical life, as the P2GP operates the HE by first converting the wind electricity into H_2, Line F, must be recovered (depreciation) and the cost of capital (Line 9) for using the invested capital must be paid. If borrowed money is used to construct the P2GP, the cost of borrowing the money is called the lender's interest. If the P2G plant owner uses their own capital to construct the P2GP HE, 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 P2GP HE 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 Interest/ROE Rate is 6%. This 6% is not "a risk adjusted rate".

Line L the capital amortization factor-CAF is 0.0872 which is the annual payment for an annuity having $1.00 as the amount borrowed, having a life of 20 years (Line 8) and an interest rate of 6% (Line 9).

Line M is the annual CapEx amortization (ACA) in US$/year. This computed to be US$28,898,124/yr (€24,044,100/yr). Line M is the product of Line F multiplied by Line L.

The levelized cost (LC) method uses a financial annuity to compute Line M. The ACA-US$/yr is one constant yearly payment over the physical life (Line 8) of the HE for both the depreciation of Line F and for the payment of Interest/ROE (Line 9). 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.

6. Computation of the LC of the H_2 Gas Used as a Feedstock to Produce CH_4 (GNG) in the SR-$LCOG_{H2}$-US$/mmBtu$_{H2}$

Line N is the annual capital amortization-ACA in US$/mmBtu$_{H2}$. The US$5.02/mmBtu$_{H2}$ is computed by dividing Line M by Line E.

Line O is the fixed O&M cost in US$/mmBtu$_{H2}$. US$1.73/mmBtu$_{H2}$ is computed by dividing Line K by Line E.

Line P is the variable O&M cost in US$/mmBtu$_{H2}$. The US$0.75/mmBtu$_{H2}$ value is transferred from Line 7.

Line Q is the after η loss cost of the solar electricity that is being converted in mmBtu$_{H2}$. The US$16.75/mmBtu$_{H2}$ value is transferred from Line H.

Line R is the HE $LCOG_{H2}$ (LCOH) to be used a feedstock to produce CH_4 in the SR-$LCOG_{CH4}$. Line R is the sum of Lines N, O, P and Q. The $LCOG_{H2}$ is in $24.25/mmBtu$_{H2}$.

Line N is 20.7% of Line R while Line Q is 69.1%. Lines O and P together are only 10.2% of Line R.

7. Difference Between the HE $LCOG_{H2}$ and the US Henry Hub Spot Price for NG-US$/mmBtu$_{H2}$

Line S is the HE $LCOG_{H2}$ value transferred from Line R above.

Line 10 is the US Henry Hub NG Spot price. US$2.91/mmBtu$_{NG}$ was the price on 05/04/21. [5]

Line T is how much the HE $LCOG_{H2}$ is greater (less) than the Henry Hub NG spot price on 05/04/21. The HE $LCOG_{H2}$ is US$21.34/mmBtu$_{H2}$ greater than the 05/19/20 Henry Hub price. Line T is Line S less Line 10.

Line U is the % that the HE $LCOG_{H2}$ (Line S) is greater (less) than the Henry Hub NG spot price (Line 10). 88% is Line T divided by Line S.

5. AUTHOR'S CONCLUSION RESTATED

Is wind (solar) P2G technology ready for prime time on the North American grid?

Based on the nine model HE spec values that the author used in this paper's Excel P2G Plant LCOG Financial Algorithm Workbook, the answer is NO.

1. The HE $LCOG_{H2}$ produced was 88% greater than the 05/04/21 spot price of NG at the US Henry Hub. Both the H_2 and the NG were priced in US$/mmBtu. [1]

2. The HE $LCOG_{H2}$ produced was 27% greater than the 05/05/21 average price of NG (average 2nd half year NG price) as reported by Eurostat. Both the H_2 and the NG were priced in €/kWh. [2]

3. In the Sabatier Reactor, the cost of the green CH_4 produced from the HE green H_2 would be even higher than the Henry Hub (Eurostat) NG market price.

4. If bankers (other readers), find a HE with a more favorable spec values perhaps their conclusion might be YES. It will be your nine specs, your conclusion and your money.

5. For example, here are alternative spec values for two of the paper's model HE nine specs that a banker (other reader) might decide to use after their engineer confirms these new values.

6. ITM Power stated [7] that its 1 GW HE manufacturing plant will currently price its HE at £800,000/MW with 10 MW/yr of HE production but it expects to price its HE at £500,000/MW with 100 MW/yr of HE production

7. If ITM Power's HE drops from £800,000 to £500,000/MW, a 37.5% reduction, the LCOH declines from US$24.25 to $21.72/mmBtu, a 10.4% reduction in the LCOH. Readers can confirm this by entering US$ equivalent for £500,000 instead of for £800,000/MW on Line 4 of their copy of this paper's Excel HE worksheet.

8. It was reported in [9] that WoodMac argued if the cost of the renewable (wind) electricity goes from US$40 to US$30/MWh (Line 5), a 25% reduction, the LCOH would decline enough to be price competitive in with NG in Germany. Based on the Eurostat average price that I used, I did not find this to be correct. I did, however, find that if the ITM Power's HE £500,000/MW CapEx is also used instead of the £800.000/MW CapEx (Line 4), the LCOH is now competitive with the Eurostat 05/05/21 average NG market price. Banker's and other readers can confirm this by entering the two alternative HE spec values on Lines 4 and 5.

9. Readers should know that the H_2 industry (brown, gray and green) currently prices H_2 in US$/$Kg_{H2}$ (€/kg_{H2}; £/kg_{H2})

10. It would be appreciated if readers who find errors in this white paper or in the paper's Excel HE worksheet would be kind enough to point these typos (what else could the be?) to the author.

11. Thanks for thanking the time to stop by my ePoster and read my white paper and use its Excel HE Worksheet.

HE WORKSHEET # 1 OF THE EXCEL P2G PLANT LCOG FINANCIAL ALGORITHM WORKBOOK

line			H_2 Production a	m/d/y	
1. Foreign Exchange					
FX	Enter	US$/€ exchange rate	$1.20188	05/03/21	COLOR CODE
2. P2G Plant HE Specifications					Entry
1	Enter	P2G Plant HE Efficiency-η-%	70%	Capacity Factor	Result
2	Enter	P2G Plant-hrs/day Operating	22	92%	Side Column Result
3	Enter	P2G Plant-HE Power Input-MW_{ELECT}	300.0		Transfer Result
A	Computed	Daily MWh_{ELECT} of Wind Electricity to be converted into H_2-MWh_{ELECT}/day	6,000		Check Value
B	Enter	Daily P2G Plant HE H_2 Produced-MWh_{H2}/day	4,262		In €; £
C	Enter	Conversion factor-mmBtu/MWh	3.4120		Conversion Factor
D	convert MWh to mmBtu	Daily P2G Plant HE H_2 Produced-$mmBtu_{H2}$/day	15,763		
E	Computed	Yearly P2G Plant HE H_2 Energy Produced-$mmBtu_{H2}$/year	5,753,656	€/kW ↓	£/MW
4	Enter	P2G Plant HE CapEx-US$/$MW_{ELECT}$	$1,104,864	€ 919	£800,000
F	Computed	Total P2G Plant HE CapEx-US$/P2G Plant HE	$331,459,200	€ 275,783,983	
3. Cost of the Solar Power to be Converted into $mmBtu_{H2}$				€/MWh↓	€₵/kWh↓
5	Enter	Cost of the Wind Power to be converted into H_2-COE_{ELECT}-US$/$MWh_{ELECT}$	$40.00	€ 33.28	€ 3.33
G	converted to mmBtu	Cost of the Wind Power to be converted into H_2-COE_{ELECT}-US$/$mmBtu_{ELECT}$	$11.7233	€ 0.03490	

[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.

€/kWh ↑

4. After the Efficiency (η) Loss Cost of the Wind Power to be Converted into $mmBtu_{H2}$

				€/kWh ↓
H	computed	After η Loss Cost of the Wind Power to be converted into H_2-$AELCOE_{ELECT}$-US$/$mmBtu_{ELECT}$	$16.75	€ 0.04986
I	computed	Extra Cost ($AELCOE_{ELECT}$-COE_{ELECT}) of the Wind Power-US$/$mmBtu_{ELECT}$	$5.02	€ 0.01496
J	computed	% Increase in the Cost of the Wind Power when converted into H_2	43%	43%

5. P2G Plant HE CapEx, OpEx and the LC Explanation

6	Enter	Annual Fixed O&M Cost-% Total HE CapEx, Line E	3.00%	€/yr↓	
K	Computed	Annual Fixed O&M Cost-US$/yr	$9,943,776	€ 8,273,518	
7	Enter	Variable O & M Cost-US$/$mmBtu_{H2}$	$0.75	€ 0.0021	←€/kWh
8	Enter	Physical Life of the HE-Years	20		
9	Enter	Interest/ROE Rate-%	6.0%		
L	Computed	Capital Amortization Factor-CAF	0.0872	€/yr↓	
M	Computed	Annual Capital Amortization-ACA-US$/yr	$28,898,124	€ 24,044,100	

6. Computation of the LC of the H_2 gas used as a feedstock to Produce CH_4 (GNG) in the SR-US$/$mmBtu_{H2}$-$LCOG_{H2}$

			US$/mmBtu↓	€/kWh ↓	%
N	Computed	Annual Capital Amortization-ACA-US$/$mmBtu_{H2}$	$5.02	€ 0.0143	20.7%
O	Computed	Fixed O&M Cost-US$/$mmBtu_{H2}$	$1.73	€ 0.0049	7.1%
P	Transferred from Line 7	Variable O&M Cost-from Line 7 above-US$/$mmBtu_{H2}$	$0.75	€ 0.0021	3.1%
Q	Transferred from Line H	After η Loss Cost of the Wind Electricity to be converted into H_2-from Line G above-$AELCOE_{ELECT}$-US$/$mmBtu_{ELECT}$	$16.75	€ 0.0475	69.1%
R	Computed	LC of the H_2 gas to be used as a feedstock to produce CH_4 in the SR-$LCOG_{H2}$-US$/$mmBtu_{H2}$ (LCOH)	$24.25	€ 0.06430	100.0%

7. Difference between the HE $LCOG_{H2}$ and the Market Price of NG at the US Henry Hub-US$/mmBtu$_{NG}$ and in the Euro Zone

			US$/mmBTu↓	€/kWh ↓	
S	Transferred from Line R	LC of the H_2 gas to be used as a feed stock to produce CH_4 in the SR-$LCOG_{H2}$-US$/mmBtu$_{H2}$	$24.25	€ 0.0688	
10	Enter	US Henry Hub Spot NG Price-US$/mmBtu$_{NG}$	$2.91	€ 0.0504	Euro Zone NG ←Price-€/kWh
T	Computed	The HE $LCOG_{H2}$ is greater (less) the Henry Hub NG Price-US$/mmBtu$_{NG}$	$24.34	€ 0.0184	
U	Computed	% that the HE $LCOG_{H2}$ is greater (-%) then US Henry Hub Spot (Future) NG Price	88%	27%	

Acronym Glossary

Acronym	Description
CH_4 =	methane
CO_2 =	carbon dioxide
EIA =	Energy Information Administration (US)
GNG =	Green natural gas
H_2 =	hydrogen
H_20 =	water
HE =	H_2 electrolyzer
IEA =	International Energy Agency (OECD)
kg_2 =	kilogram-H_2
LC =	levelized cost
LCOE =	levelized cost of energy
LCOH =	levelized cost of H_2
mmBtu =	million British thermal units
MW =	megawatt
MWh =	megawatt hour
NA =	North American
NG =	natural gas

[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.

Acronym	Description
Nm^3_{H2} =	nominal cubic meter-H_2
O_2 =	oxygen
P2G =	power to gas
P2GP =	power to gas plant
ROA =	return on assets
ROE =	return on equity
SI =	Système International d'Unités
SR =	Sabatier Reactor
SNG =	synthetic natural gas
WACC =	weighted average cost of capital
WS =	worksheet
η =	efficiency

FIGURE # 1, Schematic of the P2G Plant

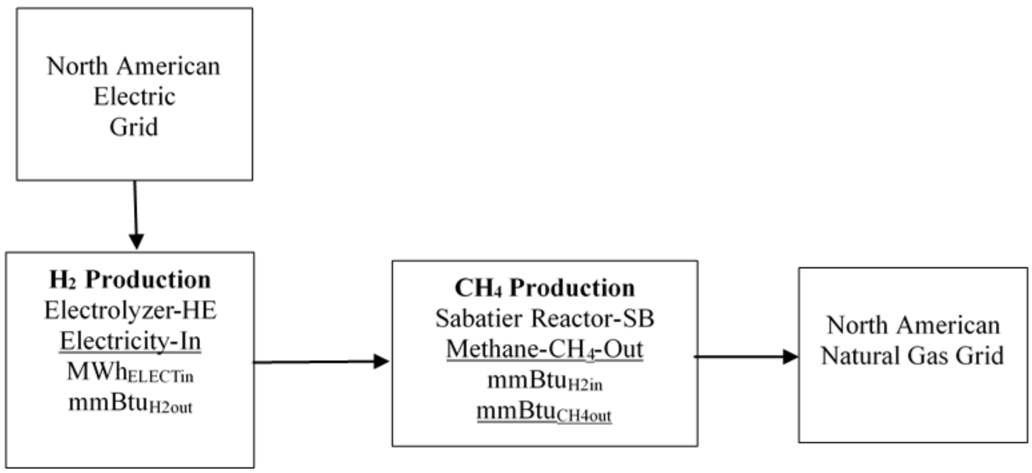

Table # 1, The Nine HE Specs and two NG Market Prices are Defined

spec #	H_2 Production-HE
1	P2G Plant HE Efficiency-η
2	P2G Plant-hrs/day Operating
3	P2G Plant HE Power Input-US$/$MW_{ELECTin}$
4	P2G Plant HE CapEx-US$/$MW_{ELECTin}$
5	Cost of the Wind Energy to be converted into H_2-COE-US$/$MWh_{ELECT}$
6	Annual Fixed O&M Cost-% Total HE CapEx, Line E
7	Variable O & M Cost-US$/$mmBtu_{H2}$
8	Physical Life of the P2G Plant-Years
9	HE Interest/ROE rate-%
	10 and 11 are not HE specs but are independent variables used to compare the LCOH with the NG market price in the US and in the Euro Zone
10	US Henry Hub NG Spot Price-US$/$mmBtu_{NG}$
11	Euro Zone NG price -€/kWh_{NG}

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