Biorefineries

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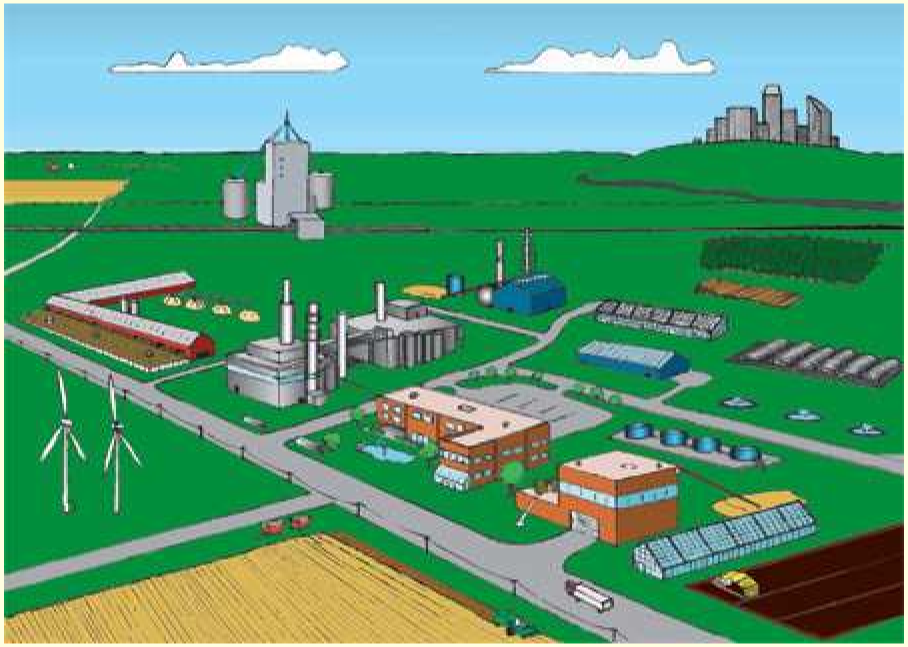
Background

- Biorefinery:
  - Biomass conversion
  - Fuels, power, chemicals



[4]

Background

- There is a wide variety of Biomass Feestock in the United States
- Mass Production of many different chemicals from biomass is not a common practice

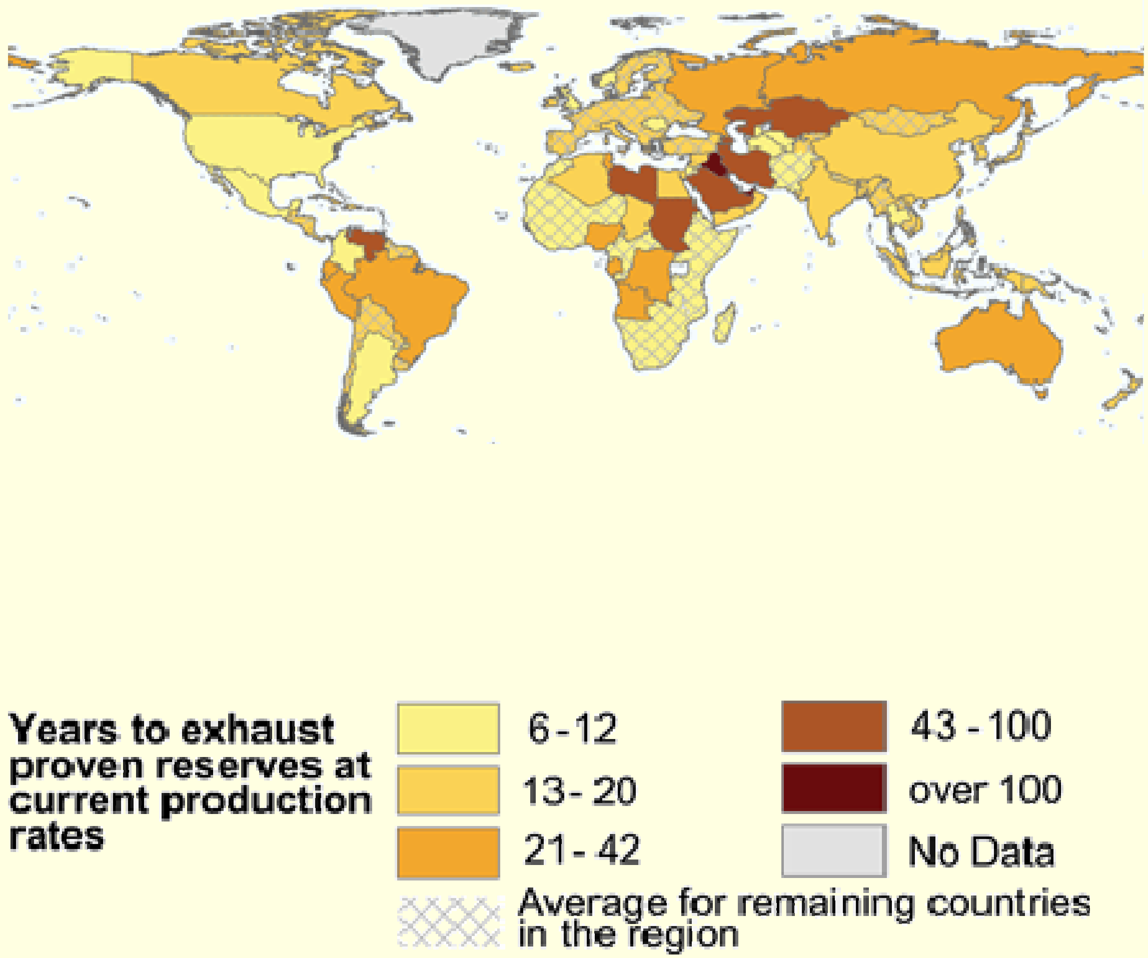
[8]

Background

- World Energy Problem: Refining Fossil Fuels Releases greenhouse gases, causing global warming

Background

World Energy Problem: Decreasing fossil fuels [2]

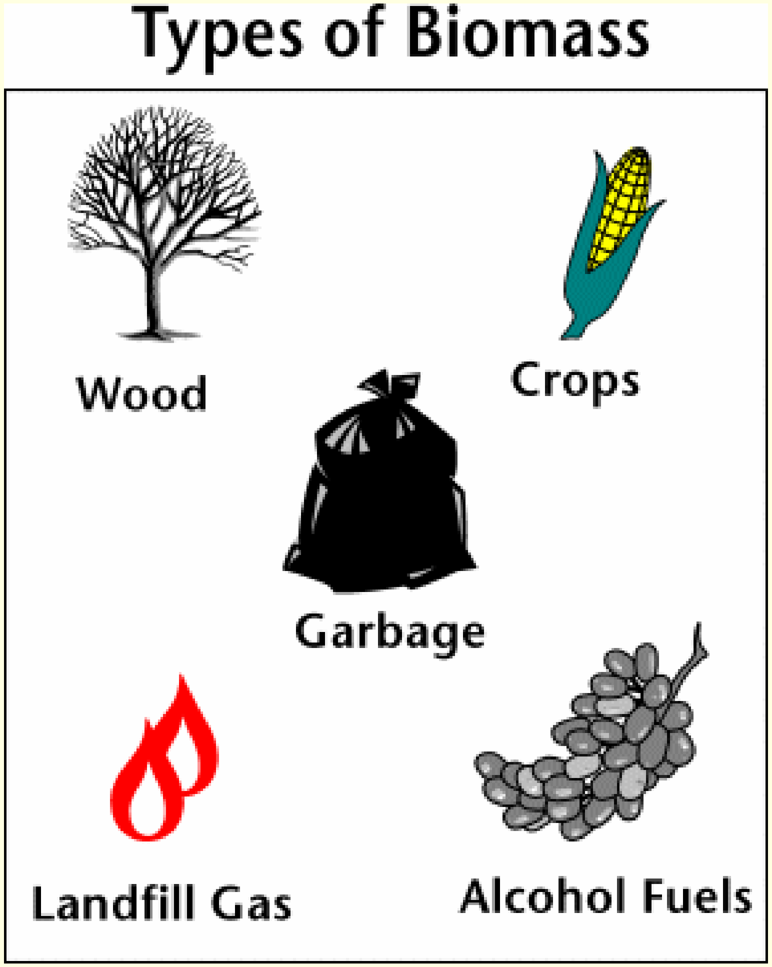


Proposal

- By having ONE refinery that will produce many things from many feedstocks, utilities, power, and energy will be conserved
- Chemicals that may be used for energy (bio-desiel and bio-gasoline) will **help** solve the world energy problem and decrease the amount of fossil fuels burned

Advantages

- Minimizes Pollution
- Reduces Waste



[5]

Products

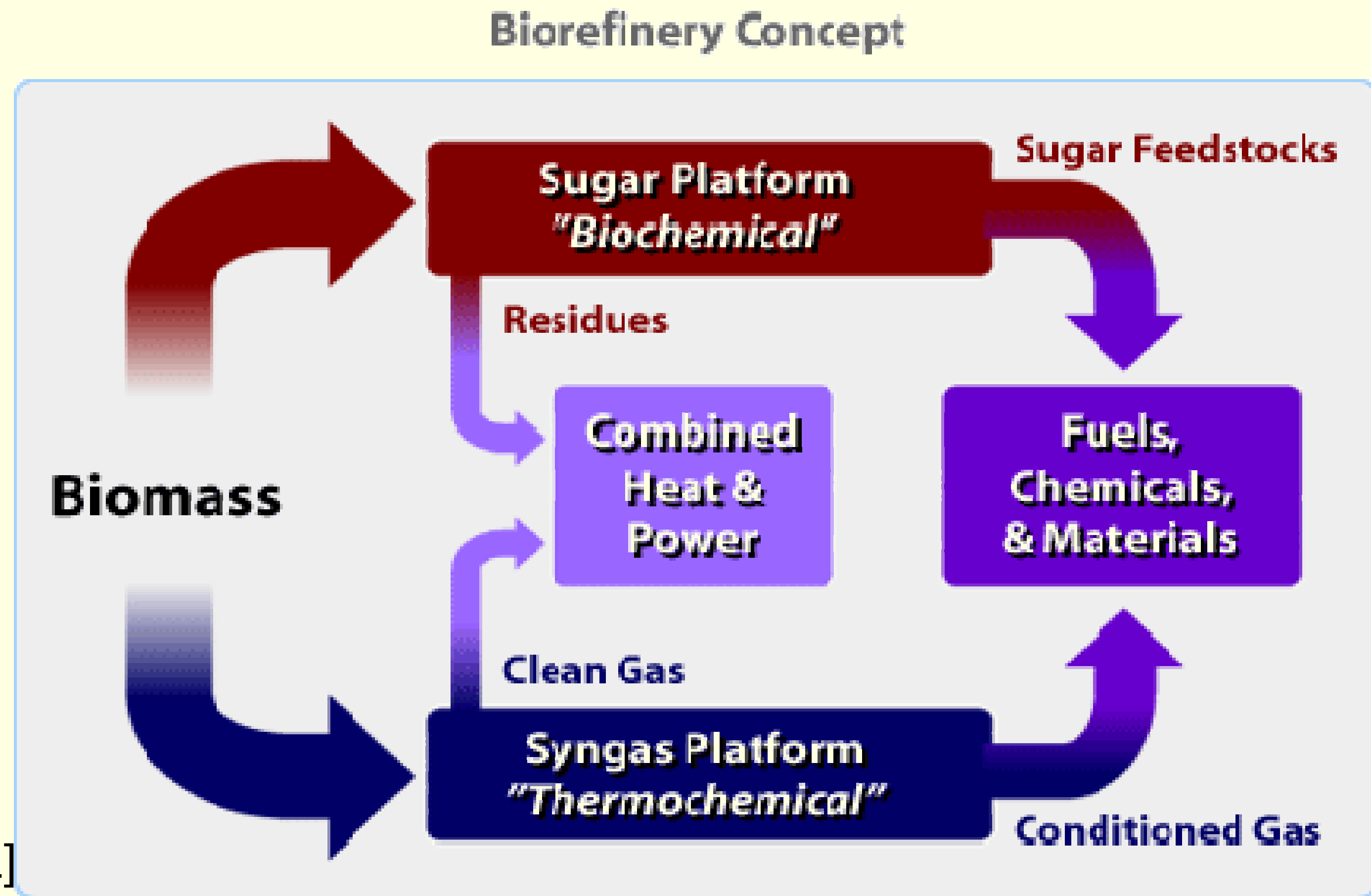
- Ethanol
- Plastics
- Solvents
- Adhesives
- Lubricants
- Chemical Intermediates

[7]

[6]

But….Its not that simple…

- Many, many different decisions to make when considering constructing and operating a biorefinery!



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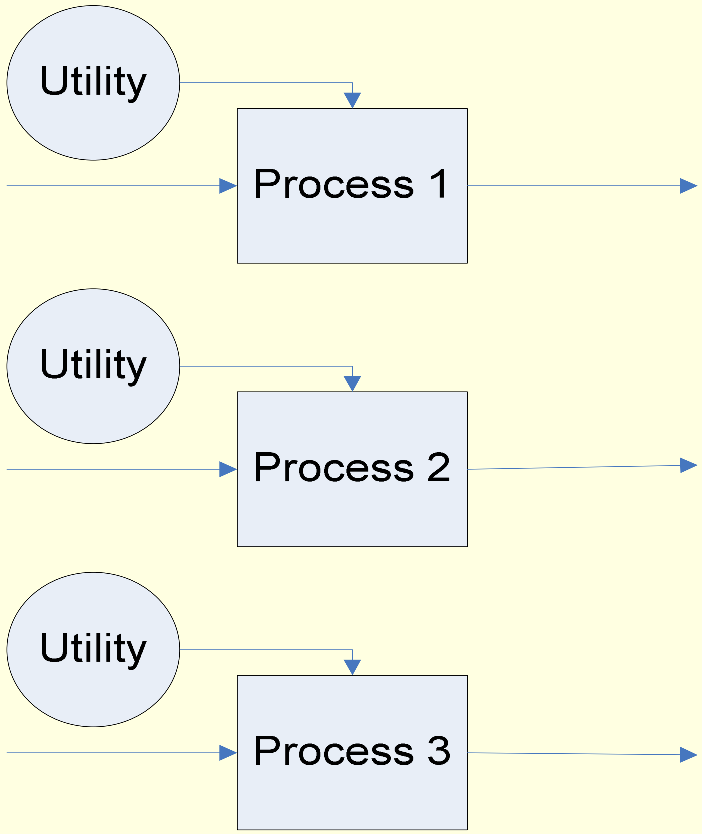
Types of Biorefineries

- Phase 1: fixed processing capabilities
- Phase 2: capability to produce various end products and far more processing flexibility
- <u>Phase 3: mix of biomass feedstocks and yields many products by employing a combination of technologies.</u>

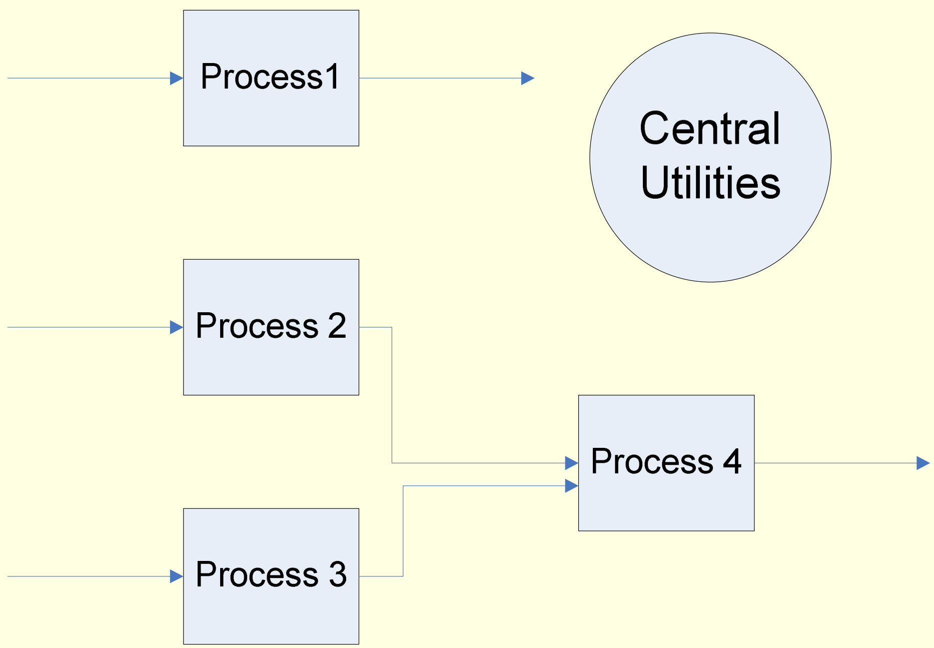
[6]

Utilities and Biorefineries



- But…would it be more profitable to integrate all processes into one refinery??

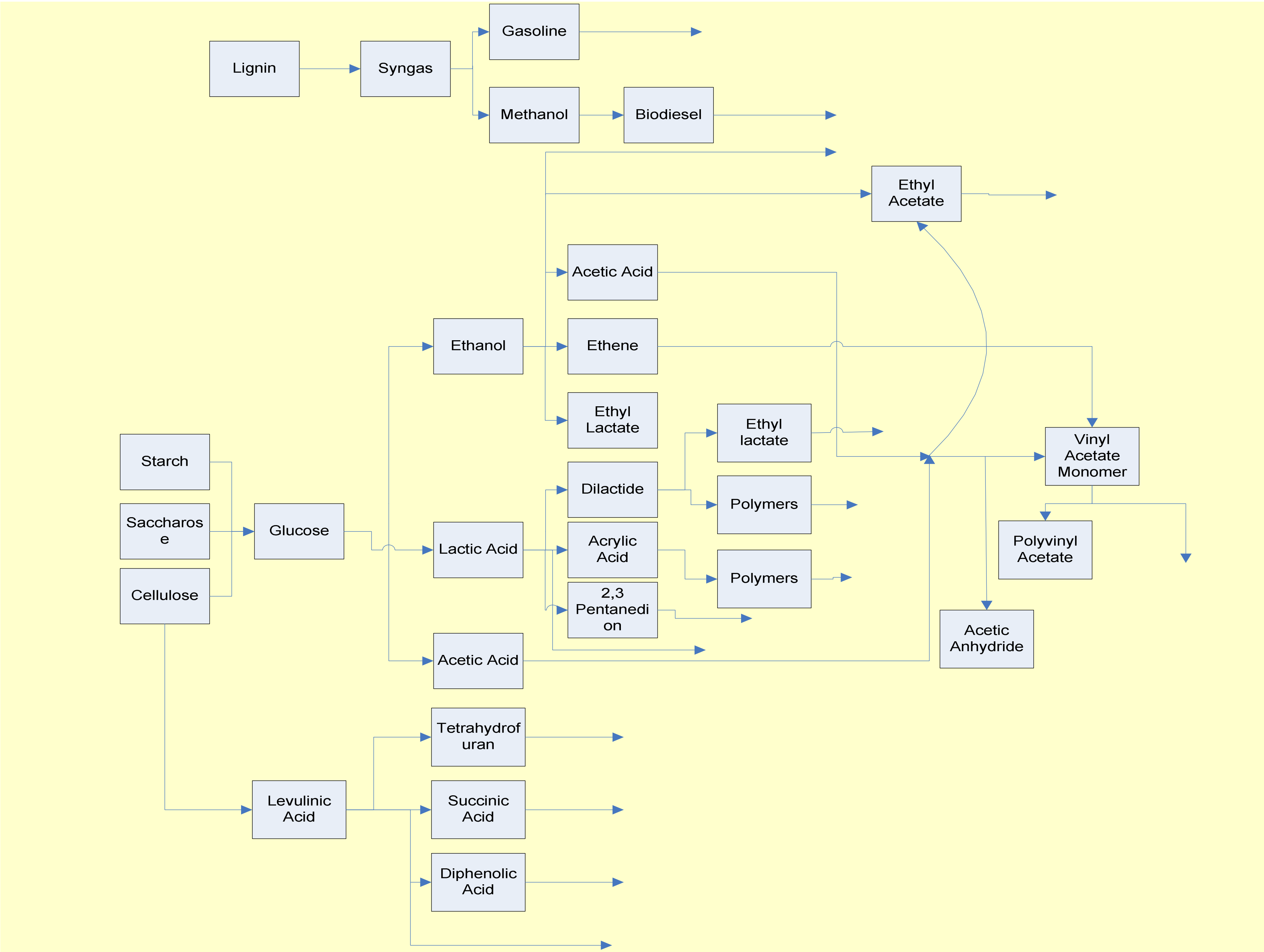
Utilities and Integrated Biorefineries



- One power plant for all processes: centralized utilities

Utilities and Integrated Biorefineries

- Overhead is minimized
- Utilities can be produced and distributed to each process
- Therefore, it is more profitable!


Lignin
Syngas
Gasoline
Methanol
Biodiesel
Ethyl Acetate
Acetic Acid
Ethanol
Ethene
Ethyl Lactate
Ethyl lactate
Vinyl Acetate Monomer
Starch
Saccharose
Cellulose
Glucose
Dilactide
Polymers
Lactic Acid
Acrylic Acid
Polymers
Polyvinyl Acetate
2,3 Pentanedion
Acetic Anhydride
Acetic Acid
Tetrahydrofuran
Levulinic Acid
Succinic Acid
Diphenolic Acid

How many different options?

- Whether or not to build each process:

- 2 options for every process:
  - $=2^{24}$

- 16,777,216 options!!!

- Not including:
  - Different Flow Rates
  - Input Options
  - Expansions

Narrowing it down

- Mathematical Model
  - Objective: Maximize the Net Present Value
  - Eliminate processes/products that are the least profitable
  - Select the most profitable processes and their corresponding capacities and production rates throughout the project lifetime

Mathematical Model

- Net Present Value:

$$NPV = \sum_t \left(\text{cash(t)}\right) \cdot \text{df}$$

The Net Present Worth (NPW) is “the total of the present worth of all cash flows minus the present worth of all capital investments.”

Mathematical Model

- Fixed Capital and Capacity

$$FC(i) = \alpha(i) \cdot Y(i,t) + \beta(i) \cdot capacity(i,t)$$

$$\sum_{i} FC(i) \le investment$$

- α is minimal cost to build a process, β is incremental capacity cost, and Y(i,t) is binary variable (0 or 1) that determines whether process will be built

Mathematical Model

- capacity(i,t) – Y(i,t) maxcapacity(i,t) ≤ 0
- capacity(i,t) – Y(i,t) mincapacity(i,t) ≥ 0

$$\sum_{j} \text{output}(i, j, t) \leq \text{capacity}(i, t)$$

- Process may not exceed maximum and minimum capacity requirements
- If Yi=0, then capacity also is 0; therefore, the process will not be built

Mathematical Model

$$\text{input}(i, j, t) = \text{raw}(i, j, t) + \sum_{k \neq i} \text{flow}(k, i, j, t)$$

- input(i,j,t) is the amount of chemical j that is input into process i
- flow(i,k,j,t) represents the flow of a chem. j from process i to k
- raw(i,j,t) is the amt of raw material to be bought for process i

Mathematical Model

$$\text{input}(i, j, t) = f(i, j) \sum_{jj} \text{input}(i, jj, t)$$

$$\text{output}(i, j, t) = g(i, j) \sum_{jj} \text{output}(i, jj, t)$$

- f(i,j) relates amounts of each input needed for each process
- g(i,j)relates amounts of each product from process i

Mathematical Model

- Mass Balances around each process:

$$\sum_{i} \text{output}(i, j, t) = \sum_{i} \text{input}(i, j, t)$$

$$\text{output}(i, j, t) = \text{sales}(i, j, t) + \sum_{k \neq i} \text{flow}(i, k, j, t)$$

- sales(i,j,t) is the amount of chemical j from process i that is sold

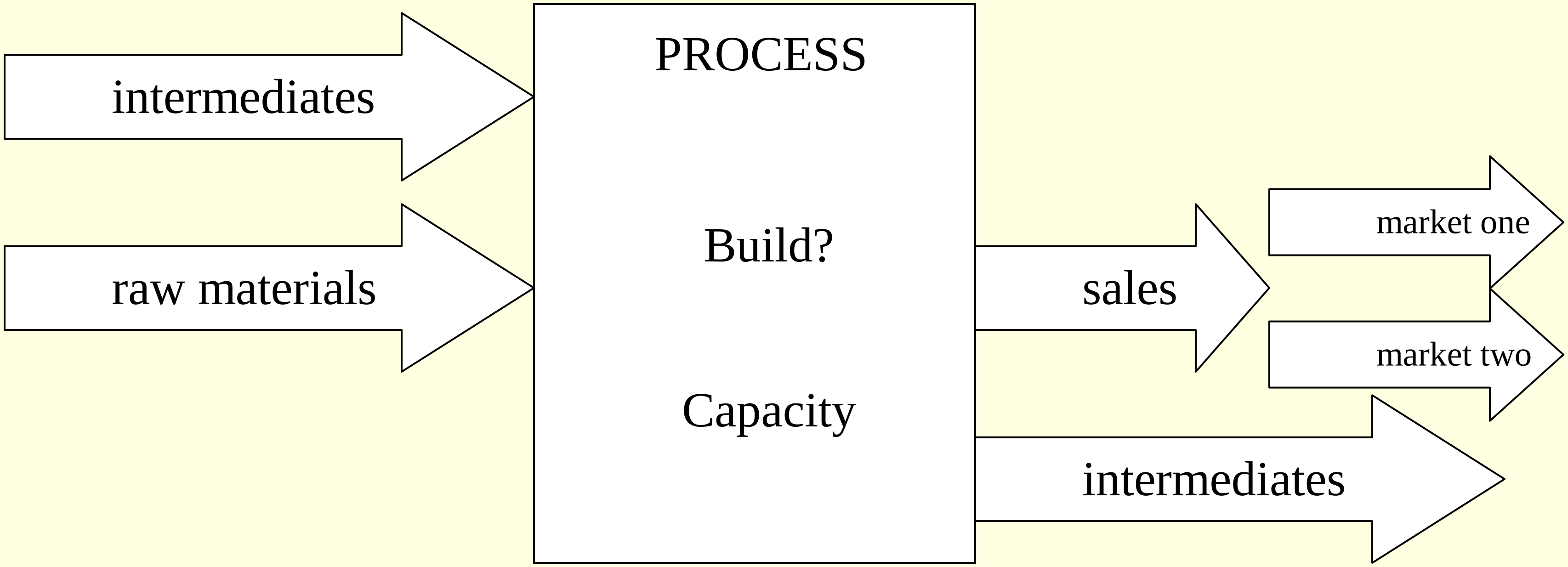
Mathematical Model

$$\text{flow}(i, k, j, t) = \gamma(i, j, k) \cdot \text{output}(i, j, t)$$

$$\text{materials}(t) = \sum_{i,j} \text{raw\_price}(j, t) \cdot \text{raw}(i, j, t)$$

- $\gamma(i,j,k)$ defines the possible transfer of products as output of process i to be used as input into process j

Review



intermediates
raw materials
PROCESS
Build?
Capacity
sales
market one
market two
intermediates

Mathematical Model

$$\text{operatingcost}(i,t) = \delta(i) \cdot Y(i,t) + \varepsilon(i) \cdot \sum_{j} \text{output}(i,j,t)$$

- δ is the minimum operating cost, ε is the incremental operating cost

$$\text{revenue}(j, t) = \text{price}(j, t) \cdot \sum_{i} \text{sales}(i, j, t)$$

$$\sum_{i} \text{sales}(i, j, t) \le \text{demand}(j, t)$$

Mathematical Model

$$\text{capacity}(i,t) = \text{capacity}(i,t\text{-}1) + \text{expansion}(i,t)$$

$$\text{expansion}(i,t) - X(i,t)\text{maxexpansion}(i,t) \leq 0$$

$$\text{expansion}(i,t) - X(i,t)\text{minexpansion}(i,t) \geq 0$$

$$\sum_{t} X(i,t) \leq \text{allowable number of expansions}$$

$$X(i,t) \leq \sum_{t}^{T} Y(i,t)$$

$$X(i,t) + Y(i,t) \leq 1$$

Mathematical Model

$$\text{utilityrequirements}(i,u,t) \le \text{utilities}(i,u,t)$$

$$\sum_i \text{utilities}(i,u,t) \le \text{utilitycapacity}(u,t)$$

$$\text{utilitycapacity}(u,t) - Z(u,t) \cdot \text{maxutilitycapacity}(u) \le 0$$

$$\text{utilitycapacity}(u,t) - Z(u,t) \cdot \text{minutilitycapacity}(u) \ge 0$$

$$\text{FCutilities}(u,t) = a(u) \cdot Z(u,t) + b(u) \cdot \text{utilitycapacity}(u,t)$$

$$\text{utilitycost}(u,t) = c(i) \cdot \sum_{t'}^{t'<t} Z(u,t') + d(u) \cdot \sum_i \text{utilities}(i,u,t)$$

Mathematical Model

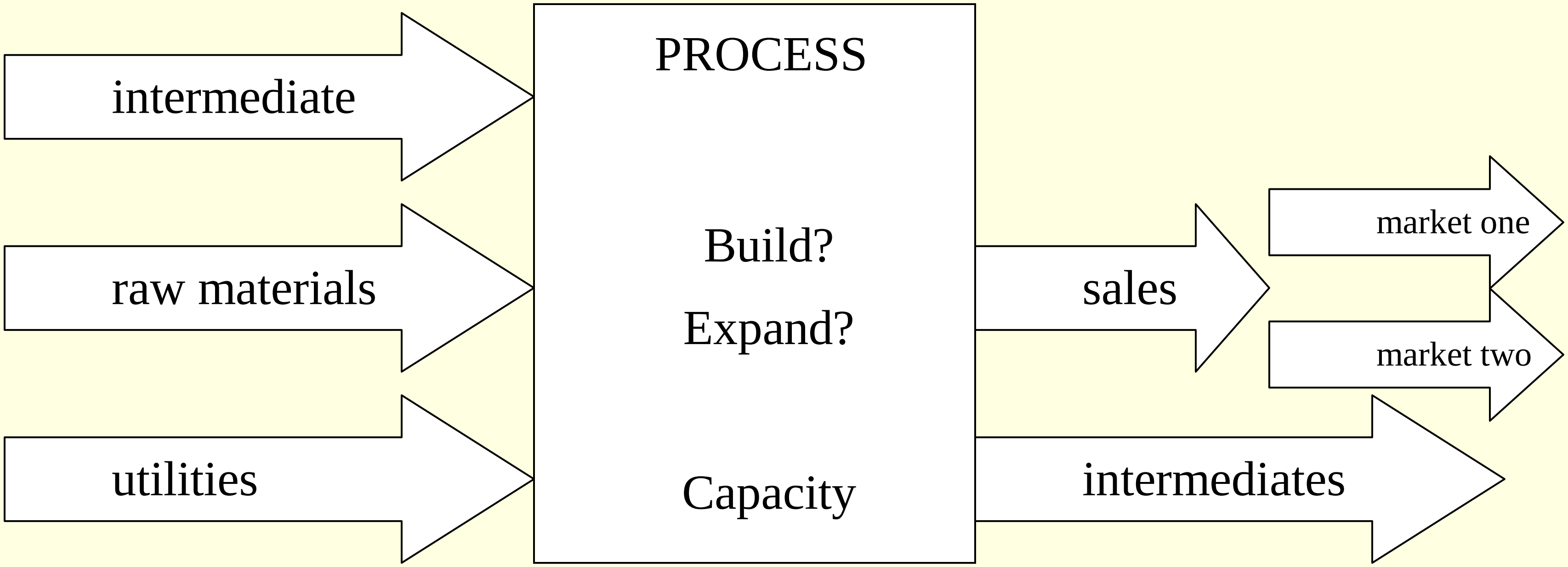
$$\text{cash}(t) = \text{revenue}(t-1) - \text{operatingcost}(t-1) - \text{investment}(t-1) - \text{materialcost}(t-1)$$

$$\text{investment}(t) = \sum_i \text{FC}(i, t) + \sum_u \text{FCutilities}(u, t)$$

$$\text{investment}(t) \le \text{cash}(t-1)$$

$$NPV = \sum_t \text{cash}(t) \cdot \text{df}$$

Overview


PROCESS
intermediate
raw materials
utilities
Build?
Expand?
Capacity
sales
market one
market two
intermediates

Overview

- Building/Expansions
  - Capacity
    - Fixed Capital Investment
- Utilized Capacity
  - Operating Costs
  - Required Utilities
    - Utilitity Capacity/Investment
  - Input/Output
    - Sales
    - Intermediate chemicals

GAMS File

```
Equations
        mincap(i,t)               maximum capacity constraint
        maxcap(i,t)               minimum capacity constraint
        maxcapacity_eq(i,t)       actual production
        input1(i,j,t)             input = raw chemical + flow from other processes
        input2(i,j,t)             stoichiometry of reactants
        output1(i,j,t)            output related to total input
        output2(i,j,t)            output = sales + flow to other processes
        output3(i,t)                   mass input = output
        flow_eq(i,k,j,t)          rules for product flow
        FCI(i,t)                  Fixed Capital Investment
        investment_eq             total available for investment
        materials(t)              material cost
        operatingcost_eq(i,t)     operating cost
        revenue_eq(j,t)           revenue
        demand_eq(j,t)            demand
        NPW                       net present worth       ;


mincap(i,t) ..  capacity(i,t) - Y(i,t)*mincapacity(i) =g= 0 ;
maxcap(i,t) ..  capacity(i,t) - Y(i,t)*maxcapacity(i) =l= 0 ;


maxcapacity_eq(i,t) .. sum(j,output(i,j,t)) =l= capacity(i,t) ;

input1(i,j,t) .. input(i,j,t) =e= raw(i,j,t) + sum(k$(ord(k)<>ord(i)),flow(k,i,j,t)) ;
input2(i,j,t) .. input(i,j,t) =e= f(i,j)*sum(jj,input(i,jj,t)) ;

output1(i,j,t) .. output(i,j,t) =e= g(i,j)*sum(jj,output(i,jj,t)) ;
output2(i,j,t) .. output(i,j,t) =e= sales(i,j,t) + sum(k$(ord(k)<>ord(i)),flow(i,k,j,t)) ;
output3(i,t) .. sum(j,input(i,j,t)) =e= sum(j,output(i,j,t)) ;

flow_eq(i,k,j,t) .. flow(i,k,j,t) =l= gamma(i,j,k)*output(i,j,t) ;

FCI(i,t) .. FC(i,t) =e= (Y(i,t)*alpha(i) + beta(i)*capacity(i,t))   ;
investment_eq .. sum((i,t), FC(i,t)) =l= investment ;

materials(t) .. materialcost(t) =e= sum((i,j), raw_price(j,t)*raw(i,j,t)) ;
operatingcost_eq(i,t) .. operatingcost(i,t) =e= delta(i)*Y(i,t) + epsilon(i)*sum(j,output(i,j,t)) ;
revenue_eq(j,t) .. revenue(j,t) =e= price(j,t)*sum(i, sales(i,j,t)) ;

demand_eq(j,t) .. sum(i,sales(i,j,t)) =l= demand(j,t) ;


NPW .. (sum((j,t), revenue(j,t)) - sum((i,t),operatingcost(i,t))) - sum((i,t), FC(i,t))- sum(t,materialcost(t))  =e= z ;


Model biorefining /all/ ;
```

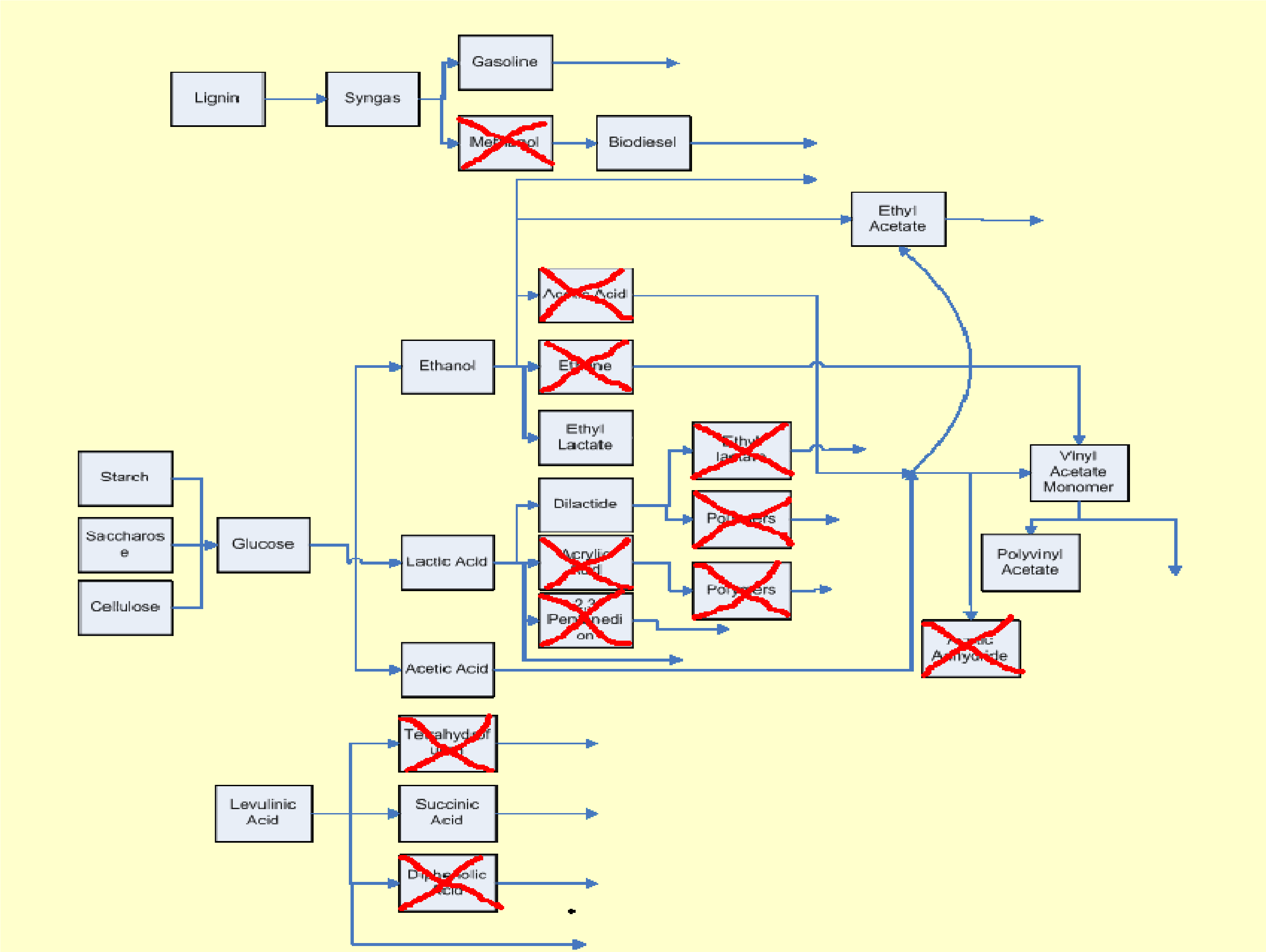
```
----    884 VARIABLE output.L  total output from process

                   1           2           3           4           5

p1 .ETH      10000.000   10000.000   10000.000   10000.000   10000.000
p2 .LAC      10000.000   10000.000   10000.000   10000.000   10000.000
p3 .ACE        504.941     504.941     504.941     504.941     504.941
p3 .H2O       2756.630    2756.630    2756.630    2756.630    2756.630
p3 .CO2       6738.429    6738.429    6738.429    6738.429    6738.429
p4 .ETHLAC   10000.000   10000.000   10000.000   10000.000   10000.000
p8 .DILAC    10000.000   10000.000   10000.000   10000.000   10000.000
p13.LEVU     10000.000   10000.000   10000.000   10000.000   10000.000
p15.SUC      10000.000   10000.000   10000.000   10000.000   10000.000
p17.SYN      10000.000   10000.000   10000.000   10000.000   10000.000
p18.GAS      10000.000   10000.000   10000.000   10000.000   10000.000
p19.METH     10000.000   10000.000   10000.000   10000.000   10000.000
p21.ETHAC    10000.000   10000.000   10000.000   10000.000   10000.000
p23.VAM      10000.000   10000.000   10000.000   10000.000   10000.000
p24.PVAC     10000.000   10000.000   10000.000   10000.000   10000.000

         +         6

p1 .ETH      10000.000
p2 .LAC      10000.000
p3 .ACE        504.941
p3 .H2O       2756.630
p3 .CO2       6738.429
p4 .ETHLAC   10000.000
p8 .DILAC    10000.000
p13.LEVU     10000.000
p15.SUC      10000.000
p17.SYN      10000.000
p18.GAS      10000.000
p19.METH     10000.000
p21.ETHAC    10000.000
p23.VAM      10000.000
p24.PVAC     10000.000
```



Lignin
Syngas
Gasoline
Biodiesel
Ethyl Acetate
Ethanol
Ethyl Lactate
Dilactide
Starch
Saccharose
Cellulose
Glucose
Lactic Acid
Acetic Acid
Vinyl Acetate Monomer
Polyvinyl Acetate
Levulinic Acid
Succinic Acid

Where do the parameters come from?

- Determine process specifics
  - Equipment
  - Reaction
    - Endothermic/exothermic
    - Required utilities
  - Labor requirements

Where do the parameters come from?

Graph of FCI vs. Feed Rate

- α is the y-intercept
- β is the slope

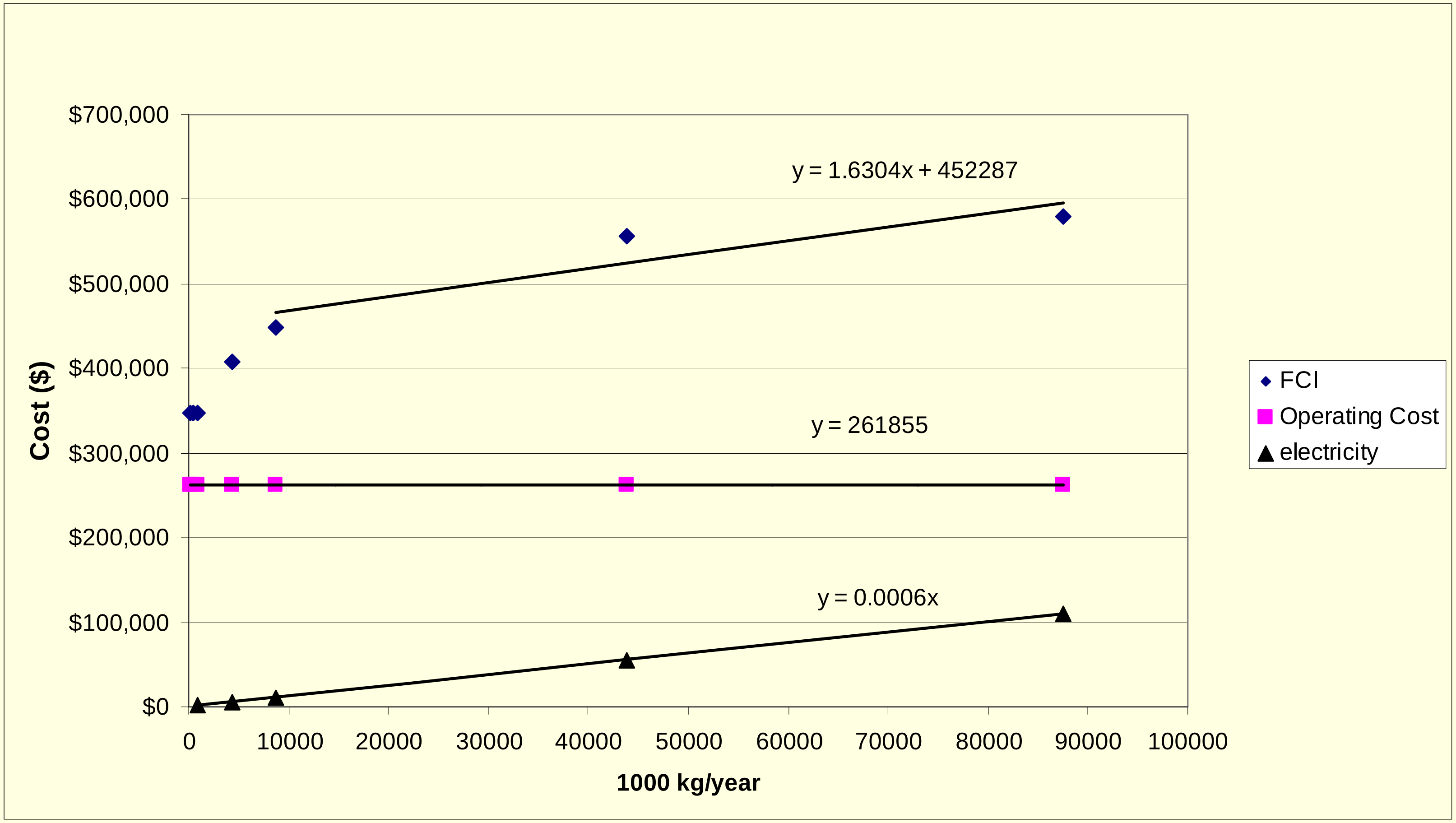
Graph of the Operating Cost vs. Feed Rate

- δ is the y-intercept
- ε is the slope

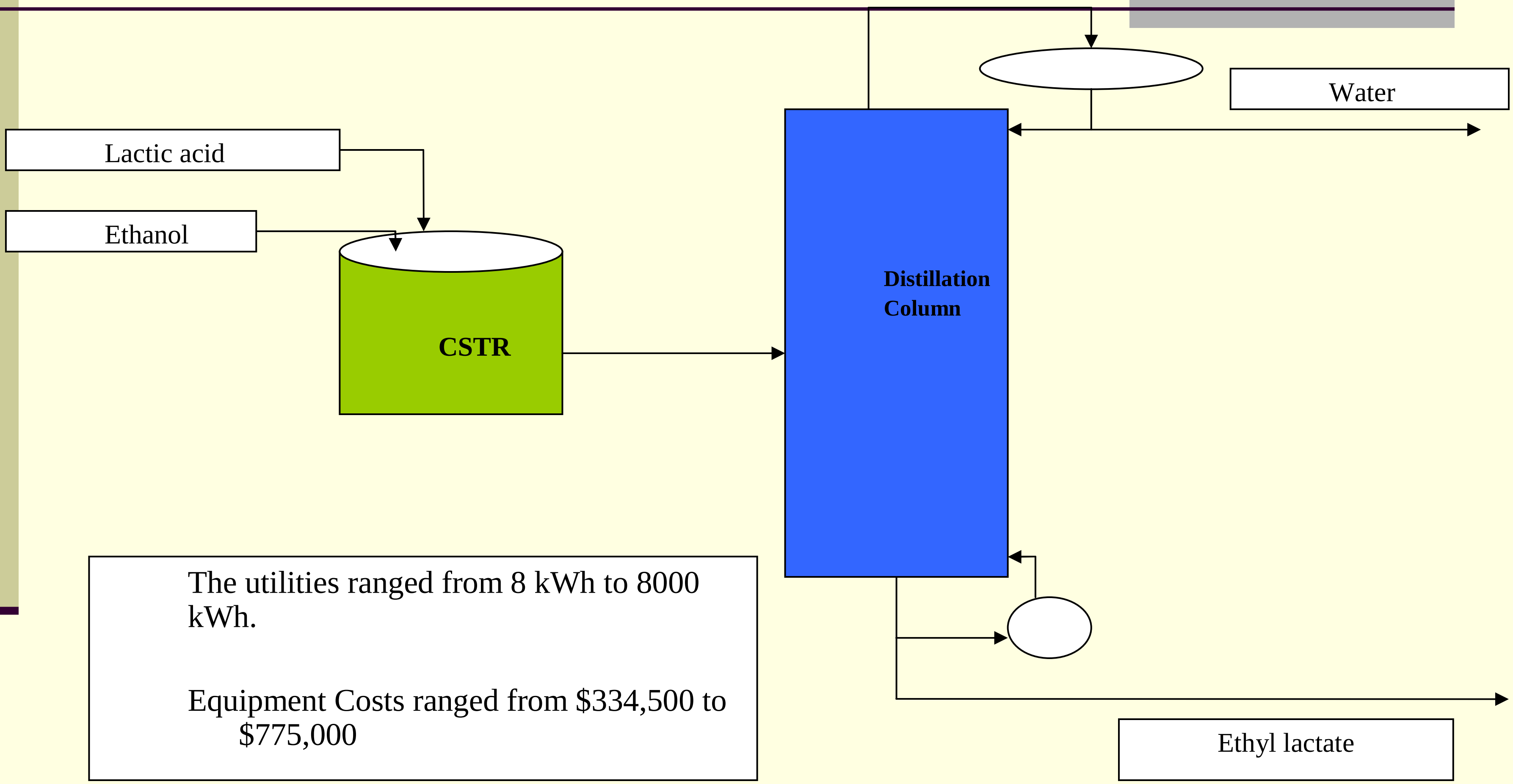
Simulations on the Individual Process

- From SuperPro & ProII:
  - Feed Rates between 10 to 10,000 kg/hr
    - Equipment costs
    - Utility costs
    - Profitability

Reactor Cost vs. Feed Rate



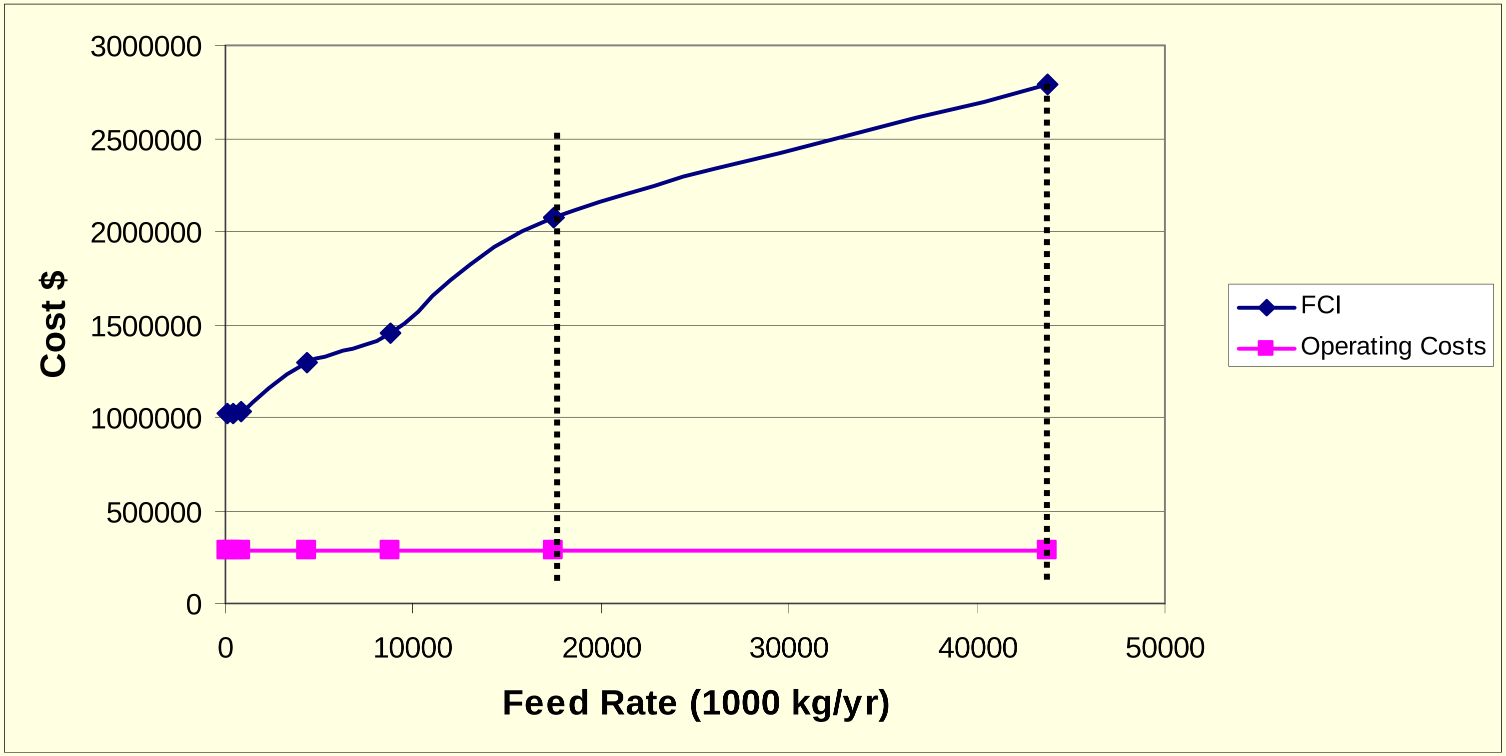
Ethyl Lactate



The utilities ranged from 8 kWh to 8000 kWh.

Equipment Costs ranged from $334,500 to $775,000

Ethyl Lactate Costs



- Operating Costs do not include utilities.

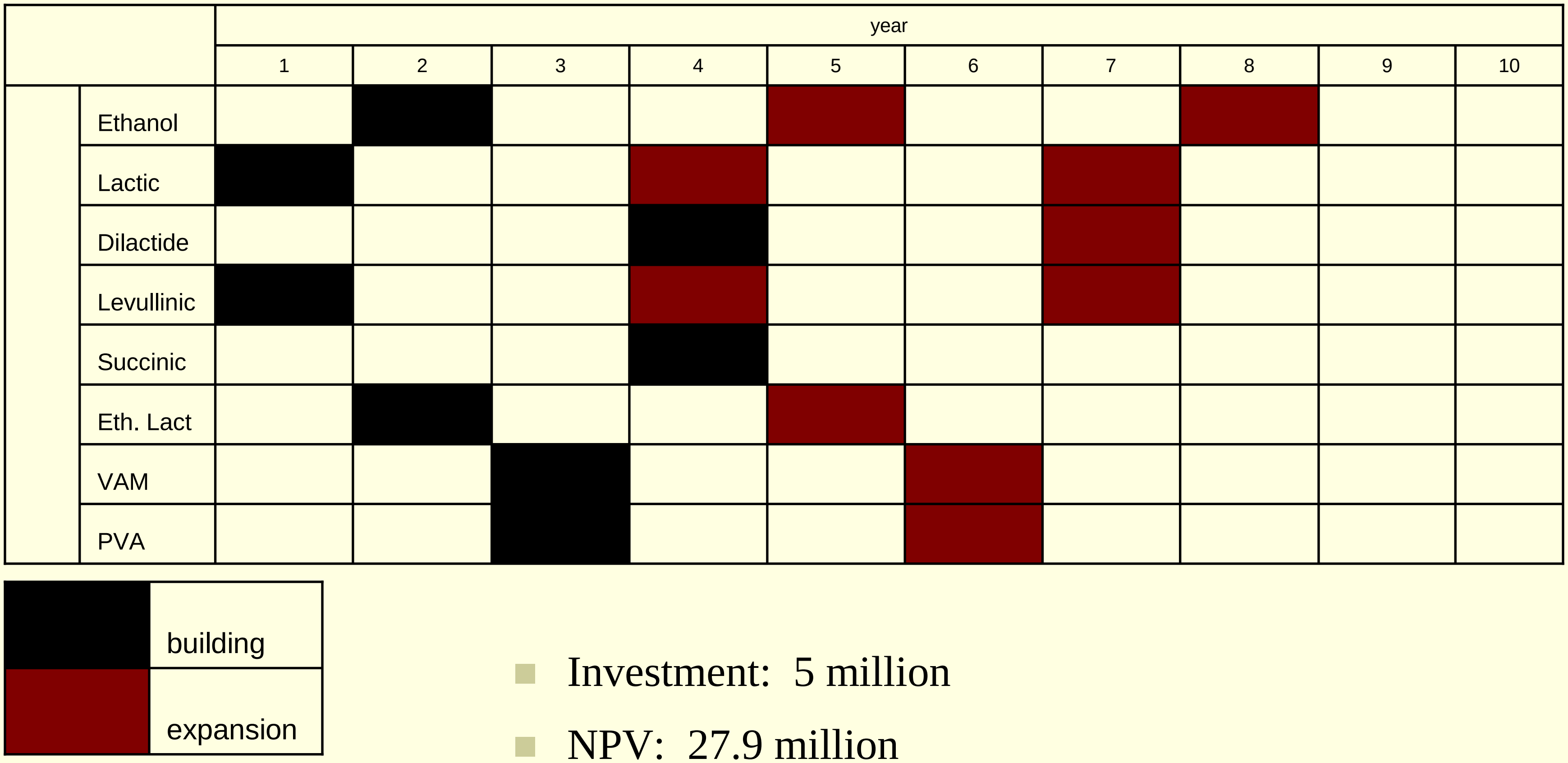
Minimum Equipment Size

- Fermentor was 225 liters.
- Reactor was 50 liters.
- CSTR for Dilactide 4.0 ft^3
- Distillation Column for Ethyl Lactate 4.0 ft^3

Results!!!

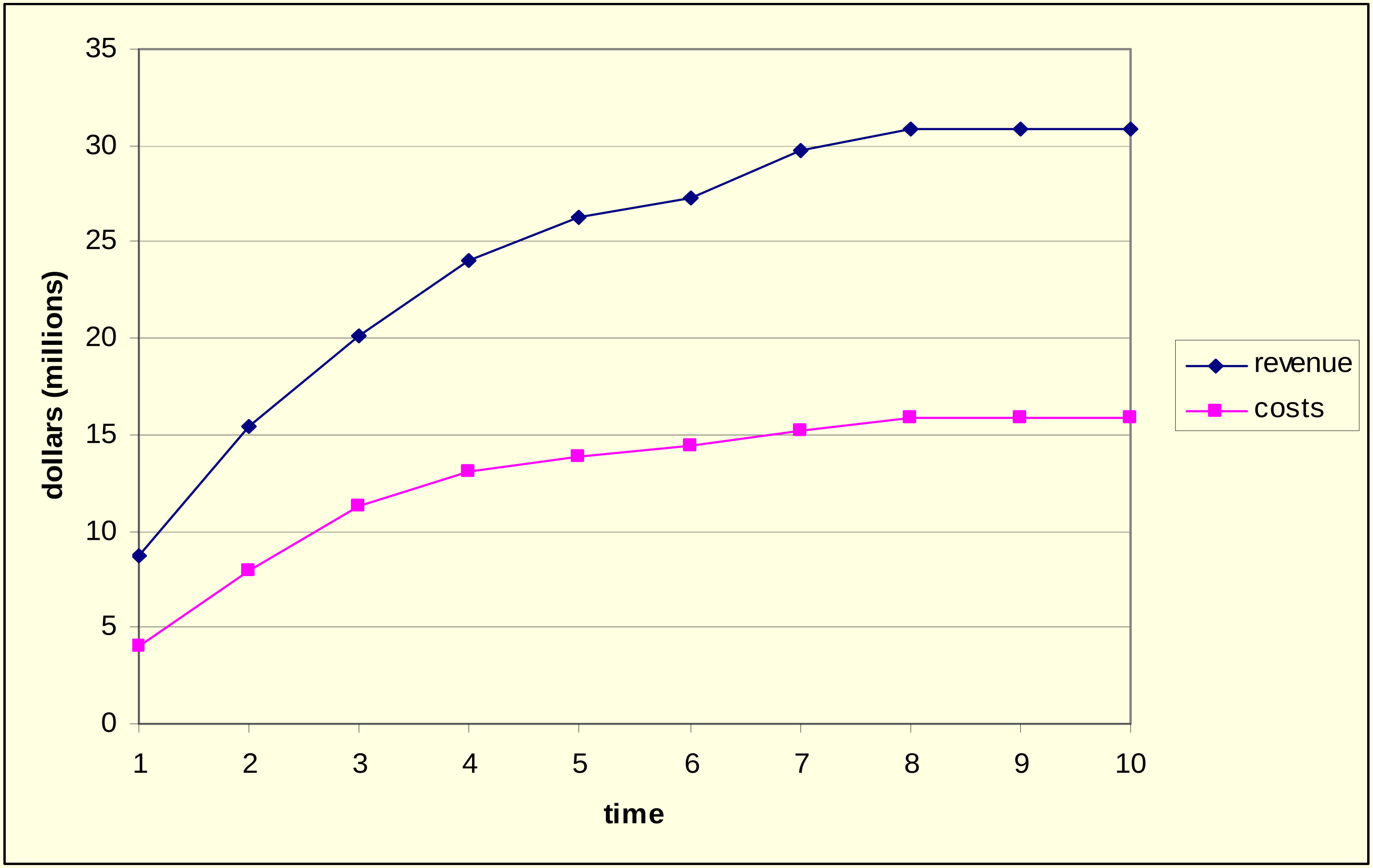
- From more than 16 million options….
- Run this model in 90 seconds

Results: 5 Million Dollar Investment

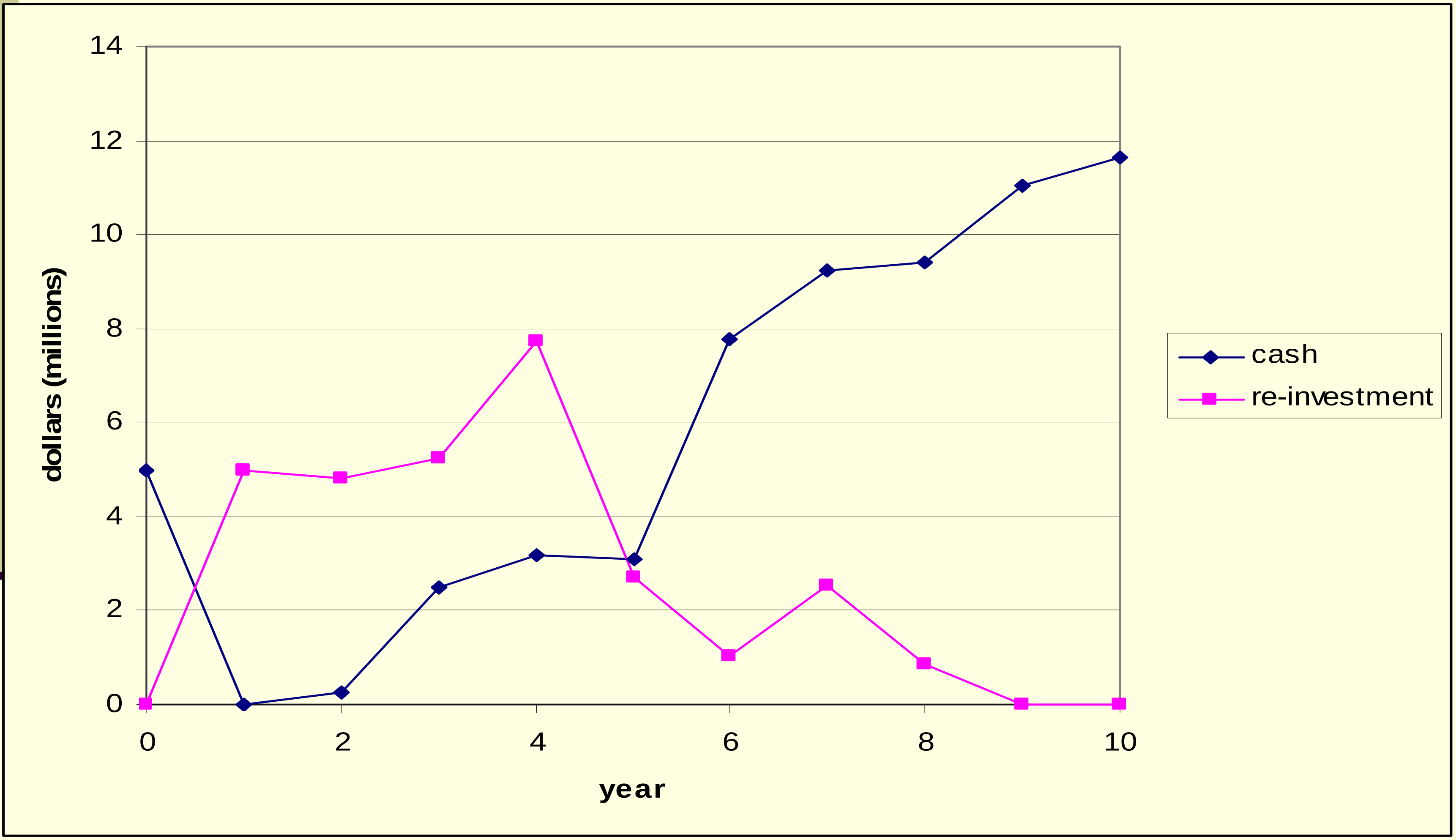


- Investment: 5 million
- NPV: 27.9 million

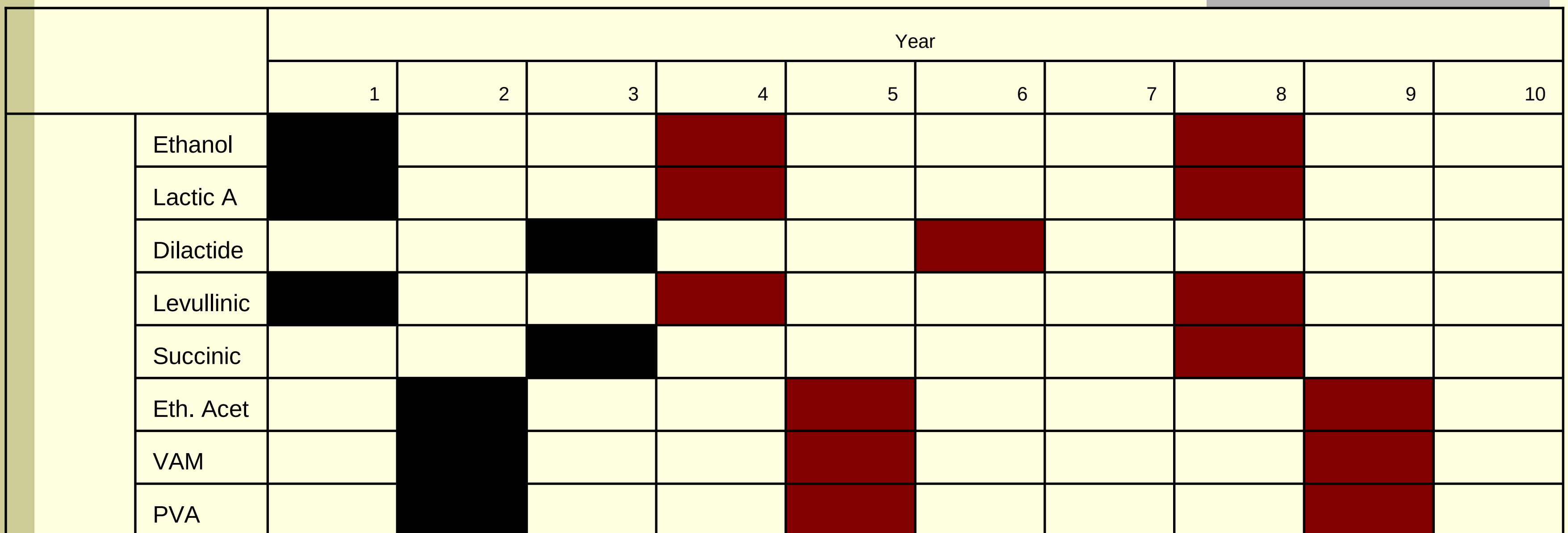
Results: 5 Million Dollar Investment

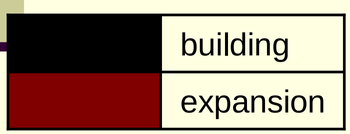


Results: 5 Million Dollar Investment



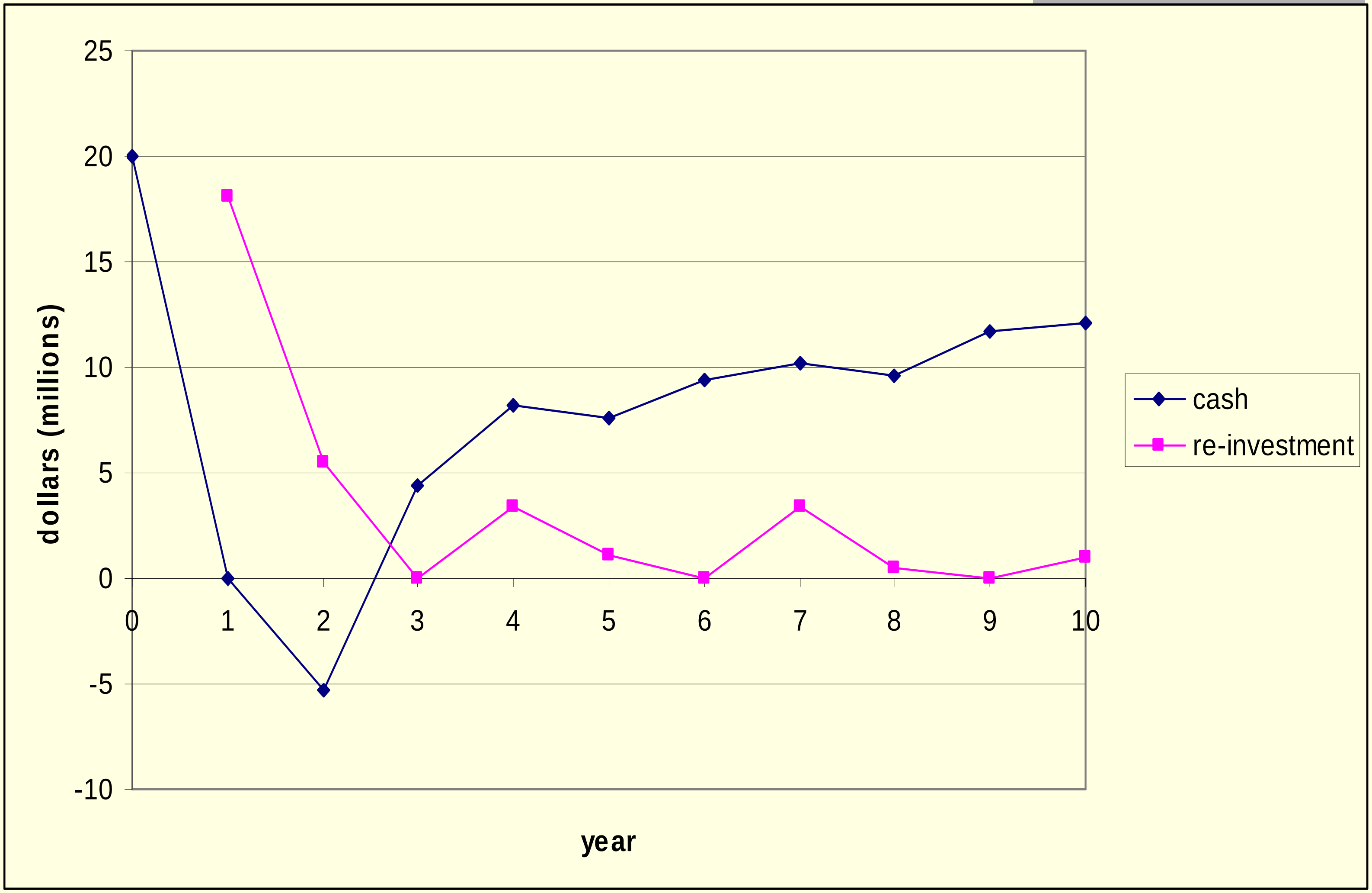
Results: 20 Million Dollar Investment



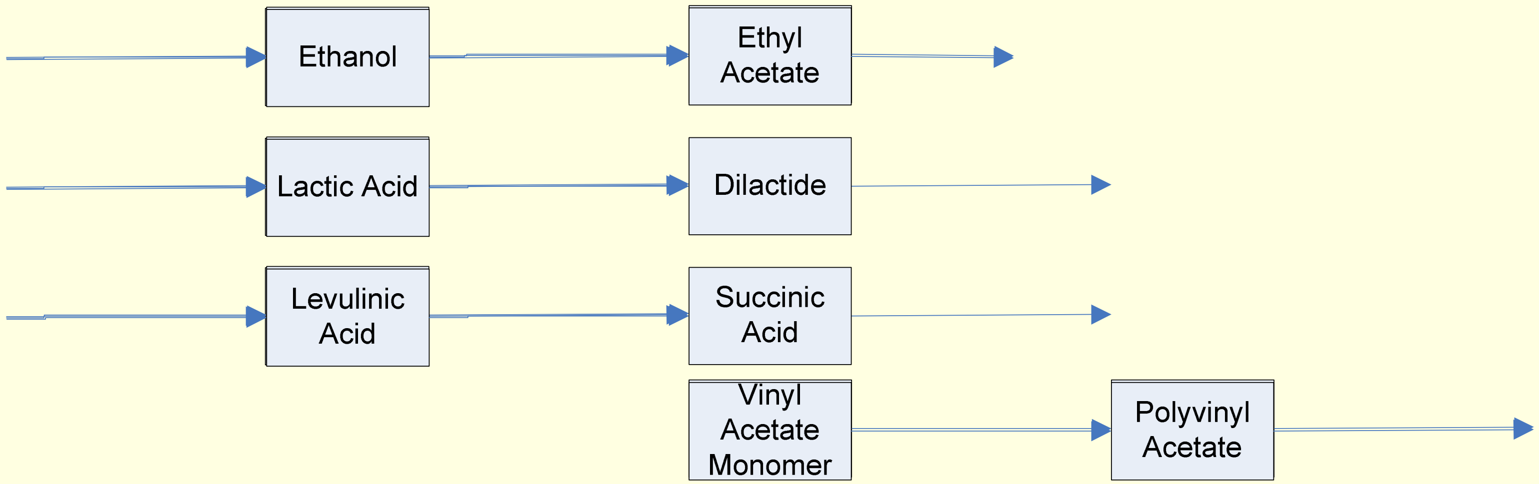


- Investment:20 million
- NPV: 24.5 million

Results: 20 Million Dollar Investment



Results: Variable Investment



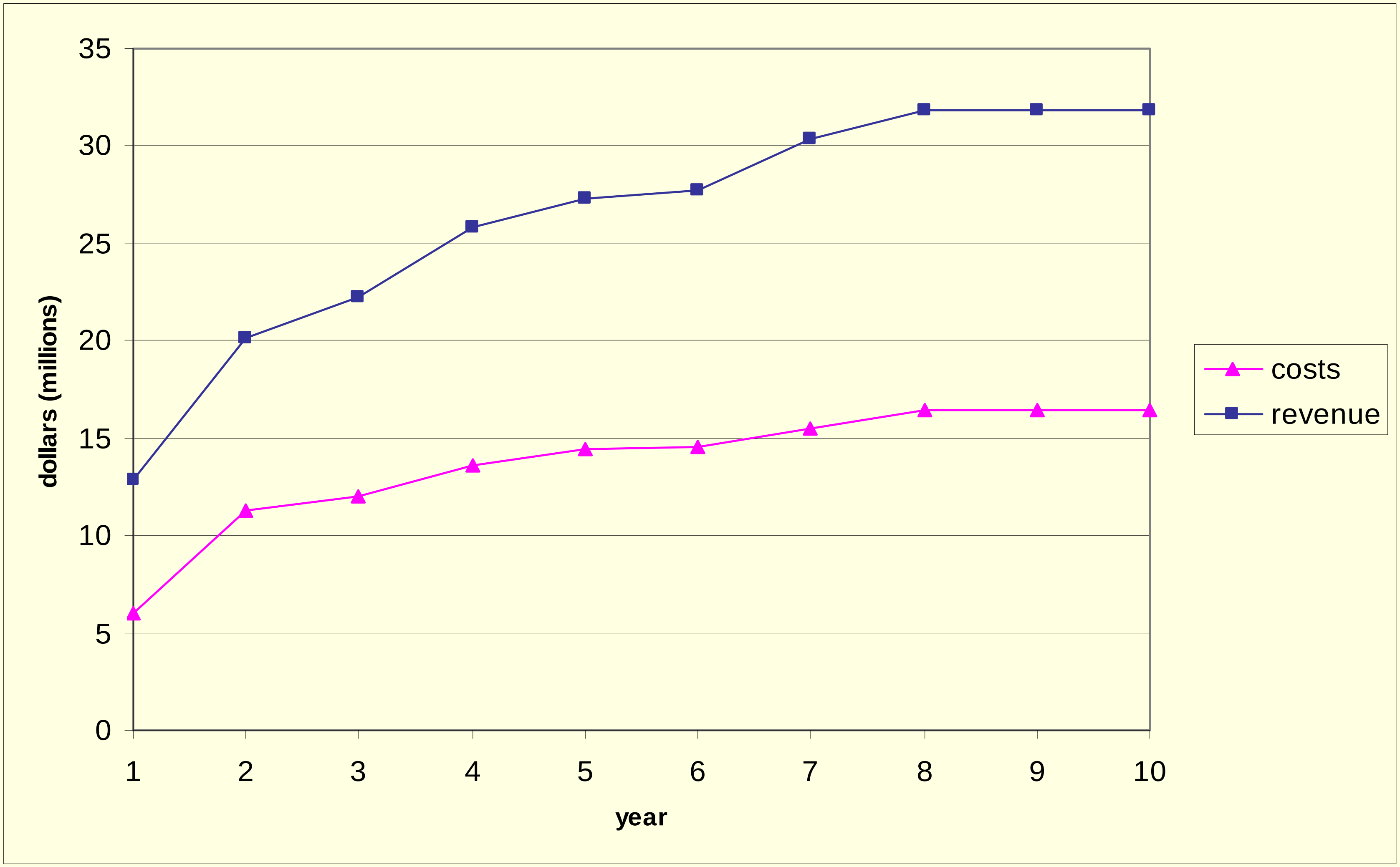
Results: Variable Investment

		year									
		1	2	3	4	5	6	7	8	9	10
	Ethanol										
	Lact.A										
	Dilactide										
	Levullinic										
	Succinic										
	Ethyl Acet										
	VAM										
	PVA										

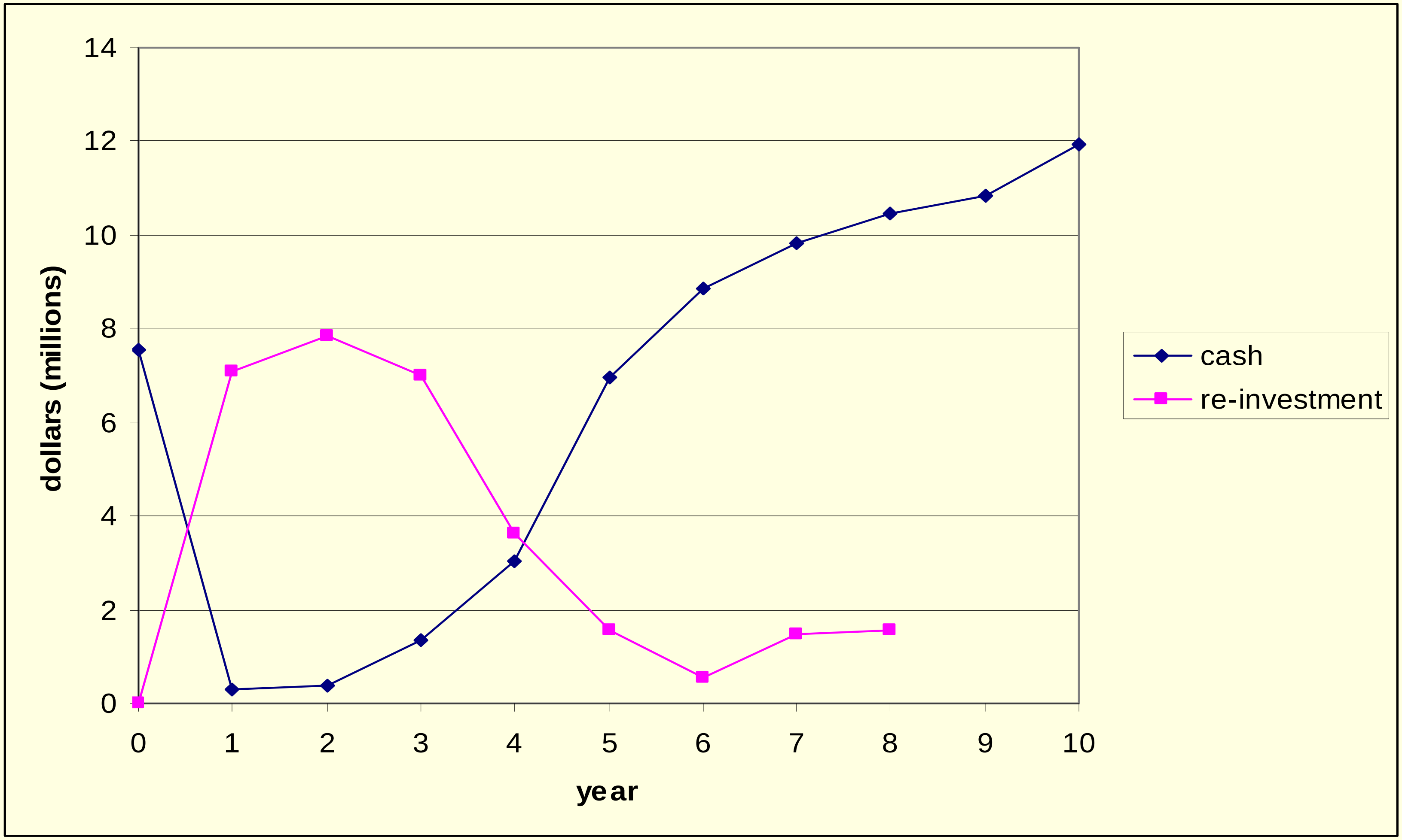
	building
	expansion

- Investment: 7.5 million
- NPV: 28.8 million

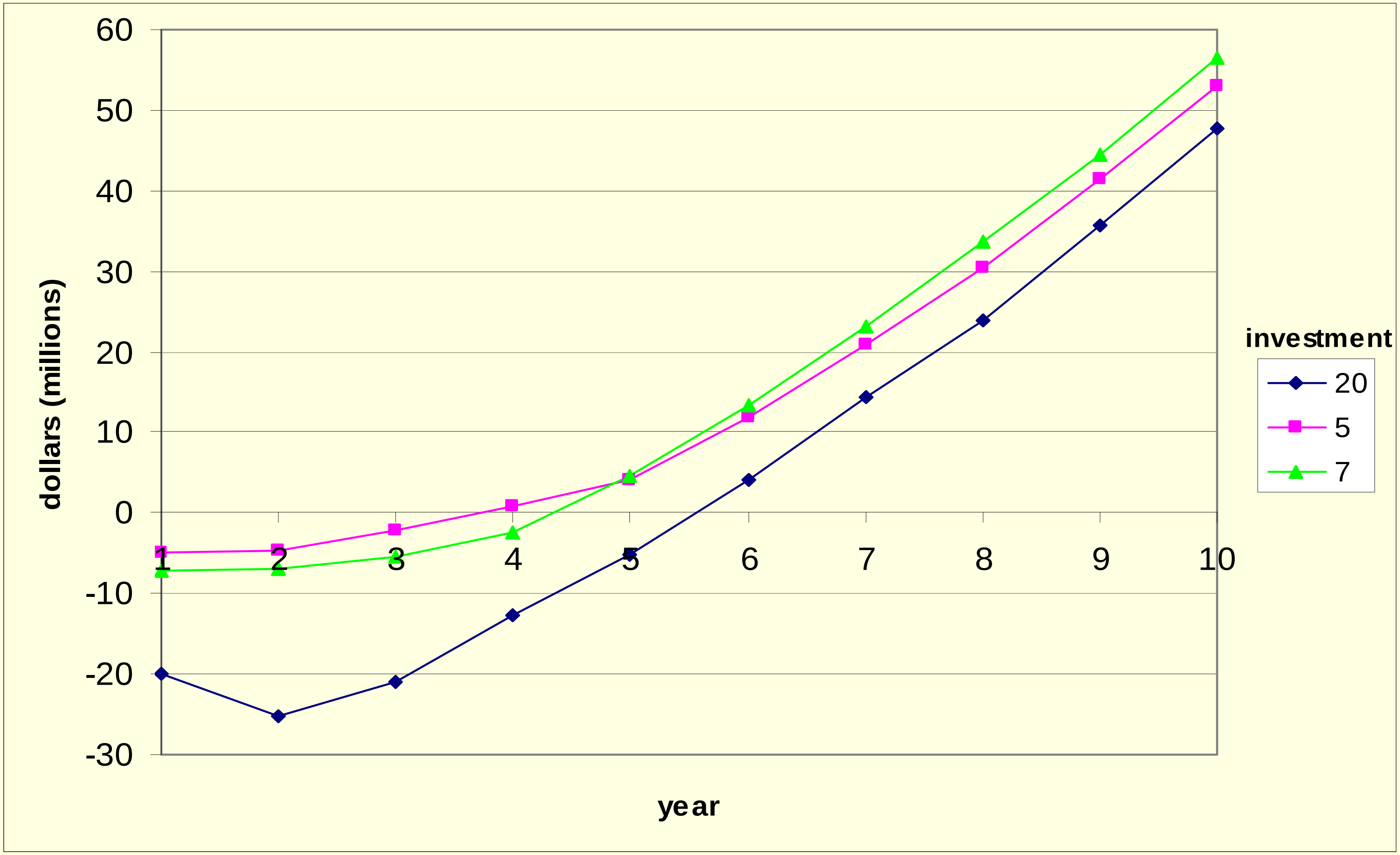
Results: Variable Investment



Results: Variable Investment



Results: Investment Comparison



Results: Non-integrated Processes

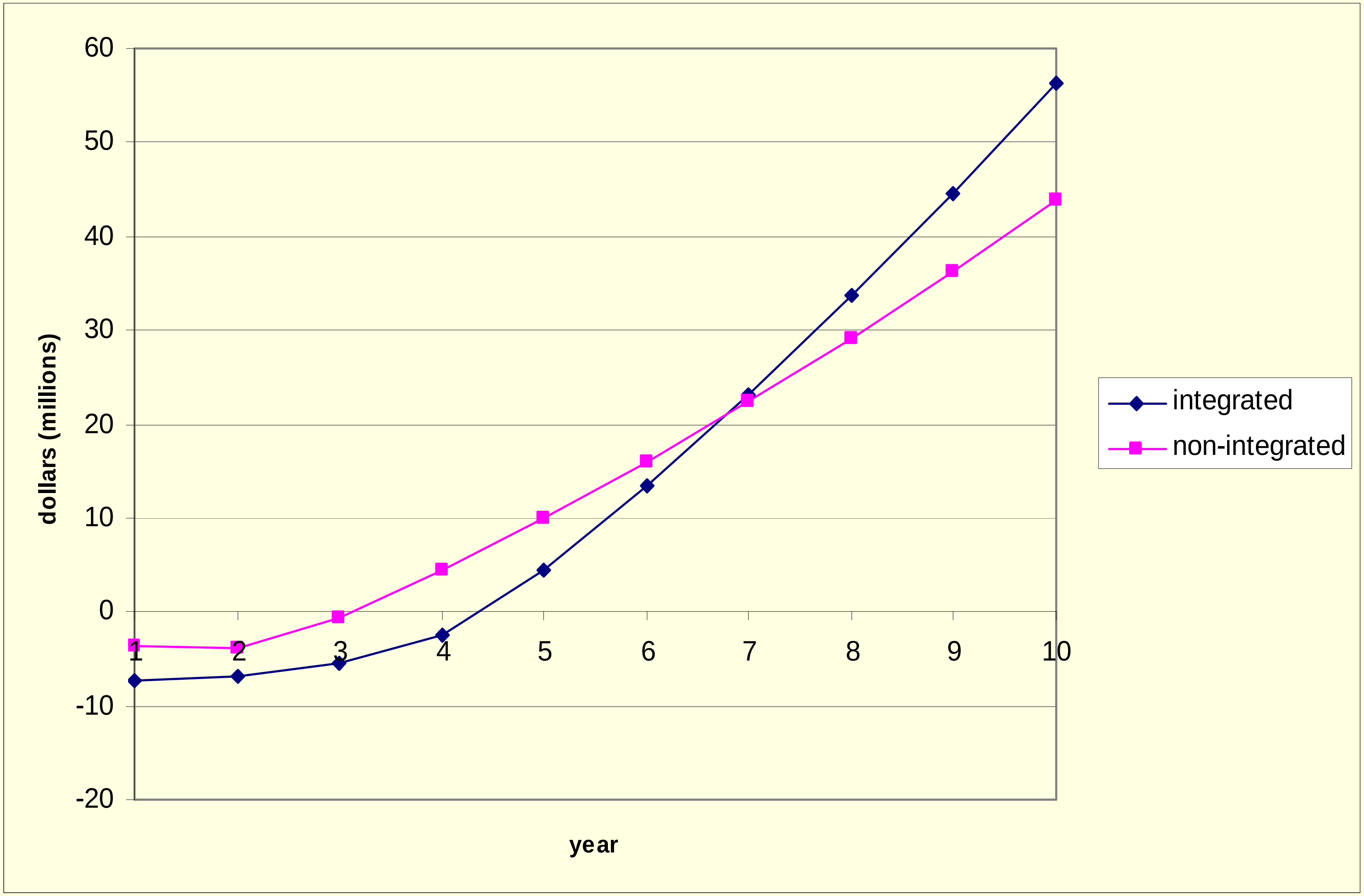
		1	2	3	4	5	6	7	8	9	10
	Ethanol										
	Lactic A										
	Levullinic										

	building
	expansion

- Investment: 5.1 million
- NPV: 24.1 million

Results: Non-integrated Processes

Results: Non-integration vs. Integrated



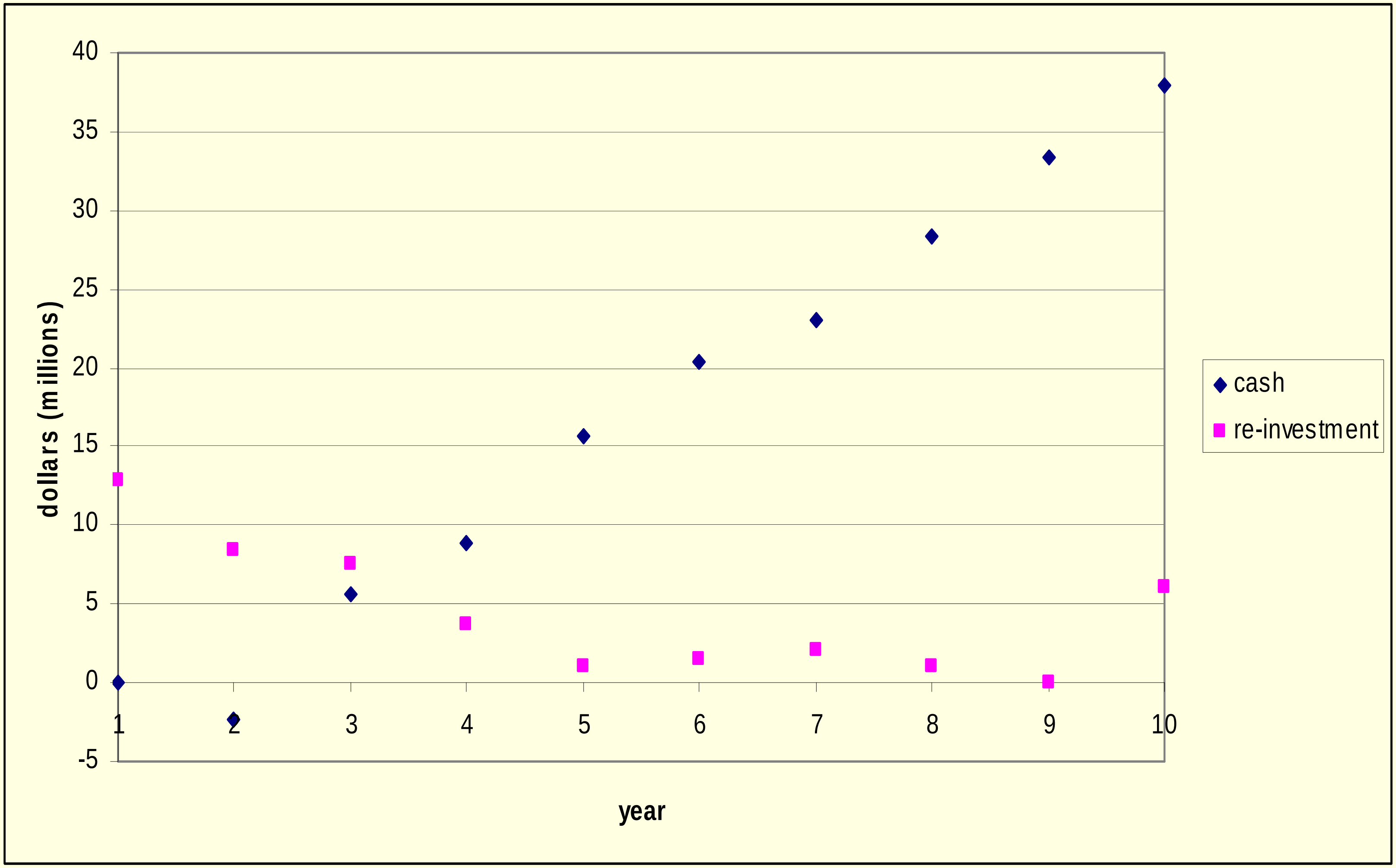
Results: Increasing Prices

	year									
	1	2	3	4	5	6	7	8	9	10
Ethanol	building			expansion			expansion			expansion
Lact. A	building			expansion			expansion			expansion
Ethyl Lact		building					expansion			expansion
Dilactide		building			expansion			expansion		
Levullinic	building			expansion			expansion			expansion
Succinic				building			expansion			expansion
Syngas			building			expansion				expansion
Ethyl Acet		building			expansion			expansion		
VAM			building			expansion				expansion
PVA			building			expansion				expansion

(black)	building
(dark red)	expansion

- Investment: 12.9 million
- NPV: 83.6 million

Results: Increasing Prices



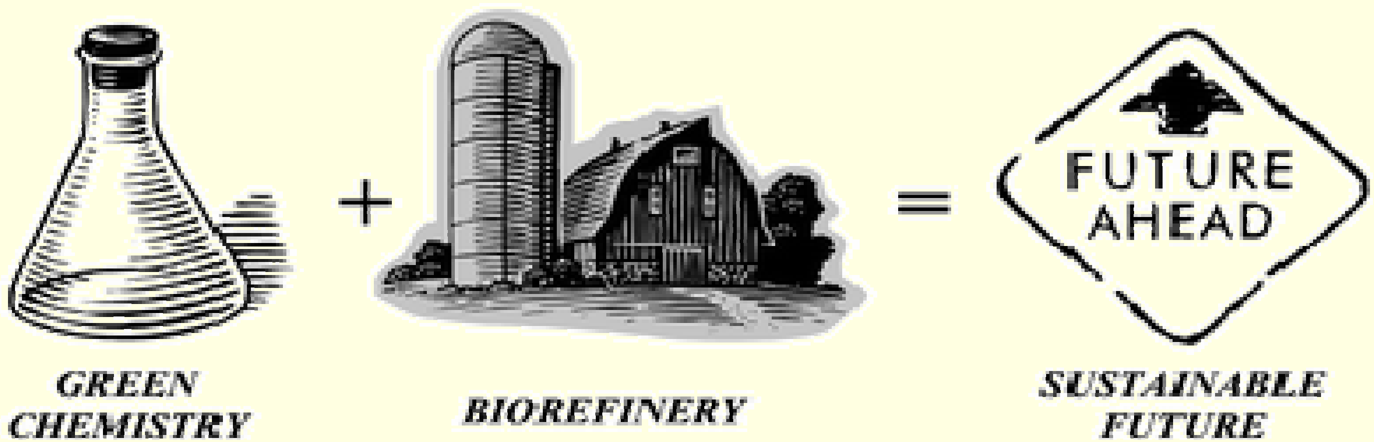
Results: Increasing Prices

Recommendations

- Products/waste can be used in the power generation plant instead of purchasing burning material from outside source
- Location options

Conclusion

- Our model can be used to find optimal operating conditions for a biorefinery!!
- Biorefineries that can produce a variety of products are more economical and profitable!!



[10]

Questions?

References

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3. 3
4. http://www.energy.iastate.edu/becon/tour/page.cfm?page=13
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8. http://www.cheshirerenewables.org.uk/images/biomass_strat.jpg
9. http://www1.eere.energy.gov/biomass/images/chart_biomass_process.jpg
10. http://www.rsc.org/ejga/GC/2006/b604483m-ga.gif
11. http://www.nrel.gov/biomass/images/biorefinery_concept.gif