# Techno-economic Modeling:

## An efficient tool to assess/evaluate new technologies and products

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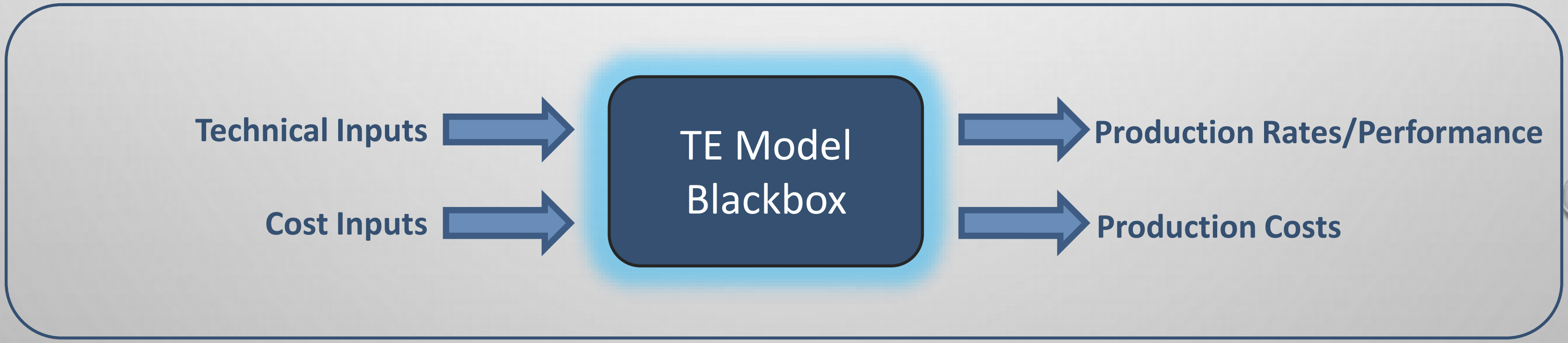
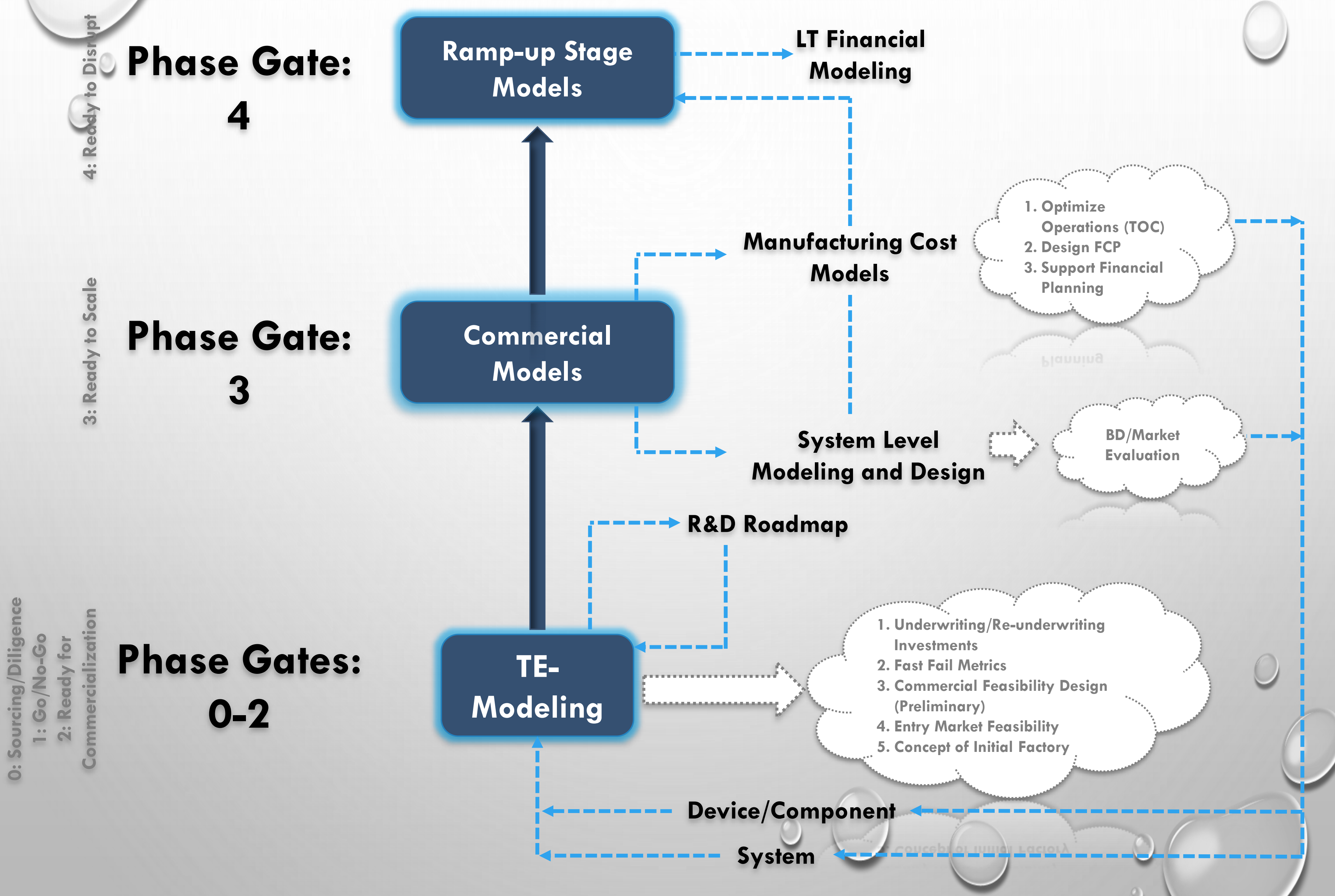
# Lecture Objectives

- Define Techno-Economic (TE) modeling and the components that constitute the TE-assessment process.
- Explain how TE modeling can be used to inform the design and development of new technologies, and guide a business through its various phase gates at all stages of development
- Illustrate these points and generalities with two, concrete TE modeling examples
- Gain a better understanding for how TE modeling can guide and influence a business based on a new technology from early stages all the way to commercialization



# TE-Modeling and Investment Phases

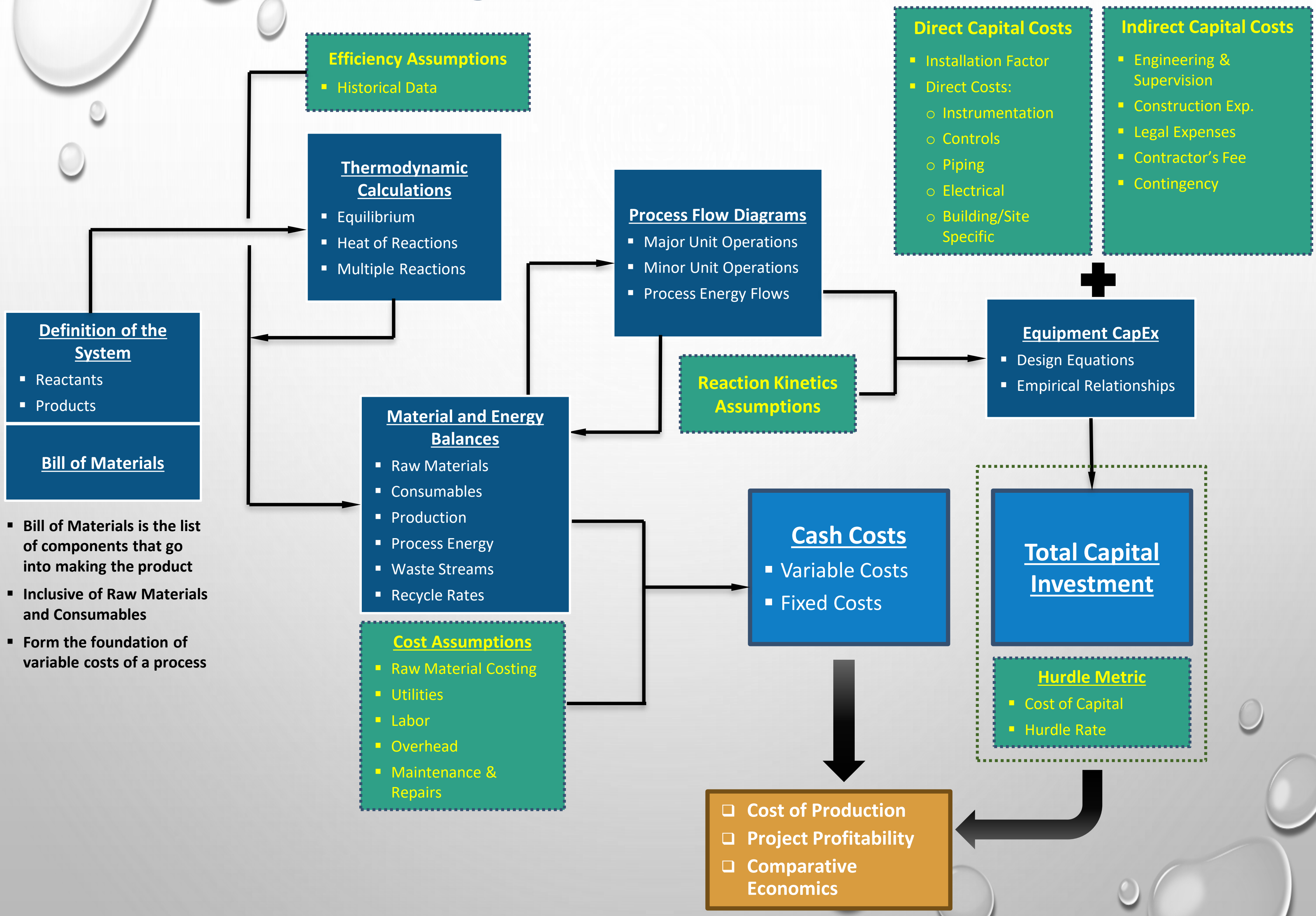


# The Role of Techno-Economic Analyses (TEA)

- Techno-Economic Analyses is a “tool” useful in providing quantifiable answers to **whether a new technology can scale up sufficiently into market** …
- TEA is fundamentally an ECONOMIC analysis
  - However, the fulcrum of the analyses is based on the technical modeling (the “techno” part) of the process/technology/product being assessed
- The outputs of this technical model are a function of:
  - Technical and Economic/Market Assumptions
  - Available Technical and Economic/Market Information
  - Known 1st Principles of Core Fundamentals (i.e. Thermodynamics, Kinetics, Manufacturing Principles etc.)
- This tool is used to answer questions relating to:
  - **Sensitivities**: Does the product unit cost change drastically as a result of small changes in any technical or cost inputs and the impact of approach to theoretical efficiencies? And if so by how much?
  - **Scale**: How does scale affect the product unit cost? Do the capital expenses scale well? What is the minimum production size required to cover the production costs?
  - **Cost Extremes**: If labor and processing costs were zero, what is the floor production cost?
  - **Markets**: Are there unique markets where this technology is advantaged with a novel value proposition to make up for its higher cost? Can we enable new market opportunities by expanding the conditions at which this technology can perform?

**The model is not a solution or end game to a problem—rather, it is a versatile tool that changes with technology and business developments, just as much as it impacts these very aspects.**

# Functional Block Diagram for a TE-Model



## **Production Costs: Cash Costs or OpEx -** recurring expenses, measured on an annual basis and categorized into:

**Variable Costs**

| What's included? | Where do we get it from? Quantity Required | Where do we get it from? Cost Assumptions* |
|---|---|---|
| **Raw Materials**<br>**Miscellaneous (e.g. Catalysts)**<br>**Process Energy**<br>**Process Consumables (e.g. Make-up fluids)**<br>**Waste-Streams**<br>**Side-Products Credits** | ▪ Mass & Energy Balances | ▪ Technical Reports<br>▪ Spot Pricing<br>▪ Preliminary Market Study<br>▪ Internet information (EIA database, press-releases etc.)<br>▪ Expert interviews<br>▪ Volume Costing considerations |
| **Incentives (e.g. RFS, LCFS, Carbon avoidance)** | | |

**Fixed Costs**

| What's included? | Where do we get it from? Quantity Required | Where do we get it from? Cost Assumptions* |
|---|---|---|
| **Direct Labor & Supervision (DL, S)** | ▪ Similar Processes<br>▪ Bottoms-up model | ▪ Costs mainly depend on Direct Labor and CapEx<br>▪ Labor Rate should be site specific<br>▪ Further explanations and ranges can be found in: "Plant Design and Economics for Chemical Engineers; Peters, M., Timmerhaus, K., and West, R." |
| **Supervision (S)** | ▪ 15% of DL | |
| **Plant Overhead** | ▪ 50-60% of (DL + S) | |
| **Maintenance & Repairs** | ▪ 2-3% of TCI | |
| **Insurance & Taxes** | ▪ 2% of FCI | |
| **Lab Charges** | ▪ 10% of OL | |
| **Operating Supplies** | ▪ 15% of Maint. & Repairs | |

***Caution: Beware of the trap of using generic cost assumptions! Your TE-model should always be 'MARKET SPECIFIC'.**

E.g. No point using 'US Natural Gas Pricing' for a facility in Japan OR 'Waste Disposal Costs' of TX for a facility in CA, is there?

Together the Variable and Fixed Costs give the "**CASH COSTS of PRODUCTION**", which is sometimes also called as "**TOTAL PRODUCTION COSTS**"

**THESE COSTS GIVE THE ABSOLUTE MINIMUM COST FOR PRODUCING ONE UNIT OF THE PRODUCT**

# CapEx Estimation

| Estimate Type | Source | Accuracy |
|---|---|---|
| **Order of Magnitude** | Similar Previous Cost Data | Over ±30% |
| **Study** | Knowledge of Major Equipment | Up to ±30% |
| **Preliminary** | Sufficient data to permit estimate to be budgeted | Within ±20% |
| **Definitive** | Almost complete data before drawings & specs. | Within ±10% |
| **Detailed** | Complete engineering drawings, site surveys etc. | Within ±5% |

## Pre-Design Capital Cost Estimates

- Most of TE-CapEx estimates are of this category
- Estimated based on engineering judgments, experience, historical data
- Critical for decision making and understanding impacts of various process elements

## Effective Method to estimate Capital Investment for a Project (Cost Components of CapEx)

| | Fraction of delivered-equipment cost for plants processing: | | |
|---|---|---|---|
| | **Solids** | **Solid-Fluid** | **Fluid** |
| **Purchased Equipment Cost (From Design & Sizing)** | **1** | **1** | **1** |
| **Direct Costs (DC)** | **1.54** | **1.90** | **2.50** |
| Installation Factor | 0.45 | 0.39 | 0.47 |
| Instrumentations & Controls | 0.18 | 0.26 | 0.36 |
| Piping | 0.16 | 0.31 | 0.68 |
| Electrical Systems | 0.10 | 0.10 | 0.11 |
| | | | |
| **Indirect Costs (IDC)** | | **1.14** | **1.25** |
| | | | |
| Legal Expenses, Contractor's Fee | 0.20 | 0.23 | 0.26 |
| Contingency | 0.25 | 0.25 | 0.25 |
| **Fixed Capital Investment (FCI = PEC + DC + IDC)** | **3.71** | **4.04** | **4.75** |
| **Working Capital (15% of TCI)** | 0.65 | 0.71 | 0.84 |
| **Total Capital Investment (TCI = FCI + WC)** | **4.36** | **4.75** | **5.59** |

**TCI = 3.2 * Purchased Equipment Cost**

A few things to note:

- The adjoining numbers have been taken from "Plant Design and Economics for Chemical Engineers; Peters, M., Timmerhaus, K., and West, R."
- While this generic rule of thumb is applicable to a "first of its kind" plant, there is scope of CapEx savings/reductions for future plants, via:
  - Process Intensification and Packaging
  - Modularization
  - Learning Cycles
- A much simpler method of estimating CapEx may also be the "Lang Factor" Method, **which multiplies the purchased cost of equipment by a factor between 3 and 5**
- Other CapEx estimation techniques include the "cost-capacity" rule or the "6/10$^{th}$ factor" rule, which is given by:

  $$CapEx_{Cap\text{-}2} = (Cap\text{-}2/Cap\text{-}1)^{0.6} * CapEx_{Cap\text{-}1}$$

- CapEx is also impacted by location factors. As a general rule of thumb; a facility in a low-cost geography (e.g. China) will cost ~70-75% of a facility in US gulf coast

# Production Costs: Return on Investment Metrics

- Two main metrics to measure the return on investment:
  1. **Return on Invested Capital (ROIC)**
  2. **Internal Rate of Return (IRR)**

- ROIC is the simpler of the two, generally defined as:

$$\boldsymbol{ROIC = \frac{(Revenue) - (Cash\ Costs)}{(Total\ Invested\ Capital)}}$$

- IRR is the discount rate that sets the Net Present Value (NPV) of a specific cash flow equal to exactly zero. More succinctly:

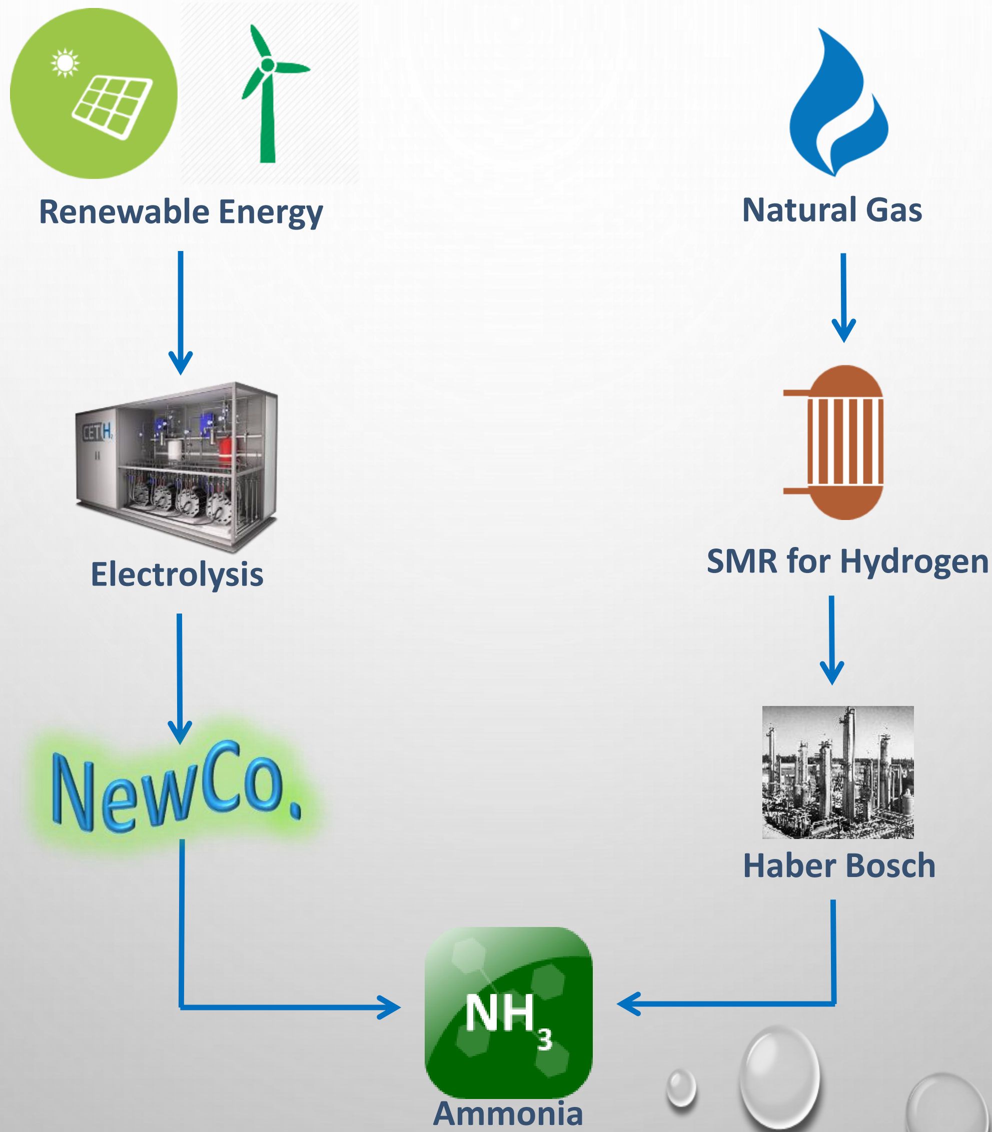
$$\boldsymbol{NPV = 0 = \sum_{t=1}^{T} \frac{(Net\ Cash\ Flow)}{(1 + IRR)^t} - (Total\ Invested\ Capital)}$$

  - Where **t** is the time period and **T** is the total number of periods.

- Generally speaking, if the IRR is higher than the cost of capital for the specific project, then it is worth pursuing; and if the IRR is lower than the cost of capital, then the project should be rejected.
  - The cost of capital is simply the Weighted Average Cost of Capital (WACC) for the project—which is the weighted average cost of debt taken on and the cost of equity for the specific project.

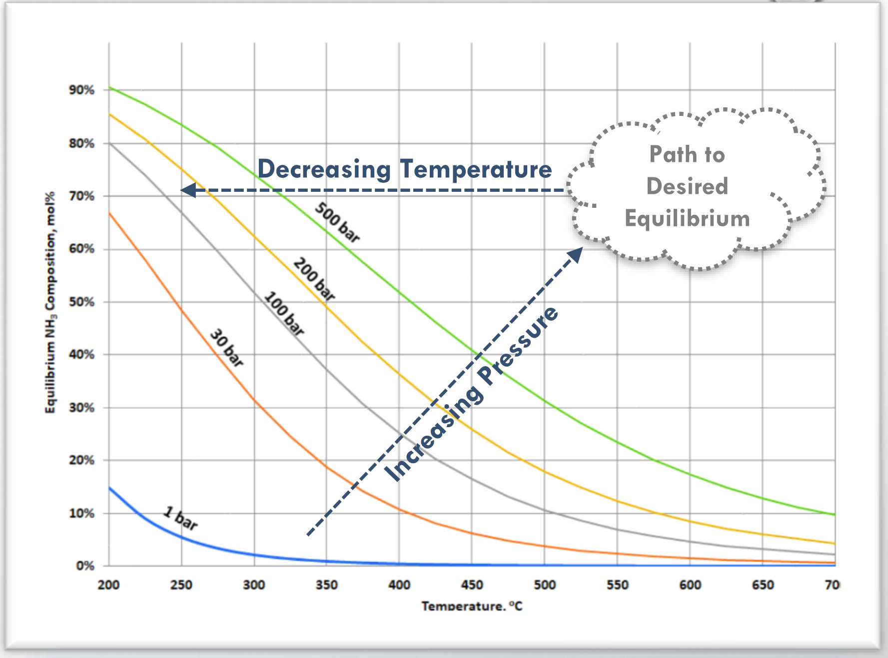
# TE-Modeling Example 1: CapEx Affordability

# CapEx Affordability Analyses:
## (A Top-Down Means of Vetting an Opportunity)



# Ammonia Synthesis: Need for an Alternative Approach?

- Synthesis of ammonia ('Haber-Bosch' Process) is plagued with challenges due to unfavorable thermodynamics of the reaction:
  - $N2(g) + 3H2(g) = 2NH3(g)$
- The above reaction is exothermic and is favored at low temperatures and high pressures
- Ammonia Yield is Maximized (see Figure) by:
  - Minimum Temperature &
  - Maximum Pressure
- This is counter-productive to process design as:
  - Low Temperature = Slow Reaction Kinetics
  - High Pressure = Expensive Equipment (i.e. reactors, compressors, piping etc.)
- To reach a compromise, the industrial Haber Bosch Process is operated at temperatures of ~450oC and pressures of ~200-220 atm. in the presence of a catalyst
- The traditional Haber Bosch Process is plagued by HIGH CAPITAL COSTS, which necessitate building high capacity plants to leverage economics of scale




**Desired Equilibrium ∝ Pressure**

$$\textbf{Desired Equilibrium} \propto \frac{1}{\textbf{Temperature}}$$

**An Alternative that can improve reaction kinetics at lower temperatures and still leverage the equilibrium benefit at reasonable pressures, is hence interesting**

# Questions to be Answered:

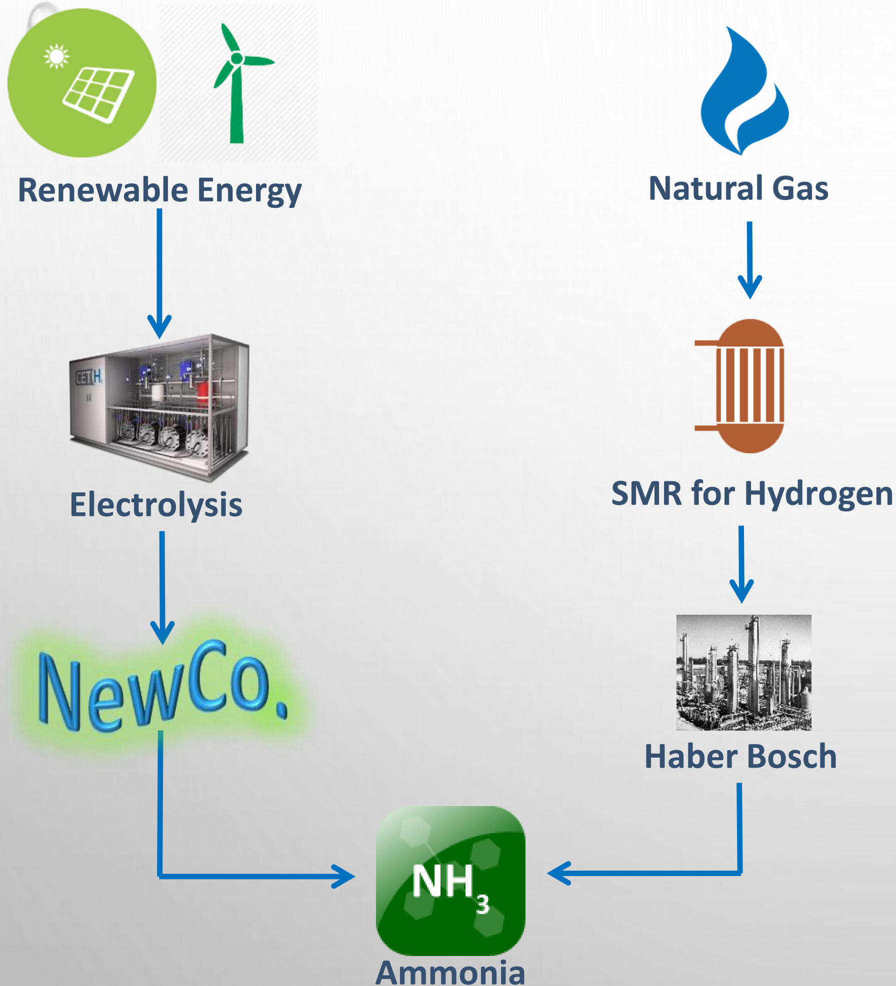
- At the given operating conditions what is the efficiency of the NewCo. Process?

- What are the main factors that the economics of the process are heavily dependent on? Some of these may include:
  - → Catalyst Costs and Replacement Intervals
  - → Efficiency of the Electrolyzer
  - → Capital Cost of the Electrolysis Section
  - → Scale of the Plant
  - → Renewable Energy Costs
  - → Solar or Wind Profile, which impacts the capacity factor and hence the size of the electrolyzer

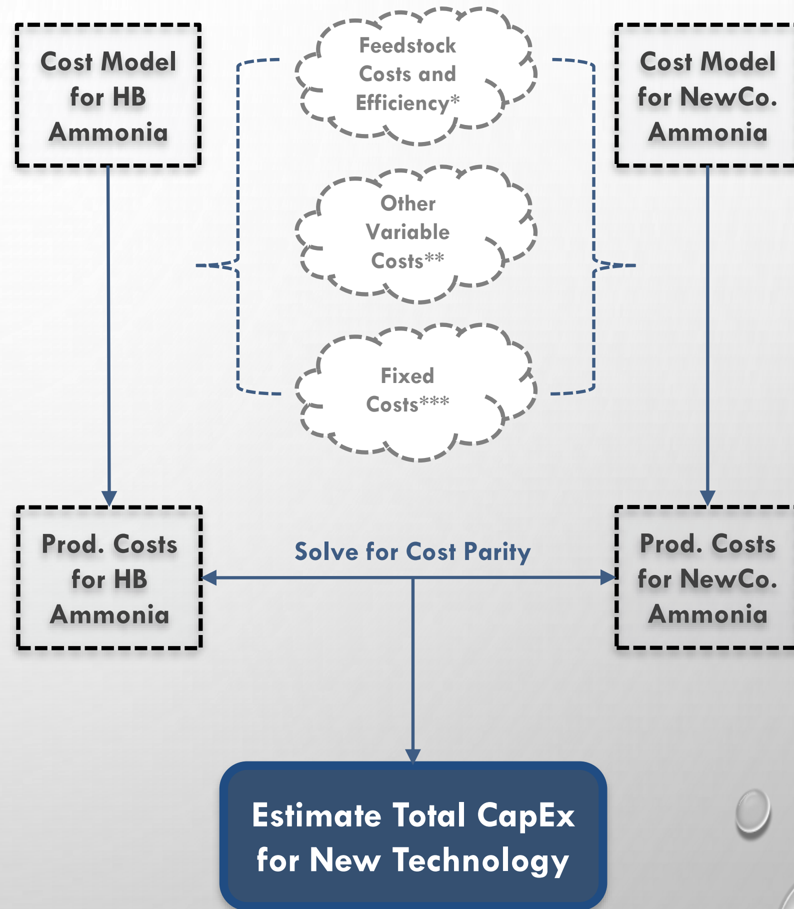
- The following analyses answers the above question by calculating the "Maximum CapEx" for the NewCo. process that would make it economically comparable with the traditional Haber-Bosch Process

# CapEx Affordability Analyses (Approach)

## New Tech. CapEx Affordability

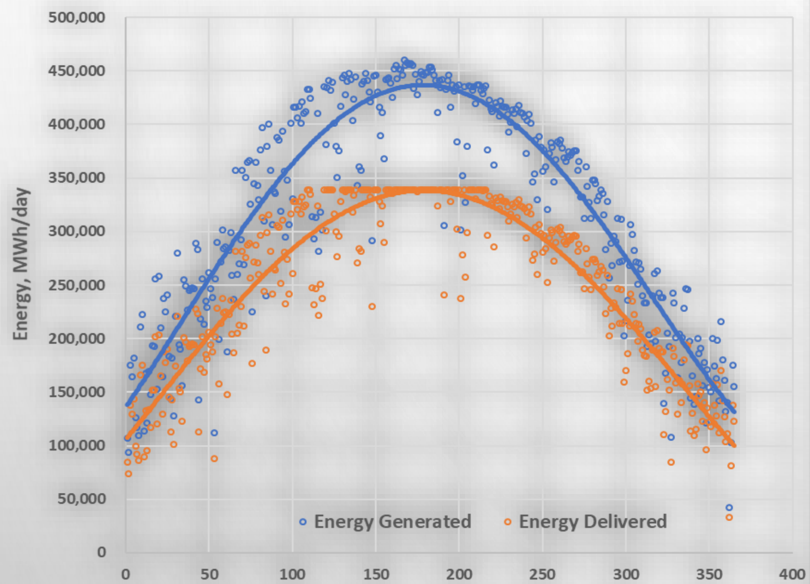



## CapEx Affordability Analyses



# Calculating the Electrolyzer Size Requirement*

Electrolyzer Size Calculated by Minimizing Levelized Cost of Hydrogen Production for the adjoining Inputs/Assumptions




| Design Parameters: | | Remarks |
|---|---|---|
| Hydrogen Production | Electrolyzer | |
| Energy Costs for Charging, $/kWh | $0.0250 | *Energy PPA price from Solar Farm* |
| Total Solar Energy Generated, MWh/yr | 116,981,931 | *Calculated from PV Load profile* |
| Total Energy Costs, $/yr | $2,924,548,279 | |
| Electrolyzer Rating, MW | 17,924 | *Calculated to find Optimum* |
| Energy Requirements, kWh/kg | 50.00 | *Using the current best in class available* |
| HHV of Hydrogen, kWh/kg | 39.41 | *Higher Heating Value/Energy Density* |
| Overall Electrolyzer Efficiency | 78.8% | |
| Nameplate Hydrogen Production, kg/day | 8,603,601 | |
| Max. Operating hours per year | 8,760 | |
| Nameplate Hydrogen Production, kmtpy | 3,140 | |
| HHV of Hydrogen, Btu/lb | 60,996 | |
| Actual Hydrogen Production, kmtpy | 2,322 | |

| Results: | |
|---|---|
| Levelized Cost of Hydrogen., $/MMBtu | $ 12.5 |
| Levelized Cost of Hydrogen., $/kg | $ 1.69 |
| Annual Electrolyzer Capacity Factor | 74.0% |
| **Solar Farm Size:** | |
| Annual Energy Generated, MWh/yr | 116,981,931 |
| PV Plant Size, MW | 13,354 |

**Calculated from the following inputs/assumptions:**

- A given solar farm load profile
- Assuming purpose built solar PV farm
- Installed Electrolyzer CapEx of $300/kW
- Available energy price of $0.025/kWh
- O&M costs of Electrolyzer: $ 20/kW/yr
- Electrolyzer System Efficiency: 78.8% (Energy Req. = 50kWh/kg)
- Efficiency Degradation of 0.75% per year (linear)
- Discount Rate: 7.5%; Project Life: 30 years

# Base Case TE-Analyses Comparison

| Technology for Ammonia | M.W. Kellogg (Haber-Bosch) | NewCo. |
|---|---|---|
| **Technical Parameters** | | |
| Source of Hydrogen | Natural Gas | Electricity |
| Hydrogen Generation Process | SMR | Water Electrolysis |
| Hydrogen Generation Energy Requirements | 0.1485 MMBtu/kg [1] | 0.1706 MMBtu/kg [2] |
| Ammonia Energy Requirements | 30.074 MMBtu/mt. [3] | 31.804 MMBtu/mt. [4] |
| Operating Temperature | 450 C | 565 C |
| Operating Pressure | 200 atm. | 10 atm. |
| Equilibrium One-Pass Conversion [5] | 26% | 0.7% |
| **Economic Parameters** | | |
| Capacity of the Plant, kmtpy | 300 [6] | 200 [7] |
| Corresponding SMR Size, MMNm3/yr | 592 | - |
| Corresponding Electrolyzer Rating, MW [8] | - | 288 |
| **Total Capital Investment** | **$ 327** | **$ 143** |
| *Hydrogen Generation Section, $MM* [9] | *$ 132* | *$ 86* |
| *Ammonia Synthesis Section, $MM* | *$ 195* | *$ 26* [10] |
| **Total Production Costs (12% ROIC), ¢/kg** | **39.96** | **39.96** |
| *Feedstock Costs, ¢/kg* [11] | *10.53* | *32.77* |
| *Other Variable Costs, ¢/kg* | *1.37* | *1.31* |
| *Total Fixed Costs, ¢/kg* [12] | *7.74* | *4.79* |
| *Depreciation/Sust. CapEx, ¢/kg* [13] | *10.89* | *0.86* |
| *Profit @ 12% ROIC, ¢/kg* [14] | *13.06* | *1.55* |

Notes:

1. Calculated from available mass and energy balances of a world-scale SMR. Based on LHV of natural gas. SMR Process efficiency is ~82%
2. Calculated from energy requirement of electrolysis of 50kWh/kg (Electrolyzer Efficiency: ~79%)
3. Energy Requirements for Haber Bosch process determined from theoretical calculations and SRI PEP Economics (Overall Thermal Efficiency: 87.7%; Theoretical to Actual Ratio)
4. Estimated from Stoichiometry and assuming 5% losses in recycle, product separation & recovery etc.
5. Estimated from thermodynamic equilibrium
6. Preliminary research shows that this is a typical plant size of an ammonia plant based on this process
7. Plant based on this technology assumed 100 kmtpy smaller than the incumbent plant
8. Calculated by minimizing levelized cost of hydrogen production for the given electrolyzer efficiency and a typical solar load profile.
9. SMR CapEx calculated from the SMR TE-model. Electrolyzer CapEx calculated based on an installed electrolyzer CapEx cost of $300/kW
10. Ammonia Synthesis CapEx section for NewCo is the “Maximum Affordable CapEx” needed to equalize the total production costs of ammonia from the two processes.
11. Natural Gas: $3.5/MMBtu, Renewable Electricity: 2.5¢/kWh. Feedstock costs for Starfire is the levelized cost of hydrogen production from electrolysis accounting for the electricity costs, electrolyzer CapEx, electrolyzer O&M, cost of capital, replacement CapEx, sustaining CapEx, capacity factor and efficiency.
12. Fixed costs include labor, maintenance and repairs, overhead, taxes and insurance etc. For NewCo. these costs are costs associated only with the ammonia synthesis section as the fixed costs for hydrogen generation are included in the feedstock costs.
13. Sustaining CapEx/Depreciation for NewCo. is calculated based on the Ammonia Synthesis Section CapEx ONLY. Calculated on 15 yr straight line basis for both processes
14. ROIC for NewCo calculated only for the Ammonia Synthesis Section

# TE-Modeling Example 2: Assessing a New Technology

# A Potential Breakthrough Technology Comes Along…

You come across an article in the 'Science' journal that outlines a potentially path-breaking chemistry, borne out of an university. The chemistry essentially converts an olefin (e.g. propylene) to a higher value diol (e.g. propylene glycol) in an aqueous process at moderate temperatures and pressures in one step! You do some due diligence and find out the following:

**Technical Points:**

- The current route for making propylene glycol is a two-step high temperature, high pressure process involving oxidation of polymer-grade propylene to propylene oxide and then further hydration of propylene oxide to propylene glycol.
    - The above route also yields di-propylene and tri-propylene glycols as side products
- The new process takes place at 120 C and almost atmospheric pressures, in the presence of an inert solvent with a catalyst complex dissolved in it.
- Preliminary reaction kinetics are known, as is the general stoichiometry and overall reactions.

**Market and Business Information:**

- Propylene glycol is a $4B market, with an average sale price of 89¢/lb
- Polymer grade propylene is available at a cost of 60¢/lb

# So How do you assess the opportunity?

Determine Chemical Reactions and Balance Them

↓

Come up with a Process Scheme and Mass/Energy Balance

↓

Design and size Main Equipment

↓

Estimate CapEx and OpEx

↓

Calculate the Production Costs

**What do we intend to achieve at the end of this exercise?**

- A reasonable first estimate of production costs from the new process:
  - Cash Costs (fixed + variable)
  - Total Production Costs (Depreciation + Cash Costs)
  - Product Value (ROIC + Total Production Costs)
- Comparative economics with the existing route
- An ROIC or an IRR based evaluation of a commercial plant performance

**AND MOST IMPORTANTLY:**

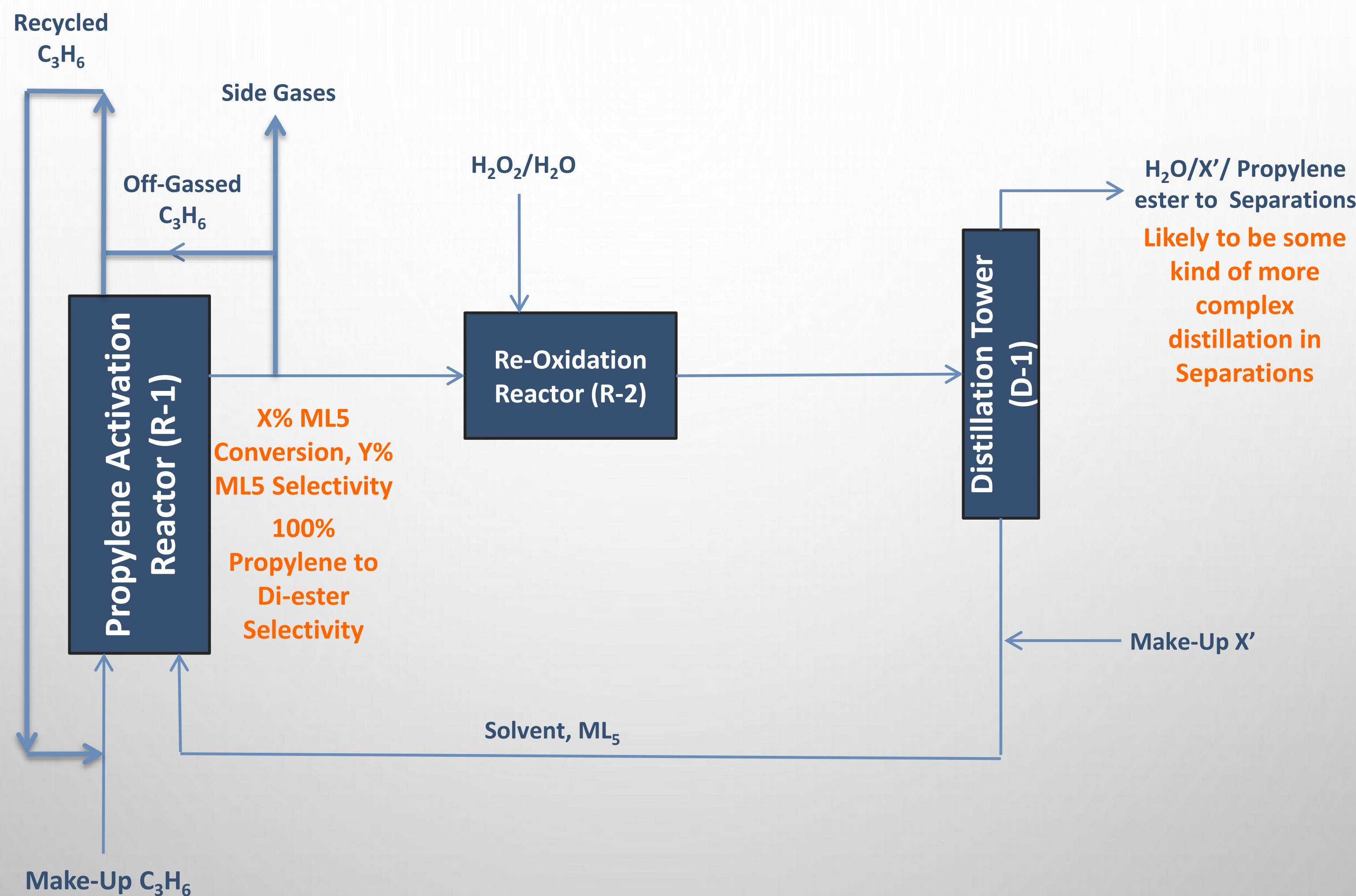
- **What technical risks (binary and others) should be retired to ensure that this science experiment can scale into something compelling and profitable?**

# Listing The Governing Equations

| Balanced Chemical Reactions |
|---|
| **Initial Propylene Activation** |
| $ML_5 + C_3H_6 + 2(X') \rightarrow ML_3H_2 + C_3H_6(X')_2 + 2L$ |
| **Hydrolysis of Propylene Compound (After Distillation)** |
| $C_3H_6(X')_2 + 2H_2O \rightarrow \mathbf{C_3H_6(OH)_2} + 2(X')$ |
| **Re-Oxidation of Metal Complex** |
| $ML_3H_2 + H_2O_2 + 2L \rightarrow ML_5 + 2H_2O$ |

- Where:
  - L = Organic Ligand
  - M = Metal Catalyst
  - X'= Activation Species
- These equations also do the job of providing the bill of materials for this process.
  - There will be other materials required to be a part of this entire process, known as consumables (e.g. solvents), but they do not go into creating the product itself.

# Creating a Basic Process Flow



# Calculating an Ideal Mass Balance

| Compound | Into R-1 | Out of R-1 | Into R-2 | Out of R-2 | Into D-1 | Out of D-2 | Total In | Total Out |
|---|---|---|---|---|---|---|---|---|
| $C_3H_6$ | 1,822,124 | 1,811,392 | 0 | 0 | 0 | 0 | 1,822,124 | 1,811,392 |
| $ML_5$ | 300,567 | 301 | 301 | 300,567 | 300,567 | 300,567 | 300,567 | 300,567 |
| $ML_3H_2$ | 0 | 193,096 | 193,096 | 0 | 0 | 0 | 0 | |
| $C_2H_4O_2$ | 122,738 | 92,107 | 92,107 | 92,107 | 92,107 | 92,107 | 122,738 | 92,107 |
| $C_3H_6(C2H3O2)_2$ | 0 | 40,849 | 40,849 | 40,849 | 40,849 | 40,849 | 0 | 40,849 |
| L | 199,578 | 307,262 | 307,262 | 199,578 | 199,578 | 199,578 | 199,578 | 199,578 |
| $H_2O$ | 4,633 | 4,633 | 4,633 | 13,824 | 13,824 | 13,824 | 4,633 | 13,824 |
| $C_3H_6(OH)_2$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $H_2O_2$ | 0 | 0 | 8,677 | 0 | 0 | 0 | 8,677 | 0 |
| **TOTAL** | **2,449,640** | **2,449,640** | **646,925** | **646,925** | **646,925** | **646,925** | **2,458,317** | **2,458,317** |

- All in units of kg/h
- The only extra information needed to create this table are the molecular masses of each compound, which can be easily found in literature.
- Energy balances for this process can simply be preformed around each unit operation.
  - If the temperatures needed for each step are known, heating requirements can be calculated, which are used to calculate raw material amounts needed for heating—such as natural gas.

# Equipment Included in CapEx Estimation

| Equipment | Metrics used for equipment design in TE-model |
|---|---|
| **Propylene Activation Reactor** | • Designed as a bubble column reactor (BCR), with X% M conversion and Y% selectivity of M to propylene di-acetic esters<br>• Reaction kinetics obtained from lab data<br>• Pressure, propylene feed rate, and Temperature calculated to achieve the required conversion in the given residence time |
| **Flash Tanks** | • Two vertical flash tanks designed after the BCR to flash off all remaining propylene in solution<br>• Sized according to the Souders-Brown equation for maximum allowable vapor velocity |
| **Re-Oxidation Reactor** | • Ideal CSTR. Model splits one reactor into multiple, parallel reactors if one becomes too large<br>• Reaction kinetics obtained from lab data |
| **Downstream Separation** | • Expected to be typical distillation tower with the associated re-boiler, condenser and pumps<br>• Tower separates out propylene-esters, trace propylene glycol, acetic acid, and water from bulk solution |
| **Post-Processing** | • Post-processing of Propylene-esters away from bulk solution avoids unnecessary oxidation of M(III)<br>• This step is assumed to be some sort complex distillation scheme. There is older literature to give a good idea of how this will be designed |
| **Balance of Plant** | • Product storage, raw material storage, ancillary, pumps, compressors, OSBL equipment |
| **Land** | • Estimated using the land requirements for typical process industry |

# Total Capital Investment (TCI) Estimation

| Equipment | Source and Costing |
|---|---|
| **Total Purchase Equipment Cost (TPEC)** | • Total Purchased Equipment Cost (TPEC) of reactors estimated from reactor design, weight of steel, required internals etc.<br>• Additional, major equipment includes Distillation towers. |
| **Total Installed Equipment Cost (TIEC)** | • TIEC = 1.4 x TPEC |
| **Total Direct Costs (DC)** | • DC = 1.6 x TPEC |
| **Total Indirect Costs (IC)** | • IC = 0.67 x TPEC |
| **Fixed Capital Investment (FCI)** | • FCI = TIEC + DC + IC |
| **Cost of Land (CoL)** | • CoL = 6% of FCI |
| **Contingency ($T_{Con}$)** | • $T_{Con}$ = 15% of FCI |
| **Total Capital Investment (TCI)** | **TCI = FCI + CoL + $T_{Con}$** |

# Annual Operation & Maintenance (OpEx) Assumptions

| Inputs | Base-Case and Sensitivity Ranges |
|---|---|
| **Feedstock Costs (Propylene)** | • Assumption: Polymer-grade Propylene<br>• Available Propylene costs corresponding to oil prices (Propylene assumed to be made from Naphtha cracking) |
| **Solvent Cost** | • Prices based on historical pricing data in the US |
| **OpEx due to Losses** | • Losses of solvent, oxidant etc. considered in terms of \$/tonne product<br>• Base-Case: No Losses<br>• Ranges: \$0-\$150/tonne |
| **Re-Oxidation Agent Cost** | • Assumed to be 50% (w/w) solution of $H_2O_2$ in water<br>• Bulk pricing available from commercial vendor sources |
| **Plant Utilities** | • Energy required calculated in a bottom-up method depending on unit operation conditions |
| **Operating Labor** | |
| **Maintenance & Repairs** | • Fixed Costs such as operating labor, maintenance & repairs and other miscellaneous costs were determined from the incumbent process for making propylene glycol (i.e. from propylene oxide). |
| **Miscellaneous** | |

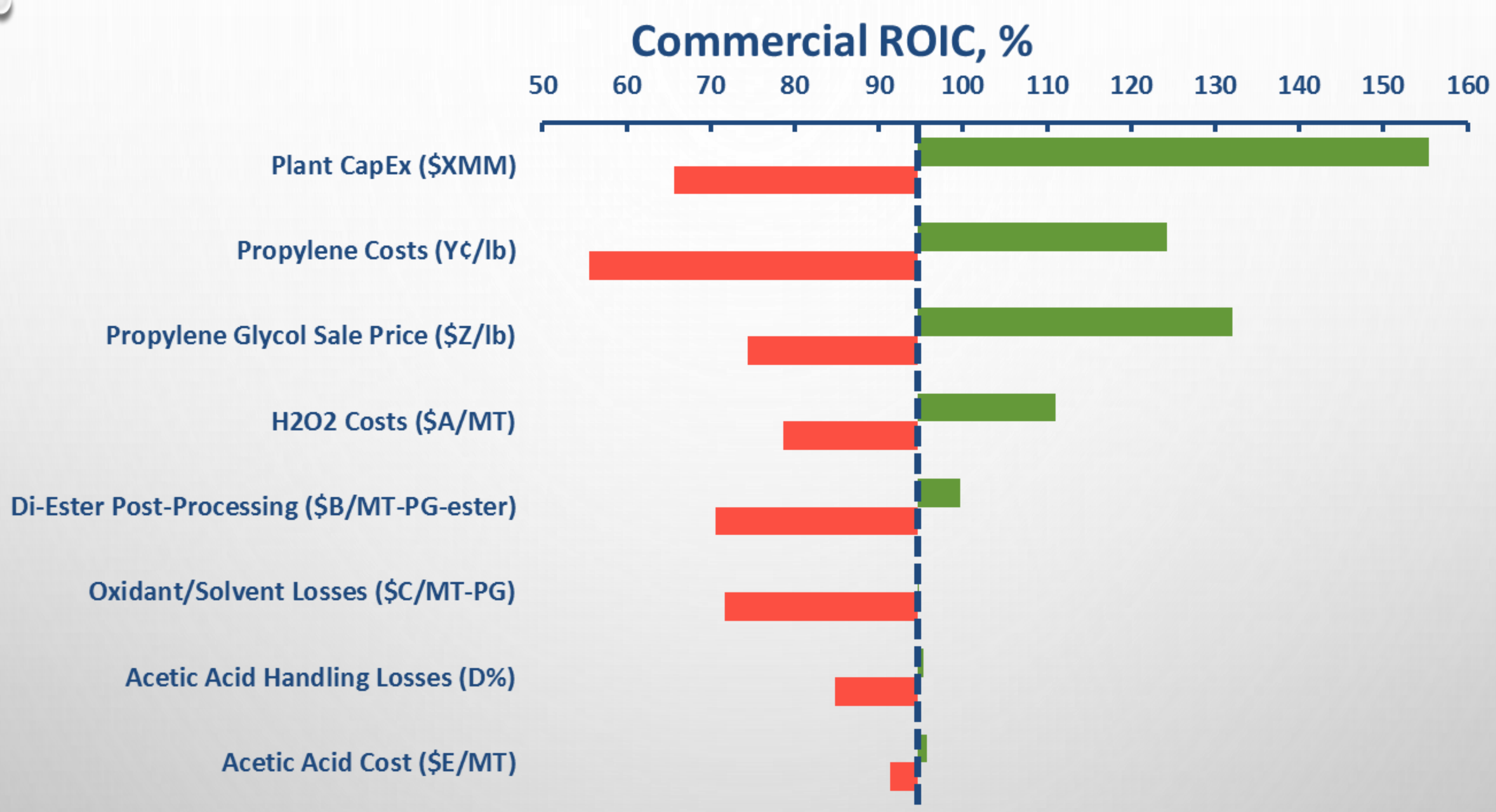
# Comparative Economics with Incumbent Process

| | New Process | Incumbent Process | MVP* Economics |
|---|---|---|---|
| **Product Capacity, tonne/yr** | **181,000** | **181,000** | **5,980** |
| **Total CapEx, $ millions** | **$103.5** | **$471.5** | **$19.4** |
| **Variable Costs of Production, ¢/kg** | **119.95** | **172.82** | **122.21** |
| Total Raw Materials | ***118.49*** | ***144.00*** | *119.46* |
| By Product Credits | *(0.00)* | *(21.96)* | *(0.00)* |
| Energy/Utilities | ***1.46*** | ***50.78*** | *2.75* |
| **Fixed Costs of Production, ¢/kg** | **17.87** | **30.15** | **43.21** |
| Maintenance & Repair | *1.11* | *5.90* | *6.87* |
| Operating Supplies & Labor | *1.11* | *2.35* | *12.46* |
| Plant Overhead, Taxes, Insurance, Lab, & Distribution | *15.65* | *21.90* | *23.88*** |
| **Product Value Calculations, ¢/kg** | | | |
| **Total Cash Cost of Production** | **137.82** | **202.97** | **165.42** |
| Depreciation-10 Year Straight Line | *5.44* | *24.01* | *30.79* |
| **Total Full Production Cost** | **143.26** | **226.98** | **196.21** |
| Return on Investment (To Drive a 25% ROI) | *14.30* | *65.12* | - |
| ***Total Product Value*** | ***157.56*** | ***292.10*** | ***196.21**** |

*MVP = Minimum Viable Plant
**ROIC not included in MVP calculation
***Assumption is that propylene glycol is sold at 196.21 ¢/kg

- To drive a 25% ROI, the incumbent process needs to value its product 1.9X higher than the new process.
- Put another way, if the new process sells at product value parity with the incumbent, the ROI would be 260%. Quite an attractive opportunity!

# Qualitative Example of Sensitivity Analysis



# Technical Risks That Must be Addressed

| Risk Item | Mainly Impacts: | Binary Risk? |
|---|---|---|
| Technical parameters like: Conversion, Selectivity to Products etc. | CapEx & OpEx | Yes |
| Commercial availability and non-toxic nature of consumables (e.g. solvents) | OpEx & Supply Chain | Yes |
| Any other losses (e.g. solvent evaporation, reactant oxidation, catalyst deactivation)? | OpEx | No |
| Can the process be demonstrated to run in a continuous fashion? If it must be run in batch operations what might this mean for the process scheme and ultimately the economics? | CapEx | No |
| Any scale-up risks? Proven commercial history of all unit-operations in the process scheme? | CapEx | No |
| Stability (thermal, mechanical, corrosivity) of the chemicals and materials involved?<br>Should the chemicals be sourced, or produced in-house? | Supply Chain, CapEx and possibly OpEx | Maybe |

# TE-Modeling Example 3: Assessing Factory Flow and Set-up

# Cost Models for Manufacturing Decisions

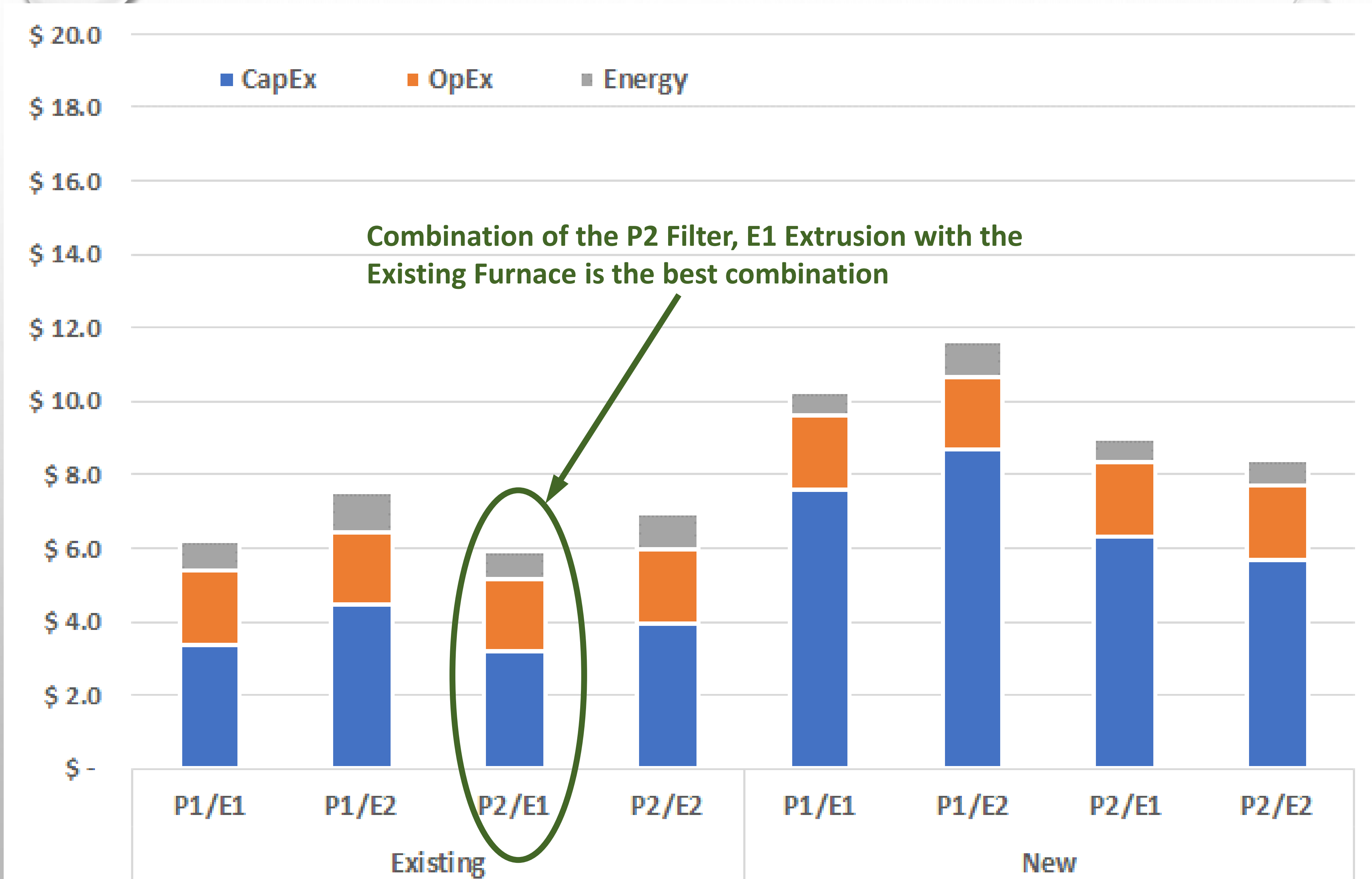
## Determine the optimum combination from the information below:

### Factory Process Flow


### Manufacturing Operations: Basic Technical Information

| | | | | |
|---|---|---|---|---|
| **Line Utilization** | **90%** | | | |
| **Market Sale Price, $/unit** | **$ 100** | | | |
| **Depreciation Period, yrs** | **10** | | | |
| **Energy Price, ¢/kWh** | **10** | | | |
| **Other OpEx, $/unit** | **$ 2.0** | | | |
| | | | | |
| **Process** | **Output, units/hr** | **Energy Req., kW** | **Step Yield** | **Equipment Cost** |
| **Filtering** | | | | |
| P1 | 3 | 5 | 100% | $ 300,000 |
| P2 | 5 | 10 | 100% | $ 500,000 |
| **Extrusion** | | | | |
| E1 | 4 | 7 | 100% | $ 500,000 |
| E2 | 7 | 15 | 100% | $ 750,000 |
| **Sintering Furnace** | | | | |
| Existing | 4 | 10 | 100% | $ - |
| New | 6 | 6 | 100% | $ 1,000,000 |

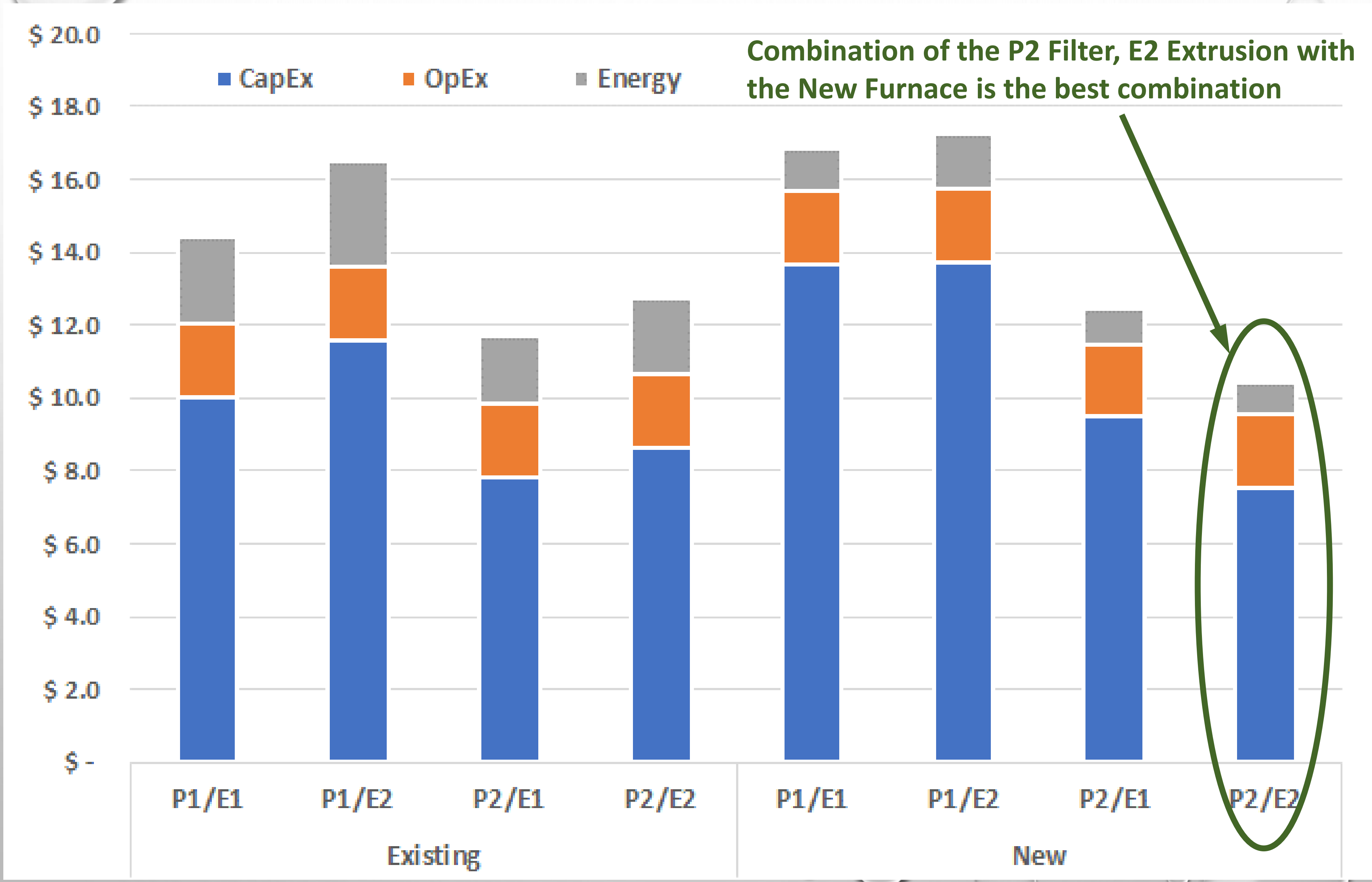
# Results: Minimizing the Production Costs



# BUT Process Qualification is Very Important!

| | | | | |
|---|---|---|---|---|
| **Line Utilization** | **90%** | | | |
| **Market Sale Price, $/unit** | **$ 100** | | | |
| **Depreciation Period, yrs** | **10** | | | |
| **Energy Price, ¢/kWh** | **10** | | | |
| **Other OpEx, $/unit** | **$ 2.0** | | | |
| | | | | |
| **Process** | **Output, units/hr** | **Energy Req., kW** | **Step Yield** | **Equipment Cost** |
| **Filtering** | | | Real | |
| P1 | 3 | 5 | 75% | $ 300,000 |
| P2 | 5 | 10 | 90% | $ 500,000 |
| **Extrusion** | | | | |
| E1 | 4 | 7 | 95% | $ 500,000 |
| E2 | 7 | 15 | 80% | $ 750,000 |
| **Sintering Furnace** | | | | |
| Existing | 4 | 10 | 80% | $ - |
| New | 6 | 6 | 99% | $ 1,000,000 |

# Results: Now They Say a Different Story



# Questions/Discussion