PUMP SYSTEM DESIGN:
OPTIMIZING TOTAL COST OVER SYSTEM LIFE CYCLE

TEAM 3

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PUMP SYSTEM DESIGN: OPTIMIZING TOTAL COST OVER SYSTEM LIFE CYCLE

Presentation Outline

Background and Engineering Considerations (Cliff)

Optimization Model (Chris)

Results and Conclusions (Tammy)

PUMP SYSTEM DESIGN: OPTIMIZING TOTAL COST OVER SYSTEM LIFE CYCLE

> “Motors use three-fifths of the world’s electricity. Pumping systems use at least a fifth of their total output. In industrial pumping, most of the motors energy is actually spent in fighting against friction.”

FROM PAUL HAWKEN, AMORY LOVINS, AND L. HUNTER LOVINS. NATURAL CAPITALISM: CREATING THE NEXT INDUSTRIAL REVOLUTION. BOSTON, MA: LITTLE, BROWN, AND CO., 1999.

Definition of Pump System

(pump, pipe, valves, fittings)

PUMP SYSTEM DESIGN: OPTIMIZING TOTAL COST OVER SYSTEM LIFE CYCLE

	Traditional	Proposed
Engineering Steps	1. Design building based on major processes, equipment, and material flows. 2. Locate pumps. 3. Layout pipe runs. 4. Select pipe diameters. 5. Calculate frictional losses and TDH. 6. Size pump based on prior decisions and calculations..	1. Design building based on major processes, equipment, and material flows including pipe runs. 2. Locate pumps to minimize pipe length and bends. 3. Select pipe diameters and size pumps as a system based on life cycle analysis.
Cost Analysis	Consider operating costs (pumping energy) vs. capital costs to install pipe.	Optimize system costs given design life cycle. Consider operating costs (pumping energy) vs. capital costs to install pipe AND capital costs to install pump.

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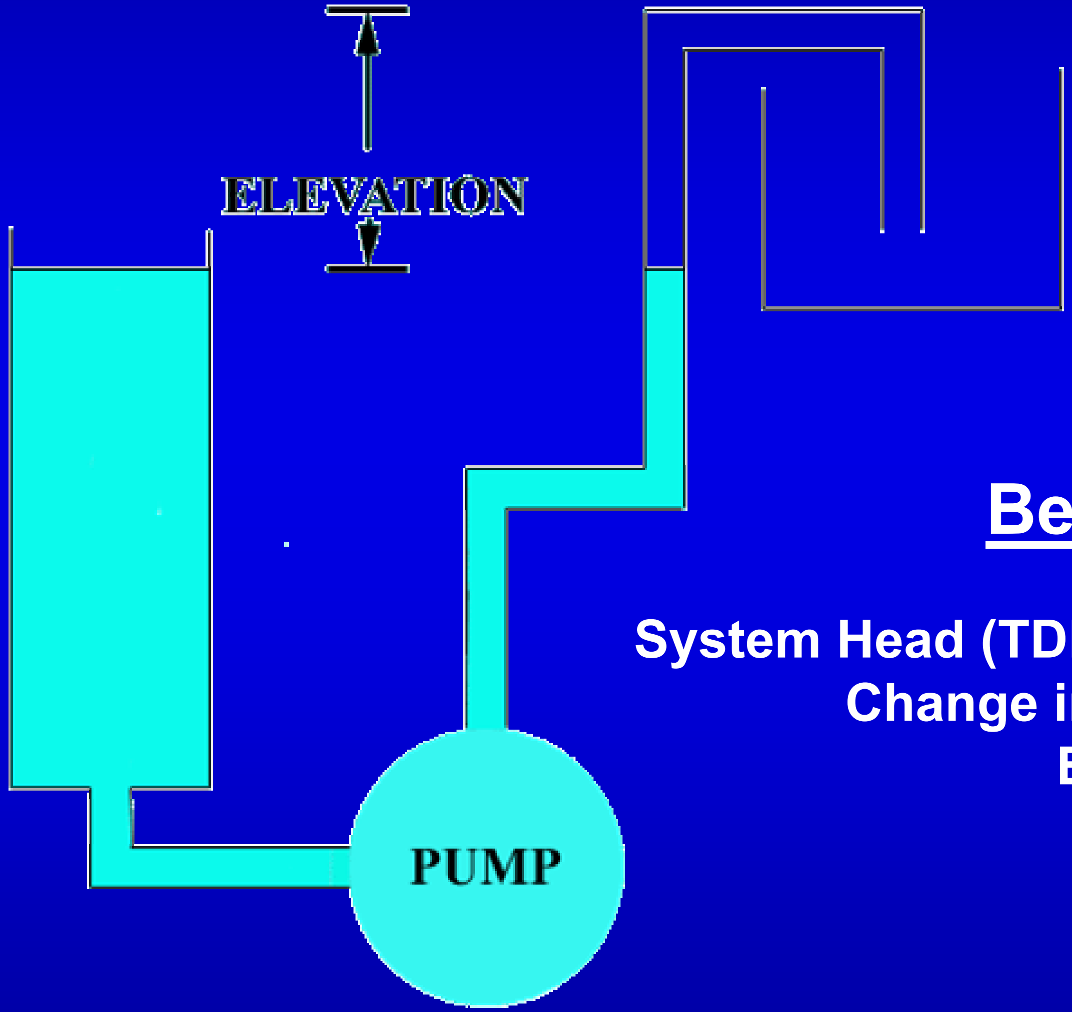
Decision Variables

D_i = pipe diameter (4", 6",8",10",12")

P_j = Pump Selection (12hp, 18hp, 20 hp, 25hp, 30hp)

D_iP_j = Binary Decision Variable representing optimal combination pipe dia and pump size

SIZING A PUMP



Bernoulli Equation

System Head (TDH) =
Change in Elevation (ΔZ) +
Energy Loss due to Friction (H_f)

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Friction Analysis

Pipe:

$$H_f = fLV^2/2gD$$

Fittings:

$$H_f = kV^2/2g$$

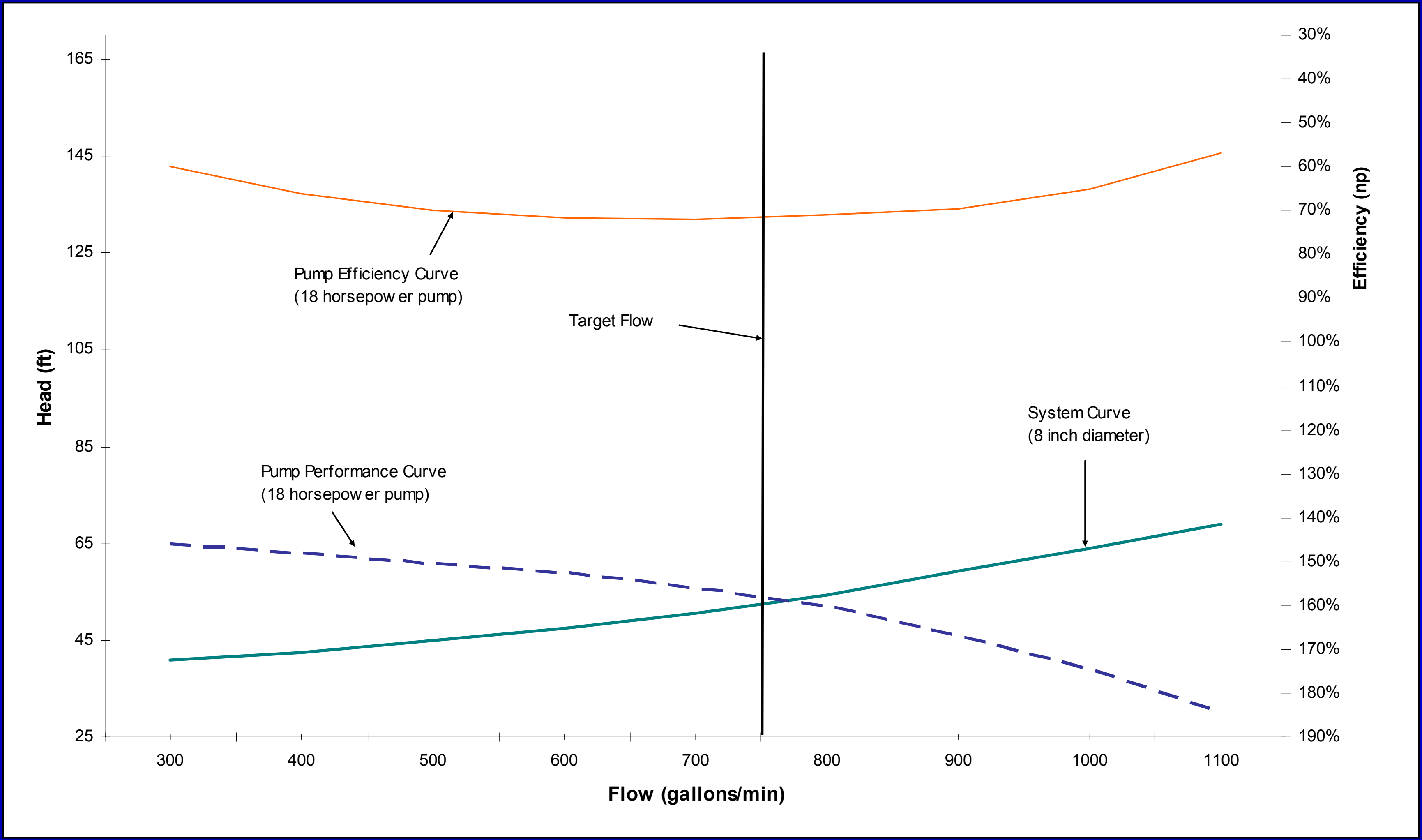
Fluid Flow

$$Q = VA$$

Area increases, Velocity decreases…

Hence, larger diameter pipe will lower friction losses!

SYSTEM AND PUMP CURVES

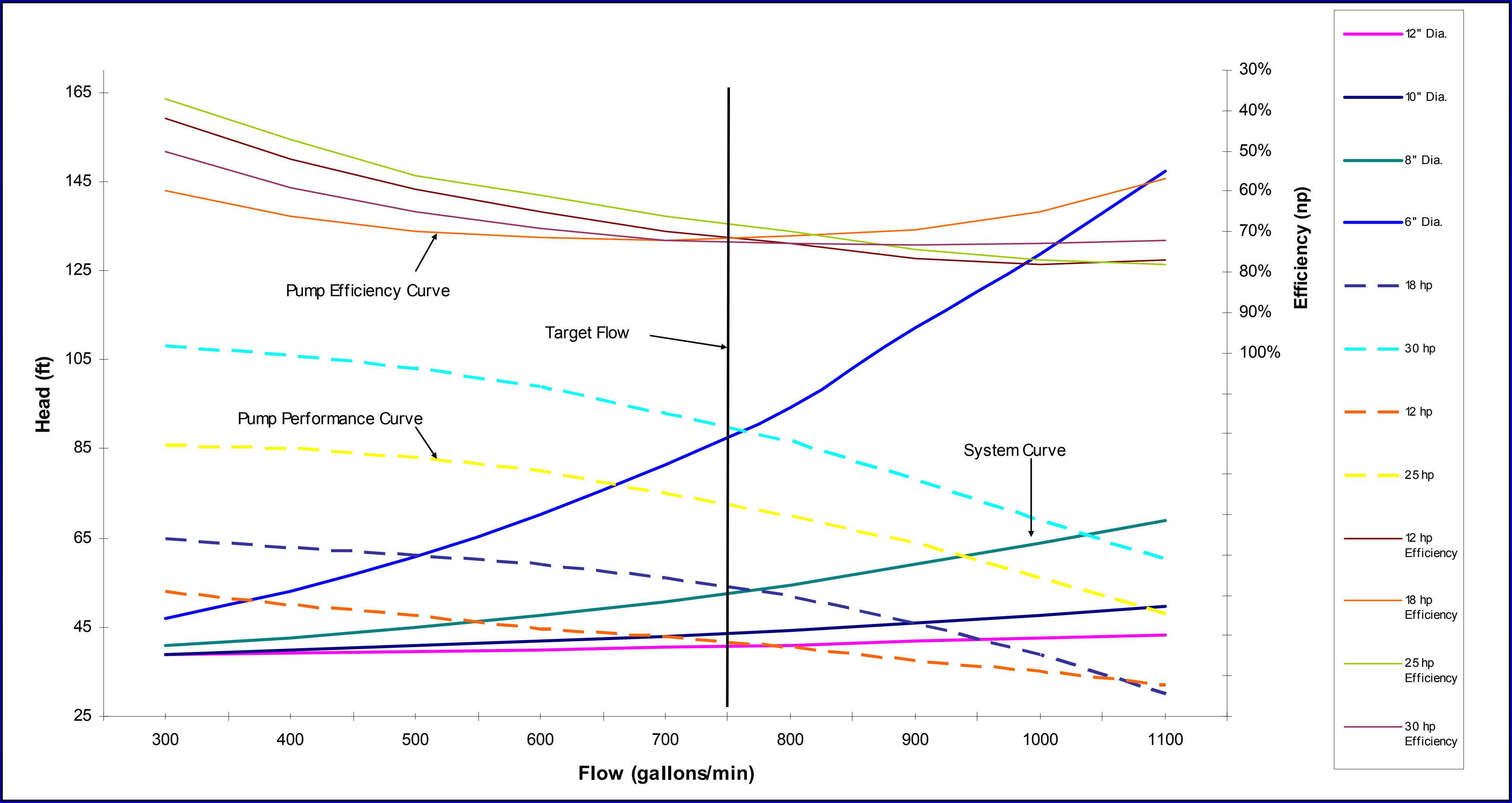


Constraints related Hydraulic Design:

$\sum$ Di Pj = 1 **- Select one pipe diameter/pump combination.**

Max. Hpump ≥ TDH **- Selected pump has Maximum Head greater than System Head at Flow Q.**

SYSTEM AND PUMP CURVES



Constraints related Hydraulic Design:

$\sum D_i P_j = 1$ - Select one pipe diameter/pump combination.

Max. $H_{pump} \geq$ TDH - Selected pump has Maximum Head greater than System Head at Flow Q.

PUMP SYSTEM DESIGN: OPTIMIZING TOTAL COST OVER SYSTEM LIFE CYCLE

Optimization Model

Pumping system design by selecting two components, pump size and pipe diameter, based on their impact on the system life cycle.

Minimize

- Capital costs for purchasing and installing pump
- Capital costs for purchasing and installing piping system
- Operating costs due to pump energy consumed over life cycle (20 years)

SUMMARY OF MODEL INPUTS

From Hydraulic Calcs:

TDH_i = System Head at Flow 750 gpm for each pipe i

From Pump Curves:

Max H = Max pressure added at 750 gpm for each pump j

η_{pij} = Hydraulic Efficiency for each specific ij pair

η_{mj} = Motor Efficiency for each pump j

$\Bigg\} \; E_{ij}$

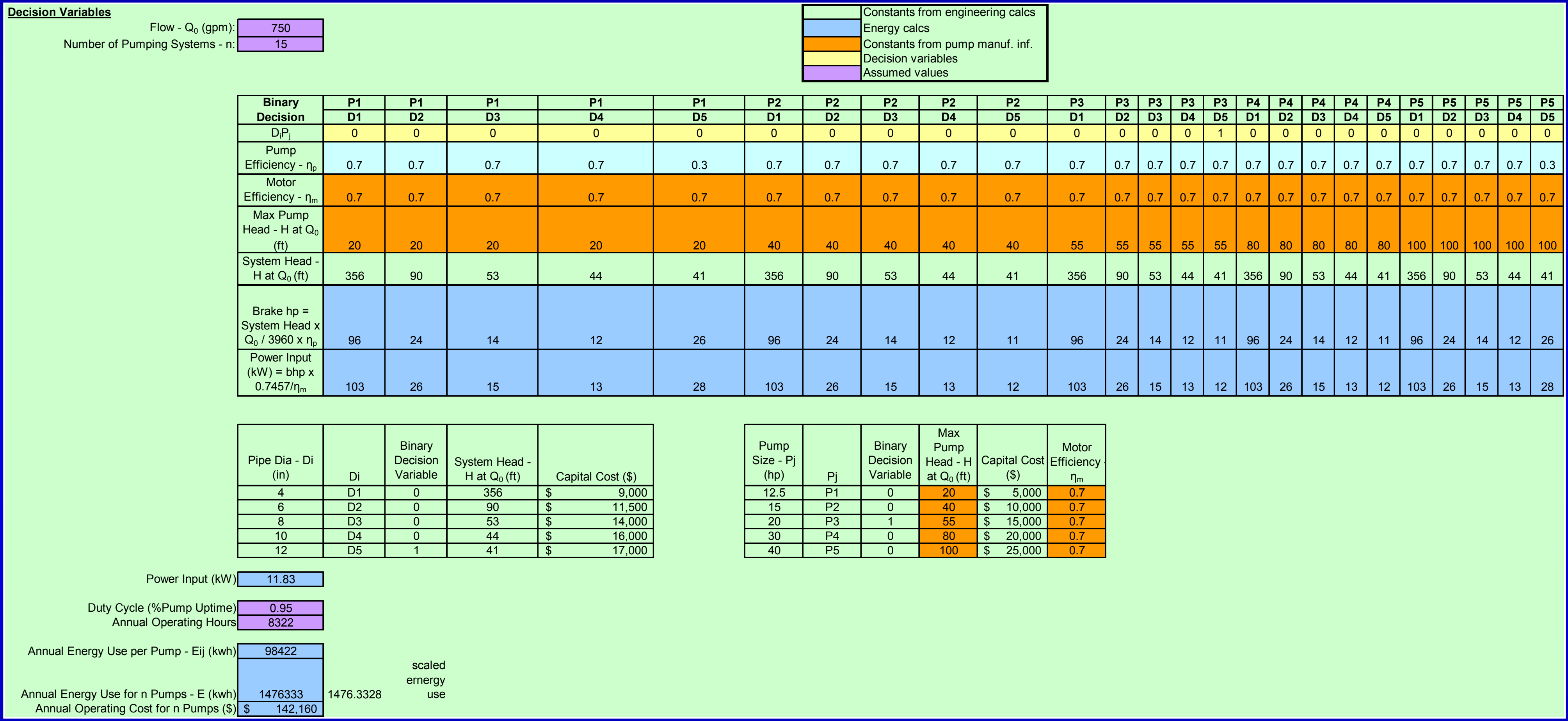
From Cost Estimates:

C_i = Capital Costs to install each piping system i

C_j = Capital Costs to install each pump j

Linear Optimization

Overview of Integer Model of Pump/Pipe Systems



Decision Variables

Flow - Q_0 (gpm): 750

Number of Pumping Systems - n: 15

🟩	Constants from engineering calcs
🟦	Energy calcs
🟧	Constants from pump manuf. inf.
🟨	Decision variables
🟪	Assumed values

Binary Decision	P1 D1	P1 D2	P1 D3	P1 D4	P1 D5	P2 D1	P2 D2	P2 D3	P2 D4	P2 D5
D_iP_j	0	0	0	0	0	0	0	0	0	0
Pump Efficiency - η_p	0.7	0.7	0.7	0.7	0.3	0.7	0.7	0.7	0.7	0.7
Motor Efficiency - η_m	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Max Pump Head - H at Q_0 (ft)	20	20	20	20	20	40	40	40	40	40
System Head - H at Q_0 (ft)	356	90	53	44	41	356	90	53	44	41
Brake hp = System Head x Q_0 / 3960 x η_p	96	24	14	12	26	96	24	14	12	11
Power Input (kW) = bhp x 0.7457/η_m	103	26	15	13	28	103	26	15	13	12

Binary Decision	P3 D1	P3 D2	P3 D3	P3 D4	P3 D5	P4 D1	P4 D2	P4 D3	P4 D4	P4 D5	P5 D1	P5 D2	P5 D3	P5 D4	P5 D5
D_iP_j	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Pump Efficiency - η_p	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.3
Motor Efficiency - η_m	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Max Pump Head - H at Q_0 (ft)	55	55	55	55	55	80	80	80	80	80	100	100	100	100	100
System Head - H at Q_0 (ft)	356	90	53	44	41	356	90	53	44	41	356	90	53	44	41
Brake hp = System Head x Q_0 / 3960 x η_p	96	24	14	12	11	96	24	14	12	11	96	24	14	12	26
Power Input (kW) = bhp x 0.7457/η_m	103	26	15	13	12	103	26	15	13	12	103	26	15	13	28

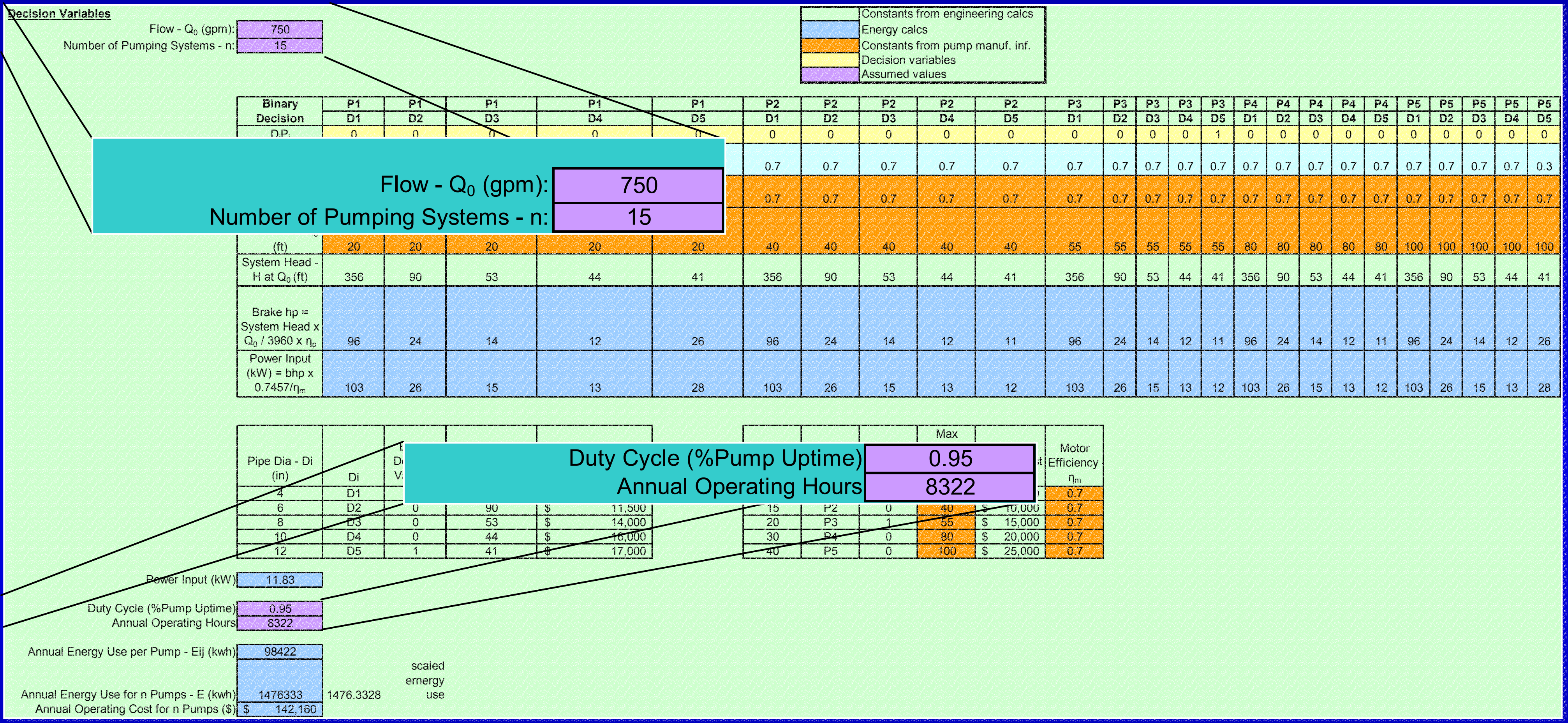
Pipe Dia - Di (in)	Di	Binary Decision Variable	System Head - H at Q_0 (ft)	Capital Cost ($)
4	D1	0	356	$ 9,000
6	D2	0	90	$ 11,500
8	D3	0	53	$ 14,000
10	D4	0	44	$ 16,000
12	D5	1	41	$ 17,000

Pump Size - Pj (hp)	Pj	Binary Decision Variable	Max Pump Head - H at Q_0 (ft)	Capital Cost ($)	Motor Efficiency - η_m
12.5	P1	0	20	$ 5,000	0.7
15	P2	0	40	$ 10,000	0.7
20	P3	1	55	$ 15,000	0.7
30	P4	0	80	$ 20,000	0.7
40	P5	0	100	$ 25,000	0.7

Power Input (kW)	11.83		
Duty Cycle (%Pump Uptime)	0.95		
Annual Operating Hours	8322		
Annual Energy Use per Pump - Eij (kwh)	98422		
Annual Energy Use for n Pumps - E (kwh)	1476333	1476.3328	scaled ernergy use
Annual Operating Cost for n Pumps ($)	$ 142,160		

Many ways to pump water from Point A to Point B

Overview of Integer Model of Pump/Pipe Systems – System Inputs



Decision Variables

Flow - Q_0 (gpm): 750

Number of Pumping Systems - n: 15

☐	Constants from engineering calcs
🟦	Energy calcs
🟧	Constants from pump manuf. inf.
🟨	Decision variables
🟪	Assumed values

Binary	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2	P3	P3	P3	P3	P3	P4	P4	P4	P4	P4	P5	P5	P5	P5	P5
Decision	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5
D.P.$_i$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
						0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.3
						0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
(ft)	20	20	20	20	20	40	40	40	40	40	55	55	55	55	55	80	80	80	80	80	100	100	100	100	100
System Head - H at Q_0 (ft)	356	90	53	44	41	356	90	53	44	41	356	90	53	44	41	356	90	53	44	41	356	90	53	44	41
Brake hp = System Head x Q_0 / 3960 x η_p	96	24	14	12	26	96	24	14	12	11	96	24	14	12	11	96	24	14	12	11	96	24	14	12	26
Power Input (kW) = bhp x 0.7457/η_m	103	26	15	13	28	103	26	15	13	12	103	26	15	13	12	103	26	15	13	12	103	26	15	13	28

Flow - Q_0 (gpm): 750

Number of Pumping Systems - n: 15

Pipe Dia - Di (in)	Di				
4	D1				
6	D2	0	90	$	11,500
8	D3	0	53	$	14,000
10	D4	0	44	$	16,000
12	D5	1	41	$	17,000

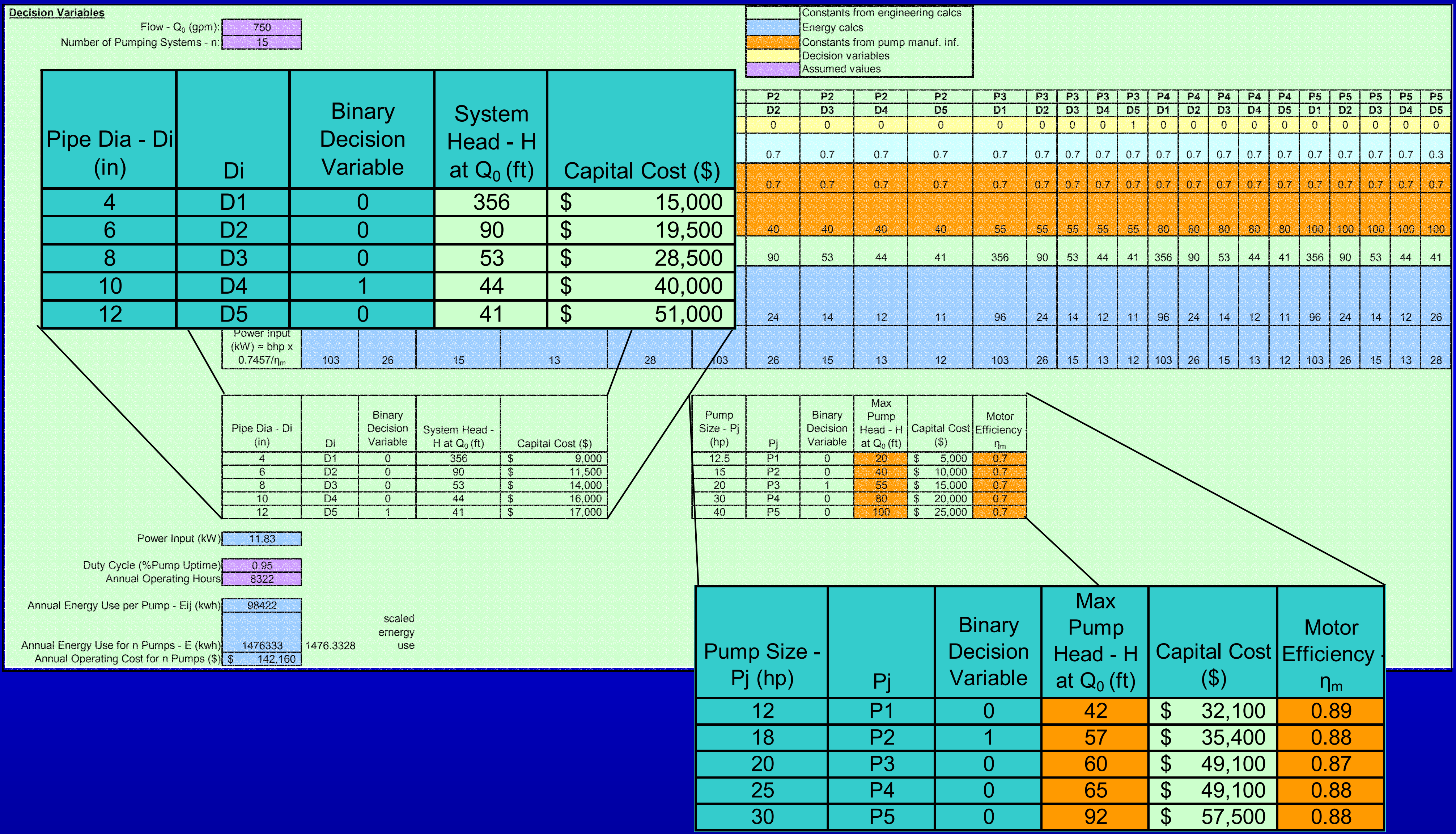
			Max			Motor Efficiency η_m
						0.7
15	P2	0	40	$	10,000	0.7
20	P3	1	55	$	15,000	0.7
30	P4	0	80	$	20,000	0.7
40	P5	0	100	$	25,000	0.7

Duty Cycle (%Pump Uptime) 0.95

Annual Operating Hours 8322

Power Input (kW)	11.83		
Duty Cycle (%Pump Uptime)	0.95		
Annual Operating Hours	8322		
Annual Energy Use per Pump - Eij (kwh)	98422		
Annual Energy Use for n Pumps - E (kwh)	1476333	1476.3328	scaled ernergy use
Annual Operating Cost for n Pumps ($)	$ 142,160		

Overview of Integer Model of Pump/Pipe Systems – Pump and Pipe Attributes



Decision Variables

Flow - Q_0 (gpm): 750

Number of Pumping Systems - n: 15

☐	Constants from engineering calcs
▨	Energy calcs
▨	Constants from pump manuf. inf.
▨	Decision variables
▨	Assumed values

Pipe Dia - Di (in)	Di	Binary Decision Variable	System Head - H at Q_0 (ft)	Capital Cost ($)
4	D1	0	356	$ 15,000
6	D2	0	90	$ 19,500
8	D3	0	53	$ 28,500
10	D4	1	44	$ 40,000
12	D5	0	41	$ 51,000

							P2	P2	P2	P2	P3	P3	P3	P3	P3	P4	P4	P4	P4	P4	P5	P5	P5	P5	P5
							D2	D3	D4	D5	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5
							0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
							0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.3
							0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
							40	40	40	40	55	55	55	55	55	80	80	80	80	80	100	100	100	100	100
							90	53	44	41	356	90	53	44	41	356	90	53	44	41	356	90	53	44	41
							24	14	12	11	96	24	14	12	11	96	24	14	12	11	96	24	14	12	26
Power Input (kW) = bhp x $0.7457/\eta_m$	103	26	15	13	28	103	26	15	13	12	103	26	15	13	12	103	26	15	13	12	103	26	15	13	28

Pipe Dia - Di (in)	Di	Binary Decision Variable	System Head - H at Q_0 (ft)	Capital Cost ($)
4	D1	0	356	$ 9,000
6	D2	0	90	$ 11,500
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10	D4	0	44	$ 16,000
12	D5	1	41	$ 17,000

Pump Size - Pj (hp)	Pj	Binary Decision Variable	Max Pump Head - H at Q_0 (ft)	Capital Cost ($)	Motor Efficiency η_m
12.5	P1	0	20	$ 5,000	0.7
15	P2	0	40	$ 10,000	0.7
20	P3	1	55	$ 15,000	0.7
30	P4	0	80	$ 20,000	0.7
40	P5	0	100	$ 25,000	0.7

Power Input (kW) 11.83

Duty Cycle (%Pump Uptime) 0.95

Annual Operating Hours 8322

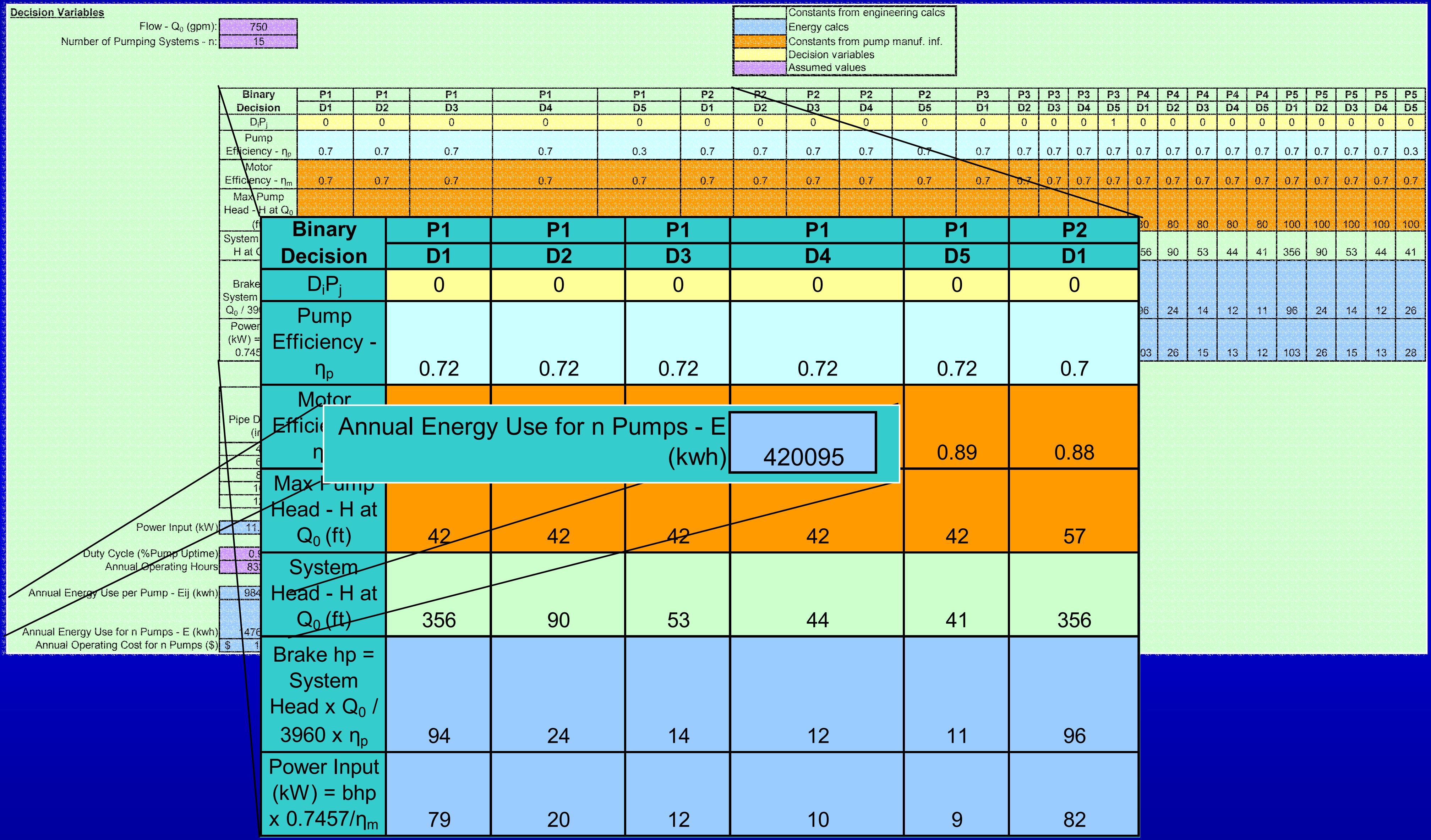
Annual Energy Use per Pump - Eij (kwh) 98422

Annual Energy Use for n Pumps - E (kwh) 1476333 1476.3328 scaled ernergy use

Annual Operating Cost for n Pumps ($) $ 142,160

Pump Size - Pj (hp)	Pj	Binary Decision Variable	Max Pump Head - H at Q_0 (ft)	Capital Cost ($)	Motor Efficiency - η_m
12	P1	0	42	$ 32,100	0.89
18	P2	1	57	$ 35,400	0.88
20	P3	0	60	$ 49,100	0.87
25	P4	0	65	$ 49,100	0.88
30	P5	0	92	$ 57,500	0.88

Overview of Integer Model of Pump/Pipe Systems – Decision Variables and Calculations



Decision Variables

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Number of Pumping Systems - n: 15

🟩	Constants from engineering calcs
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🟨	Decision variables
🟪	Assumed values

Binary Decision	P1 D1	P1 D2	P1 D3	P1 D4	P1 D5	P2 D1	P2 D2	P2 D3	P2 D4	P2 D5	P3 D1	P3 D2	P3 D3	P3 D4	P3 D5	P4 D1	P4 D2	P4 D3	P4 D4	P4 D5	P5 D1	P5 D2	P5 D3	P5 D4	P5 D5
D_iP_j	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Pump Efficiency - η_p	0.7	0.7	0.7	0.7	0.3	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.3
Motor Efficiency - η_m	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Max Pump Head - H at Q_0 (f																30	80	80	80	80	100	100	100	100	100
System H at C																56	90	53	44	41	356	90	53	44	41
Brake System Q_0 / 39																96	24	14	12	11	96	24	14	12	26
Power (kW) = 0.745																03	26	15	13	12	103	26	15	13	28

Pipe D (in

4

6

8

1

1

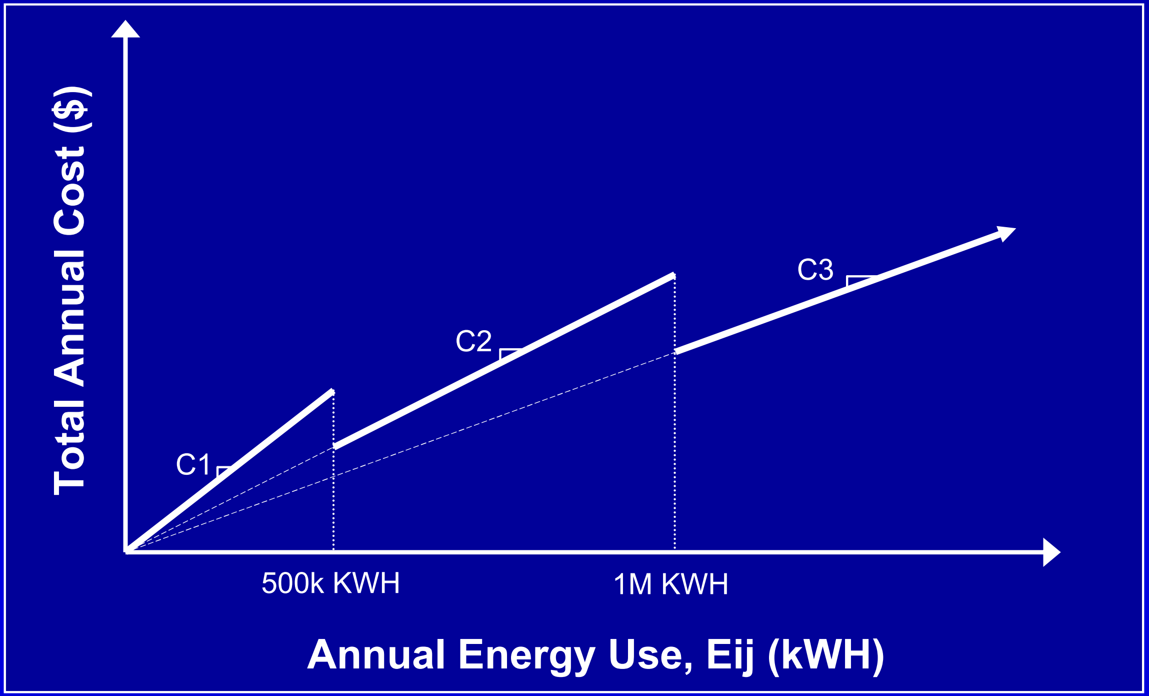
Power Input (kW)	11.
Duty Cycle (%Pump Uptime)	0.9
Annual Operating Hours	83
Annual Energy Use per Pump - Eij (kwh)	984
Annual Energy Use for n Pumps - E (kwh)	476
Annual Operating Cost for n Pumps ($)	$ 1

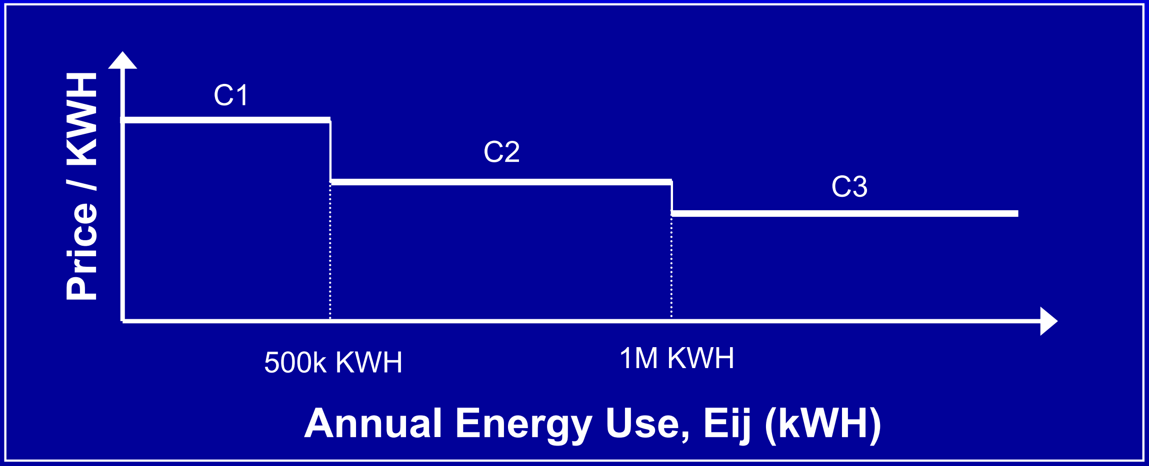
Binary Decision	P1 D1	P1 D2	P1 D3	P1 D4	P1 D5	P2 D1
D_iP_j	0	0	0	0	0	0
Pump Efficiency - η_p	0.72	0.72	0.72	0.72	0.72	0.7
Motor Effici… η…					0.89	0.88
Max Pump Head - H at Q_0 (ft)	42	42	42	42	42	57
System Head - H at Q_0 (ft)	356	90	53	44	41	356
Brake hp = System Head x Q_0 / 3960 x η_p	94	24	14	12	11	96
Power Input (kW) = bhp x 0.7457/η_m	79	20	12	10	9	82

Annual Energy Use for n Pumps - E (kwh)	420095

Energy Pricing Option 1

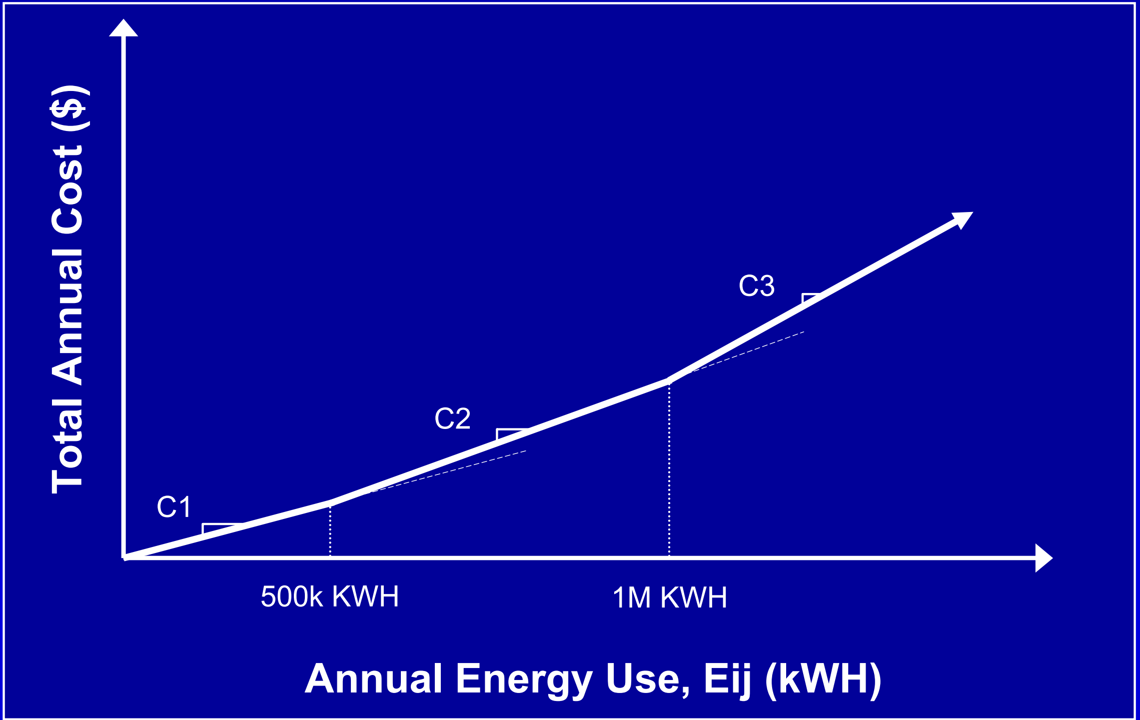
Price Breaks at Discrete Power Usages

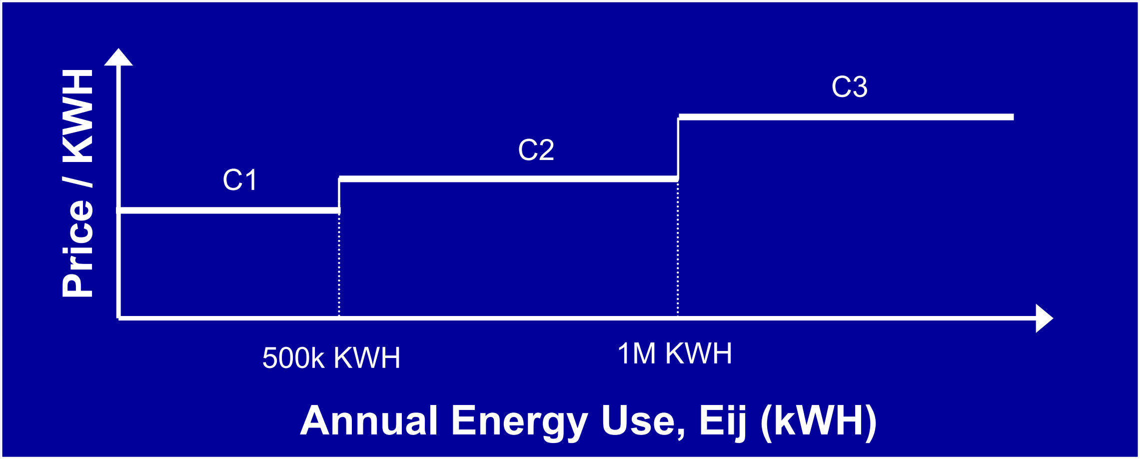




Energy Pricing Option 2

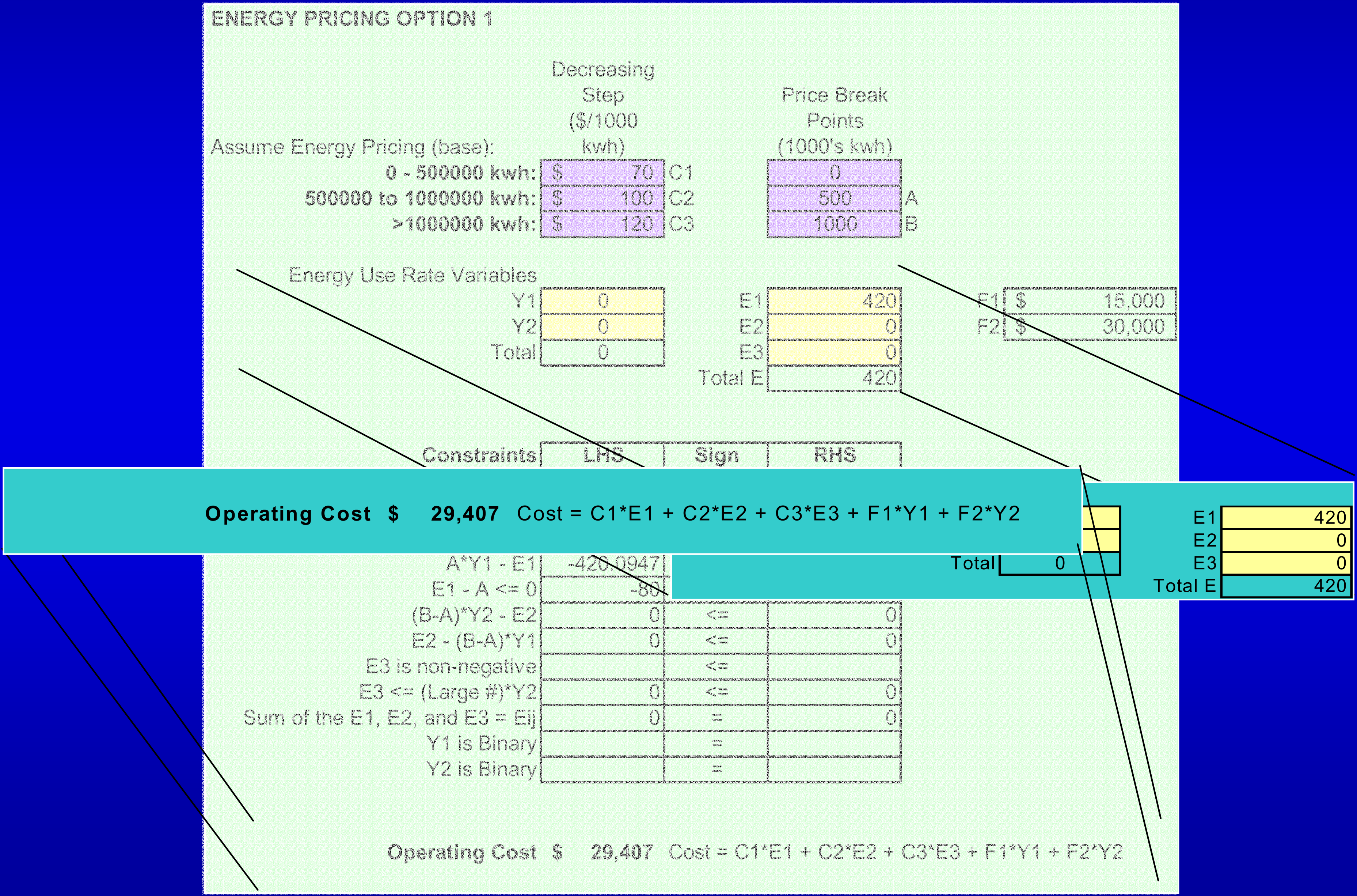
Price Increases at Discrete Power Usages (Internal Power Generation)





- The next step is to optimize the choice of pump size and pipe diameter under the two rate structures

Computation of the Annual Operating Cost



ENERGY PRICING OPTION 1

	Decreasing Step ($/1000 kwh)		Price Break Points (1000's kwh)	
Assume Energy Pricing (base):				
0 - 500000 kwh:	$ 70	C1	0	
500000 to 1000000 kwh:	$ 100	C2	500	A
>1000000 kwh:	$ 120	C3	1000	B

Energy Use Rate Variables

Y1	0	E1	420	F1	$ 15,000
Y2	0	E2	0	F2	$ 30,000
Total	0	E3	0		
		Total E	420		

Constraints	**LHS**	**Sign**	**RHS**
A*Y1 - E1	-420.0947		
E1 - A <= 0	-80		
(B-A)*Y2 - E2	0	<=	0
E2 - (B-A)*Y1	0	<=	0
E3 is non-negative		<=	
E3 <= (Large #)*Y2	0	<=	0
Sum of the E1, E2, and E3 = Eij	0	=	0
Y1 is Binary		=	
Y2 is Binary		=	

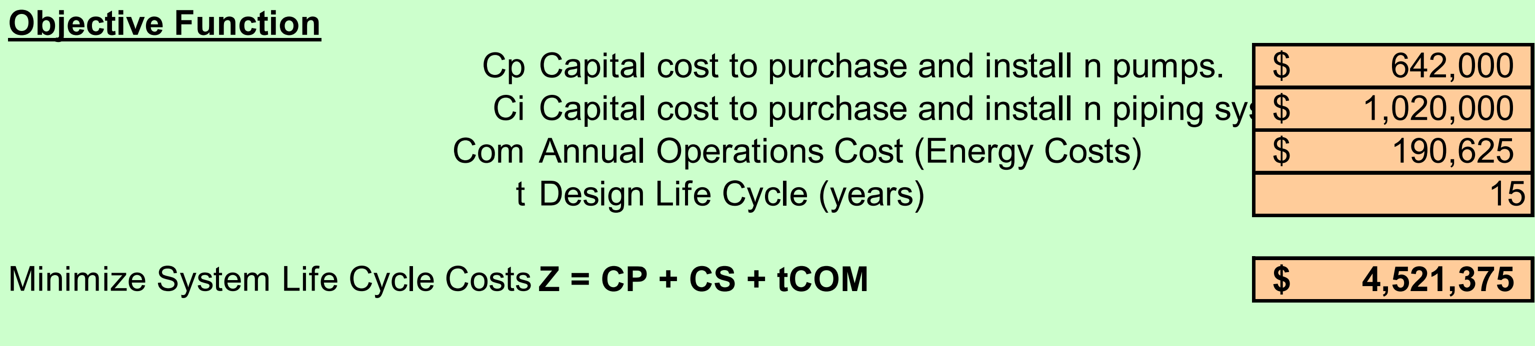
Operating Cost $ 29,407 Cost = C1*E1 + C2*E2 + C3*E3 + F1*Y1 + F2*Y2

Operating Cost $ 29,407 Cost = C1*E1 + C2*E2 + C3*E3 + F1*Y1 + F2*Y2

Total	0

E1	420
E2	0
E3	0
Total E	420

Computation of the Objective Function



Objective Function

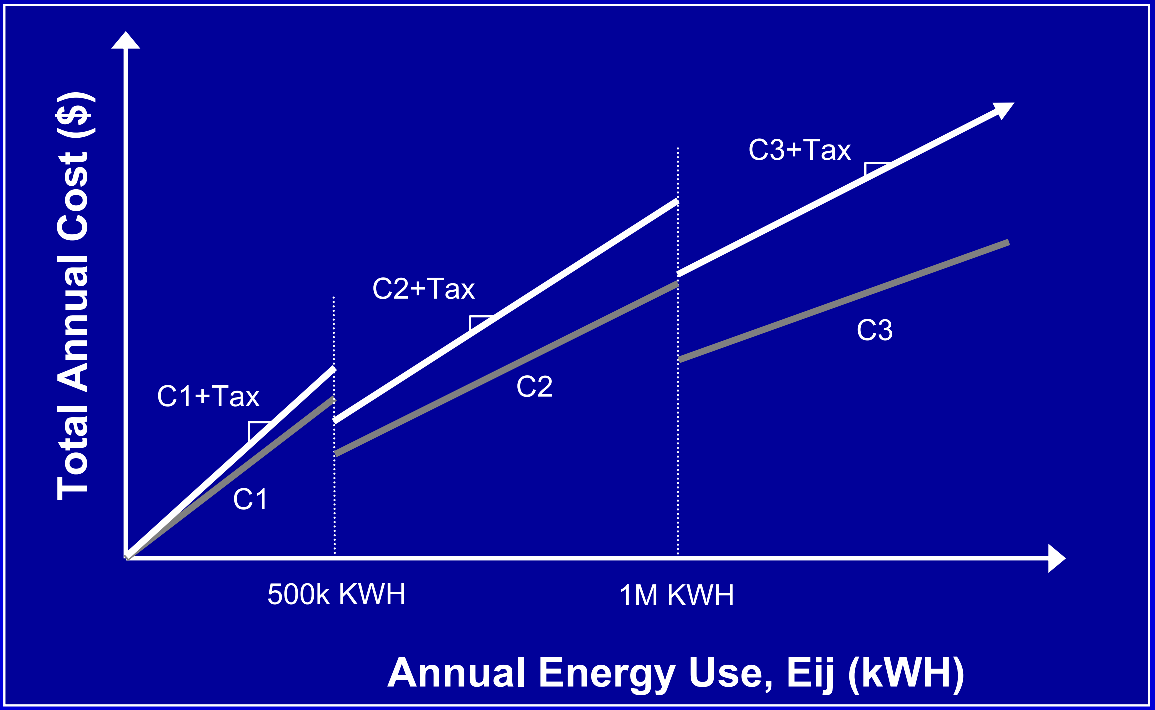
Cp	Capital cost to purchase and install n pumps.	$ 642,000
Ci	Capital cost to purchase and install n piping sy	$ 1,020,000
Com	Annual Operations Cost (Energy Costs)	$ 190,625
t	Design Life Cycle (years)	15
Minimize System Life Cycle Costs	**Z = CP + CS + tCOM**	**$ 4,521,375**

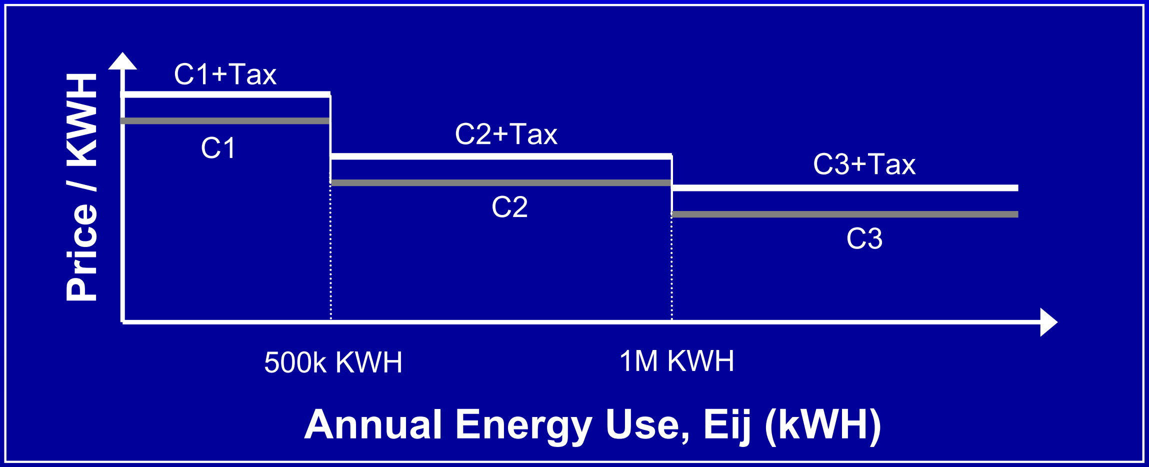
Potential Tax on Carbon Emissions

- There is currently a proposed tax pending in Maryland – potentially taxing at a rate of between $5 and $20 per 1000 pounds of Carbon emissions
- We assumed that the costs associated with this type of tax would be passed onto the final customer
- We added scenarios to account for this type of tax and the relative probabilities of different tax rates
- The goal was to see if the expected cost of the taxes would affect our decision making

Energy Pricing Option 1 with Taxes

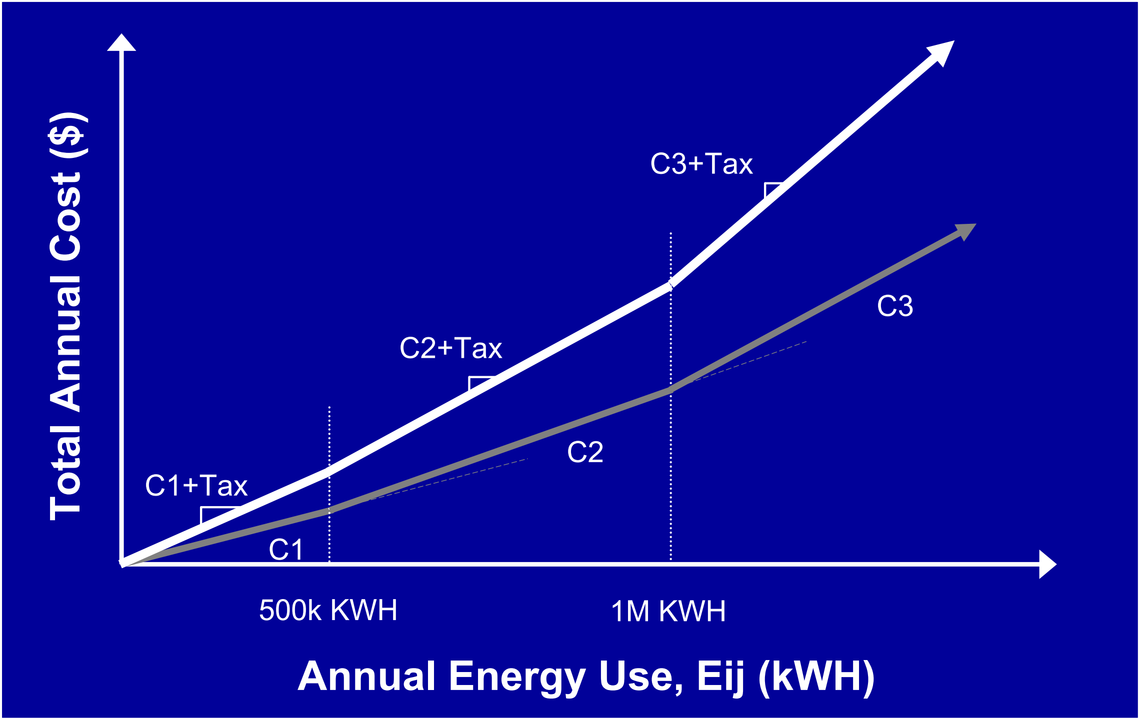
Price Breaks at Discrete Power Usages, Including Potential Taxes (XXX $/lb C)

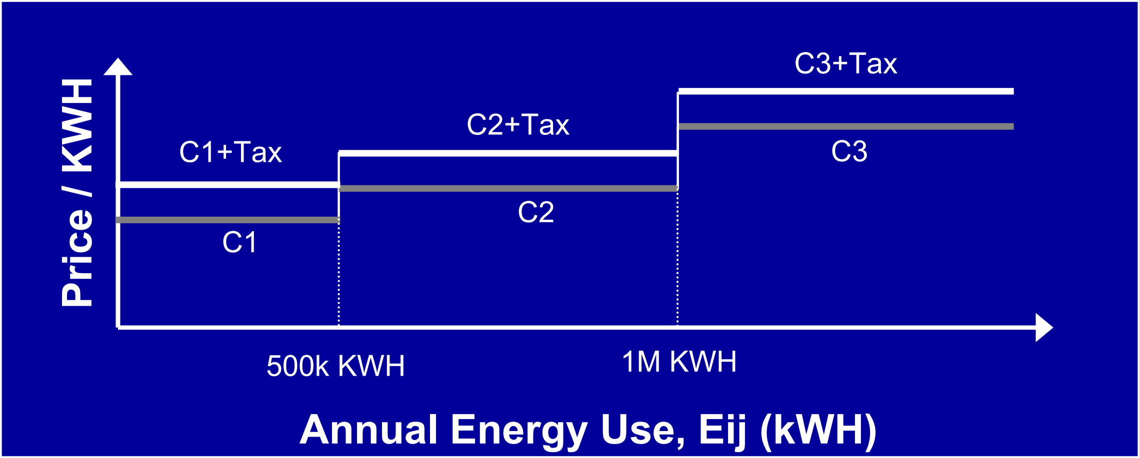




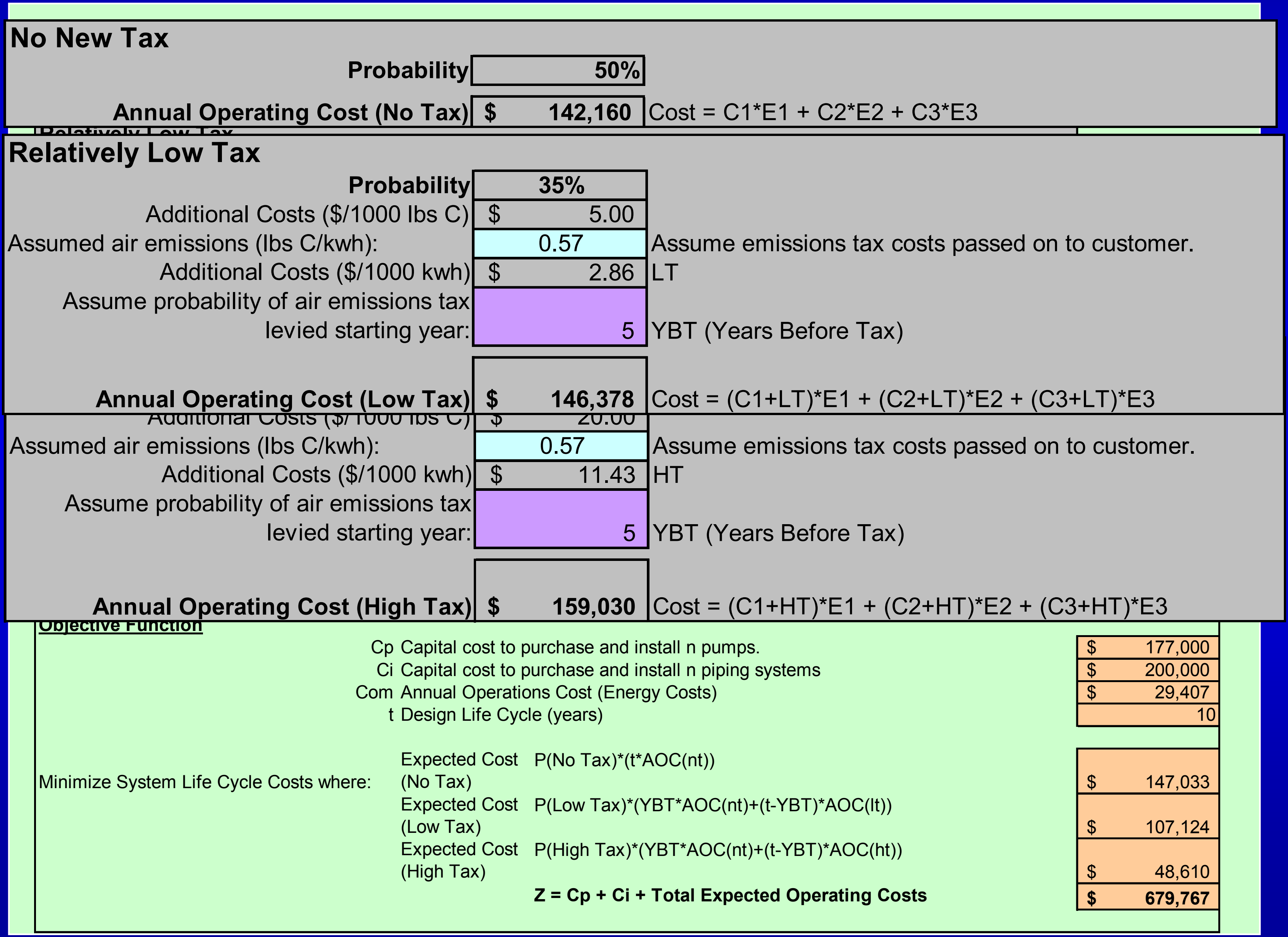
Energy Pricing Option 2 with Taxes

Price Increases at Discrete Power Usages, Including Potential Taxes (XXX $/lb C)





Addition of *Total Expected Costs Due to Taxes* to Model



No New Tax

Probability	**50%**	
Annual Operating Cost (No Tax)	**$ 142,160**	Cost = C1*E1 + C2*E2 + C3*E3

Relatively Low Tax

Probability	**35%**	
Additional Costs ($/1000 lbs C)	$ 5.00	
Assumed air emissions (lbs C/kwh):	0.57	Assume emissions tax costs passed on to customer.
Additional Costs ($/1000 kwh)	$ 2.86	LT
Assume probability of air emissions tax levied starting year:	5	YBT (Years Before Tax)
Annual Operating Cost (Low Tax)	**$ 146,378**	Cost = (C1+LT)*E1 + (C2+LT)*E2 + (C3+LT)*E3

Additional Costs ($/1000 lbs C)	$ 20.00	
Assumed air emissions (lbs C/kwh):	0.57	Assume emissions tax costs passed on to customer.
Additional Costs ($/1000 kwh)	$ 11.43	HT
Assume probability of air emissions tax levied starting year:	5	YBT (Years Before Tax)
Annual Operating Cost (High Tax)	**$ 159,030**	Cost = (C1+HT)*E1 + (C2+HT)*E2 + (C3+HT)*E3

Objective Function

Cp	Capital cost to purchase and install n pumps.		$ 177,000
Ci	Capital cost to purchase and install n piping systems		$ 200,000
Com	Annual Operations Cost (Energy Costs)		$ 29,407
t	Design Life Cycle (years)		10
Minimize System Life Cycle Costs where:	Expected Cost (No Tax)	P(No Tax)*(t*AOC(nt))	$ 147,033
	Expected Cost (Low Tax)	P(Low Tax)*(YBT*AOC(nt)+(t-YBT)*AOC(lt))	$ 107,124
	Expected Cost (High Tax)	P(High Tax)*(YBT*AOC(nt)+(t-YBT)*AOC(ht))	$ 48,610
		Z = Cp + Ci + Total Expected Operating Costs	**$ 679,767**

Results and Analysis

RESULTS

1. Does the optimal design change when pump capital costs are included in the life cycle analysis?

2. How do the different power rate options impact the optimal design?

3. Other design constraints.

Does the optimal design change when pump capital costs are included in the optimization?

Increase Pipe Diameter

Increase Pipe Capital Costs (bigger pipe)

Decrease Operating Costs (less Energy loss due to friction)

Decrease Pump Capital Costs (smaller pump)

Life Cycle Costs = Pipe Capital Costs + Operating Costs

vs.

Life Cycle Costs = Pipe Capital Costs + **Pump Capital Costs** + Operating Costs

Industrial Process Retrofits
Pump Design Experience

- Locate pumps based on available space, layout piping to connect pumps, tanks, and process equipment.
- Select pipe diameter based on reasonable velocity (~field version of life cycle analysis).
- Given pipe diameter, calculate TDH to generate System Curve. Include a safety factor to ensure that pump capacity is adequate.
- Send System Curve to pump manufacturer to make pump recommendations.

Does the optimal design change when pump capital costs are included in the optimization?

	TRADITIONAL ANALYSIS	PROPOSED SYSTEM ANALYSIS
Objective Function	**Pipe Capital + Annual Operating Cost x 15 yrs.**	**Pipe Capital + Pump Capital + Annual Operating Cost x 15 yrs.**
Pump Selected	**18 hp**	**12 hp**
Pipe Selected	**10" Dia.**	**12" Dia.**
Life Cycle Cost	**$ 818,099**	**$ 810,617**
Energy Consumption	**420,095 kwh**	**376,302 kwh**

Given a 15 year life cycle and 5 identical pumping systems, taking a systems design approach saved $ 7482, reduced energy consumption by 43,793 kwh, and (assuming a coal-fired power plant) reduced CO2 emissions by 87,586 lbs over the system life cycle.

How do the different power rate structure options impact the design decision?

- Option 1: Decreasing Step Unit Cost Rate Structure – “Volume Discount”

- Option 2: Increasing Step Unit Cost Rate Structure - “On site power generation” rate structure

- Carbon tax implementation – probabilistic analysis

Option 1: Decreasing Step Unit Cost Rate Structure

Number of Systems - n	Decision Variable Design Results	Energy Consumption (kwh)
1	12 hp, 12” dia.	75260
2	12 hp, 12” dia	150521
3	12 hp, 12” dia	225781
4	12 hp, 12” dia	301042
5	12 hp, 12” dia	376302
6	**18 hp, 10” dia**	**504111**
7	12 hp, 12” dia	526823
8	12 hp, 12” dia	602083
9	12 hp, 12” dia	677344
10	**18 hp, 8” dia**	**1012046**
15	12 hp, 12” dia	1128906
20	12 hp, 12” dia	1505208

Rate structures can provide financial incentive to be less energy efficient.

Option 2: Increasing Step Unit Cost Rate Structure - “On Site Power Generation”

Number of Systems - n	Selection	Life Cycle (yrs)
1	18 hp, 10” dia.	15
5	18 hp, 10” dia.	15
10	12 hp, 12” dia.	15
15	12 hp, 12” dia.	15
1	12 hp, 12” dia.	20

As expected, increasing unit energy costs provides incentive to be more efficient.

Carbon Tax

The carbon tax was interesting with respect to modeling a probabilistic situation, but not interesting with respect to our results. The carbon tax did not impact the optimal design selected given our assumed situation.

Other Common Design Constraints

- Minimum fluid velocity requirements.
- Maximum amount of time in system.
- Physical space in an existing facility.
- Manual valve actuation

CONCLUSIONS

Integrated systems design may yield lower life cycle costs. Magnitude of savings varies with situation.

Power rate structures can impact design decisions based on life cycle analysis. Impact varies with situation.

POTENTIAL APPLICATION

Linear program is not practical for hydraulic modeling. It gives an accurate answer, but limits the flexibility of the analysis.

Modify existing hydraulic modeling software to include systems life cycle analysis?

Utilize linear program to further analyze results of existing modeling software?