Techno-economic Modeling: Cost Modeling & Capital Efficient Scaleup

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Techno-Economic Modeling Principal

True North Venture Partners

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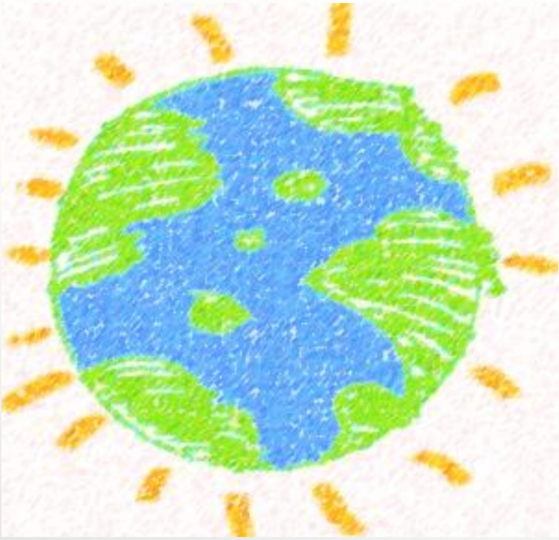
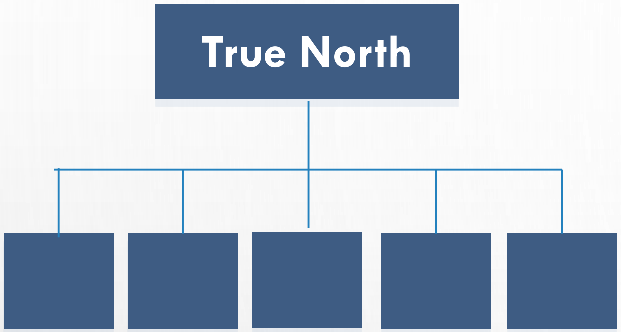


We are developing an interconnected and symbiotic set of innovative technologies and businesses that will reshape core industries and help the world transition to a clean and sustainable future

- Sectors that provide products and services vital to economic growth and social advancement – such as **energy, water, fuels and chemicals** – will not scale to meet future demands using legacy technologies and business models
- True North's roots trace back to the founding and scale up of **First Solar, Inc**. We are expanding on that experience to build a **portfolio of innovative technologies and businesses** that will reshape these core industries and help the world transition to a clean and sustainable future
- The **Ahearn family, members of the Walton family, Ted Turner and Cox Enterprises** have committed $700 million of equity and formed True North as a perpetual holding company with the ability to re-invest profits back into new business opportunities

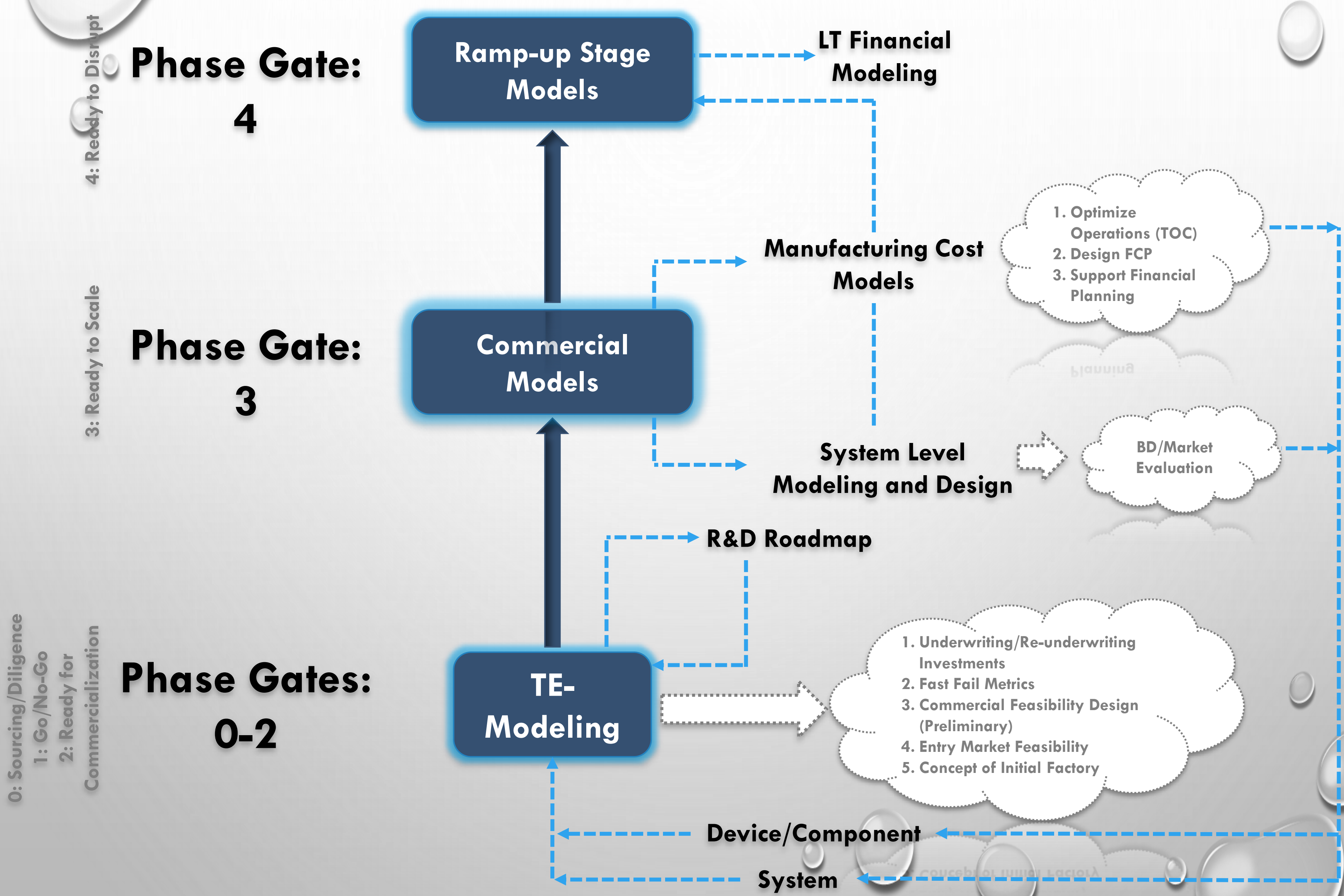
True North Venture Partners: Our Approach



We are building businesses that fit strategically and symbiotically into the overall vision we are bringing to fruition

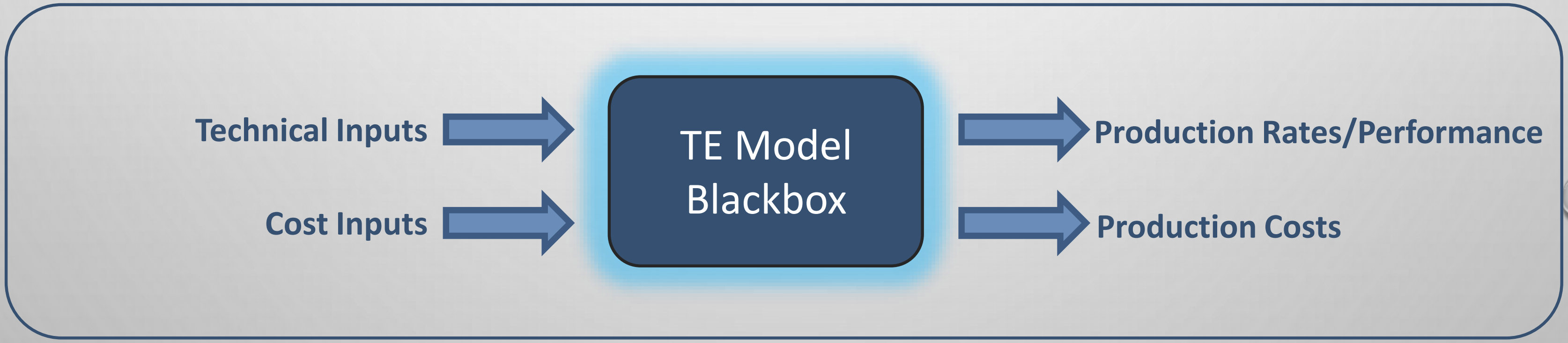
- ***Strategically Selected Businesses:*** Transformative businesses that fit strategically and symbiotically into our overall vision for the future with the intent to build, own and operate them together over the long term
- ***Integrated Under a Common Operating Platform:*** Businesses with a common culture and set of operating principles, with inter-business team collaboration to stimulate creativity, accelerate learning and exploit symbiotic technological and commercial opportunities
- ***Talent Development:*** Attracting top talent and developing the high performing people in our businesses to their full potential through structured talent development plans and programs
- ***Thorough Investment Underwriting:*** Investments based on strict criteria and supported by detailed **techno-economic models**, which are frequently revisited over the course of early stage development
- ***Structured Risk Management:*** We employ a structured risk management process that forces early failures and assures that capital flows inversely to risk levels
- ***Fast Scale Playbook:*** We accelerate commercialization and scale-up with time-proven engineering, project management, strategic marketing and operating methodologies that are deployed across our companies

TE-Modeling and Investment Phases



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
    - Additionally, show that it can 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



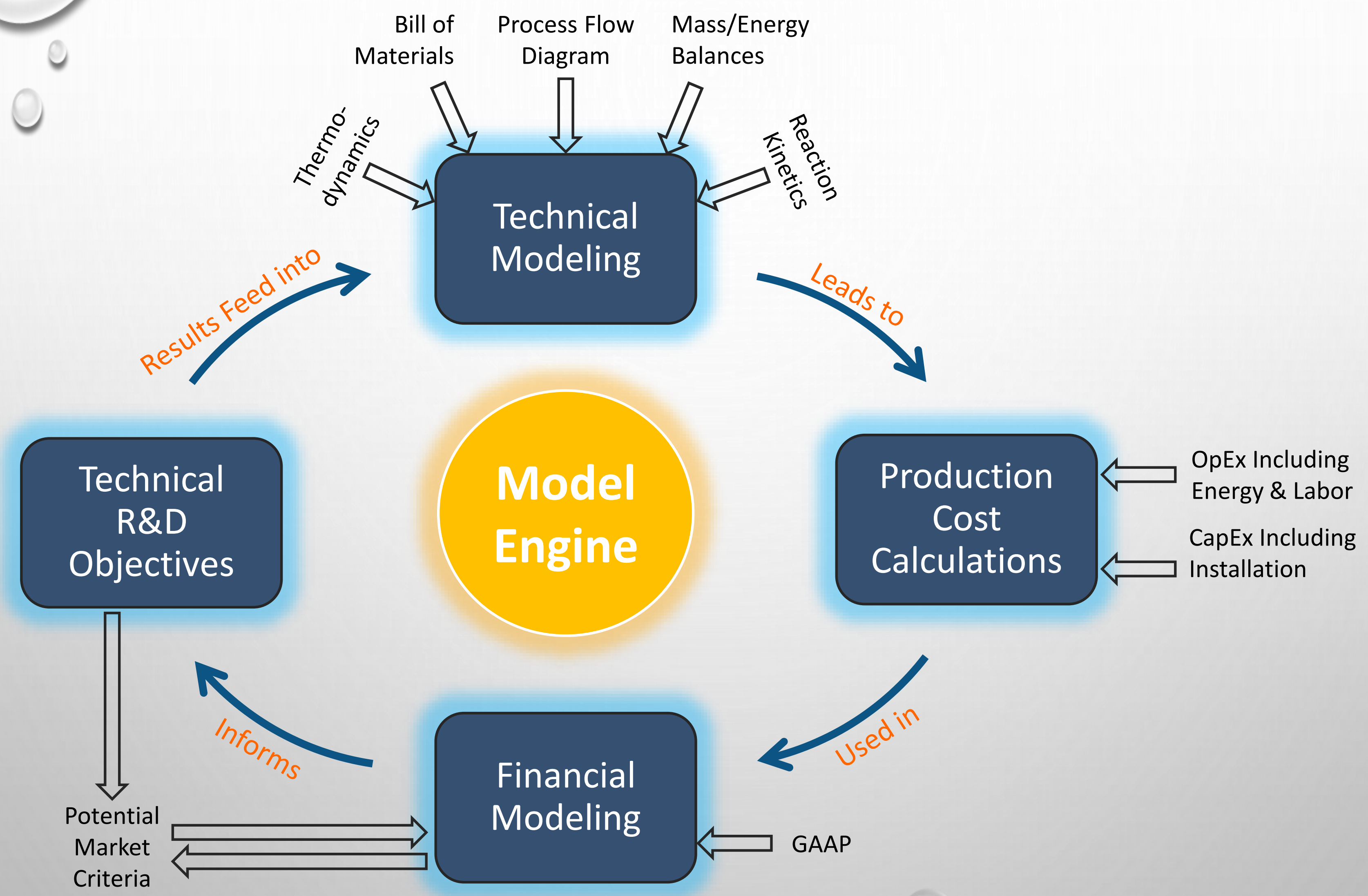
What is a TE Model?

- A special type of dynamic cost model where the output is calculated from/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.)

- A tool useful in providing quantifiable answers to whether a new technology can scale up sufficiently into market, and achieve business objectives.
  - **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.**

- 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?

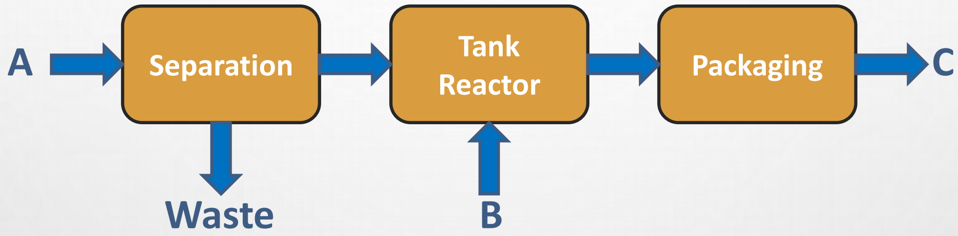
What Goes into a Complete TE Model System



Technical Modeling

- First step to modeling a technical process is assembling a bill of materials (BOM).
  - The BOM is an exhaustive list of materials that will go into the final product
    - If you are interested in producing a chemical, C, and you know it is created by the following equation: **A + B → C**, then your BOM would be A and B.

- Next step is developing a process scheme, that adheres to the principles of chemical engineering and results in a product of appropriate specifications (e.g. purity)



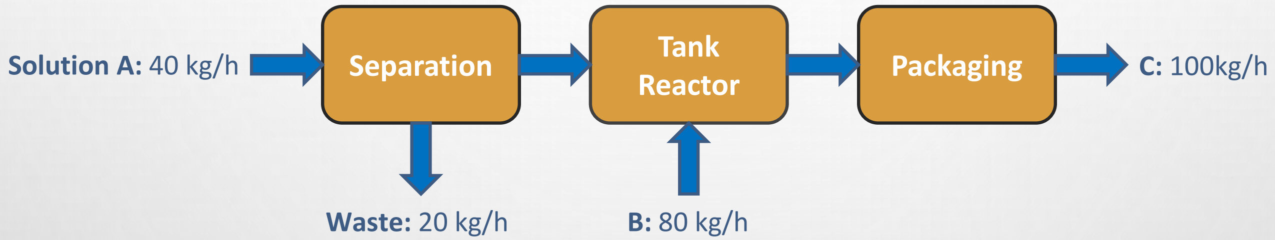
- The developed process scheme will inadvertently become more complex as the project develops, but this sets up the groundwork for developing a mass and energy balances.
  - Balancing mass is as simple as obeying the following equation for all components involved

$$\textbf{Input} - \textbf{Output} + \textbf{Generation} - \textbf{Accumulation} = 0$$

  - Often times Accumulation will not be important and Generation will not matter for a non-chemical process, which reduces the equation down to the simpler and more immediately intuitive: **Input = Output**

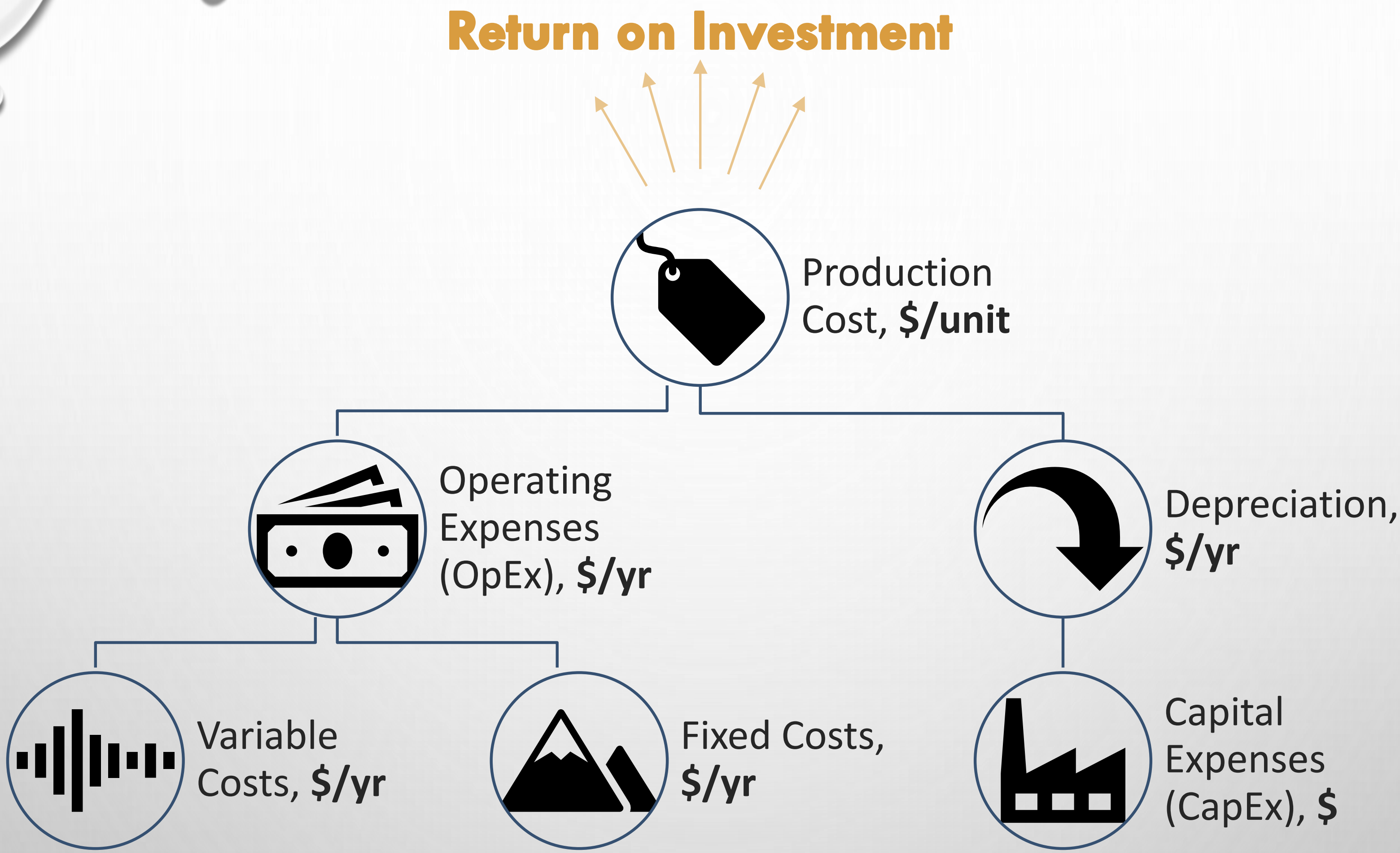
Technical Modeling (contd.)

- To build off of our theoretical process, an example of a developed mass balance on the following basis is give below
  - Production rate of C is required to be 100 kg/h
  - Each component has the following molecular mass: A = 10 kg/kmol; B = 40 kg/kmol; C = 50 kg/kmol
  - Component A comes in as a solution that is 50% by weight, with the other 50% mixed in as water



- To do a mass balance check on the entire system, we simply need to make sure that the inputs are equal to the outputs:
  - 40 + 80 = 20 +100 → **120 = 120**; it checks out.
- Performing an energy balance on a system is similar, where the above calculations are performed based on Enthalpy of the constituting species.
- Completing mass and energy balances will lead directly into calculating production costs for a given process.

Production Costs



Bill of Materials | Process Scheme | Mass & Energy Balances

Production Costs: Cash Costs

- OpEx are recurring expenses, usually measured on an annual basis and categorized into:
  - Variable Costs:
    - Costs that vary with product output (i.e. process efficiency); e.g. cost of ink for a pen manufacturer
    - Mass and Energy balances give required quantities for all materials, and variable costs can be calculated by knowing the unit cost of each material.
      - For things like commodities or relatively abundant materials, historical data is usually widely available and the preferred method to use for determining unit costs.
      - If unit costs of certain materials are not easily found, start with an educated guess, and verify assumptions over time.
  - Fixed Costs:
    - Static costs that do not change with process efficiency; e.g. operating labor, scheduled equipment maintenance, overhead, taxes & insurance etc.
      - Estimating labor, overhead and maintenance costs (which form the majority of the Fixed Costs) can be done in many ways: Extrapolating from projects of a similar nature, using methods from credible process design textbooks, or most rigorously calculating costs through a complete bottoms up approach.

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

Production Costs: CapEx Estimation

- Estimating CapEx for a process can be done in many ways:
  - Cost per unit of capacity for a similar plant (e.g. $/kWh for a battery),
  - Lang factors for installation costs,
  - Power factors applied to capacity ratios (if estimates on scaling up or down are needed),
  - Detailed, itemized bottoms up approach of calculating capital expenditures.

- Bottoms up approaches require relatively intimate knowledge of the details for each unit operation;
  - For instance, understanding the kinetics of a chemical process to be able to size a reactor, or knowing the specific temperatures, pressures, corrosion rates of the process fluids, so the correct grades of steel can be chosen for certain tanks, vessels, or product housings.

- Depreciation is a function of CapEx, and can be calculated simply as straight line depreciation or by any other depreciation method appropriate for the specific scenario.

TE-Modeling Example 1: Assessing a Chemical Process 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:

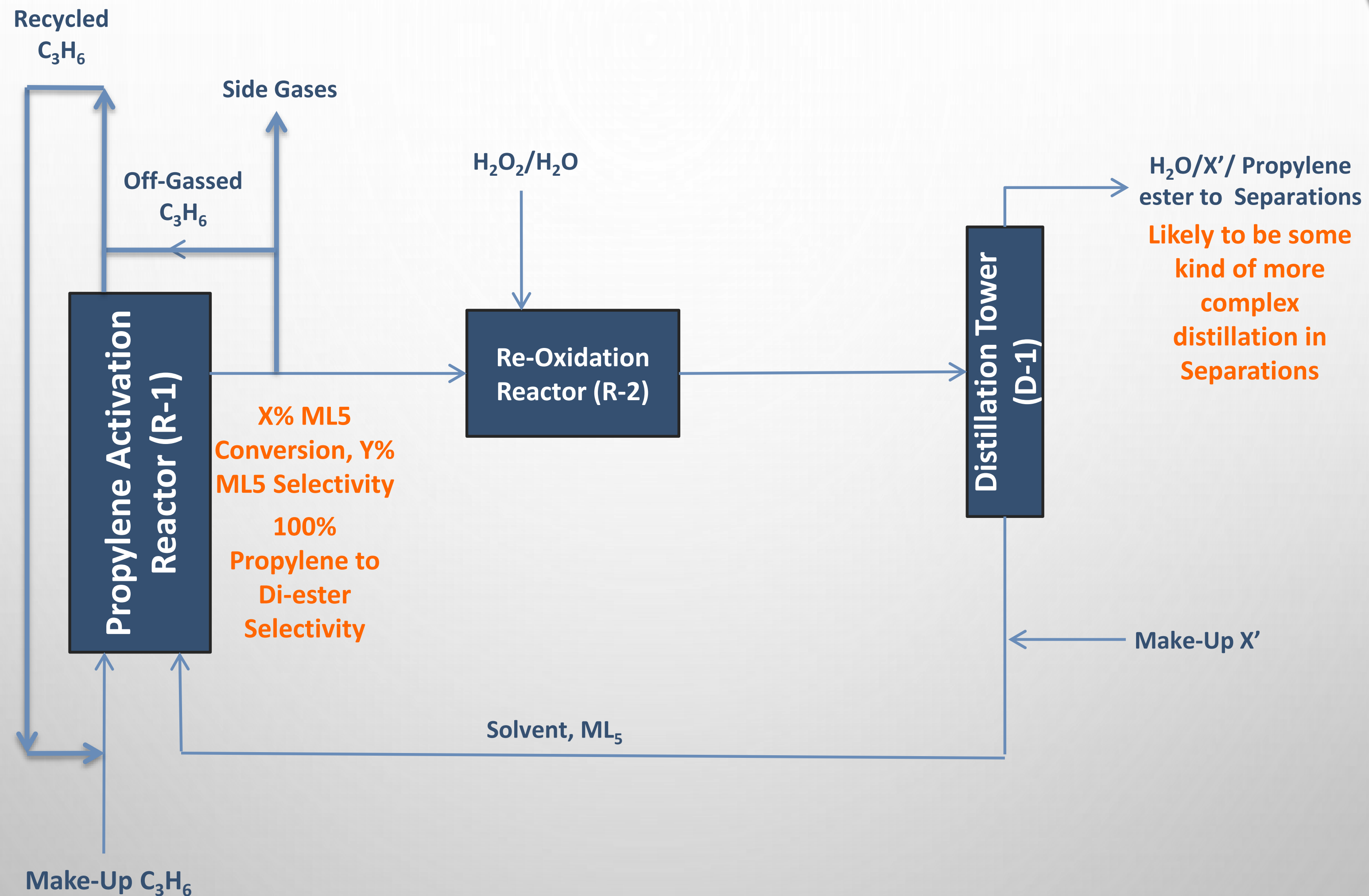
- **What technical risks (binary and others) should be retired to ensure that this science experiment can scale into something compelling and profitable?**

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 • Reaction kinetics obtained from lab data • 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 • 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 • Reaction kinetics obtained from lab data
Downstream Separation	• Expected to be typical distillation tower with the associated re-boiler, condenser and pumps • 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) • 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. • 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 • Available Propylene costs corresponding to oil prices (Propylene assumed to be made from Naphtha cracking)
Acetic Acid Cost	• Acetic Acid prices based on historical pricing data in the US
OpEx due to Losses	• Losses of solvent, oxidant etc. considered in terms of $/tonne product • Base-Case: No Losses • Ranges: $0-$150/tonne
Re-Oxidation Agent Cost	• Assumed to be 50% (w/w) solution of H_2O_2 in water • Bulk pricing available from commercial vendor sources
Plant Utilities	• Energy required calculated in a bottom-up method depending on unit operation conditions
Operating Labor	• 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).
Maintenance & Repairs	
Miscellaneous	

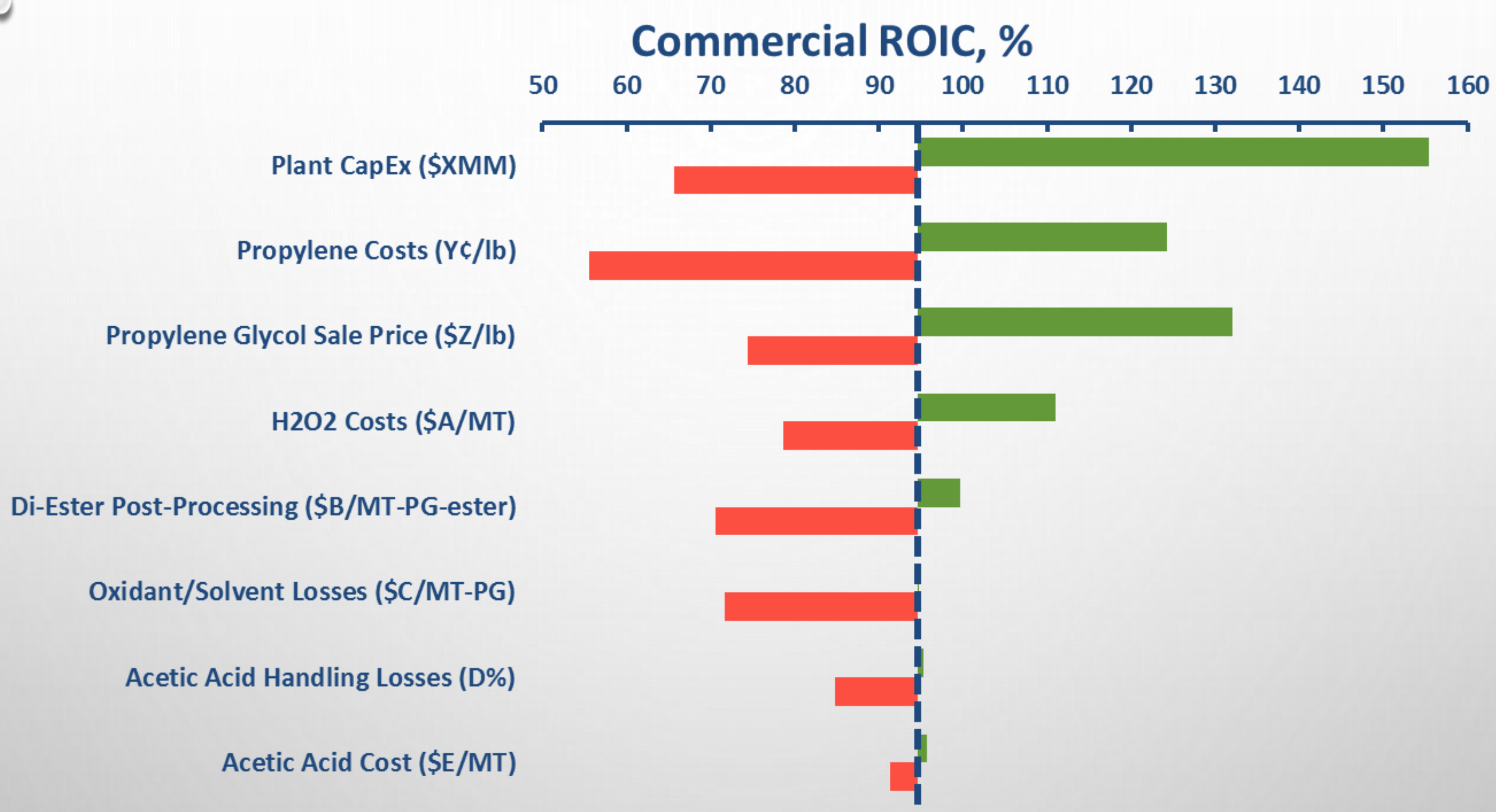
Comparative Economics with Incumbent Process

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

TE-Modeling Example 2: Assessing Factory Flow and Set-up

Cost Models for Manufacturing Decisions

Determine the optimum combination from the information below:

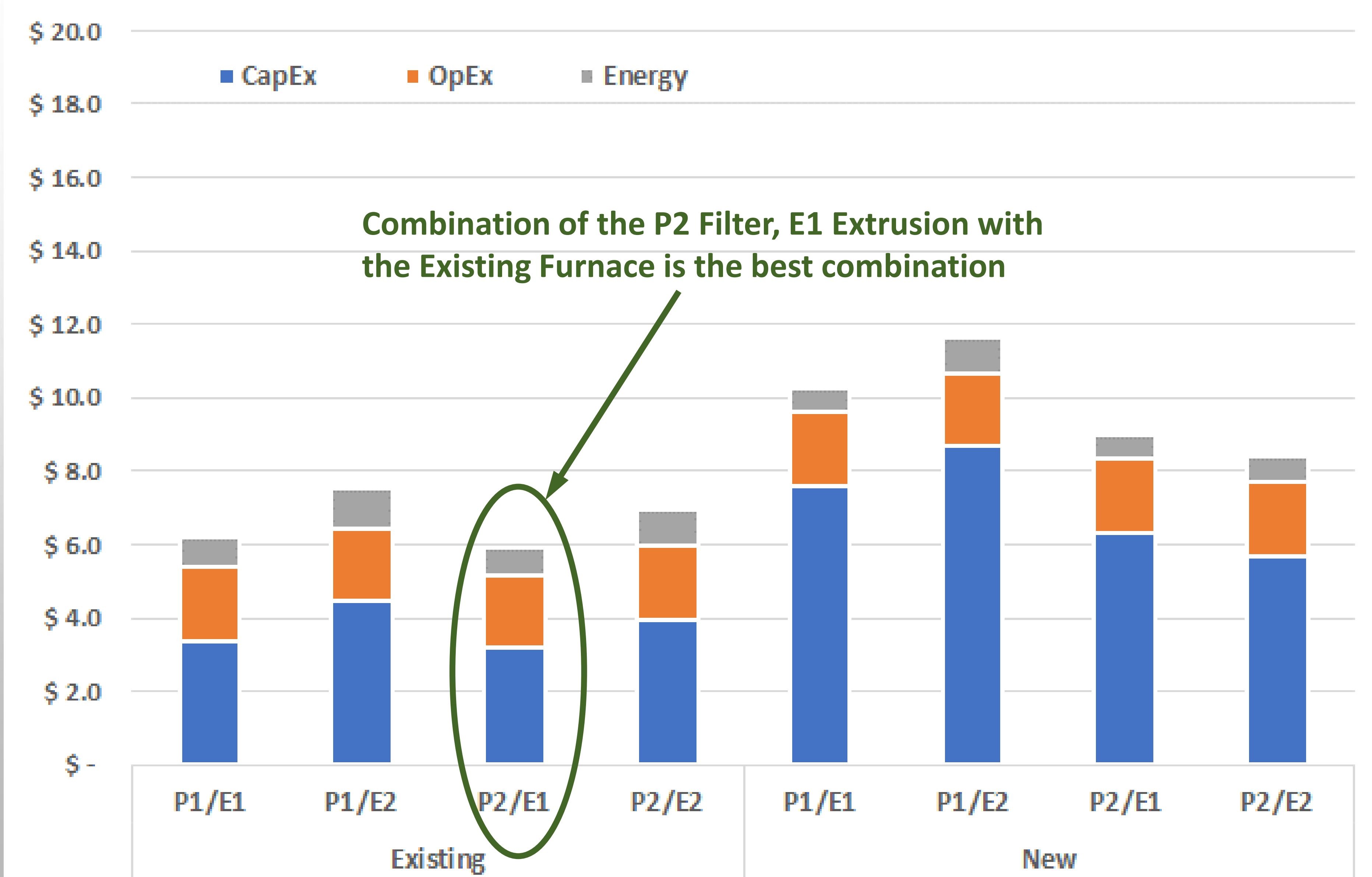
Factory Process Flow

Filter → Extrusion → Sinter

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

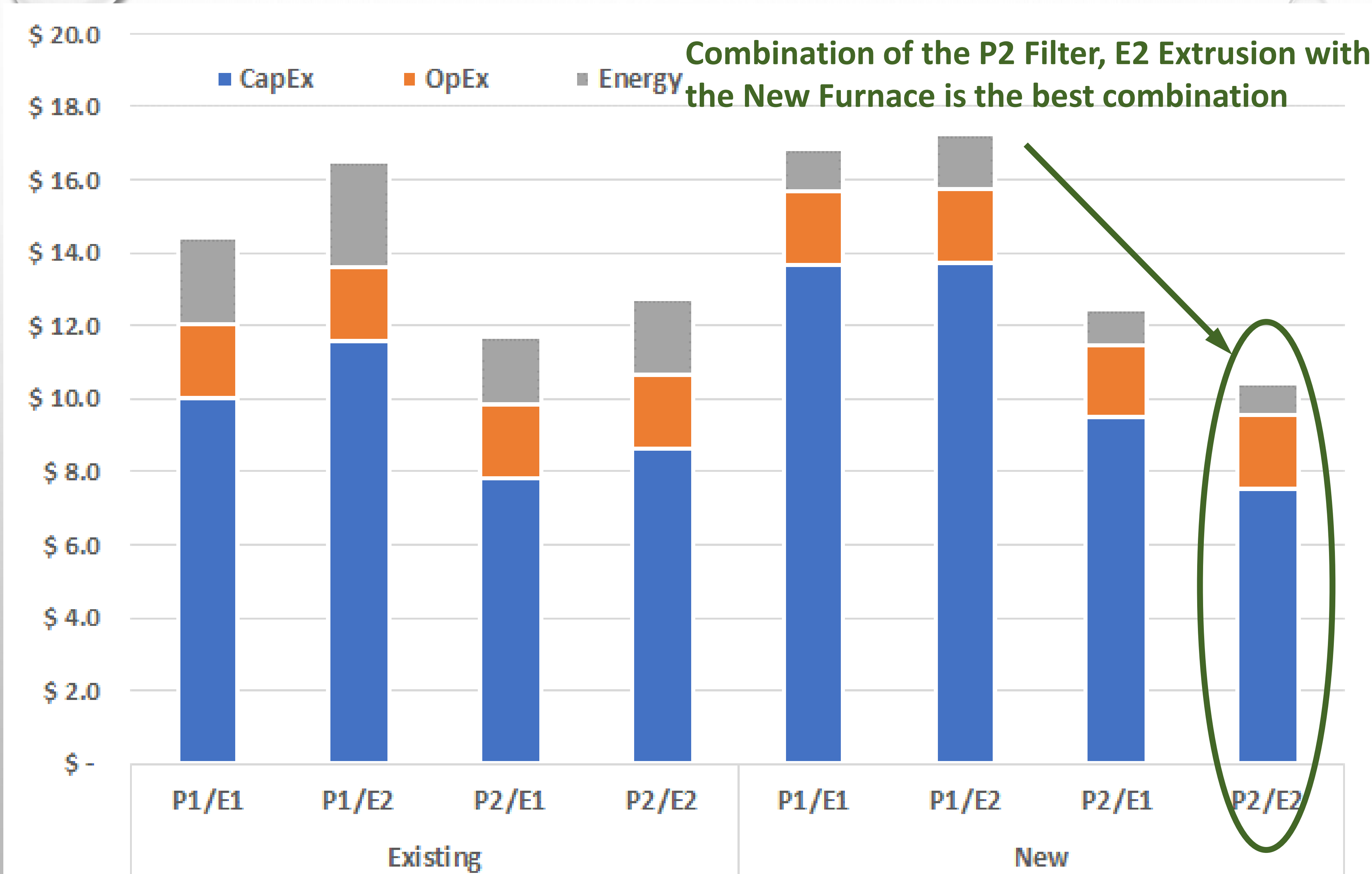
Results: Minimizing the Production Costs



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