UC DAVIS SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

Reporting results of STEPS advanced biofuels cost study

8 December, 2017
STEPS Fall Symposium

Rob Williams
Development Engineer

ITS UCDAVIS INSTITUTE OF TRANSPORTATION STUDIES

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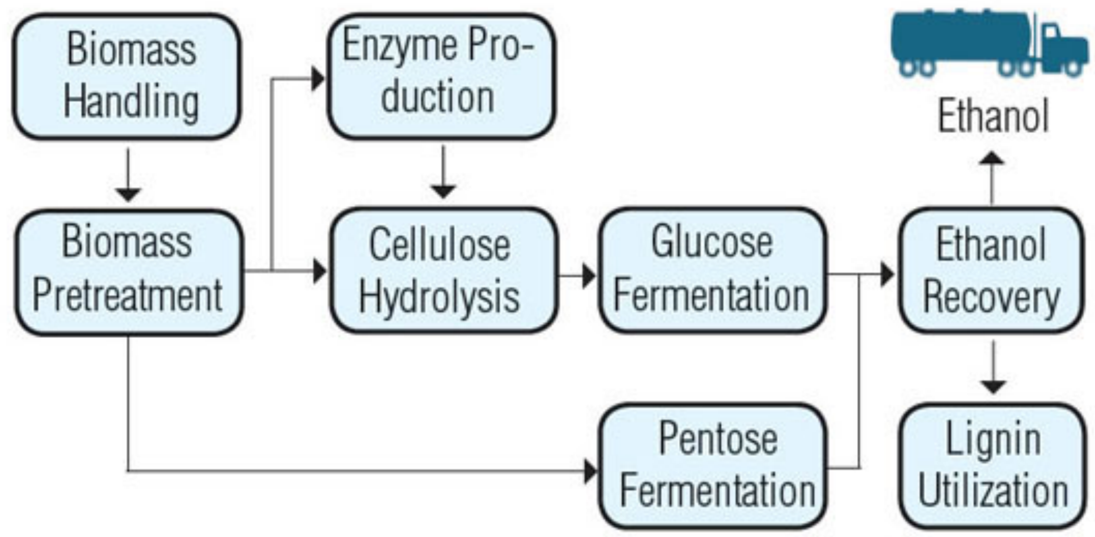
An Institute of Transportation Studies Program

Four Advanced Fuels Considered:

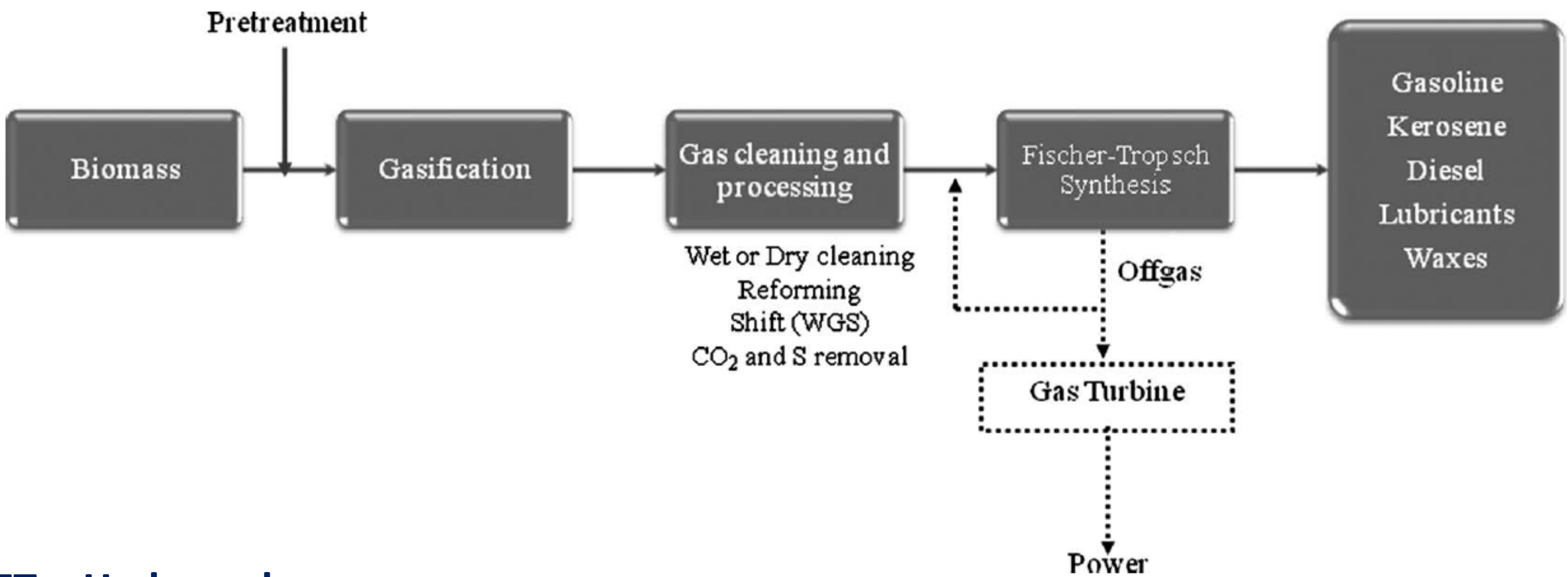
Cellulosic Ethanol



- **Cellulosic Ethanol** (Enzymatic or Acid Hydrolysis then Fermentation/Distillation)
- Feedstocks: Stovers, straw, switchgrass, etc.
- Lignin co-product
- Possible heat & power co-product

Image Source: http://switchgrass.okstate.edu/processingswitchgrasstobiofuel/liquid-biofuels

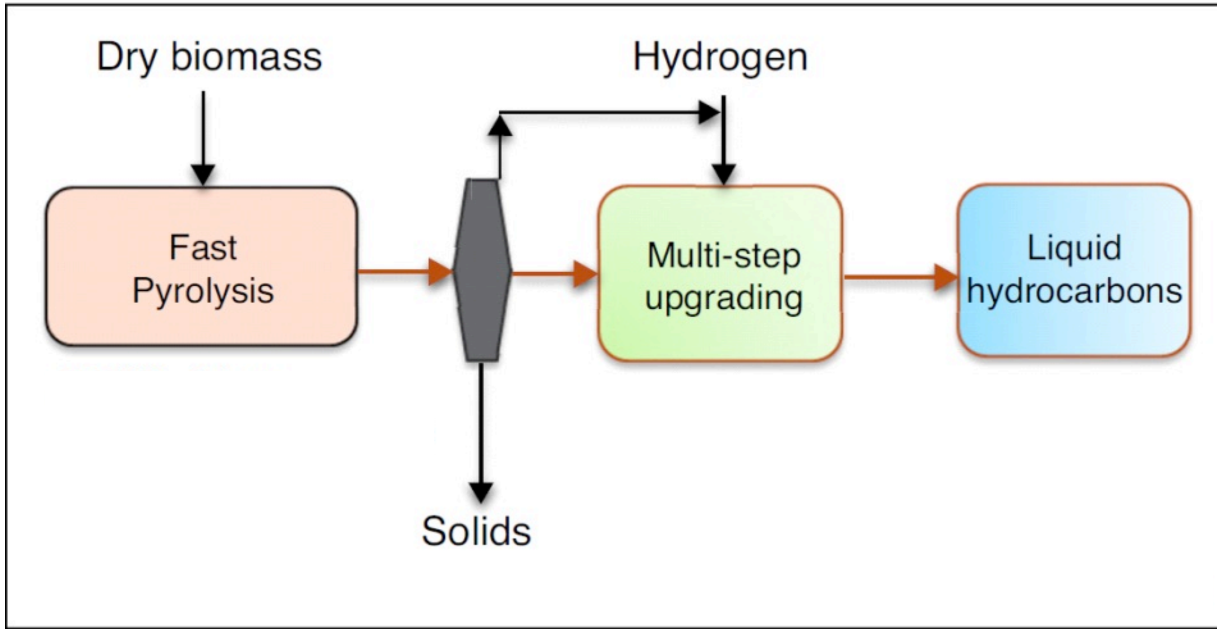
FT – Hydrocarbons
(or BTL – Biomass to Liquids)



- **FT – Hydrocarbons =**
  - **Gasification-to-Syngas-to-Fischer Tropsch Synthesis**
- Woody Biomass, stovers, straw, switchgrass, etc.
- Often heat & power co-product

Image Source: Luque, et al., (2012). "Design and development of catalysts for Biomass-To-Liquid-Fischer-Tropsch (BTL-FT) processes for biofuels production." Energy & Environmental Science **5**(1): 5186-5202.

Pyrolysis to Hydrocarbons

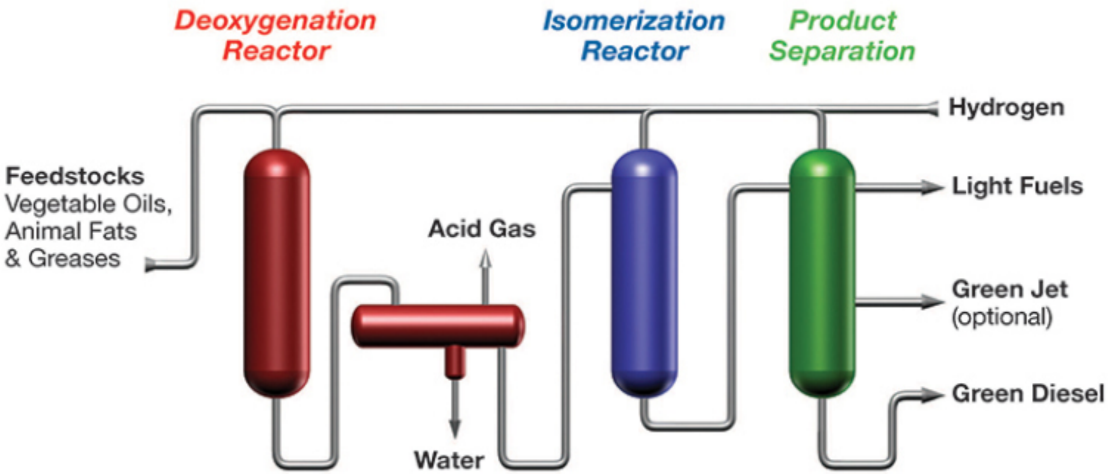


Pyrolysis to Hydrocarbons = Pyrolysis-to-biocrude then hydrotreatment

- Woody Biomass, stovers, straw, switchgrass, etc.
- Hydrogen needed
- Biochar co-product potential

Image Source:Elliott, D. C. (2015). "Biofuel from fast pyrolysis and catalytic hydrodeoxygenation." Current Opinion in Chemical Engineering **9**(Supplement C): 59-65.

HEFA Renewable Diesel



HEFA= Hydrogenated Esters & Fatty Esters (or hydrotreated vegetable oil)

-Renewable Diesel and/or Renewable Jet Product

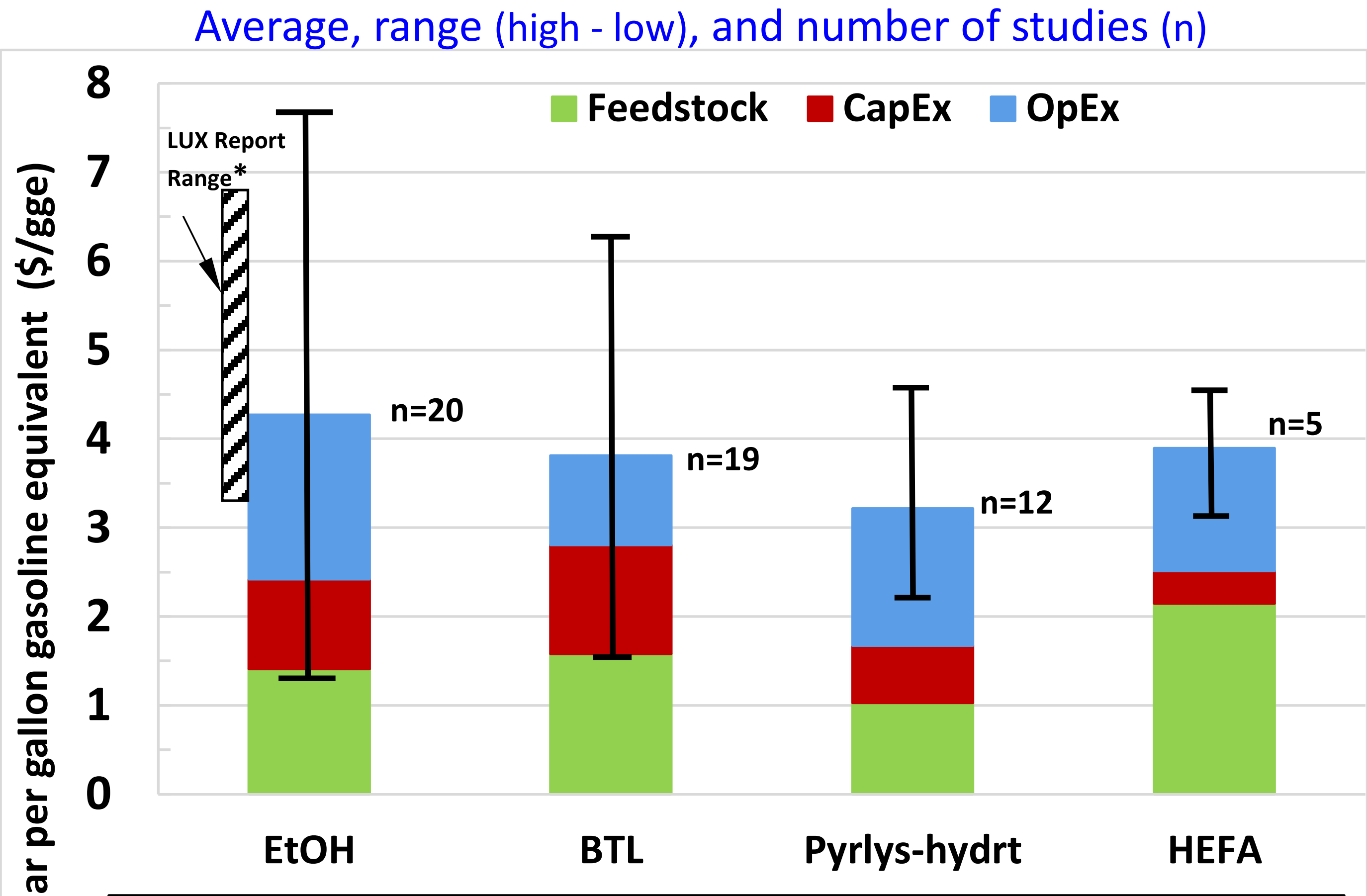
- Feedstocks: virgin and used vegetable oils, animal fats, etc.
- Hydrogen needed
- E.g., NESTE oil, UOP/Honeywell process

Image: https://www.uop.com/ecofining/#

Method Summary

- Production Cost from the Techno-economic biofuel literature:
  - Data from approximately 50 sources (1998 -2017)
    - NREL Transparent Cost Database (https://openei.org/apps/TCDB/),
    - Topped up w/ newer sources.
    - International peer reviewed lit., NREL T-E 'Aspen-type' model results, Industry trade journals.
  - Updated (converted) raw data to **year 2016 dollars** (2016 $) using:
    - Chemical Engineering Plant Cost Index (CEPCI) for capital costs and
    - Consumer Price Index (CPI) for OpEx & Feedstock costs
- Calculated a Levelized Cost of Fuel (LCOF) :
  - Dollars per Gallon-Gasoline Equivalent ($/gge)
  - Used common capital amortization schedule for all study CapEx's
    - i.e., Debt:Equity 60:40, Debt Interest = 5% for 20 years, Return on Equity = 15%, 30 year life
- Technology maturity level is early commercial deployment (i.e., some cost reductions could occur with more learning) but beyond "pioneer plant" stage
- Production Cost Only - no RIN, LCFS, or other credits accounted.

Fuel Production Cost Estimates from Literature



Key:
EtOH = Cellulosic Ethanol
BTL=Biomass to Liquid Hydrocarbons (gasification - Fischer Tropsch)
Pyrlys-hydrt = Pyrolysis-to-biocrude then hydrotreatment.
HEFA = hydrogenated esters and fatty esters.

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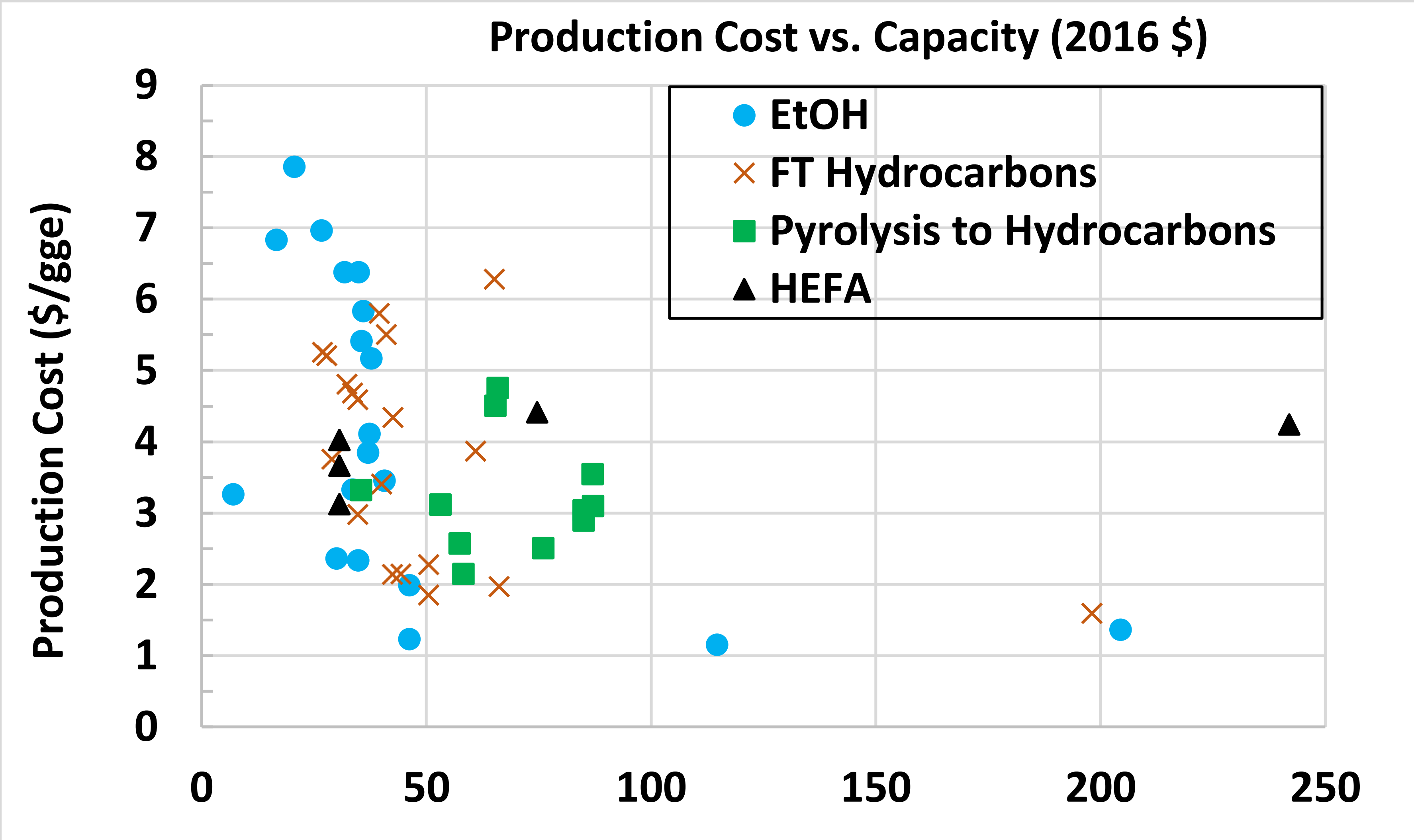
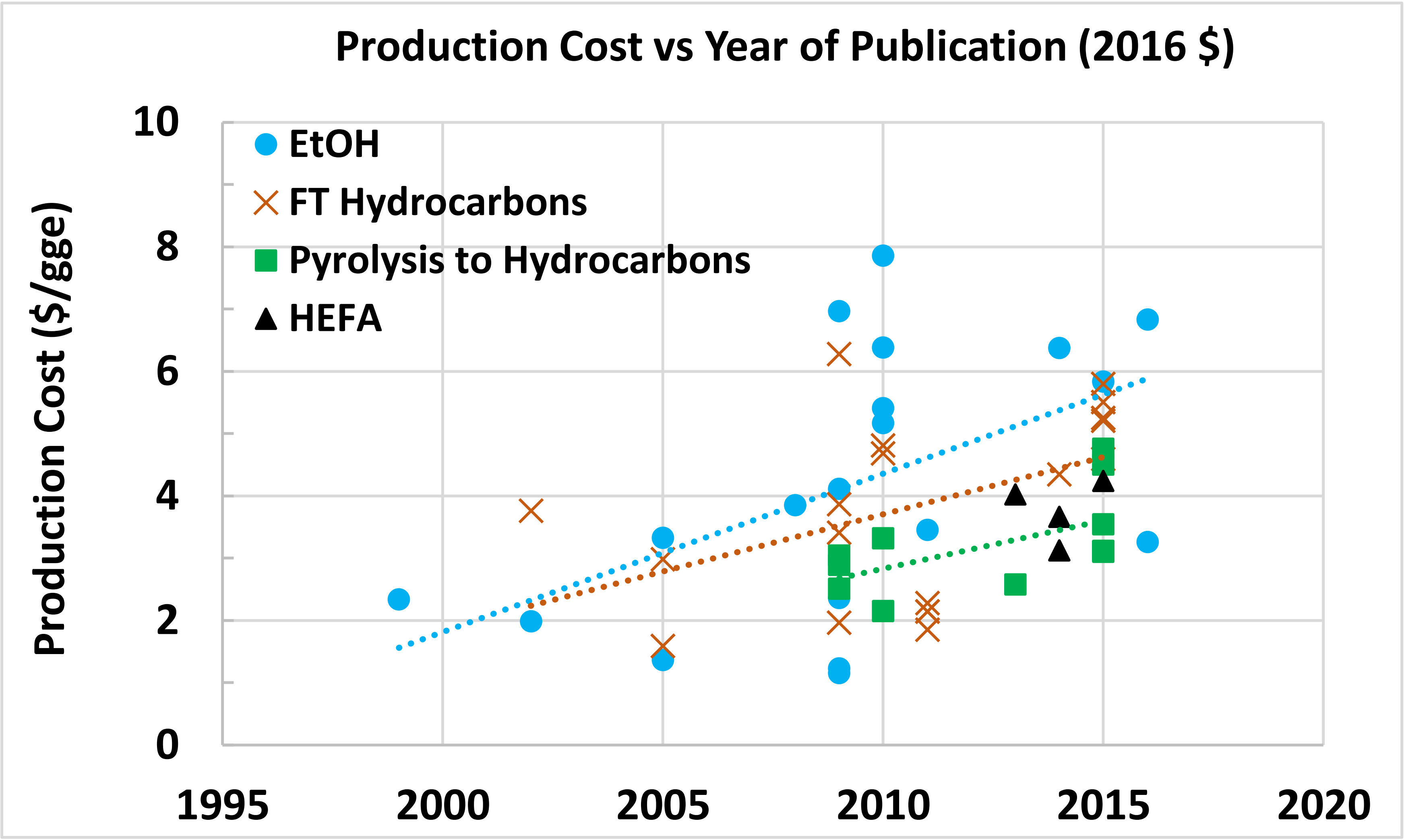

Production Cost vs. Capacity (2016 $)
Production Cost ($/gge)
9
8
7
6
5
4
3
2
1
0
0
50
100
150
200
250
EtOH
FT Hydrocarbons
Pyrolysis to Hydrocarbons
HEFA



Production Costs trend higher in newer literature

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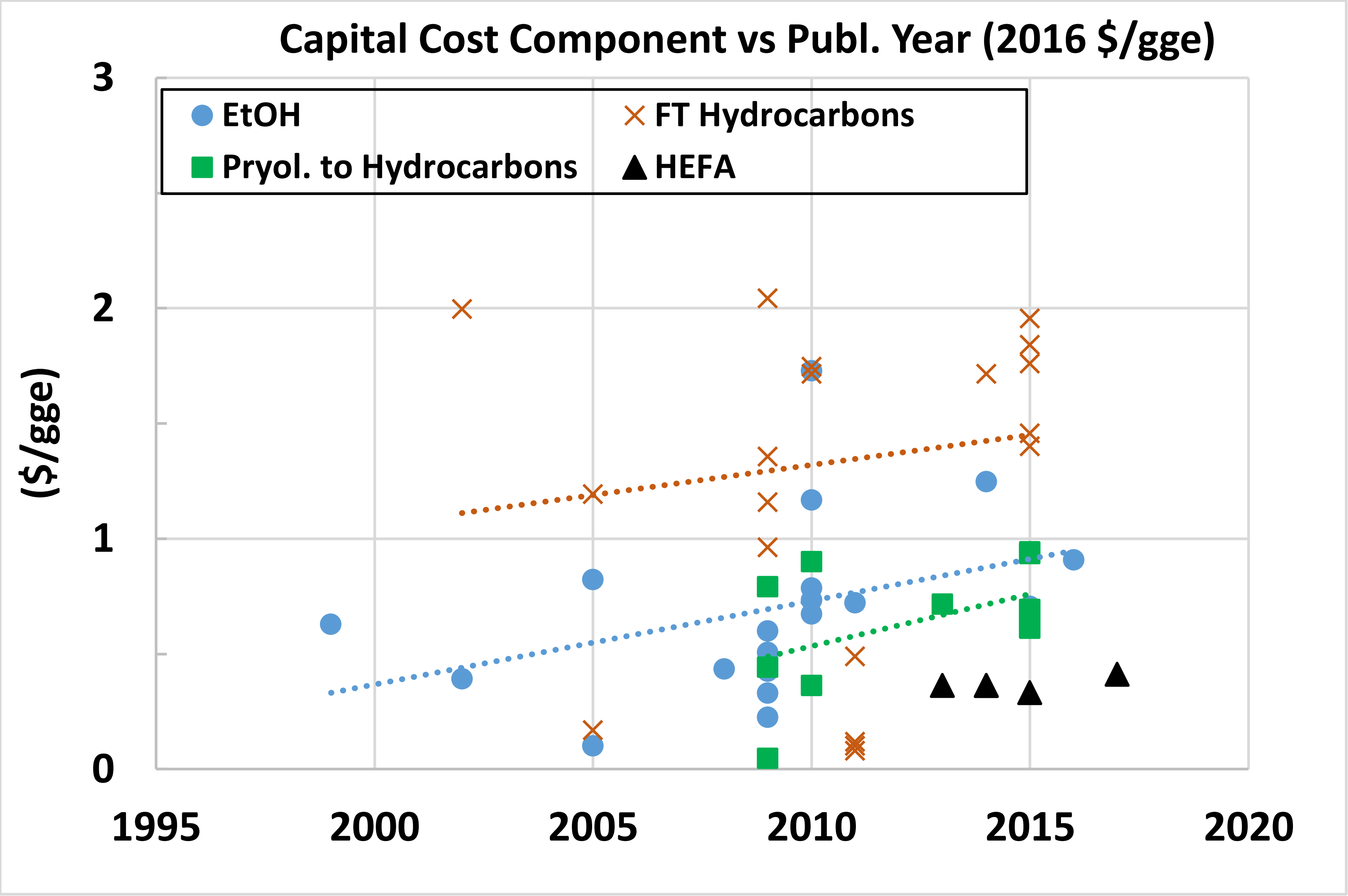

- Perhaps a real trend reflected in Ethanol studies
- Thermal conversion data is quite scattered

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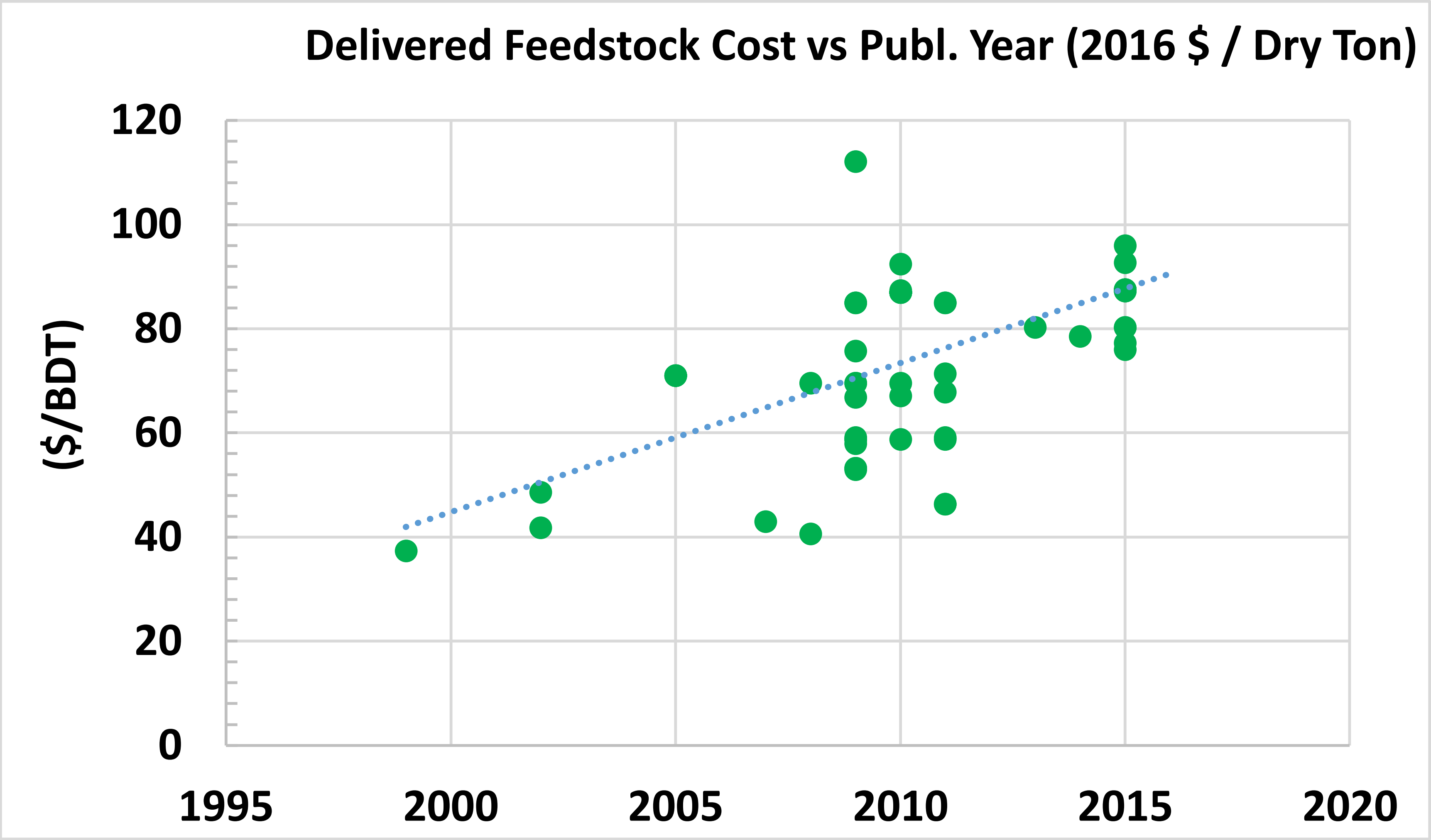
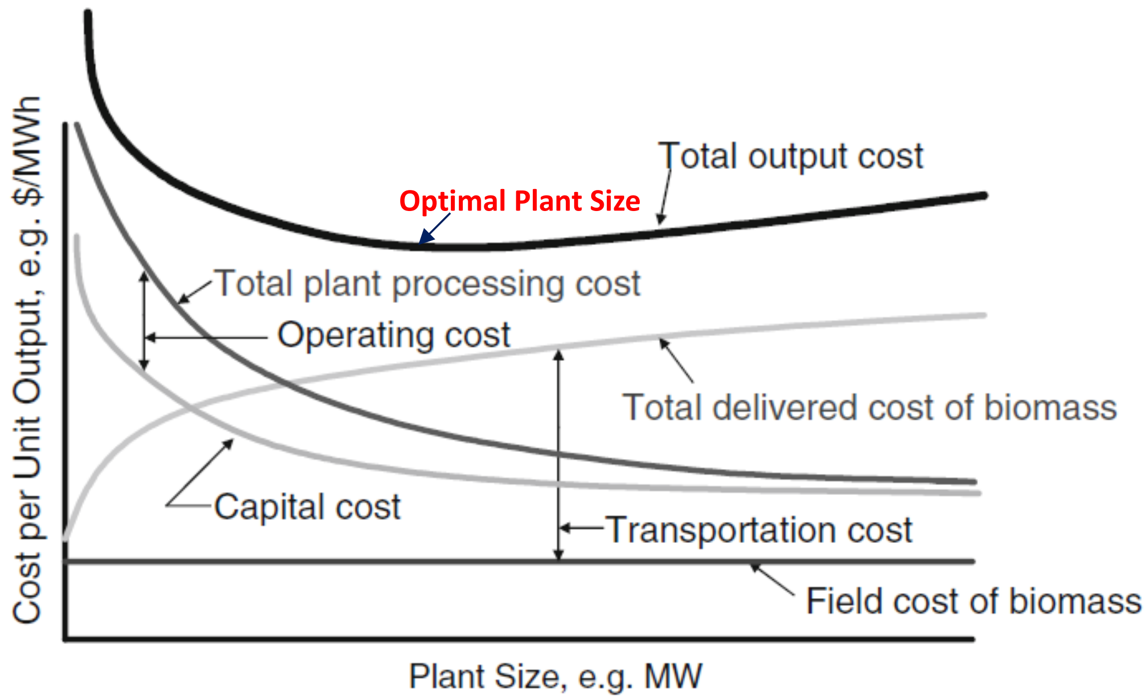


- Delivered Feedstock Costs trending up
- From < $40/dry-ton to > $90 /dry-ton
- Reduces classic optimal plant size
    - (tension between CapEx economy of scale vs. larger feedstock draw area/higher delivered cost)

Classic optimal plant size- tension between :

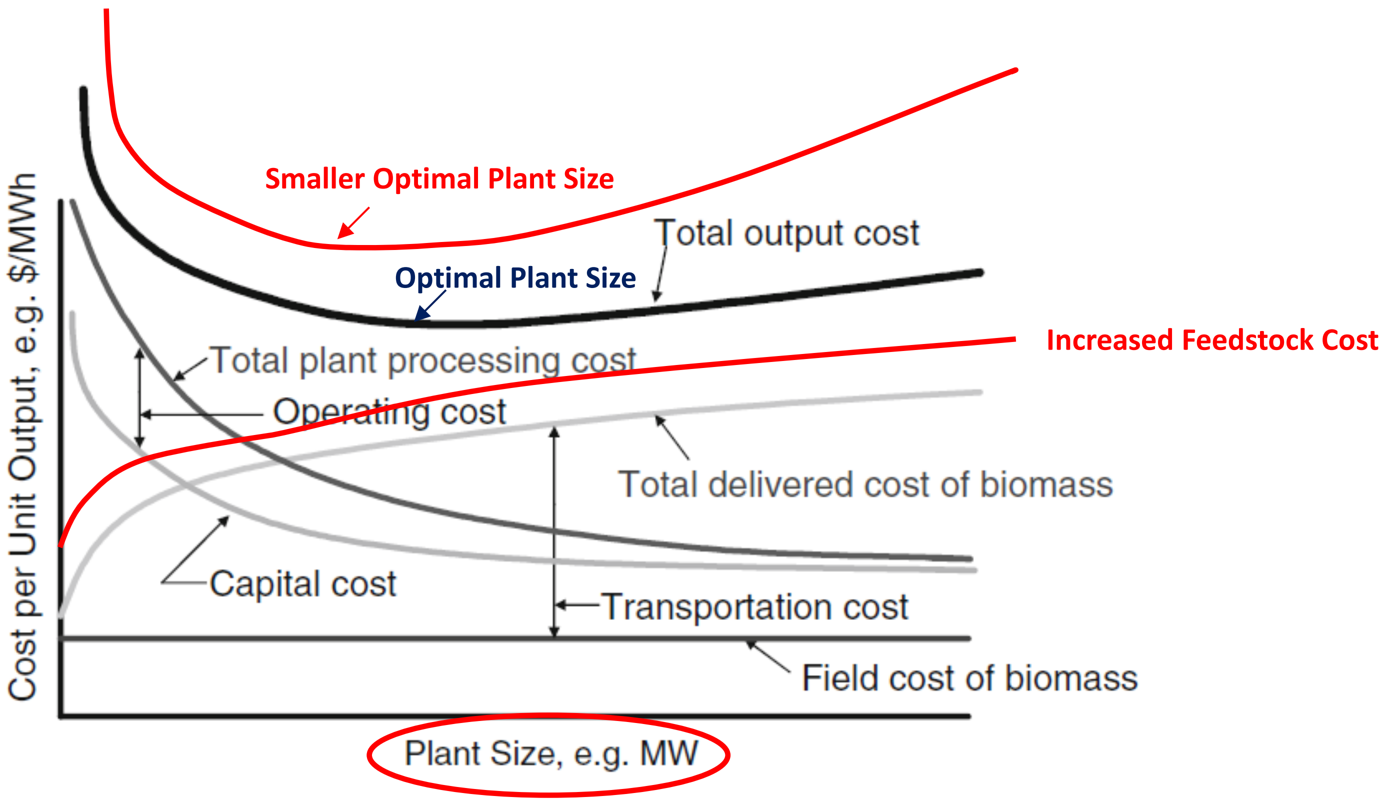
- CapEx economy of scale vs.
- larger feedstock draw area/higher delivered cost)



Searcy, E. and P. Flynn (2009). "The Impact of Biomass Availability and Processing Cost on Optimum Size and Processing Technology Selection." Applied Biochemistry and Biotechnology **154**(1-3): 271-286.

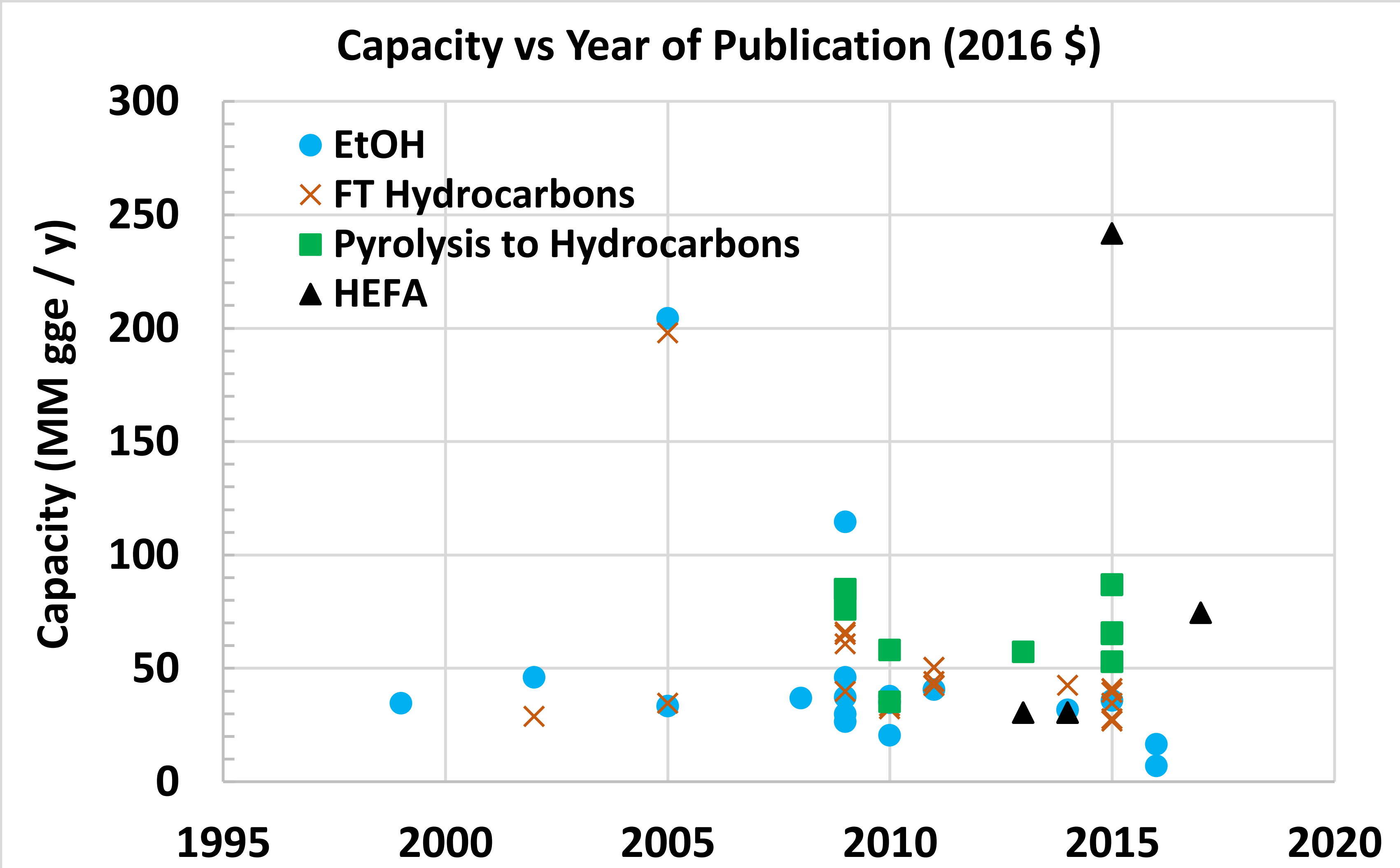
Classic optimal plant size- tension between :

- CapEx economy of scale vs.
- larger feedstock draw area/higher delivered cost)



Higher Feedstock cost reduces optimal plant size (all else equal)

Searcy, E. and P. Flynn (2009). "The Impact of Biomass Availability and Processing Cost on Optimum Size and Processing Technology Selection." Applied Biochemistry and Biotechnology 154(1-3): 271-286.

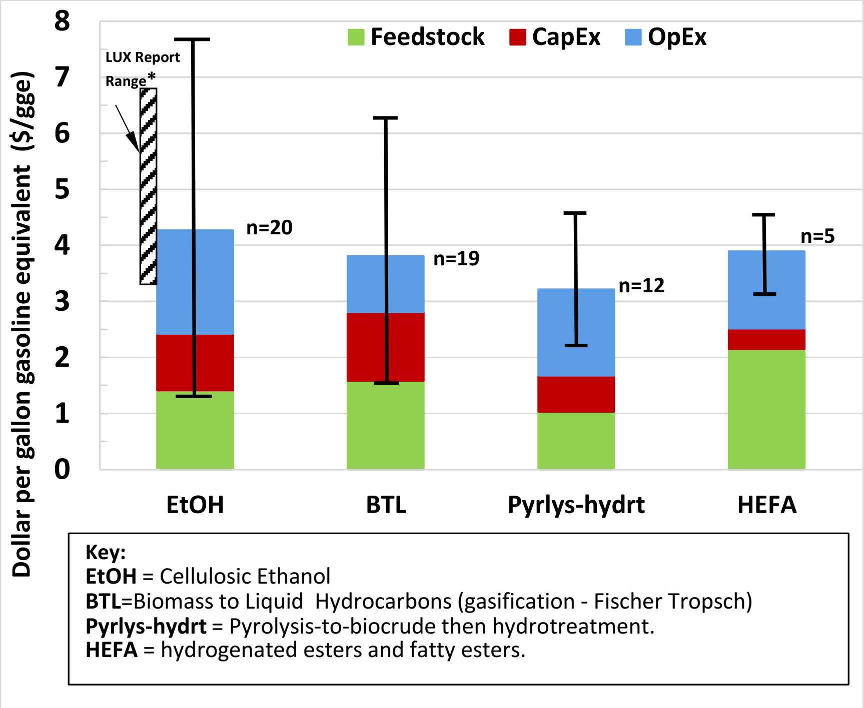


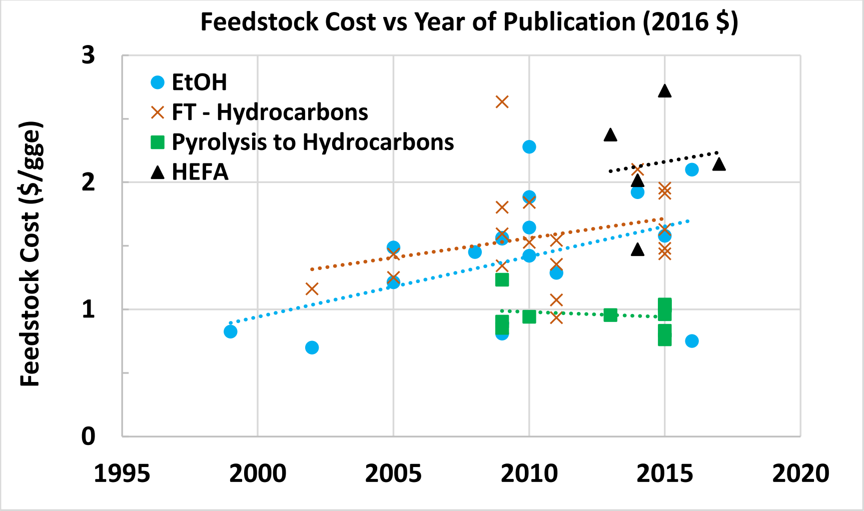
Capacity vs. Year of Publication

- Has ‘learning/experience’ or time influenced capacities reported in the literature?
- Difficult to say due to high-capacity outliers, but there maybe a slight trend to lower capacity as academics/industry learn…

Conclusions…..

- Biofuel production cost in the literature ranges from $1.15 to $7.80 per gge (2016 $)
  - Absent RIN, LCFS and other credits
- Cellulosic EtOH averages highest
- Pyrolysis to biocrude upgraded to hydrocarbons has the lowest average
- Production costs in the literature have increased over time
  - Increased raw feedstock cost
  - Increased CapEx ($/gge)
- Reduction in modeled plant sizes over time?
  - Uncertain
  - Would be influenced by feedstock cost rise





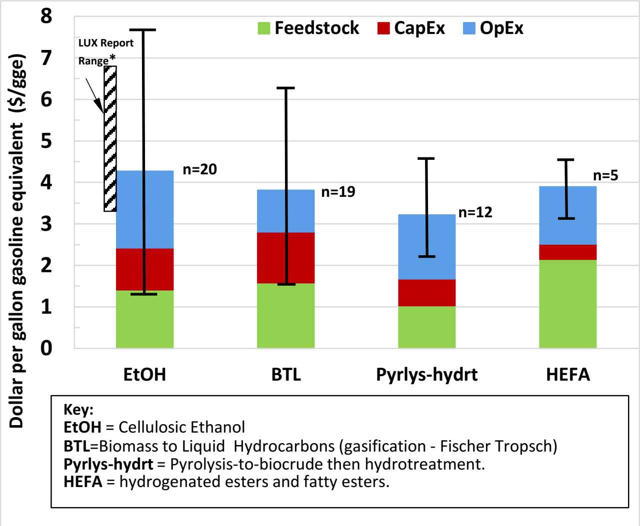
Thank you

Rob Williams
rbwilliams@ucdavis.edu

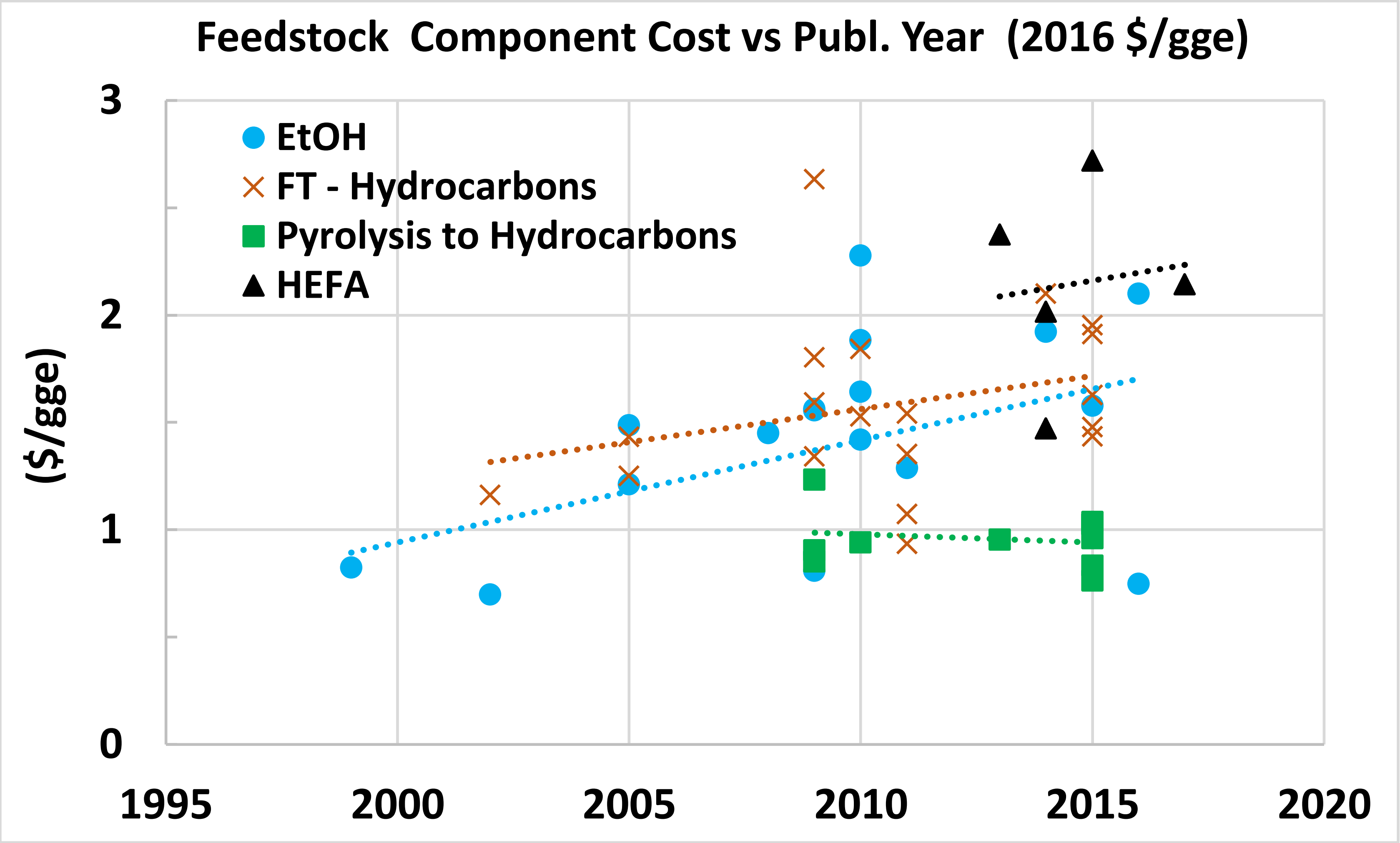
Extra Slides

Fuel Cost Estimates from Literature

Average, range (high - low), and number of studies (n)



2016 $/gge	n	High	Low	Feedstock	CapEx	OpEx	Total	Yield ave (gge/BDT)
EtOH	20	7.88	1.15	1.41	1.01	1.85	4.23	49.6
BTL	19	6.28	1.59	1.58	1.22	1.01	3.81	49.6
Pyrlys-hydrt	12	4.76	2.15	1.03	0.65	1.54	3.22	80.1
HEFA	5	4.41	3.12	2.15	0.37	1.38	3.89	257.8



- Feedstock component in fuel production cost is trending higher over time (function of delivered and processed feedstock cost ($/ton) and fuel yield (gge/ton))
- Reduces classic optimal plant size
  - (tension between CapEx economy of scale vs. larger feedstock draw area/higher delivered cost)

Separated by fuel/process type

- Clear cost rise for EtOH studies over time (1999 – 2016)
- Also for FT- Hydrocarbons (gasification-syngas-Fischer Tropsch liquid synthesis- hydrocarbons), though not as steep (2002-2015)
- Pyro-to-Hydrocarbons, essentially constant 2009 - 2015