A Stochastic, Multi-Objective, Mixed-Integer Optimization Model for Biosolids Management program at the Blue Plains AWTP

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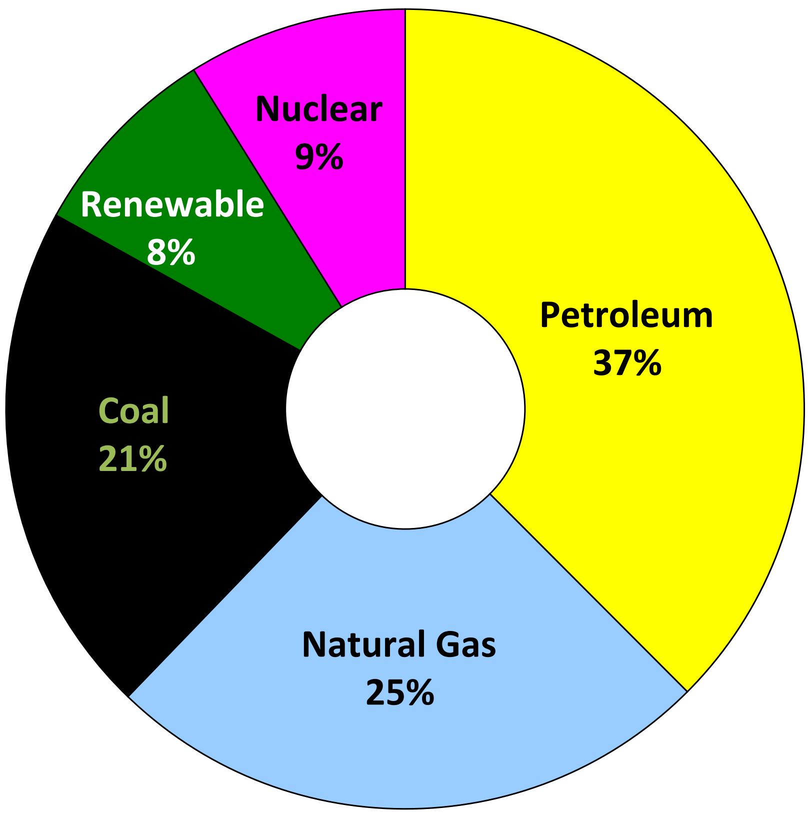
Outline

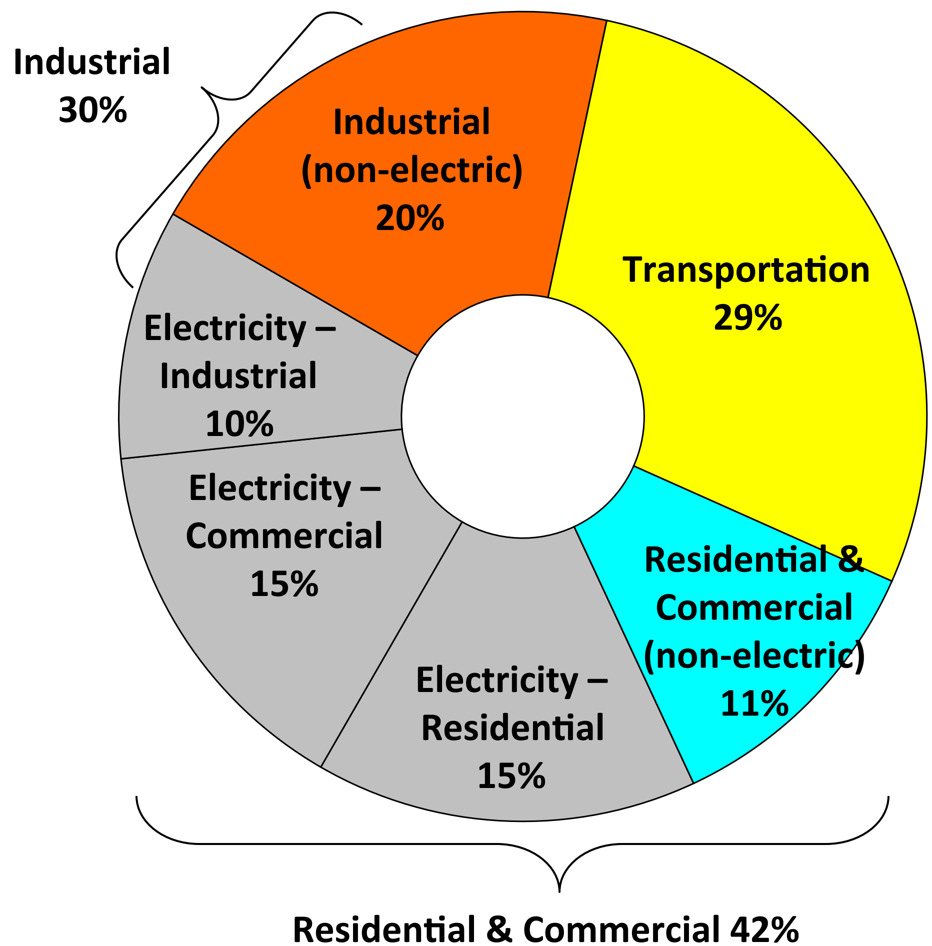
- Overview of energy and renewable energy
- The Blue Plains advanced wastewater treatment plant (AWTP) and biosolids management program
- Flowchart of modeling decisions/processes
- Preliminary results and discussion
- Conclusions
- Future work

2009 total U.S. energy use = 94.6 quadrillion BTU

Energy supply



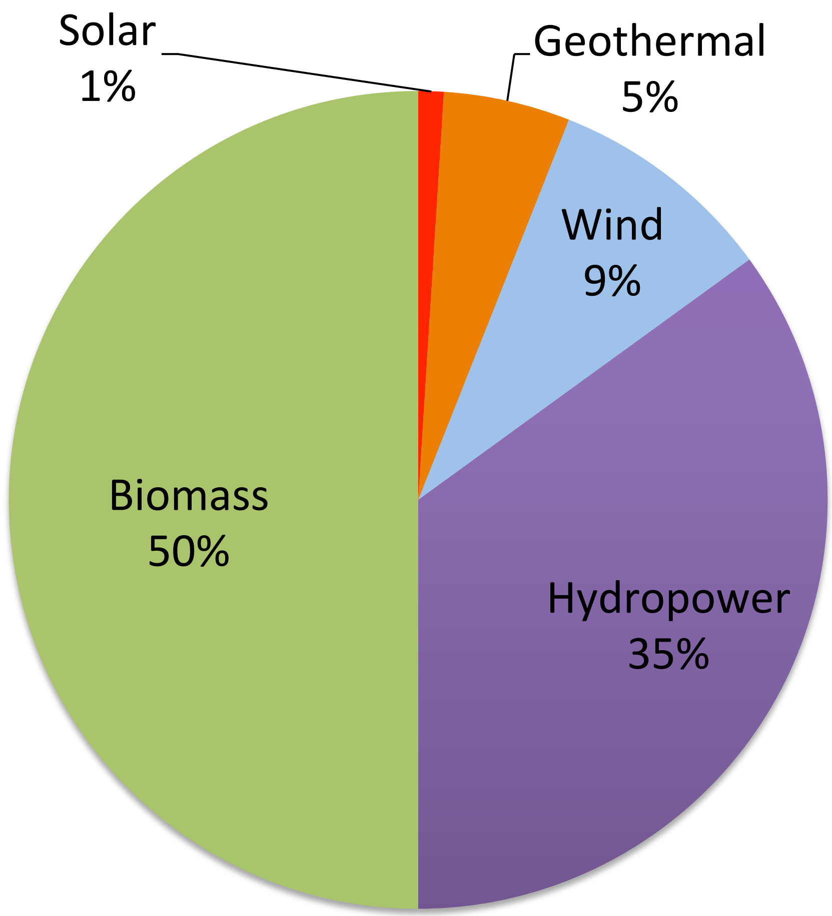
Energy demand



Source: EIA *Annual Energy Review 2009*

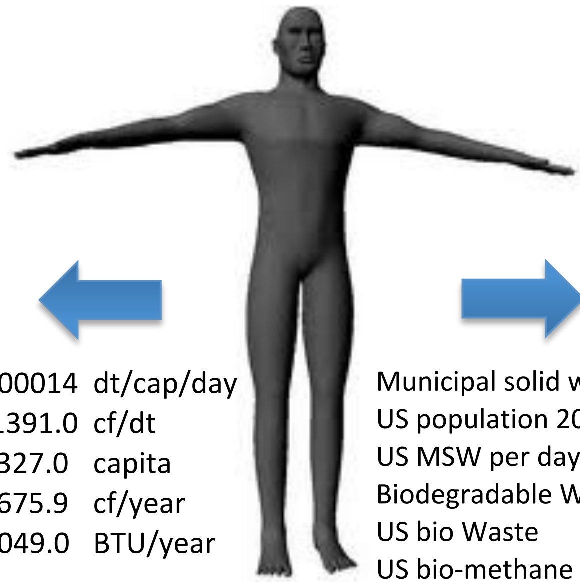
Richard Newell, December 16, 2010

8% of the U.S. renewable energy use is about 7.6 quadrillion BTU



1.7 quadrillion BTU can get from human's waste

What's in Your Waste



Wastewater

Biosolids	0.00014	dt/cap/day
Biogas	11391.0	cf/dt
US population 2010	321,471,327.0	capita
US bio-methane	93,560,784,675.9	cf/year
US biogas Energy	112,272,941,611,049.0	BTU/year

Municipal solid waste

Municipal solid waste(MSW)	4.6	lbs/cap/day
US population 2010	321,471,327.0	capita
US MSW per day	1,478,768,104.2	lbs/day
Biodegradable Waste	28.30%	
US bio Waste	418,491,373.5	lbs/day
US bio-methane	1,332,214,160,021.1	cf/year
US biogas energy	1,598,656,992,025,310.00	BTU/year

U.S. biogas as renewable energy potential is 1,425,774,944,697 cf/year or 1.7 quadrillion BTU/ year (about 1.7% of US energy used in 2009)

Carbon Dioxide Emission Advantage from Waste

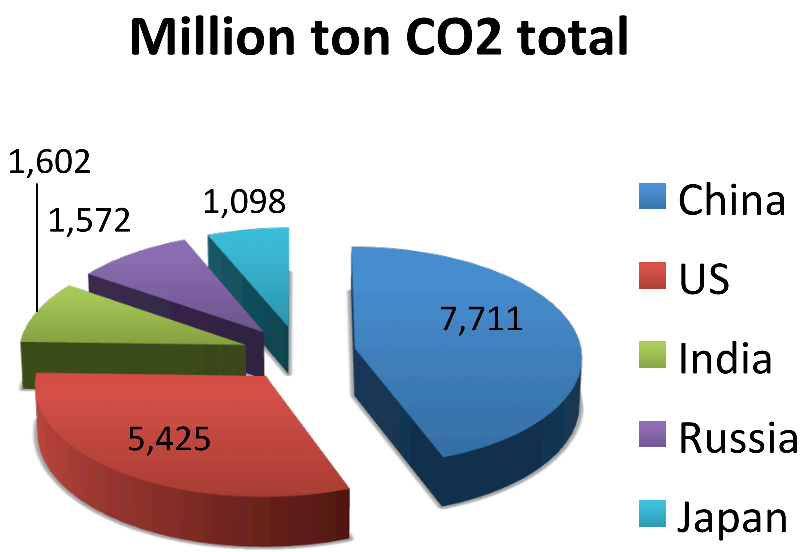
	Coal	Petroleum	Natural gas	Biomass		
				Wood	**Landfill gas**	**WWT biogas**
CO_2 emission factor kg CO_2/MMBTU	103.62	73.15	53.06	93.87	52.07	52.07
CO_2 emission factor kg CO_2/scf (for Gas)	-	-	0.0546	-	0.0262	≈0.0262

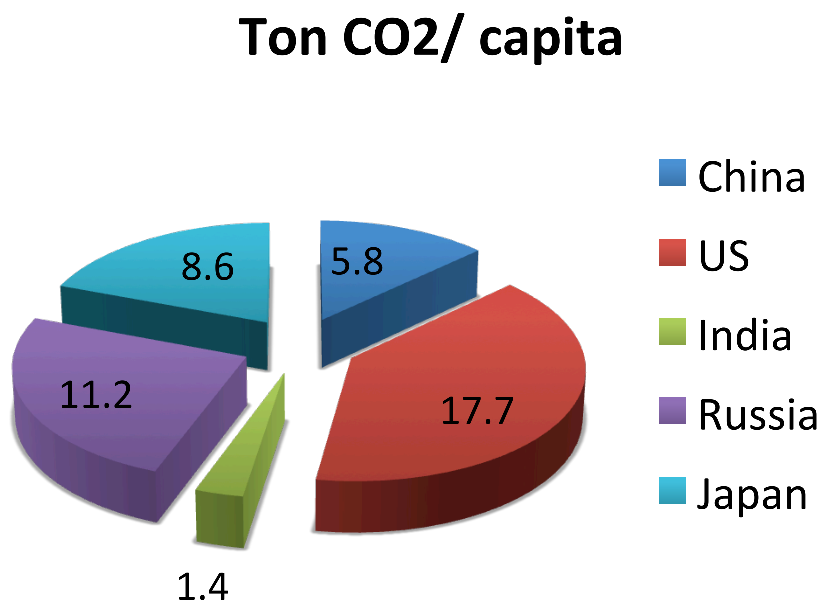
Note:

1. CO_2 emission factors (per unit energy) are calculated as: Carbon Content × Fraction Oxidized × 44/12.
2. CO_2 emission factors (per unit mass or volume) are calculated using : Heat Content × Carbon Content × Fraction Oxidized × 44/12 × Conversion Factor (if applicable). Heat content factors are based on higher heating values (HHV)
3. Waste from wastewater treatment plant produce WWT biogas
4. Municipal solid waste produce landfill gas

(Source: U.S. EPA Climate Leaders, Stationary Combustion Guidance (2007), Table B-2)

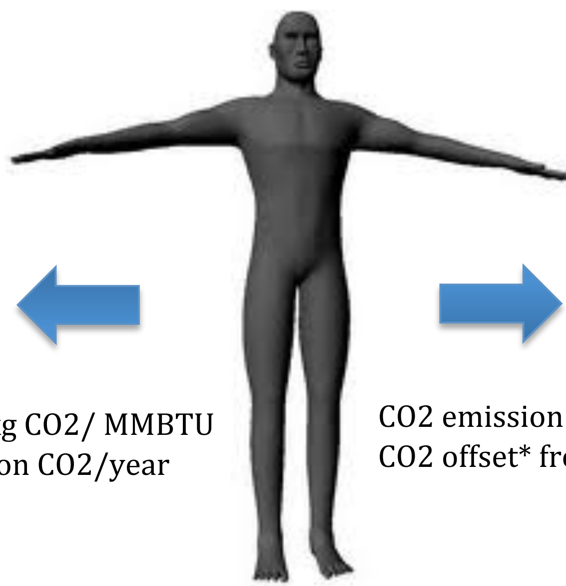
World Carbon Dioxide Emissions Data by Country





Source: http://www.guardian.co.uk/news/datablog/2011/jan/31/world-carbon-dioxide-emissions-country-data-co2
http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=90&pid=44&aid=8

CO_2 Offset from Using Your Waste



Wastewater

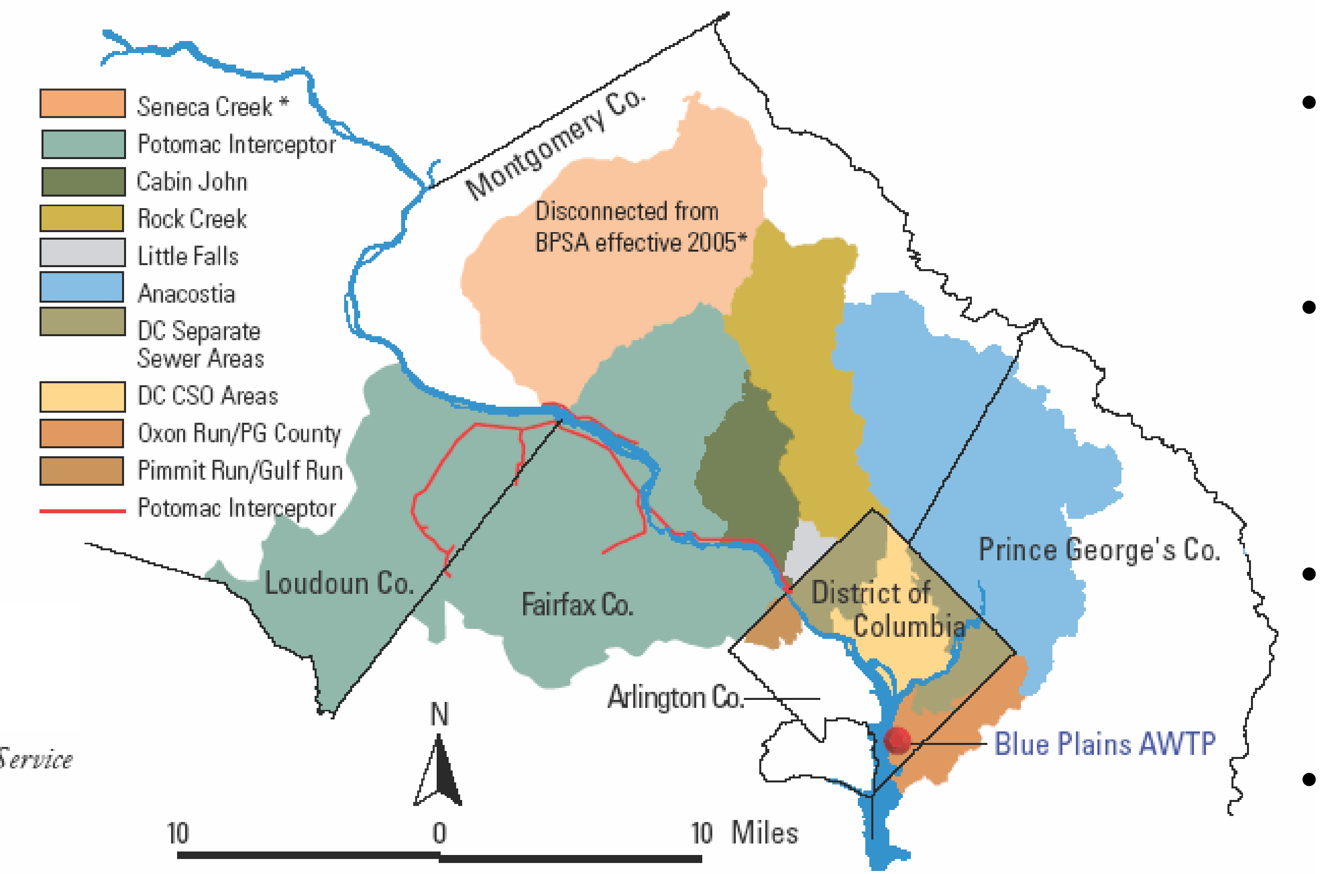
CO2 emission factor	52.070	kg CO2/ MMBTU
CO2 offset* from WWTP	5,846,052.070	ton CO2/year

Municipal solid waste

CO2 emission factor	52.070	kg CO2/ MMBTU
CO2 offset* from MSW	83,242,069.575	ton CO2/year

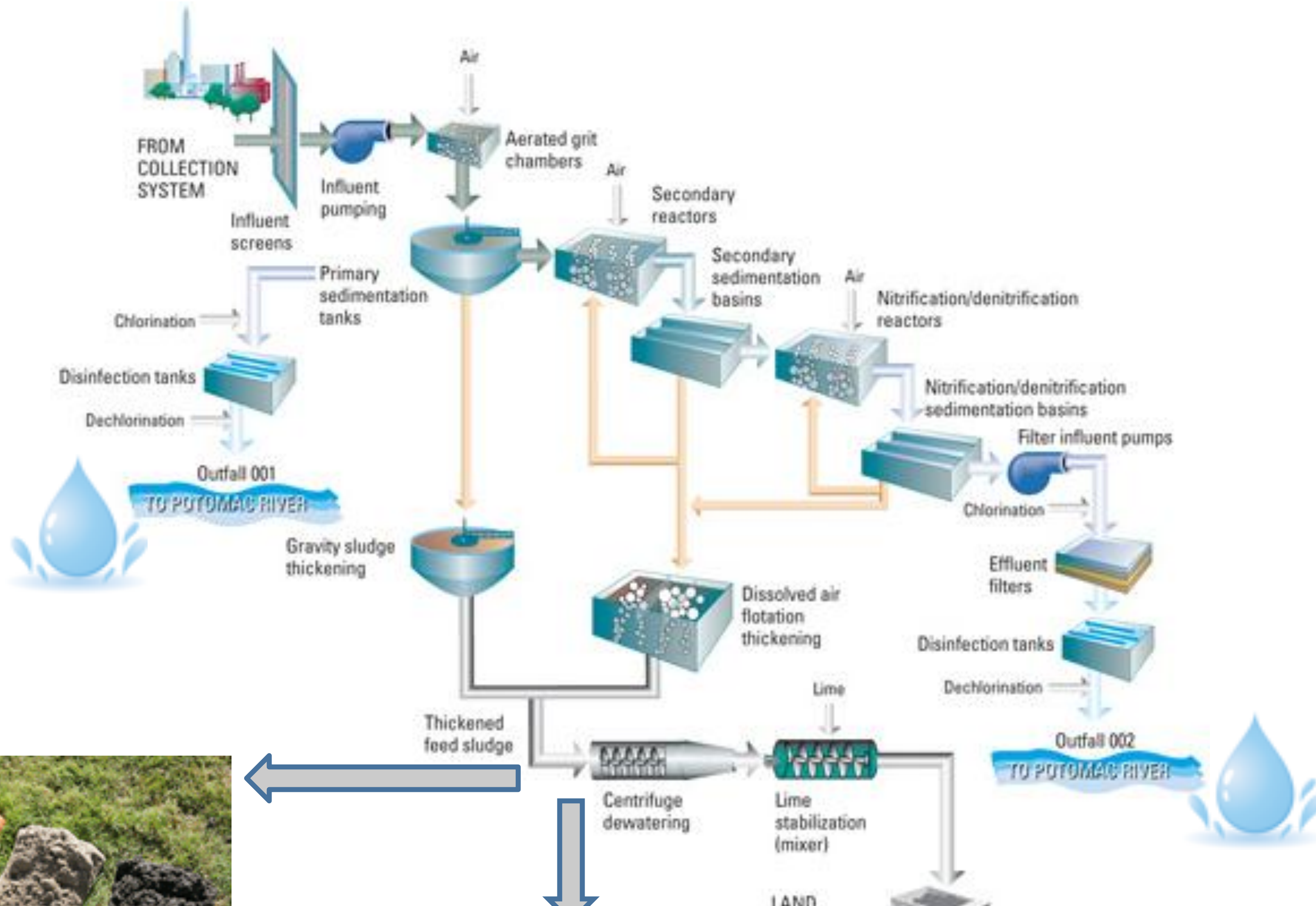
Use biogas from waste can offset 89,088,121.6 ton CO2/year
(about 1.64 % of US CO_2 emission amount in 2009)

The Blue Plains AWTP, DC Water Service Area

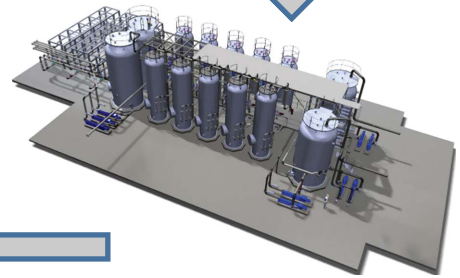


- Washington, DC, Maryland and Virginia service area
- Provides wholesale wastewater services to a population of 1.6 million
- Retail water and sewer cover 1880 km^2 service area for
- 370 MGD average flow

The Blue Plains AWTP, DC Water Operational Process



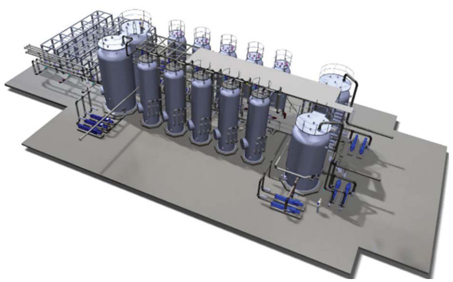
TAGRO Mix components: sawdust, sand and Class A biosolids.



Biosolids management program	Lime stabilization	Digester
Recover nutrients from the WWT process	Yes	Yes
Preserve farming in the Mid-Atlantic region	Yes	Yes
Quantity of biosolids	174-684dt/d	~180dt/d
Quality of biosolids	Class B	Class A + biogas
Generate carbon credits	How many?	How many?
Produce biogas for heat & power	NO	How much?
Cost of biosolids management	How much?	How much?
Benefit from byproduct (sold biosolids, sold biogas, sold electricity)	How much?	How much?

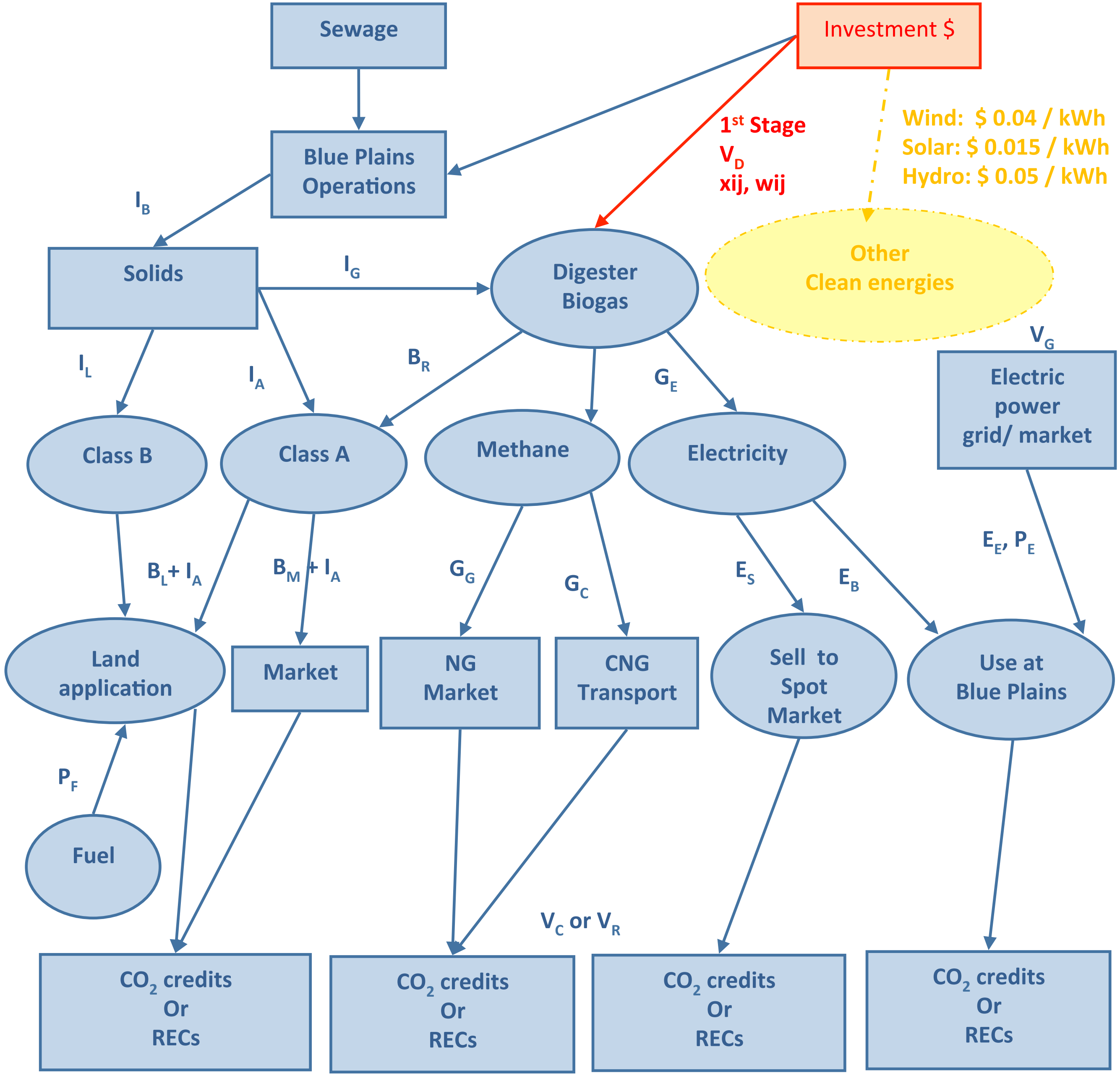
This research uses a stochastic, multi-objective, optimization model under uncertainty to answer questions like "what we get from recycle biosolids"

- The first stage makes a decision "which process (digestion, producing Class A or Class B biosolids) will be the effective choice for Blue Plains to manage biosolids"




- The second stage answers questions, which are how many carbon credits we will get, how much energy we have to purchase , how much cost we can reduce

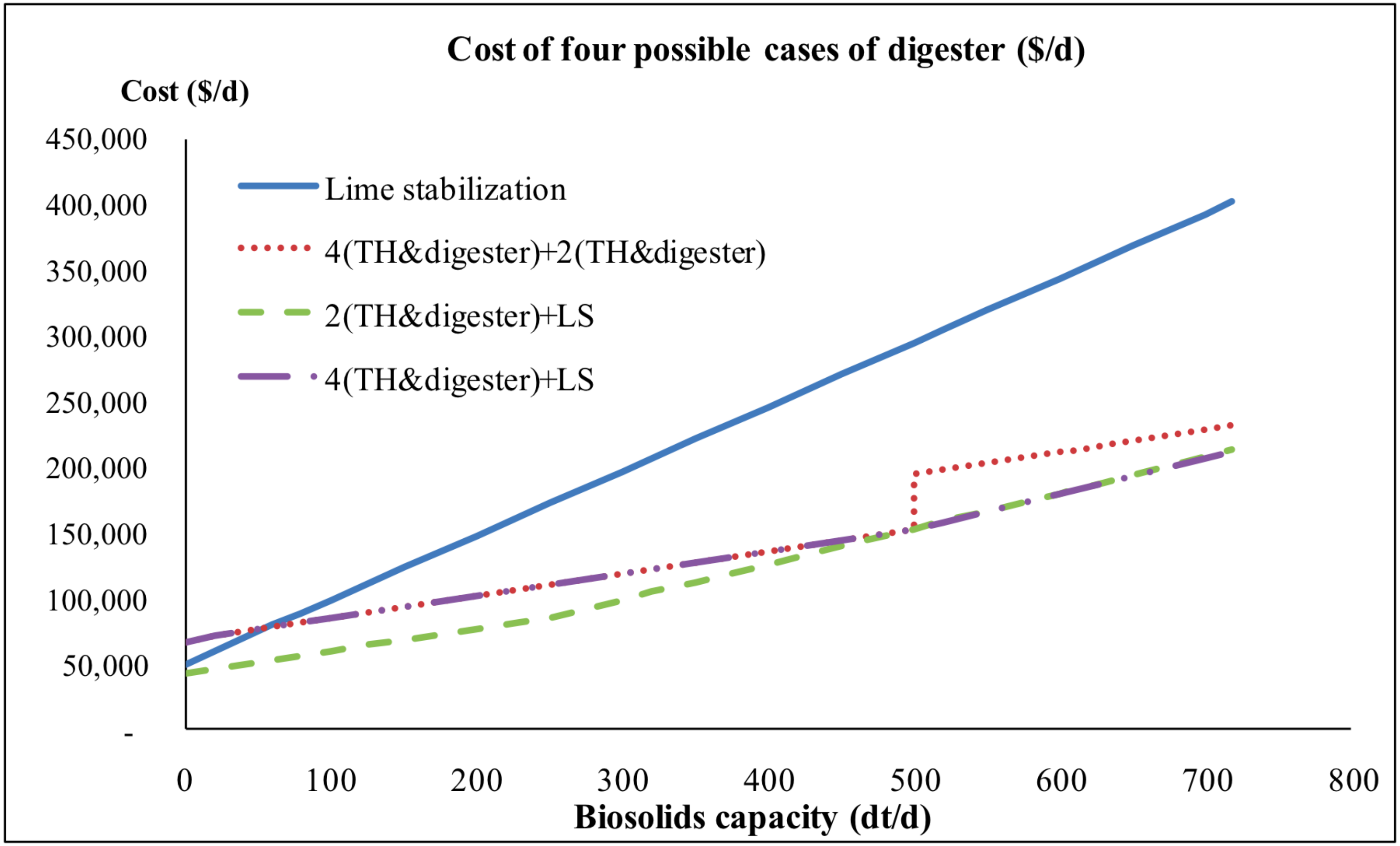




Flowchart for a stochastic multi-objective optimization model for biogas production at the Blue Plains AWTP, DC Water

1st Stage Decision Variable

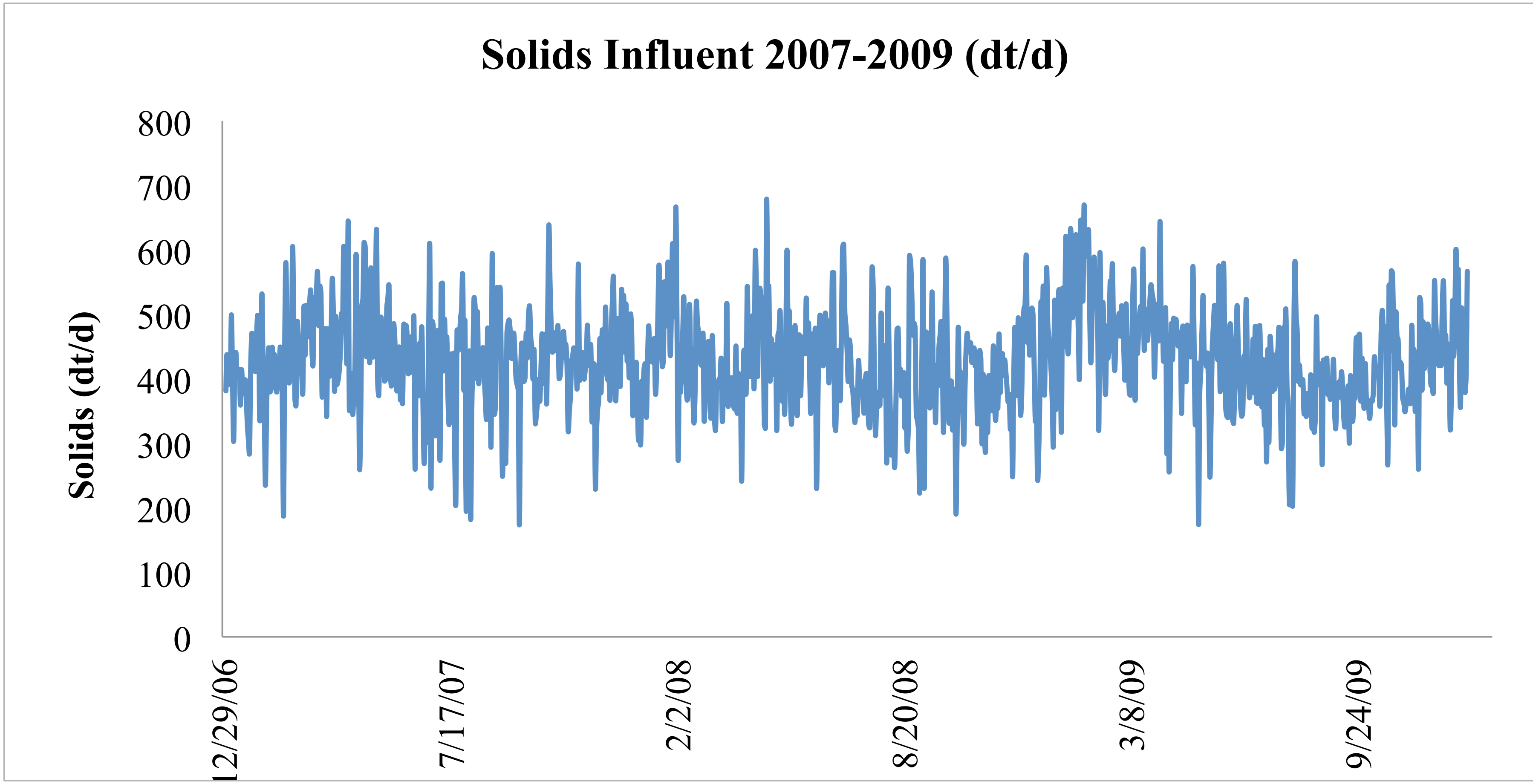
Four possible cases for construction and operational costs (50-years horizon) of digester related to biosolids capacity



Uncertain Data Used in Stochastic Model

- Solids influent data (inflow for digestion) in dry tons per day (dt/d)
- U.S. natural gas electric power prices in dollars per cubic feet ($/cf)
- DC Water electricity consumption in kilo watt hour per day (kWh/d)
- U.S. electricity prices for PJM area in $ per kilo watt hour ($/kWh)
- DC water electricity cost in $ per kilo watt hour ($/kWh)
- Fossil fuel (Diesel) prices in $ per gallon ($/gallon)
- Biosolids as fertilizer prices in $ per ton ($/ton)
- Carbon credits in $ per ton CO_2 equivalent ($/ton CO_2 e)
- Renewable energy credits in $ per ton CO_2 equivalent ($/ton CO_2 e)
- Analyze probability distributions with ARENA software

"We will go over some examples of uncertainty data on the next slides"



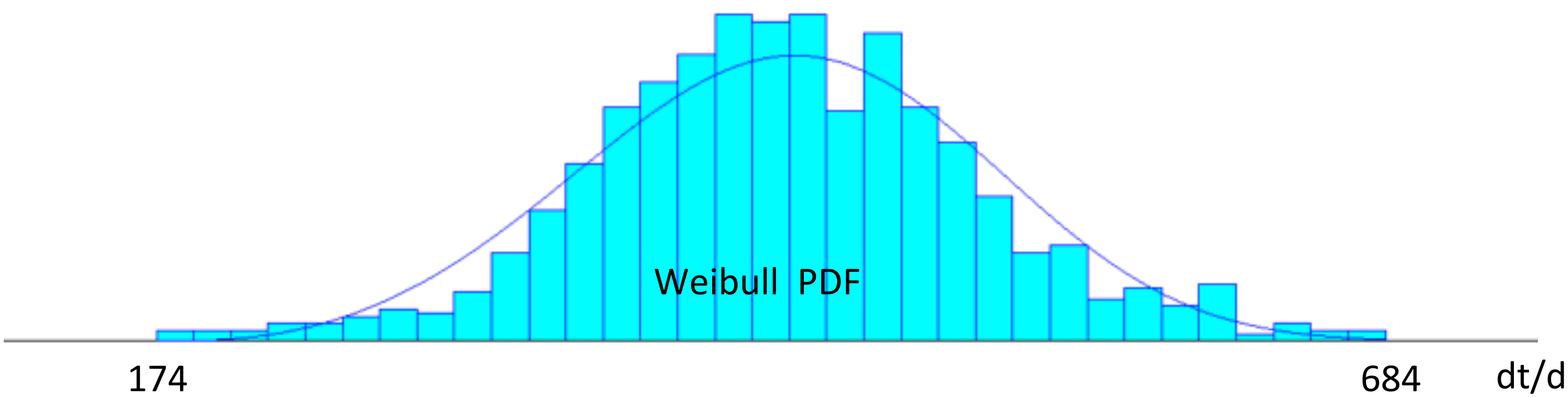
Solids influent for digester

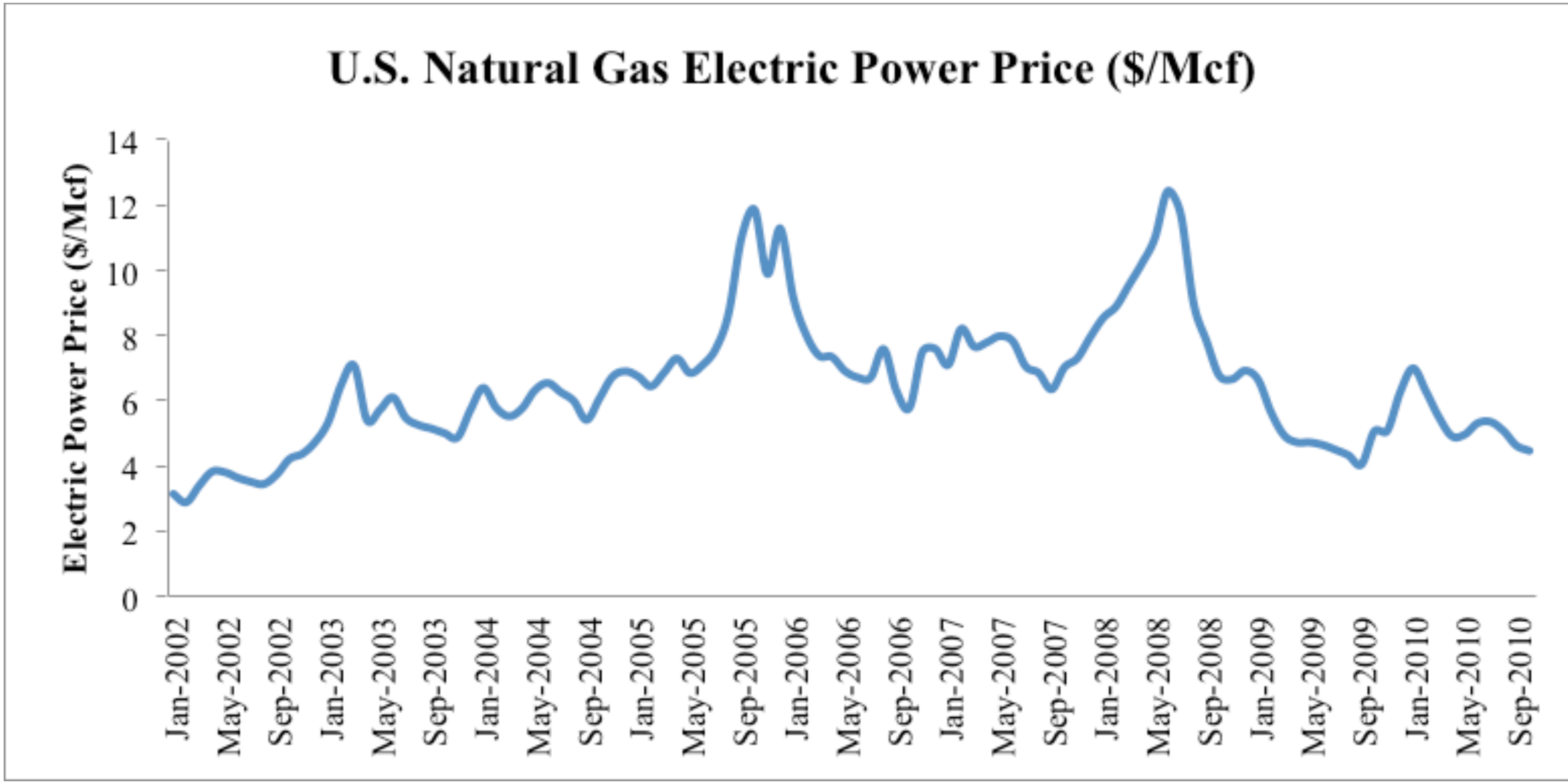
Solids influents are 174 - 684dt/d, data from 2007-2009 and project to 2030

Source: Technical memorandum number 1 from Brown and Caldwell, March 2009

Probability Density Function of Solids Influent for Digester 2007-2009

Distribution	Chi Squ	KS	Squ Err		Equation
Normal	<0.005	>0.15	0.00107	μ=429, σ=78.5	$f(x) = \begin{cases} \frac{1}{\sigma x\sqrt{2\pi}} e^{-(x-\mu)^2/(2\sigma)^2} & for\ x > 0 \\ 0 & otherwise \end{cases}$
Beta	<0.005	0.0676	0.00153	β=5.35, α=4.98	$f(x) = \begin{cases} \beta^{-\alpha} x^{\alpha-1} e^{-x/\beta} & for\ 0 < x < 1 \\ 0 & otherwise \end{cases}$
Weibull*	<0.005	**0.106**	**0.00159**	**β=285, α=3.59**	$\boldsymbol{f(x) = \begin{cases} \alpha\beta^{-\alpha} x^{\alpha-1} e^{-(\frac{x}{\beta})^{\alpha}} & for\ x > 0 \\ 0 & otherwise \end{cases}}$
Erlang	<0.005	<0.01	0.00321	β=32, k=8	$f(x) = \begin{cases} \frac{\beta^{-k} x^{k-1} e^{-k/\beta}}{(k-1)!} & for\ x > 0 \\ 0 & otherwise \end{cases}$



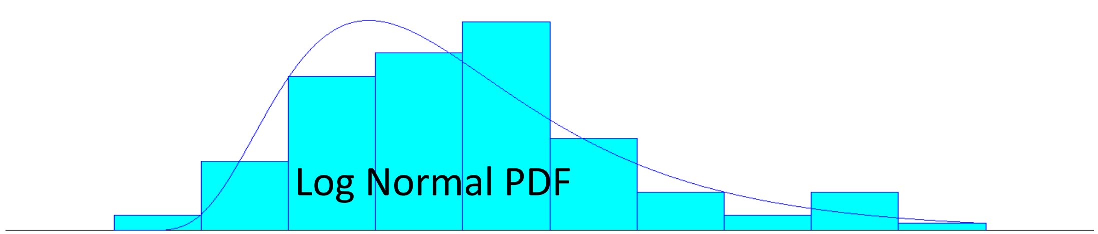


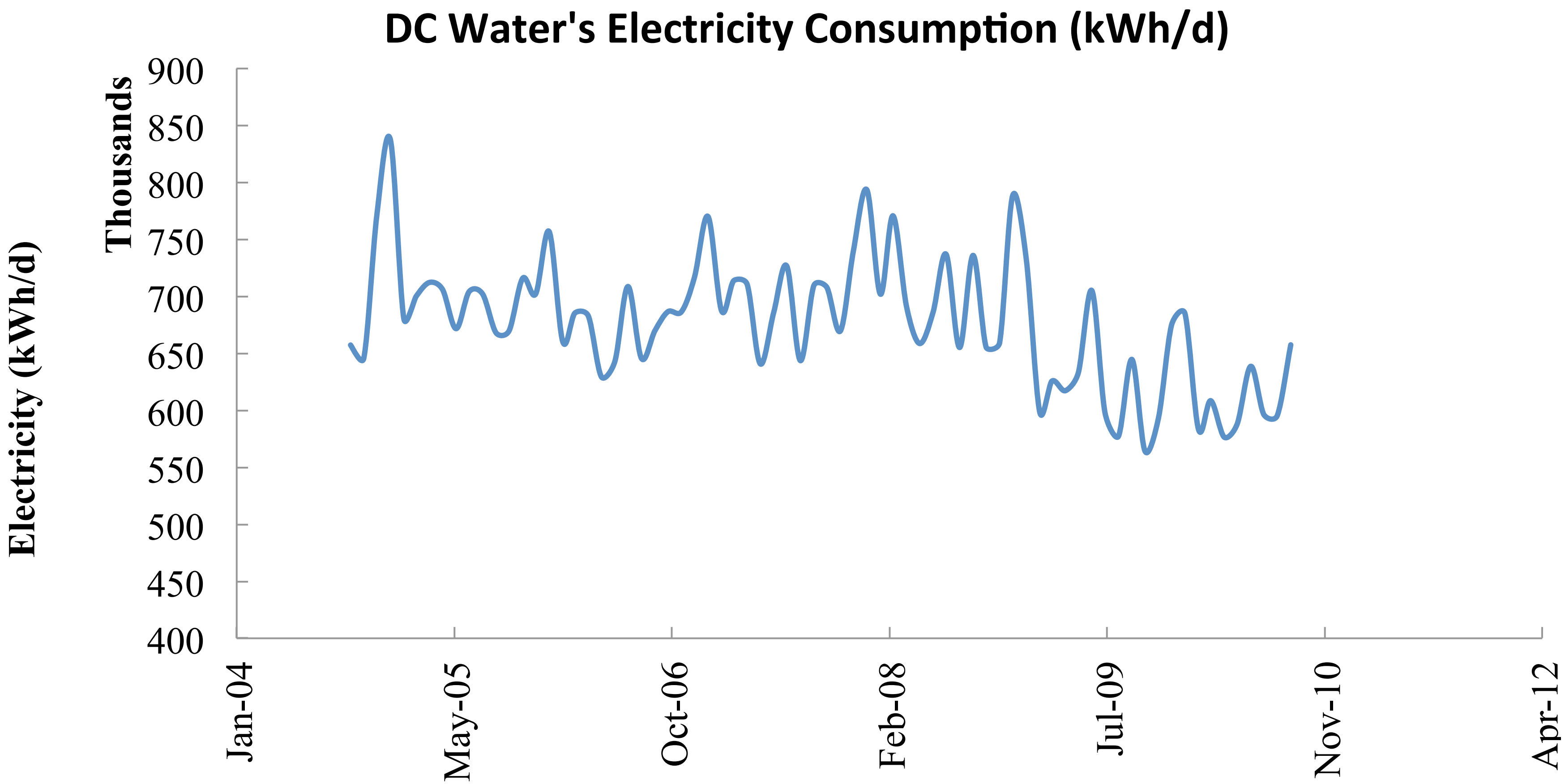
U.S. Natural gas prices for electric power generation are 2.86-12.41 $/ Mcf (2.76-11.97 $/MMBtu), data from 2002-2010

Source : http://tonto.eia.gov/dnav/ng/hist/n3045us3m.htm

Probability Density Function of U.S. Natural Gas Price 2002-2010

Distribution	Chi Squ	KS	Squ Err		Equation
Erlang	0.21000	>0.15	0.00712	β=0.89, k=5	$f(x) = \begin{cases} \frac{\beta^{-k} x^{k-1} e^{-k/\beta}}{(k-1)!} & for\ x > 0 \\ 0 & otherwise \end{cases}$
Gamma	0.21300	>0.15	0.00714	β=0.89, α=5.01	$f(x) = \begin{cases} \frac{\beta^{-\alpha} x^{\alpha-1} e^{-x/\beta}}{\Gamma(\alpha)} & for\ x > 0 \\ 0 & otherwise \end{cases}$ $\Gamma(\alpha) = \int_0^\infty t^{\alpha-1} e^{-t} dt$
Weibull	0.09170	>0.15	0.00789	β=5.04, α=2.41	$f(x) = \begin{cases} \alpha\beta^{-\alpha} x^{\alpha-1} e^{-(\frac{x}{\beta})^\alpha} & for\ x > 0 \\ 0 & otherwise \end{cases}$
Normal*	0.00876	>0.15	0.0115	μ=6.46, σ=1.96	$f(x) = \frac{1}{\sigma x\sqrt{2\pi}} e^{-(x-\mu)^2/(2\sigma)^2}\ for\ all\ real\ x$
Beta	0.05390	>0.15	0.0108	β=2.64, α=3.88	$f(x) = \begin{cases} \frac{x^{\beta-1}(1-x)^{\alpha-1}}{B(\beta,\alpha)} & for\ 0 < x < 1 \\ 0 & otherwise \end{cases}$ $B(\beta,\alpha) = \int_0^1 t^{\beta-1}(1-t)^{\alpha-1} dt$
Log normal*	**0.07810**	**>0.15**	**0.0115**	**μ=4.51, σ=2.27**	$f(x) = \begin{cases} \frac{1}{\sigma x\sqrt{2\pi}} e^{-(\ln(x)-\mu)^2/2\sigma^2} & for\ x > 0 \\ 0 & otherwise \end{cases}$
Triangular	<0.0050	0.081	0.0232	a=260, m=304, b=360	$f(x) = \begin{cases} \frac{2(x-a)}{(m-a)(b-a)} & for\ a \le x \le m \\ \frac{2(b-x)}{(b-m)(b-a)} & for\ m \le x \le b \end{cases}$



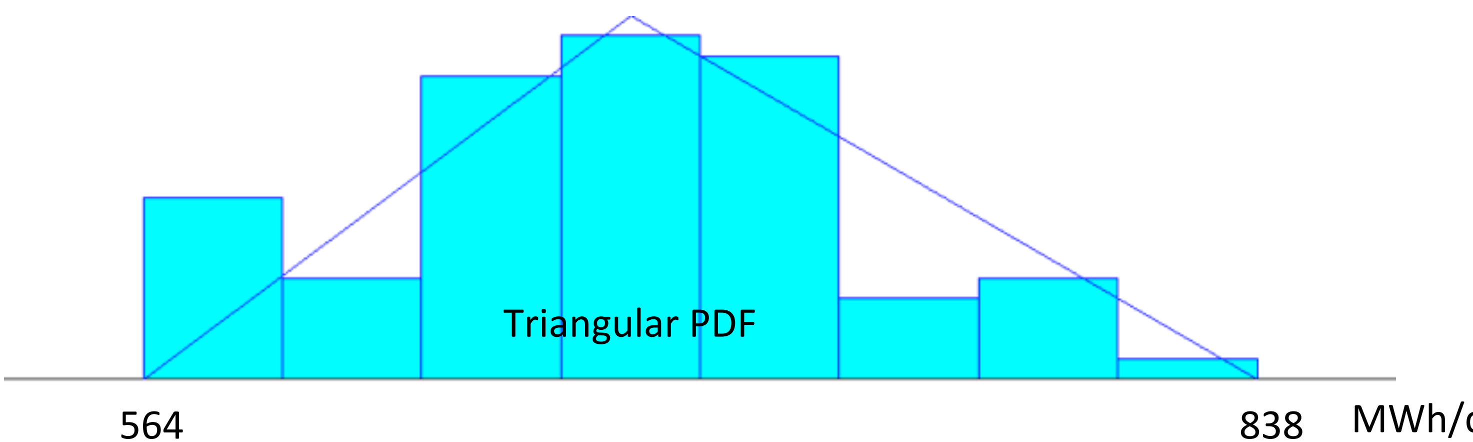


DC water electricity consumptions are about 564-838 MWh/d data from 2004-2010

Source : DC Water financial report 2011, data from February 2010 to February 2011

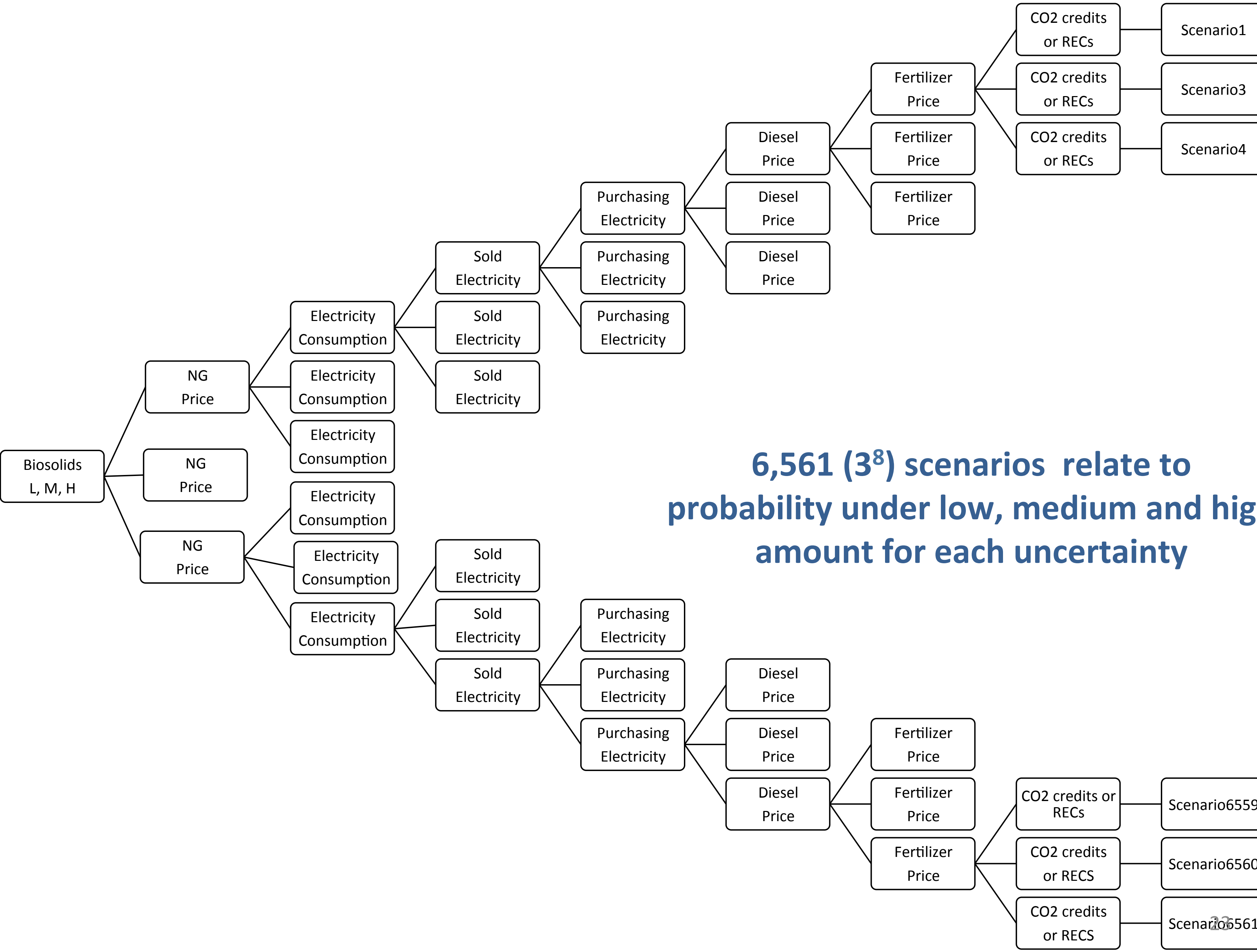
Probability Density Function of DC Water Electricity Consumption 2000-2010

Distribution	Chi Squ	KS	Squ Err		Equation
Normal	0.722	>0.15	0.0130	μ=677000, σ=55600	$f(x) = \frac{1}{\sigma x\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2}$ *for all real x*
Triangular*	**0.206**	**>0.018**	**0.0184**	**a=564000, m=684000, b=838000**	$\boldsymbol{f(x) = \begin{cases} \frac{2(x-a)}{(m-a)(b-a)} & for\ a \le x \le m \\ \frac{2(b-x)}{(b-m)(b-a)} & for\ m \le x \le b \end{cases}}$
Beta	0.078	>0.15	0.0209	β=1.95, α=2.78	$f(x) = \begin{cases} \frac{x^{\beta-1}(1-x)^{\alpha-1}}{B(\beta,\alpha)} & for\ 0 < x < 1 \\ 0 & otherwise \end{cases}$ $B(\beta,\alpha) = \int_0^1 t^{\beta-1}(1-t)^{\alpha-1}dt$
Weibull	<0.005	0.034	0.0359	β=121000, α=1.57	$f(x) = \begin{cases} \alpha\beta^{-\alpha}x^{\alpha-1}e^{-(\frac{x}{\beta})^\alpha} & for\ x > 0 \\ 0 & otherwise \end{cases}$



Probability Density Function of all Uncertainty Data

1. weibull biosolids influent PDF
2. log normal U.S. natural gas prices PDF
3. triangular DC Water electricity consumption PDF
4. log normal DC Water electricity cost PDF
5. log normal U.S. electric power prices PDF
6. triangular diesel prices PDF
7. weibull fertilizer prices PDF
8. triangular carbon credits PDF
9. Renewable energy credits $1.89 per ton CO_2 e



6,561 (3^8) scenarios relate to probability under low, medium and high amount for each uncertainty

A Stochastic Model for Biogas Production at the Blue Plains AWTP

- **Three objective functions**

1. Minimize net carbon dioxide equivalent emission		(t/d)
2. Minimize energy purchasing		(kWh/d)
3. Maximize DC Water total value		($/d)
s.t.	1st stage constraints relate to digester investment cost	($/d)
	2nd stage constraints relate to 6,561 scenarios	
	- solids influent constraints	(dt/d)
	- biogas constraints	(cf/d)
	- biosolids class A constraints	(dt/d)
	- natural gas consumption constraints	(cf/d)
	- electricity constraints with recourse	(kWh/d)
	- carbon dioxide emission constraints	(t/d)
	- energy consumption constraints	(kWh/d)
	- value constraints	($/d)

- **Using Mixed-integer nonlinear programming (MINLP)and special ordered sets type 1 (SOS1) variables solve two-stage problem with recourse**
- **Optimization by General Algebraic Modeling System (GAMS)**

Preliminary Results and Discussion

- Maximizing DC Water total value
- Here-and-Now (RP) result (two-stage stochastic model include risk and the capability to taking recourse problem)
- Expected results by using expected value (EVV), which fixed the 1st stage variable by using the bigger digester; *four trains of thermal hydrolysis & anaerobic digester* and using digester from RP result to find value of stochastic solution (VSS*)*
- Important of stochastic model for WWTP

Here- and- Now (RP) for Maximizing DC Water Total Value Objective

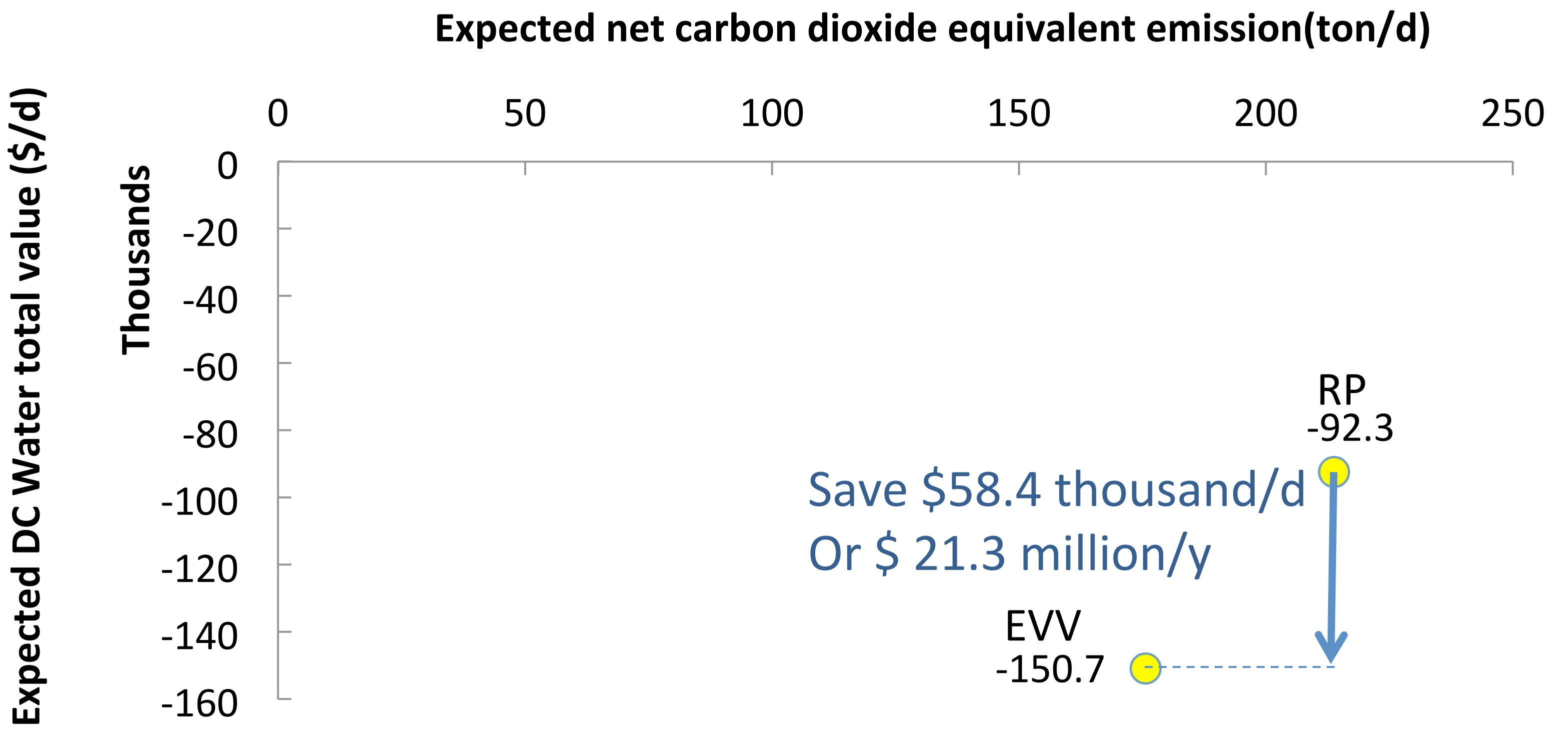
1. First stage picked *two trains of thermal hydrolysis & anaerobic digester* up
2. Expected DC Water operational value $-92,270 per day (cost)
3. Expected CO_2 e emissions is about 213.89 tons per day
4. Expected energy purchasing is about 425,070 kWh per day
5. Execution time for this model is about 12 hours

How to Increase DC Water Total Value for Biosolids Management Program?

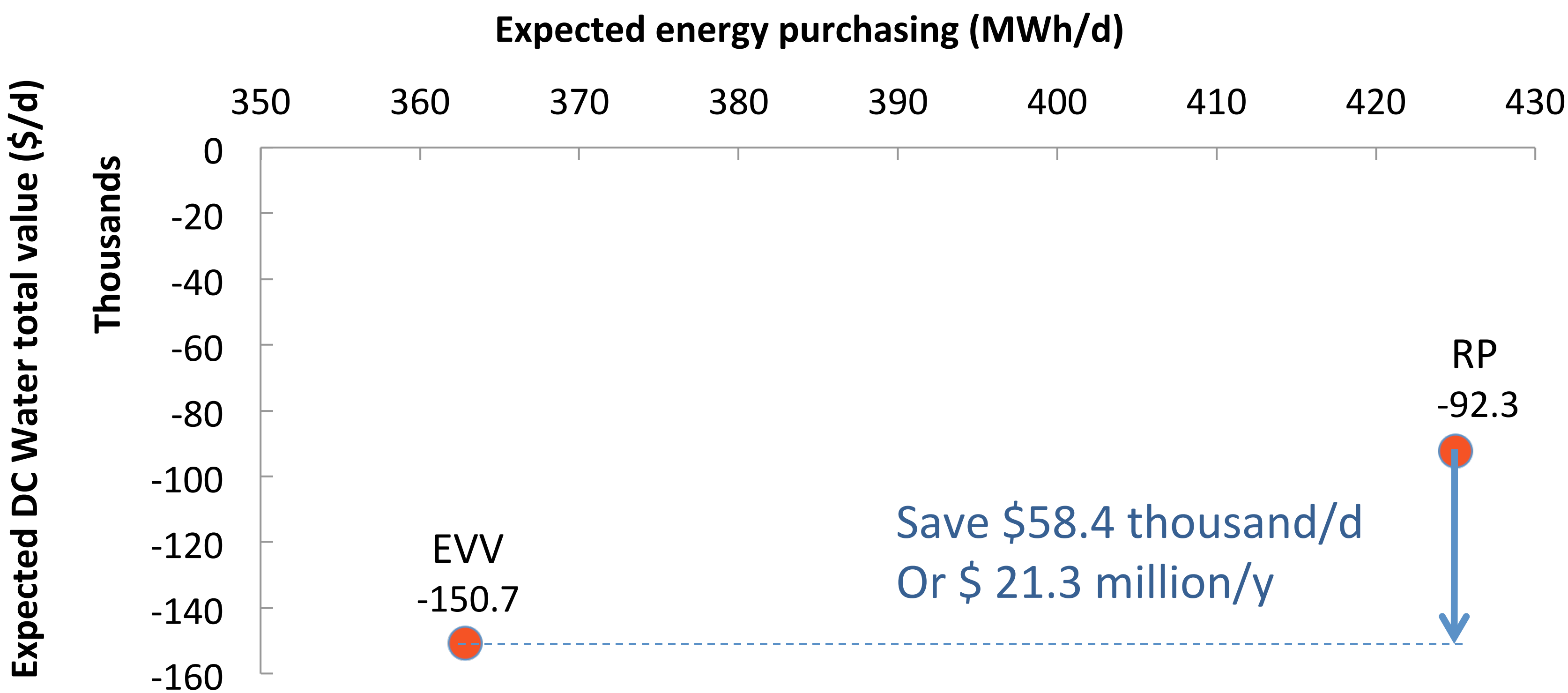
Cost (constraints in model)	Revenue (constraints in model)
Digester (construction and O&M)	Sold class A biosolids
Purchased electricity	Sold biogas
Delivering biosolids to the field	Sold electricity
	Carbon or renewable energy credits

Digester cost is the most influent variable for operational cost. Therefore DC Water should use the smallest digester in order to reduce digester cost, then generating electricity from biogas.

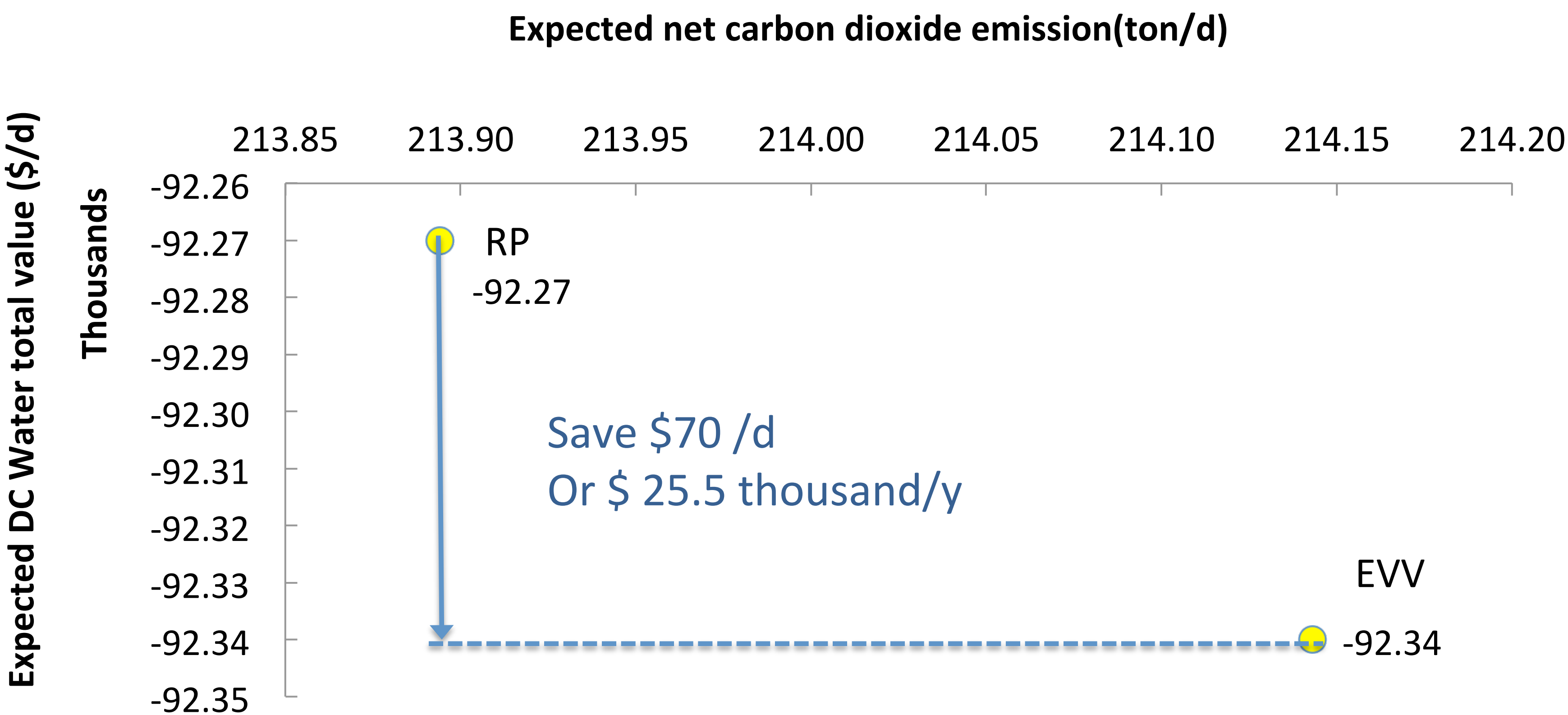
Most Likely Solution (Fixed four trains of TH & anaerobic Digester) under Maximizing DC Water Total Value



Most Likely Solution (Fixed Four Trains of TH & anaerobic Digester) under Maximizing DC Water Total Value



Value of stochastic solution under maximizing DC Water total value



Conclusions

- Stochastic model can help DC Water make a decision to use digester under real uncertain data and also reduce operation cost
- Results from maximizing DC Water total value may not be the best choice for DC Water if we have environmental concern
- This result supports multi-objective optimization idea (think both sides between economic and environment aspects).

Future Work

- Run stochastic model under other two objective functions, which are minimizing carbon dioxide equivalent emission and energy purchasing
- What is the best choice for DC Water considering under all three objective functions together? (Pareto optimal analysis)
- Add other investment choices of renewable energy sources

Thank you