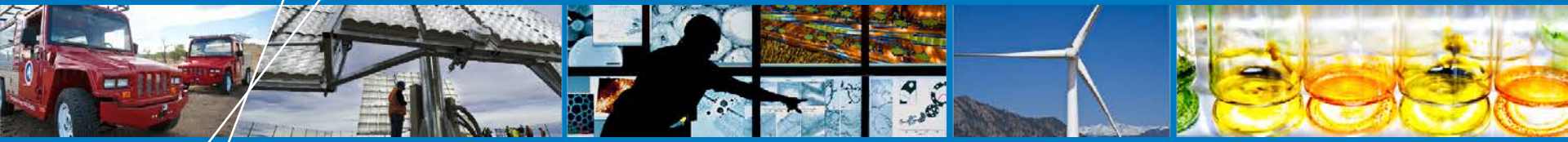
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Algal Biofuels Can Make a Difference



Renewable Energy Roundtable

Philip T. Pienkos

March 27, 2012

NREL/PR-7A40-54590

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

What is Lignocellulosic Biomass?



Hardwoods



Grasses



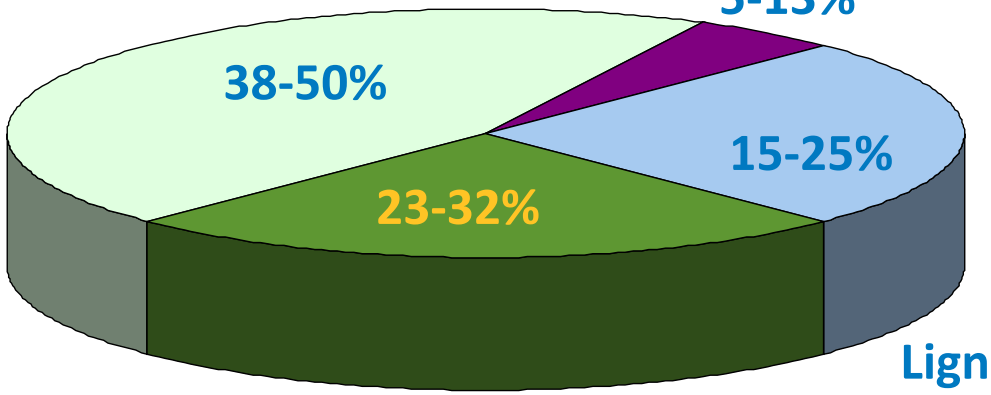
Crop residues



Softwoods



MSW



Primary Conversion Routes



Transformation through Intermediates (sugars)

Gasification (reduction to CO, H_2) and Pyrolysis

Biochemical Conversion

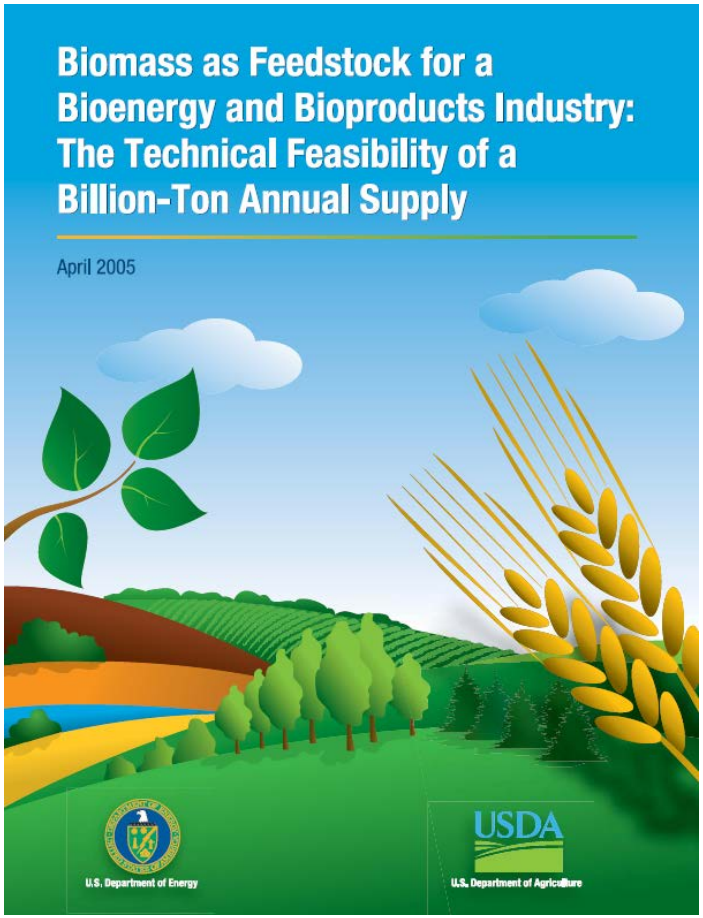
Initial focus on ethanol and mixed alcohols. Now attention turning to advanced hydroccarbon biofuels

Thermochemical Conversion

Photo by David Parsons, NREL/PIX 06809

Terrestrial Biomass Is Not Enough

- **Potential sustainable biomass production: 1.3B tons per year**
  - Ag wastes
  - Municipal solid wastes
  - Forestry wastes
  - Energy Crops
- **Convert to 130B gallons ethanol = 87B GGE**



Source: http://www1.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf

U.S. Transportation Fuel Demand

Gasoline* (Finished Motor Gasoline – E10) (cars & trucks)



126 bgy

* Peaked in 2004 at 136 bgy

Diesel (on-road, rail)



43 bgy

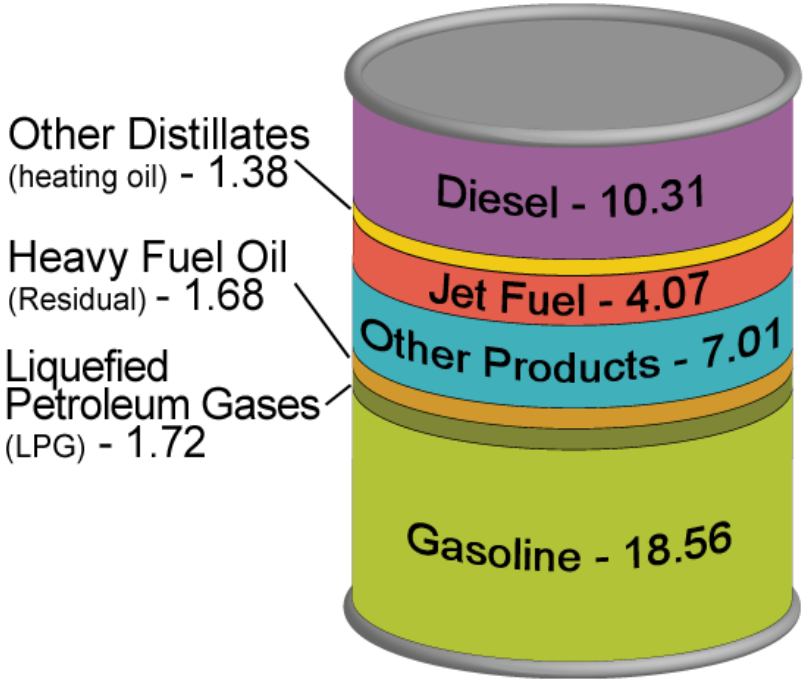
Aviation (jet fuel)



23 bgy

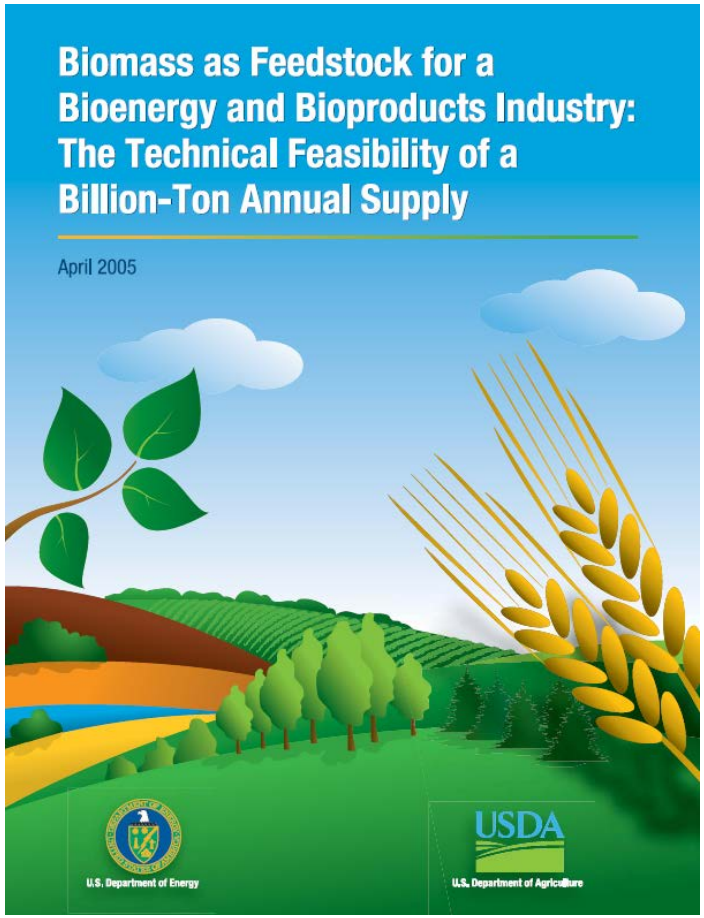
	2010	2035
Gasoline	126	116
Diesel	43	64
Jet fuel	23	27

Products in a Barrel of Crude (gal)



Source: http://www1.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf

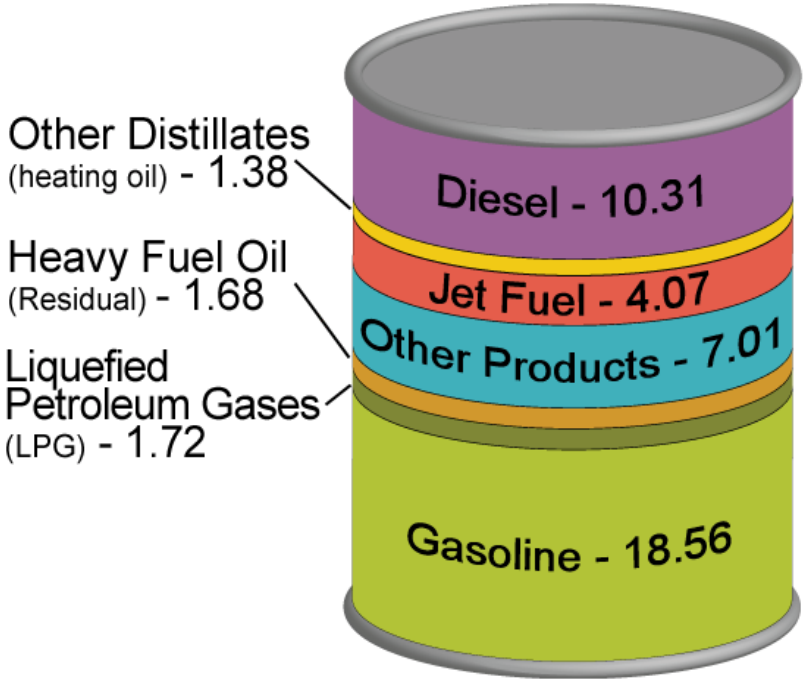
U.S. Transportation Fuel Demand



One billion tons is not enough. Ethanol only addresses the gasoline fraction.

	2010	2035
Gasoline	126	116
Diesel	43	64
Jet fuel	23	27

Products in a Barrel of Crude (gal)



Source: http://www1.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf

Multiple Paths to Energy Security

- Domestic coal and natural gas reserves can be converted to liquid fuels
- Supplement biomass to provide path to energy security
- Environmental impact
  - Greenhouse gas emissions
  - Water usage and contamination
  - Land usage



Photo by David Parsons, NREL/PIX 06734

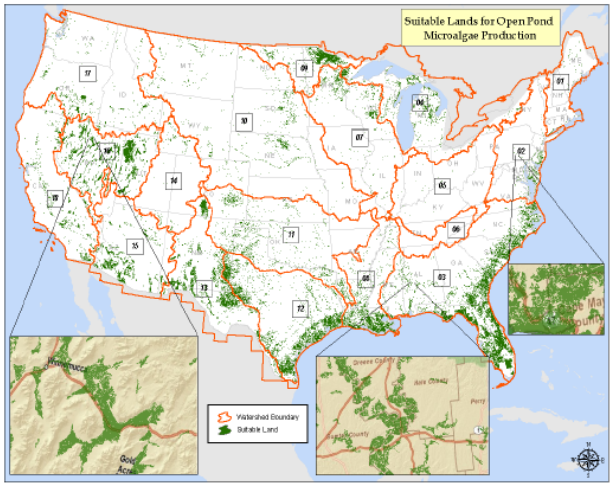


Photo by David Parsons, NREL/PIX 05048

What Can Algae Contribute?

- Wigmosta et al. evaluated available US lands appropriate for algal cultivation
  - 166,000 square miles
  - 57B gallons oil per year
- Based on conservative productivity estimates
  - 600 gallons/acre/year
  - Mascarelli (2009): 1400 gallons/acre/year
  - Weyer et al. (2010): 3800-5500 gallons/acre year
- Job creation
  - Total workers: 37,498
  - Acres per worker: 144
  - Typical farm acres per worker: 100-200

Land Constraints: Open Pond



Base data at 30 m spatial resolution

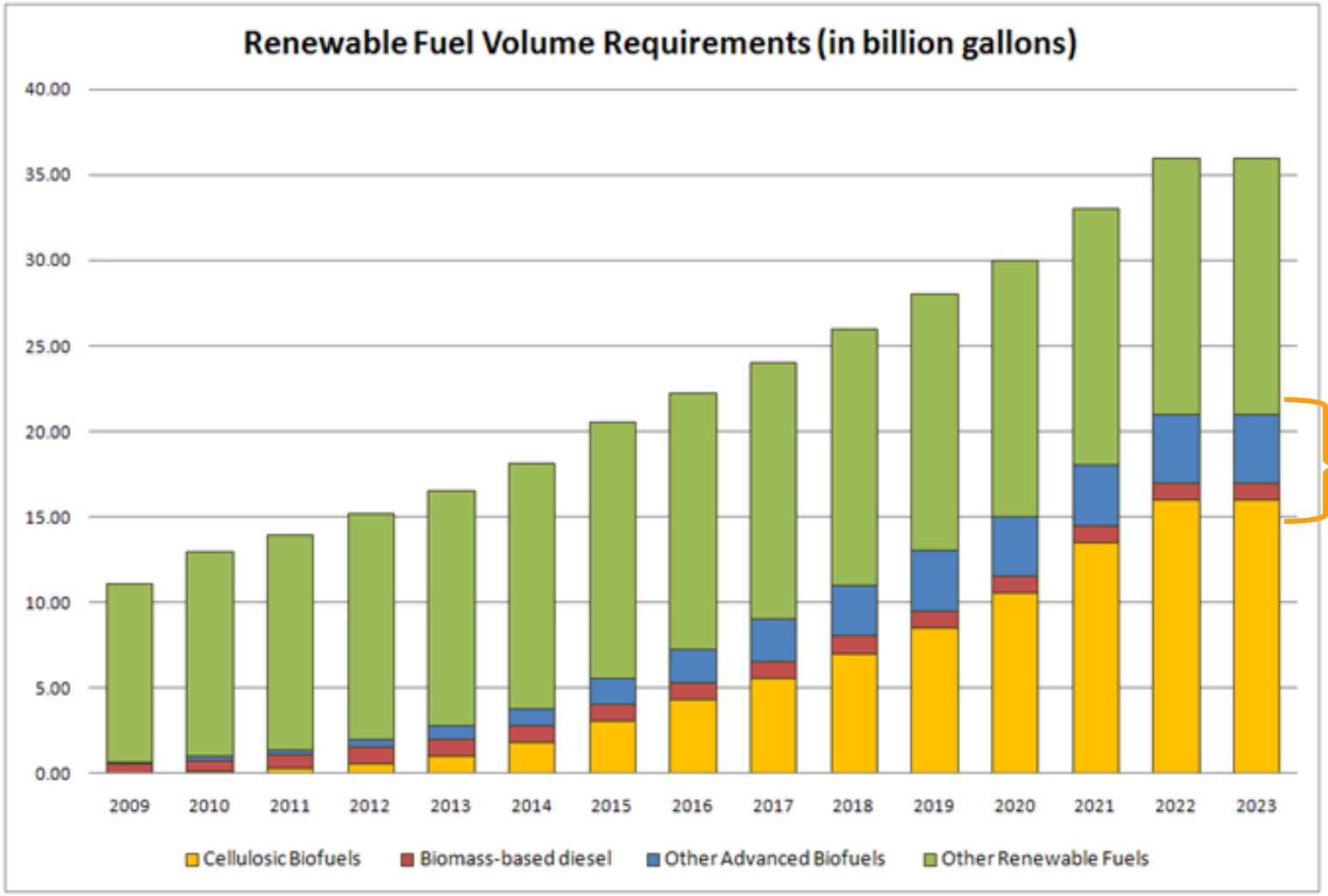
Area ≥ 1,200 ac
Slope ≤ 1 %

Exclude:
- Croplands
- Urban
- Open water
- Wetlands
- Riparian zones
- State Parks
- NPS protected
- FS protected
- Wilderness
- FWS protected
- BLM protected

- Potential: 89,756 areas (≥ 1,200 ac) suitable for open ponds
  - 430,830 km^2 of the conterminous United States
  - 5.5 % of the conterminous United States

Wigmosta, M. S., A. M. Coleman, R. J. Skaggs, M. H. Huesemann, and L. J. Lane (2011), National microalgae biofuel production potential and resource demand, Water Resour. Res., 47, W00H04, doi:10.1029/2010WR009966.
Figure courtesy Mark Wigmosta, PNNL

How Algal Biofuels Figure Into Renewable Fuel Standards



5 billion gallons could come from algae

Why Fuels from Algae?



Photo by Dennis Schroeder, NREL/PIX 18070



Photo by Warren Gretz, NREL/PIX 01723

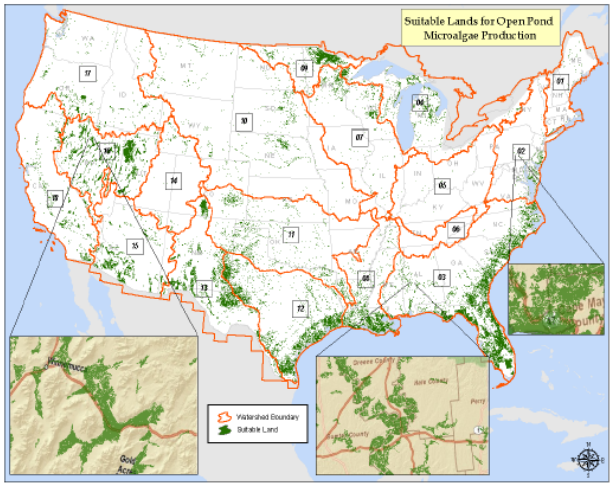
- Algae can produce more lipids per acre than terrestrial plants -- potentially 10x - 100x
- Can use marginal, non-arable land
- Can use saline/brackish water
- No competition with food, feed, or fiber
- Can utilize large waste CO_2 resources
- Potential to displace significant amount of U.S. diesel and jet fuel usage
- An algal biorefinery could produce oils, protein, and carbohydrates and a variety of other products

Input/Output

- Wigmosta et al. evaluated available US lands appropriate for algal cultivation
  - 166,000 square miles
  - 57B gallons oil per year
  - Human Resources
    - Total workers: 37,498
    - Acres per worker: 144
    - Typical farm acres per worker 100-200
  - Evaporative losses of 8 x 1,013 gallons water per year
  - 1,400 gallon water per gallon fuel

Base data at 30 m spatial resolution

Land Constraints: Open Pond



Area ≥ 1,200 ac
Slope ≤ 1 %

Exclude:
- Croplands
- Urban
- Open water
- Wetlands
- Riparian zones
- State Parks
- NPS protected
- FS protected
- Wilderness
- FWS protected
- BLM protected

- Potential: 89,756 areas (≥ 1,200 ac) suitable for open ponds
  - 430,830 km^2 of the conterminous United States
  - 5.5 % of the conterminous United States

Wigmosta, M. S., A. M. Coleman, R. J. Skaggs, M. H. Huesemann, and L. J. Lane (2011), National microalgae biofuel production potential and resource demand, Water Resour. Res., 47, W00H04, doi:10.1029/2010WR009966.
Figure courtesy Mark Wigmosta, PNNL

Bio-based Products from Algae







Photo by Toshi Otsuki, NREL/PIX 08332

Image Removed for Publication

Algae



Cyanobacteria

Image Removed for Publication

Photosynthetic Bacteria

Image Removed for Publication

Commodity Chemicals (Ethylene)

Specialty Chemicals (Carotenoids)

Fatty Acids

TAGs

Image Removed for Publication

TAGs

Refinery

Gasoline

Diesel

Jet Fuel

Photo by Dartmouth Electron Microscope Facility, Dartmouth College, NREL/PIX 19459

Comparing Potential Oil Yields

Crop	Oil Yield Gallons/acre
Corn	18
Cotton	35
Soybean	48
Mustard seed	61
Sunflower	102
Rapeseed/Canola	127
Jatropha	202
Oil palm	635
Algae (Wigmosta et al.)	600
Algae (Mascarelli)	1,400
Algae (Weyer et al.)	3,800-5,500



Photos by Oak Ridge National Lab, John De La Rosa, Warren Gretz, NREL/PIX 19965, 01768, 03016, 04078

Land Usage: A Matter of Scale



Photos by Warren Gretz, Dennis Schroeder, Bob Allan, NREL/PIX 03246, 10512, 19549

Land Usage: A Matter of Scale



Photos by Warren Gretz, Dennis Schroeder, Bob Allan, NREL/PIX 03246, 10512, 19549

What Is the Definition of Marginal Land?



Photos by Warren Gretz, NREL/PIX 08026

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Freeport, TX

Image Removed for Publication

Southeast Coast

Image Removed for Publication

Untilled Farmland

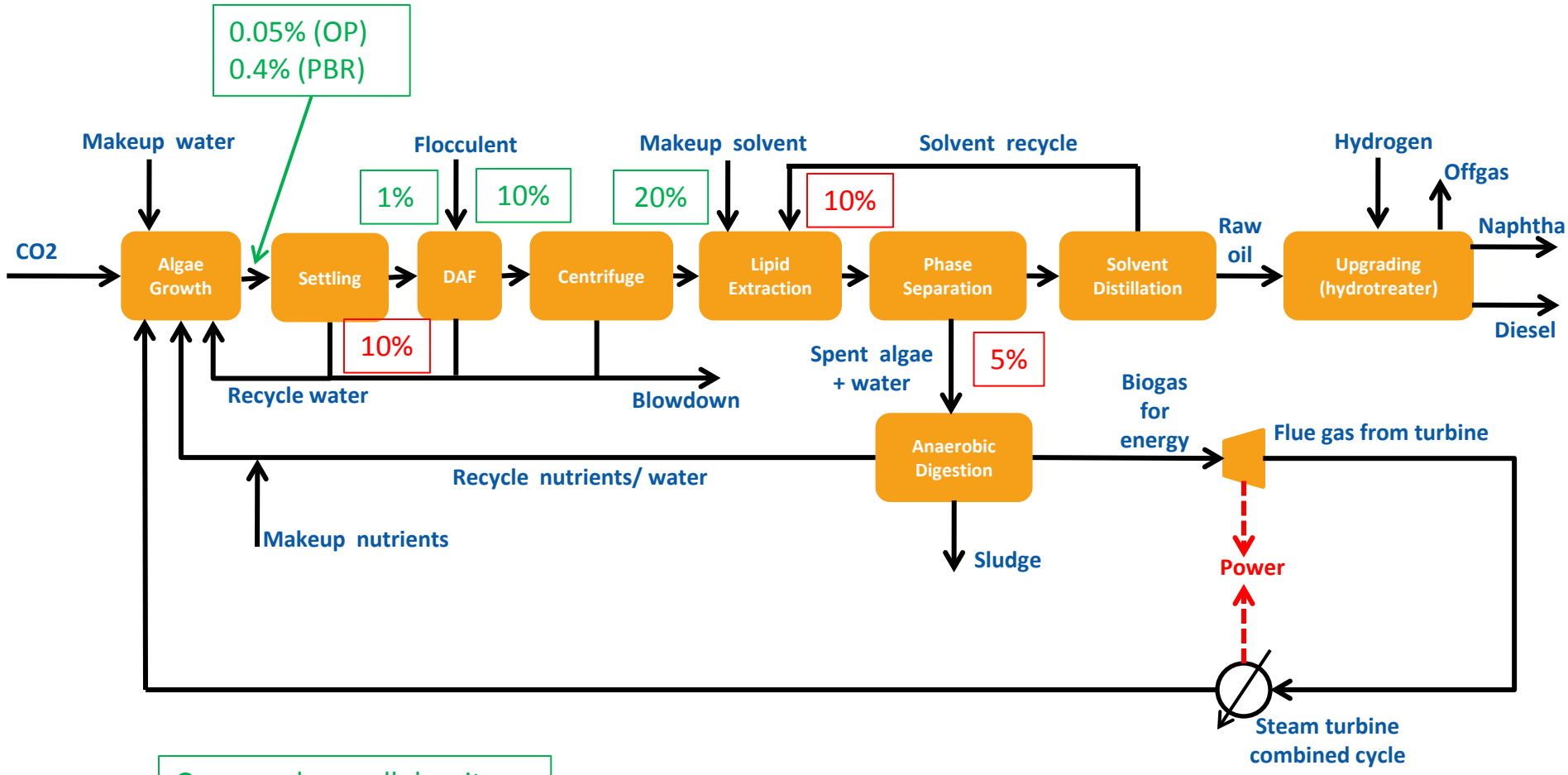
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Ft. Myers, FL

Land Usage: Competition



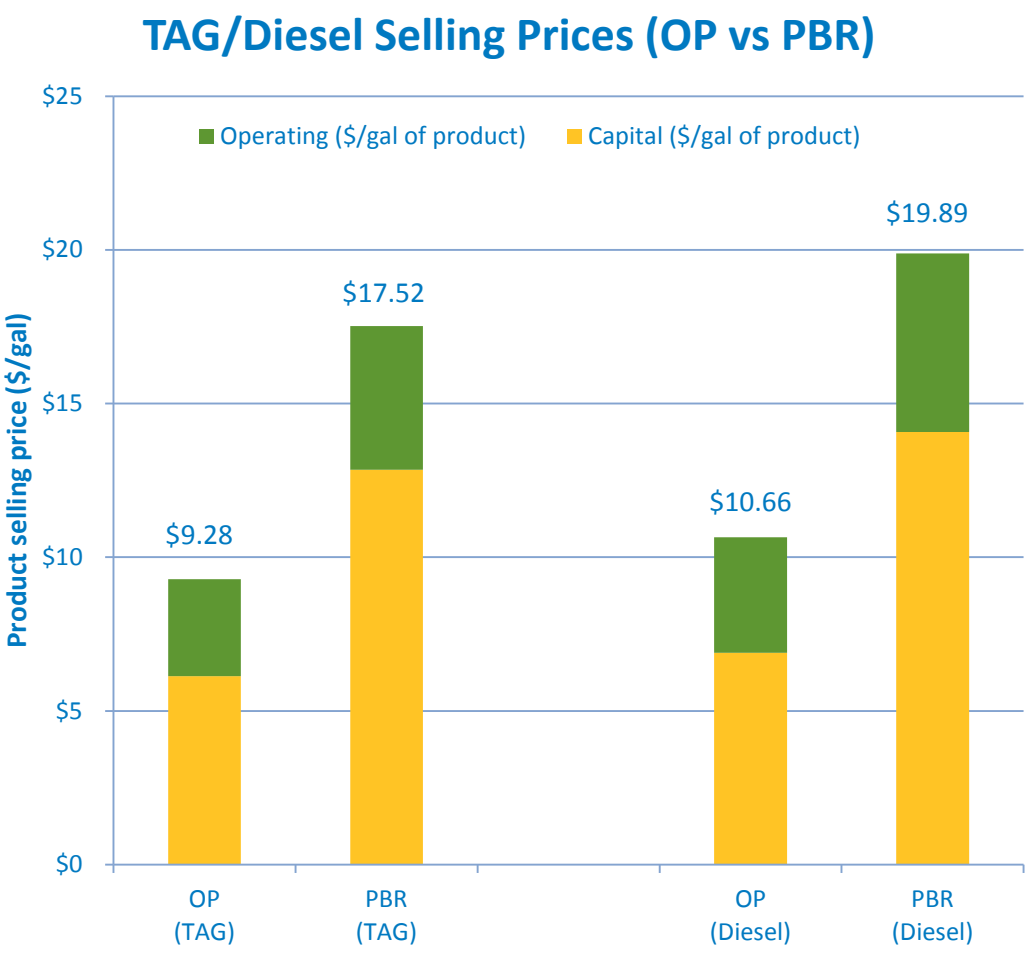
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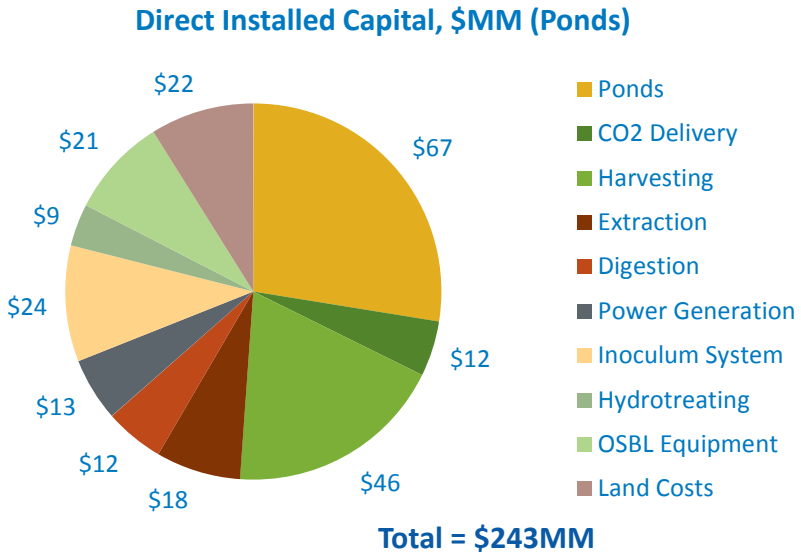


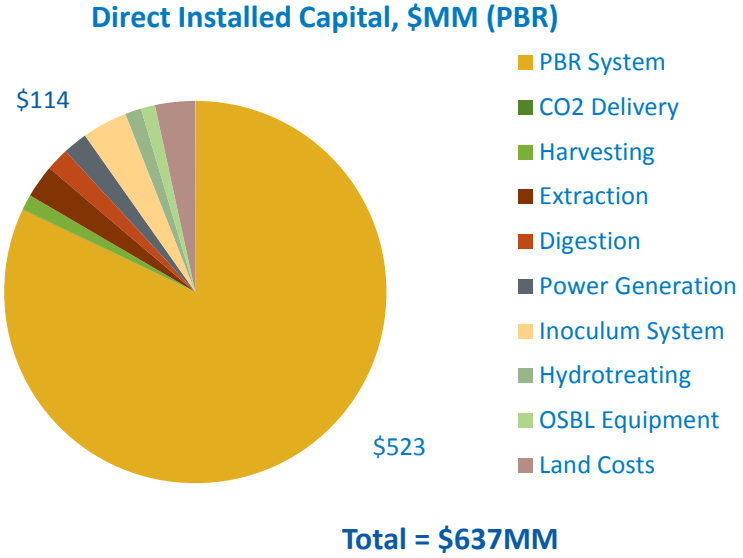
Green = algae cell density

Red = harvesting/extraction losses

Results: Baseline Costs

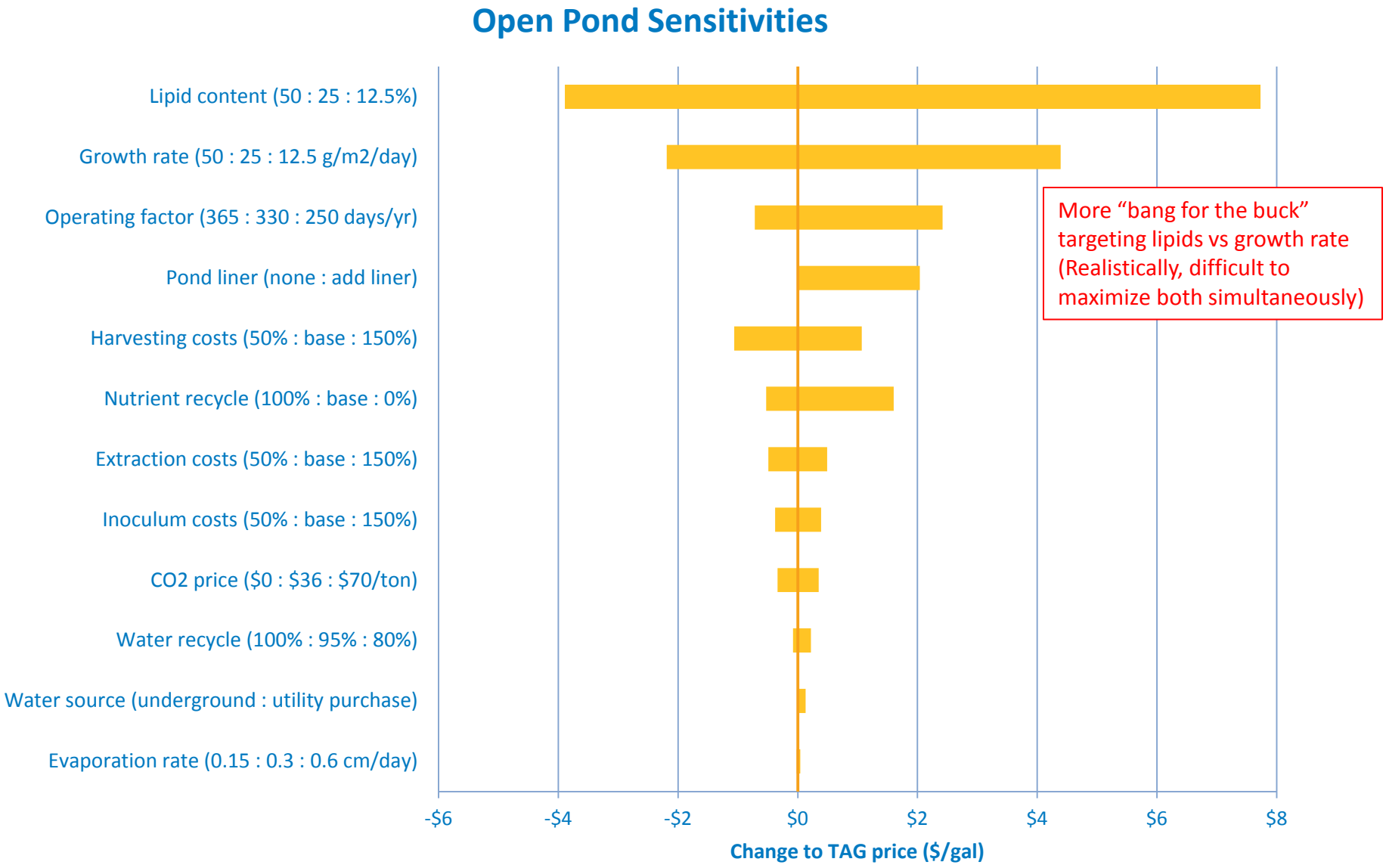




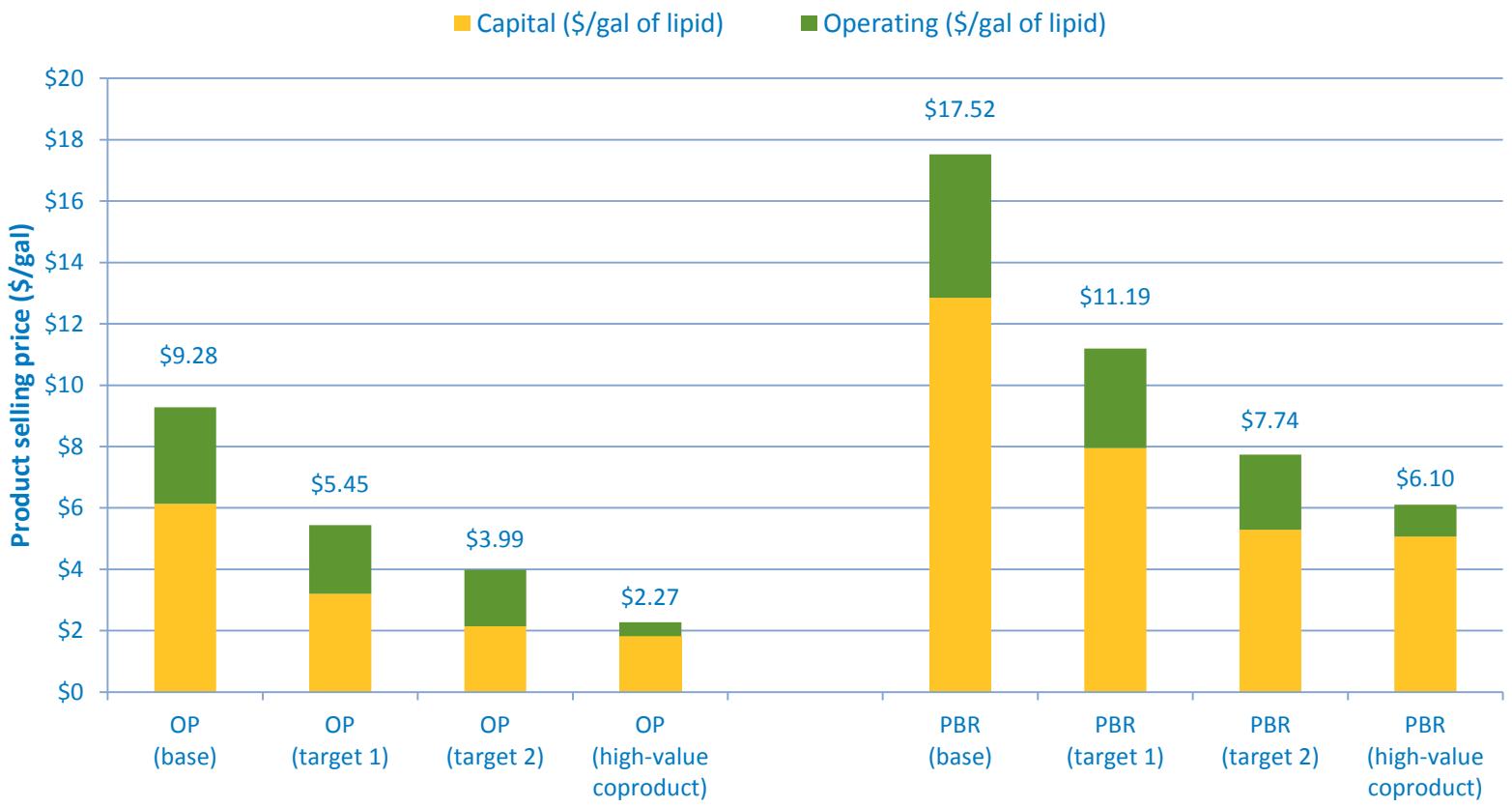


Baselines show high costs of today's currently available technologies, opportunities for cost reduction

Sensitivity: Ponds

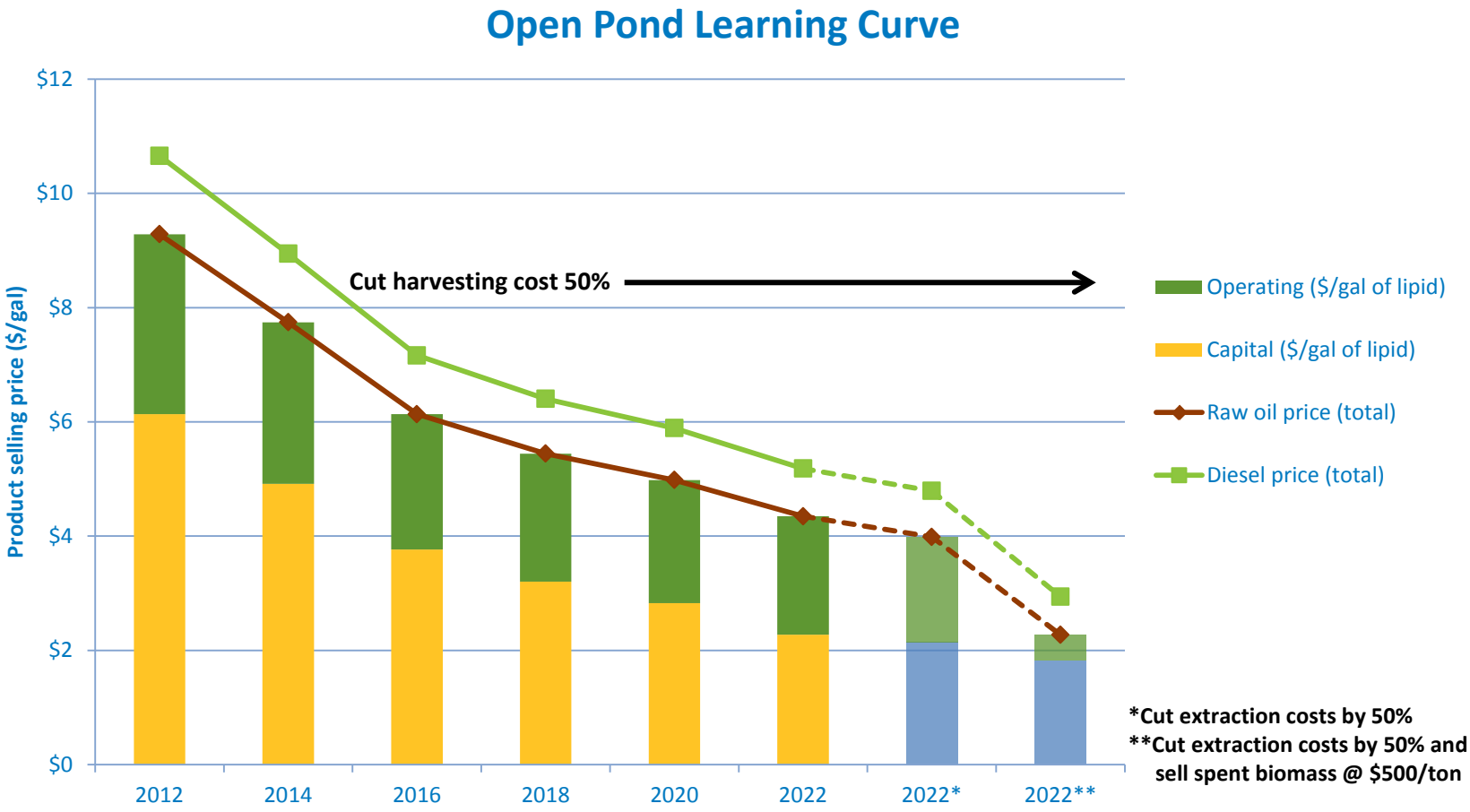


Projecting future costs



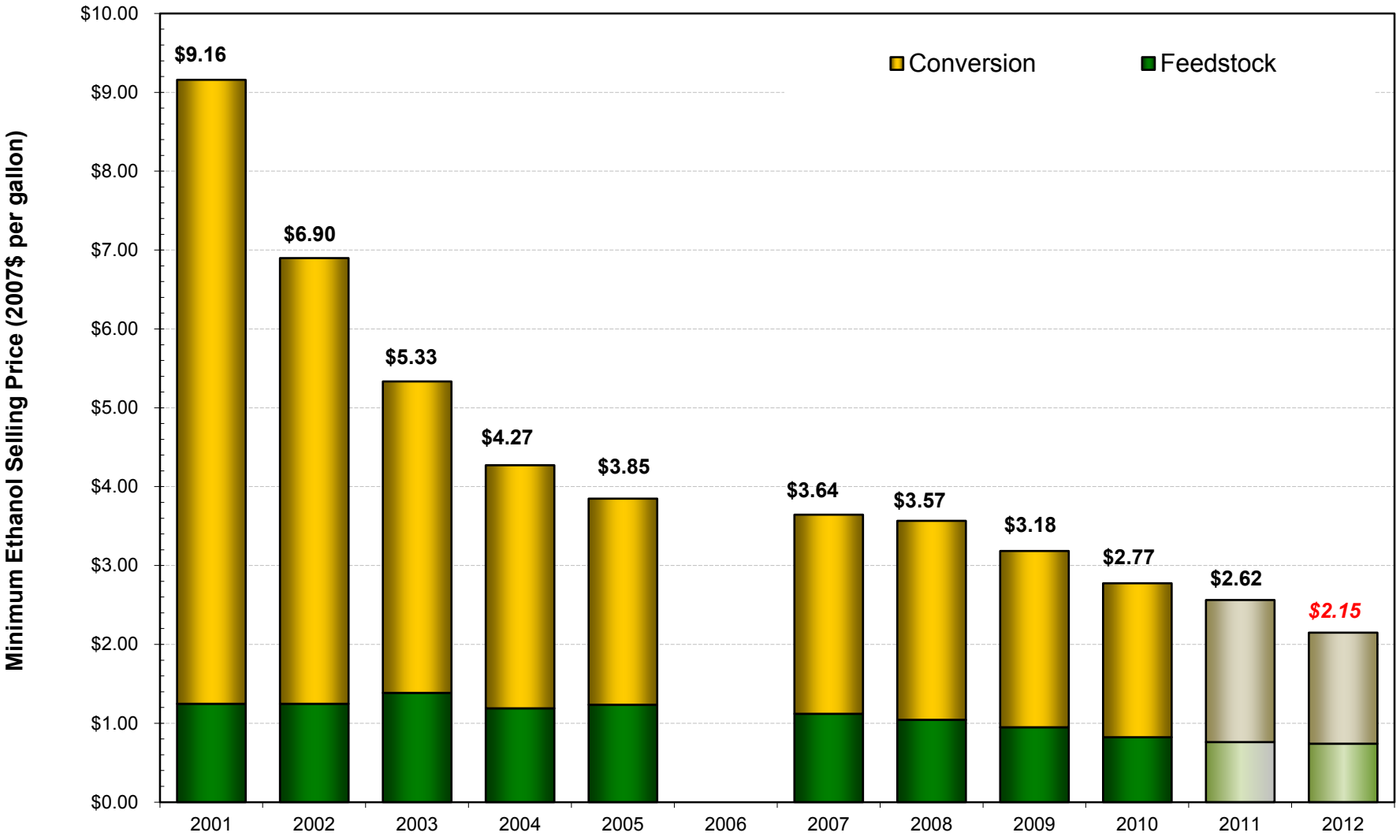
Growth rate	25 g/m²/d	25 g/m²/d	30 g/m²/d	30 g/m²/d	1.25 g/L/d	1.25 g/L/d	1.5 g/L/d	1.5 g/L/d
Lipid content	25%	40%	50%	50%	25%	40%	50%	50%
Harvesting cost	Base	Cut by 50%	Cut by 50%	Cut by 50%	Base	Cut by 50%	Cut by 50%	Cut by 50%
Extraction cost	Base	Base	Cut by 50%	Cut by 50%	Base	Base	Cut by 50%	Cut by 50%
Spent biomass utilization	AD	AD	AD	Sell @ $500/ton	AD	AD	AD	Sell @ $500/ton

Establishing cost targets (MYPP)

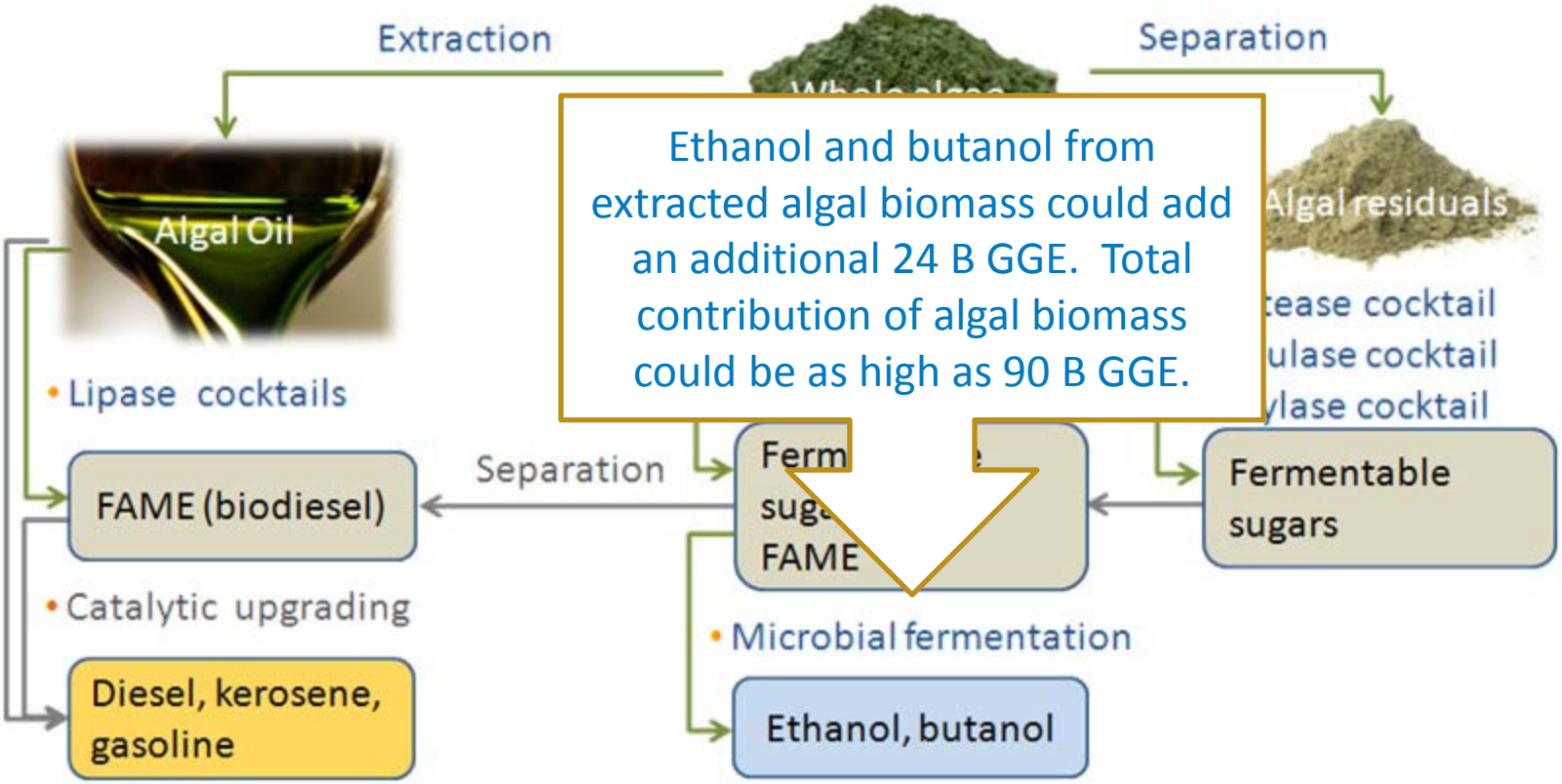


Growth rate [g/m²/day]	25	20	20	25	30	30	30	30
Lipid content [dry wt%]	25%	35%	40%	40%	40%	50%	50%	50%

Comparison to Biochemical Ethanol Cost Curve



Multiple Biomechanical Conversion Strategies and Routes of Algal Feedstocks Into Bio Fuels



Algal Biofuels Can Reshape the Food vs. Fuel Debate

- **Algal biomass used as food supplement since pre-columbian times**
- **Extracted biomass could provide approximately 180M tons protein per year**
  - Aquaculture
  - Animal feed
  - Pet food
  - Human food
- **Indirect land usage very different for algae compared to terrestrial crops**
- **Possible competition for fertilizer inputs especially potassium**
  - Recycle option for some processes
  - Capture nutrients from wastewater or natural blooms



Photos by Roger Taylor NREL/PIX 07491

Algae and Carbon Capture

- Algal biomass sufficient to produce 57B gallons oil per year would require approximately 1B tons CO_2
- This is equivalent to output from 350 500 MW coal-fired power plants or 70% of US capacity
- A 500 MW power plant would require approximately 200 square miles of algae ponds to capture CO_2
- Capture occurs only in daylight hours
- Transportation/distribution will add to capital costs
- CO_2 pipelines carry fossil CO_2
  - Collected, transported and re-injected for enhanced oil recover
  - Use for algae cultivation will add to greenhouse gases
- Concentrated forms of CO_2 (cement kilns, fermentation offgas, anaerobic digester) better scaled and more economical for transport
- Air capture CO_2 could be game changer



Conclusions

- Even by conservative calculations, algal biomass could surpass terrestrial biomass for contribution to liquid fuel replacements
- Land requirement would be significant (~5% of conterminous US area)
  - Competition for other uses
  - Indirect land use mitigated by complexity of shift from agriculture to algae culture
  - brine disposal could greatly reduce reliance on freshwater
- Algae could mitigate significant CO_2 emissions, but it will be difficult to balance local supplies and demand
- Algae could add to global food supply rather than take away
  - Issues of scale and quality must be considered