

Techno-economic Modeling: An efficient tool to assess/evaluate new technologies and products

Technical R&D
Objectives

TE Model
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Production
Cost
Calculations

Potential
Market
Criteria

Financial
Modeling

Used in

GAAP

Bill of
Materials

Mass/Energy
Balances

Inputs Flow into
the TE Model

Outputs Flow out of
the TE Model

Inputs Flow into
the Financial Model

Outputs Flow out of
the Financial Model

Inputs Flow into
the Production Cost Model

Outputs Flow out of
the Production Cost Model

Inputs Flow into
the Bill of Materials

Outputs Flow out of
the Bill of Materials

Inputs Flow into
the Mass/Energy Balances

Outputs Flow out of
the Mass/Energy Balances

Inputs Flow into
the Financial Model

Outputs Flow out of
the Financial Model

Dev Gavaskar: Brief Introduction

- Background in Chemical Engineering
 - ✓ Bachelors: Mumbai University, India
 - ✓ Ph.D.: Illinois Institute of Technology
- Partner at True North Venture Partners, since 2014
 - ✓ Primary role: Techno-Economic Modeling Principal
 - ✓ Secondary Roles: New Investment Opportunities, Engineering Leadership, Business & Strategic Development.
- Before TNVP, held multiple leadership roles across industries for technology scale-up & commercialization.
- Technical Advisor at Current Water (<http://https://www.currentwater.org/>)
- Have given this lecture here since 2015 and also give this lecture at Northwestern University (Kellogg School of Management, since 2018)



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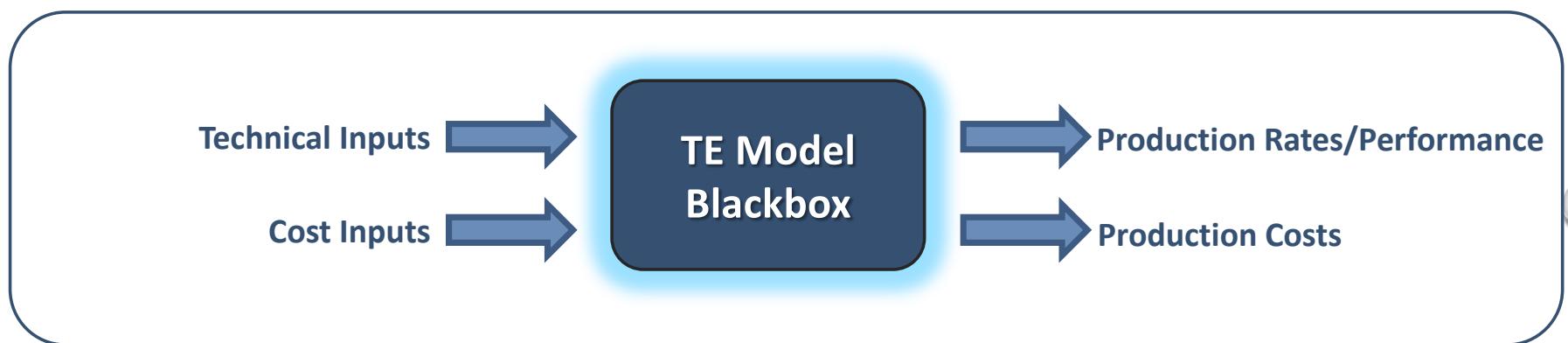
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Lecture Objectives

- 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 some 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

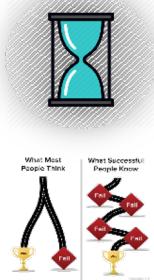


True North Overview



- Invests in and Develops Innovative Technologies and Businesses that could Reshape Core Industries and help the World Transition to a Clean & Sustainable Future.
- A 20-year History, to the founding and scale up of First Solar, a global leader in photovoltaics.
- We are well-funded (USD 700+ MM) and long-term oriented.

Strategy: Long-Term Value Creation



Invest early in the development of promising technologies



Execute “fast fail” programs



Commercialization using core engineering methodologies and strong entry markets



Scale rapidly to drive economies of scale and efficient learning cycles

Migrate from entry markets toward disruptive long-term opportunities

Core Capabilities



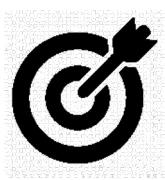
Technology assessment and development



Robust Engineering

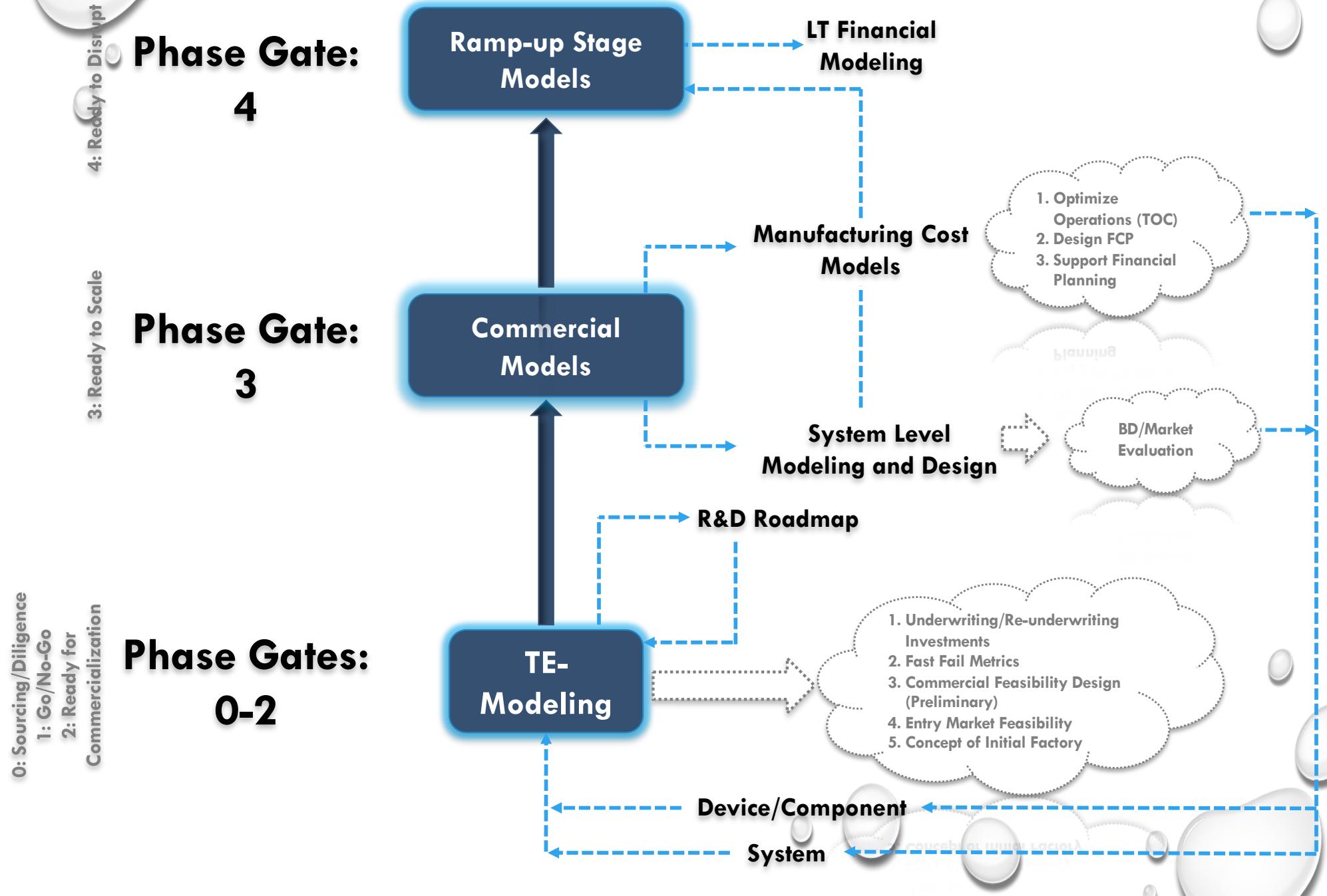


Organizational Excellence and Development



Strategic Marketing

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.

Levels of Techno-Economic Model: Extent of Rigors Needed

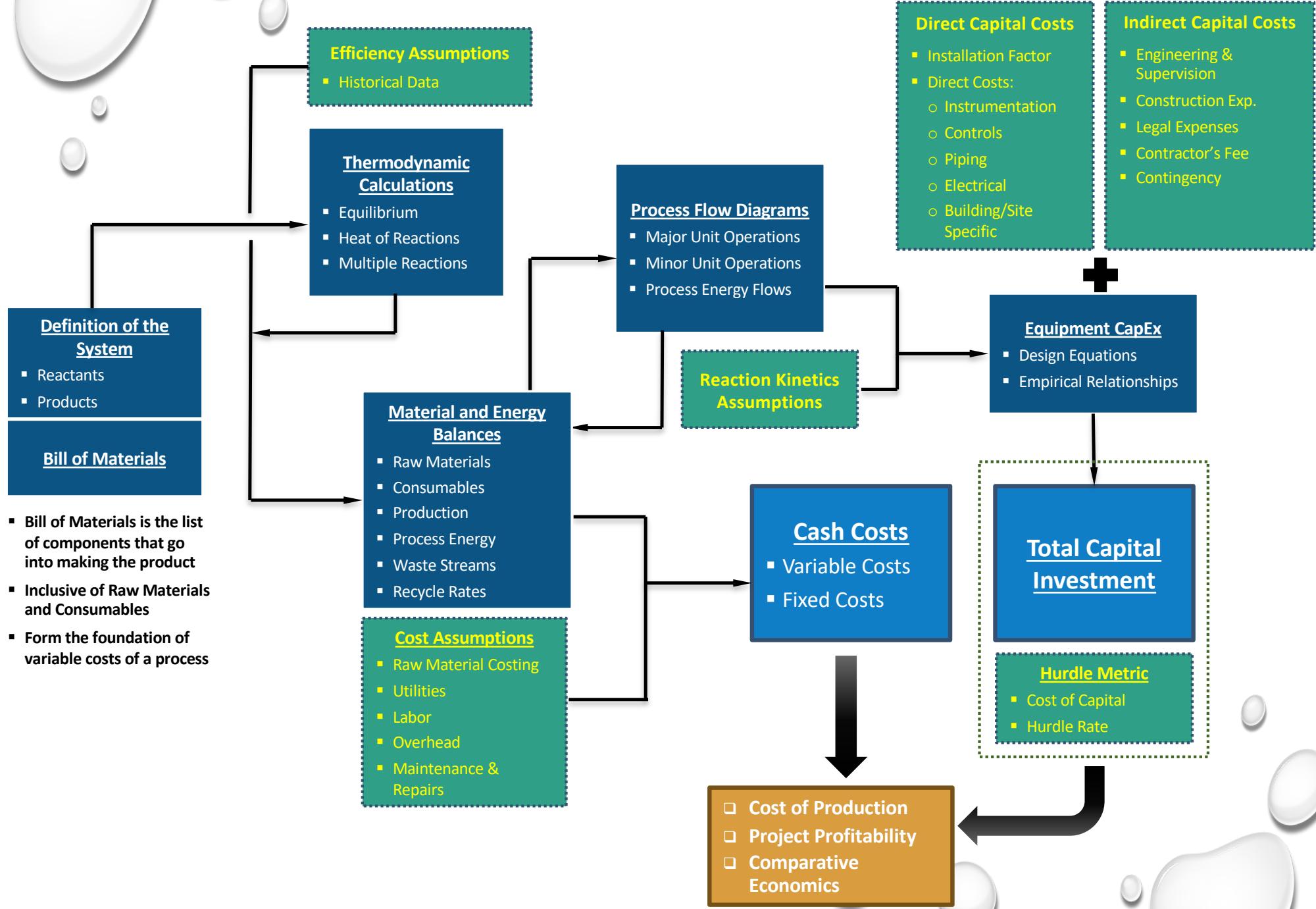
**Remember: Not every Technoeconomic Analyses needs to be overly complicated.
Your first objective is always to determine if the IDEA MAKES SENSE !!!**

- **Preliminary (Sniff Test/Binary Test):**
 - Analysis on absolute basics (e.g., reaction equations, Bill of Materials)
 - Compare incumbents with the new scheme on Variable Margin basis (i.e., difference of product price and raw material costs)
- **Moderate (most common to begin with):**
 - Perhaps a preliminary reaction scheme and production yields
 - Few adders for Fixed Costs (labor, power, M&R etc.)
 - Some initial capex estimates (from similar processes or manufacturing units)
- **Full/Comprehensive:**
 - Complete process block diagram
 - Efficiency Analyses to get a full idea of variable costs and fixed costs
 - Capital estimation (Level 1 through 3)

No Matter What the LEVEL of TEA – one should have clarity about:

- **Exact Problem to be Solved**
- **Uniqueness of the Solution**
- **Competition**

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			Fixed Costs		
What's included?	Where do we get it from?	Quantity Required	What's included?	Where do we get it from?	Quantity Required
		Cost Assumptions*			Cost Assumptions*
Raw Materials		<ul style="list-style-type: none"> ▪ Technical Reports ▪ Spot Pricing ▪ Preliminary Market Study ▪ Internet information (EIA database, press-releases etc.) ▪ Expert interviews ▪ Volume Costing considerations 	Direct Labor & Supervision (DL, S)	<ul style="list-style-type: none"> ▪ Similar Processes ▪ Bottoms-up model 	<ul style="list-style-type: none"> ▪ Costs mainly depend on Direct Labor and CapEx
Miscellaneous (e.g., Catalysts)			Supervision (S)	<ul style="list-style-type: none"> ▪ 15% of DL 	<ul style="list-style-type: none"> ▪ Labor Rate should be site specific
Process Energy	▪ Mass & Energy Balances		Plant Overhead	<ul style="list-style-type: none"> ▪ 50-60% of (DL + S) 	<ul style="list-style-type: none"> ▪ Further explanations and ranges can be found in: "Plant Design and Economics for Chemical Engineers; Peters, M., Timmerhaus, K., and West, R."
Process Consumables (e.g., Make-up fluids)			Maintenance & Repairs	<ul style="list-style-type: none"> ▪ 2-3% of TCI 	
Waste-Streams			Insurance & Taxes	<ul style="list-style-type: none"> ▪ 2% of FCI 	
Side-Products Credits			Lab Charges	<ul style="list-style-type: none"> ▪ 10% of OL 	
Incentives (e.g., RFS, LCFS, Carbon avoidance)			Operating Supplies	<ul style="list-style-type: none"> ▪ 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 $\pm 30\%$
Study	Knowledge of Major Equipment	Up to $\pm 30\%$
Preliminary	Sufficient data to permit estimate to be budgeted	Within $\pm 20\%$
Definitive	Almost complete data before drawings & specs.	Within $\pm 10\%$
Detailed	Complete engineering drawings, site surveys etc.	Within $\pm 5\%$

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
TCI = 3.2 * Purchased Equipment Cost			
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

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 "6/10th factor" rule, which is given by:

$$\text{CapEx}_{\text{Cap-2}} = (\text{Cap-2}/\text{Cap-1})^{0.6} * \text{CapEx}_{\text{Cap-1}}$$
- CapEx is also impacted by location factors. Generally; 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:

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

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

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

- 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.

Minimum Viable Plant (MVP): Concept

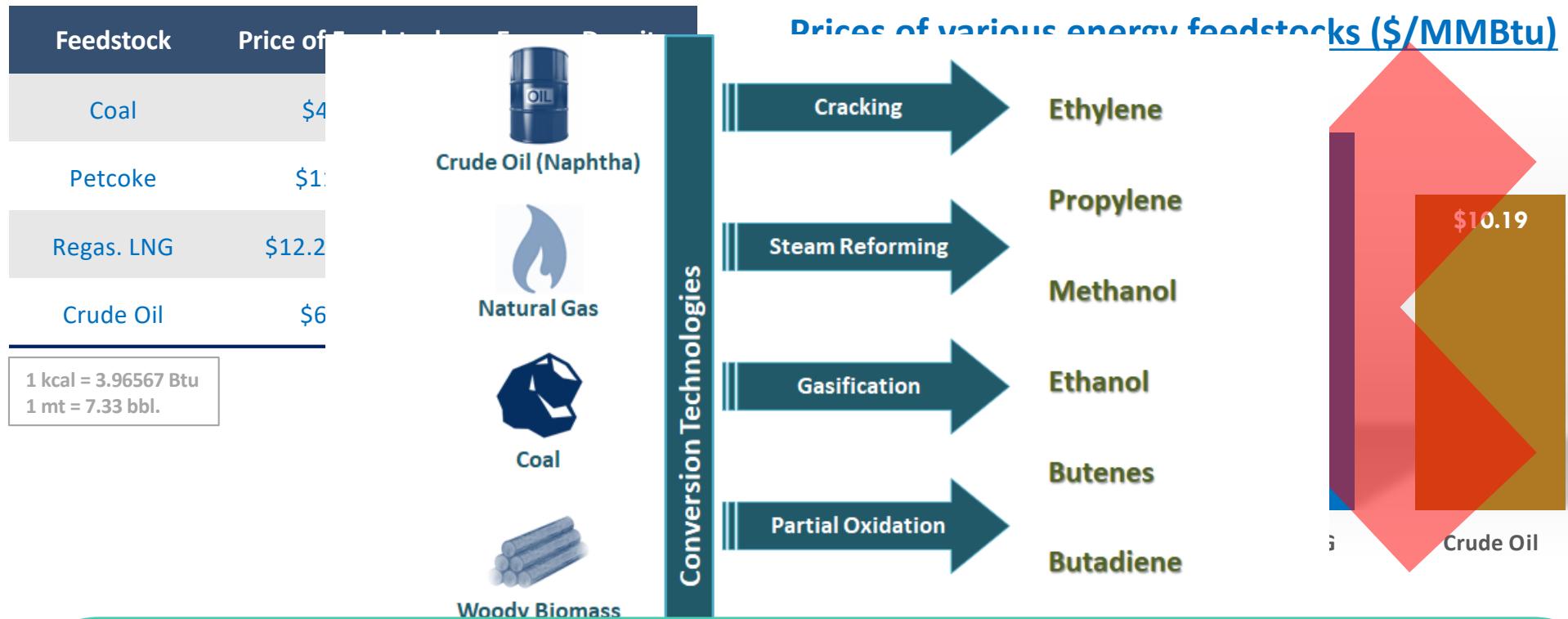
Definition: MVP is the scale that is “big” enough to **retire the scale-up risks** and “smallest” enough to **meet the ‘economic targets’**

- **Meet Economic Targets:** Meet a certain ‘Return on Capital Investment’: First target can be, e.g., Revenue **equal to** the ‘cash costs’ of the plant (i.e., ROIC = 0%)
- **Retire the Scale-up Risks:** This comprises of:
 - **Prove out technology....** Meet targets achieved in the lab that prove out economics.
 - **Prove out product....** First-gen product that can/will be accepted in the market.
 - **Procure Future Partnerships & Investments....** Proven technology eases the burden for the ‘commercialization’ plans of the technology
- **Other Advantage(s):**
 - Potential for use as a platform for technological pivots and developments

The Smaller the MVP the more economical & transformative your technology is...

Refresher Question – 1: Choice of feedstock

You have a technology that converts carbonaceous/fossil feedstocks into products – via different conversion techniques. Based on the information below, which feedstock will be the most advantageous for this technology? What is the assumption for your choice?



Main Assumption to Reach this Conclusion: Energy Efficiency of Conversion of all Feedstocks to Syngas IS THE SAME!

Refresher Question – 2: Electrolysis

An electrolyzer technology, splits water into hydrogen and oxygen using electricity.

Which of the below choices form the main variable cost components of the process?

- Instrumentation & Controls
- Water
- Electricity
- Current Collectors & Separators
- None of the Above
- All of the above

Note: The general working of an electrolyzer constitutes of a degradation rate of the electrodes at some rate. After the degradation rate has fallen below a certain level, the “stack” is replaced. The “stack” comprises of the entire assembly of the coated electrodes. As is expected, to keep costs low one would want the degradation rate to be as low as possible

Variable costs, by definition, refer to the expenses directly associated with the production. These costs include expenditures for raw materials, consumables, process energy and utilities.

TE-Modeling Example 1: 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 institute. 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



Hydrolysis of Propylene Compound (After Distillation)

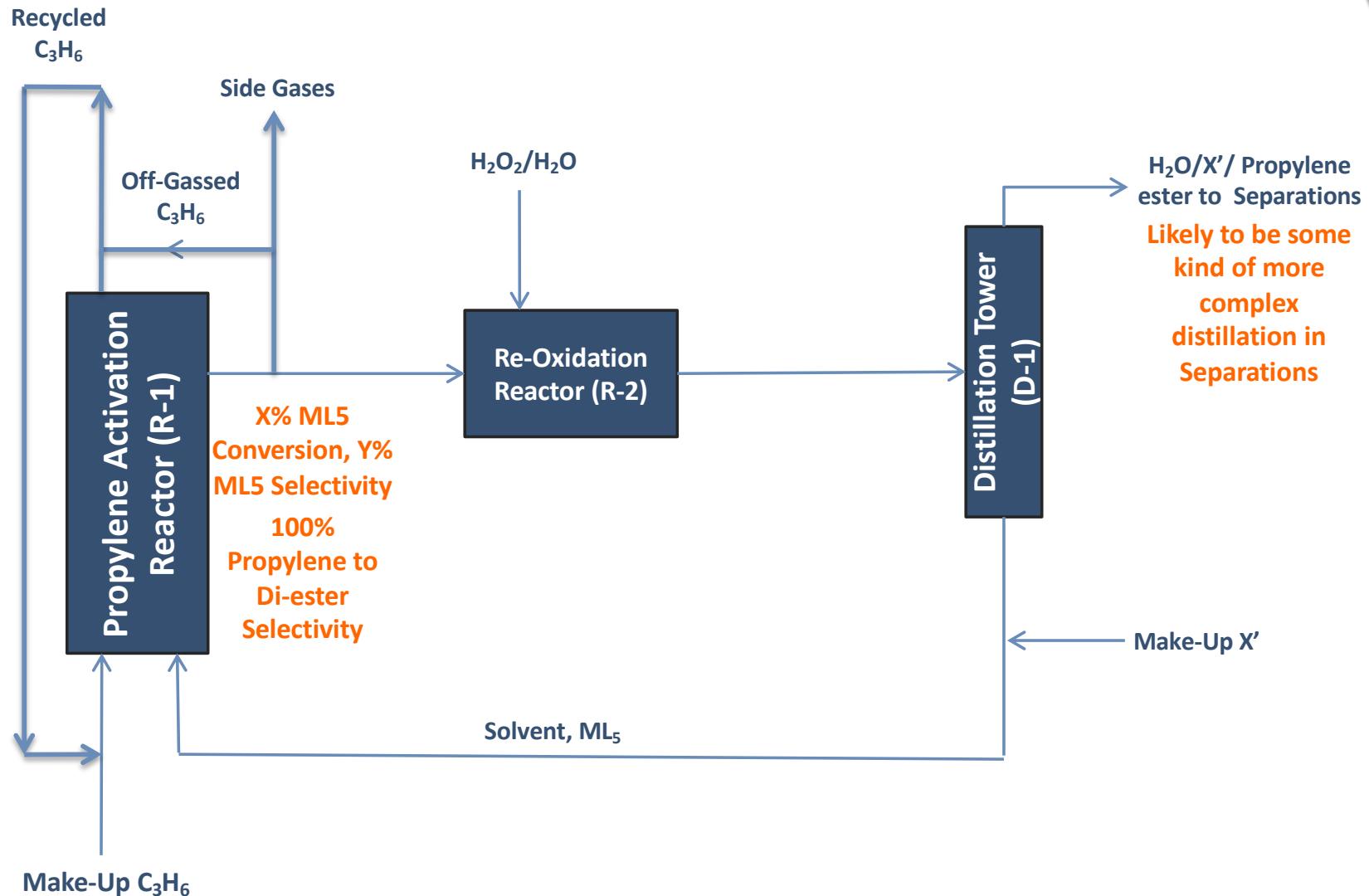


Re-Oxidation of Metal Complex



- 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 ₃ H 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 ₃ H ₂	0	193,096	193,096	0	0	0	0	0
C ₂ H ₄ O ₂	122,738	92,107	92,107	92,107	92,107	92,107	122,738	92,107
C ₃ H ₆ (C ₂ H ₃ O ₂) 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 ₂ O	4,633	4,633	4,633	13,824	13,824	13,824	4,633	13,824
C ₃ H ₆ (OH) ₂	0	0	0	0	0	0	0	0
H ₂ O 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 performed 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	<ul style="list-style-type: none">Designed as a bubble column reactor (BCR), with X% M conversion and Y% selectivity of M to propylene di-acetic estersReaction kinetics obtained from lab dataPressure, propylene feed rate, and Temperature calculated to achieve the required conversion in the given residence time
Flash Tanks	<ul style="list-style-type: none">Two vertical flash tanks designed after the BCR to flash off all remaining propylene in solutionSized according to the Souders-Brown equation for maximum allowable vapor velocity
Re-Oxidation Reactor	<ul style="list-style-type: none">Ideal CSTR. Model splits one reactor into multiple, parallel reactors if one becomes too largeReaction kinetics obtained from lab data
Downstream Separation	<ul style="list-style-type: none">Expected to be typical distillation tower with the associated re-boiler, condenser and pumpsTower separates out propylene-esters, trace propylene glycol, acetic acid, and water from bulk solution
Post-Processing	<ul style="list-style-type: none">Post-processing of Propylene-esters away from bulk solution avoids unnecessary oxidation of M(III)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	<ul style="list-style-type: none">Product storage, raw material storage, ancillary, pumps, compressors, OSBL equipment
Land	<ul style="list-style-type: none">Estimated using the land requirements for typical process industry

Total Capital Investment (TCI) Estimation

Equipment	Source and Costing
Total Purchase Equipment Cost (TPEC)	<ul style="list-style-type: none">• Total Purchased Equipment Cost (TPEC) of reactors estimated from reactor design, weight of steel, required internals etc.• Additional, major equipment includes Distillation towers.
Total Installed Equipment Cost (TIEC)	<ul style="list-style-type: none">• $TIEC = 1.4 \times TPEC$
Total Direct Costs (DC)	<ul style="list-style-type: none">• $DC = 1.6 \times TPEC$
Total Indirect Costs (IC)	<ul style="list-style-type: none">• $IC = 0.67 \times TPEC$
Fixed Capital Investment (FCI)	<ul style="list-style-type: none">• $FCI = TIEC + DC + IC$
Cost of Land (CoL)	<ul style="list-style-type: none">• $CoL = 6\% \text{ of FCI}$
Contingency (T_{Con})	<ul style="list-style-type: none">• $T_{Con} = 15\% \text{ of FCI}$
<u>Total Capital Investment (TCI)</u>	<u>$TCI = FCI + CoL + T_{Con}$</u>

Annual Operation & Maintenance (OpEx) Assumptions

Inputs	Base-Case and Sensitivity Ranges
Feedstock Costs (Propylene)	<ul style="list-style-type: none">Assumption: Polymer-grade PropyleneAvailable Propylene costs corresponding to oil prices (Propylene assumed to be made from Naphtha cracking)
Solvent Cost	<ul style="list-style-type: none">Prices based on historical pricing data in the US
OpEx due to Losses	<ul style="list-style-type: none">Losses of solvent, oxidant etc. considered in terms of \$/tonne productBase-Case: No LossesRanges: \$0-\$150/tonne
Re-Oxidation Agent Cost	<ul style="list-style-type: none">Assumed to be 50% (w/w) solution of H₂O₂ in waterBulk pricing available from commercial vendor sources
Plant Utilities	<ul style="list-style-type: none">Energy required calculated in a bottom-up method depending on unit operation conditions
Operating Labor	
Maintenance & Repairs	<ul style="list-style-type: none">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	<u>119.95</u>	<u>172.82</u>	<u>122.21</u>
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	<u>17.87</u>	<u>30.15</u>	<u>43.21</u>
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***

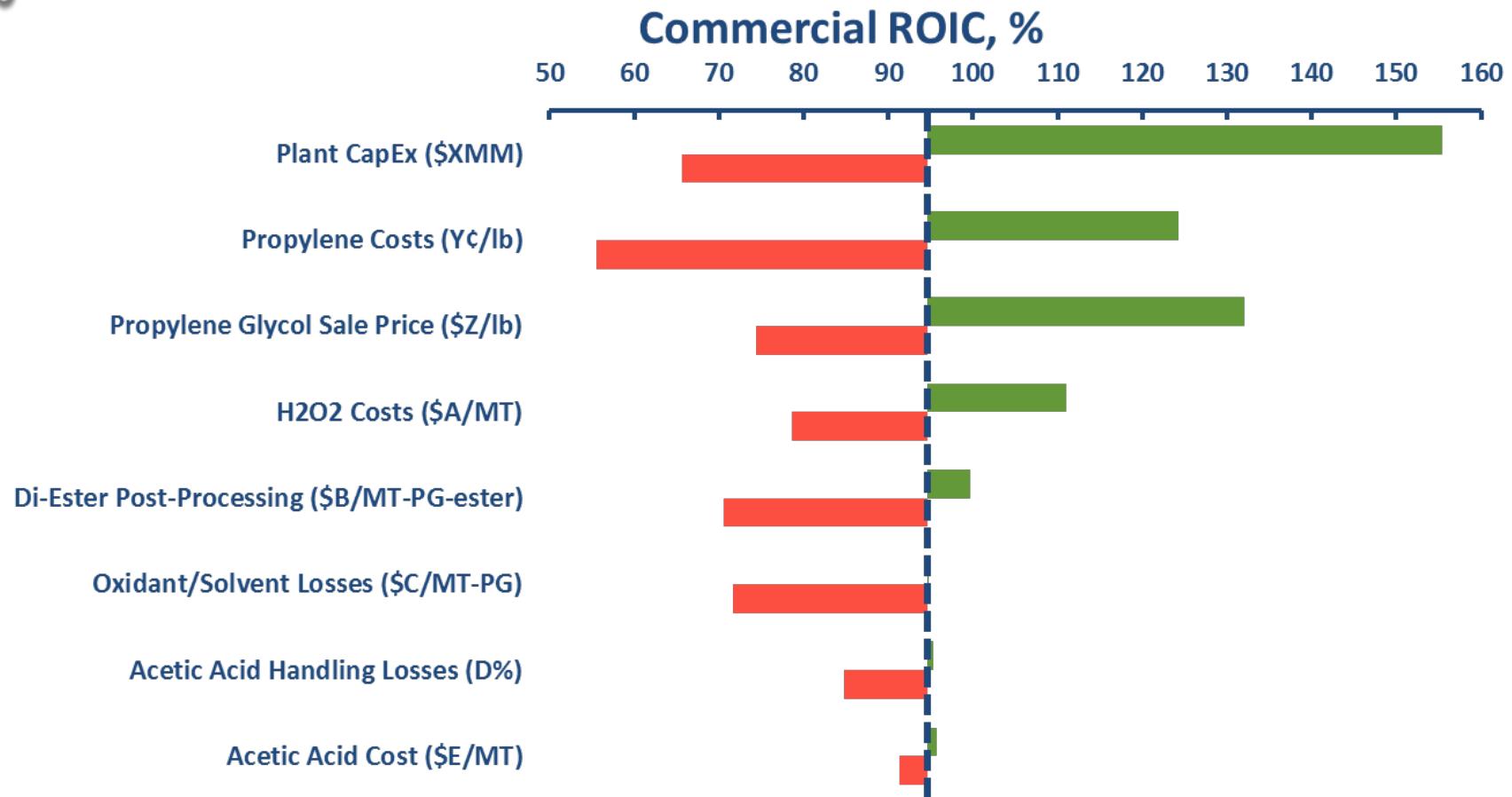
*MVP = Minimum Viable Plant

**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

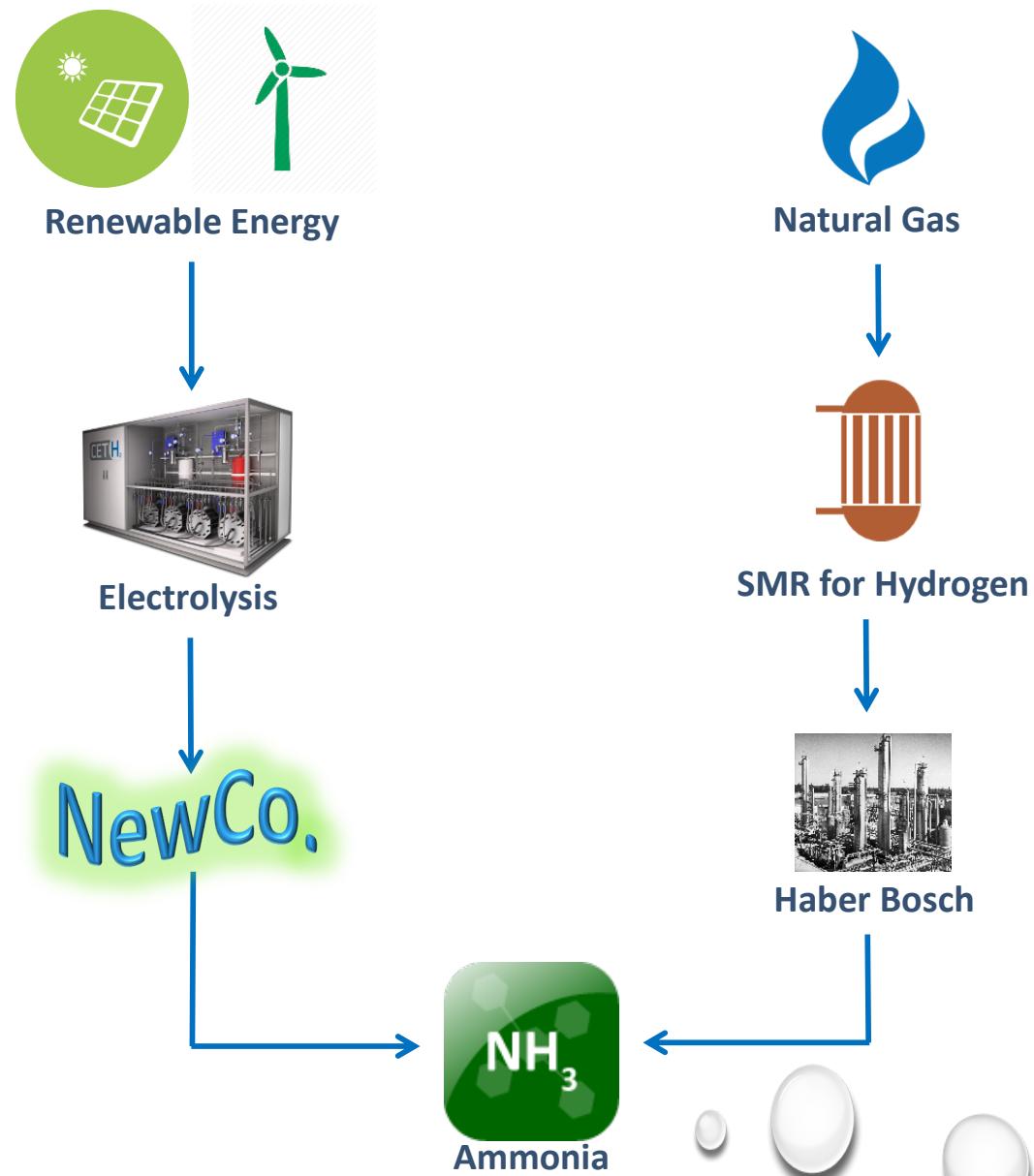


Technical Risks That Must be Addressed

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? Should the chemicals be sourced, or produced in-house?	Supply Chain, CapEx and possibly OpEx	Maybe

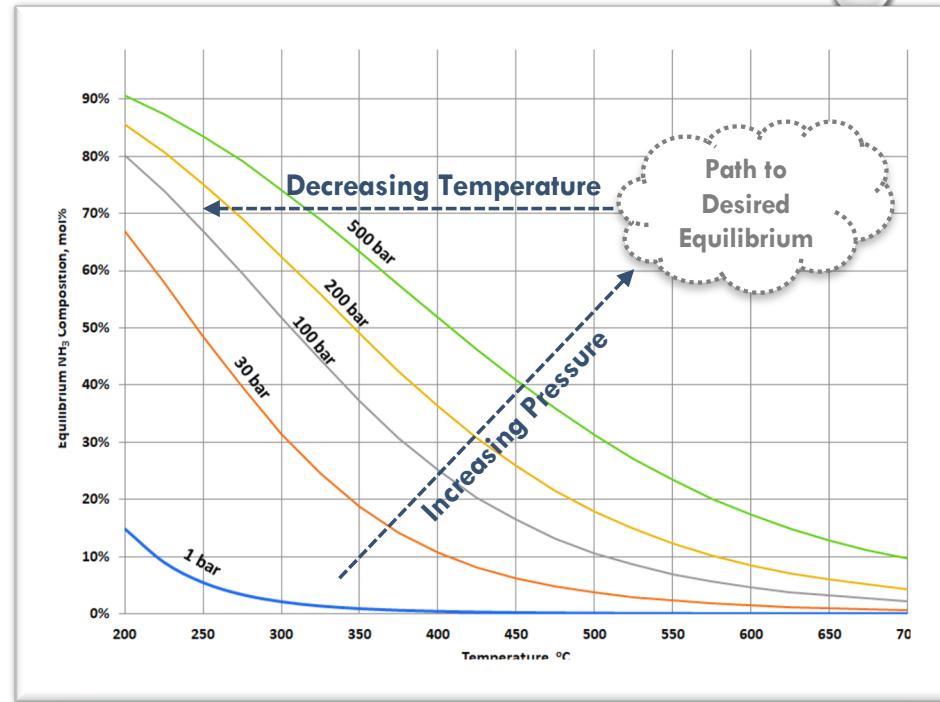
TE-Modeling Example 2: CapEx Affordability

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:
 - $\text{N}_2(\text{g}) + 3\text{H}_2(\text{g}) = 2\text{NH}_3(\text{g})$
- 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 $\sim 450^\circ\text{C}$ and pressures of $\sim 200\text{-}220 \text{ atm}$. 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 \propto Pressure

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

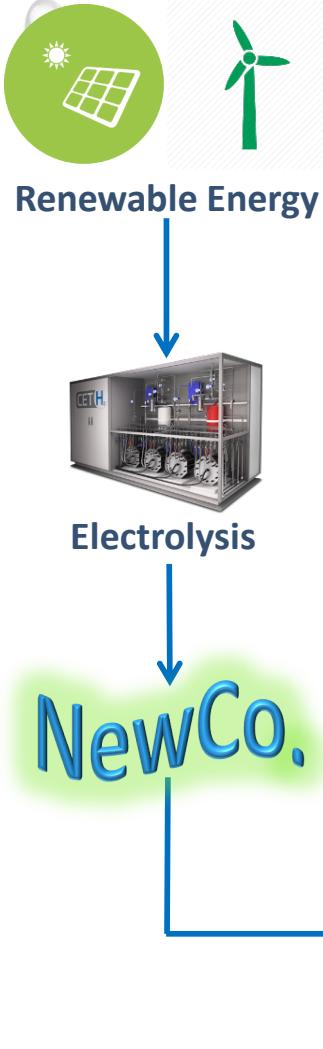
An Alternative that can improve reaction kinetics at lower temperatures and still leverage the equilibrium benefit at reasonable pressures, is hence interesting

Questions to be Answered:

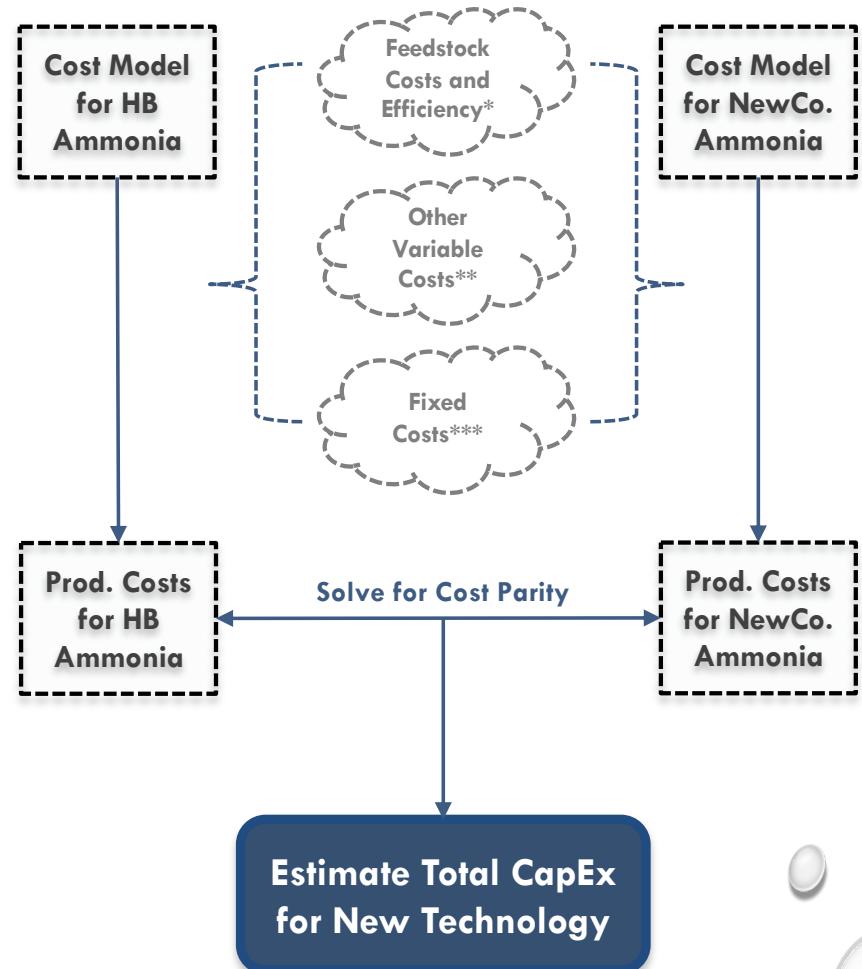
- At the given operating conditions what is the efficiency of the NewCo. Process?
- What are the main factors that the economics of the process are heavily dependent on? Some of these may include:
 - Catalyst Costs and Replacement Intervals
 - Efficiency of the Electrolyzer
 - Capital Cost of the Electrolysis 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

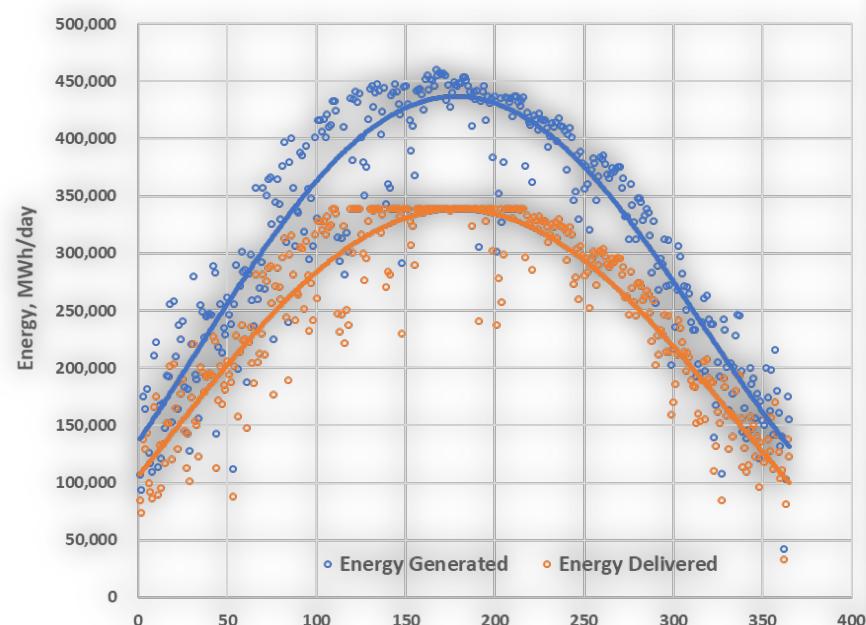


CapEx Affordability Analyses



Calculating the Electrolyzer Size Requirement*

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



Design Parameters:		<u>Remarks</u>
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, MMNm ³ /yr	592	-
Corresponding Electrolyzer Rating, MW ⁸	-	288
Total Capital Investment	\$ 327	\$ 143
<i>Hydrogen Generation Section, \$MM ⁹</i>	<i>\$ 132</i>	<i>\$ 86</i>
<i>Ammonia Synthesis Section, \$MM</i>	<i>\$ 195</i>	<i>\$ 26 ¹⁰</i>
Total Production Costs (12% ROIC), ¢/kg	39.96	39.96
<i>Feedstock Costs, ¢/kg ¹¹</i>	<i>10.53</i>	<i>32.77</i>
<i>Other Variable Costs, ¢/kg</i>	<i>1.37</i>	<i>1.31</i>
<i>Total Fixed Costs, ¢/kg ¹²</i>	<i>7.74</i>	<i>4.79</i>
<i>Depreciation/Sust. CapEx, ¢/kg ¹³</i>	<i>10.89</i>	<i>0.86</i>
<i>Profit @ 12% ROIC, ¢/kg ¹⁴</i>	<i>13.06</i>	<i>1.55</i>

Notes:

- Calculated from available mass and energy balances of a world-scale SMR. Based on LHV of natural gas. SMR Process efficiency is ~82%
- Calculated from energy requirement of electrolysis of 50kWh/kg (Electrolyzer Efficiency: ~79%)
- Energy Requirements for Haber Bosch process determined from theoretical calculations and SRI PEP Economics (Overall Thermal Efficiency: 87.7%; Theoretical to Actual Ratio)
- Estimated from Stoichiometry and assuming 5% losses in recycle, product separation & recovery etc.
- Estimated from thermodynamic equilibrium
- Preliminary research shows that this is a typical plant size of an ammonia plant based on this process
- Plant based on this technology assumed 100 kmtpy smaller than the incumbent plant
- Calculated by minimizing leveled cost of hydrogen production for the given electrolyzer efficiency and a typical solar load profile.
- SMR CapEx calculated from the SMR TE-model. Electrolyzer CapEx calculated based on an installed electrolyzer CapEx cost of \$300/kW
- Ammonia Synthesis CapEx section for NewCo is the “Maximum Affordable CapEx” needed to equalize the total production costs of ammonia from the two processes.
- Natural Gas: \$3.5/MMBtu, Renewable Electricity: 2.5¢/kWh. Feedstock costs for Starfire is the leveled 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.
- 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.
- 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
- ROIC for NewCo calculated only for the Ammonia Synthesis Section

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

Cost Models for Manufacturing Decisions

Determine the optimum combination from the information below:

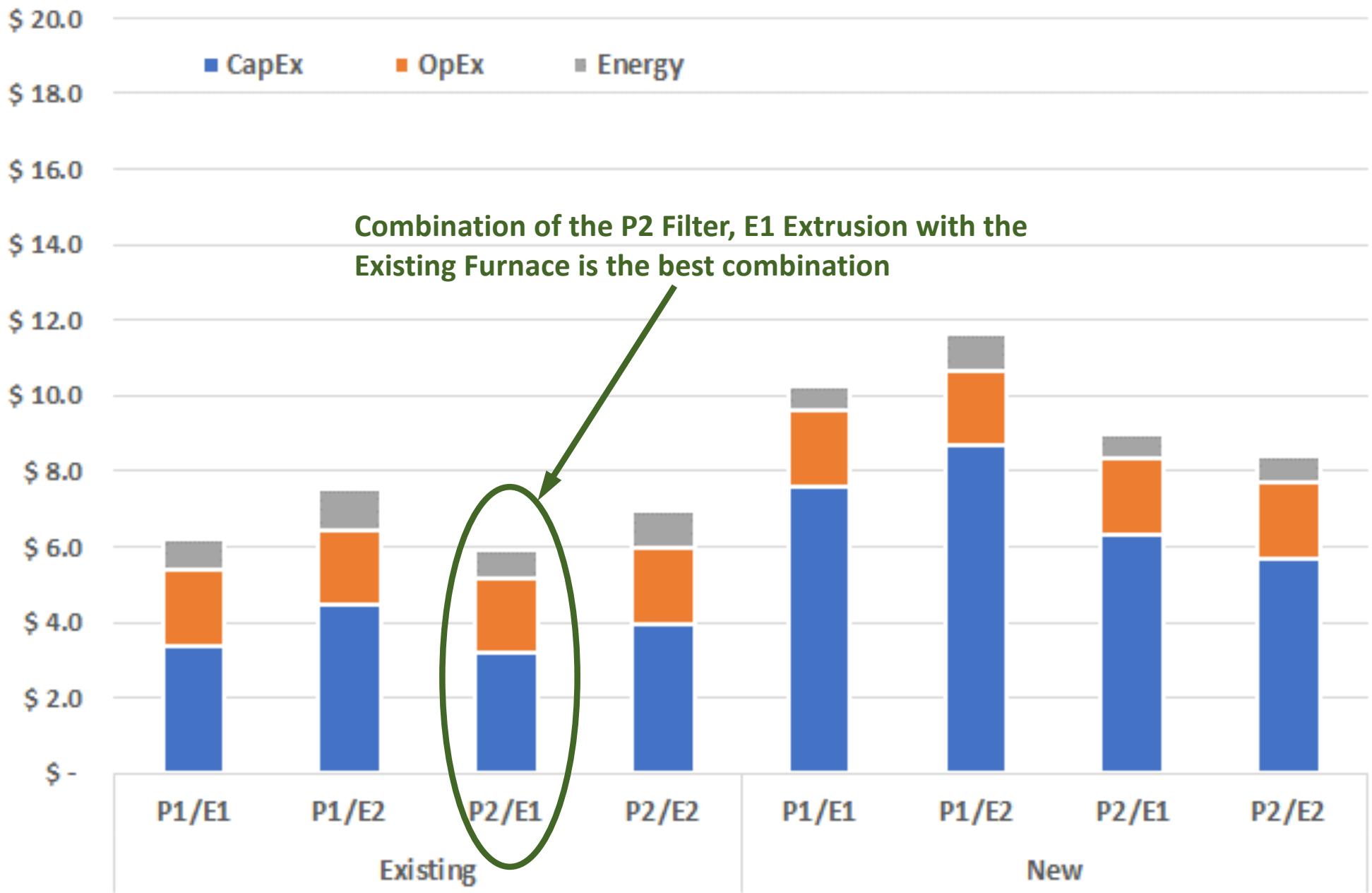
Factory Process Flow



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	

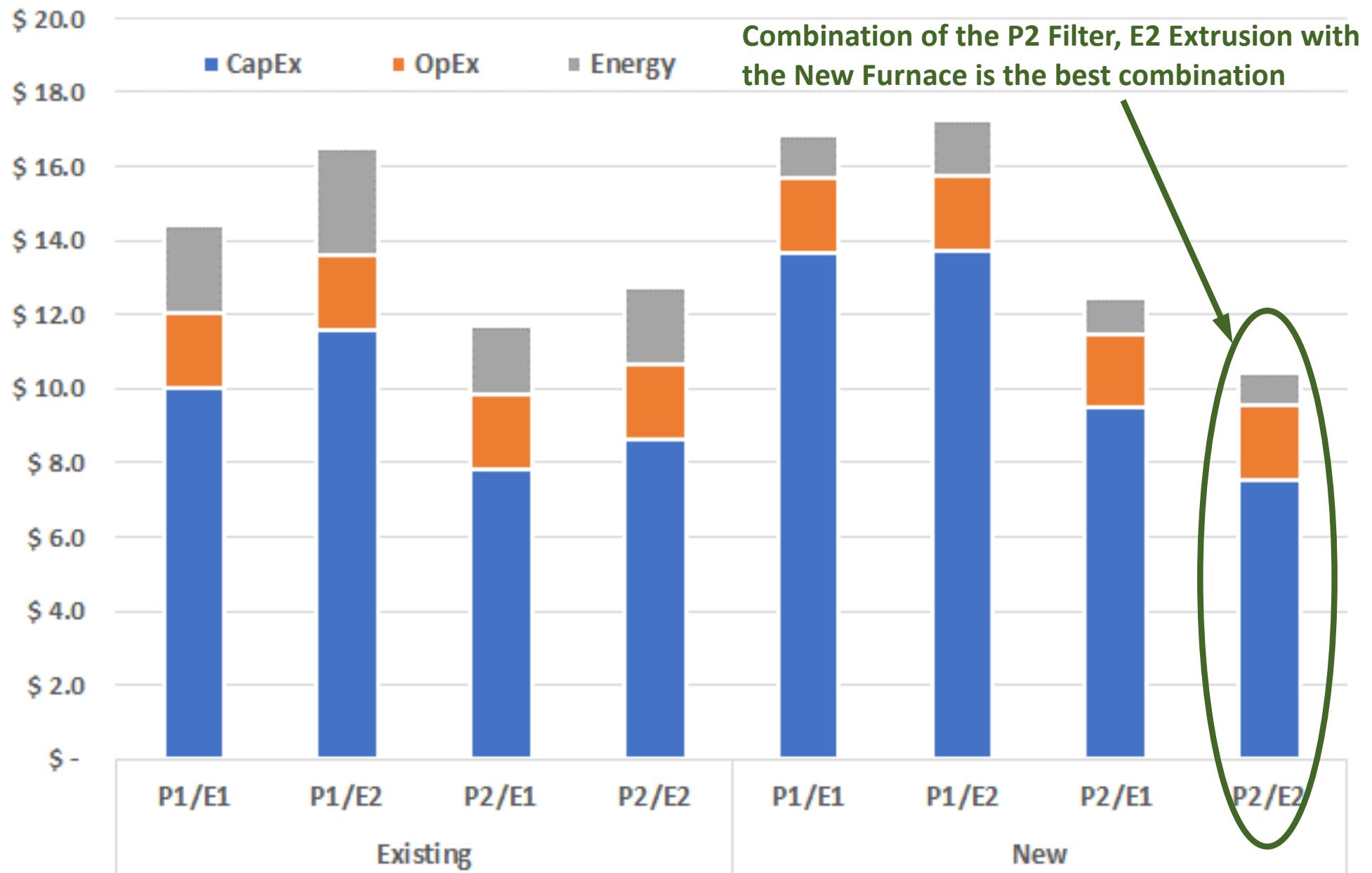
Results: Minimizing the Production Costs



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

