Techno-economic modeling for an electrochemical process

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Outline:

- References and Introduction
- Step 1: Thermodynamic analysis of the minimum energy input
- Step 2: Stoichiometry and flow rates
- Step 3: Electrochemical reactor modeling
- Step 4: System level schematic and costing
- Step 5: Synthesis

References:

This resource provides a brief overview of techno-economic modeling (TEM) for electrochemical systems. This write-up should be used as a tool to help you get started, but not be the only resource used. These five resources are recommended:

1. Goodridge, F., Scott K., "Electrochemical process Engineering: *A Guide to the Design of Electrolytic Plant"* Plenum Press (1995).;
2. Turton R., Baile R., Whiting W., Shaeiwitz, J., Bhattacharya D., "Analysis, Synthesis, and Design of Chemical Processes" Prentice Hall (2012).
3. CAPcost free xls software: link
4. Peters, M., Timmerhaus K., West R., "Plant Design and Economics for Chemical Engineers"
5. Morgan, Eric. Dissertation. "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind" University of Massachusetts – Amherst: link

Find the latest edition that you can of 2), 3) in order to have the most up to date index values.

Introduction:

We begin our study of techno-economic modeling for electrochemical processes with two definitions:

Techno-economic model: We rely on a definition of TEM from Dr. Dev Gavaskar of True North Venture Partners as: *"a type of dynamic cost model where the output is calculated from a function of technical and economic assumptions and known 1st principles. A TEM is a useful tool in providing quantifiable answers to whether a new technology can scale up sufficiently into market, and achieve business objectives."*

Electrochemical system: A process with an electrolytic stage involved either to produce chemicals or for the generation of power.

It is important to recognize that an electrochemical process is one component of a larger system. An electrochemical reactor does not sit alone but is one of four fundamental parts of a chemical process plant. Those four parts are: 1) raw material pre-processing, 2) electrochemical reactor, 3) output stream post processing, 4) storage of product. For a study level (also known as "major equipment level") cost model these four components may be sufficient, however, for more detailed TEM's there will be many additional factors.

The First Step | Thermodynamic analysis of the minimum energy input

Thermodynamics: the first step is to find the minimum energy a process requires. This value is important to calculate for three reasons: 1) to ensure that you are not breaking any of the of the laws of thermodynamics, 2) protect yourself from embarrassment, and 3) to have the ability to quickly assess candidate technologies for a process. In order to calculate this value, begin by listing the chemical reaction(s) that your process enables. We prefer listing this reaction per 1 mole of output product. For example:

$$\left(\frac{1}{2}\right) N_2 + \left(\frac{3}{2}\right) H_2O \rightarrow \left(\frac{3}{4}\right) O_2 + NH_3$$

Next, take the Standard Gibbs free energy of formation for each species (found here) and compute the change in energy between reactants and products. This calculation gives the minimum possible energy input or maximum energy output for the electrochemical process. Because many processes today are fueled by hydrocarbons, it may be a useful to compare your process against one starting with different (hydrocarbon) reactants. As an example, consider electrochemical ammonia production compared with a global reaction for the thermochemical Haber-Bosch process:

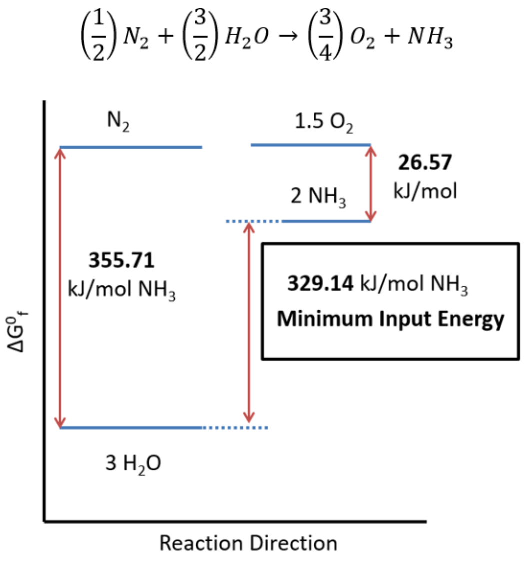


Figure 1: Ammonia from N_2 and H_2O

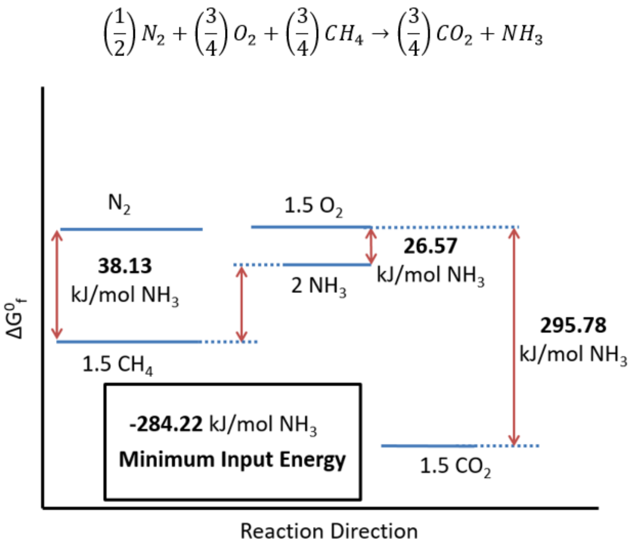


Figure 2: Ammonia from N_2 and CH_4

Many processes coming from hydrocarbons are exothermic and release energy, while the electrochemical ammonia reaction using water as an input is endothermic and requires a large energy input to push the reaction forward. Understanding how an individual technology compares to the thermodynamic minimum can be a very informative exercise when comparing multiple different technologies or assembling a techno-economic analysis.

The Second Step | Stoichiometry and flow rates

After understanding the energy requirements that will drive the desirable reaction (or the reaction that will drive the energy output) the next step is to focus on the flow rates of material through the electrochemical system. To constrain the system, choose and drive a desired flowrate of product over a specified time. For example, if studying an electrochemical system that produces a chemical, define a mass flowrate of product to be:

$$\dot{m}_{product} = X\ tons/day$$

Other examples can be in kg/s or any choice mass per unit time. If the system in question produces power as the product, choose and drive a desired power output (in units of energy/time). By specifying the rate of production, one can backtrack through the chemical process to determine required inputs at various scales.

The next step is to calculate the required flow rates of reactants and other products in the system using stoichiometric relations. With this information, a table of global flows through the process plant can be developed. It should be noted that the stoichiometric flow rates represent the minimum flow rates required for a certain process. Additional information about reaction rates, yields, and efficiencies are often required to achieve more accurate input requirements, and incorporating them into the relevant calculations is trivial. It is often helpful to build a working table with all of the units that could be required to specify equipment components. The table below shows an example of such a table for an electrochemical ammonia process. A common unit used for engineering specifications on equipment is scf/min (or per day) which can be calculated using the mass flowrate and the ideal gas law (link).

Global Flows

Flow Stream	***ton/day***	***kg/day***	***mole/s***	***kg/s***	***m3/s***	***sm3/s***	***scf/min***	***scf/day***	***gpm***
NH3 out	100.0	90700.0	61.8	1.0	1.5	1.5	3192.1	4596646.1	62986.1
N2	82.4	74694.1	30.9	0.9	0.8	0.8	1596.1	2298323.1	51870.9
H2O	47.1	42682.4	61.8	0.1	0.0	0.0	0.3	376.5	7469.4
O2 out	23.5	21341.2	30.9	0.6	0.8	0.8	1596.1	2298323.1	33364.1

For the above example, the flow rates of reactants can be determined by the reaction:

$$\left(\frac{1}{2}\right)N_2 + \left(\frac{3}{2}\right)H_2O \rightarrow \left(\frac{3}{4}\right)O_2 + NH_3$$

If the electrochemical process produces power instead of a chemical, the calculation of the global flows takes place while modeling the electrochemical reactor in the subsequent step.

The Third Step | Electrochemical reactor modeling

Before modeling an electrochemical reactor, a brief review of relevant electrochemical parameters is provided:

1) *Faradaic Efficiency:* A measure of an electron's efficiency of making the desired product. [no units]
2) *Current Density:* Current per area. This is a measure of the size of the system needed to drive the chosen flow rate of product [units: A/m^2]
3) *Reaction Rate*: If a reaction rate for the reactor is known, it is often provided in normalized units per weight of catalyst. This information can be used directly to determine the amount of catalyst needed for a given output.
4) *Voltage*: The potential difference across the cell. This is needed to calculate the total power of the cell.
5) *Liquid electrolyte required per surface area:* if the system uses a liquid electrolyte, an important specification is the amount of liquid needed per m^2 of surface area.
6) *Solid electrolyte membrane thickness:* Electrolyte thickness informs cost in the same way as the catalysts thickness

Find the cathode and anode reaction for the process in question. For the familiar case study on electrochemical ammonia production, the following reaction is possible:

Cathode rxn: $\left(\frac{1}{2}\right)N_2 + 3e^- + 3H_2O \rightarrow NH_3 + 6OH^-$

Anode rxn: $6OH^- \rightarrow \left(\frac{3}{2}\right)O_2 + 3H_2O + 3e^-$

Upon finding the anode and cathode reactions, use the faradaic efficiency to find the current required to produce the specified rate of product. For the 3 electron process above, we will use four parameters to find the current and catalyst surface area required:

Value	**Description**	**Units**
$\dot{m}_{molar}$	Molar flowrate	Moles/second
F	Faraday Constant	Coulombs/mol
η_F	Faradaic efficiency	-
CD	Current Density	A/m^2

The current required and catalyst surface area are given as:

$$I_{req} = \frac{(n_{electrons})(\dot{m}_{molar})F}{\eta_F}\ [A] \quad , \quad Area = \frac{I_{req}}{CD}\ [m^2]$$

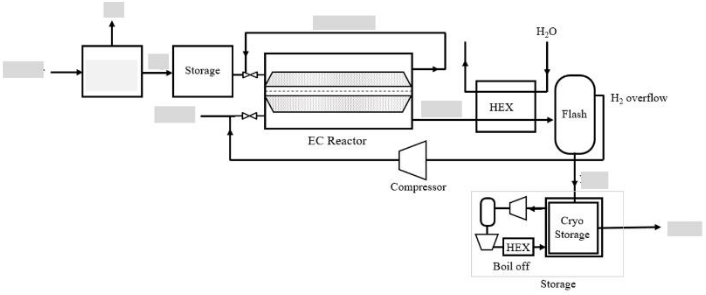
Assuming a certain thickness of the catalyst, d, we can calculate the required catalyst volume. Often, the thickness is provided in the literature. Alternatively, a representative value can be chosen (consider 20 microns) as a first-order estimate. $Catalyst\ mass\ required = (Area * d)/density.$

Next, the power consumption (in Watts) can be determined by: $Power = I_{req} * (voltage)$

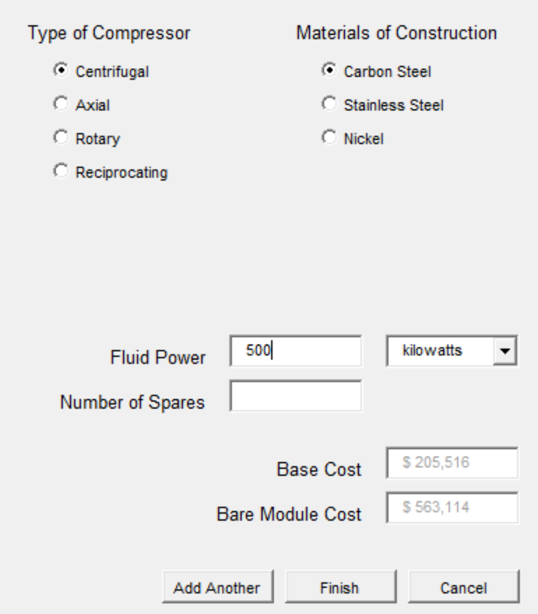
Following this stage, find the volume and weight of a solid electrolyte membrane in the same fashion (same surface area but different thickness). Or, for a liquid electrolyte you can calculate how much liquid is needed based on the surface area of the catalyst. A common value of fluid per surface area used in batteries is 100µL/cm^2. If you can find $/L value for the electrolyte liquid, the total electrolyte cost can be readily calculated.

The Fourth Step | System level schematic and costing

We turn our attention to capital equipment costs of an electrochemical system. At the study level, understanding the major equipment required for a scaled chemical plant is sufficient for a first-order cost estimation. First, rough sketch a schematic and identify the major pieces of equipment that will be needed in the system. Use the resources provided at the beginning of this write-up to aid in this process.



You do now need to know the exact size needed for each of the components in the system to start. Once you find a reference cost and capacity you can use industry scaling factors to find the cost at any capacity. A useful software called CAPCOST (we've provided a link to a free version of CAPCOST found online here) will estimate the capital cost at some reference capacity for any piece of process equipment. For example, we've shown how to spec out a reference cost for a compressor of arbitrary size in CAPCOST. Note that CAPCOST offers a base cost and a bare module cost. Base cost is the purchased cost of a component, while bare module cost includes the direct and indirect costs associated with contracting, designing, delivering, and installing the component as a standalone piece. The bare module cost is the more accurate of the two, as it also corrects for the operating pressure of the component.


Type of Compressor
● Centrifugal
○ Axial
○ Rotary
○ Reciprocating

Materials of Construction
● Carbon Steel
○ Stainless Steel
○ Nickel

Fluid Power: 500 kilowatts
Number of Spares:
Base Cost: $ 205,516
Bare Module Cost: $ 563,114

A compressor provides a working example of cost estimation. Using CAPCOST, we have a reference capacity of ($A_1 = 500kW$), and an estimated purchase cost at that capacity of ($C_1 = \$205{,}561$). At this point we can estimate the cost at any other capacity we desire with the following equation:

$$C_2 = C_1 \left(\frac{A_2}{A_1}\right)^n$$

Where "n" is a cost exponent that can be found readily in the resources provided, and "A" is the capacity of the component. We provide here a short table with common cost exponents on this page.

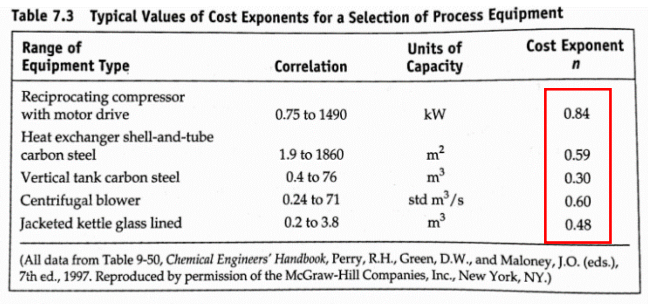


Table 7.3 Typical Values of Cost Exponents for a Selection of Process Equipment

Range of Equipment Type	Correlation	Units of Capacity	Cost Exponent *n*
Reciprocating compressor with motor drive	0.75 to 1490	kW	0.84
Heat exchanger shell-and-tube carbon steel	1.9 to 1860	m^2	0.59
Vertical tank carbon steel	0.4 to 76	m^3	0.30
Centrifugal blower	0.24 to 71	std m^3/s	0.60
Jacketed kettle glass lined	0.2 to 3.8	m^3	0.48

(All data from Table 9-50, *Chemical Engineers' Handbook*, Perry, R.H., Green, D.W., and Maloney, J.O. (eds.), 7th ed., 1997. Reproduced by permission of the McGraw-Hill Companies, Inc., New York, NY.)

The effect of time on reference cost: As the prices of goods such as compressors change over time, inflation on such industrial materials must be recognized and adjusted for with a tool called a Cost Index. There are a number of different cost indices, each designed to target a different "basket" of similar industrial equipment. A cost index provides a value for every year (sometimes quarter) that can be used as a ratio to estimate the cost of equipment purchased years apart. Typically, these indices begin in 1950 with an arbitrary reference value, which increases according to inflation with each year. For this write-up, we will make use of the CEPCI (Chemical Engineering Plant Index Cost) cost index. Other indices include the Marshall & Swift Equipment Cost Index and the Nelson-Farrar Refinery Construction Cost Index. The cost of the example compressor quoted above was given in 2012 dollars, corresponding to a CEPCI index of 500. The CEPCI is about 560 in 2017. Thus, to estimate a new cost we will apply the following equation to find the base (purchased) cost of the compressor:

$$Cost^{2017} = Cost^{2012}\left(\frac{I_{new}}{I_{ref}}\right) = Cost^{2012}\left(\frac{560}{500}\right)$$

Hence, given a reference cost, capacity, and year for a piece of equipment, the current cost at the required capacity can be given by the equation:

$$Cost_{current} = \left(\frac{I_{current}}{I_{ref}}\right)(C_{ref})\left(\frac{A_{current}}{A_{ref}}\right)^{n}$$

In addition to delivery and basic installation, each component needs to be integrated into the system to operate as a whole. These installation costs are also significant. In order to estimate the total installed cost of each process component, the Bare Module Cost is multiplied by an installation factor to account for these expenses. We suggest surveying the references provided to find an installation factor for major pieces of equipment. However, a standard installation factor is 1.3. If only the base cost, not the bare module cost, is given, installation factors will include delivery and additional installation costs. In such cases, the installation factor can range from 3 to 8, depending on the complexity of the component.

$$Installed\ Cost = (installation\ factor) * (base\ cost)$$

Costing the Electrochemical Reactor: For an electrochemical process the most challenging piece of equipment to cost will be the reactor because there will not be available reference costs. The reactor will be a combination of material costs (as determined in step three) and an analogous pieces of large equipment with standard index values. We suggest the summation of a heat exchange and/or agitated reactor with the material costs calculated in the previous section. Investigate an analogous piece of equipment and add the material costs that are unique to the catalyst and electrolyte. Consider using an installation factor of 2 or higher.

Adding in additional direct and indirect costs: After finding the installation cost for the major equipment needed in the electrochemical system we must account for several additional costs. These subsequent costs can be estimated as fractions of the delivered costs of components. If the delivered cost of materials is not known directly, using the bare module cost will suffice. A representative list of direct and indirect costs, as well as their estimating fraction, is shown below. Consult the reference list to determine accurate estimating fractions for the specific process in question, as they vary widely based on whether the plant processes solids, liquids, gases, or a mixture.

Other Direct Costs

Component	Fractional Cost Addition	Additional Expense
Instrumentation & Controls	0.11	$ 392,855
Piping	0.50	$ 1,785,707
Electrical Systems	0.11	$ 392,855
Buildings	0.18	$ 642,854
Yard Improvements	0.10	$ 357,141
Services Facilities	0.70	$ 2,499,989
TOTAL DIRECT COSTS		$ 13,214,229

Indirect Costs

Services	Fractional Cost Addition	Additional Expense
Engineering and supervision	0.33	$ 1,178,566
Constrution Expenses	0.41	$ 1,464,279
Legal Expenses	0.04	$ 142,857
Contractor's Fee	0.22	$ 785,711
Contingency	0.44	$ 1,571,422
TOTAL INDIRECT COSTS		$ 5,142,835
FIXED CAPITAL COST		$ 18,357,064

Straight-line Depreciation: Once the total fixed capital cost of an electrochemical system has been found we can gauge the severity of this capital cost on each unit of product that the system produces. Take an estimated system lifetime and calculate the effective capital cost that is paid out on every one unit of product. Assume a 10 year operating lifetime of the plant. For example, if a plant costs $3.65 million and produces 1 ton per day (365 tons per year, 3,650 tons over the total plant lifetime), then the effective cost per ton of product is $1,000. This cost will be incorporated into the total normalized cost of a plant through the line item “depreciation.”

Operational expenses for an electrochemical system:

Variable costs: these costs include 1) raw materials, 2) byproduct credits, and 3) utilities.

1) Raw material costs are projected based on the global flow rates of material into and out of the plant. What reactants are needed to produce the product?
2) Byproduct credits are an important line item that factors in the cost of material waste, the costs of exit flow rates of chemicals that are not sold, or the value added by byproduct exit streams.
3) Utilities include water, sewage, telephone, internet, and natural gas. Cooling water for heat exchangers and processes falls under this category. Natural gas can be a line item under raw materials (if used as an input stream) and as a utility (if a natural gas line from a utility is also used for heating). The largest potential line item under utilities for an electrochemical process is the cost of electricity. It is important to sum the electricity requirements of the electrochemical reactor and that of the additional system components. To find the electricity input of the additional pumps, compressors, etc… use the fluid work done by each step. This value can be found in many equipment specifications or by conducting a 1st order thermodynamic analysis of the enthalpy change across a component and taking a reasonable efficiency value of the component. Sum all of the components that require electricity and find the energy required per unit of product. Refer to chapter 7 of reference 2 for further information or see a common table of basic fluid power formulas (link).

In addition to variable costs, there are more operational expenses that must be factored in. Luckily, there are standard ratios and methods to estimate the expense of this items. These additional items include:

- maintenance supplies/labor = 5% of the total fixed capital costs
- operating supplies = 15% of the maintenance supplies/labor costs
- operating labor = $(units\ of\ product/day)^{0.27} * \frac{10*(number\ of\ shifts\ per\ day)}{(units\ of\ product/day)}$
    - Note: the power factor 0.27 depends on the type of process. Low maintenance plants have a power factor of 0.27, whereas high maintenance/solid processing plants have much higher factors refer to the provided references to find the appropriate labor exponential.

Calculating the operating labor is non-trivial. We've provided a cursory overview of one method here. We refer to the cost of operating labor pages included in this write-up (chapter 8 section 2 of reference 2). The typical number of shifts per day (needed for the previous equation) is 3 for large chemical plants.

- Supervision = an additional 15% of the operating labor cost
- Plant overhead = 60% of the sum of the following four parameters: 1) maintenance supplies/labor, 2) operating supplies, 3) operating labor, and 4) supervision
- Control laboratory = an additional 20% of the operating labor

Plant Gate Cost: At this point, find the sum of all of the expenses mentioned until now. This cost (given per unit product and included straight line depreciation) is called the "plant gate cost". How much does it costs to get a product to the plant gate? After calculating the plant gate cost, there are three additional expenses that must be estimated and accounted for:

- General and Administrative Expenses (G&A) = an additional 15% of the operating labor costs
- Sales = 3% of the plant gate cost
- Research and development = 5% of the plant gate cost.

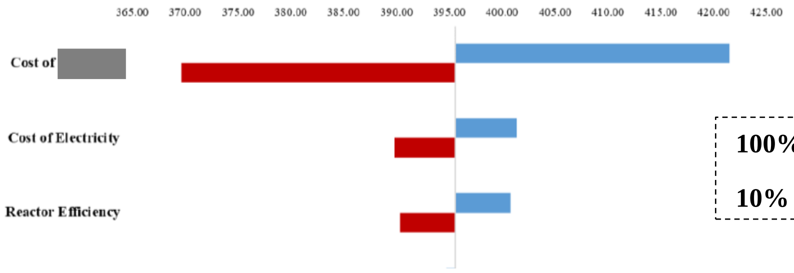
Step 5: Synthesis

The objective of a TEM is to estimate the costs associated with developing a system, and thus determining whether the system will be profitable. For the steps given above, the uncertainty range is large: -40% to + 50%. For this reason, the resulting values of an analysis should be understood to define a range of potential costs. They offer "ballpark" estimates that allows for the informed comparison between early-stage technologies and a filtering mechanism for pursuing certain ideas further. These estimates can also be very helpful in helping to understand how a system cost will vary with size and the effect that maintenance or other down-time have on the projected financials.

Capacity factor and facility size: Due to unforeseen circumstances, or scheduled maintenance times commercial facilities do not always run at 100% capacity. It is important to model an electrochemical system under varying capacity factors. Preform the same analysis as presented in the previous section but now multiply the production rate (units of product/time) by a capacity factor (multiplying the production rate by 0.5 gives the system operation costs at 50% capacity). This will affect all costs that are determined off of the percentage of the production capacity affecting the capital equipment costs more and operation expenses less. It is important to note that all equipment costs stay the same, however their fractional contribution to the total cost of one units of product increases. This is distinctly different, but related to *facility size* - where all components are different and sized for a different capacity. It is also very valuable to vary the facility size and analyze the plant costs and equipment costs for different design capacities. Chemical process engineering and economics of scale will become immediately apparent by varying the plant capacity – as will the value of having a high capacity factor.

Sensitivity analysis: A sensitivity analysis provides insight to how sensitive the bottom line production cost is to individual parameters. In essence, what are the key parameters that will lead to the financial success or failure of an electrochemical system? Conduct a sensitivity analysis by varying individual parameters (such as current density, faradaic efficiency, cost of electricity, etc.) and measure the corresponding change in the total cost of production.

Example sensitivity analysis on production cost



100%, capacity factor,

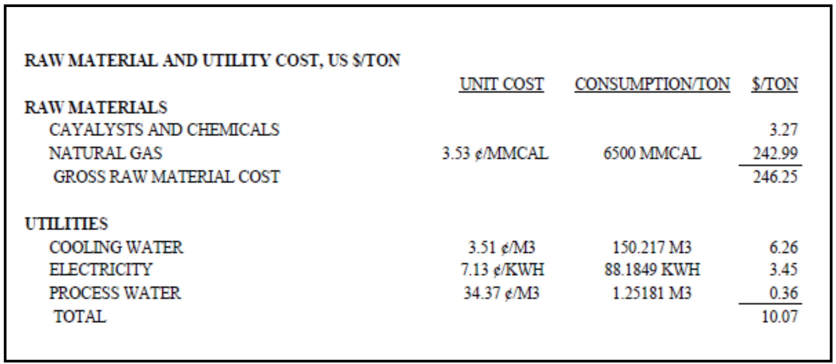
10% variance of parameters

Examples:

Here we provide two examples: 1) a TEM conducted by SRI International (with modified units) for a thermo-chemical process and 2) a potential electrochemical technology that creates the same product and is being assessed by the authors. A proprietary electrochemical ammonia synthesis assessed by the authors is presented here with material redacted. It is immediately apparent that the capital equipment costs are dramatically lower for the electrochemical process without the high pressures and the equipment needed to preprocess natural gas that the thermochemical process uses. The increased fraction of total cost due to electricity is dramatically increased.

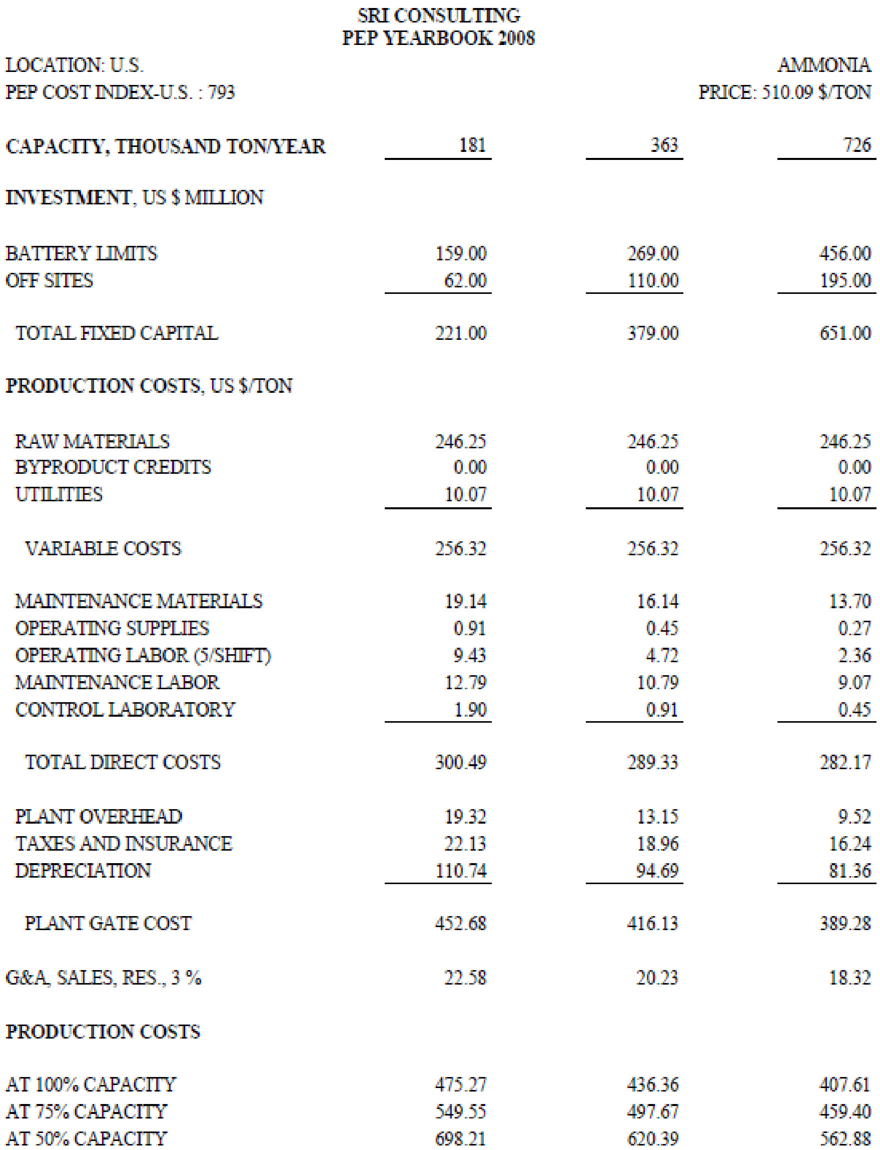
Thermochemical TEM example: Haber-Bosch

(M.W. Kelloggs Improved Process)



RAW MATERIAL AND UTILITY COST, US $/TON

	UNIT COST	CONSUMPTION/TON	$/TON
RAW MATERIALS			
CAYALYSTS AND CHEMICALS			3.27
NATURAL GAS	3.53 ¢/MMCAL	6500 MMCAL	242.99
GROSS RAW MATERIAL COST			246.25
UTILITIES			
COOLING WATER	3.51 ¢/M3	150.217 M3	6.26
ELECTRICITY	7.13 ¢/KWH	88.1849 KWH	3.45
PROCESS WATER	34.37 ¢/M3	1.25181 M3	0.36
TOTAL			10.07



SRI CONSULTING
PEP YEARBOOK 2008

LOCATION: U.S. — AMMONIA
PEP COST INDEX-U.S. : 793 — PRICE: 510.09 $/TON

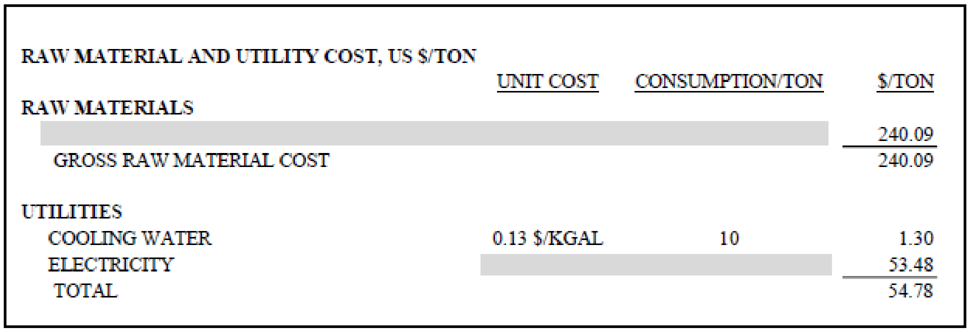
CAPACITY, THOUSAND TON/YEAR	181	363	726
INVESTMENT, US $ MILLION			
BATTERY LIMITS	159.00	269.00	456.00
OFF SITES	62.00	110.00	195.00
TOTAL FIXED CAPITAL	221.00	379.00	651.00
PRODUCTION COSTS, US $/TON			
RAW MATERIALS	246.25	246.25	246.25
BYPRODUCT CREDITS	0.00	0.00	0.00
UTILITIES	10.07	10.07	10.07
VARIABLE COSTS	256.32	256.32	256.32
MAINTENANCE MATERIALS	19.14	16.14	13.70
OPERATING SUPPLIES	0.91	0.45	0.27
OPERATING LABOR (5/SHIFT)	9.43	4.72	2.36
MAINTENANCE LABOR	12.79	10.79	9.07
CONTROL LABORATORY	1.90	0.91	0.45
TOTAL DIRECT COSTS	300.49	289.33	282.17
PLANT OVERHEAD	19.32	13.15	9.52
TAXES AND INSURANCE	22.13	18.96	16.24
DEPRECIATION	110.74	94.69	81.36
PLANT GATE COST	452.68	416.13	389.28
G&A, SALES, RES., 3 %	22.58	20.23	18.32
PRODUCTION COSTS			
AT 100% CAPACITY	475.27	436.36	407.61
AT 75% CAPACITY	549.55	497.67	459.40
AT 50% CAPACITY	698.21	620.39	562.88

Straight-line depreciated capital cost for 10 yr plant lifetime

Gate cost

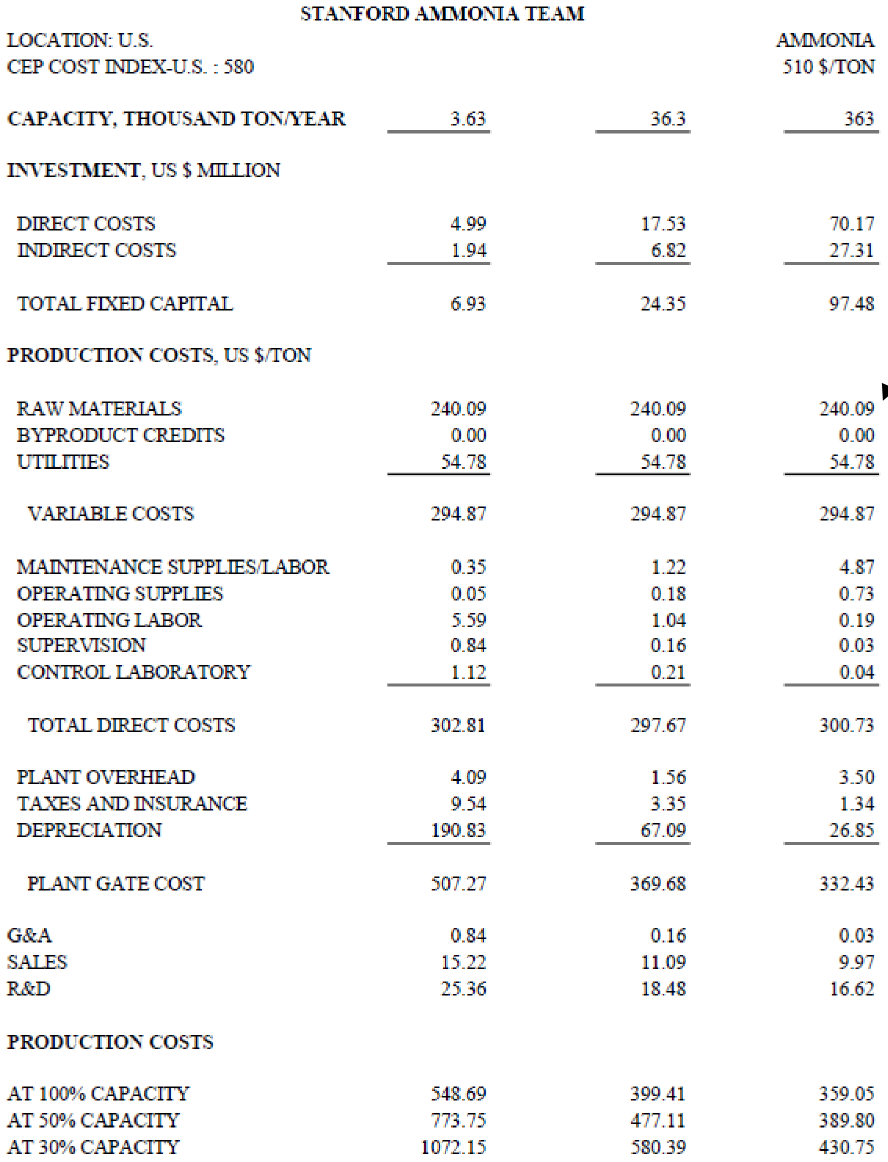
Cost of production

Electrochemical TEM example: ammonia synthesis



RAW MATERIAL AND UTILITY COST, US $/TON

	UNIT COST	CONSUMPTION/TON	$/TON
RAW MATERIALS			
[redacted]			240.09
GROSS RAW MATERIAL COST			240.09
UTILITIES			
COOLING WATER	0.13 $/KGAL	10	1.30
ELECTRICITY	[redacted]	[redacted]	53.48
TOTAL			54.78



STANFORD AMMONIA TEAM

LOCATION: U.S.
CEP COST INDEX-U.S. : 580

AMMONIA
510 $/TON

CAPACITY, THOUSAND TON/YEAR	3.63	36.3	363
INVESTMENT, US $ MILLION			
DIRECT COSTS	4.99	17.53	70.17
INDIRECT COSTS	1.94	6.82	27.31
TOTAL FIXED CAPITAL	6.93	24.35	97.48
PRODUCTION COSTS, US $/TON			
RAW MATERIALS	240.09	240.09	240.09
BYPRODUCT CREDITS	0.00	0.00	0.00
UTILITIES	54.78	54.78	54.78
VARIABLE COSTS	294.87	294.87	294.87
MAINTENANCE SUPPLIES/LABOR	0.35	1.22	4.87
OPERATING SUPPLIES	0.05	0.18	0.73
OPERATING LABOR	5.59	1.04	0.19
SUPERVISION	0.84	0.16	0.03
CONTROL LABORATORY	1.12	0.21	0.04
TOTAL DIRECT COSTS	302.81	297.67	300.73
PLANT OVERHEAD	4.09	1.56	3.50
TAXES AND INSURANCE	9.54	3.35	1.34
DEPRECIATION	190.83	67.09	26.85
PLANT GATE COST	507.27	369.68	332.43
G&A	0.84	0.16	0.03
SALES	15.22	11.09	9.97
R&D	25.36	18.48	16.62
PRODUCTION COSTS			
AT 100% CAPACITY	548.69	399.41	359.05
AT 50% CAPACITY	773.75	477.11	389.80
AT 30% CAPACITY	1072.15	580.39	430.75

Straight-line depreciated capital cost for 10 yr plant lifetime

Gate cost

Cost of production

Presenting the results of a techno-economic model: A techno-economic model is only a scholastic activity unless it is used to draw conclusions that may be valuable for a commercial enterprise. TEM's greatly help in determining the potential benefits (and risks) of new technology is presented in a cohesive manner. We suggest the format provided in the following two examples with several additional pieces of information. A complete TEM should include:

- Written and visual description of the technology
- First order thermodynamic analysis of the minimum energy input
- System level electrochemical reactor schematics
- Stoichiometry and flow rates
- List of capital costs
- List of operational costs
- An overview and cost stack for the production of 1 unit of product (see examples) for several different capacity factors and system capacities.
- Sensitivity analysis
- Conclusions – is this technology economically feasible?

Conclusion:

A techno-economic model is a valuable tool to assess to economic viability of prospective electrochemical processes. It is important to note that all models are inherently wrong and should not be blindly trusted. However, some models may be *useful*. An in-depth techno-economic model, as presented here, has the ability to be a useful tool to aid in the financial assessment of an electrochemical technology.