An Aeroponic Greenhouse and Anaerobic Digester: Linking sustainability with research and education on Clarkson University's campus

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Acknowledgements

- Co-PI's:
  - Susan Powers, Shane Rogers, Daqing Hou, Jan DeWaters
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  - U.S. EPA P3 program
  - NY Pollution Prevention Institute
  - Dept. Civil and Environmental Engineering
  - National Science Foundation

National Science Foundation
WHERE DISCOVERIES BEGIN

P3 award competition
people prosperity planet
a student design competition for sustainability

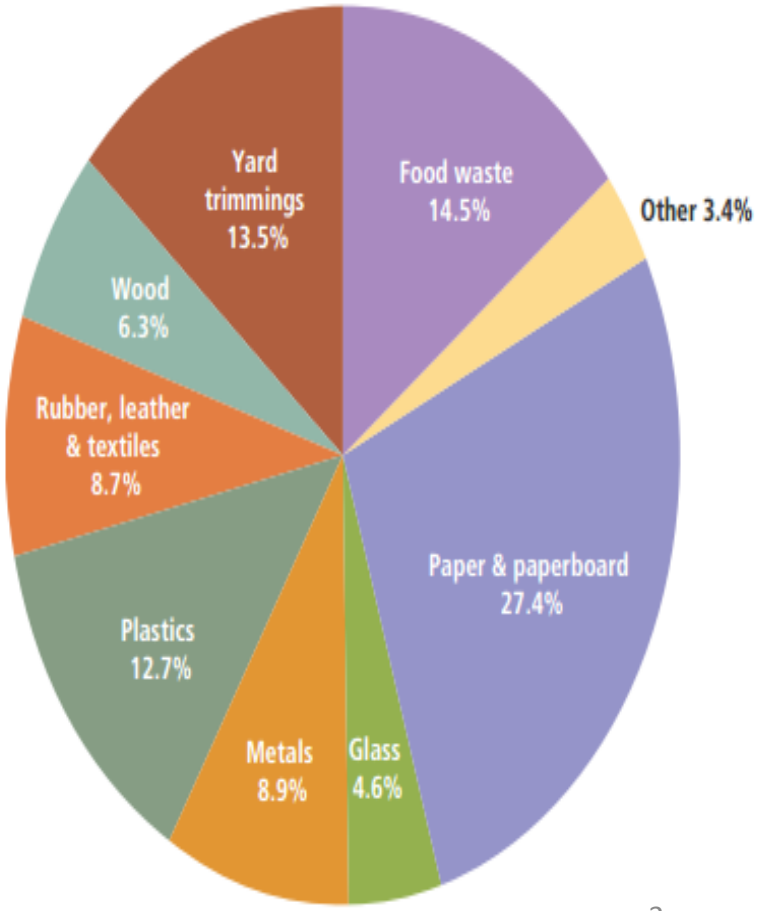
NYS P2I
POLLUTION PREVENTION NEW YORK STATE INSTITUTE

The Problem

- About 36.39 million tons on food waste is buried in U.S. landfill each year[1]
  - With limited oxygen, water, sunlight, and organisms food waste decomposes very slowly
- The older landfill are not set up to capture methane

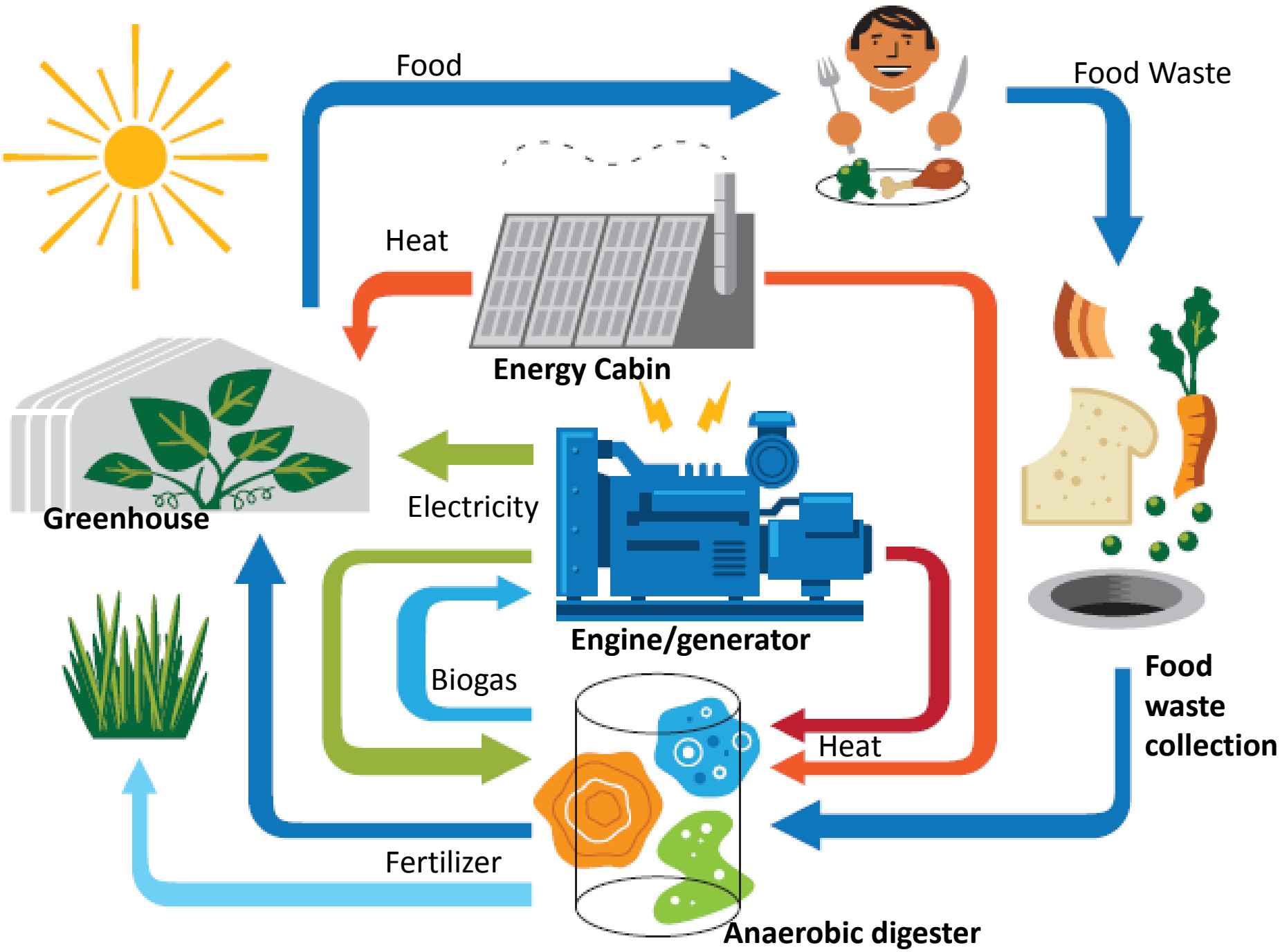
William Rathje, An American Archaeologist with a PhD in anthropology from Harvard University

Total Municipal Solid Waste Generation by Material, 2012
251 Million Tons (before recycling)
Source: EPA



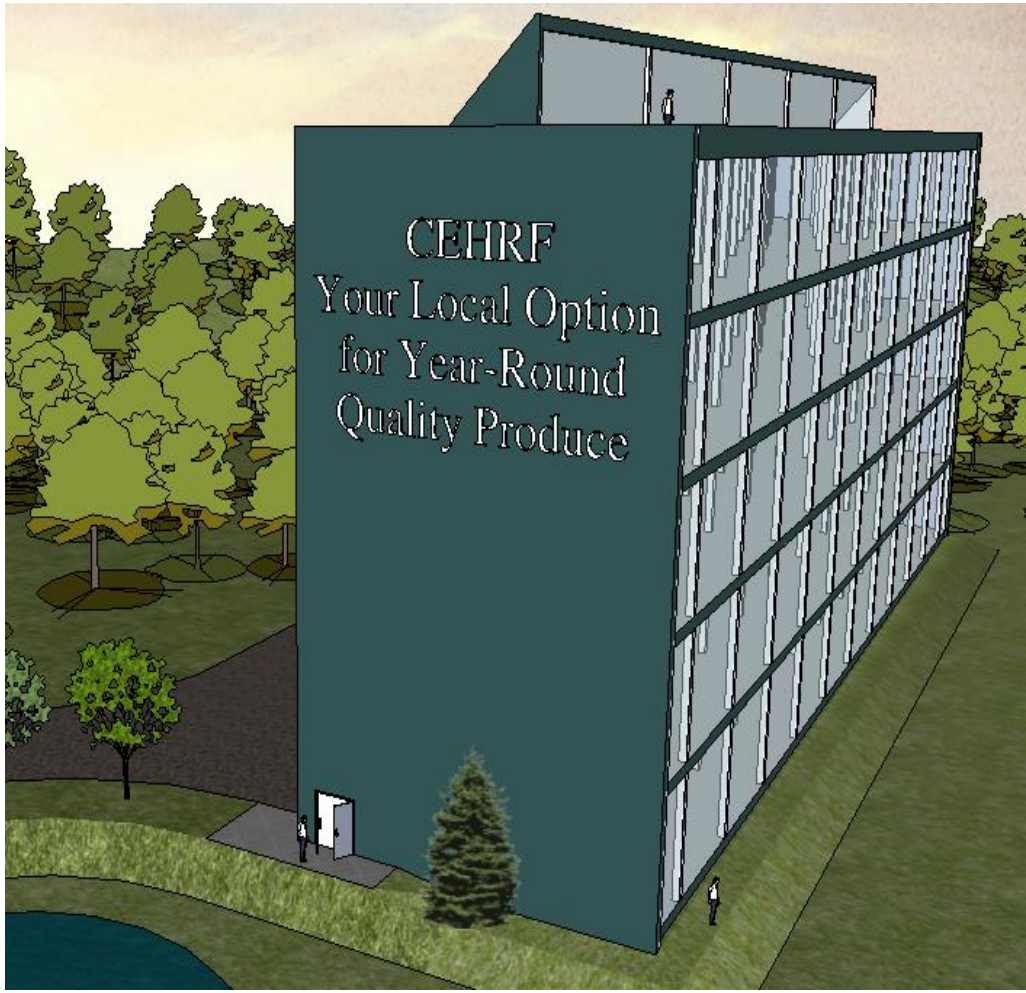
System Overview

- Vertical aeroponic greenhouse.
- Wood pellet and passive solar boiler.
- Anaerobic digester for food waste.


Food
Food Waste
Heat
Energy Cabin
Greenhouse
Electricity
Engine/generator
Biogas
Heat
Food waste collection
Fertilizer
Anaerobic digester

Vision for Year-round Sustainable Food in Cold Climates

- Controlled environment
- Continuous production
- Low land footprint
- Local production
- Technical Innovations
  - Aeroponic growth
  - LED lighting
  - Passive solar design w/ renewable energy inputs
  - Sensors and controls
  - Materials and energy recycling



(Summer 2008)

February 2012

Pilot Scale Green House Structure

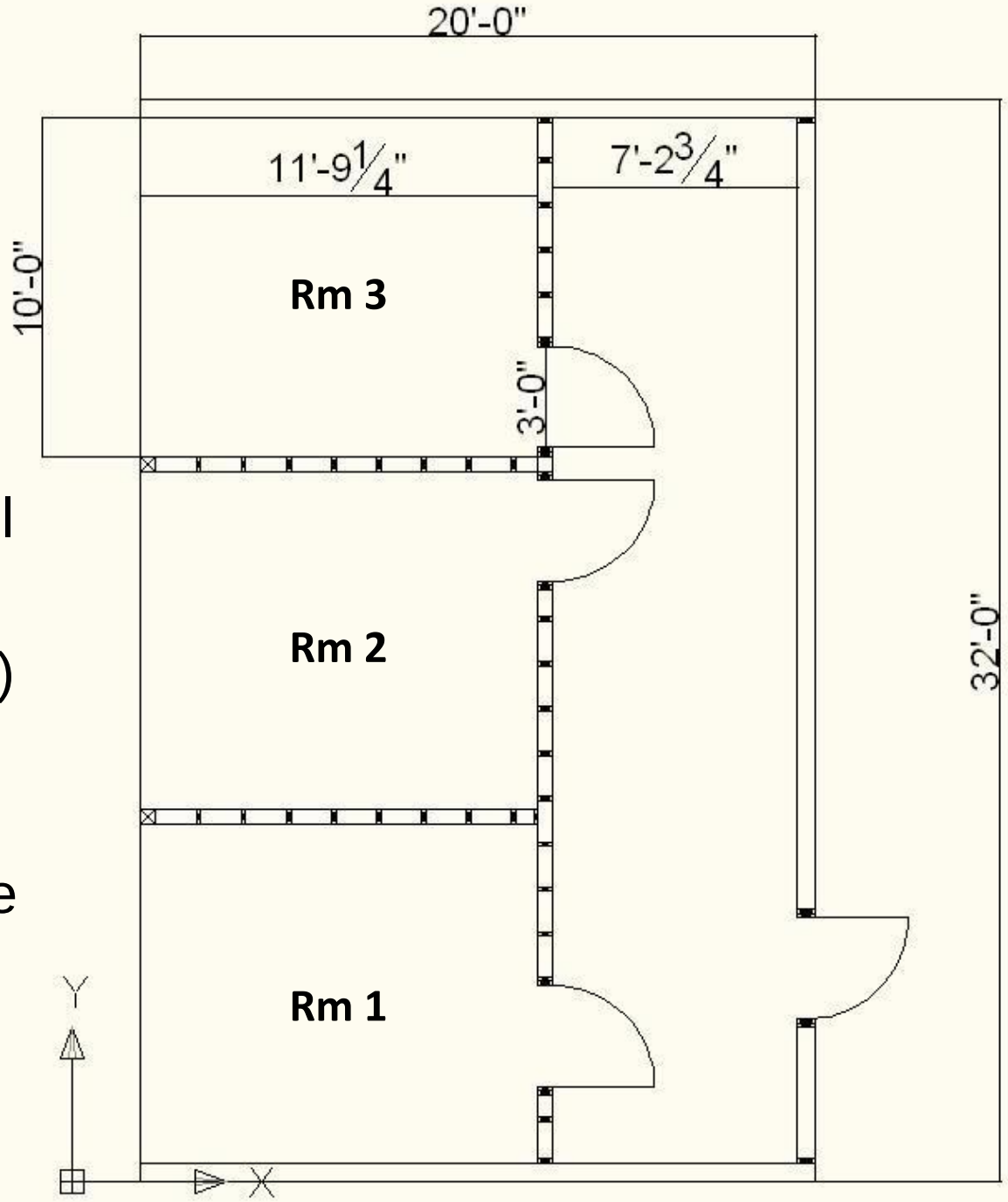
Daylighting – transmissive south wall

Insulated - Structural insulated panels (SIPs) elsewhere

Slightly sloping roof – gutter along north edge

Three rooms for experimental variables

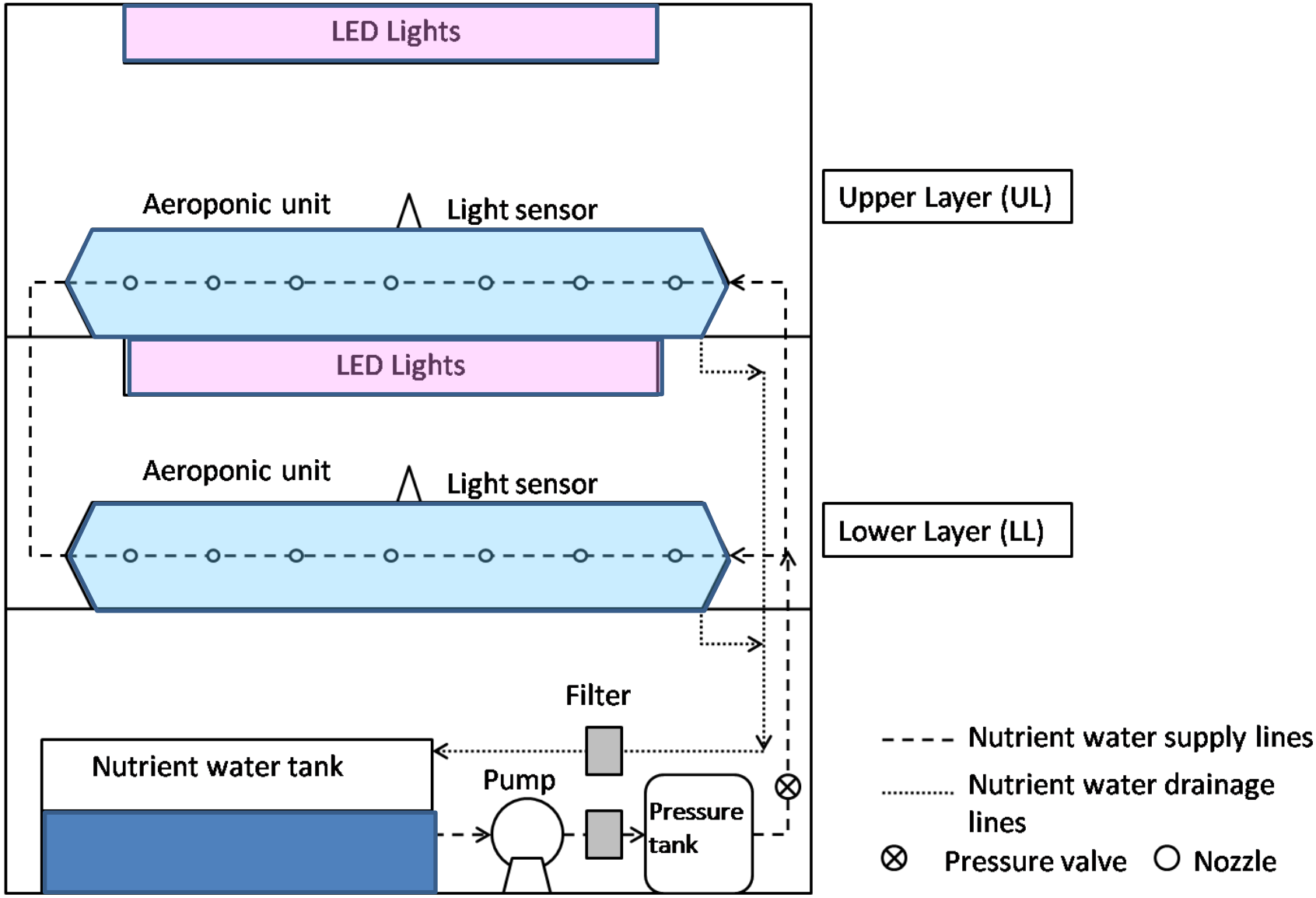
Lettuce and tomatoes



System Components

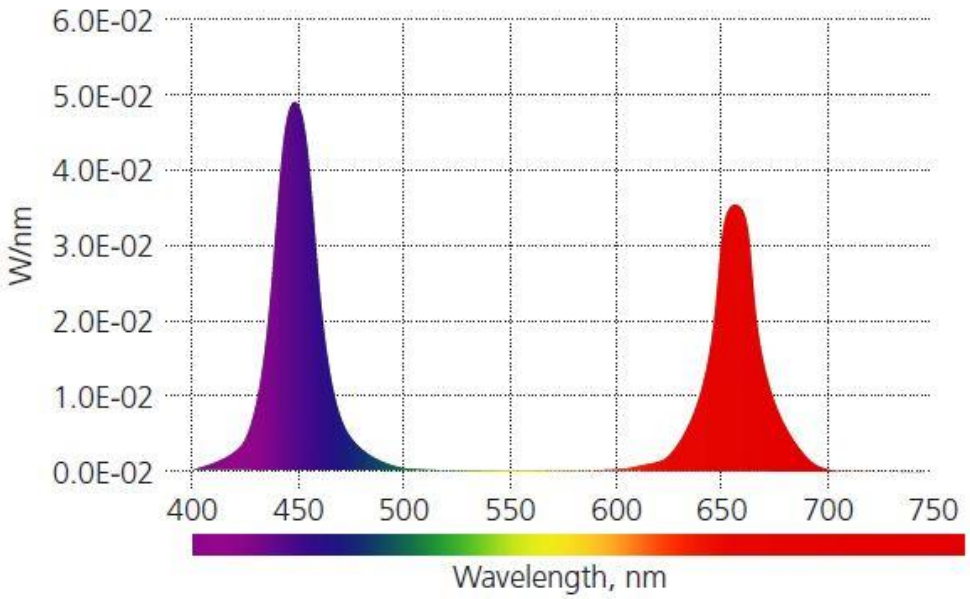
- CEHRF structure
- Aeroponics/plants
- Water quality, recovery, treatment, nutrification and distribution
- Heating and ventilation
- Electricity and lighting
- Sensors, controls, data acquisition
  (for all other systems)

Aeroponic System

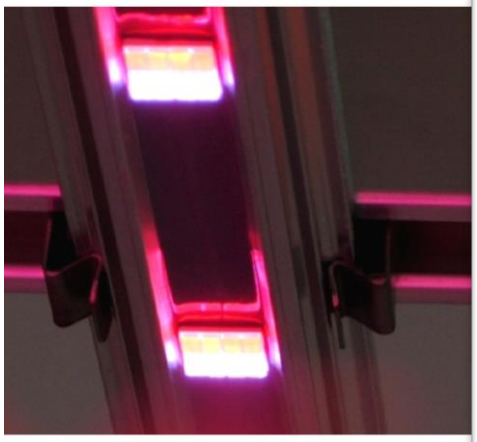


Aeroponic growing system with LED lights in Room 1 and Room 3

Lighting

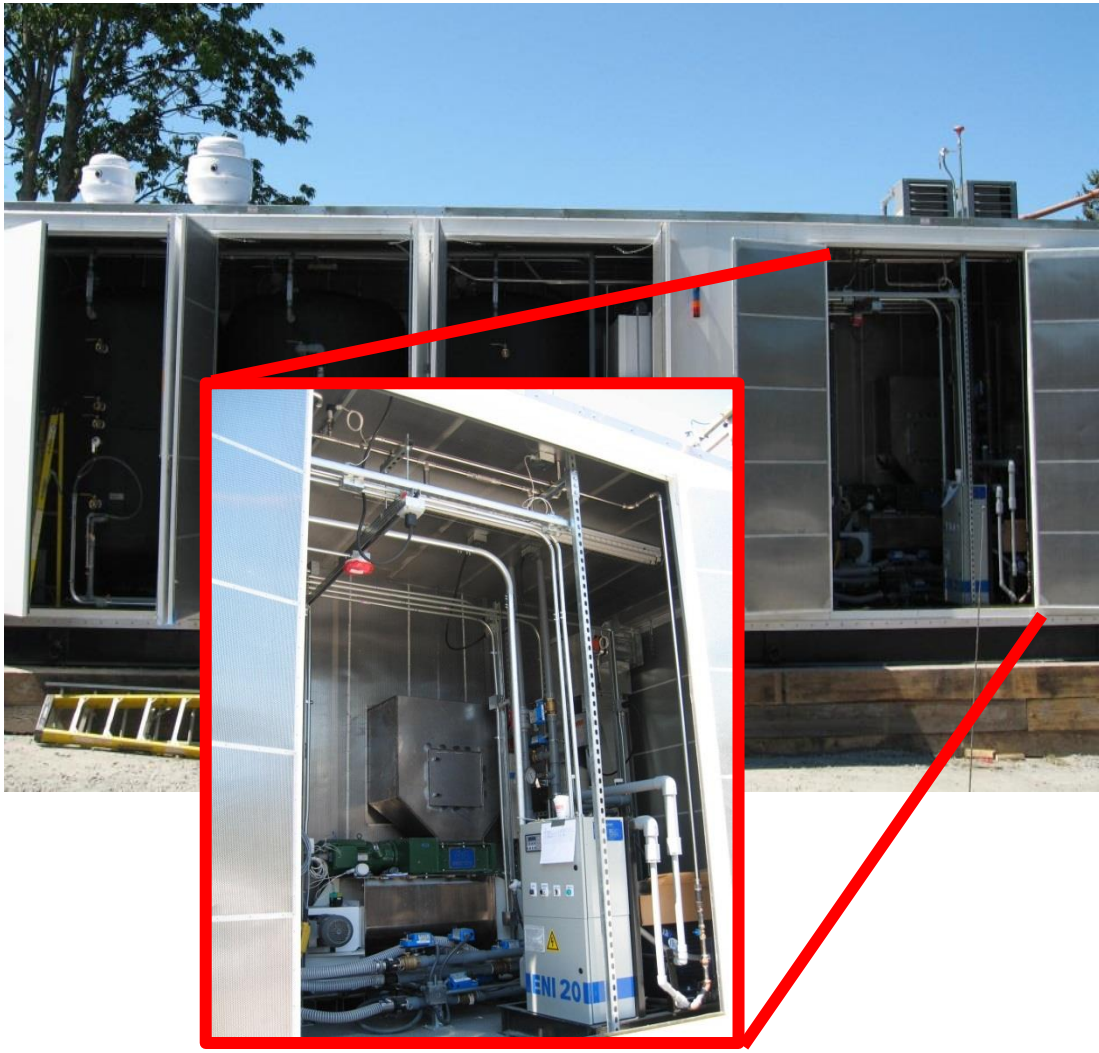


- Daylight necessary
  ??% through south wall
- LEDs - Surexi^{tm} Horticulture LED Series by Illumitex
- Controlled to provide sufficient photosynthetic photon flux density (PPFD)



Anaerobic Digester

- Material grinding and feeding system
- Three 1,400 gallon reactors operated as two-stage digester
- Biogas generated in the anaerobic environment
- ENI 20kW co-generation combustion engine → CHP
- Instrumentation for independent operation and remote control



Anaerobic digester
Up to 300 kg food waste/day
Transformed into biogas
Savings - $190/ton food waste diverted from landfill

Current Digester Food:

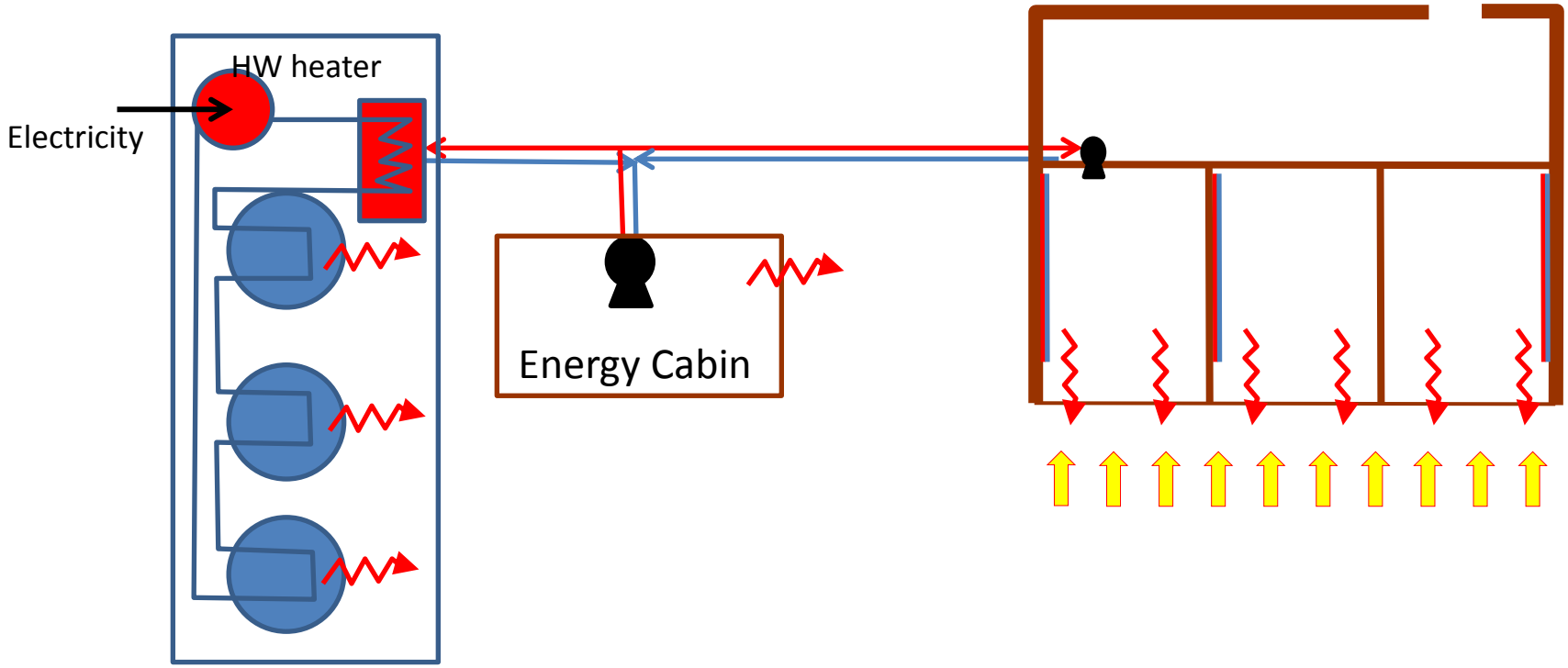
- Cheel kitchen (pre-consumer) ~100-150 lb/d
- Apartment collection ~100-150 lb/wk
- Student Center kitchen (pre-consumer) ~100-150 lb/d
- On-going – efforts to increase feeding rate →increase the biogas production

Heating System

- Energy Cabin
- European designed and built
- Solar thermal hot water (2 kW)
- Wood pellet boiler (20 kW)

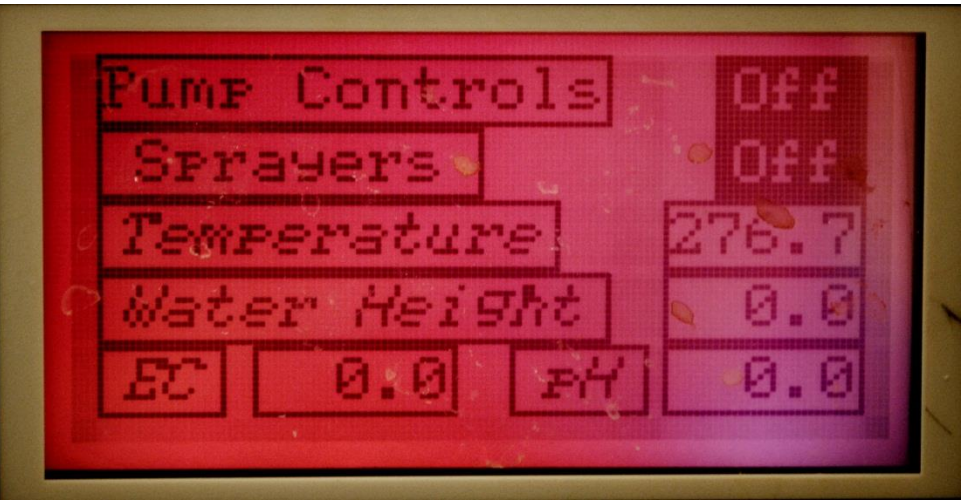
Heating System

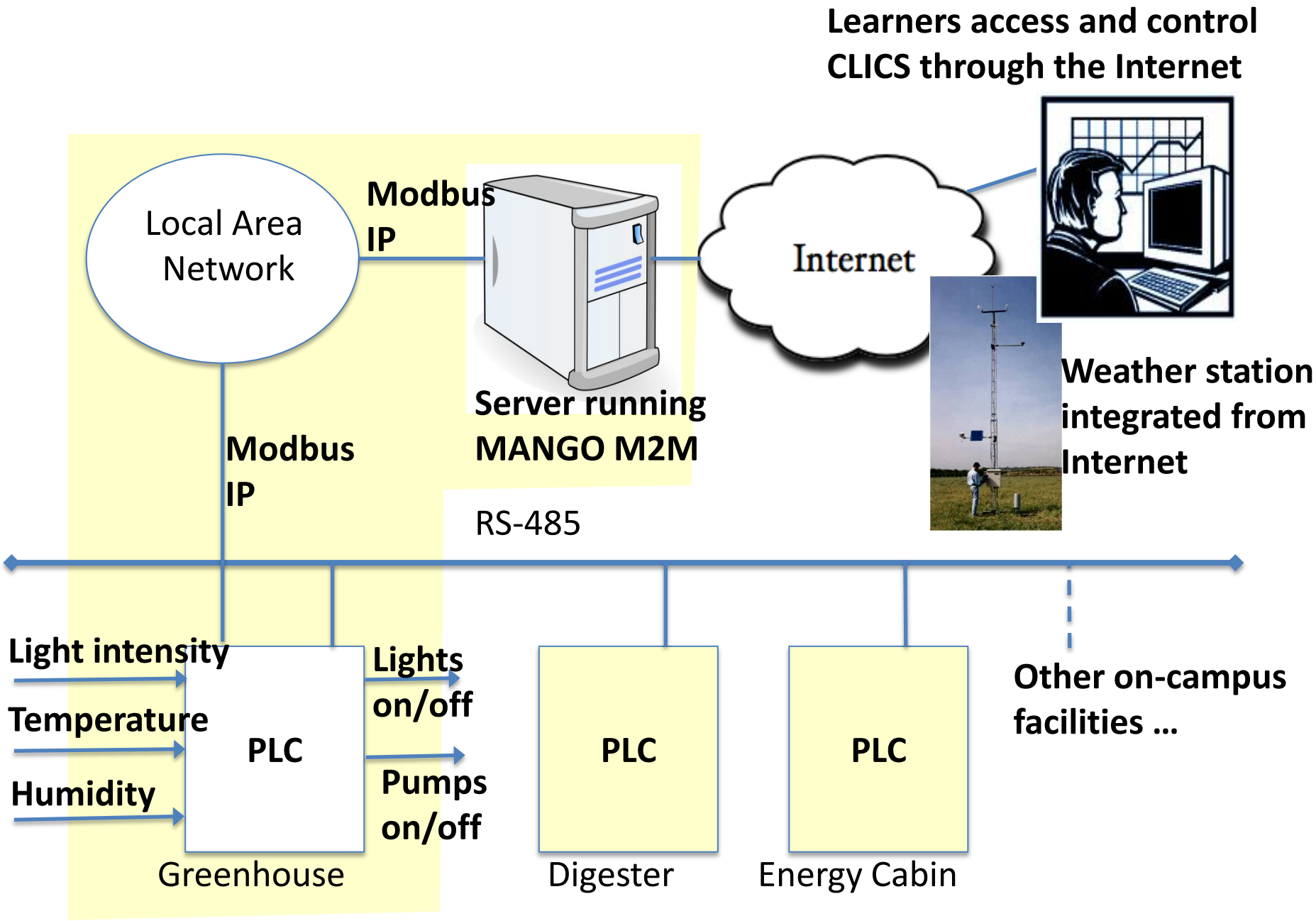
- Hot water/glycol (T ~80°C) Pumped from Energy Cabin
- Digester
  - heat exchanger to transfer heat to internal AD heating loop
  - Supplemental electric HW heater
  - Eventually – additional heat recovered from engine loss
- Greenhouse
  - Solar gain substantial
  - 3 supplemental pumps in GH distribute HW to rooms
  - T independently controlled in each room



Control System

- Program logic controller (PLC) connected to all 3 rooms
- Frequency of spraying
- Lights on/off
- Temperature
- Other possibilities
  - Water tank volume
  - pH

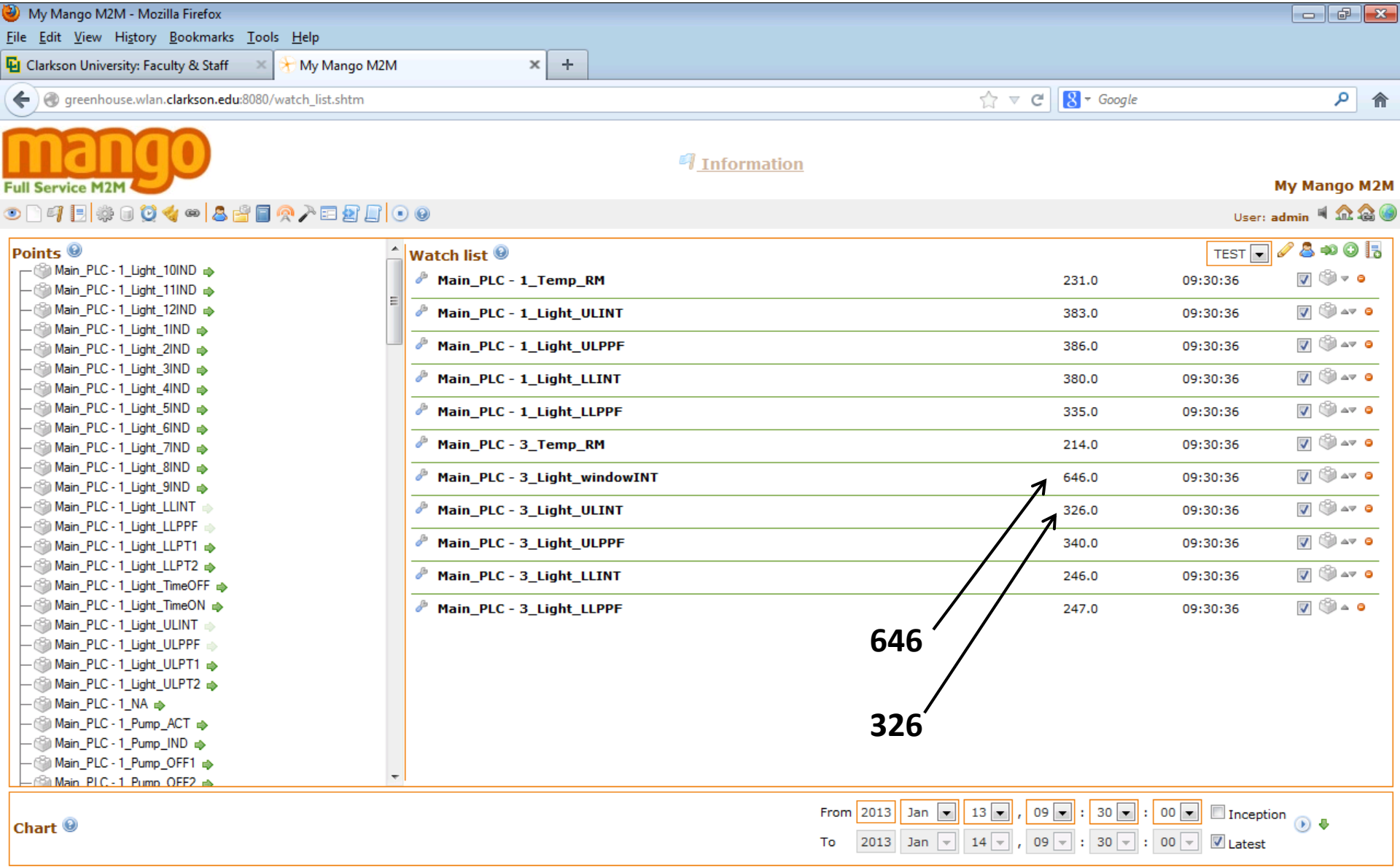



Learners access and control CLICS through the Internet
Local Area Network
Modbus IP
Internet
Server running MANGO M2M
Weather station integrated from Internet
Modbus IP
RS-485
Light intensity
Temperature
Humidity
PLC
Lights on/off
Pumps on/off
Greenhouse
PLC
Digester
PLC
Energy Cabin
Other on-campus facilities …

Mango Database for Data Acquisition

- Graphical interface to select datasets
- Pre-defined “reports” with sensor/data required for your project
- Virtual data available to clean up the database
  - All 30 min. intervals
  - Missing data recorded as blanks
  - Calculated variables derived from original data (e.g., heat content)
- Graphical output with student selected variables
  - Time series
  - X-Y scatter
  - Dual Y-axis graph
- Data download to MS Excel

Data Acquisition and Archiving



mango
Full Service M2M

Information

My M

User: admin

Go to: Main_PLC - 3_Light_LLPPF | Find by XID: DP_856192

3_Light_LLPPF

Value 199.0

Time 09:39:16

Set Enter a value to set: 199.0 Set

Export ID (XID) DP_856192

History (as of 2013/01/14 09:35:43)

Show 10 most recent records

Value	Time	Annotation
224.12786666666665	09:34:34	
231.40106666666662	09:33:34	
237.72146666666663	09:32:34	
245.02079999999998	09:31:34	
209.5852	09:30:34	
180.67	09:29:34	
230.65879999999999	09:28:34	
238.8150666666666	09:27:34	
200.51493333333332	09:26:34	
210.7793333333333	09:25:34	

User n

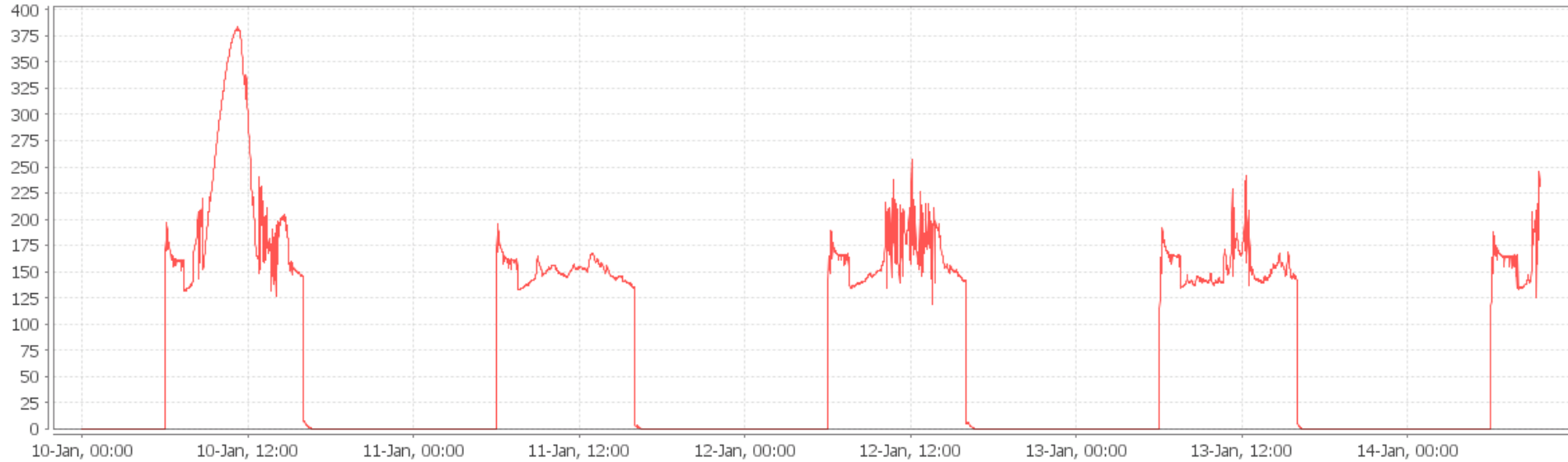
Statistics (as of 2013/01/14 09:35:30)

Time period: 1 day(s)

Start: 2013/01/13 09:34
End: 2013/01/14 09:34
Minimum: 0.0 @ Jan 13 16:20
Maximum: 245.02079999999998 @ 09:31:34
Average: 65.750805768395
Sum: 94864.39573333328
Log entries: 1441

Chart (as of 2013/01/14 09:35:04)

From 2013 Jan 10 , 00 : 00 : 00 Ince
To 2013 Jan 14 , 09 : 34 : 00 Late



Events

My Mango M2M - Mozilla Firefox

File Edit View History Bookmarks Tools Help

Clarkson University: Faculty & Staff | My Mango M2M

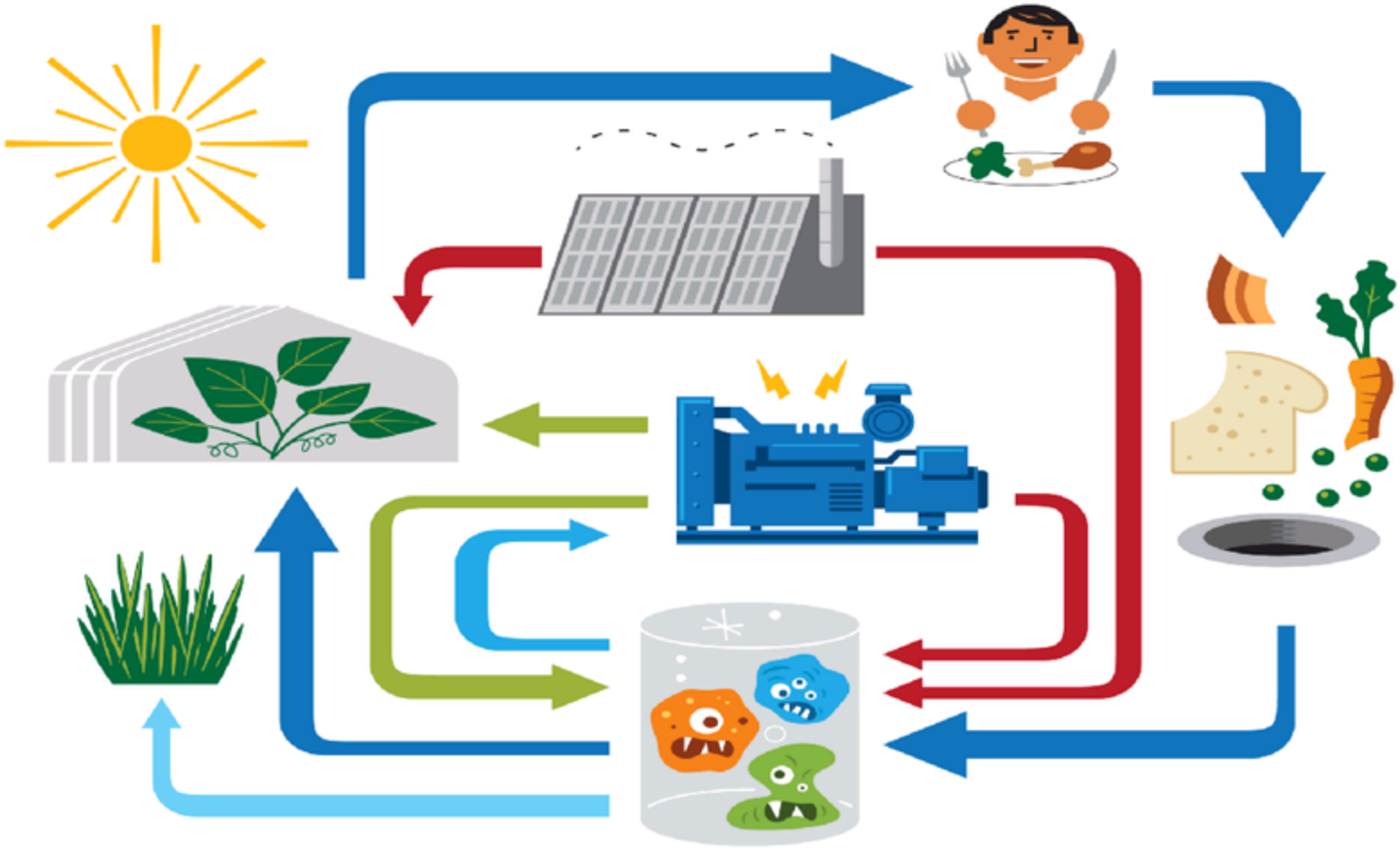
greenhouse.wlan.clarkson.edu:8080/mango/threeSystems.shtm

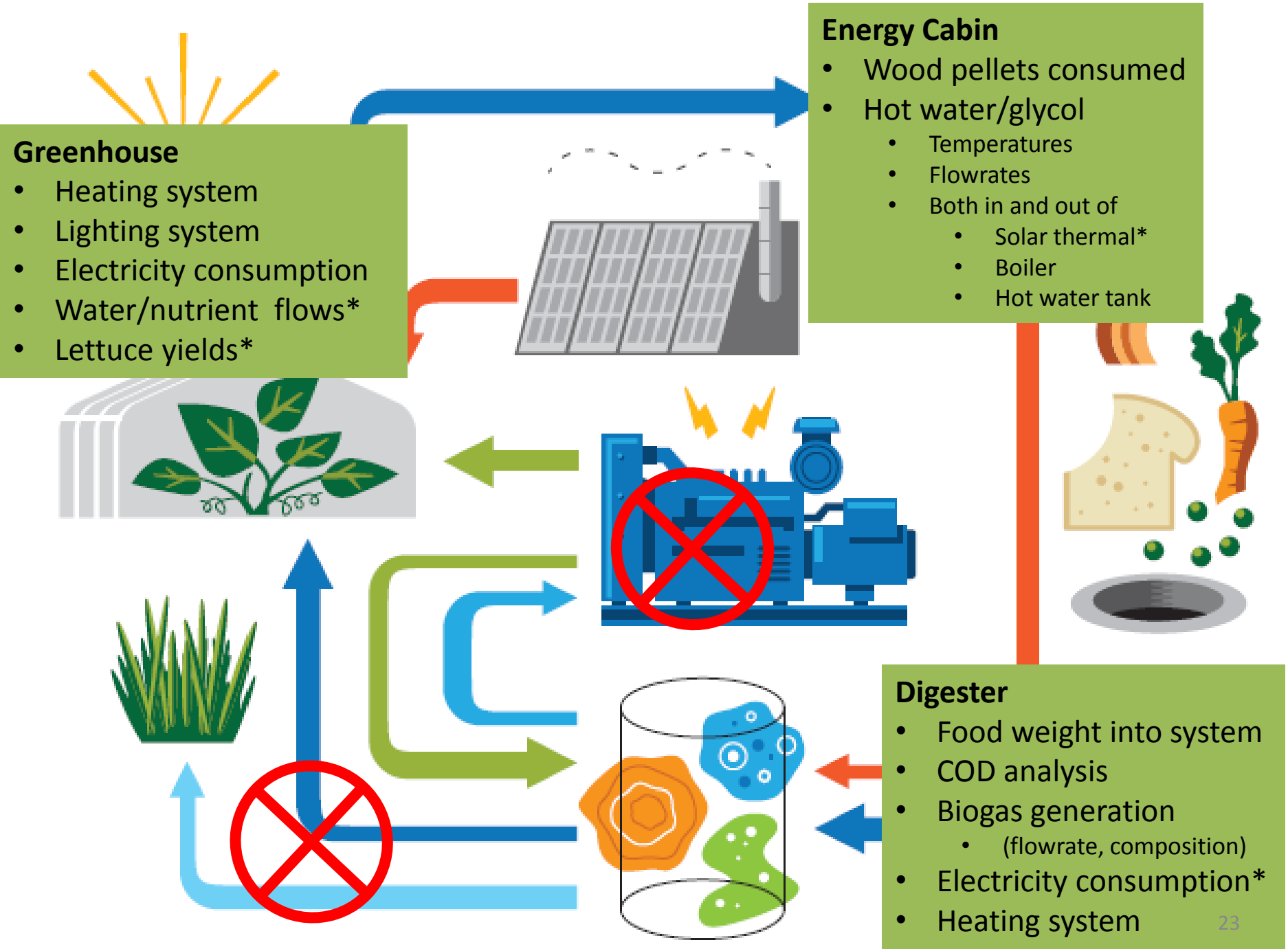
mango Full Service M2M

Improved GUI for student access to data

My Mango M2M

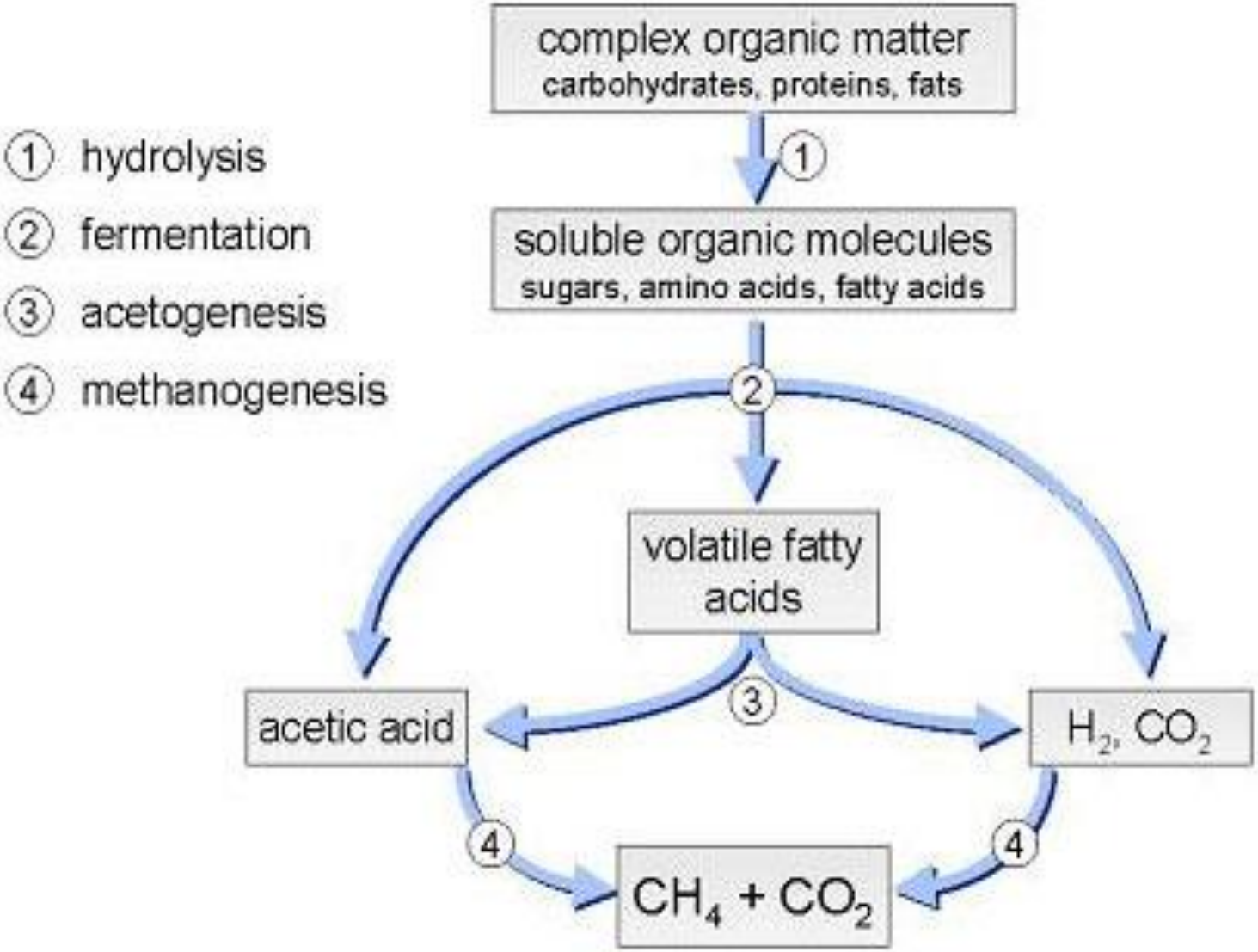
User: spowers




Energy Cabin
• Wood pellets consumed
• Hot water/glycol
• Temperatures
• Flowrates
• Both in and out of
• Solar thermal*
• Boiler
• Hot water tank
Greenhouse
• Heating system
• Lighting system
• Electricity consumption
• Water/nutrient flows*
• Lettuce yields*
Digester
• Food weight into system
• COD analysis
• Biogas generation
• (flowrate, composition)
• Electricity consumption*
• Heating system

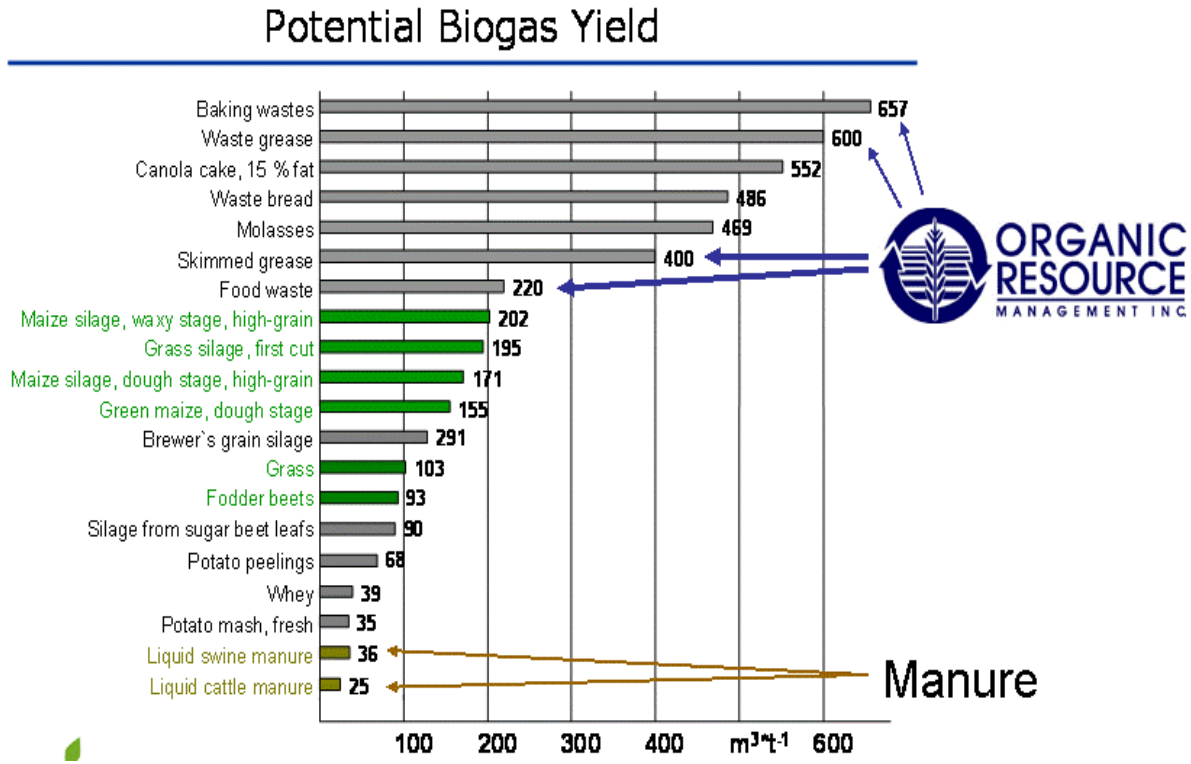
Example
Digester Research

Basic Digestion Process



Food Waste Potential

- Food waste has higher biogas potential then other sources like agriculture and wastewater sluc



Food Waste Success Stories

- East Bay Municipal Utility District, Oakland, CA
  - First wastewater treatment plant in the nation to convert post-consumer food scraps to energy via anaerobic digestion.
  - Methane powers plant and produces natural fertilizer.

- University Wisconsin, Oshkosh
  - Use dry fermentation technology to digest university food waste scraps and city yard waste to produce enough electricity to power up to 15% of institution's electricity.

University of Wisconsin - Oshkosh Biodigester

BIOFERM™
ENERGY SYSTEMS

VIESSMANN Group

Oshkosh System

- Dry AD technology
  - High solids content (25% and above)
  - Material stays stationary within chamber
  - HRT = 28 days
  - No additional liquid input
  - Liquid is recirculated
  - Feedstock can be composted after AD
- Power generation 370 kW treating 8,000 tons of waste annually (22 ton/day)

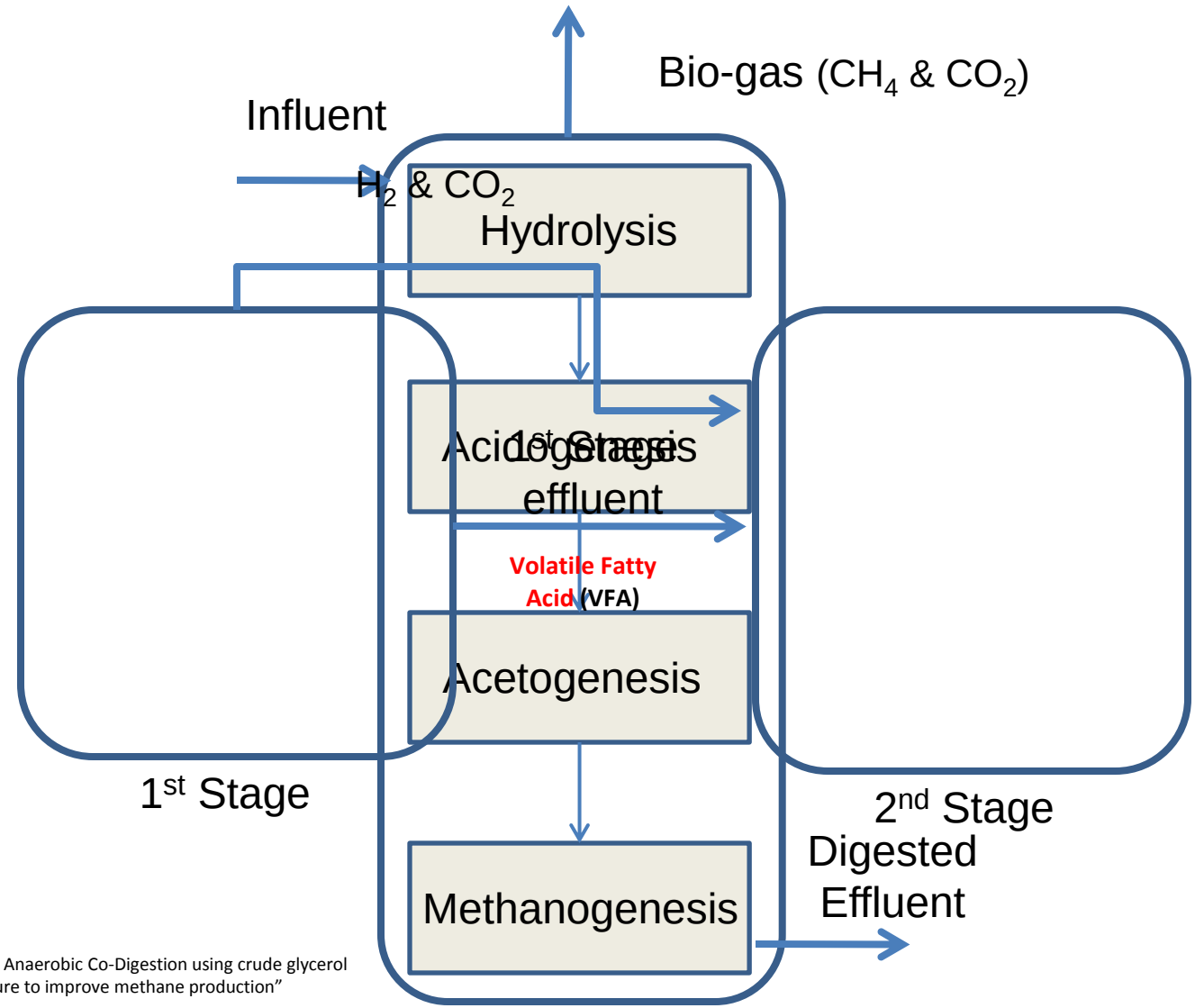
16.8 kW per ton of Feedstock

So Can We Do Any Better?

Clarkson's Mixed Food Waste Composition

- Chemical Oxygen Demand (COD) = 268,264 ± 181,549 mg/L
- Total Solids (TS) = 19.66 ± 12.88%
- Volatile Solids (VS) = 18.74 ± 12.60%

Phases of Anaerobic Digestion



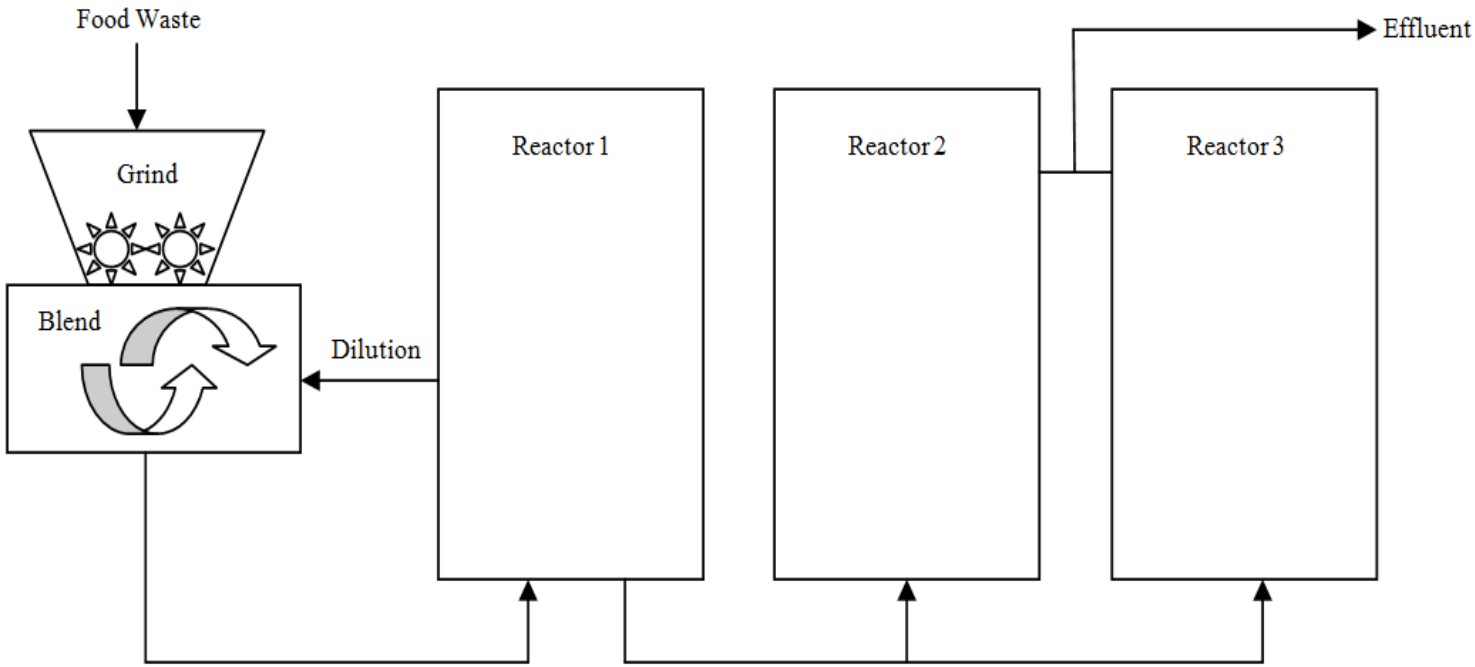
*K. Venkiteshwaran "Two-Stage Anaerobic Co-Digestion using crude glycerol or cheese whey with dairy manure to improve methane production"

Single vs. Two Phase Comparison

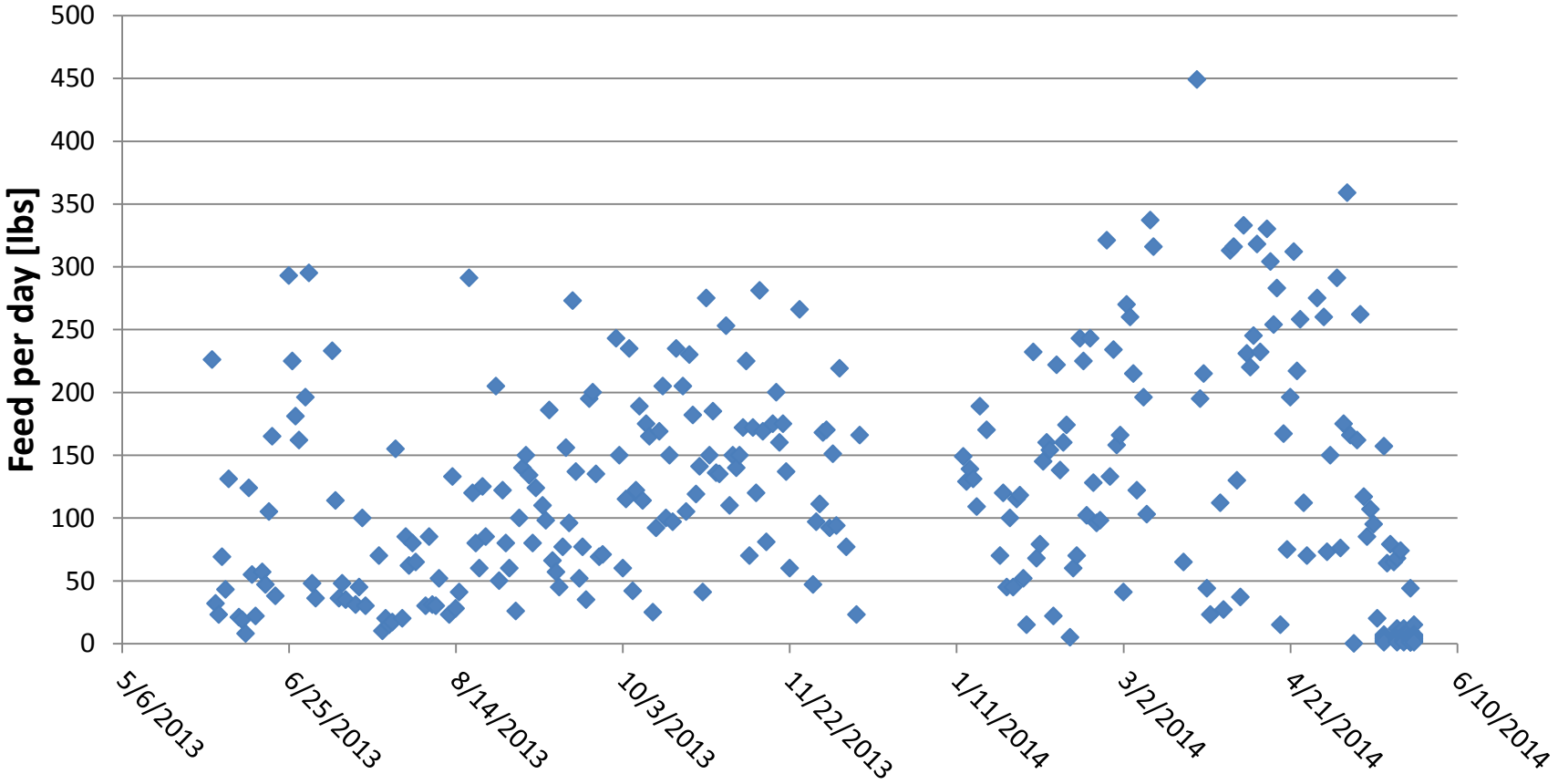
- Single Stage
  - Easier to maintain.
  - Simpler to operate.
- Two-Phase
  - Environmental control of each phase (temp, pH).
  - Control of hydraulic retention time (HRT).
  - Optimization of process by increased volatile fatty acid (VFA) production.
  - Smaller overall reactor volume due to smaller HRT.

Clarkson's Digester Operation

- Ability to run single stage and two-phase digestion.
- Separate mixing cycles for each stage.



Food Loading Variation



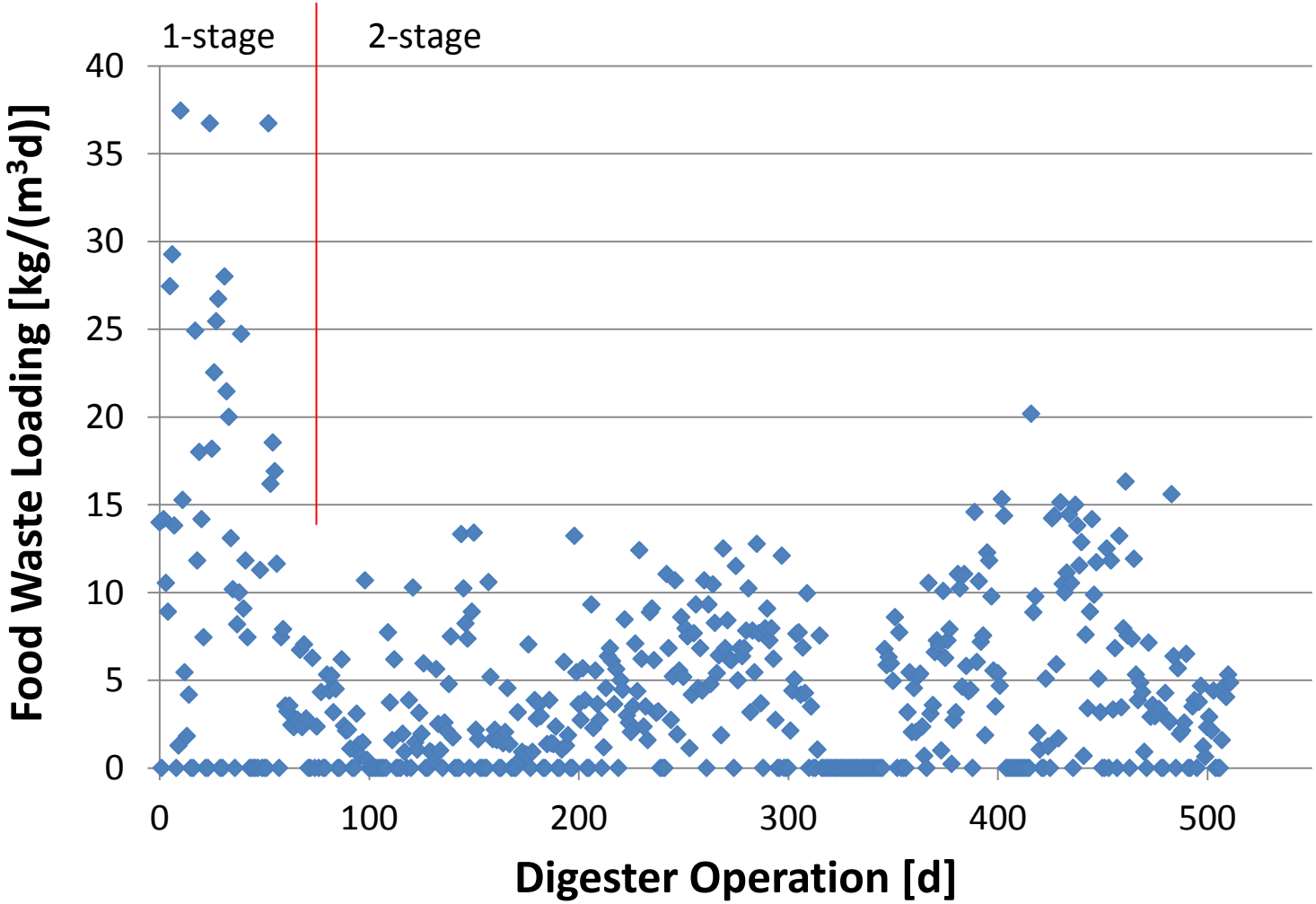
Given the variable loading what process will be most reliable and efficient?

- Single stage system could result in overloading at high loading conditions, or
- Fermentation stage of 2-stage system may be difficult to maintain during low loading conditions

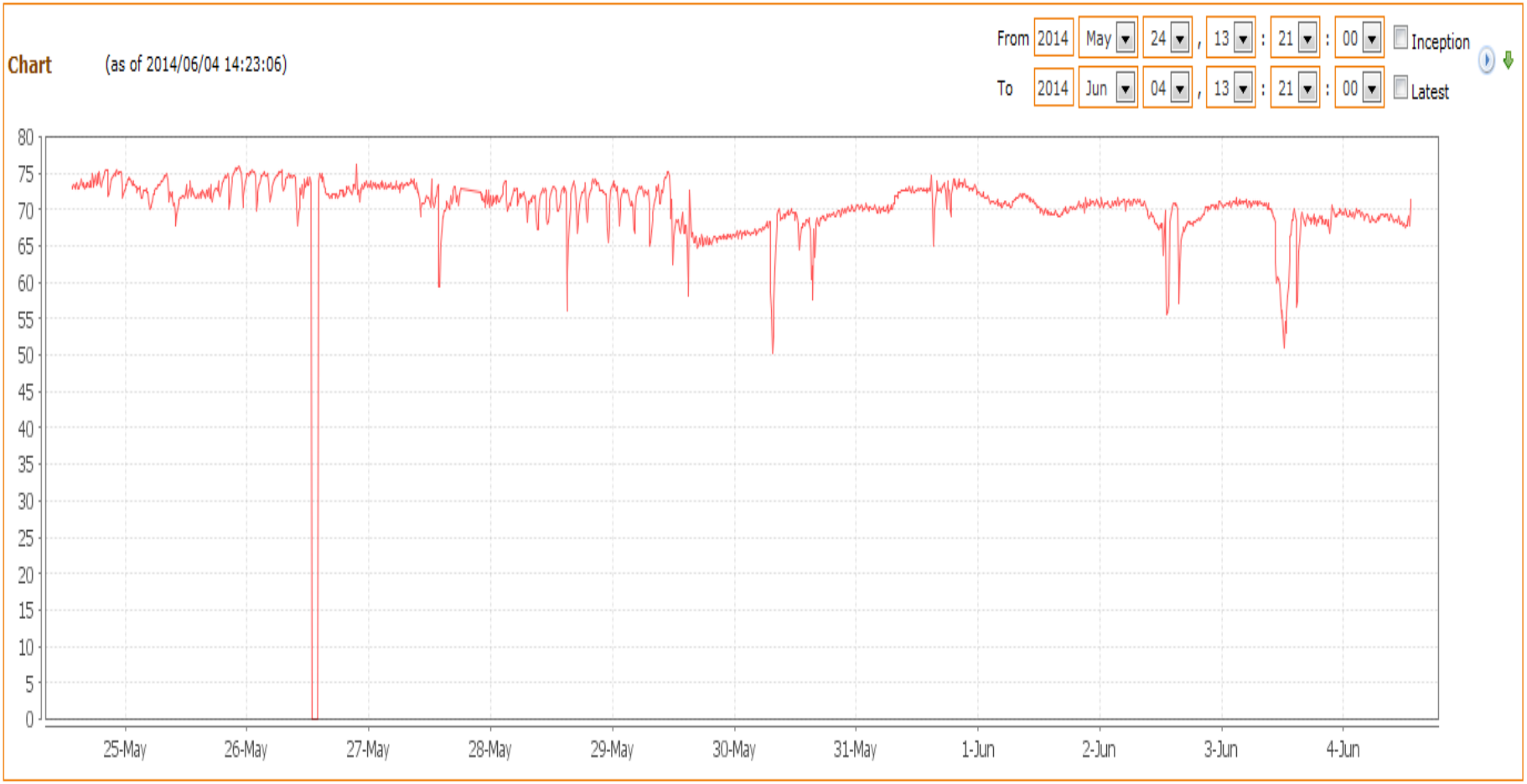
Approach

- Operate system first as single stage system at higher loading rates
- Followed by 2-stage operation at low loading

Digester Loading Rate

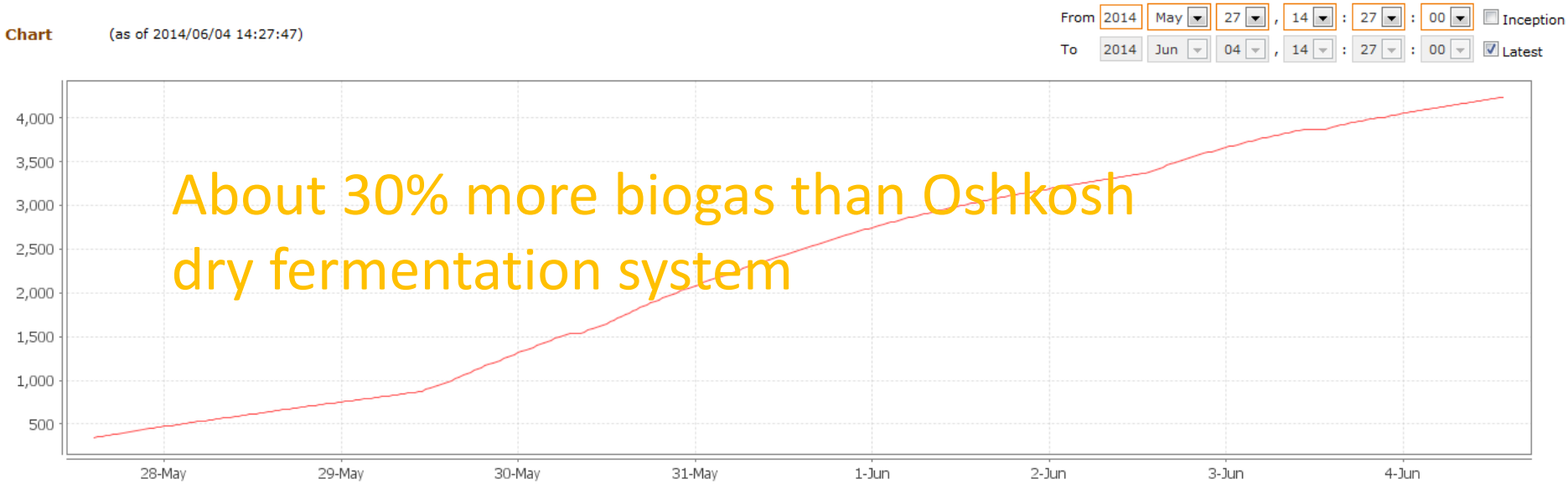


Methane Content



http://greenhouse.wlan.clarkson.edu:8080/mango/login.htm

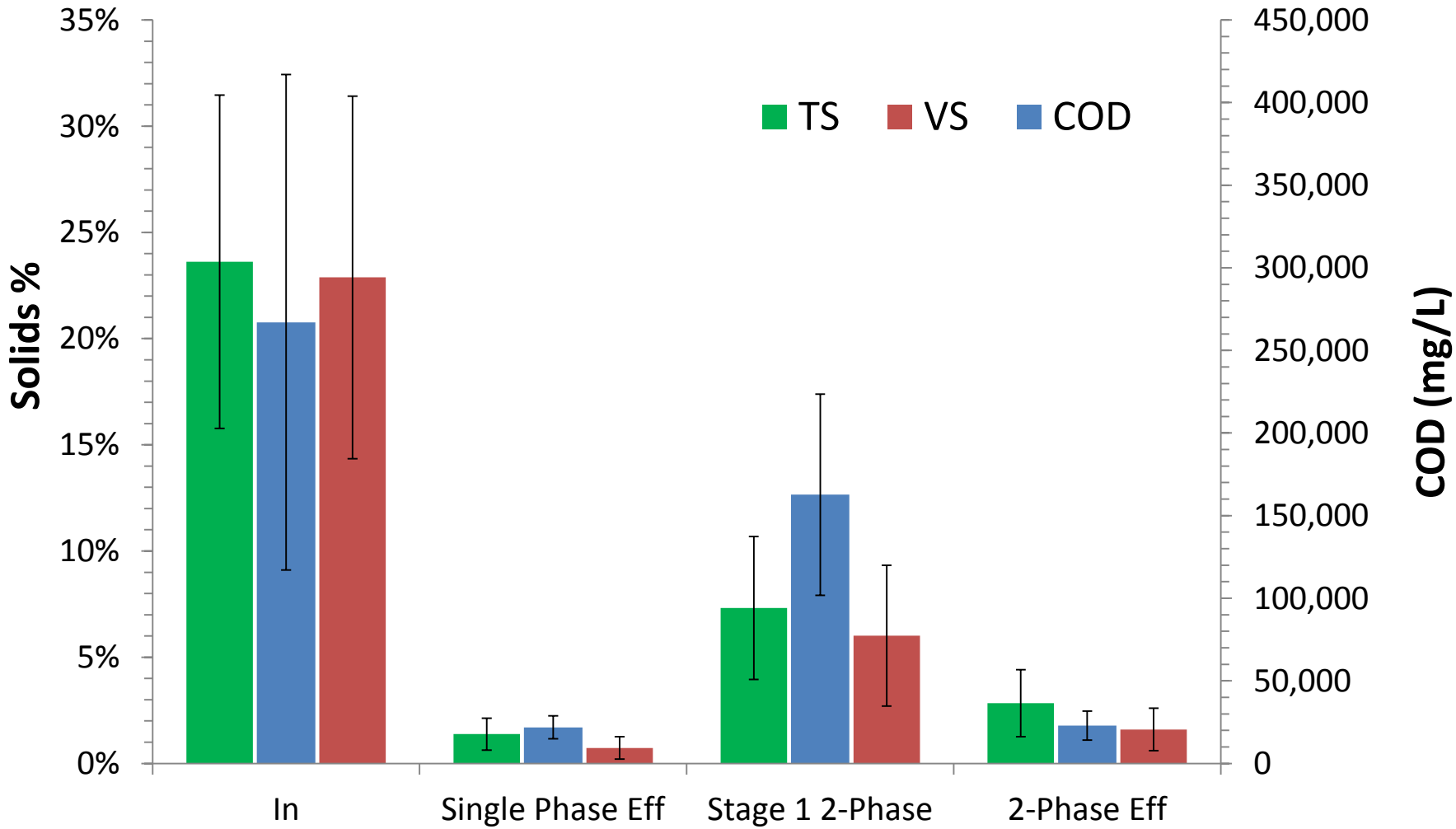
Biogas Production



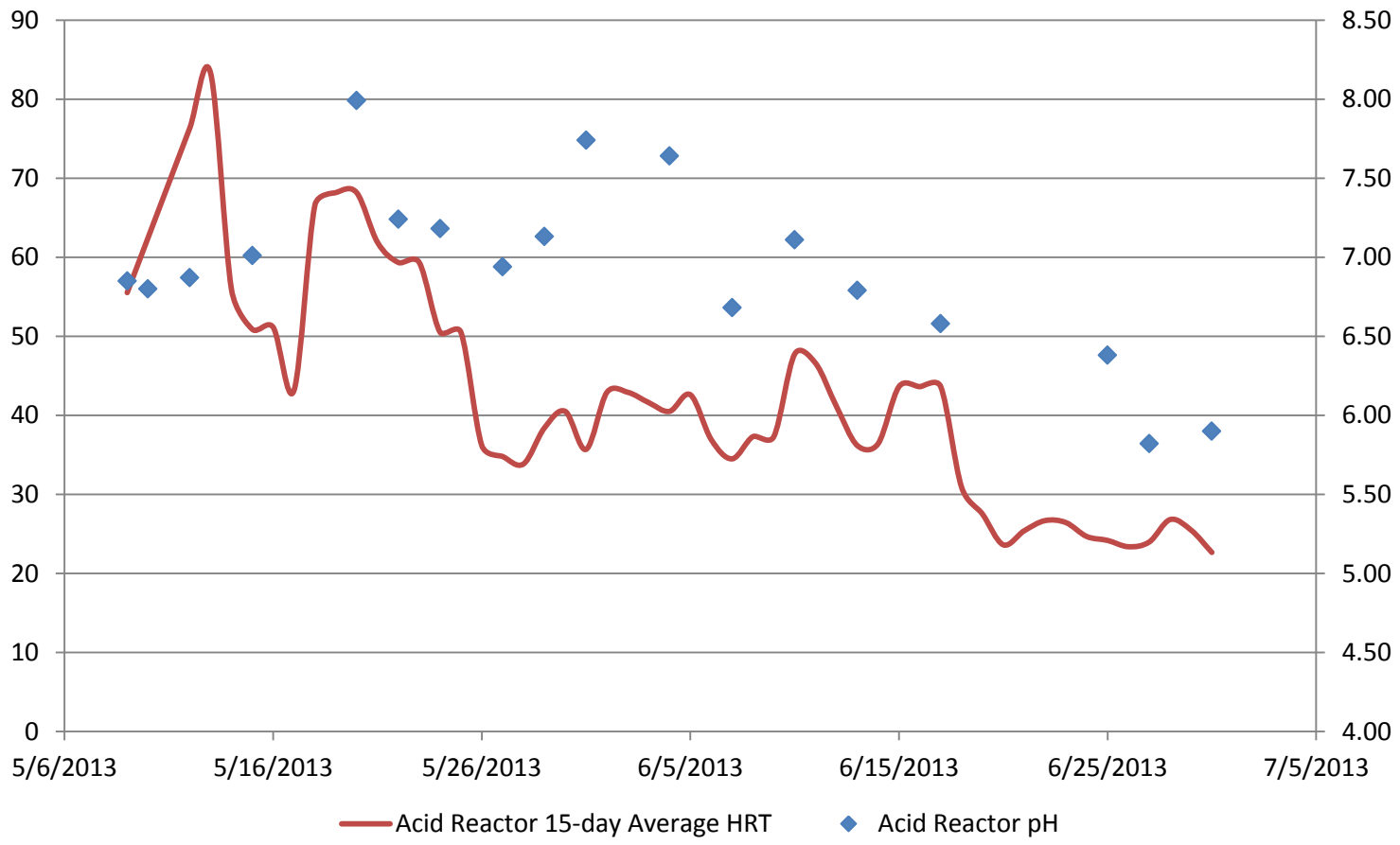
Approximately 500 ft^3/d feeding an average of 113 lbs/d at 12±8 % VS
Approximately 1,362±544 L CH4/kg VS added
Or 272 m^3 biogas per ton of foodwaste or 21 kW per ton of FW

http://greenhouse.wlan.clarkson.edu:8080/mango/login.htm

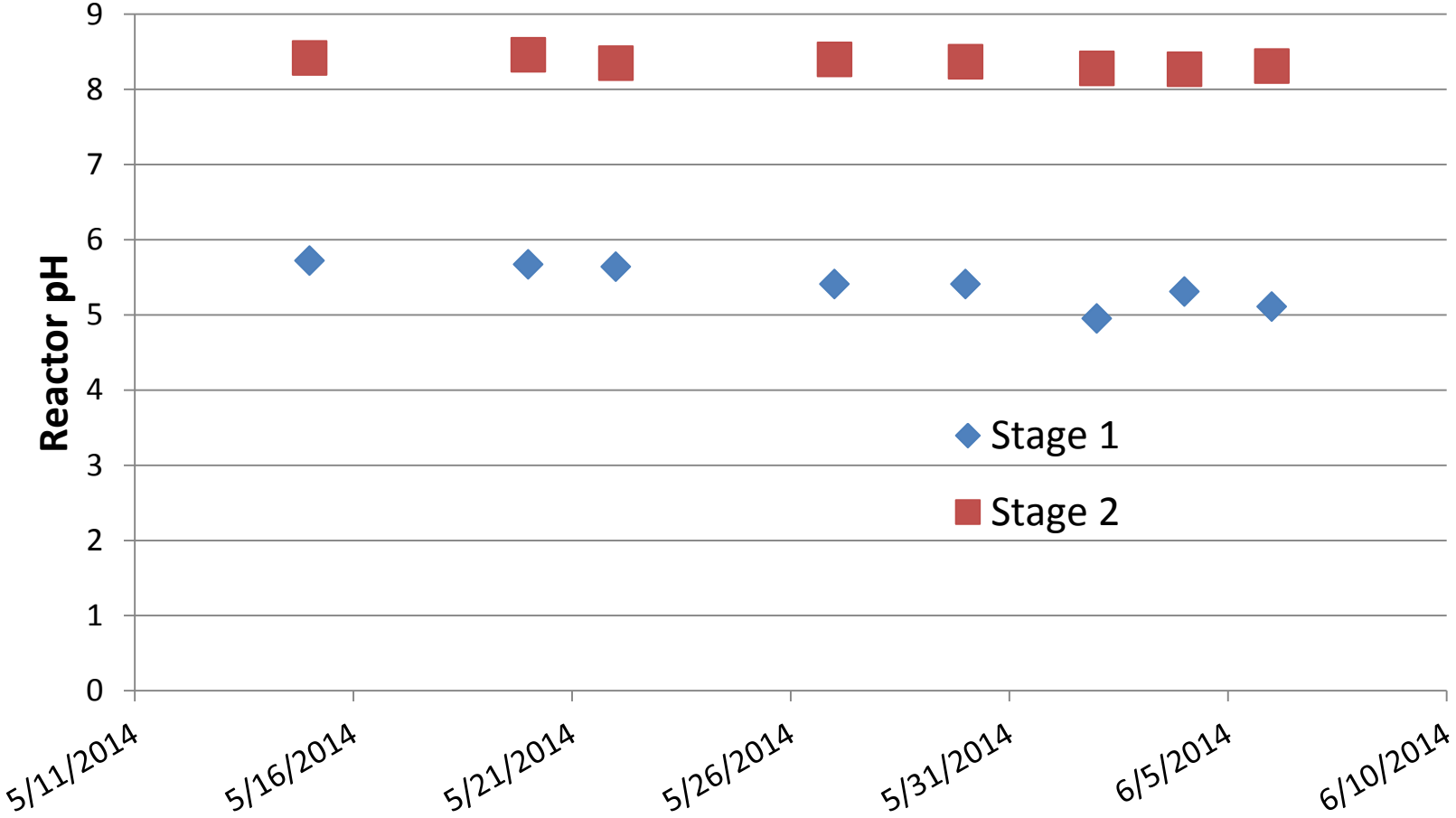
Average Chemical Characterization



Acidogenesis HRT Affecting pH in Reactor



Recent pH condition's



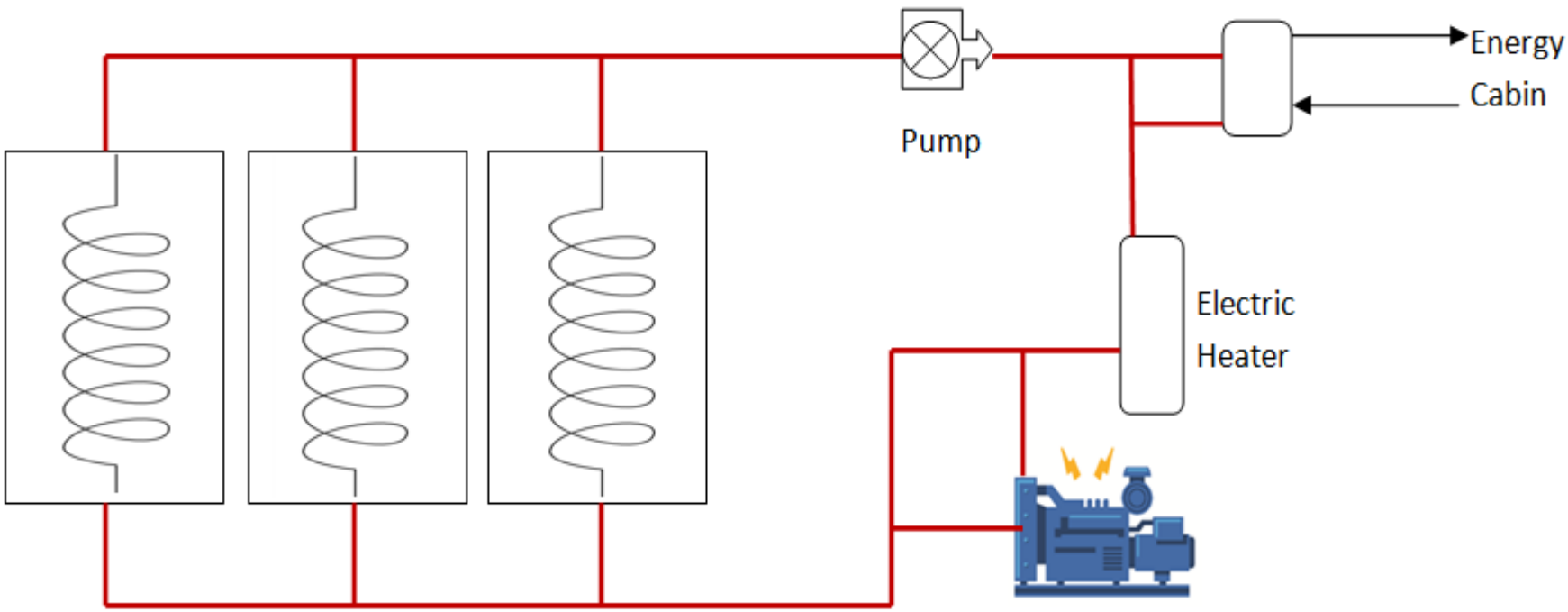
	One-stage	Two-stage	
Substrates			
COD ($mg \cdot L^{-1}$)	273400	267000±149900	
TS (%)	19.62	23.62±7.85%	
VS (%)	18.69	22.88±8.53%	
Digester operation			
VS loading rate ($kg \cdot m^{-3}\ d^{-1}$)	3.79	0.78±0.42	
COD loading rate ($kg \cdot m^{-3}\ d^{-1}$)	3.87±1.93	0.79±0.16	
Digester characteristics		Stage 1	Stage 2
pH	7.32	5.2±0.4	8.4±0.1
COD ($mg \cdot L^{-1}$)	19730	162700±60900	22900±8800
VS (%)	0.84	6.01±3.31%	1.60±1.00%
TS (%)	1.54	7.32±3.37%	2.84±1.58%
VFA ($mg \cdot L^{-1}$as HAc)		38900±4800	6300±3600
Digester performances			
Temperature (°C)	37.32	37.32	
VS removal (%)	96	93	
COD removal (%)	93	91	
Methane concentration (%)	58.60	58.98	
Methane yield (L-$CH_4 \cdot kg\ VS^{-1}$)	380	446	
Methane yield (L-$CH_4 \cdot kg\ COD^{-1}$ removed)	359	481	

CLICS in Classes

Senior Design Engineering & Management
Senior Design Environmental Engineering
Summer Undergraduate Research on Ammonia Inhibition
Mechanical Engineering Senior Design
Industrial Ecology
Applied Statistics
Calculus 2
Numerical Methods
Introduction of Environmental Engineering
Biological Processes

EM456: Digester Heating

- Three sources of heat energy for digester reactors.



Energy Balance

- **Energy production**

  $E_A = (Mp) \cdot (\text{L.H.V. of methane})$

  Where Mp is the daily methane production rate.

- **Heat required to heat feedstock**

  $E_B = Q \cdot Cp \cdot \delta(Ti - T0)$

  Where Q (m^3 per day) is the load flow rate, Cp (kJ/kg ◦C) is the specific heat of feed, δ (kg/m^3) is the specific weight of feed and Ti − T0 (◦C) is the difference between these two temperatures.

- **Heat loss through reactor walls**

  $E_C = k \cdot S(Ti - Te)$

  Where k (Wm^2/◦C) is the global heat transfer coefficient and S (m^2) the heat surface exchange. Temperature difference between digester reactor (Ti) and the pervading environmental temperature Te.

- **Mechanical energy requirements**

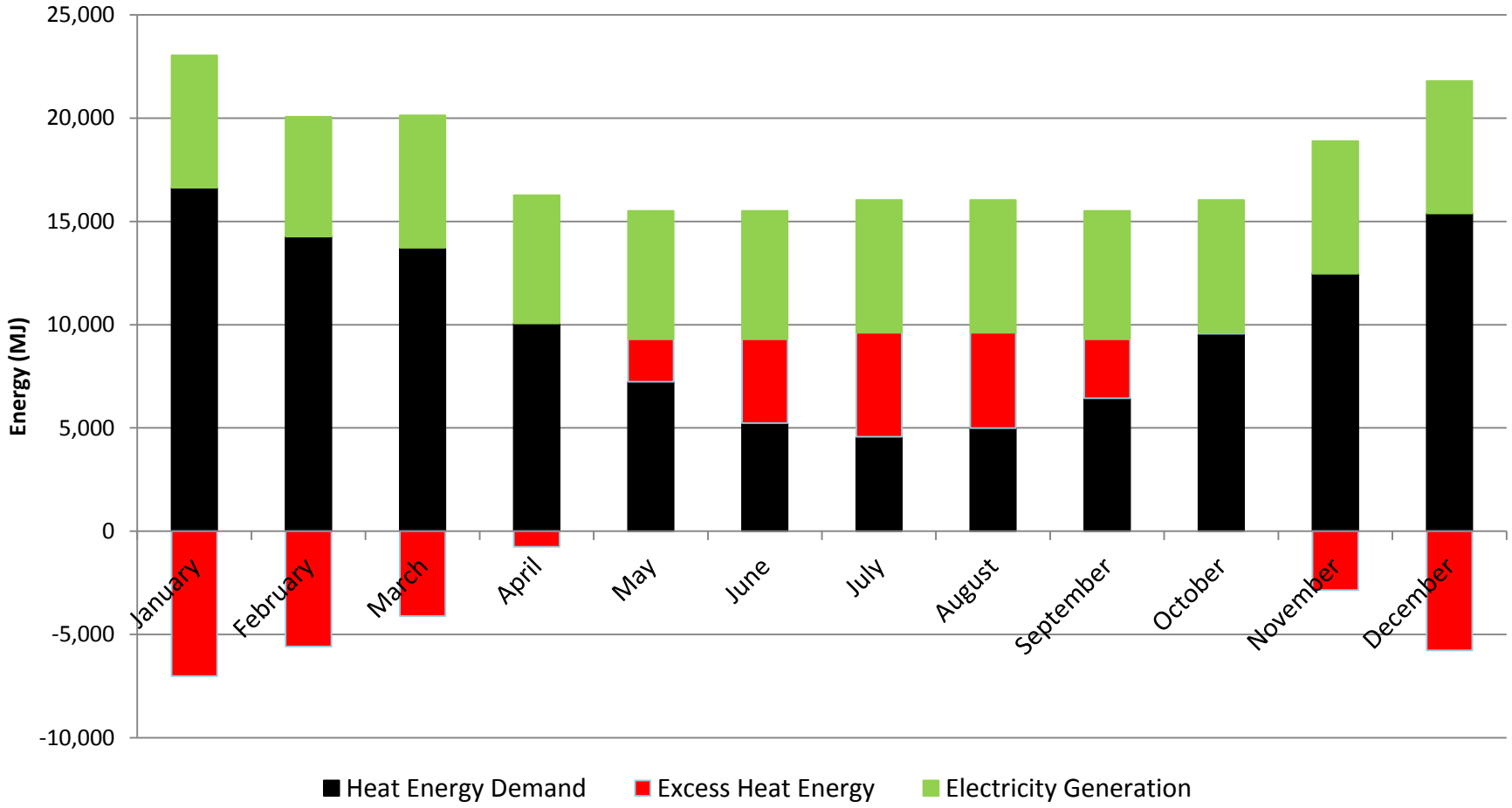
  $E_D = P \cdot Tps$

  Where P is the power (W) and Tps its daily functioning duration.

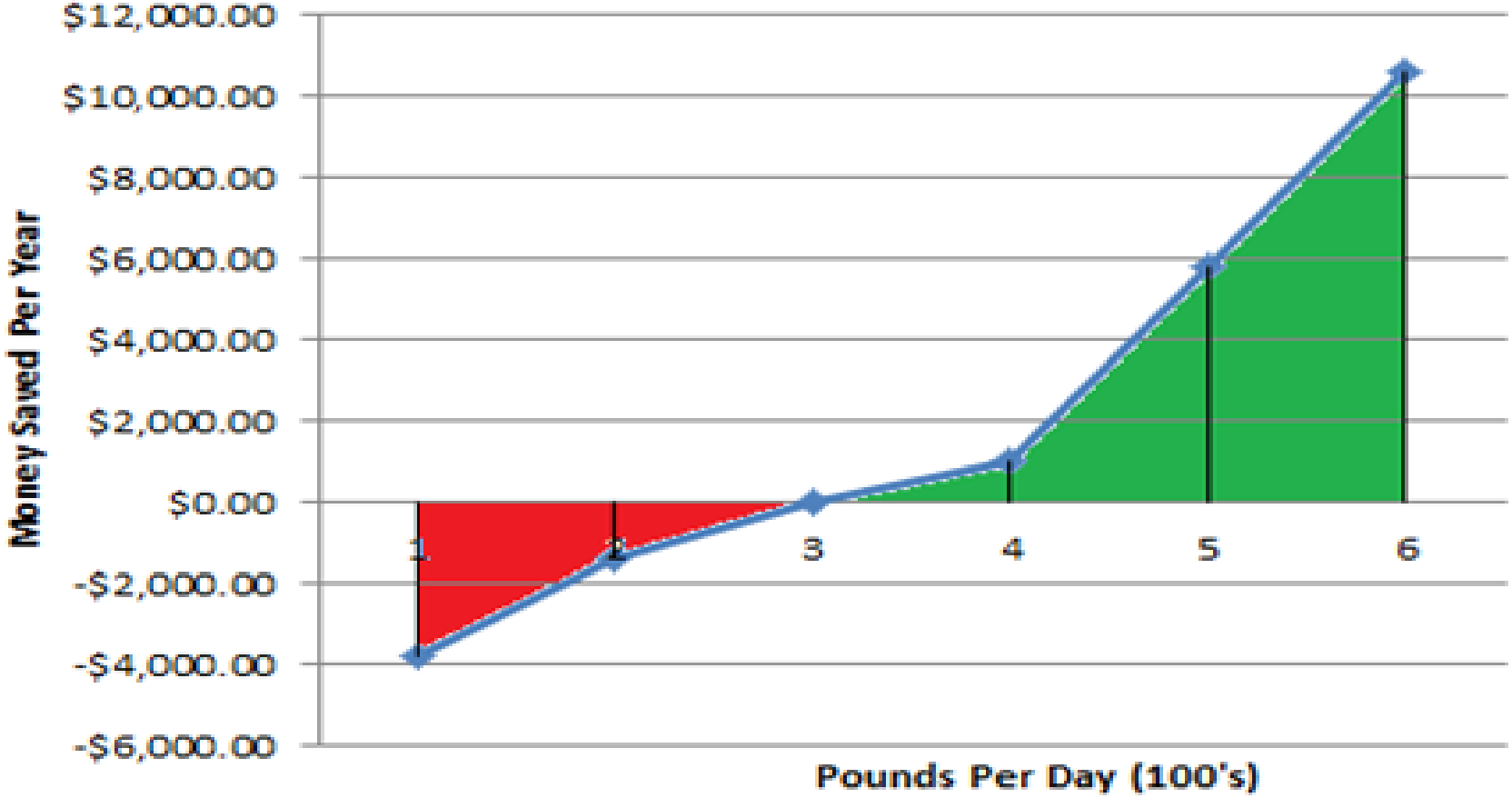
- **Net energy production**

  $E_P = E_A - (E_B + E_C + E_D)$

2-phase system with CHP



Economically viable?



CE491: Current focus – increase food throughput

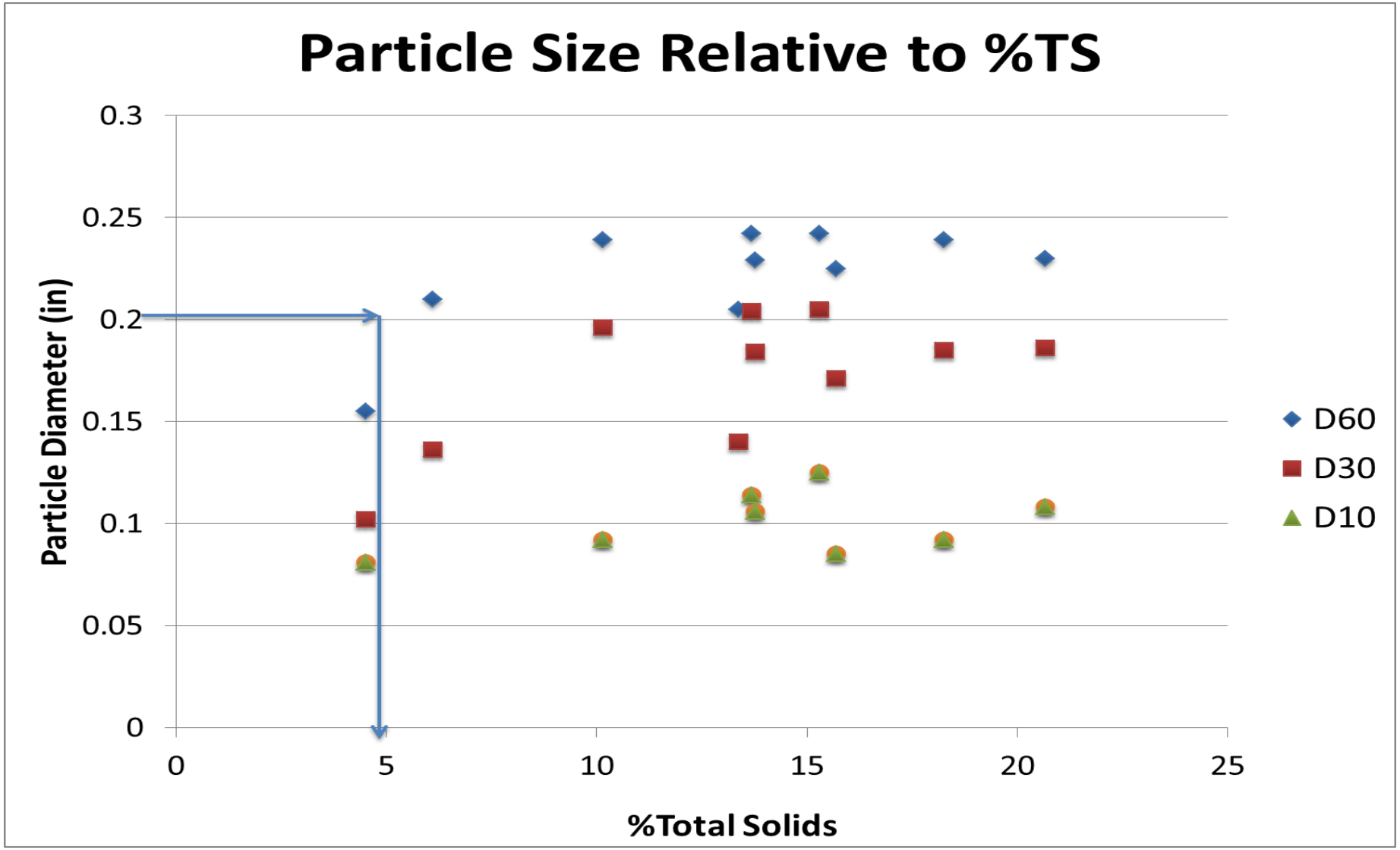
- Evaluate pre-processing to reduce particle size
- Disposer vs pulping

vs

Improve Waste Handling

- So we can increase waste production reliably
- E.g. pulping

Pulping results



Lighting Needs in GH

CE486/586 – Industrial Ecology

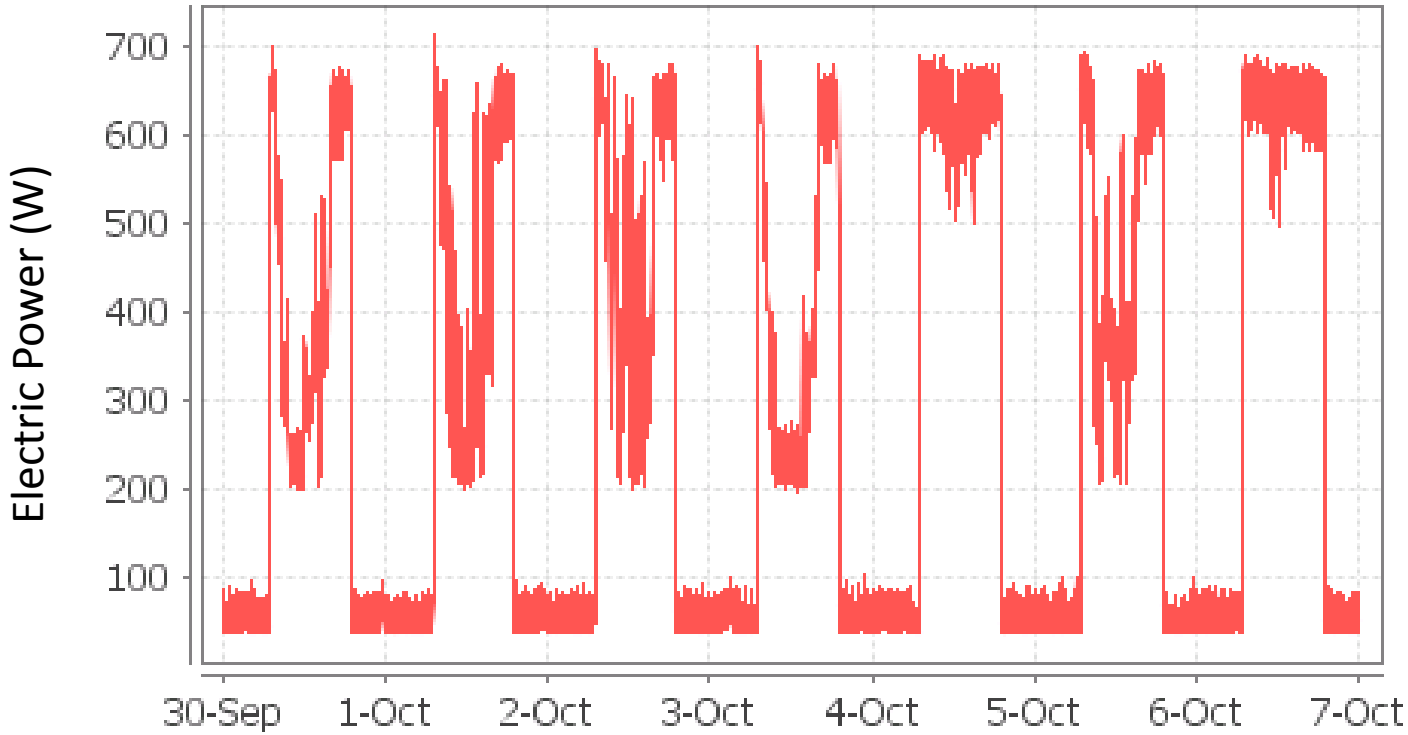
Assignment

- Evaluate the use of electricity and associated emissions required to grow lettuce in our pilot greenhouse. Use both Mango to create reports for lighting and the excel spreadsheet included on Moodle (Sept 30-Oct 4).
  - Create reports for "GH Rm 3 Light" to compare lighting requirements for seasons. (copy required graph images to paste into a word document)
    - Sept 30 – Oct 7, 2013
    - June 14 – June 22, 2013
    - Dec 1 – Dec 8, 2012
  - Using graphs included for each of these reports -
    - compare the amount of light received by the green house (hours and intensity) and the resulting general change in the number of lights on during sunny periods.
  - Using the Excel spreadsheet (on Moodle),
    - determine the number of lights on for each time step.
    - estimate the electric energy required for each time step for the actual number of lights that were on (note- each strip requires 72 W power)
    - estimate the electric energy required if all of the light strips were on during that same time period
    - Calculate the savings in daily electric energy for each day included in the excel spreadsheet.
  - Calculate the daily CO_2, NOx and SO_2 emissions for the total electricity and savings due to our use of daylight
  - Discuss the value of using day light for supplementing electric light in the greenhouse and the application of sensors and controls to automate lighting.

Lighting Efficiency Efforts

- Timers – on/off 12 hours/day
- LED bulbs (72W/strip)
- Only red & blue light generated
- Daylight sensors – some lights off when sufficient daylight entering

What is the value of day lighting to reduce electric energy use?



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greenhouse.wlan.clarkson.edu:8080/mango/threeSystems.shtm

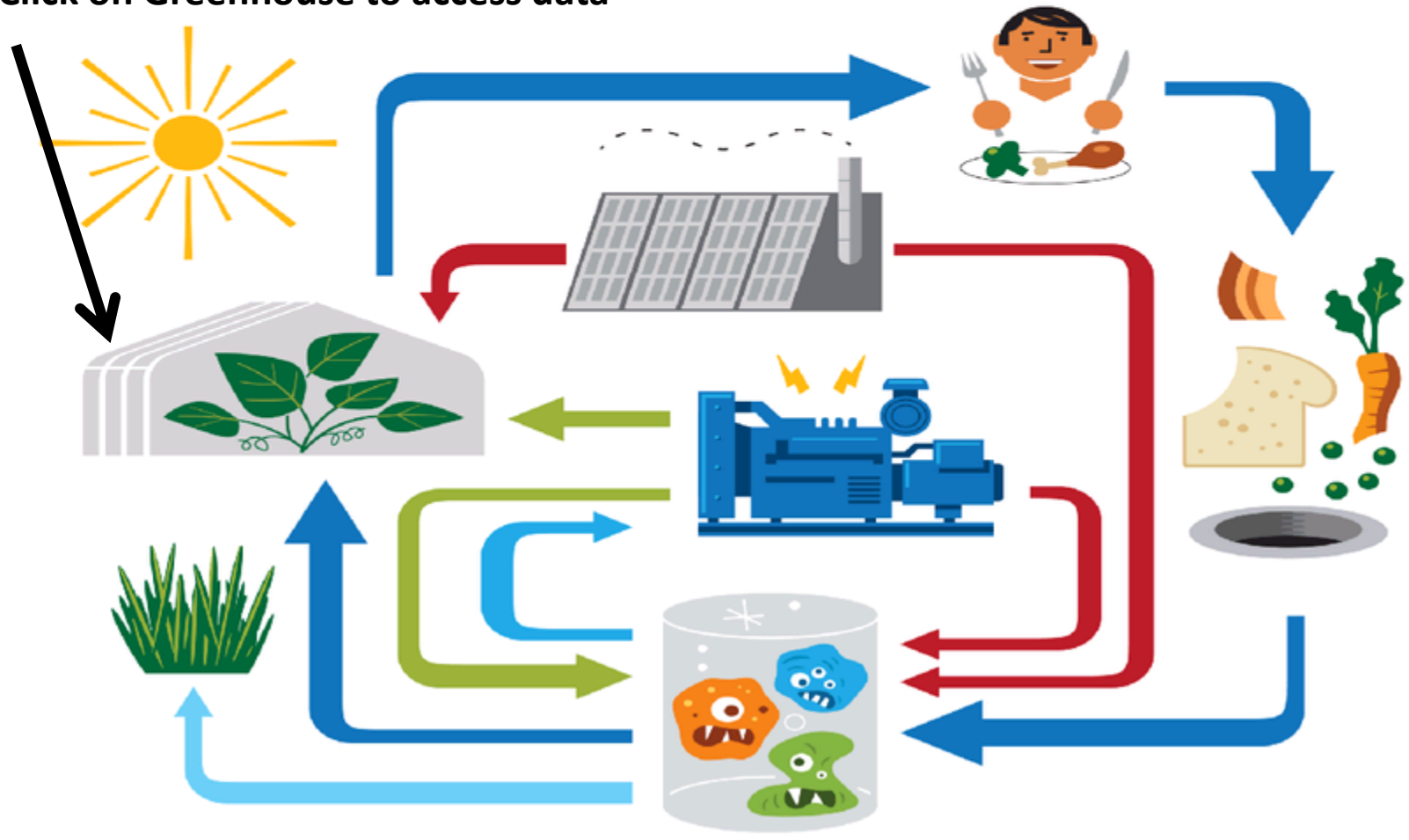
mango Full Service M2M

http://greenhouse.wlan.clarkson.edu:8080/mango

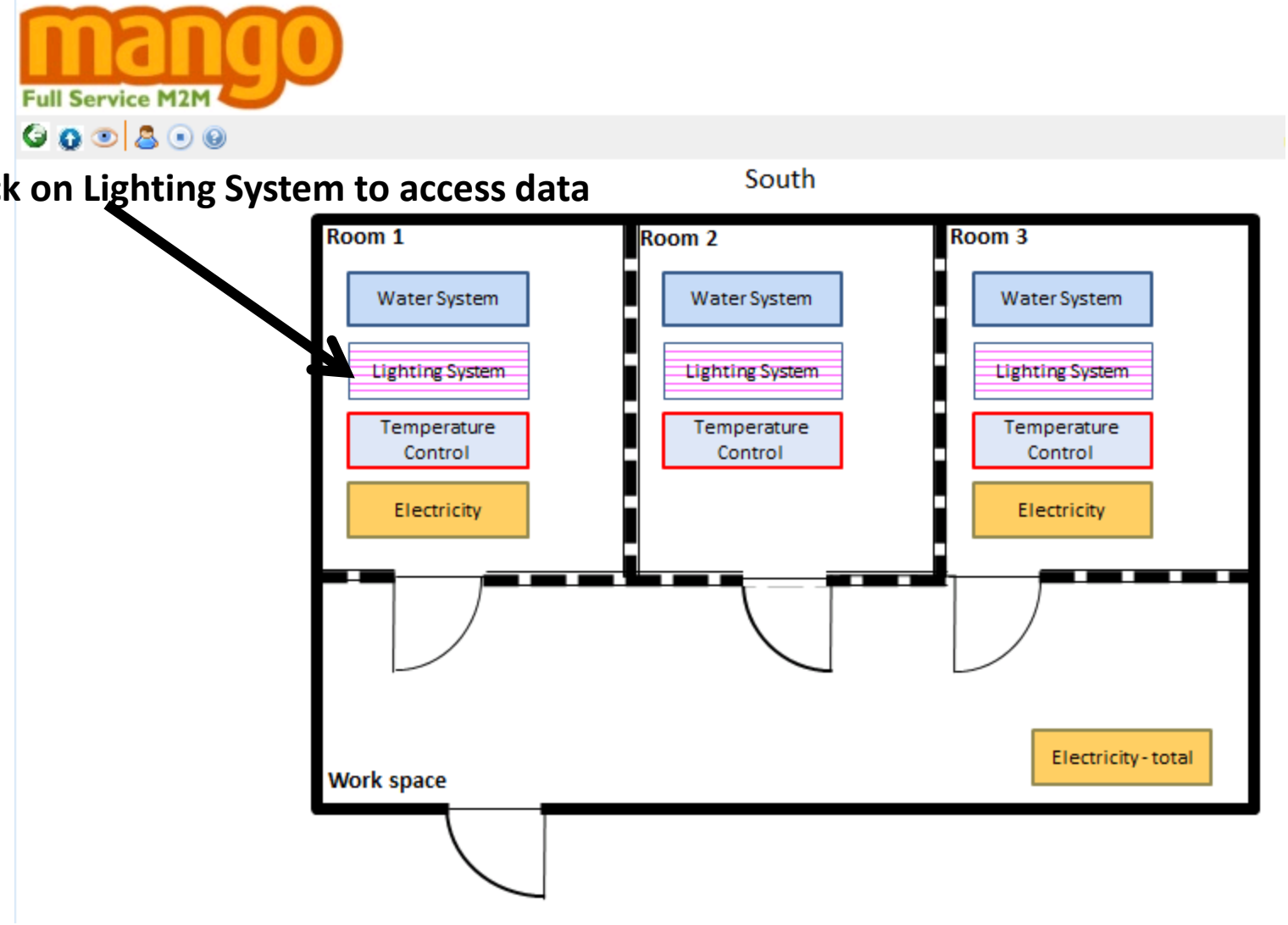
My Mango M2M

User: spowers

1. Click on Greenhouse to access data



2. Click on Lighting System to access data



Report templates

- GH RM 1 Electricity
- GH Rm 3 Electricity
- GH Rm 1 Light
- GH Rm 3 Light

Note:

Due to change in Sensor placement within the GH:

1. For incoming solar intensity, "Light_window intensity "correct sensor until Sept. 2013. Use "Light intensity South" for access to these data after
2. Electric power sensor was switched. Electric power data and sensor labeled "Rm 1" provides data until Oct. 7, then "Rm 3" sensor correct thereafter.

4. Change Dates for each report you run

5. Run report

Report criteria

Report name GH Rm 3 Light

Points

Point name	Data type	Colour	Consolidated char
GH - 3_Light_1IND	Binary		☐
GH - 3_Light_2IND	Binary		☐
GH - 3_Light_3IND	Binary		☐
GH - 3_Light_4IND	Binary		☐
GH - 3_Light_5IND	Binary		☐
GH - 3_Light_6IND	Binary		☐
GH - 3_Light_7IND	Binary		☐
GH - 3_Light_8IND	Binary		☐
GH - 3_Light_9IND	Binary		☐
GH - 3_Light_10IND	Binary		☐
GH - 3_Light_11IND	Binary		☐
GH - 3_Light_12IND	Binary		☐
GH - 3_Light_LLINT	Numeric		☑
GH - 3_Light_LLPPF	Numeric		☑
GH - Light-Intensity-South	Numeric		☑
GH - 3_Light_ULPPF	Numeric		☑
GH - 3_Light_windowINT	Numeric		☑
power - GH-Energy -Rm 3 (kWh)	Numeric		☐
power - GH-Power - Rm 3 (W)	Numeric		☐
power - GH-Power - Rm1 (W)	Numeric		☑
power - GH-Energy - Rm1 (kWh)	Numeric		☑

Date range

○ Relative to report time

○ Previous 1 day(s)

◉ Past 1 day(s)

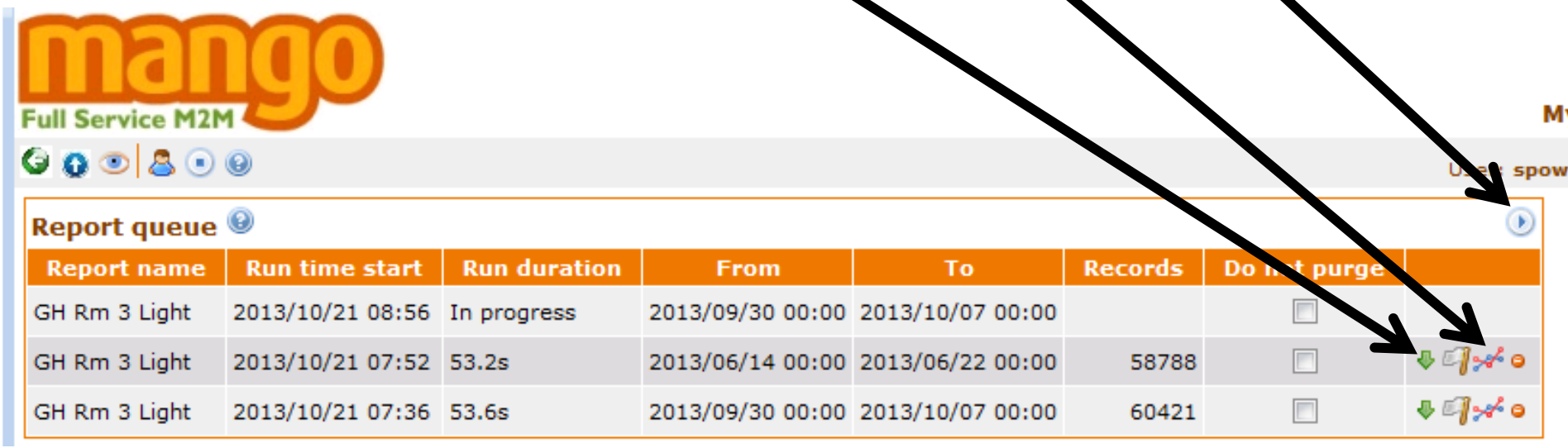
◉ Specific dates

	year	month	day	hour	minute	
From	2013	Sep	30	00	00	☐ Inception
To	2013	Oct	07	00	00	☐ Latest

6. Mango requires you to refresh the page before the report is completed
(~1 min after report button clicked)

7. Review the report graphics

8. Download report values for use in Excel for further analysis



GH - 3_Light_6IND

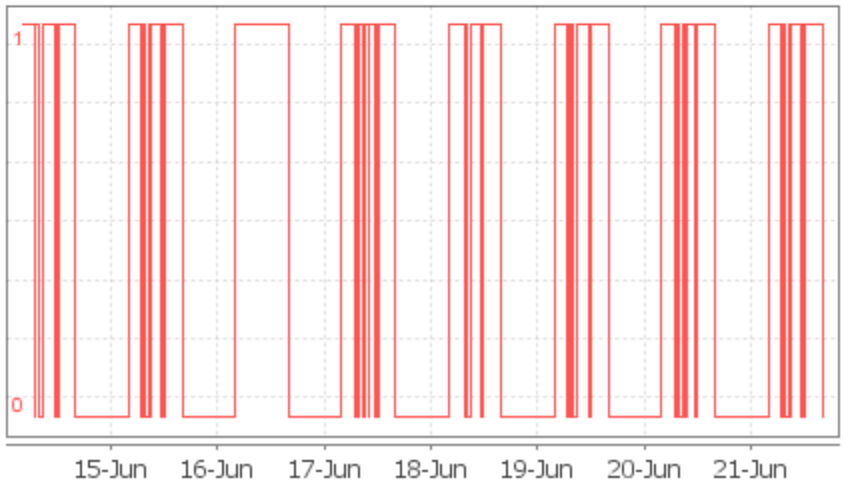
Data type Binary
Start 0

Value	Starts	Runtime
0	15	50.3%
1	15	49.7%

GH - 3_Light_7IND

Data type Binary
Start 0

Value	Starts	Runtime
0	119	54.5%
1	119	45.5%



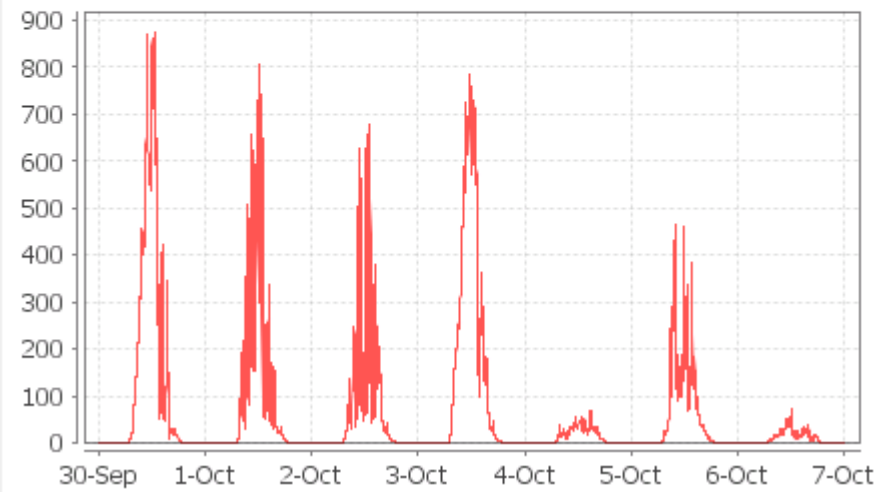
Light strips On or OFF

light strips on X 72 W/strip = electric power for each time step (W)

∑ power each time interval X Δt = daily energy consumed (Wh)

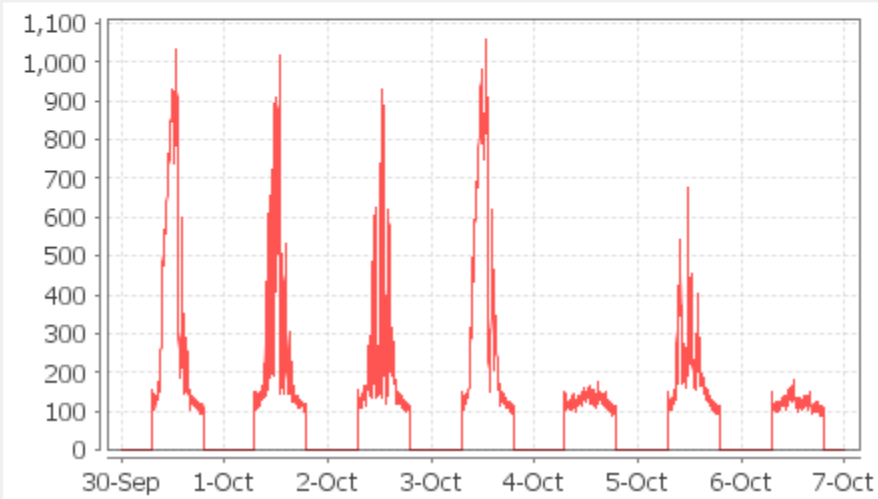
GH - Light-Intensity-South

Data type	Numeric
Start	0.0
Minimum	0.0 @ 2013/09/30 00:00
Maximum	875.0528333333332 @ 2013/09/30 12:32
Average	70.96014205523628
Sum	715298.1286712629
Count	10081



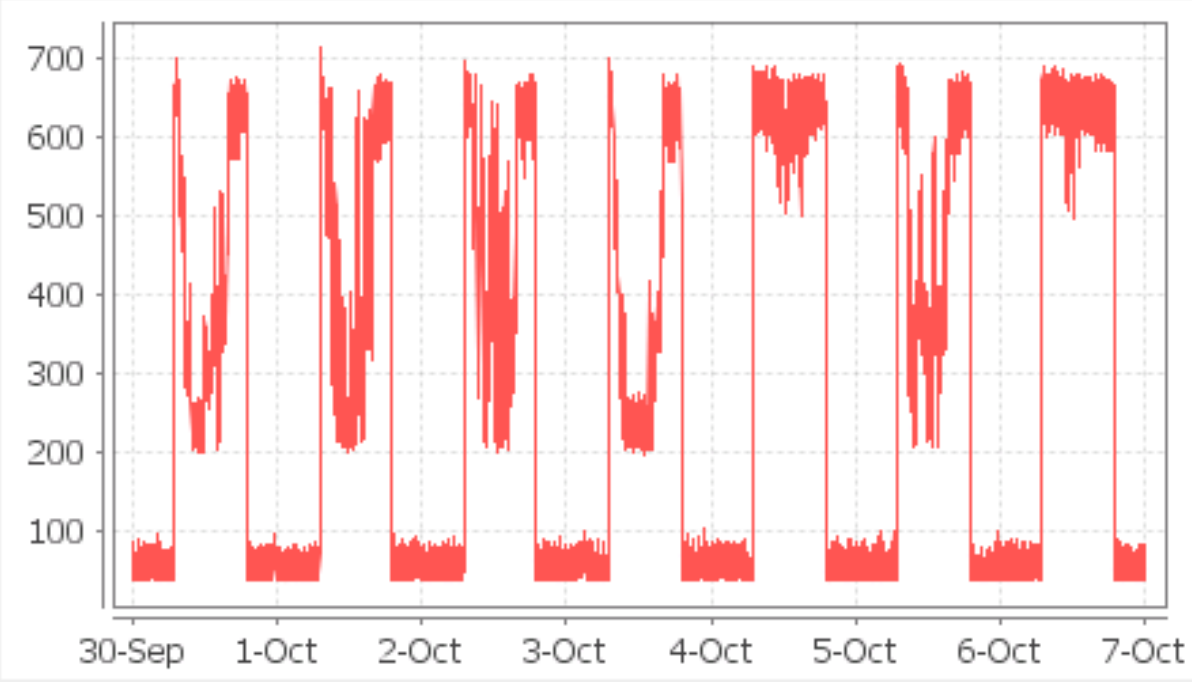
GH - 3_Light_LLPPF

Data type	Numeric
Start	0.0
Minimum	0.0 @ 2013/09/30 00:00
Maximum	1060.0453333333332 @ 2013/10/03 12:45
Average	119.20196666216295
Sum	1201536.9549302722
Count	10080



Rm 3 data – Power (W)

Data type	Numeric
Start	38.0
Minimum	31.0 @ 2013/10/05 19:00
Maximum	772.0 @ 2013/10/05 07:03
Average	279.0095511606587
Sum	1.6911529E7
Count	51697



Data collected from Mango describing light system in the Greenhouse Sept 30 - Oct 4, 2013 (not - data file too large to collect an entire week)													
downloaded and "massaged" 10/21/13, S. Powers									power per light strip	72	W		
Date	Time	GH - 3_Light_1 IND	GH - 3_Light_2 IND	GH - 3_Light_L LINT (W/m2)	GH - 3_Light_LLPP F (umol/m2/s)	GH - Light-Intensity-South (W/m2)	GH-Power - Rm3 (W)		day-time	# lights on	time step (h)	electric energy - lights (Wh)	total electric energy (Wh)
9/30/2013	0:00:24	0	0	0	0	0	37		9/30/2013 0:00	0			
9/30/2013	0:00:27	0	0	0	0	0	37		9/30/2013 0:00	0	0.0008333	0.0000	0.030833
9/30/2013	0:00:31	0	0	0	0	0	37		9/30/2013 0:00	0	0.0011111	0.0000	0.041111
9/30/2013	0:00:35	0	0	0	0	0	37		9/30/2013 0:00	0	0.0011111	0.0000	0.041111
9/30/2013	0:00:39	0	0	0	0	0	37		9/30/2013 0:00	0	0.0011111	0.0000	0.041111
9/30/2013	0:00:48	0	0	0	0	0	83		9/30/2013 0:00	0	0.0025000	0.0000	0.2075
9/30/2013	0:00:53	0	0	0	0	0	87		9/30/2013 0:00	0	0.0013889	0.0000	0.120833
9/30/2013	0:00:58	0	0	0	0	0	88		9/30/2013 0:00	0	0.0013889	0.0000	0.122222
9/30/2013	0:01:08	0	0	0	0	0	105		9/30/2013 0:01	0	0.0027778	0.0000	0.291667
9/30/2013	0:01:13	0	0	0	0	0	119		9/30/2013 0:01	0	0.0013889	0.0000	0.165278
9/30/2013	0:01:18	0	0	0	0	0	69		9/30/2013 0:01	0	0.0013889	0.0000	0.095833
9/30/2013	0:01:23	0	0	0	0	0	50		9/30/2013 0:01	0	0.0013889	0.0000	0.069444

Downloaded data (w/more columns)

Calculations

65,541 rows of data

Day	daily electricity Use - lights	electricity if lights on 12 h	energy saved
	kWh/d	kWh/d	kWh/d
9/30/2013	6.81	10.37	3.56
10/1/2013	7.13	10.37	3.24
10/2/2013	7.45	10.37	2.92
10/3/2013	6.18	10.37	4.18
4-d average	6.89	10.37	3.47
annual*	2516	3784	1268
cost /y**	**$ 252**	**$ 378**	**$ 127**
% savings			**33.5%**
* assume 4-d average can be extrapolated to 365 days/y			
** assume electricity costs $0.10/kWh			

Turning off lights in daytime could save $127 for each room in the greenhouse (if extrapolation to the year is reasonable). This is approximately 33% savings of the light energy/cost versus if all lights on for 12 h/d

(33%=(electricity used if all on for 12 hours – actual electricity used)/ electricity used if all on for 12 hours)

So Far

- CLICS project has been integrated into 12 classes reaching 660 students over the past three semesters
  - Introduction to Statistics class accounts for 37% of the total student number
- Nearly 75% of all students strongly agreed/agreed that the overall experience of using campus data was positive and recommended that CLICS should be used in other classes.

Instruments/Methodology

Student Questionnaire

- Measures:
  - Sustainability Literacy (pre vs. post)
  - STEM Self-efficacy (pre vs. post)
  - Overall satisfaction with use of real-world data in assignments/projects (post-only)
- Administration:
  - Anonymous via SurveyMonkey
  - Coded to match pre and post responses

Rubric Review of Selected Projects/Assignment

- Measures:
  - Critical Thinking
  - Communication Administration:
  - Random selection(10 or 10% of projects)
  - 2 reviewer team

Faculty Questionnaire

- Measures:
  - Efficacy of the interface
  - Student engagement in course content
  - Impact on content mastery
  - Instructor support
- Administration:
  - Anonymous via SurveyMonkey
  - Post only

Focus Group Discussion

- Direct input
- Open ended
- Critical to process

Highlights from 2014 Administration

- Sustainability Literacy- 69 questions
  - Knowledge (46), Affect (12), Behavior (9), level of concern (12)
  - Overall, students had higher scores on affect and self-efficacy subscales than on knowledge or behavior
  - Students scored highest on knowledge questions about systems concepts, which are highly 'affective' in character (understanding the impact of our actions on other people and the environment)
  - In general, students do NOT feel they know a lot about sustainability (11.6% agree/strongly agree)

- STEM- related Self-Efficacy – 8 questions
  - increased skills at data retrieval (64% agree/strongly agree)
  - stimulated my thinking (65% agree/strongly agree)
  - made me better able to visually present data effectively (58% agree/strongly agree)
  - enhanced my understanding of course content/concepts (58% agree/strongly agree)

- Overall Satisfaction 19 questions +1 open ended
  - 72% agreed/strongly agreed that “Using data made the assignment more relevant for me”
  - 76% of the students agreed/strongly agreed that the data were overall useful
- Faculty Survey- 24 questions +1 open ended
- Focus Group Discussion
  - Consensus that use of real world data had value
  - Consensus was that faculty would use real world data again

Conclusions

Campus digester/greenhouse/energy cabin system

- Provides research platform to study individual systems and integrated system
- Diverts food waste from solid waste stream saving revenue
- Provides real-life data for class room instruction improving students appreciation of sustainability efforts and engagement in STEM subjects.
- Significantly contributes to sustainability effort of the university.

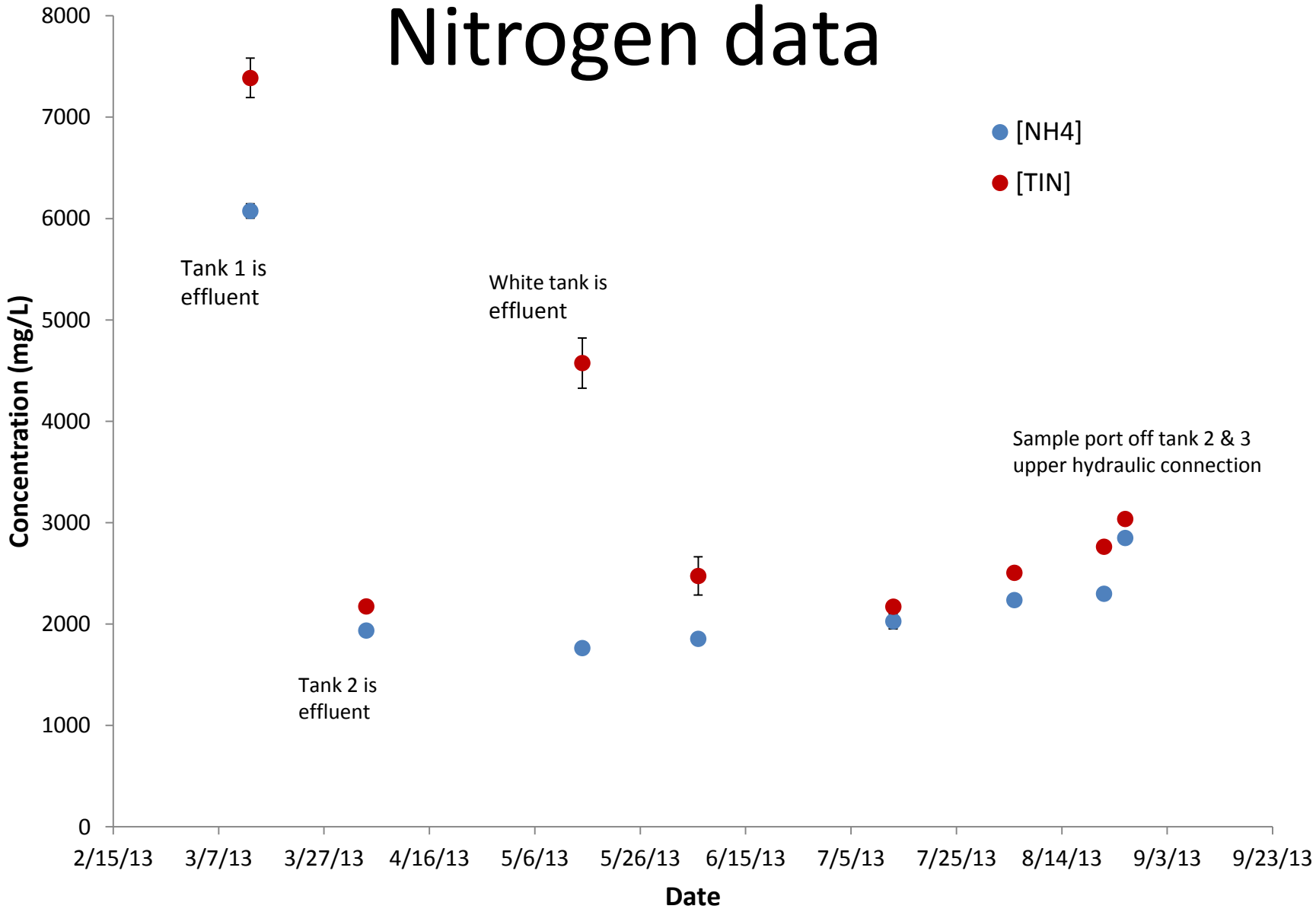

FEED ME
Anaerobic Digester
COMING SOON:
Separate your food waste from your trash
to feed the anaerobic digester!
Institute for a Sustainable Environment
ISE
at Clarkson University

Questions/Comments?

Thank you for listening!

Student research on Ammonia Inhibition of AD

Nitrogen data



More nutrient data on dropbox: Dropbox\Green House Data\Digester\Nutrient Data

Toxicity: Ammonia

- Major toxicant in full-scale anaerobic digesters
- Produced through the biological breakdown of nitrogenous matter
  - Beneficial at <200 mg/L[6]
- Free Ammonia (NH_3) is known to be the most toxic form[6,7,8]
- FA increases with increasing pH

$$NH_4^+ \longleftrightarrow NH_3 + H^+$$

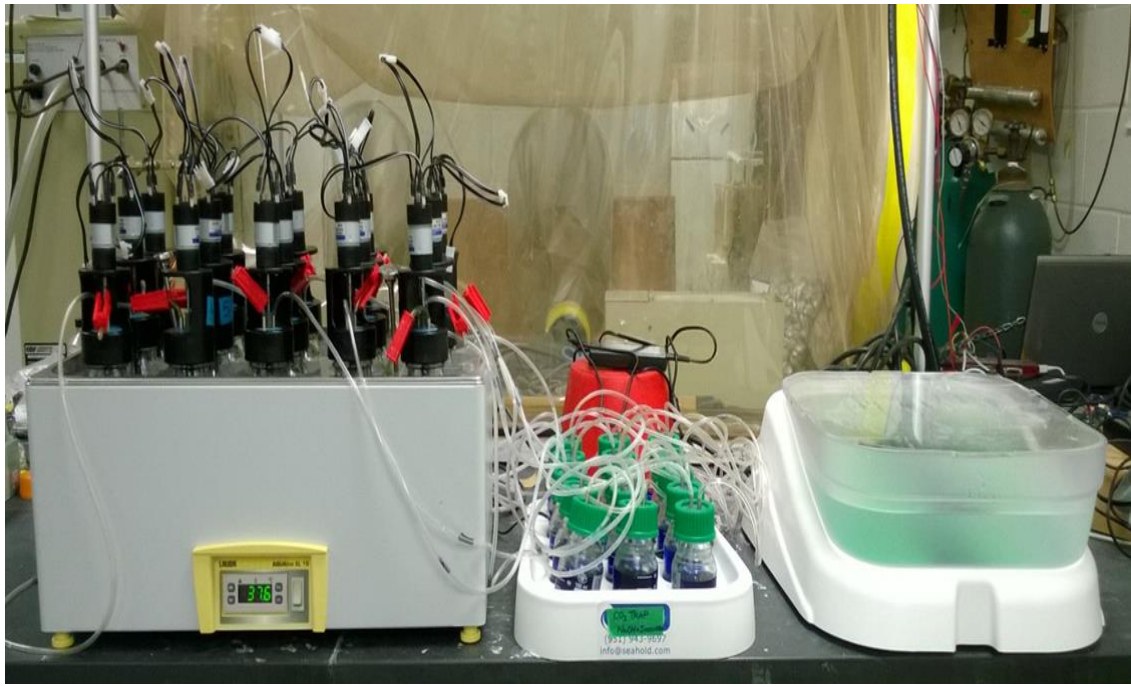
- Concentration at which ammonia is inhibitory remains uncertain

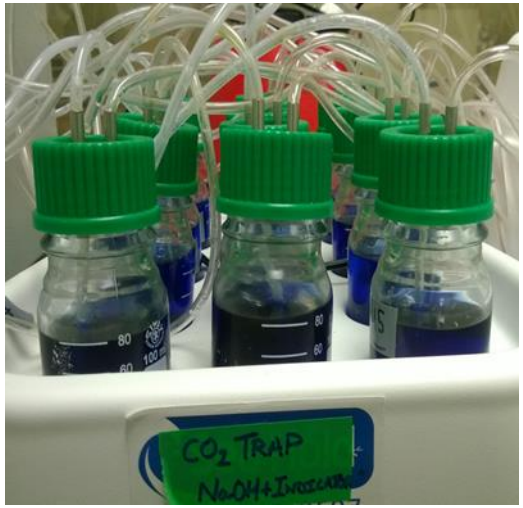
  0.088 g/L to 14g/L

The Project: Methods

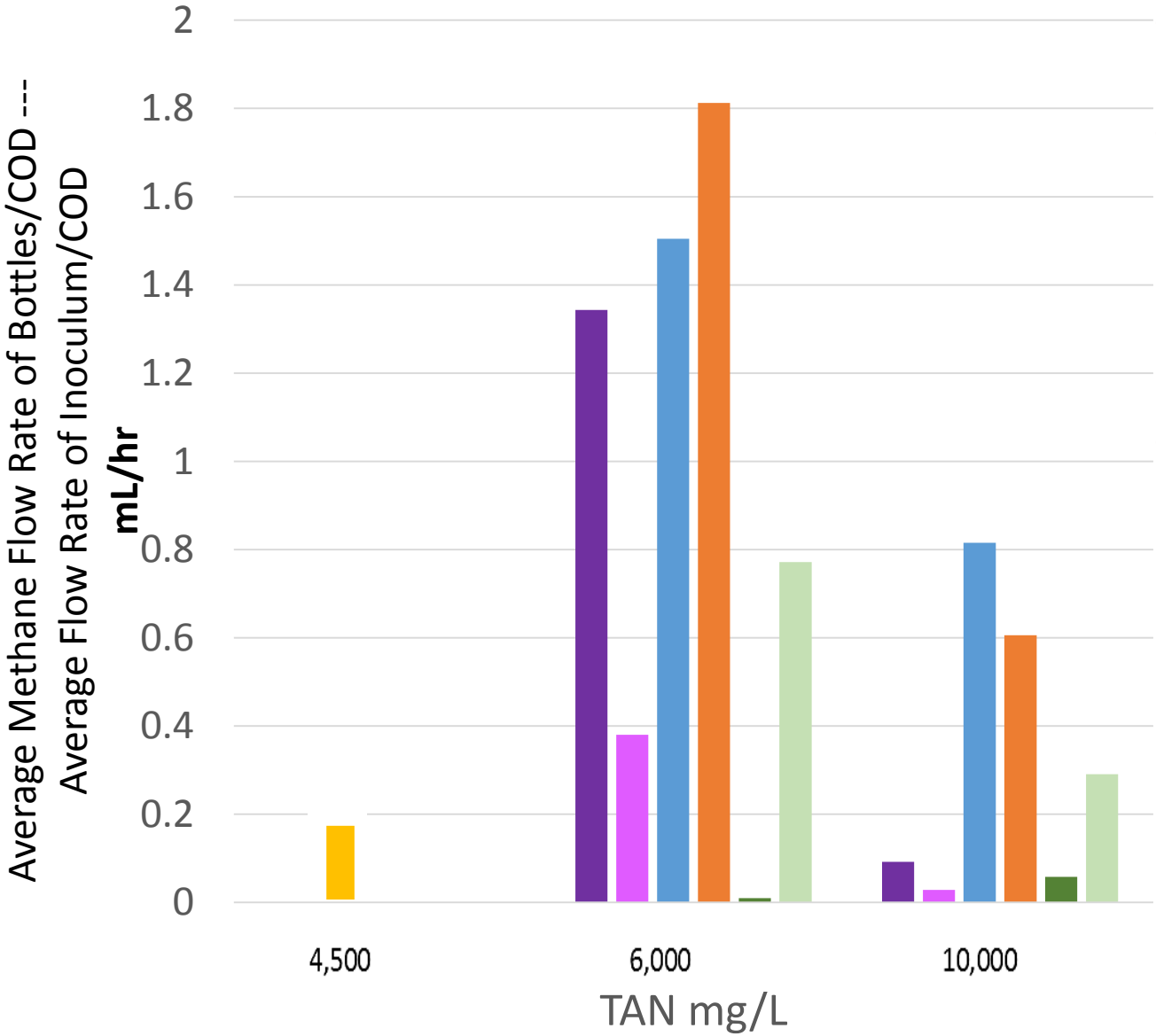
Experimental Set Up

- 500 mL reactors operated under mesophilic conditions (35-37 °C) at varying ammonia levels
- Ammonia added in the form of NH4Cl
- Methane measured using the AMPTS II Bio Methane Potential Instrument
- VS/TS, COD, and NH3-N
- pH ≈ 7.0-8.0
- Inhibition determined by methane production rate and biogas volume
- Ammonia Inhibition Constant determined graphically using Monod Kinetics





Average Rate of Methane Production Normalized by Initial COD



	COD mg/L	[NH3-N] mg/L
Greens	46,288	
Meats	679,690	
Manure	48,752	
Heterogeneous Food Waste	198,939	

Monod Kinetics

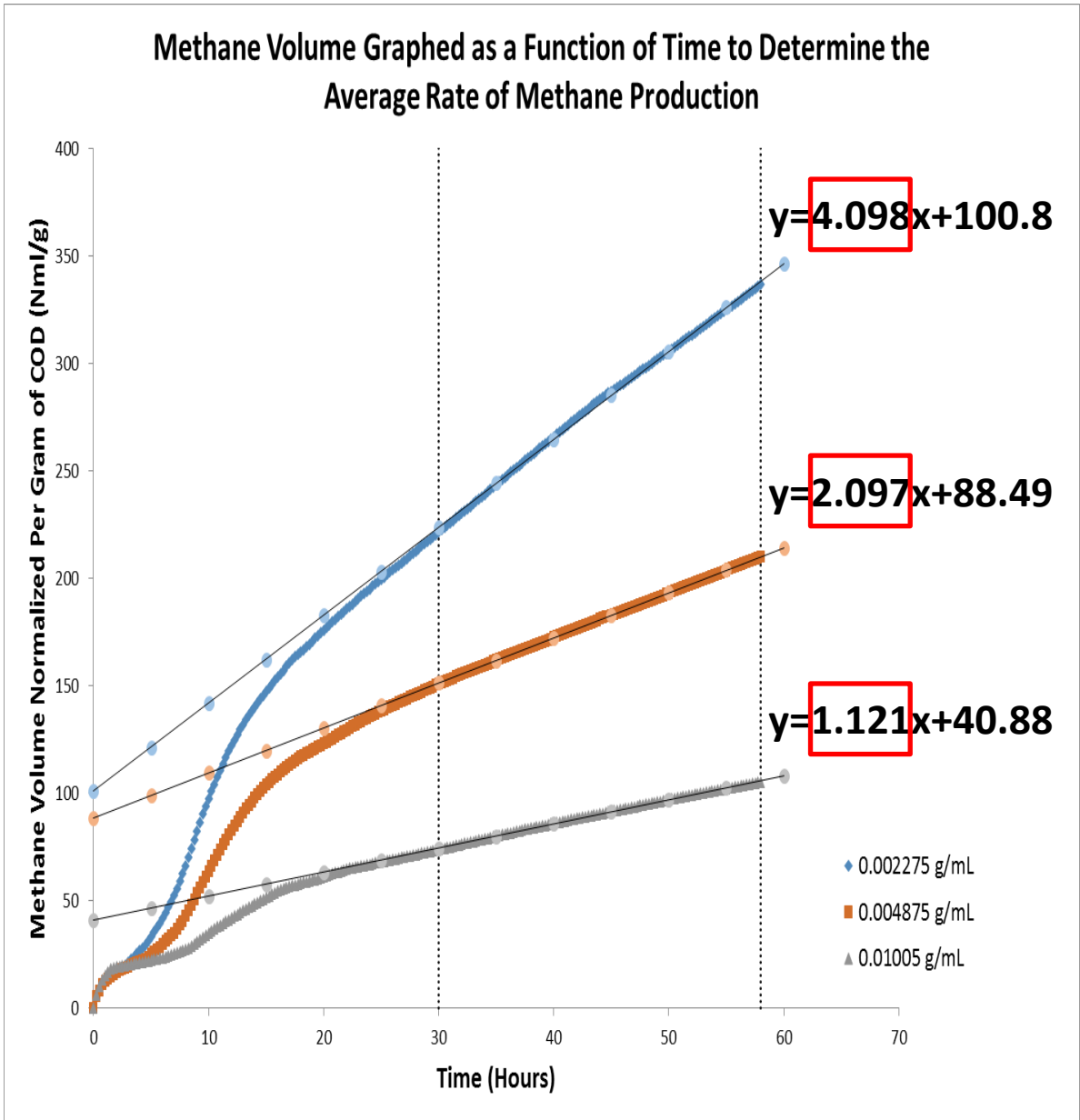
- Common microbiological model to evaluate the biodegradation process[9]
- Describes microbial growth kinetics[10]
- Equation adapted from Monod Kinetic Growth Model

➢ $q_{CH_4} = -\frac{1}{C} \cdot \frac{k_m S}{K_s + S} X \cdot \frac{1}{1+\frac{S_I}{K_I}}$

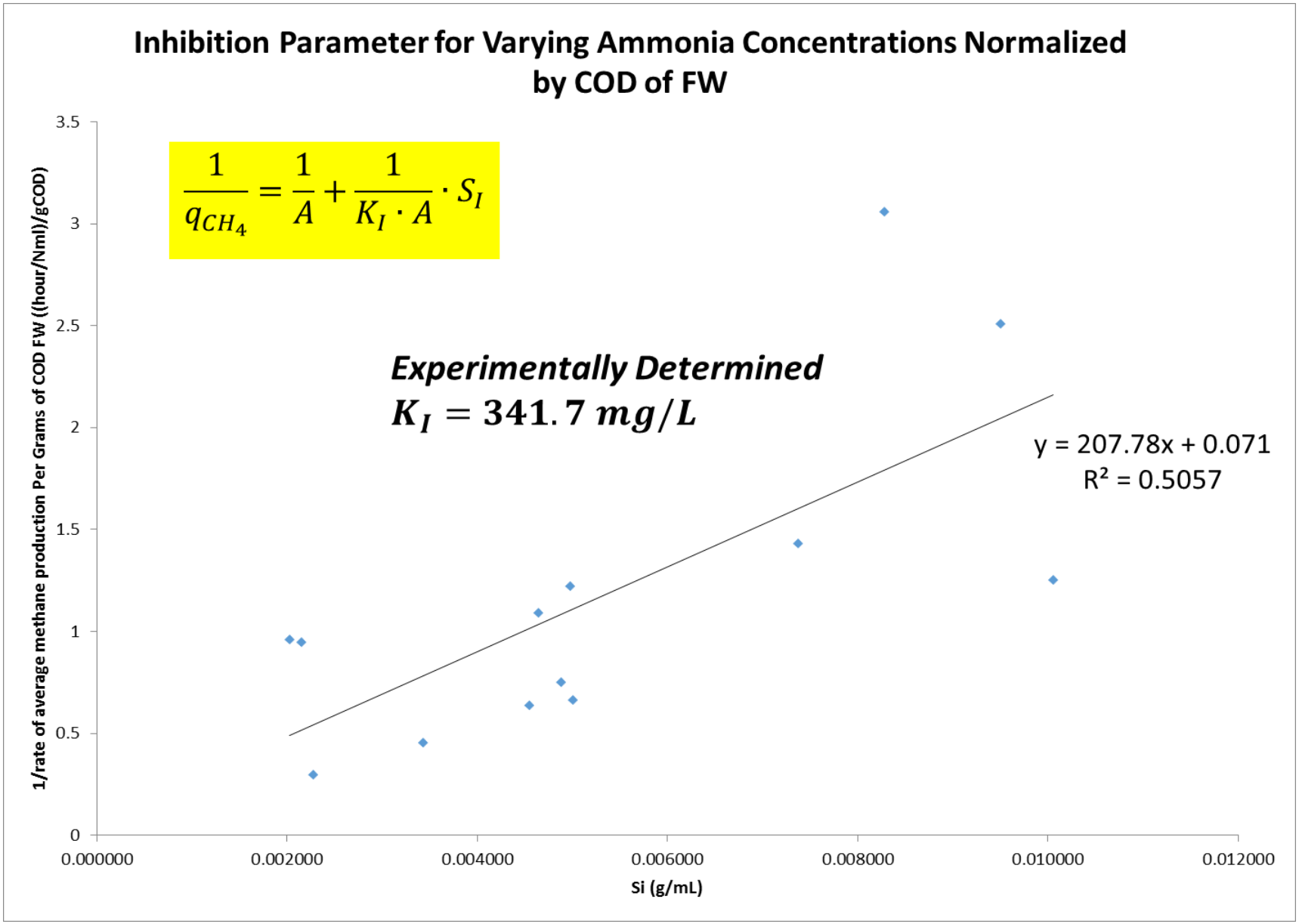
➢ S_I -ammonia concentration

➢ K_I -inhibition parameter of ammonia

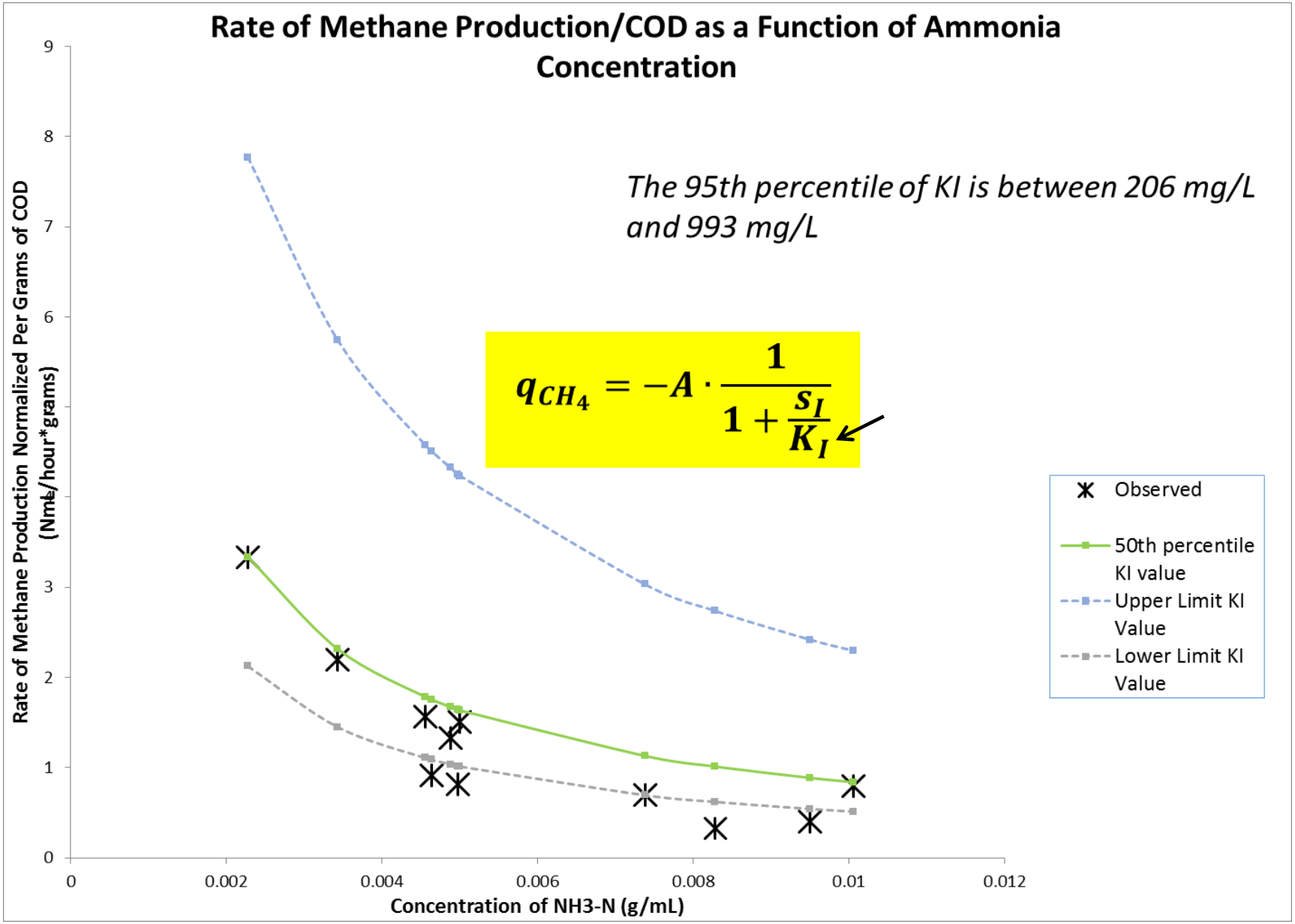
- $q_{CH_4} = -A \cdot \frac{1}{1+\frac{S_I}{K_I}}$



Results


Inhibition Parameter for Varying Ammonia Concentrations Normalized by COD of FW
$$\frac{1}{q_{CH_4}} = \frac{1}{A} + \frac{1}{K_I \cdot A} \cdot S_I$$
Experimentally Determined
$K_I = 341.7\ mg/L$
y = 207.78x + 0.071
R² = 0.5057
1/rate of average methane production Per Grams of COD FW ((hour/Nml)/gCOD)
Si (g/mL)
0
0.5
1
1.5
2
2.5
3
3.5
0.000000
0.002000
0.004000
0.006000
0.008000
0.010000
0.012000

Model of the Inhibitory Effects of Ammonia



Literature Comparison

K_I Values Manure/ Animal Waste	K_I Values OFMSW	K_I Value Clarkson's Kitchen Waste
• 4 mg/L NH3-N • 213.3 mg/L NH3-N • 1600 mg/L NH3-N • 1450 mg/L NH3-N	• 215 mg/L NH3-N • 98.7 mg/L NH3-N • **88.0 mg/L NH3-N** • 180.9 - 230.3 mg/L NH3-N • 158.4 - **395.4 mg/L NH3-N** • 161.9 - 219.8 mg/L NH3-N • 237.6 mg/L NH3-N	• 341 mg/L NH3-N

- Variance with linearizing the Monod model & the complexities of AD
- Research other mathematical models to better fit our data and more accurately determine the inhibition constant of ammonia

The 95th percentile of KI is between 206 mg/L and 993 mg/L