DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

PRocess Intensification for the reduced CommErcial CAPEX of Biofuels Production (PRICE CAP) using Dynamic Metabolic Control

March 6, 2019

Biochemical Conversion

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Duke Pratt School of Engineering

Overview

- Goals
  1. Capex as a Key Barrier for Next Generation Bio-products
- Approach
  1. 2-Stage Dynamic Metabolic Control Overview
  2. PRICE CAP Overview
  3. Review of TEA & Process Model driving technical targets
  4. Technical Approach
- Progress to Date
  1. High Cell Density Fermentations
  2. Cellulosic Sugar Co-utilization
  3. Farnesene Production
  4. Semi-continuous Process Development
- Next Steps

Goal Statement

- The goal of this project is to design and develop next generation biocatalysts and bioprocesses enabling low cost capital costs for cellulosic biofuels production. This will be achieved via process intensification and the utilization of dynamic metabolic control (DMC). DMC converts growing cells into productive stationary phase biocatalysts which can be recycled at high cell densities to achieve high volumetric productivities and reduce plant costs. Key goals are given in Table 1 below.

Table 1: Program Goals

Key Performance Metric	Units	State of the Art	Current	Program Targets
Rate	g/L-hr	2-4	<0.1	> 25
Specific Rate	g/gDCW-hr	0.05-0.2	<0.1	>0.75
Scale	L	>100K	300L	20L
TRL	--	--	TRL 3	TRL 5/6

Relevance Capex is a Key barrier to commercialization

Reported Capex for Various Processes		
Example Process	Capex ($ per gal annual capacity)	$ per 100Mgal/y facility
Petrochemical Plant	$3-$12	$300 M-$1.2 B
Cellulosic EtOH – NREL 2012	$6.92	$692 M
Cellulosic EtOH –Poet-DSM 2014	$13.75	$1.4 B
Cellulosic h-carbon–NREL-2013	$18.60	$1.8 B
Corn starch ethanol *	$1.10	$110M
Proposed Process	$0.50	$50 M

* Does not include corn milling costs

Large Capital Costs are a NO-GO Point on the commercialize bio-based processes.

- Often risky first of their kind plants
- Competitive Capital investments (petro) are proven
- Plant level ROI are not manageable even with low costs of capital

- For a $500M investment 20% minimal ROI and ten year payback period you would need to make a profit of $0.60/gallon on a 100M gallon/year facility, assuming 0 cost of capital. - No-one should put their money here.

- A $50M investment only requires a $0.06/gallon profit.

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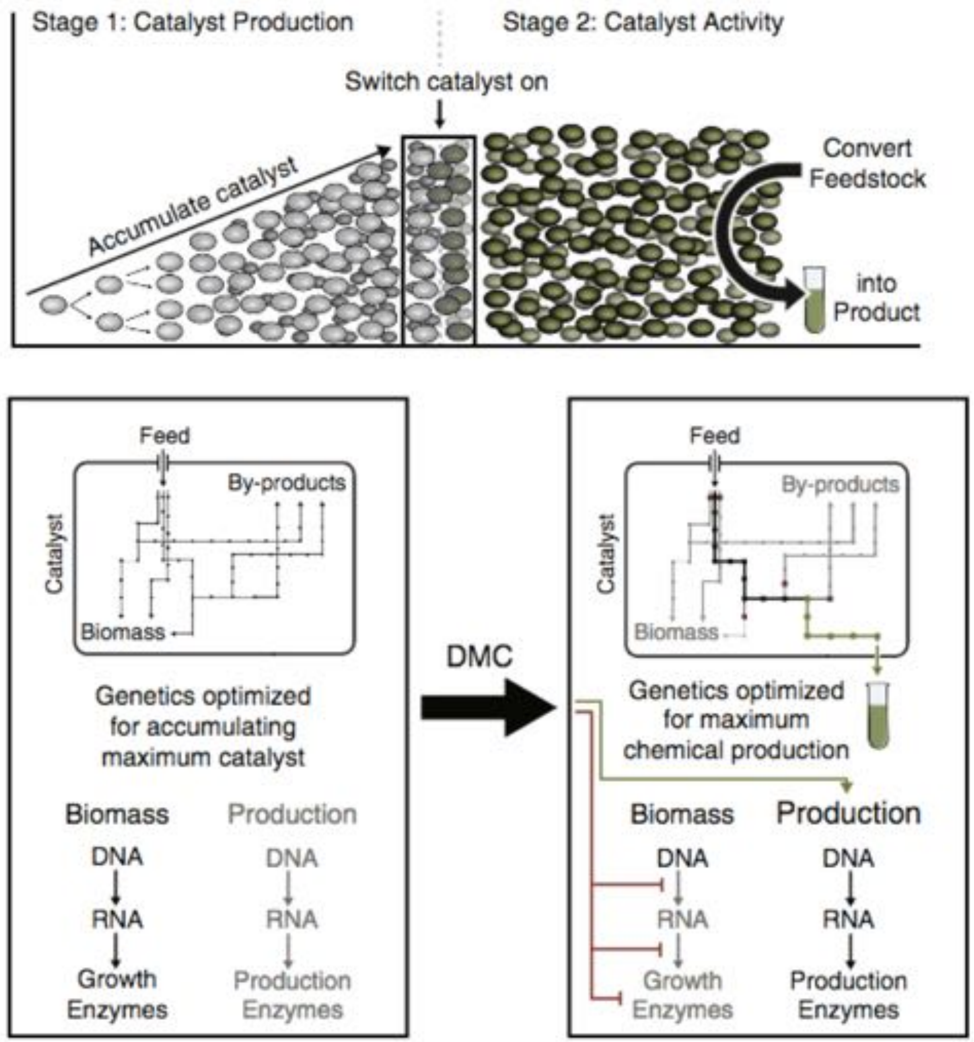
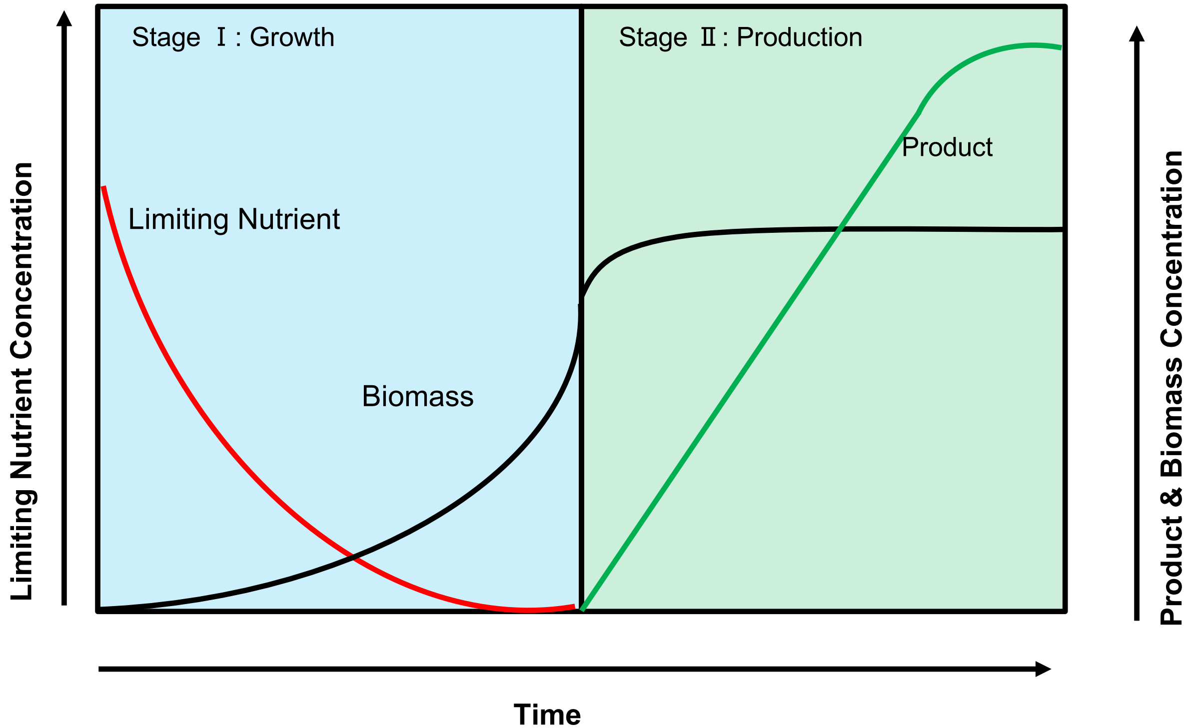
Approach: Two Stage Dynamic Metabolic Control



Adapted from Burg et al, Current Opinions Chem. Eng., 2016

Approach: Two Stage Dynamic Metabolic Control



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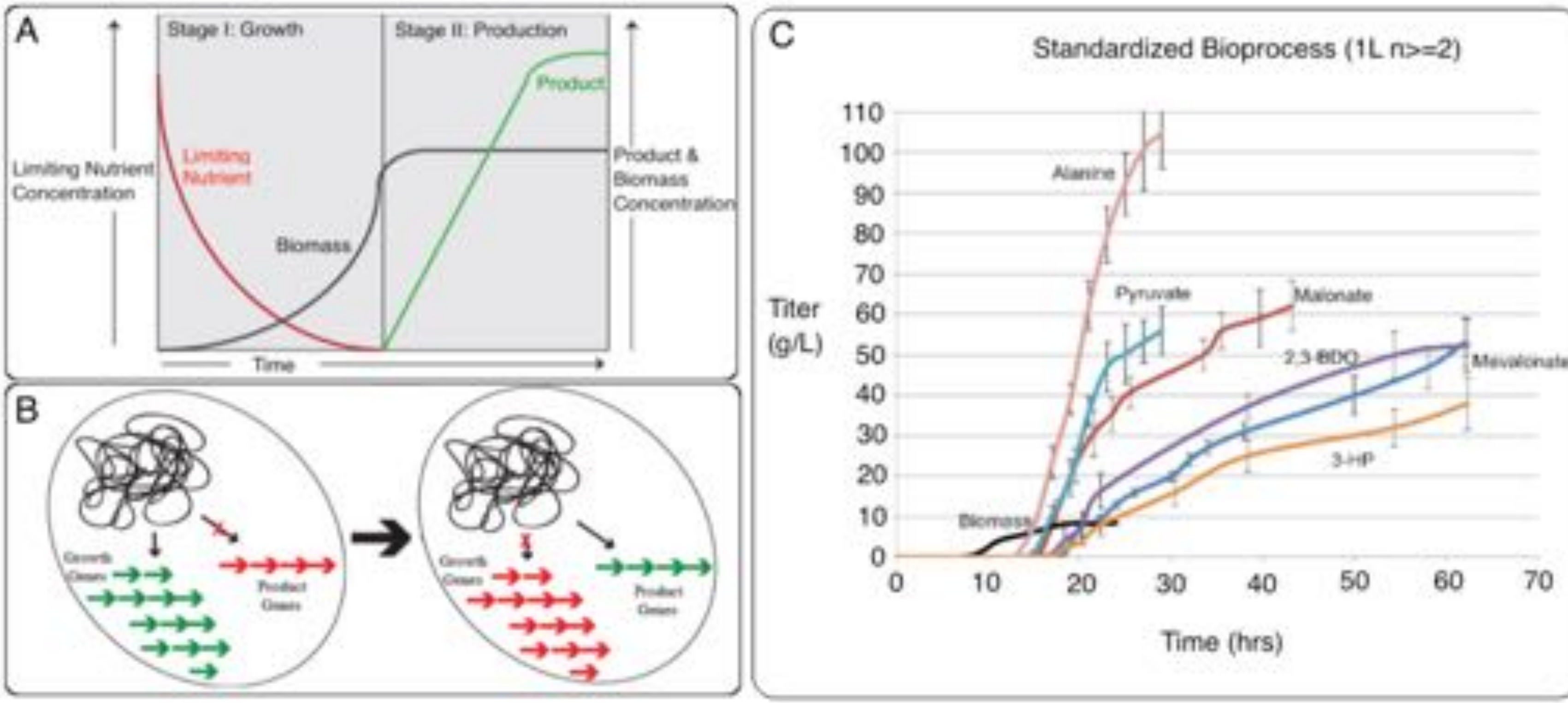
Approach: Two Stage Dynamic Metabolic Control



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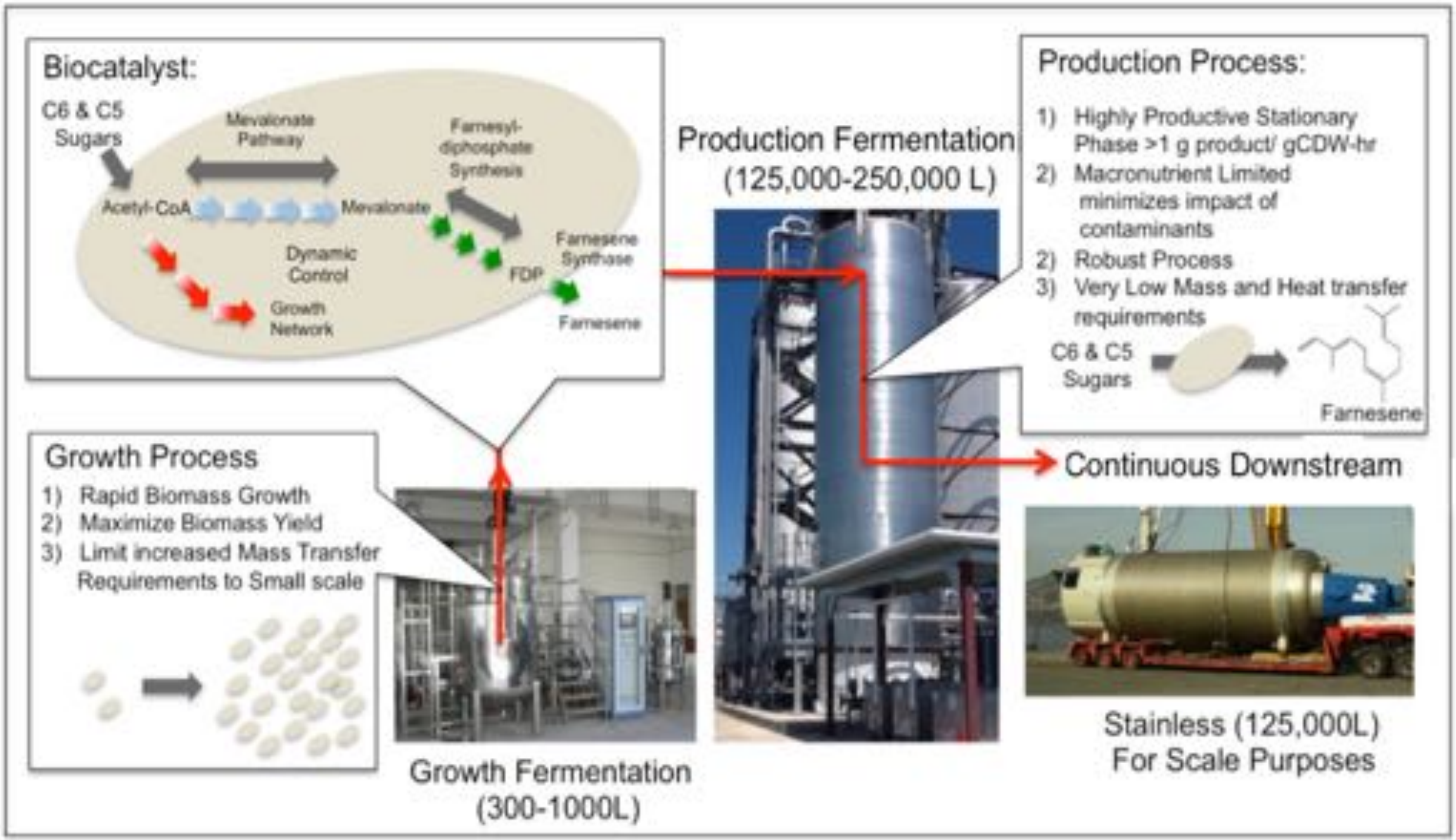
PRocess Intensification for the reduced CommErcial CAPEX of Biofuels Production (PRICE CAP)



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Technical Approach: Key Program Deliverables

1) Techno-economic Analysis to validate the Price Cap Approach
2) High Cell Density Fermentations
3) Develop *E. coli* strains engineered cellulosic sugar co-utilization
4) Demonstrate high rates of farnesene production
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TEA & Process Model

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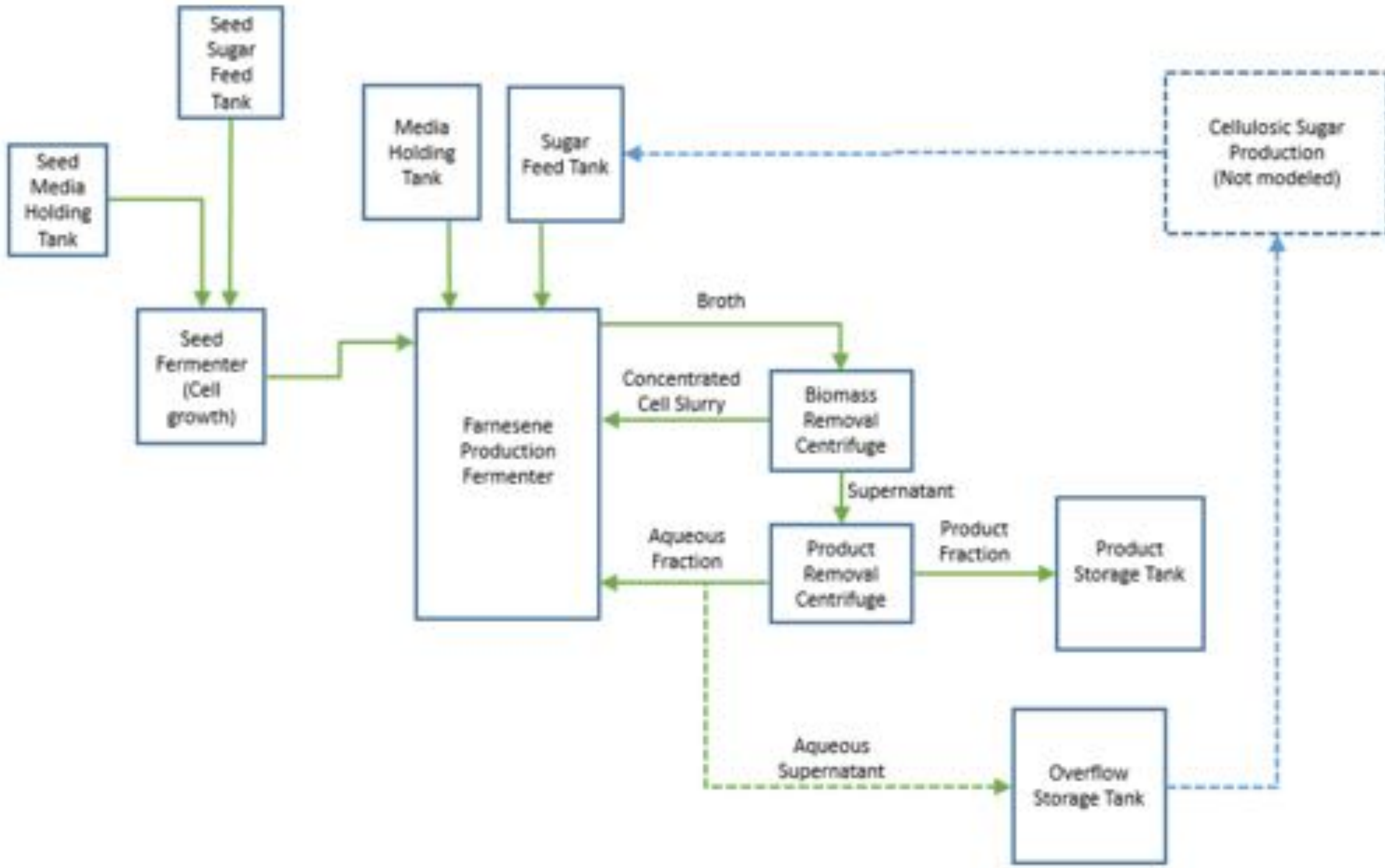
Process Flow Diagram



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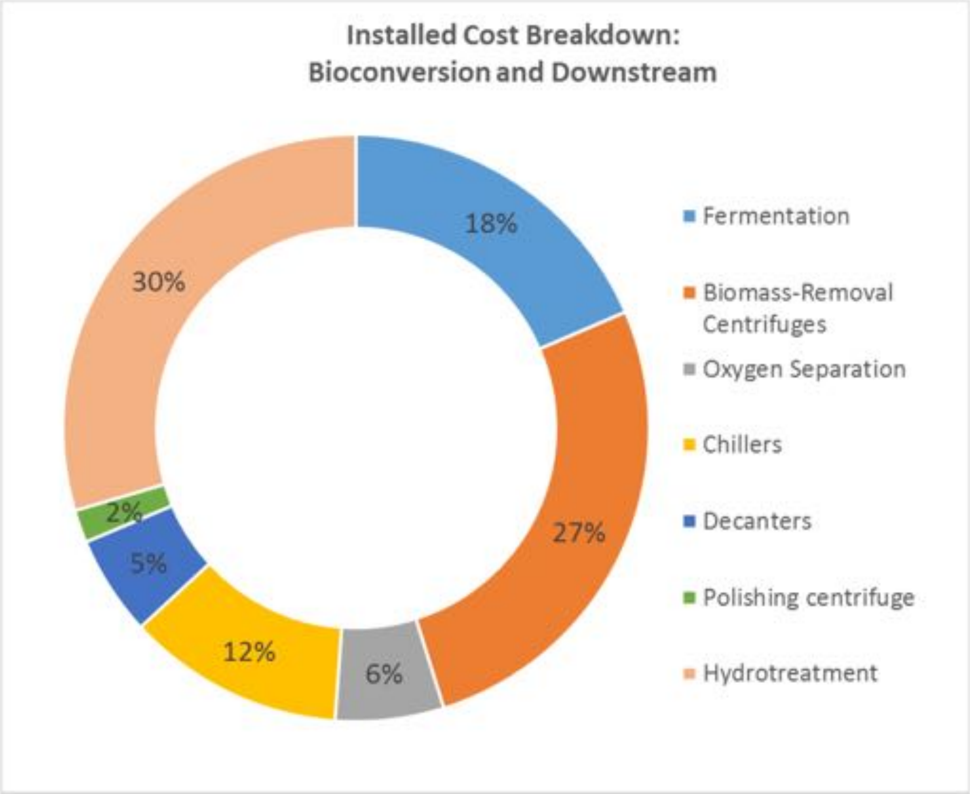
Price Cap TEA Summary

- Base Case:
  - Spec. Rate = 0.75 g/gDCW-hr
  - Yield = 80% of theoretical
  - Cellulosic sugars supplied at 14wt%
  - IRR = 10%
  - 30-year plant life
  - Biomass Concentration = 40 gDCW/L
  - Working volume = 275m^3 per vessel
- Fermentation and biomass separation: ~45% of total capex
- Downstream recovery and utilities: ~55% of total capex
- Fermentation share of capex small compared to incumbent processes
- Model Accuracy +/- 30%



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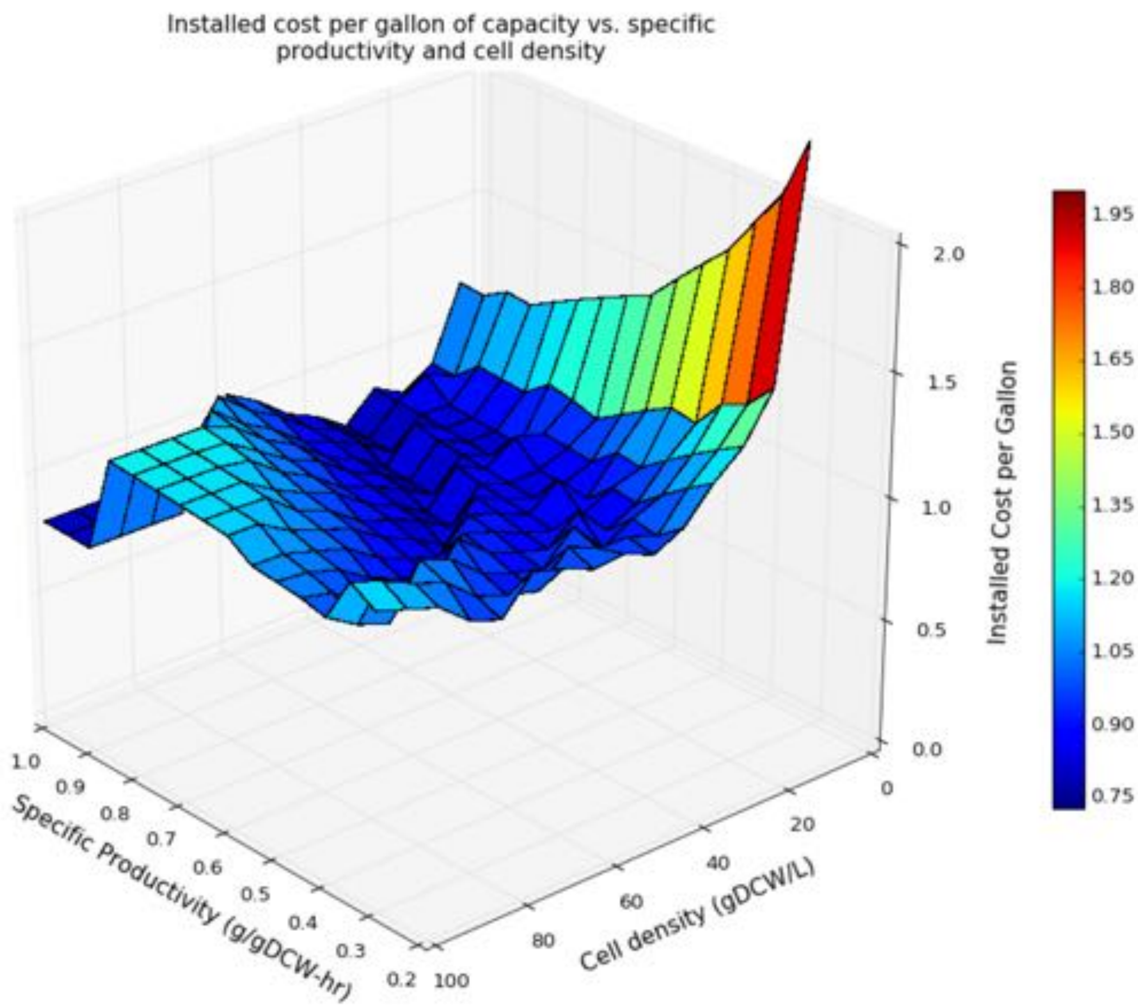
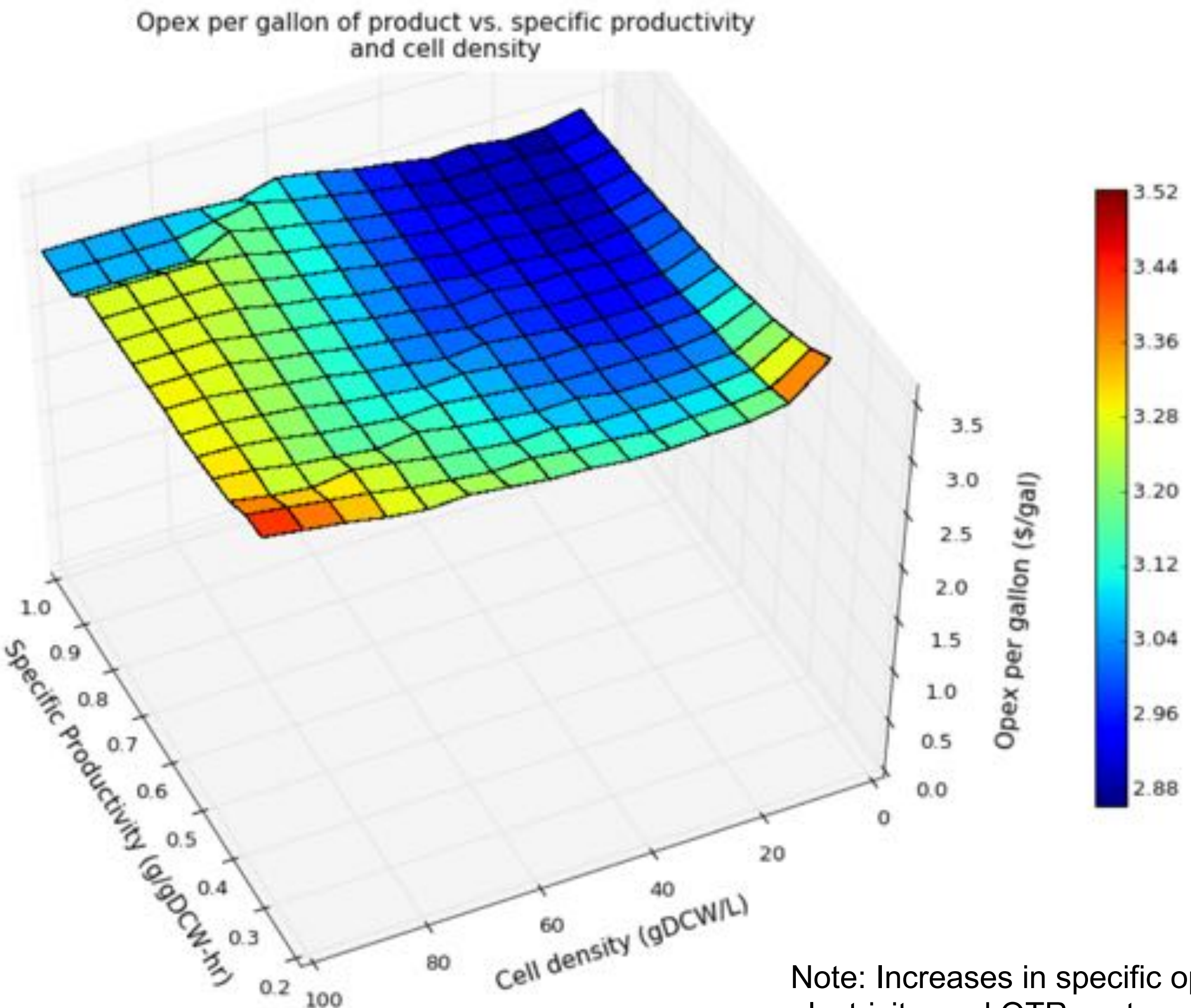
Capex Sensitivity



- Minimum capex is achieved at 30-50 gDCW/L
- For biomass > 60 gDCW/L, capex increases due to challenges associated with heat production and oxygen transfer

Note: Equipment sizing is discrete, resulting in various “steps” in the response surface

Opex Sensitivity



Minimum opex is achieved in the range of 20-50 gDCW/L

Note: Increases in specific opex are due to increased cooling, electricity, and OTR costs

TEA Summary

	Units	Goal	NREL 2013 Hydrocarbons	PRICE CAP Base	PRICE CAP Stretch	PRICE CAP Stretch Low cell-recycle capex [2]	PRICE CAP Stretch Farnesane [3]	PRICE CAP Stretch Farnesane Low cell-recycle capex [2 3]
Capex	Installed cost/gal of capacity	$0.50	$2.02	0.75	$0.72	$0.63	$0.50	$0.41
Opex	$/gal	- -	$2.84	$2.93	$2.61	$2.60	$2.59	$2.59
Start Up MSP	$/gal	- -	$5.35	$5.18	$4.61	$4.59	$4.49	$4.48
Final Plant MSP [1]	$/gal	--	$4.80	$4.36	$3.87	$3.87	$3.85	$3.85
Fermentation Product	--	--	FFA	Farnesene	Farnesene	Farnesene	Farnesane	Farnesane

•Notes

[1] After full depreciation of capital and repayment of loan.
[2] Low cell-recycle capex proposes 50% reduction for cell recycle capital.
[3] Production of farnesane would eliminate need for hydrotreatment.

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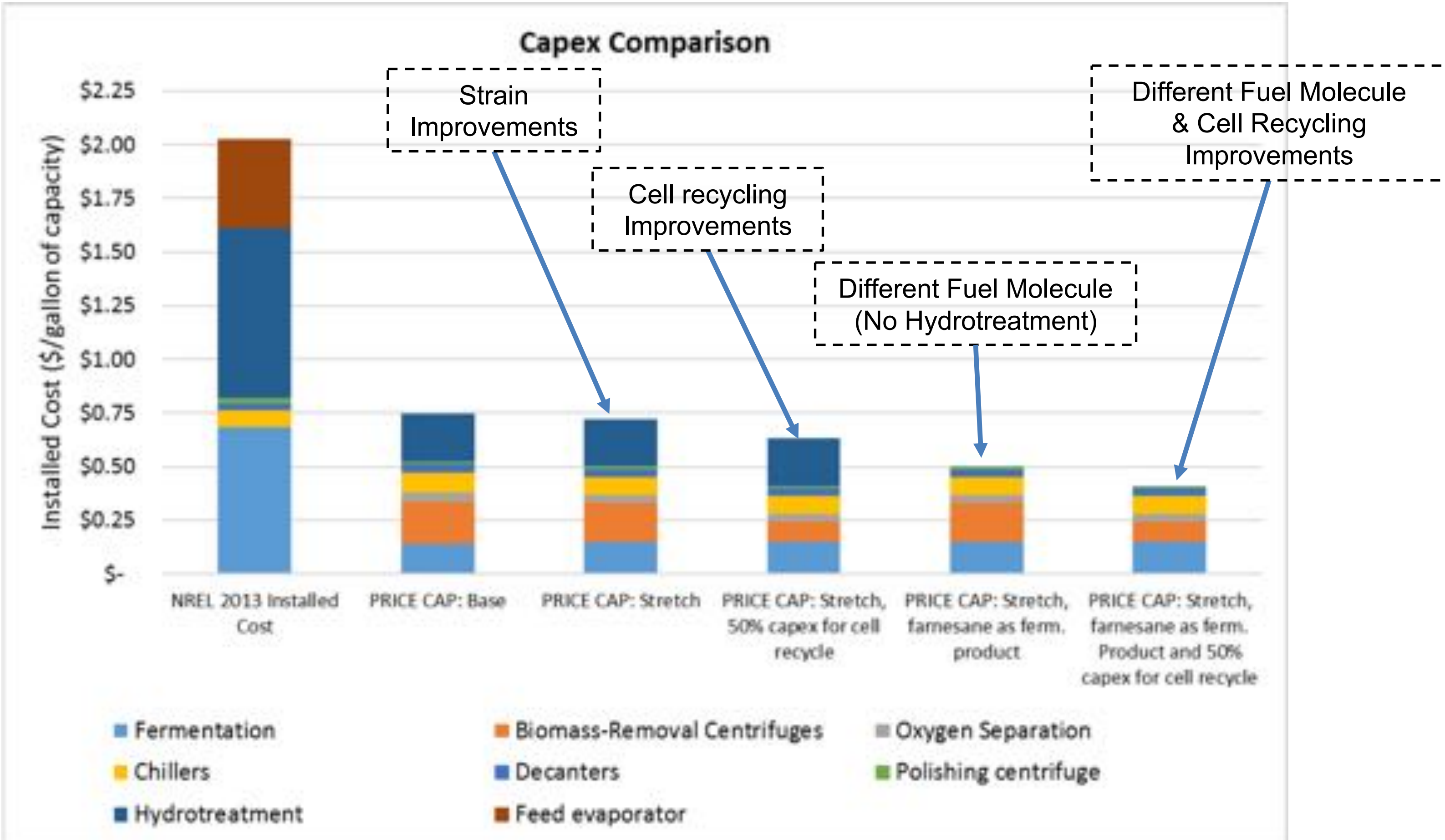
Capex Glide Path for Cost Reduction



- PRICE CAP addresses high cost of fermentation capex
  - Some DSP cost reductions as well, due to lower cost of hydrogenation vs. decarboxylation
- Further efforts needed to reduce cell recycle and downstream conversion costs

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High Biomass Fermentations

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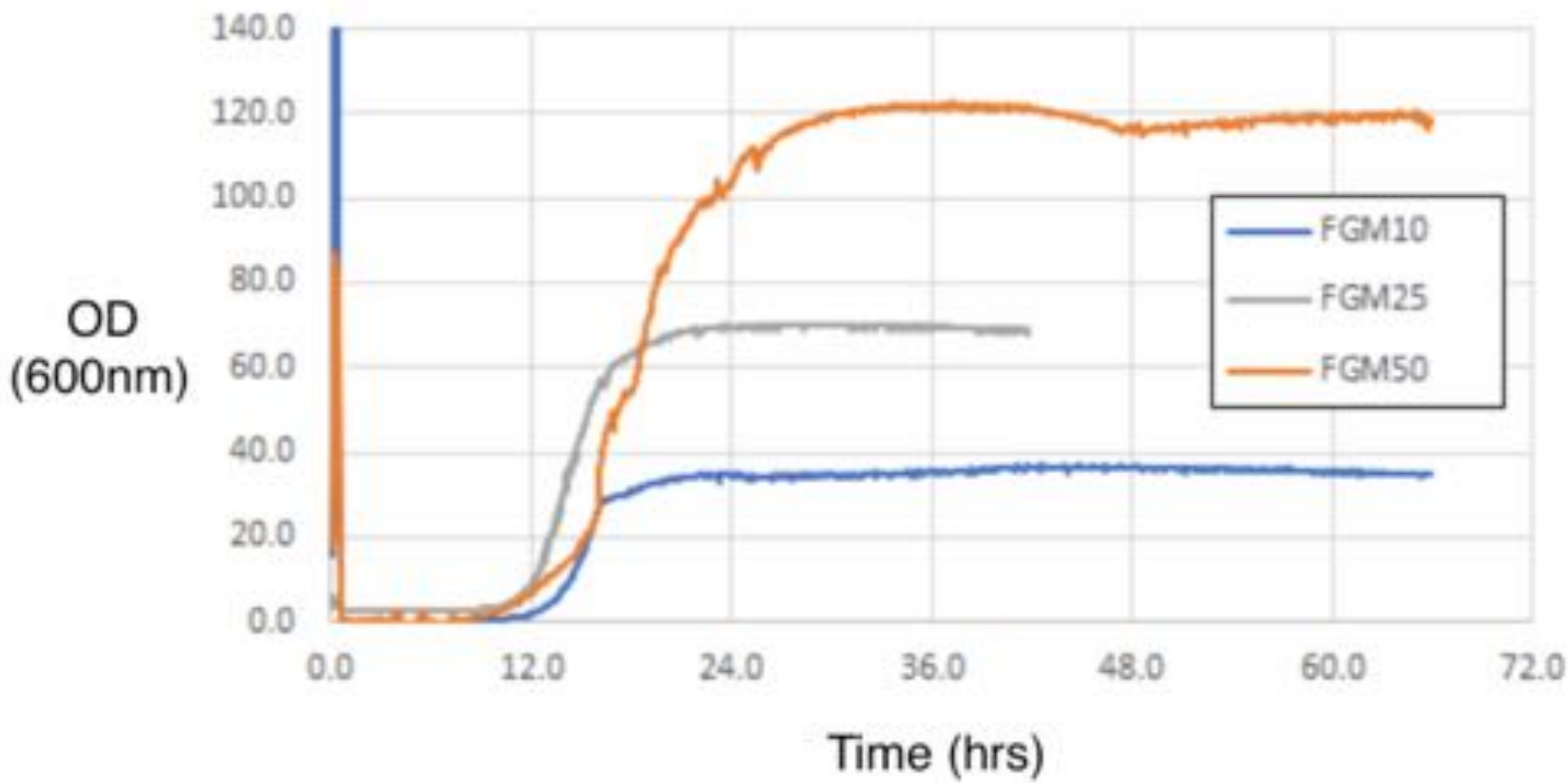
High Biomass Fermentations

Impact of Media Formulation on Growth/Biomass Levels



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Cellulosic Sugar Utilization

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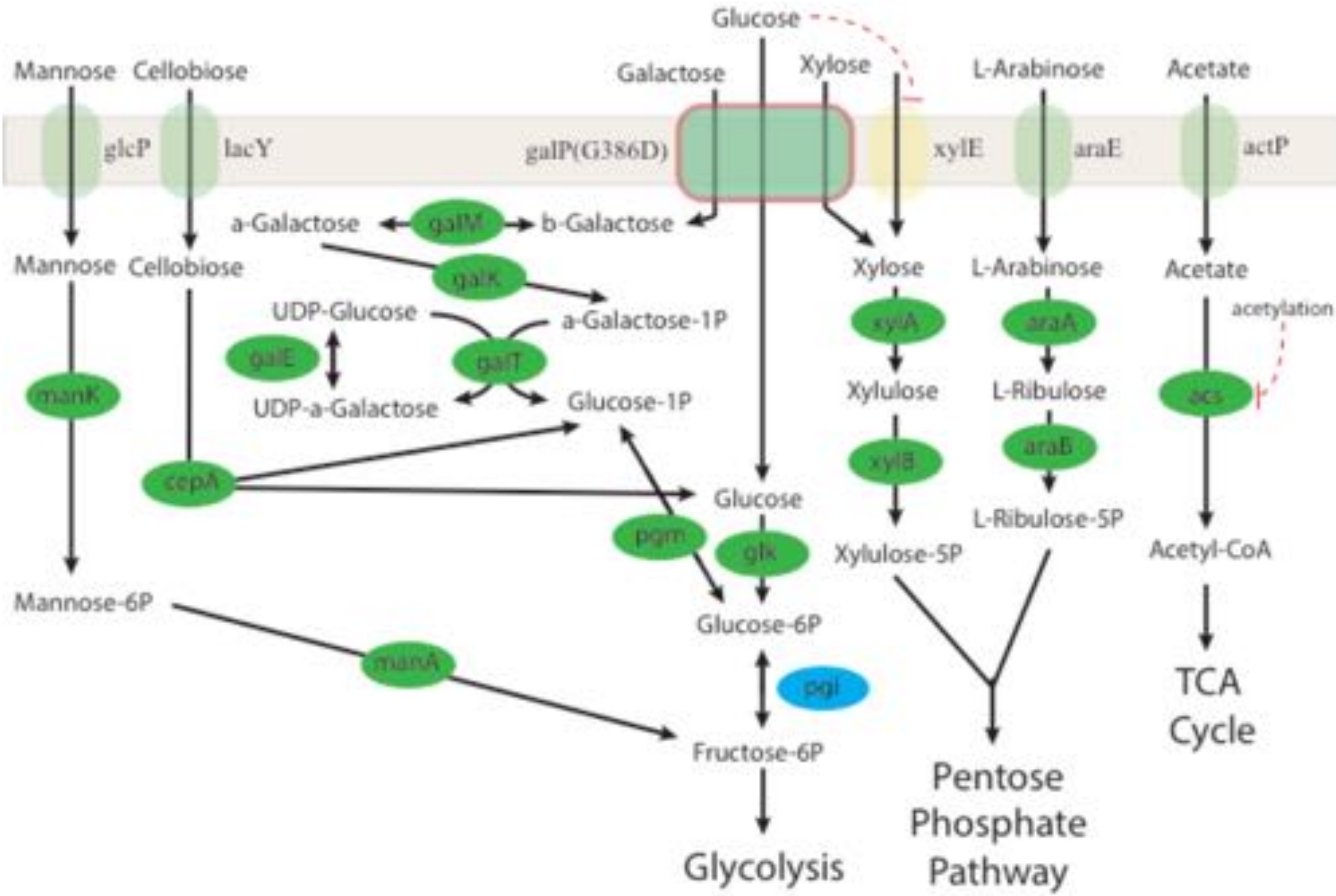
Cellulosic Sugar Pathways



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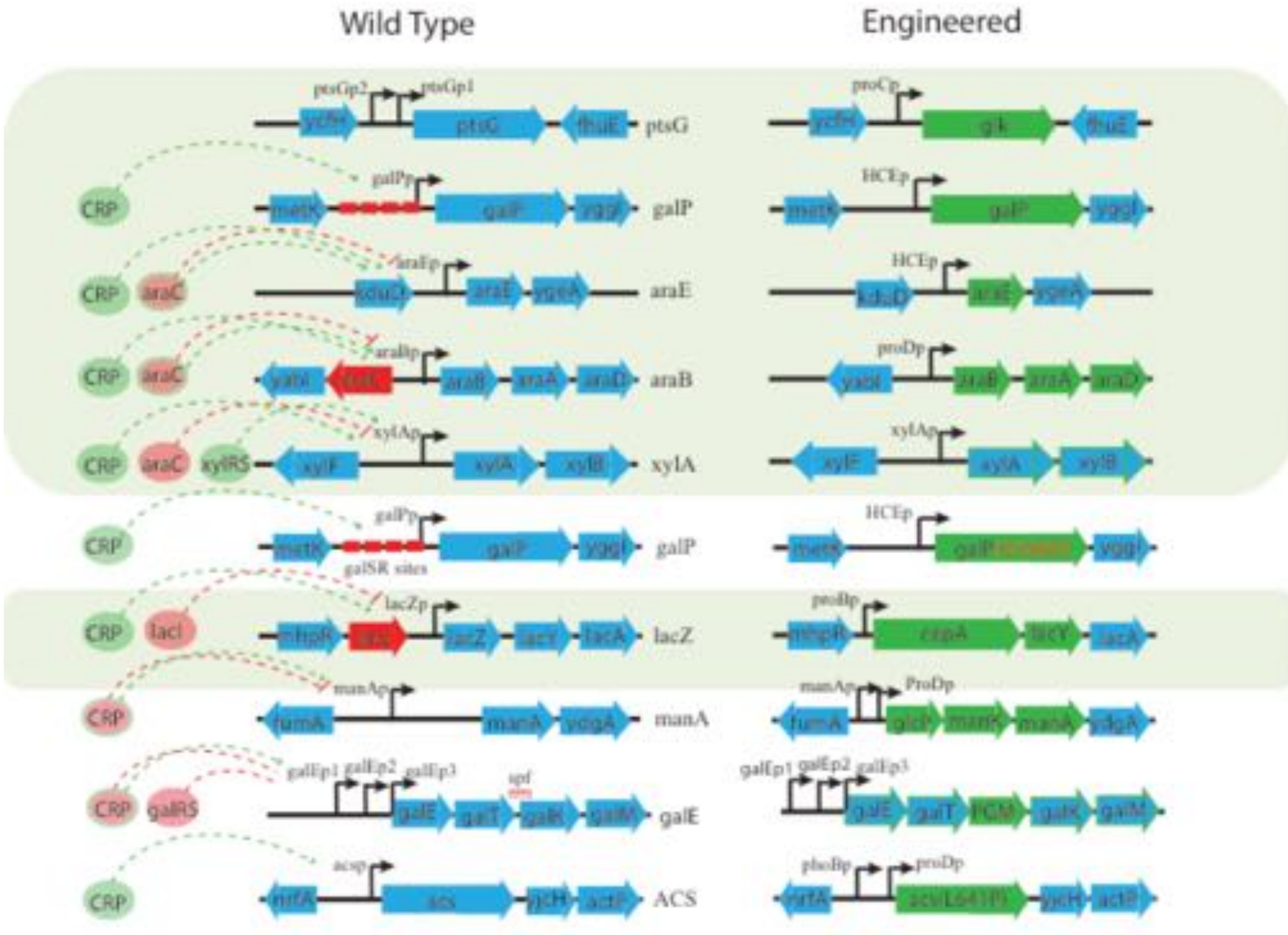
Strain Engineering Plan



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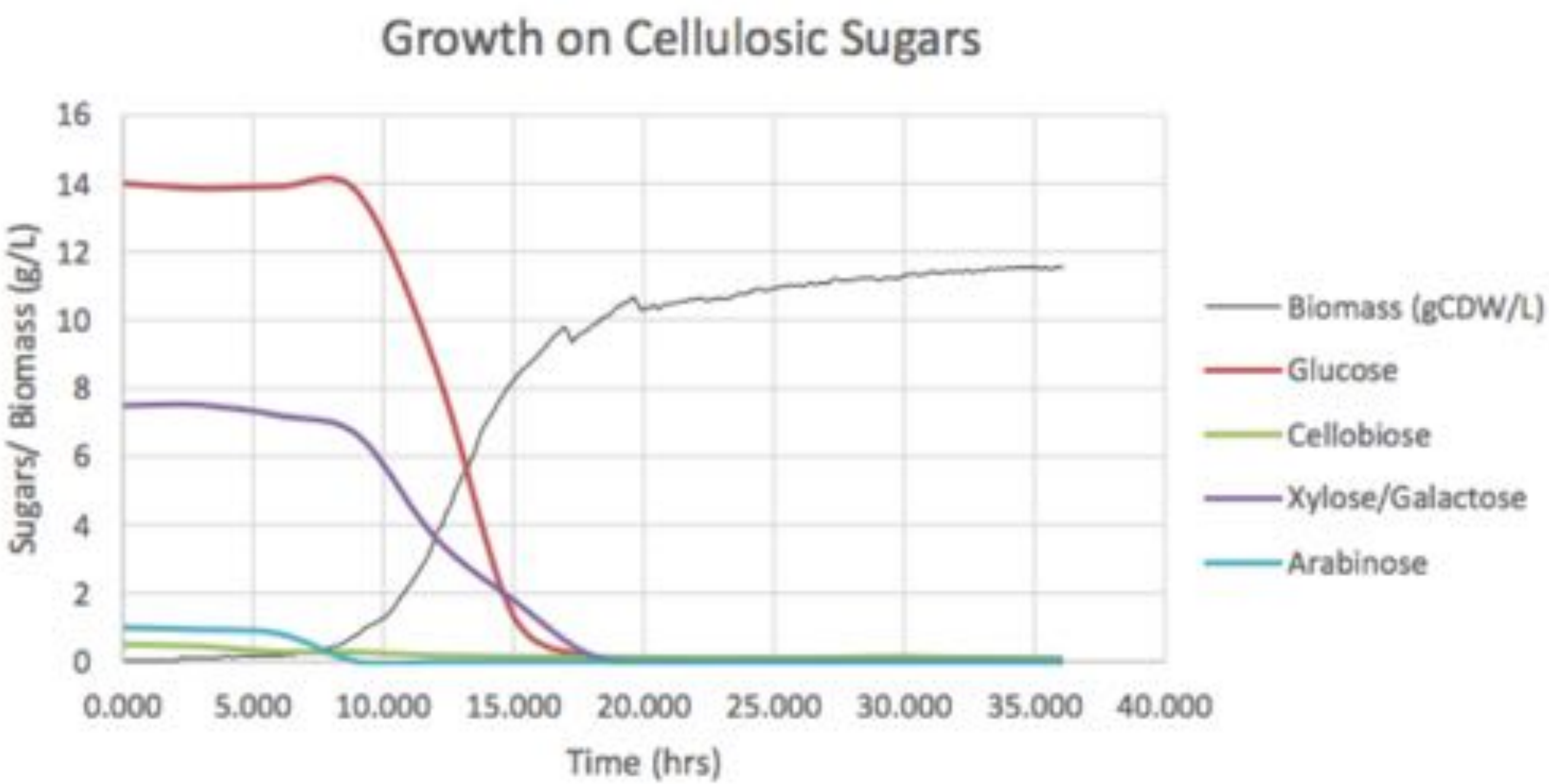
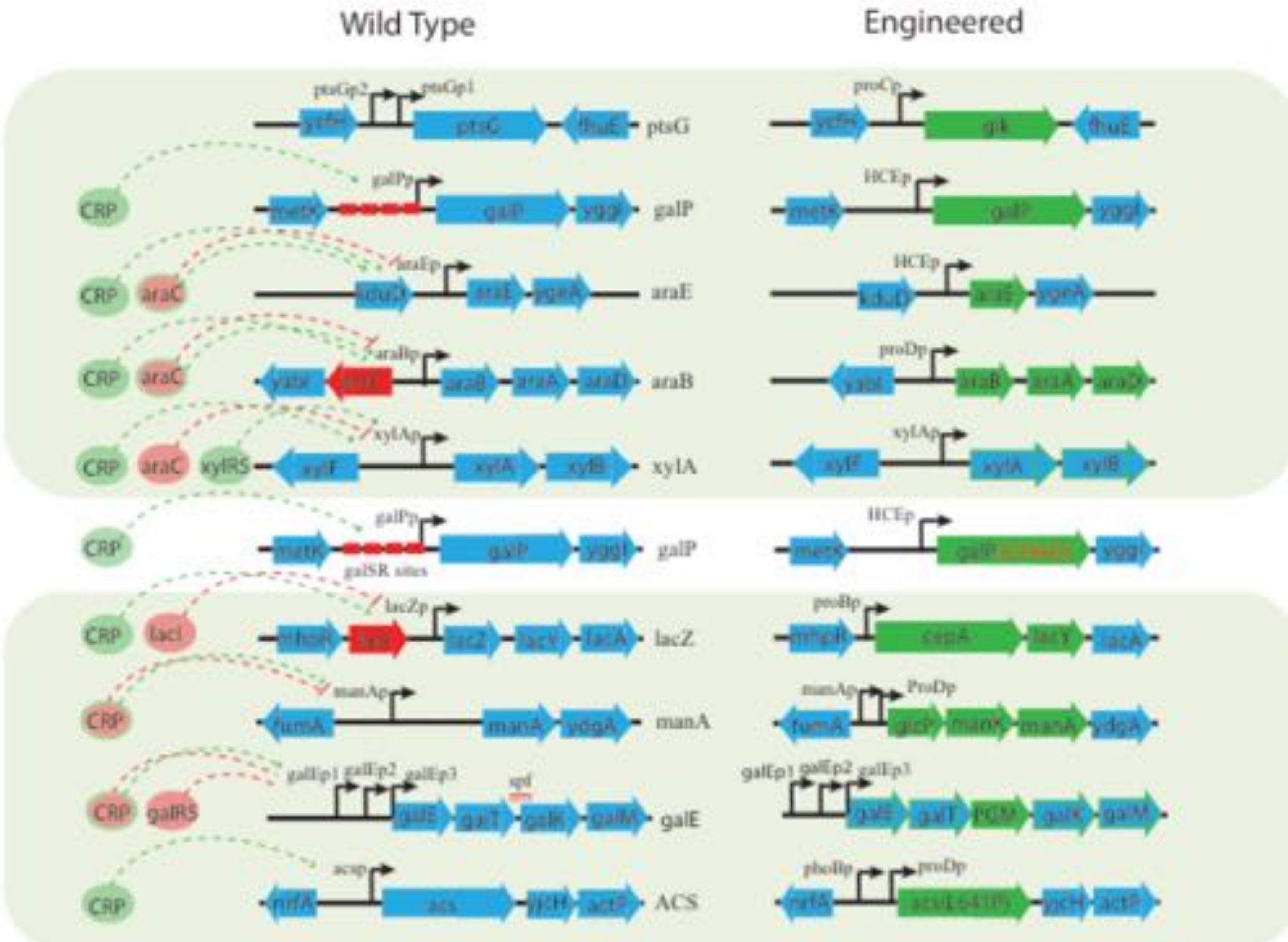
Cellulosic Sugar Co-Utilization – Year 1 Results

Co-utilization of Glucose/Xylose, Arabinose & Cellobiose



Total Sugars ~ 25g/L
(14.1 g/L Glucose,7.5 g/L Xylose, 1.2 g/L Arabinose, 0.6 g/L Galactose, 0.6 g/L Cellobiose, 0.3 g/L Acetate)

Strain Engineering Plan



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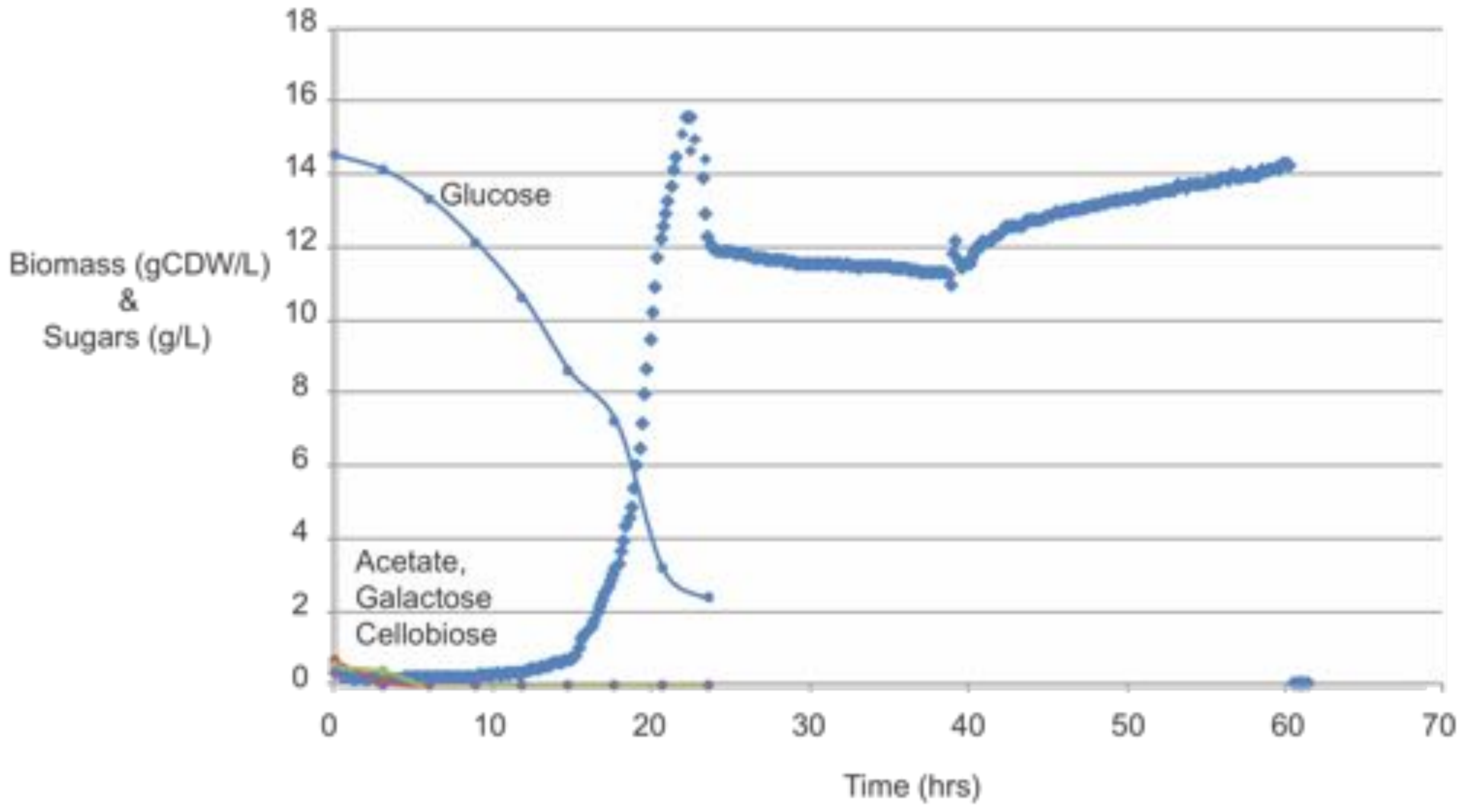
Cellulosic Sugar Co-Utilization- Recent Results

Co-utilization of Glucose, Cellobiose, Galactose, Acetate



Starting sugar levels are low, and quickly go below limit of detection, repeat experiments are planned with higher sugar levels.

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Technical Approach: Key Program Deliverables

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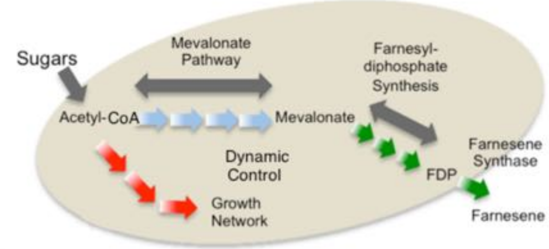
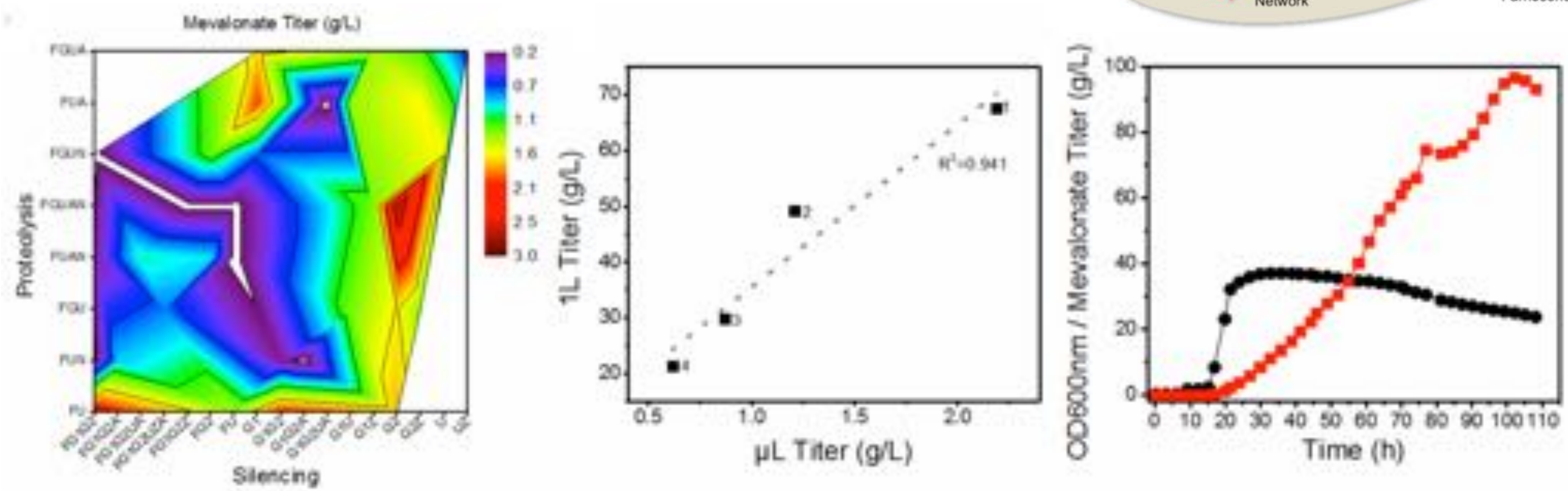
Farnesene Production

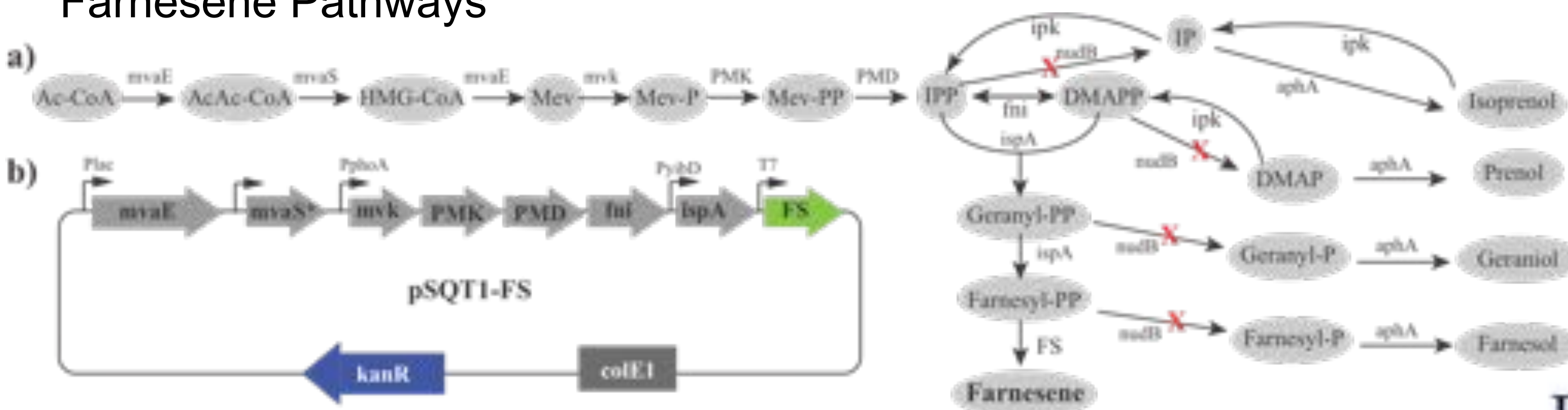
Mevalonate/Farnesene Production



Mevalonate Production



Farnesene Pathways



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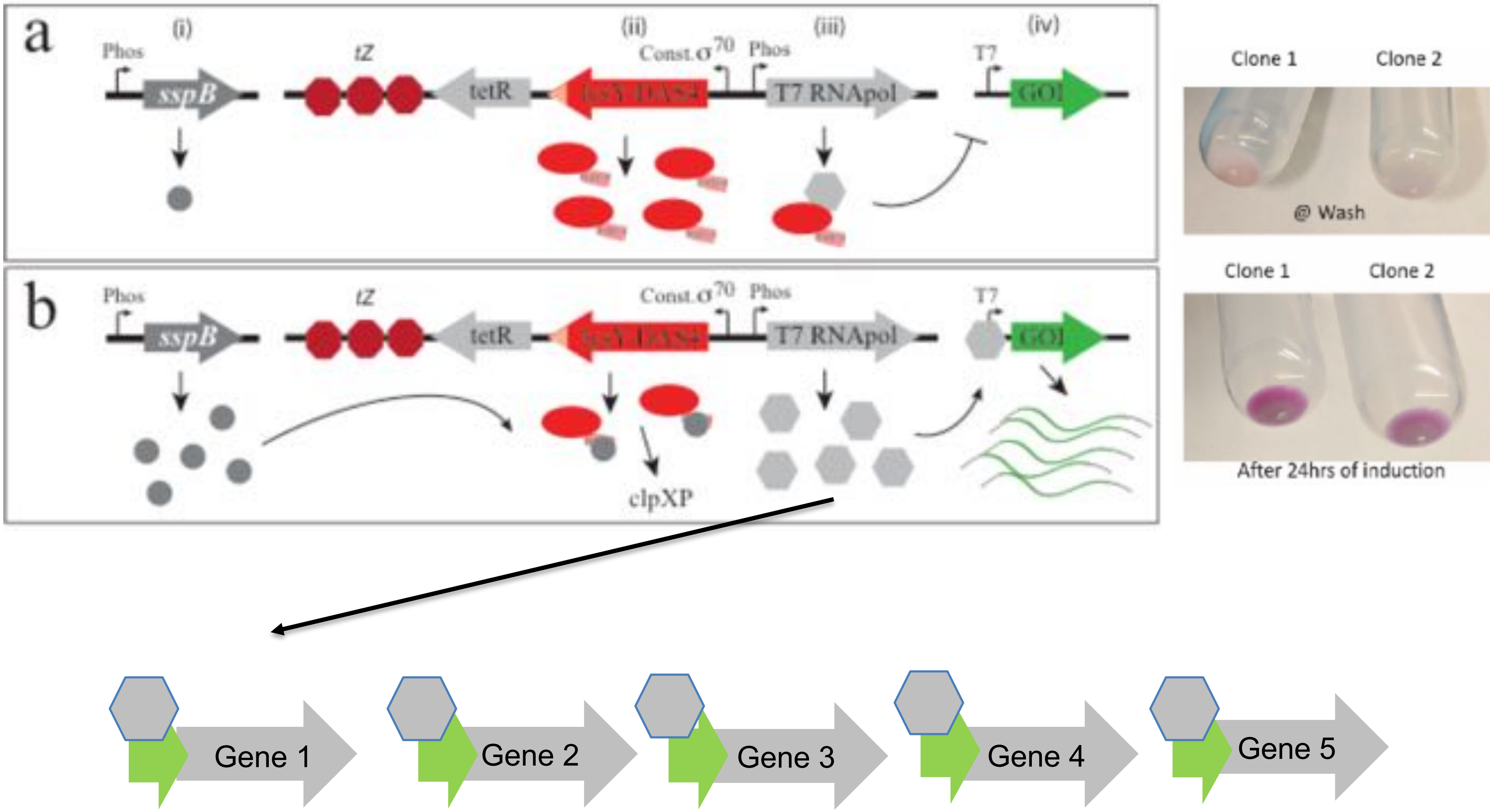
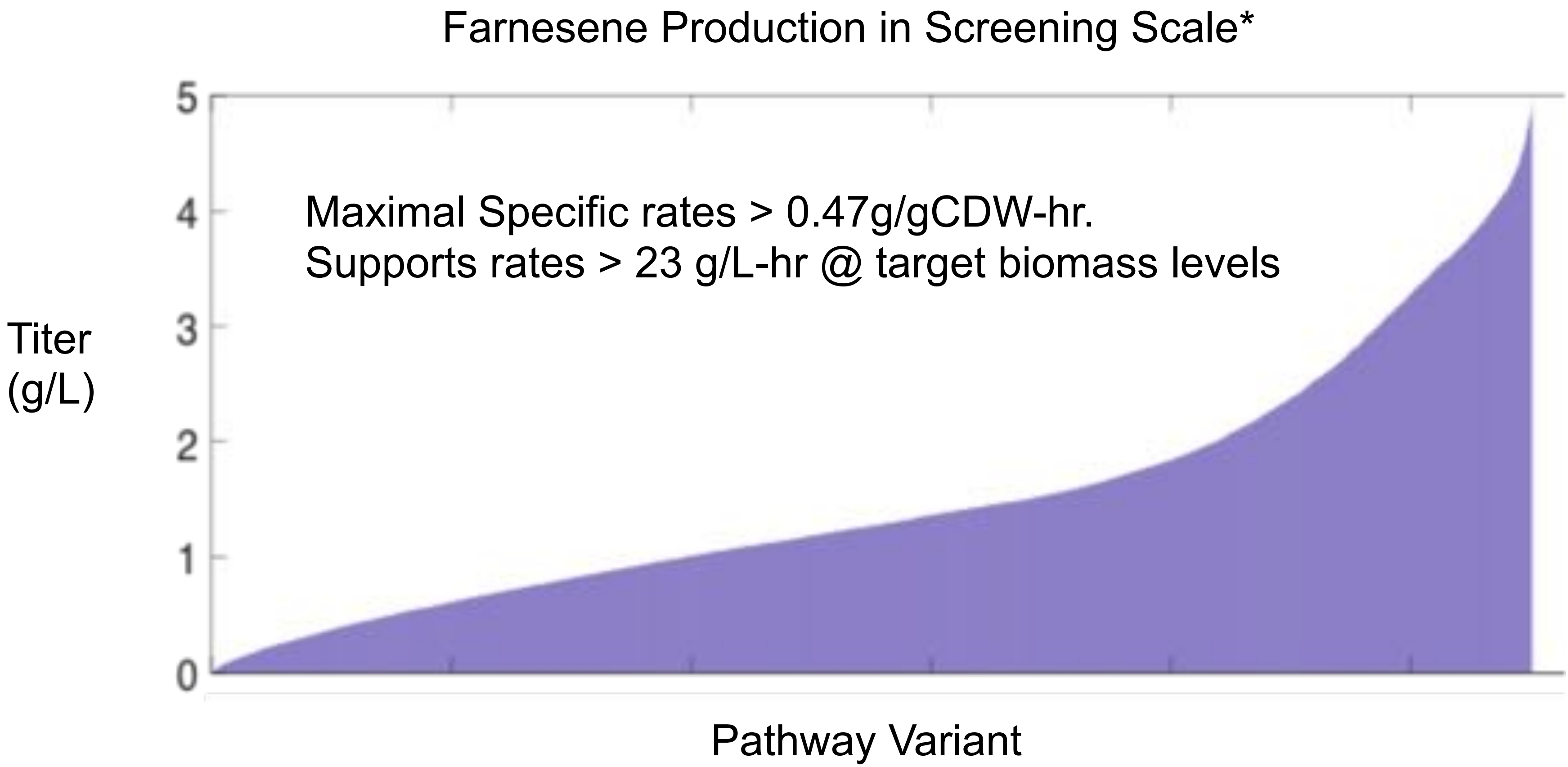
Higher Levels of Pathway Expression Engineered



Farnesene Pathway Genes/Variants

Screening of Farnesene Pathway Variants



*Farnesene screening results are using strains from previous iteration of the T7 induction system

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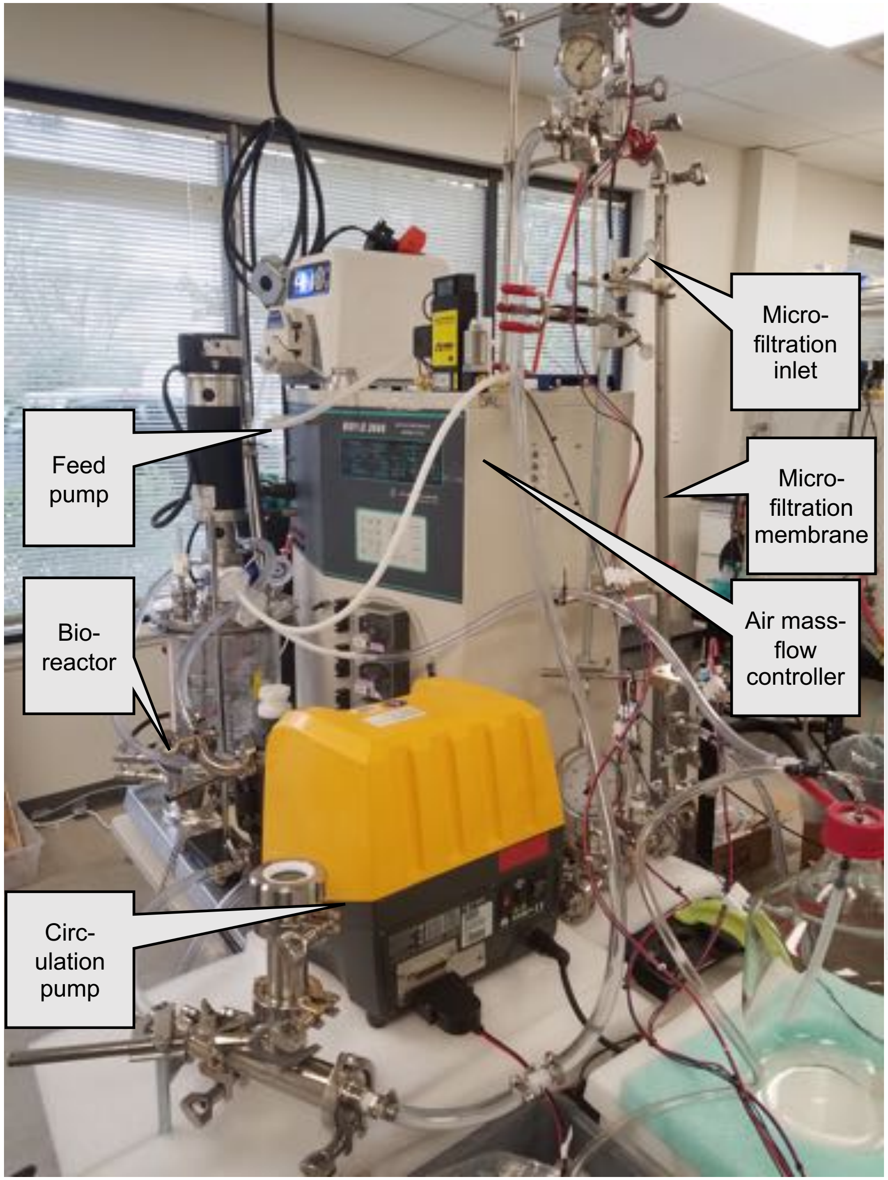
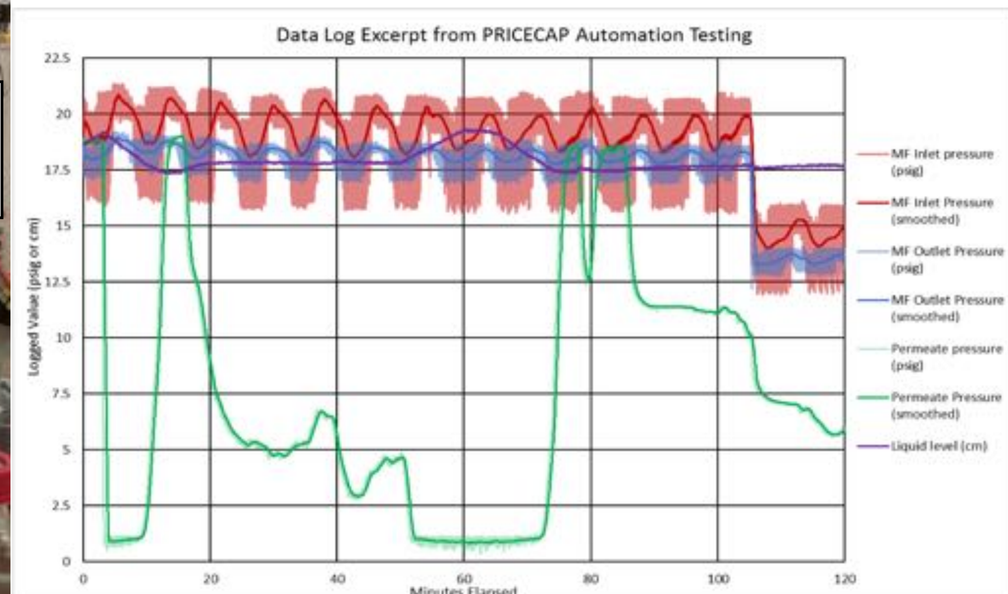
Semi-Continuous Processing

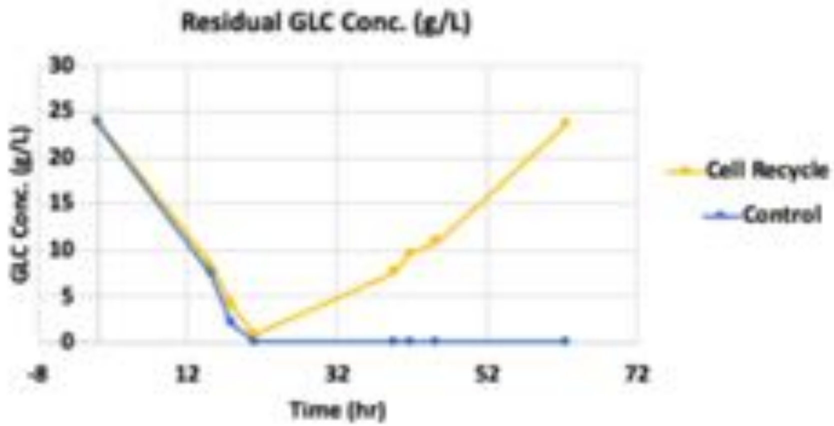
Semi-Continuous Process Automation

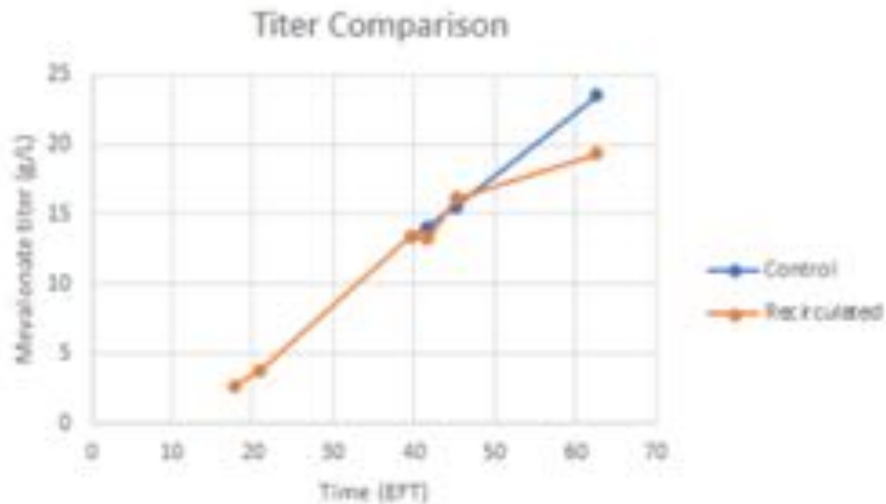


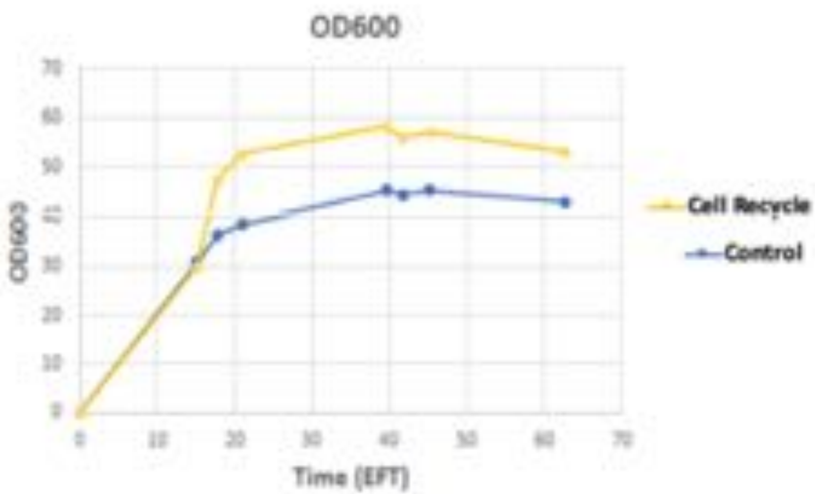
Hardware and control systems developed for automated semi-continuous fermentation



Semi-Continuous Process Initial Results - Mevalonate



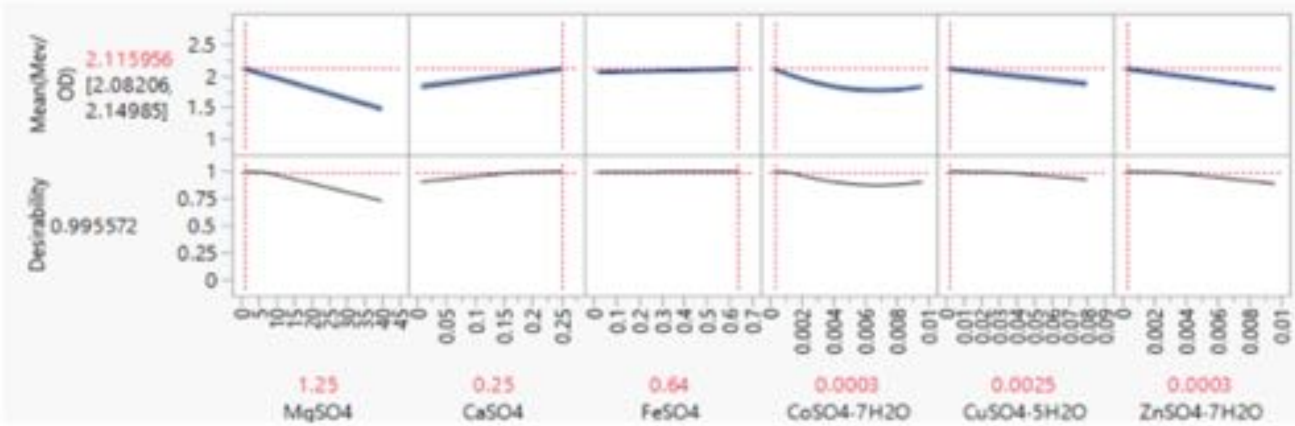


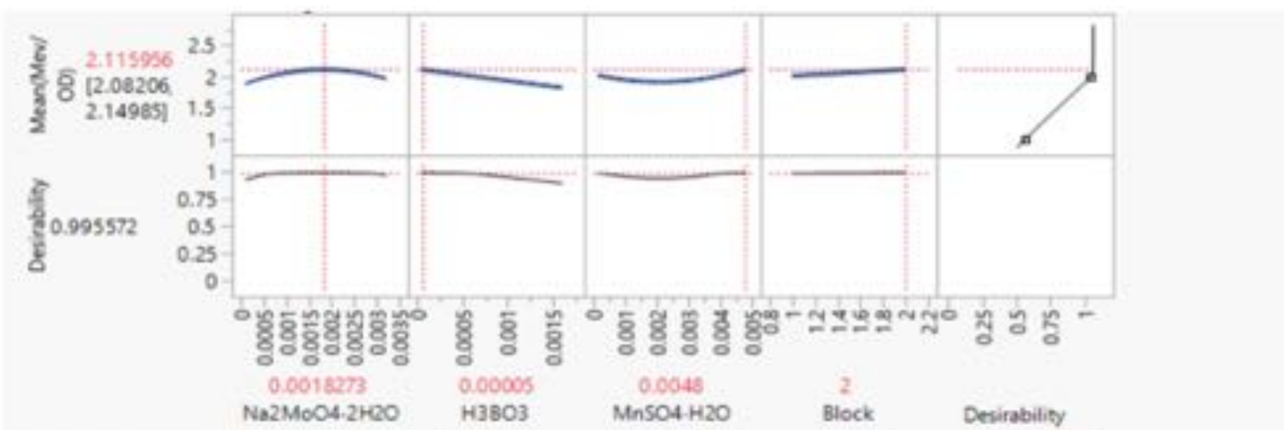


	Titer	Rate	Yield
Cell Recycling	20.3	0.33	0.14
Control	23.5	0.38	0.19

Media Optimization - DoE

Design of Experiments utilized to optimize media formulation





Trace metals have a large impact on mevalonate productivity.
Media Optimization for continuous process ongoing.

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4) Demonstrate high rates of farnesene production ✓
5) Demonstrate semi-continuous processing (50% Complete)
6) Demonstrate system integration - Ongoing

Future Work

- Complete Evaluations of cellulosic co-utilization strains
- Integration of strain components into combined strains
- Continued optimization of semi-continuous process.
- Deployment with real-world cellulosic sugars.

Quad Chart

Timeline

- Project start date:
- Project end date: July 2019
- 75% complete

Barriers addressed

- Integration and Intensification.

	Total Costs Pre FY17**	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date)
DOE Funded		$1279504	$38,846	$561,201
Cost Share*	-	$127950	$3885	$56,120
Duke	-	82%	60%	75%
DMC	-	18%	40%	25%

- **Partners: If multiple DOE recipients are involved in the project, please list level of involvement, expressed as percentages of project funding from FY 17-18. [(i.e. NREL (70%); INL (30%)]**

Objective

Develop technologies to enable reduced capital requirements for next generation cellulosic fuel production.

End of Project Goal

Demonstrate > 25 g/L-hr rates of fuel production from cellulosic feedstocks in a semi-continuous process supporting large scale capital costs less $0.50/gallon of installed capacity.

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Questions