Influence of variable electricity supply on synthetic fuel price.

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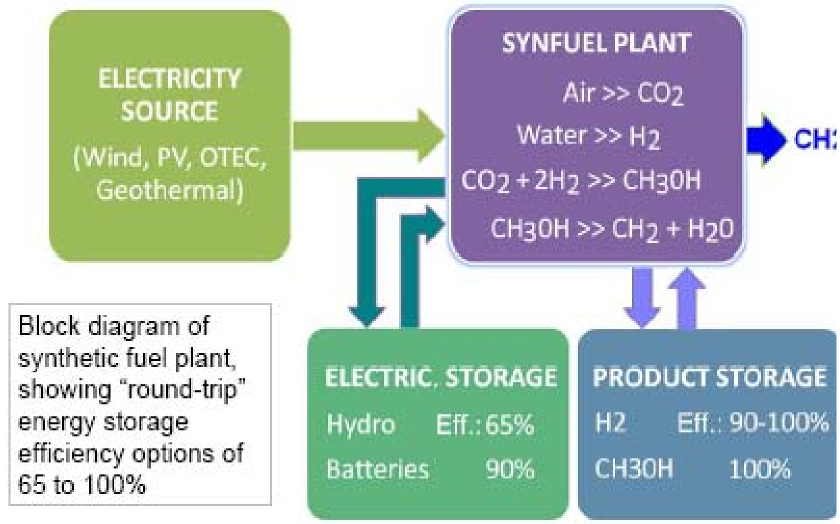
Abstract

We looked into the economics of how much the cost of renewable but variable wind, PV or grid electricity would have to drop to compensate for the added cost of enlarged but part-load equipment and/or storage, to achieve (1) an effectively 24/7 steady power supply to a synthetic fuels plant, and (2) produce fuel of the same price as with a constant electricity supply.

We used a simplified life-cycle cost analysis in which electric energy availability varies according to an assumed periodic daily cycle. Equipment and/or battery size and cost increase, as electricity supply capacity factor and the fraction of time decrease at which electricity flows directly from source to plant without storage (batteries) or enlarged front-end equipment with product storage, as shown in the block diagram at right.

Of course in reality, wind speed, PV and grid power averages may not only experience daily cycles, but also longer, seasonal cycles, which were ignored in this analysis.



Block diagram of synthetic fuel plant, showing *round-trip" energy storage efficiency options of 65 to 100%.

For one example involving an electricity availability capacity factor of 50%, using popular lead-acid batteries, electricity cost would have to drop by over 5 ¢/kWh to compensate for the battery cost, and enable synfuel to be priced at the same level as with a 100 % capacity factor. An enlarged H2 front-end plant production system with appropriate H2 tank storage, whereby H2 needs to be produced anyway for further processing, turned out to be more economical than battery storage. In this case, a capacity factor of 50% may only require a decrease of 0.6 ¢/kWh in the maximum cost of electricity, in order to still meet the same fuel price goals.

We also quantified what effect profit goals can have on the maximum allowable electricity cost: For example a 5% drop in the 30-year-levelized ROI was equivalent to a 1 ¢/kWh of allowable increase in the cost of electricity.

By not including in this analysis the effects of CPI (consumer price index) and fuel price escalations, the results are more conservative than if those effects had been included.

Introduction

To power a synthetic fuel production process plant with a variable supply of electricity (as may be represented by wind-turbines), there are at least four basic options: 1. Oversize the wind generators to enable plant operation even at low wind speeds, 2. Enlarge the plant so that it can turn up and down its processing rate and throughput as electricity supply changes, 3. Enlarge only the front-end of the plant and its product storage, or 4. Install electricity storage to buffer and mitigate the variability of available power output,.

For power levels of 2-10 MW, the capital costs of wind-turbines, synfuel plants and batteries are presently in the range of 2-3, 5-10 and 1-3 $/W, respectively, which is why his paper is about the economics of the 3rd or 4th and maybe lowest-cost options, i.e. to determine how much would variable, renewable wind energy cost have to drop to compensate for the cost of in-plant storage to achieve an effectively 24/7 steady, output power from a wind generator + battery system.

System Model Assumptions -- By using a simple model of total life-cycle costs (including electricity costs) to drive the life-cycle production of synthetic fuel (H2, NH3 or hydrocarbons) in terms of GGEs (Gallons of Gasoline (energy) Equivalents), we present the estimated results in terms of simple plots of needed electricity cost vs. fraction of direct energy delivery w/o battery use, i.e. vs. average wind capacity factor, to achieve a set market price of fuel in terms of $/GGE, while making allowances for battery use and its "round-trip" energy conversion efficiency of 80-90%. Its "use" determines size and cost addition to the capital cost expenditure (capex) of the synfuel plant system.

For the duration of the plant's service life, the above battery cost is part of the overall equation for product price, P, from which we want to determine the electricity cost, Ce, needed for economic viability:

P = Product price before taxes & distribution in $/GGE =
= (Sum of all costs over plant life) / (GGEs produced over plant life), (1)
= (Capex(Plant+Batteries) – **Subsidies** + Loan + **Equity** + Opex + Energy Cost) / (GGEs produced over plant life) in $/GGE

where the numerator is given in normalized units of M$/MW or $/W and the denominator in MGGE/MW or $/GGE. The color coding is to help identify the individual terms:

- Subsidies refer to government funds to reduce capex;
- Loan represents the total life-cycle cost of interest payments made to cover that part of capex;
- Equity represents the interest payments made to cover that part of capex;
- Opex are all life-cycle costs of operation and maintenance: labor, replacement parts, insurance, property taxes, feed-stock such as water, etc., except energy
- Energy cost is the total life-cycle cost of input energy

Energy storage cost. As wind availability or grid energy capacity factor, q_p, decreases, nominal peak battery power and battery energy storage all need to increase. Theoretically, the battery power output capability, Qs, should match the total plant input needs, Qp, even if it is only for one minute out of many years of operation and may be assumed to be independent of q_p. Although battery power input capability may need to be larger than its output capability under certain power source variability conditions, it may also be lower as q_p values approach 100%. We therefore could assume that power to storage occurs when power availability is larger than plant needs and power from storage occurs when power availability is less than plant needs, so that we can set Qs ~ Qp*(1- q_p), implying well-behaved source power availability, which never drops below Qp*(1- q_p). But rather conservatively, we chose Qs ~ Qp. However, battery energy storage capability clearly needs to depend on q_p. Therefore, we set the q_p-dependence of battery capex, Cs, in M$/MW, to deliver steady, 24/7 power to the synfuels plant as:

$$Cs = Cso+24*(1- q_p)/(Es/100)*Cse \text{ in M\$/MW} \quad (2)$$

where

Cso = battery capex to handle the needed power or flow of electricity to storage or to plant, in M$/MW
24 = length of the assumed typical daily demand and power availability cycle, in hours
Cse = additional battery capex for each hour of energy storage; in M$/MWh
Es = storage battery round-trip efficiency in %.

Equation (2) is thus enabling battery costs to vary continuously according to its basic power (MW) and energy storage (MWh) requirements.

Maintenance cost. Just as Cs depends on qp, so will its maintenance cost, Ms, which was assumed to be equal to that of general plant maintenance, Mp, except for the need and cost of having to periodically replace the energy storage cells every Ls years, so that we get:a storage maintenance cost of:

$$Ms = (Cso+24*(1-qp)/(Es/100)*Cse/Ls/(Mp/100)) *Mp/100*L \text{ in M\$/MW} \quad (3)$$

where

Ls = life of battery of storage elements, in years
Mp = overall plant O&M cost in % capex/year, and assumed to be equal for Cso and plant capex, Cp
L = plant service life in years

The cost of electricity, Ce, is included in the life-cycle energy cost term, which depends on the plant power use and life cycle electricity use:

Energy Cost = (qp+(1-qp)/(Es/100))***Ce/1E3***8760*Ft/100*L , in M$/MW, where (4)
Ft = fractional plant "up-time."

The life-cycle total production of fuel is given by eq.(5)

Produced Product = (Ft/100*0.2720*Ep/100*L), in MGGE/MW, (5)

where

0.2720 = 8760*3600/1054/110000 theor. max. fuel output in (MGGE/y)/MW, for 110,000 Btu (LHV)/GGE
Ep = overall plant electricity-to-fuel energy conversion efficiency in %

The bank-loan repayment is represented by the total interest, paid over the term of the loan, t in years, according to the std. equation of

Total interest = Capex*{(r/100)*(1+(r/100))^t/((1+(r/100))^t-1)*t -1}, (6)

where r = interest rate in %/y, while making sure that the sum of the grant, loan and equity fractions add up to 100%. The levelized ROI or profit over the life of the plant was typically set at 10%/y. The assumption that all profit was used to pay back the loan, typically sets the payback time to ~7.5 years.

Appendix 1 describes all the remaining terms and parameters of eq.(1).

Results -- The reference plot of Fig. 1 shows electricity costs and fuel prices representing a reference but unreal scenario in which the enlarged equipment and storage costs are zero (Cso = 0 $/W and Cse = 0 $/Wh), and the relationship between fuel price and electricity cost results from an assumed constant overall energy conversion efficiency of 70% in a synfuel plant producing 20 MGGE/y (million gal. gasoline equivalent). As mentioned earlier, the shown wholesale prices (before taxes and distribution) from 3 to 6 $/GGE assume zero escalation of CPI or fuel prices over time, and are therefore higher (relative to input electricity costs) than the results would be with escalation.. Note that to produce 20 MGGE/y of fuel at a whole-sale price of 3 $/GGE, an electricity cost input of no more than 0.04 $/kWh is needed, so that a retail price of ~ 4 $/GGE can be achieved.

Fig. 2 represents a simple scenario, in which electricity variability is buffered by the sole addition of sealed lead-acid (SLA) batteries at a nominal low cost of 100 $/kWh, as are available from CostCo and others[1,2]. Note that these results entail an assumed replacement of the batteries after Ls=5 years (or ~1800 major daily cycles). The "round-trip" charge-&-discharge efficiency was assumed to be Es = 90%. No cost was included for a BMS (Battery Management System)

Fig. 3 represents a system of which the front-end-producing hydrogen (H2) from water and means to store H2 is gradually enlarged as electricity capacity factor, q_p, decreases. The double lines represent two scenarios in which: 1. H2 is stored at a pressure higher than needed in subsequent plant processing of this H2, so that a Ls = 90% "storage efficiency" was assumed; or 2. H2 is stored at the same pressure as needed for further processing at the plant, so that we could assume Ls = 100%, as represented by the upper lines in Fig. 3.

Overall, the economics for the Fig.3 case are more favorable than those shown with the lowest possible battery costs in Fig. 2. But note that, as pointed out in ref.[2], this advantage of H2-storage over batteries only applies in this synfuel plant scenario, in which the stored H2 is not reconverted to electricity (as with a fuel cell with a reconversion efficiency of ~65% of its H2-energy*) but rather processed further to make synfuel. * The cost of the extra fuel cell and the ~65% reconversion efficiency would make the H2-fuel-cell storage option less attractive economically than the battery option, as described in ref.[3]

The above results were obtained under synfuel plant financing based on paying off a bank loan at 6%/y in 7.5 years (during which time no profit is paid out to anyone), which coincides with a 30-year, levelized ROA (Return on Assets of 130 M$) or ROI of 10%/y. However, if a profit of 10% were based on sales of 20 MGE/y at 3 $/GGE for30 years, input electricity costs could be allowed to rise by ~ 1 ¢/kWh, compared to profit based on 10%/y of assets or on initial investment

Conclusions – The above analysis has shown that

- For an electricity availability capacity factor of 50%, as with some wind-turbines, using popular lead-acid batteries[1,2], electricity cost would have to drop by over 5 ¢/kWh to compensate for the battery cost, and enable producing synfuel at a price equal to that of a system with a 100 % capacity factor.
- An enlarged H2 storage system (H2-generation throughput and tank storage) at the front-end of a synfuel plant, in which H2 needs to be generated anyway for further processing, a capacity factor of

50% may only incur a penalty equivalent to a decrease of 0.6 ¢/kWh in the maximum cost of electricity.

- Although H2-storage is more economical than battery storage if H2 is to be processed further to gasoline, it is not if H2 is re-converted to electricity with a fuel cell. In the latter case the capital and electricity recovery costs are ~2x higher than with battery storage[3]
- Profit goals can also affect the maximum allowable electricity cost: A 5% drop in the 30-year-levelized ROI was found to be equivalent to allowing a 1 ¢/kWh increase in the cost of electricity.

References

[1] Car and golf-cart sealed lead-acid batteries at CostCo, see http://www.costco.com/ and others

[2] Long Battery Power Inc, Burlington, CA, POC: kara@longbatterypower.com (650)787-4497

[3] U. Bonne (Kailua-Kona, Hawaii), "Electricity storage via batteries or electrolyzers and H2-fuel cells: Comparison of capital costs," http://energyfuturehawaii.org/files/PB-11-H2FuelCells-or-Batteries.pdf

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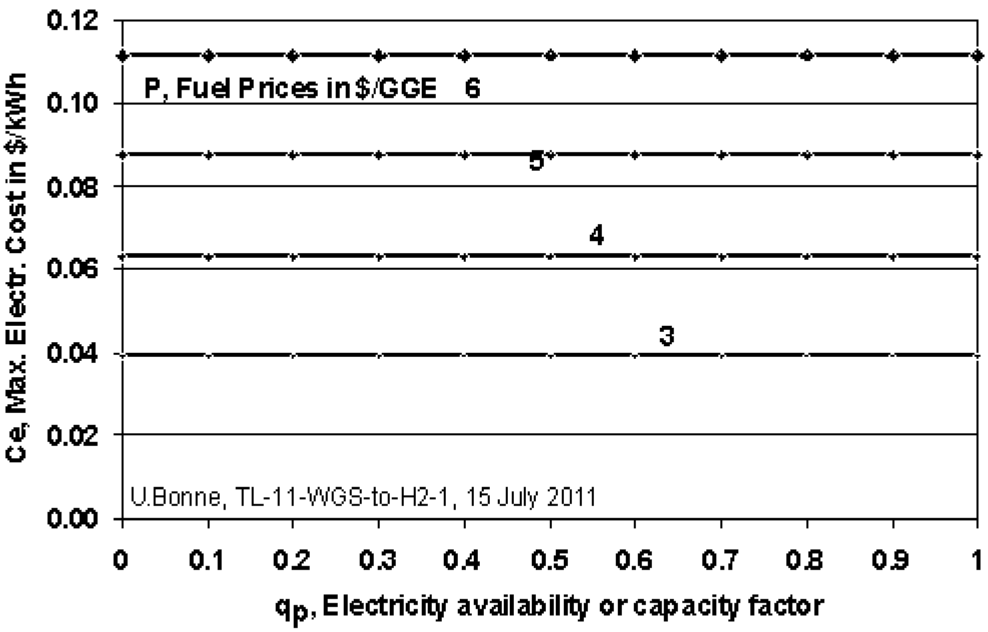
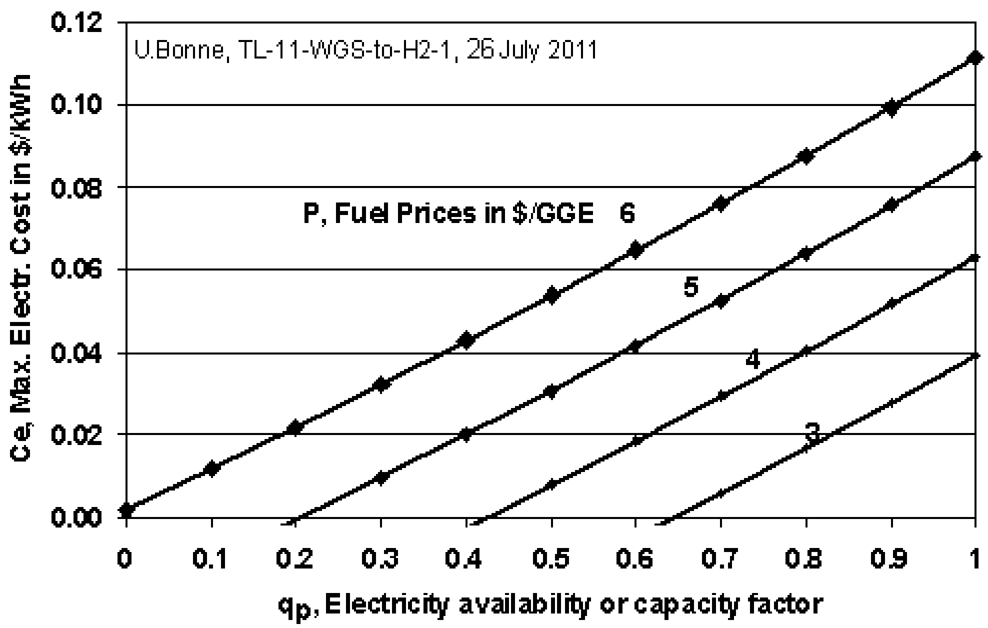


L =	30	years plant life.
Ft =	95	% Plant up-time
Fg =	0	% capex gov. cl
Fl =	100	% loan
nl=	7.5	years payback
il=	6	%/y interest
Fe=	100	% equity
ne =	30	years at
ie=	10	%/y ROI
Cso=	0	M$/MW capex-s
Cse=	0	M$/MWh for eac
Es=	100	% storage batte
Ep=	70	% overall plant e
Cp=	1.71	M$/MW(out) = c
Mp =	2	% capex/y for pl
Ls=	5	years before bat
Output	20	MGGE/y

Fig. 1. Electricity cost to produce fuel between 3 & 6 $/GGE, without storage equipment costs



L =	30	years plant life.
Ft =	95	% Plant up-time
Fg =	0	% capex gov. cl
Fl =	100	% loan for
nl=	7.5	years payback
il=	6	%/y interest
Fe=	100	% equity
ne =	30	years at
ie=	10	%/y ROI
Cso=	0	M$/MW capex-s
Cse=	**0.1**	M$/MWh for eac
Es=	90	% storage batte
Ep=	70	% overall plant e
Cp=	1.71	M$/MW(out) = c
Mp =	2	% capex/y for pl
Ls=	5	years before bat
Output	20	MGGE/y

Fig. 2. Electricity cost to produce fuel between 3 & 6 $/GGE, with low-cost SLA battery storage

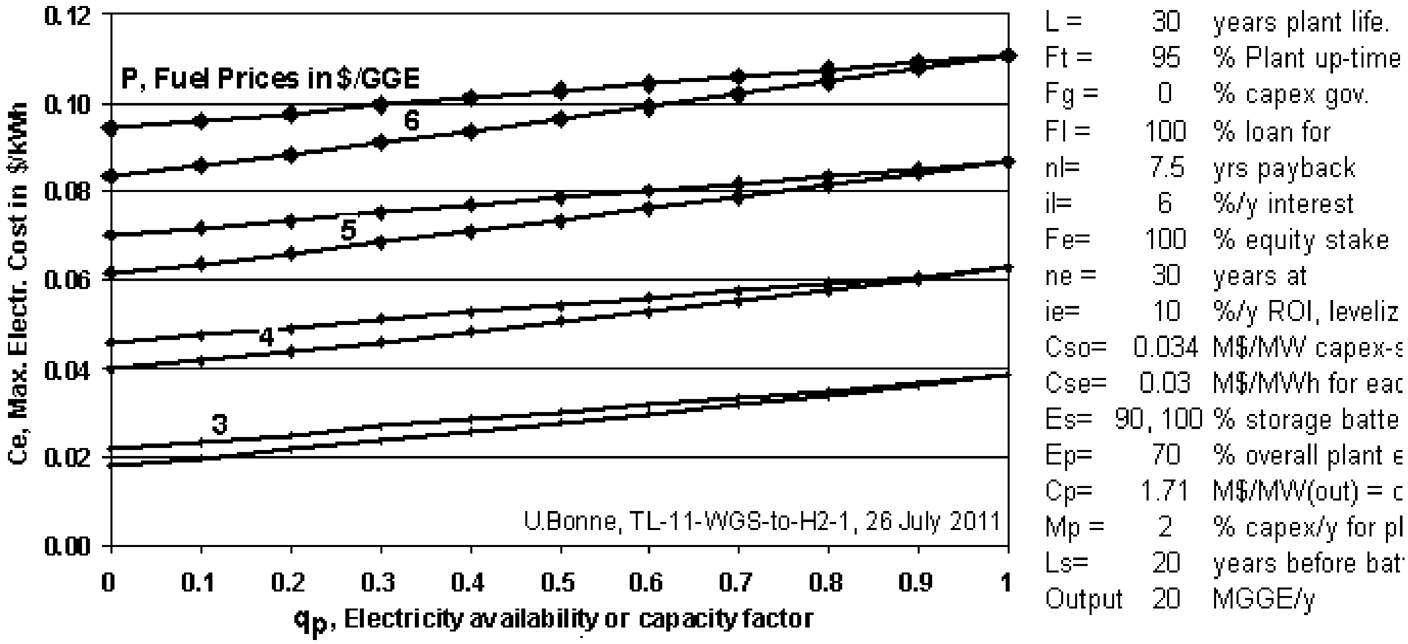


Fig. 3. Electricity cost to produce fuel at 3 – 6 $/GGE, with front- end H2-byproduct storage. The lower & upper lines represent H2-storage with extra H2 compression energy losses of 10% and 0%

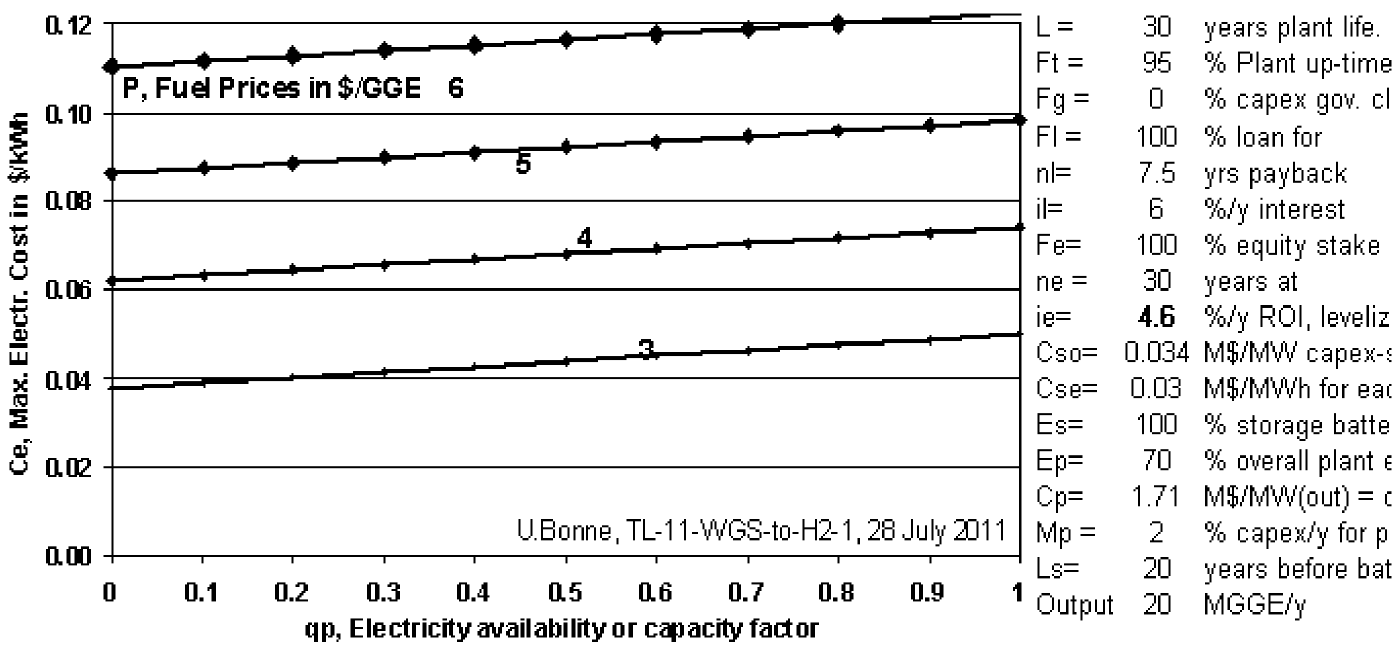


Fig. 4. Electricity cost to produce fuel between 3 & 6 $/GGE, with front- end H2-byproduct storage, but instead of a 10%/y 30-year-levelized ROA, the profit is 10% of sales, equivalent to 4.6%/y ROA.

Appendix

1. Detailed model description -- To get a plot of Max. Energy Cost vs. Fraction of Day w/o Battery Use (equivalent to electricity capacity factor), while keeping the desired product price constant in terms of $/GGE) lets assume:

No inflation and no market fuel price escalation over 30 years

L =	30	years plant life.
Ft =	90	% Plant up-time
Fg =	30	% capex gov. clean energy subsidy
Fl =	25	% capex of loan for
nl=	7.5	years payback time
il=	6	%/y interest of loan
Fe=	100	% capex equity stake
ne =	30	years at
ie=	10	%/y, "ne" years of levelized ROI
Cso=	1.0	M$/MW(out) capex-storage: e.g.1.5 MW power capability with xx MWh energy storage
Cse=	0.2	M$/MWh capex for each additional h of storage. For 24*(1-qp) in h/day, the total cost e.g. for qp=0.5: Cs =Cso+24*(1-qp)*Cse/(Es/100) = 1+24*0.5*0.2/0.9 =3.67 $/W
Es=	90	% storage battery round-trip charge-discharge energy efficiency;
Ls=	4	service life of (battery) storage device in years
D=	50	% average Depth of Discharge per day (parameter not in use)
Ep=	80	% overall plant energy conversion efficiency
Cp=	6	M$/MW(out) = capex-plant
Mp =	2	% capex/y for plant O&M and battery O&M, excluding replacement every Ls years
Ls=	5	years between storage materials replacement; e.g. Ls=5 is equiv. to O&M of 20%Cse/y
qp = variable		power fraction directly to plant, i.e. fraction of day or "eletr. vailability" capacity factor

qs = (1-0.5)/(Es/100) = power fraction to battery, augmented by its "round-trip" efficiency i.e. energy loss

P = Product price before taxes & distribution in $/GGE =
= (Total costs over plant life per MW) / (GGEs produced over plant life per MW), in $/GGE (1a)
= (Capex(Plant+Batteries) – **Subsidies** + Loan + **ROI for Equity** + Opex + Energy Cost) / (GGEs produced over plant life) in $/GGE
= {(Cp + Cso+24*(1-qp)/(Es/100)*Cse)*(1 **– Fg/100**+ Fl/100*A*(1-Fg/100) + **Fe/100*ne*ie/100**)*
***(1-Fg/100)** + Cp*Mp/100*L + (Cso+24*(1-qp)/(Es/100)*Cse/Ls/(Mp/100))*Mp/100*L
+ (qp+(1-qp)/(Es/100))***Ce/1E3***8760*Ft/100*L} / (Ft/100*Ep/100*8760*3600/1054/110000*L)

By rearranging we get Ce directly in $/kWh:
Ce = (P* (Ft/100/0.9*Ep/100*8760*3600/1054/110000*L) -(Cp + Cso+24*(1-qp)/(Es/100)*Cse)*(1 - Fg /100+ Fl/100*A + **Fe/100*ne*ie/100**) + Cp*Mp/100*L + (Cso+24*(1- qp)/(Es/100) *Cse/Ls/(Mp/100))*Mp/100*L))/ ((qp+(1-qp)/(Es/100))**/1E3***8760*Ft/100*L) (7)
where A = (il/100)*(1+(il/100))^nl/((1+(il/100))^nl-1)*nl-1 i.e. the cumulative interest paid during standard amortization over nl years with an interest rate of il %/y, as a fraction of capex(Plant+Batteries)

This Ce is the one plotted in above Figs. 1-4 vs. q_p, the power or electricity capacity factor (whether from wind, PV or grid) to the fuel plant

As indicated in eqs.(1a and 7), the O&M costs for plant and storage equipment are added separately, so their individual features can be better represented and be easier to input

2. Overall Economics – A few comments shall clarify the assumed financing and rewards philosophy used in the above formulas:

- 100% debt financing, except for capex grants from government or philanthropists
- Levelized, L=30-year ROI (Return on Invested capex or Assets (ROA)) of 10%/y is paid out to investors, after the payback period, which typically ~ 7.5 years for above ROI.. Levelized 10- or 20-year ROI is correspondingly less than 10%/y

- All profit is used to pay off the debt in the first ~ 7.5 years
- Capex grants or subsidies do reduce loan interest and ROI payments (but not %/y)but do not reduce the O&M costs
- Questions that come to mind:

(A) What is or should be the expected profit after we get the 20 MGGE/y plant running?
Assuming we pay back all of the guaranteed loan (6%/y interest) in 7.5 years, we can either:

1. Take home a 30-year levelized ROI of 10%/year, i.e. return on assets, worth a total of 30*130*0.10 = 390 M$ or 13 M$/year or somewhat (~30%) less if we get government capex support
2. Take home a 30-year levelized profit of 10% on sales of 30years*20 MGGE/y*3*0.10 = 180 M$ or 6 M$/year

Remember that (according to my <u>model assumption</u>) during the first 7.5 years we did not get any take-home profit. We only paid O&M labor & materials at 2% capex/y = 2.6 M$/year, incl. materials, property taxes, insurance, water, etc

(B) What scenario does one expect for a startup, and what biases may have been introduced with the above <u>assumptions</u>?

(C) What preferences and/or guidelines would investors have for financing our synfuel plant at start-up during loan-payment time and there-after?

(D) Several ratios to indicate performance are listed in the book by Richard M. S. Wilson, Colin Gilligan, "Strategic mktg mgmt: planning, implementation and control," 3rd Ed., Elsevier, Butterworth-Heinemann (2005) ISBN 0 7506 5938

3. Economic Performance -- There are other measures of corporate or venture success, besides payback period and ROI. The table below shows average performance ratios listed in ref.[A] and the values corresponding to our simulation of a synfuels plant during the first 7.5 years servicing the loan and data averaged over the full 30 years of assumed plant life.

Table 1. Company performance ratios for 20 MGGE/y w/o gov. capex subsidy*

Performance Indicators	Units	Averages*	0-7.5 yrs	30-year avg.
Op.profit / assets employed	%	4 - 18	0	10
Op. profit / sales	%	2 - 15	0	21.7
Sales / assets employed	times	1 - 2	0.5	0.5
Assets empl / avg. daily sales	days	180-370	180	180
Prod. cost of sales / sales	%	70-79	100	78.4
Distr. & mktg costs / sales	%	8 - 17	~20	~20
G & A costs / sales	%	4 - 5.8		

* Richard M. S. Wilson, Colin Gilligan, "Strategic mktg mgmt: planning, implementation and control," 3rd Ed., Butterworth-Heinemann (2005) ISBN: 0 7506 59386