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Determining Conditions of Intermittently Fed Digesters from Biogas Production Rate Data

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Agenda

- Introduction
- Background
- Lab Scale Measurements
- Pilot Scale Measurements
- Data Analysis
- PID Controller for Simulations
- Limitations & Conclusions

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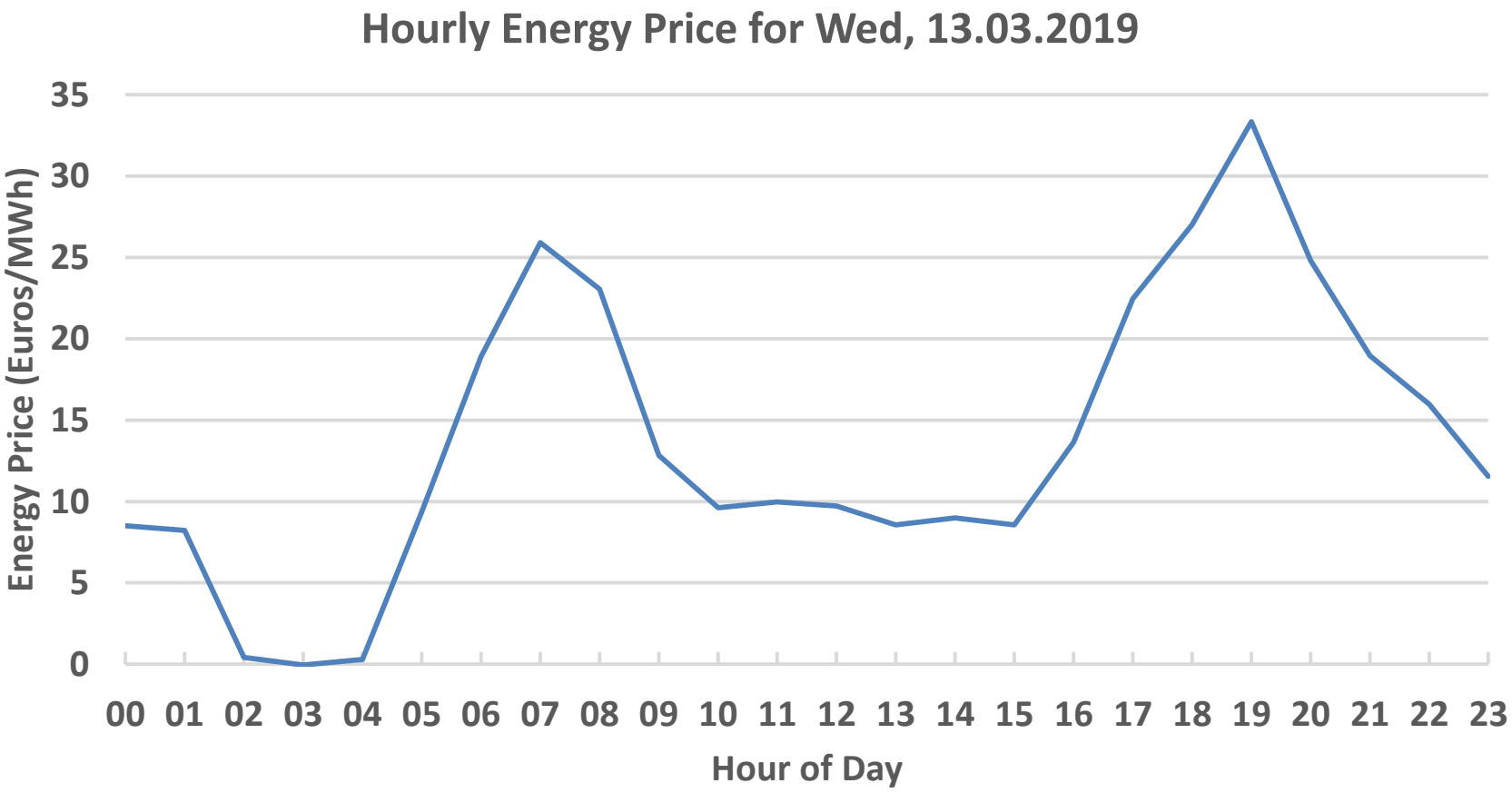
Introduction

- Changing requirements for subsidies
  - New regulations favour intermittent production, financial supplement for flexibility [1].
- Without subsidies, on-demand production can earn more money.
  - Electricity from Solar & Wind power are intermittent.
  - Demand is also intermittent.
  - Higher percentage of renewables leads to larger gap between generation & demand.
  - Larger gap results in larger price difference.
- Intermittent feeding can supplement available gas storage [2].

[1] German Federal Ministry for Economic Affairs and Energy, *Erneuerbare-Energien-Gesetz: 2017*. 2017.
[2] E. Mauky, H. F. Jacobi, J. Liebetrau, and M. Nelles, "Flexible biogas production for demand-driven energy supply - Feeding strategies and types of substrates.," *Bioresour. Technol.*, Sep. 2014.

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Time Variation of Energy Price



[3] "EPEX SPOT SE: European Electricity Index (ELIX) Chart." [Online]. Available: https://www.epexspot.com/en/market-data/elix/chart/index-chart/2019-03-13/. [Accessed: 13-Mar-2019].

Background - Gas transient response for optimisation

- Previous work by J. P. Steyer et al [4].
- Method for continuously fed systems.
- Principle is that as digester approaches inhibition, digester response to feeding events changes.
- Uses gas production rate.

[4] J. P. Steyer, P. Buffière, D. Rolland, and R. Moletta, "Advanced Control of Anaerobic Digestion Through Disturbances Monitoring," *Water Res*, vol. 33, no. 9, pp. 2059–2068, 1999.



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Transient response of the system

- Transient response as a parameter.
- No transients with continuous feeding.
- Requires a shift from continuous feeding
  - Daily feeding will happen in some sites as a result of shifts to on-demand energy production.
- Only need to measure total biogas production (optionally biogas composition)
  - Cheaper instrumentation with some basic analysis.
  - Often already installed.
- Response characteristics give info about system performance.
  - Response profile will be limited by slowest stage.
  - Slowest stage is what we need to consider when adjusting the feeding rate.

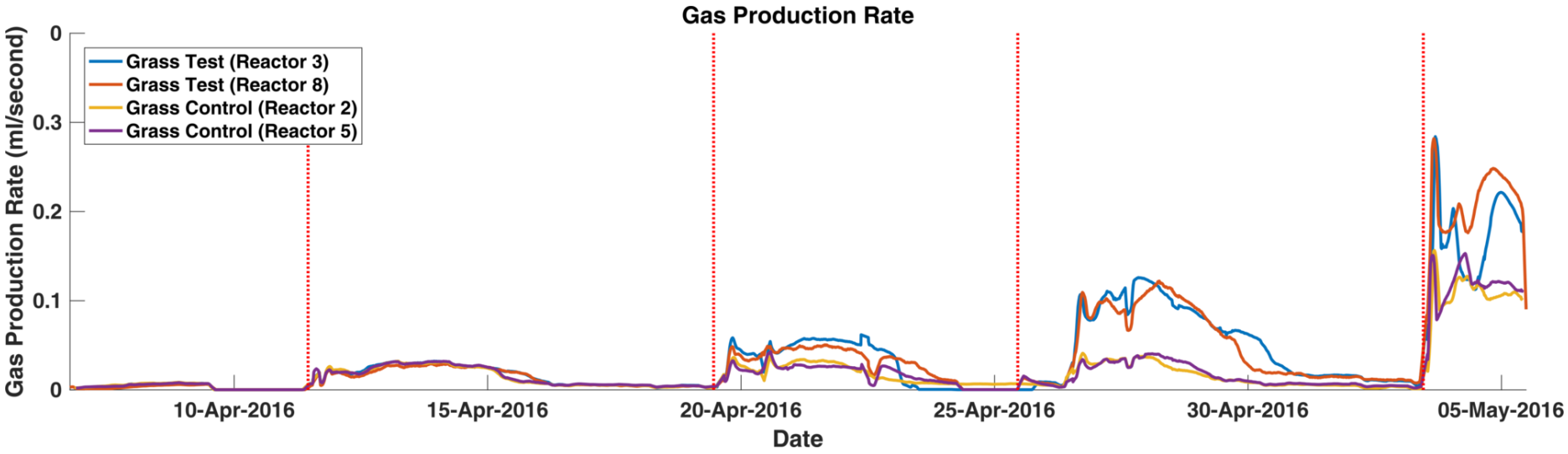
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Lab Scale Measurements



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Gas Production Rate



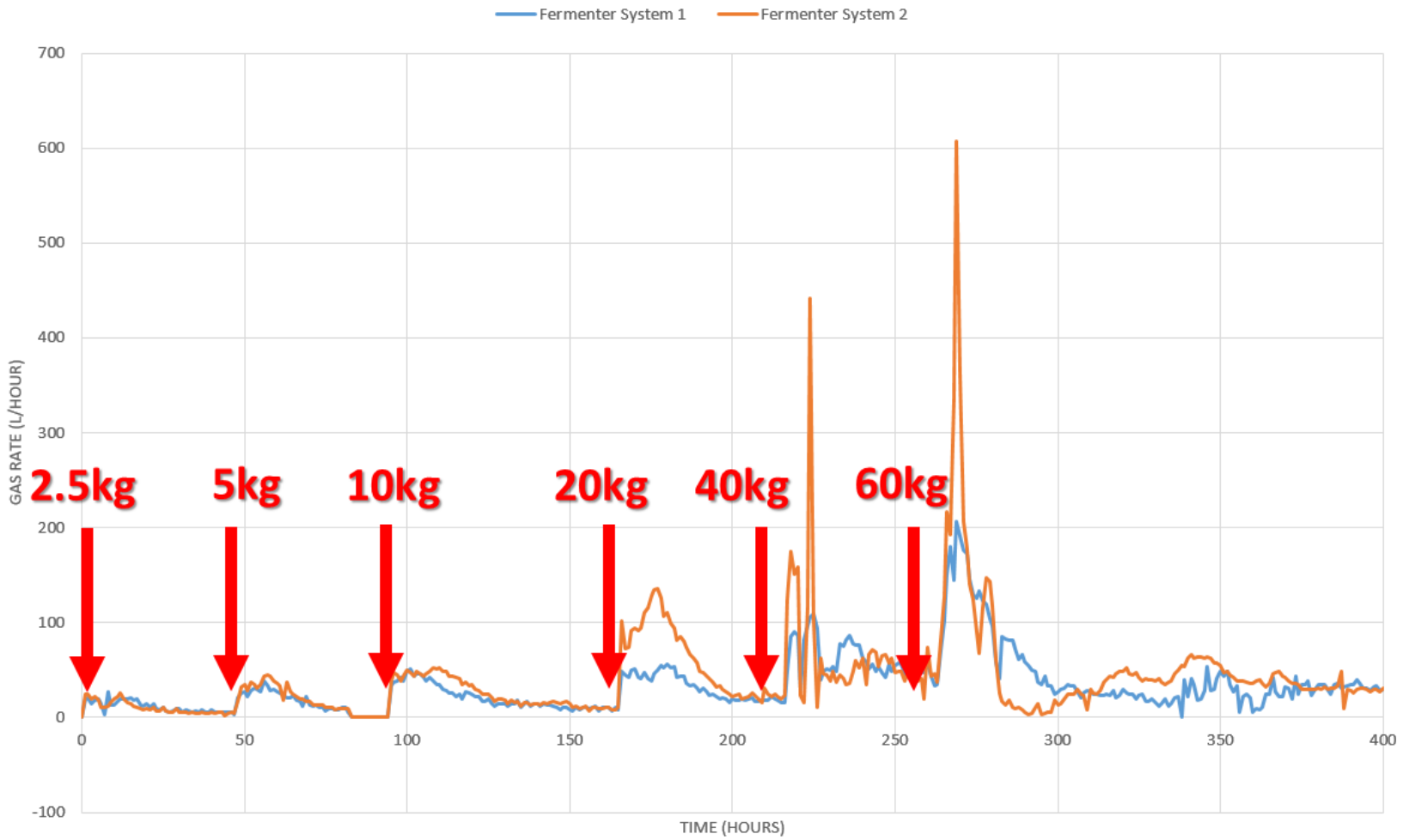
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Pilot Scale Plant Measurements



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Gas Production Rate – Pilot Plant Results



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Change to System Load Levels

- Response to feeding events changes as digesters are fed higher amounts and approach limit.
- Try to estimate how close we are to system capacity.

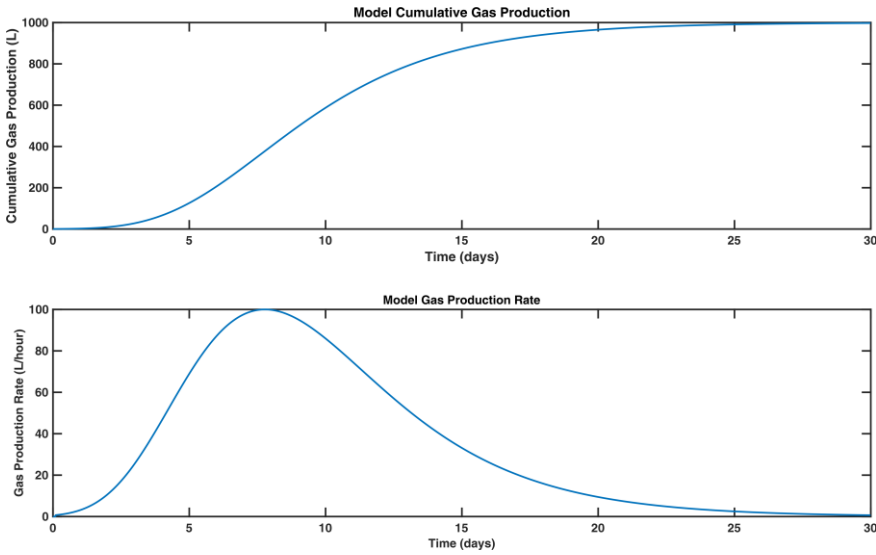
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Bio methane potential model

- Modified Gompertz model for biomethane potential [5]:

$$y = y_{max} \times exp\Big(- exp\big(U \times \frac{e}{y_{max}} \times (\lambda - t) + 1\big)\Big)$$

- *y*: cumulative amount of methane at time *t*.
- *y_max*: BMP.
- *U*: The maximum gas production rate
- lambda: The lag phase before the maximum rate is reached.
- *t*: The time at which the values are calculated.

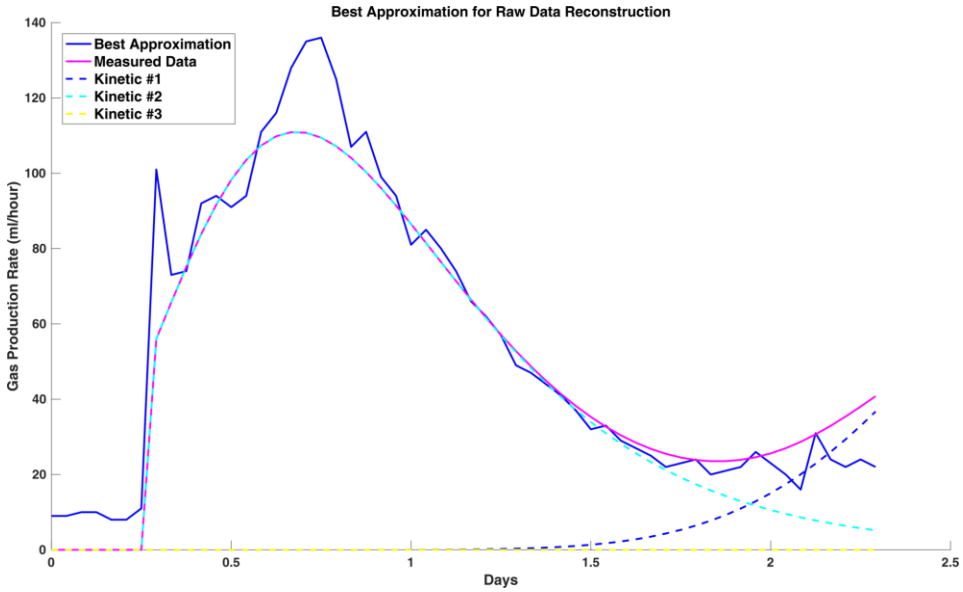


[5] D. M. Wall, P. O'Kiely, and J. D. Murphy, "The potential for biomethane from grass and slurry to satisfy renewable energy targets," *Bioresour. Technol.*, vol. 149, pp. 425–431, 2013.

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Curve Fitted With Genetic Algorithm

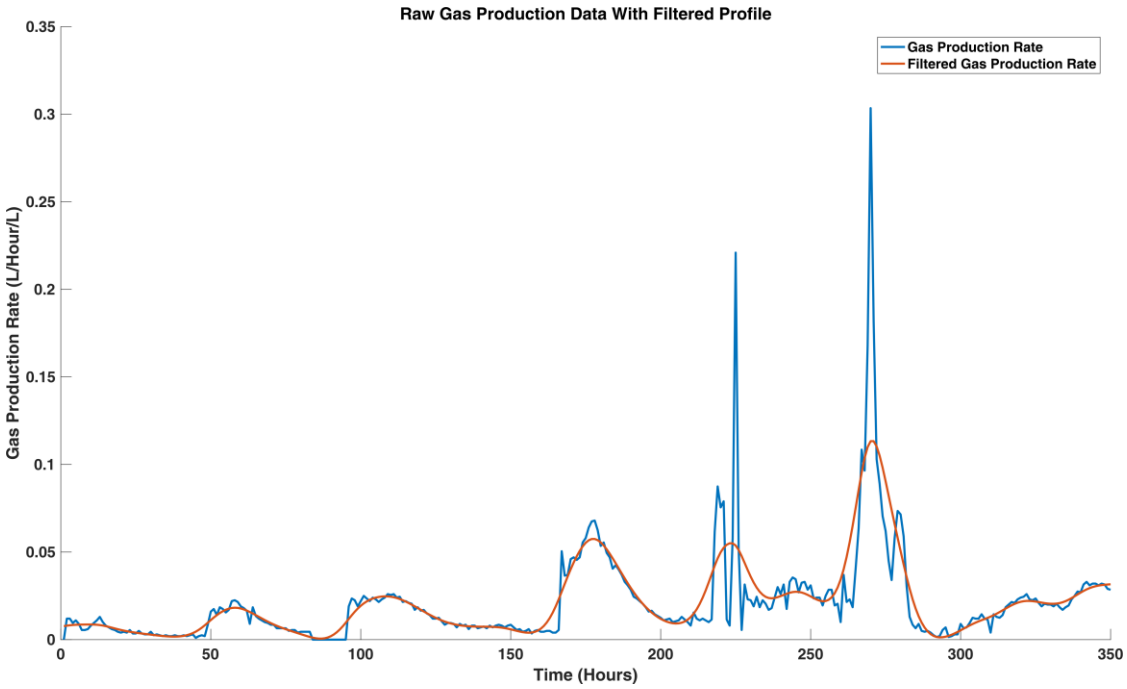
- Worked well in cases with no inhibition.
- Including inhibition became too computationally intensive.
- With inhibition present, GA solution similar to curve fitting.



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Simpler Curve Fitting

- Curve fitting with smoothing splines [6].
- Results very similar to GA approach.
- Matches raw data well when stable.
  - Differences when system is stressed.



[6] "Smoothing Splines - MATLAB & Simulink - MathWorks Deutschland." [Online]. Available: https://de.mathworks.com/help/curvefit/smoothing-splines.html. [Accessed: 17-Jun-2018].

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“Inhibition” metric

- Combination of scaled absolute error and R^2 gave good performance.
- R^2 value from previous 18 hours of data.
- “Hold-off” after high levels of inhibition can be adjusted.
- Estimates system stress level.
- Thresholds are defined per L of reactor volume.

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Scaling Absolute Error Value

$$se = \begin{cases} 0 & \text{if } |e| < L_{Thresh}, \\ \dfrac{|e| - L_{Thresh}}{U_{Thresh} - L_{Thresh}} & \text{if } L_{Thresh} \leq |e| < U_{Thresh}, \\ 1 & \text{if } |e| \geq U_{Thresh}. \end{cases}$$

- *e* = error between the raw value and the smoother fitted curve
- *se* = scaled error, the result of the calculation
- L_{Thresh} = 0.005, the lower threshold for the error in litres/hr/litre
- U_{Thresh} = 0.01, the upper threshold for the error in litres/hr/litre

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Combined Error and R^2

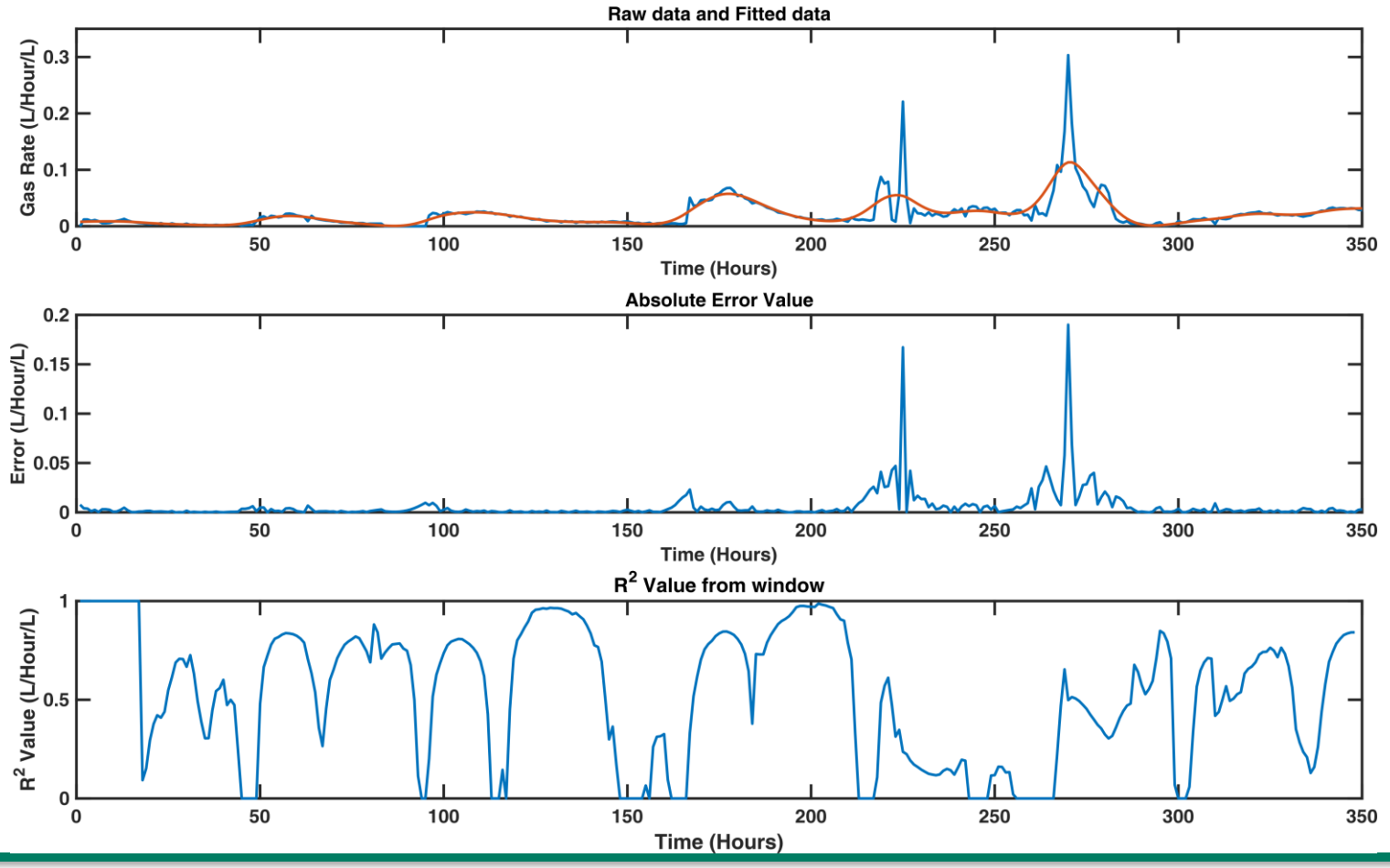
- High correlation when stable, so use $(1-R^2)$
- As both are scaled from 0-1, take the product

$$stress\ factor = (1 - R^2) \times scaled\ error$$

- Adjustable "Hold-off" factor – after high stress levels would want to wait before feeding.

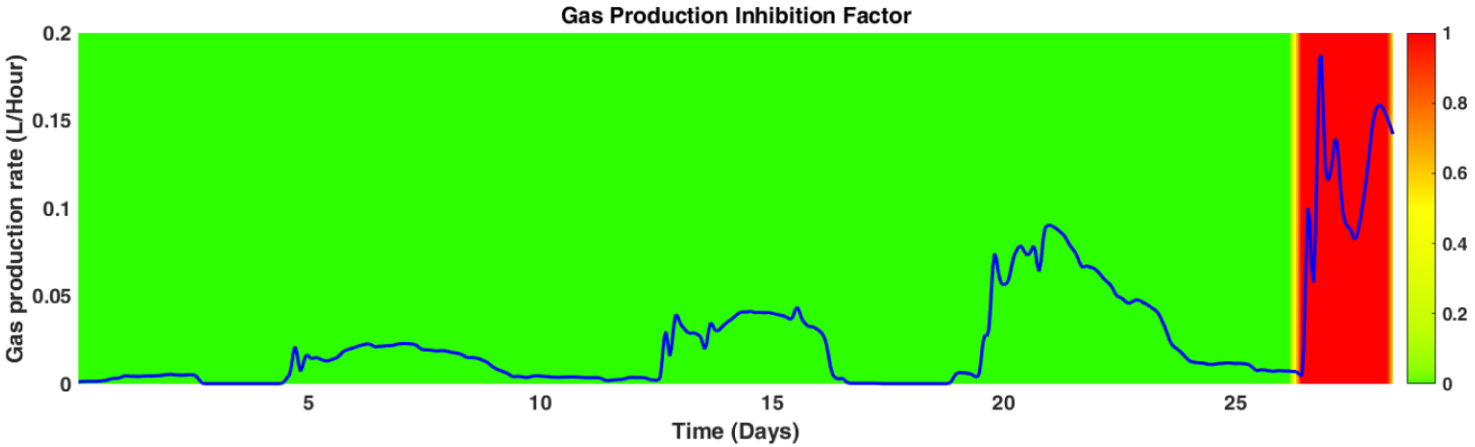
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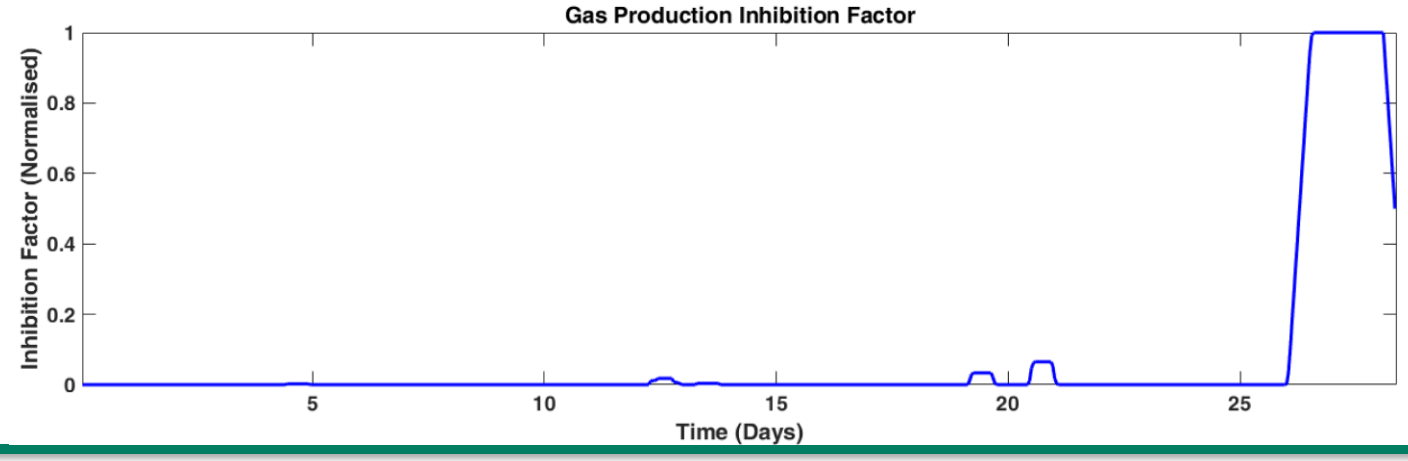
Curve Fitting Statistics



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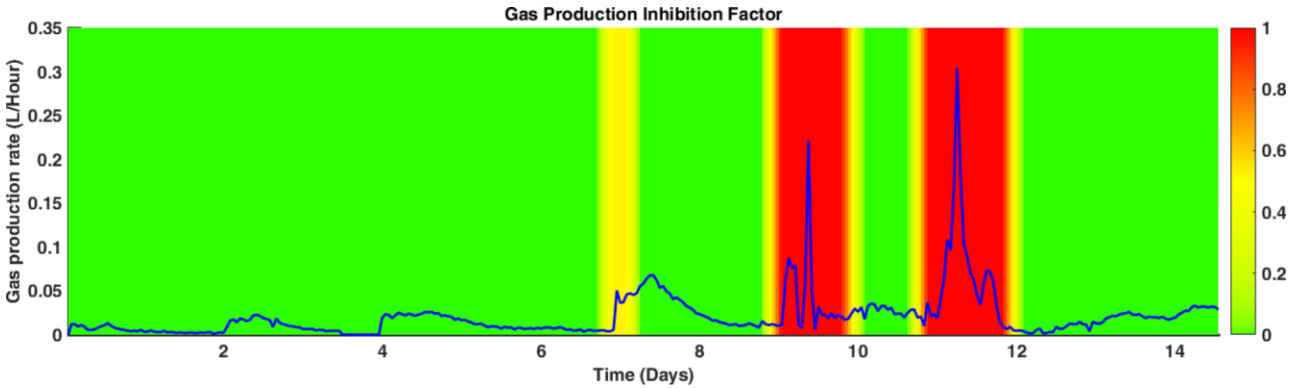
Calculated Inhibition – Milled Grass fed 5L CSTR

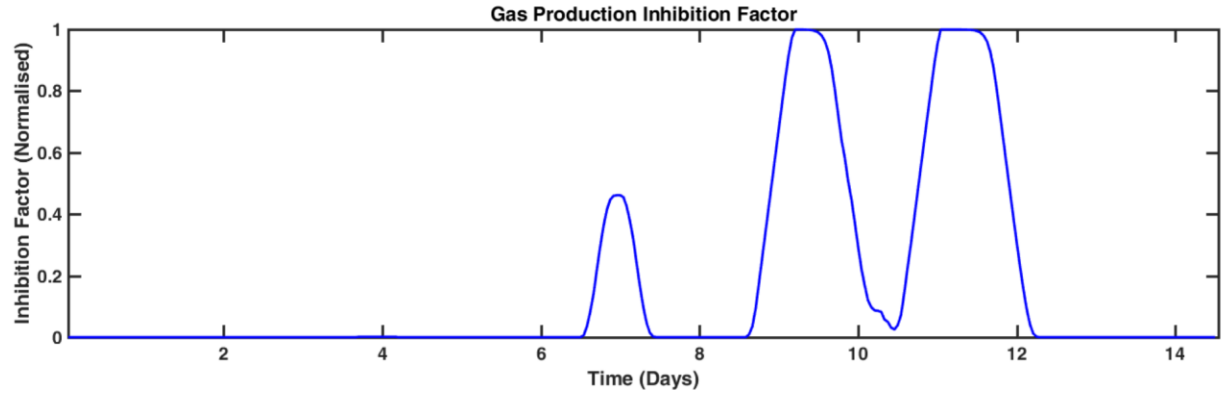




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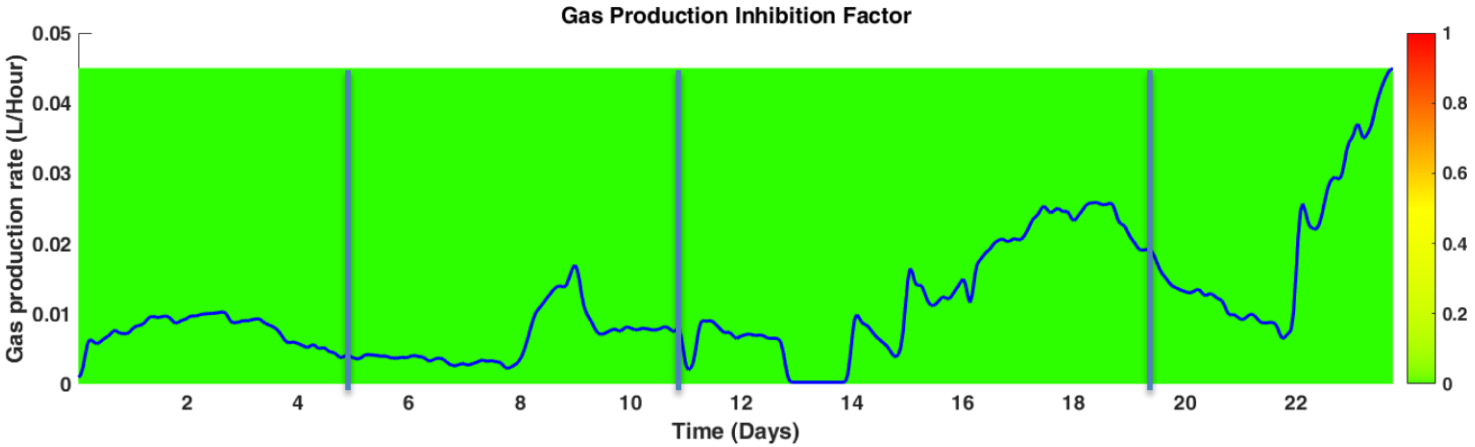
Gas Production Rate – Pilot Plant Results

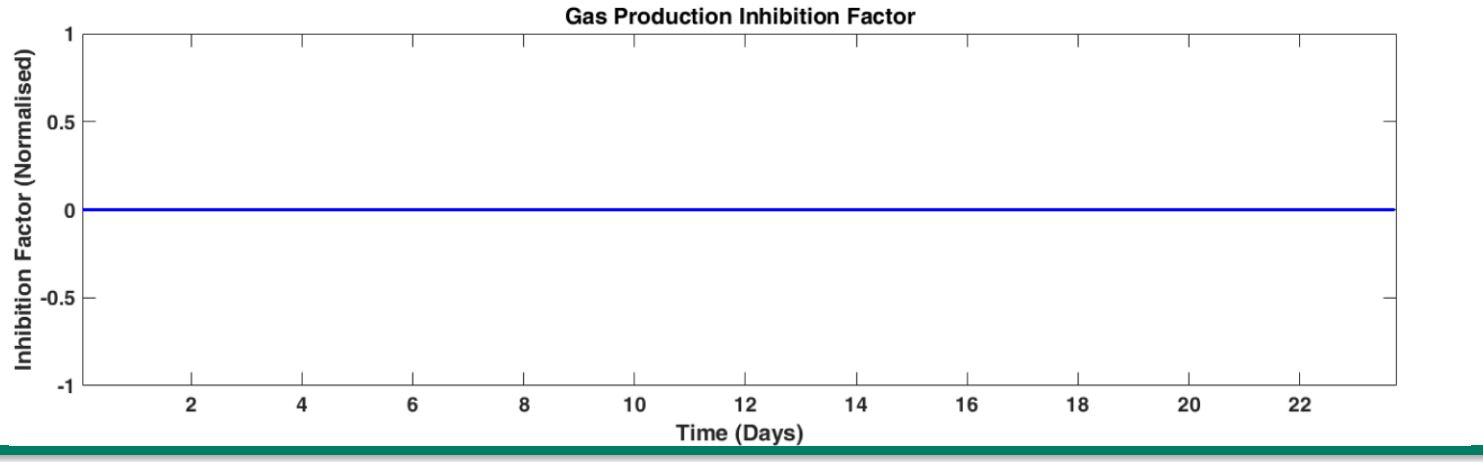




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Calculated Inhibition – Cattle Slurry fed 5L CSTR

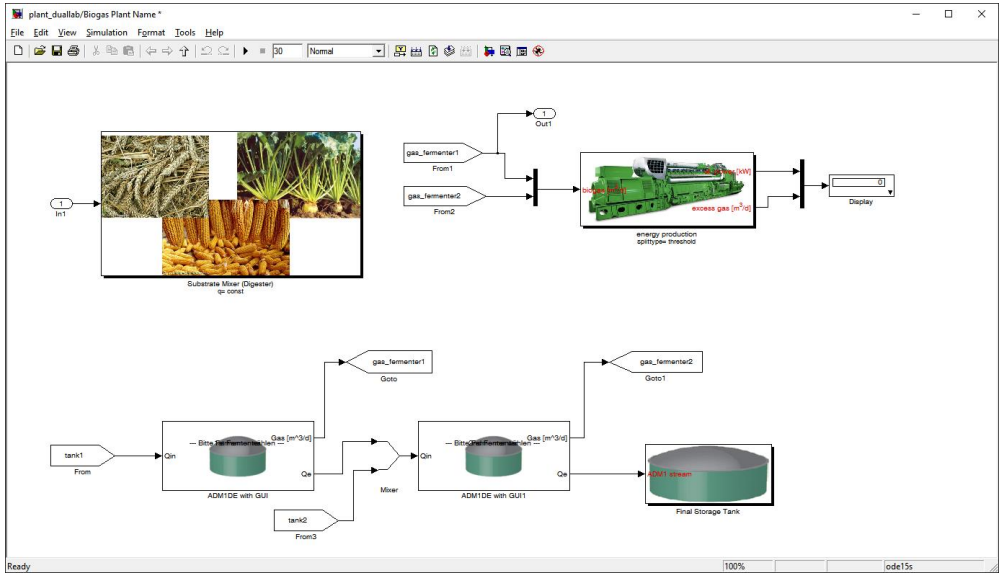




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Long Term Simulation

- Ran on ADM1 [6] toolbox for Matlab® created by Daniel Gaida [7].
- Tuned parameters so simulation outputs matched tests.
- Simulated 1000L plant.



[6] D. J. Batstone, J. Keller, I. Angelidaki, S. V Kalyuzhnyi, S. G. Pavlostathis, A. Rozzi, W. T. M. Sanders, H. Siegrist, and V. a Vavilin, "The IWA Anaerobic Digestion Model No 1 (ADM1).," *Water Sci. Technol.*, vol. 45, no. 10, pp. 65–73, Jan. 2002.

[7] D. Gaida, "Dynamic Real-time substrate feed optimization of anaerobic co-digestion plants," Leiden University, 2014.

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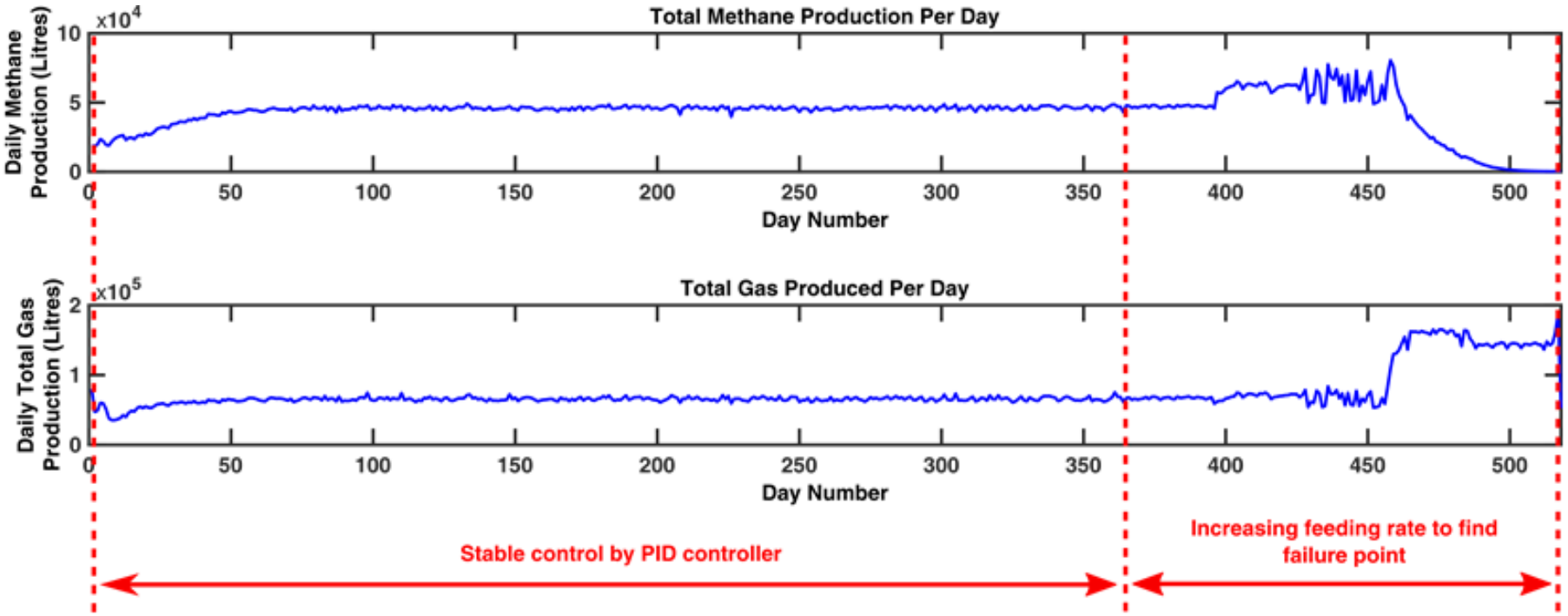
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PID Controller

- Software performed analysis to estimate inhibition factor
- Input to PID controller was target of 0.1
- Output is the feeding amount for the next day.
- Simulation in 24 hour blocks.
- Analysis & controller takes gas production data.
  - Decides feeding amount for next day.

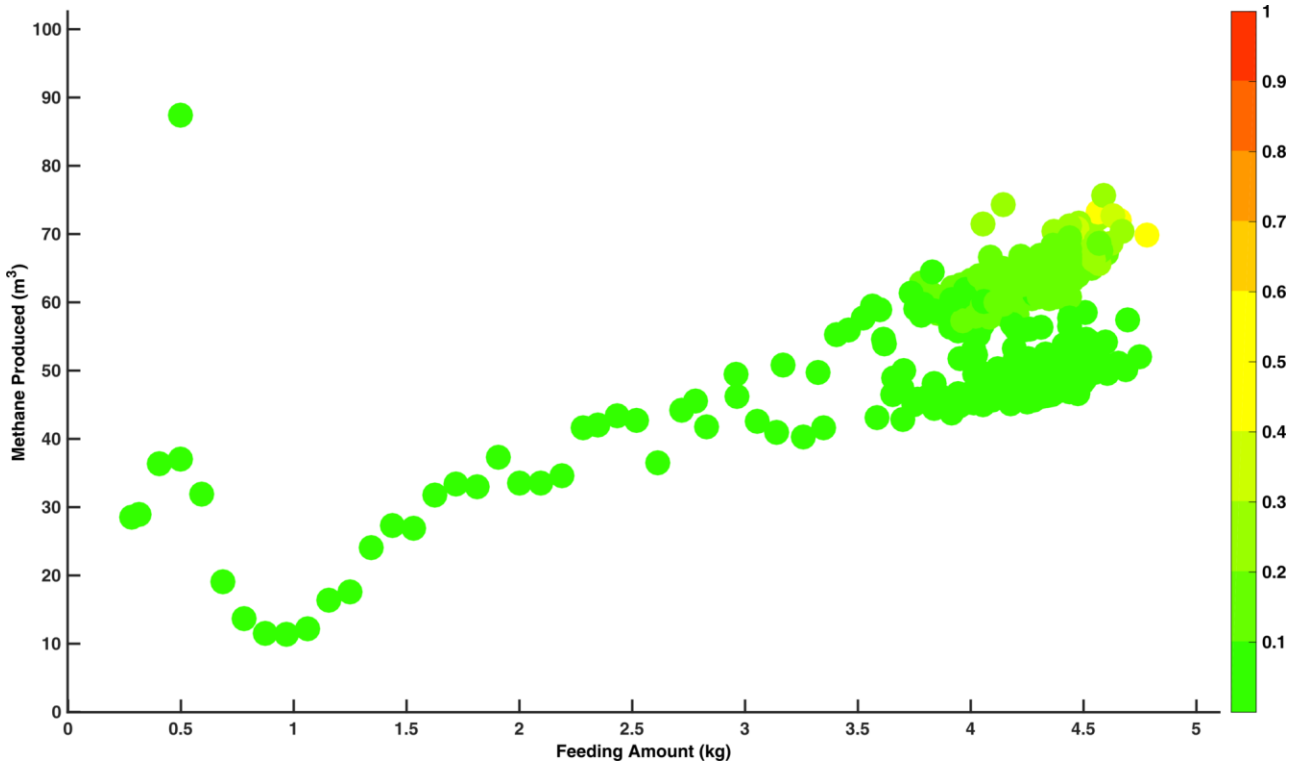
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PID Controlled Simulation Results



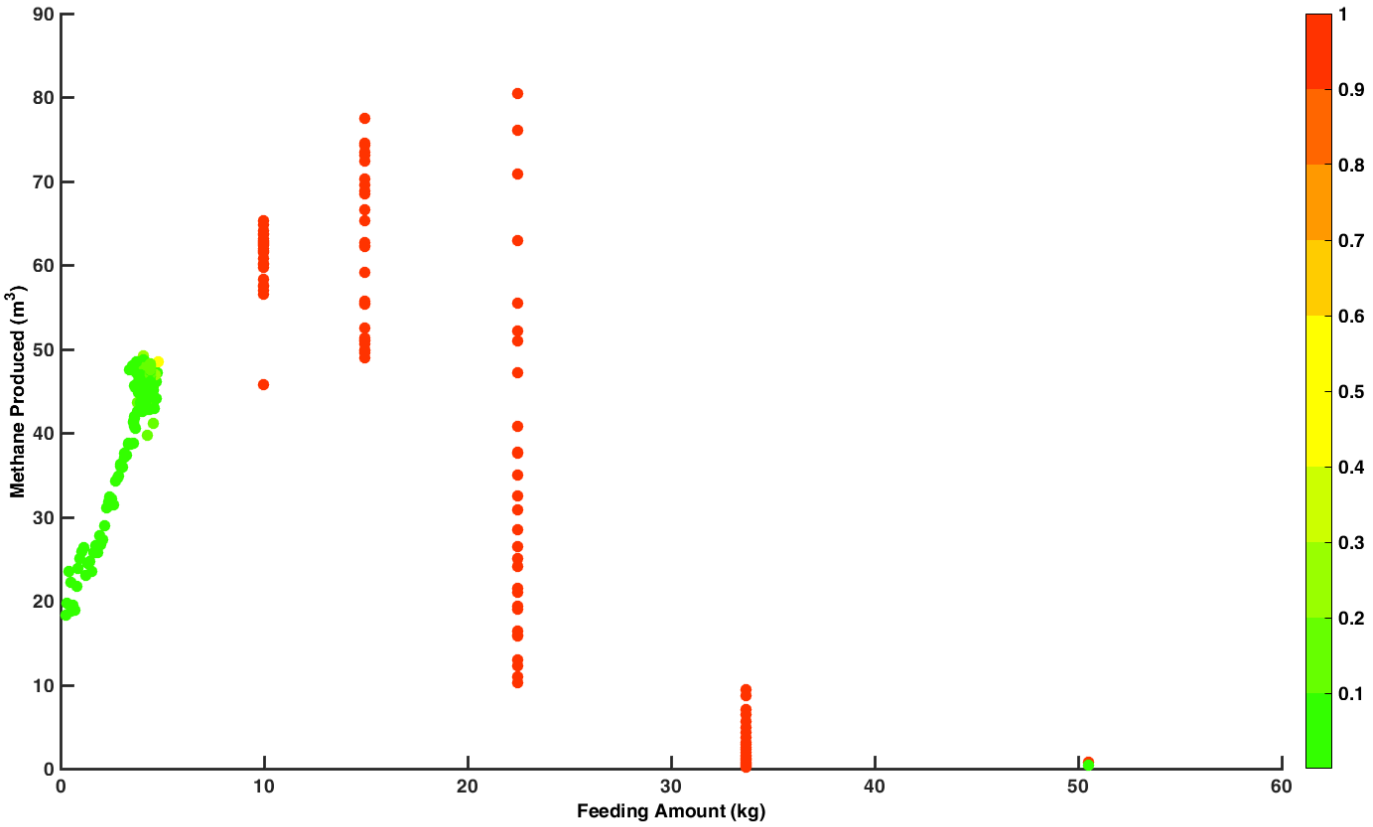
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Fed Amount vs Methane Production During Stable Control



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Fed Amount vs Methane Production with overloading



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Limitations

- Application primarily for energy crop based AD
  - Needs fast response after feeding within a few hours
- Cannot detect washout.
- “Inhibition factor” is an arbitrary scale
  - Higher values mean system is more stressed, not that we have reached max feeding rate.
- Bacteria behavior could change over time
  - Indicators/thresholds might change.
- Inhibition is an edge case not so accurately represented by the ADM1.

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Conclusions

- Expectation for some AD plants to move towards on-demand production.
- Response to feeding events provides information about process.
- Simple statistical analysis can automatically analyse process response.
- Transient response analysis combined with PID controller gives stable operation.

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