Feedstocks for biogas and how it replaces 50% of US transportation fuel

Arpa-E Rewiring AD Workshop – Post-Conference Submission

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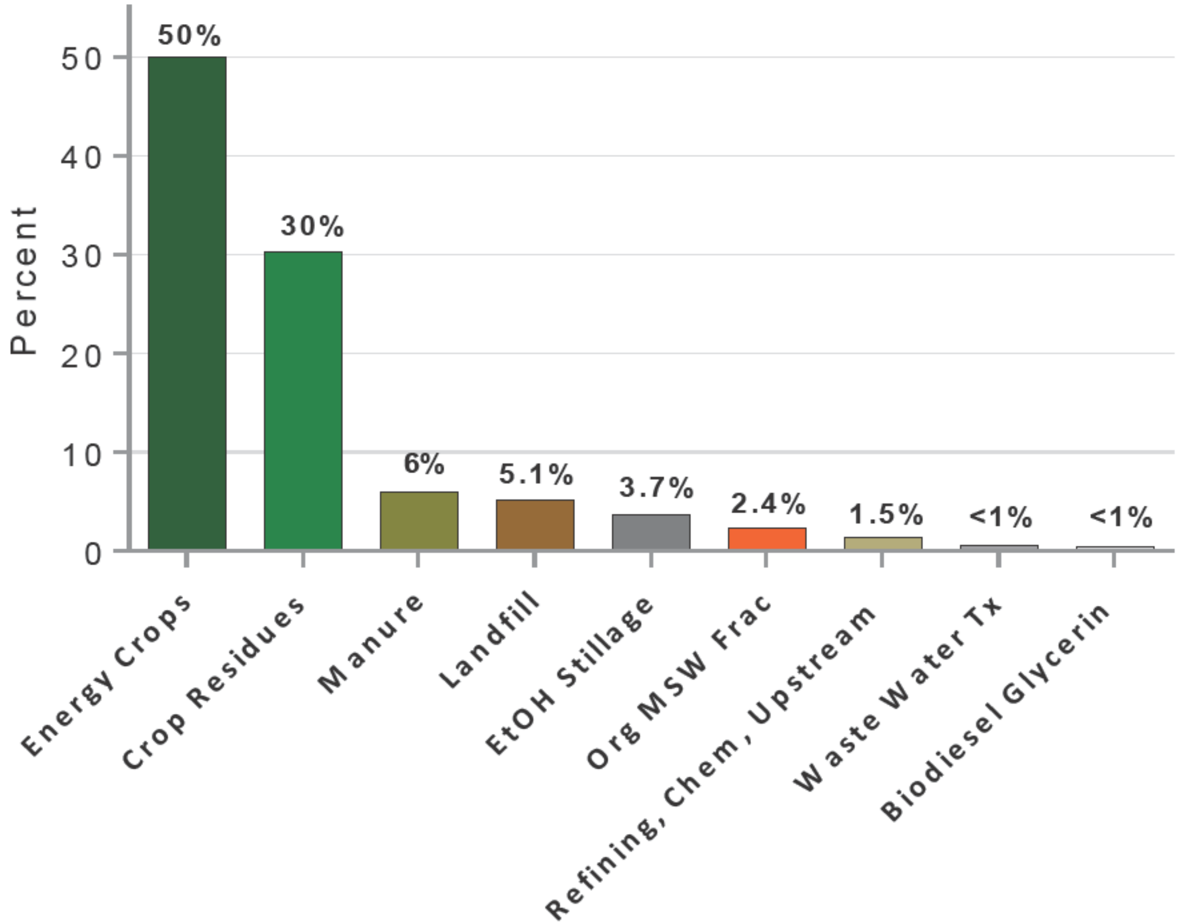
U.S. Biogas Potential from Crops, Residues & Waste

- Significant biogas feedstocks include **energy crops and crop residues**, only to a lesser degree **manure, organic waste**
- Taking all feedstocks into account, the US can replace **51% of fossil transportation fuel** through biogas (**8.81 Quad or 77 billion GGE**)
- From crop residues & waste alone, 33 states could generate >10% of their transportation fuel (4 Quad / 35 billion GGE)
- From crop residues and waste streams alone at least 8,300 plants would be needed, for a total of $210 billion in investment, creating 2.5 million jobs
- Extending biogas to energy crops would add 5,000 plants, $240 billion in investment, and 2.8 million jobs more
- Unique opportunity to replace 50% of fossil transportation fuel:
  - renewable, domestic, sustainable **cellulosic biofuel**: biogas
  - proven technology with **compelling economics** for investors, consumers
  - creates **significant number of domestic jobs** in rural & city economies
  - **lowers the U.S. GHG footprint** with low carbon fuels

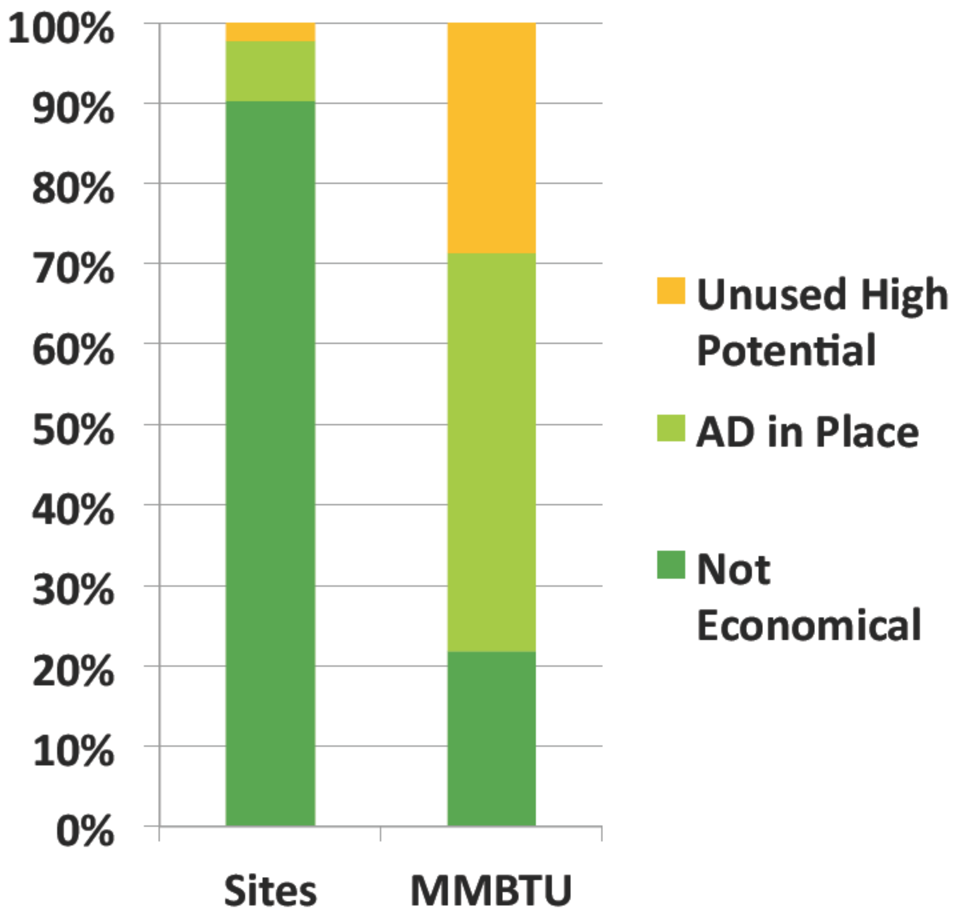
In sum: Biogas can replace 51% of US fossil transportation fuel

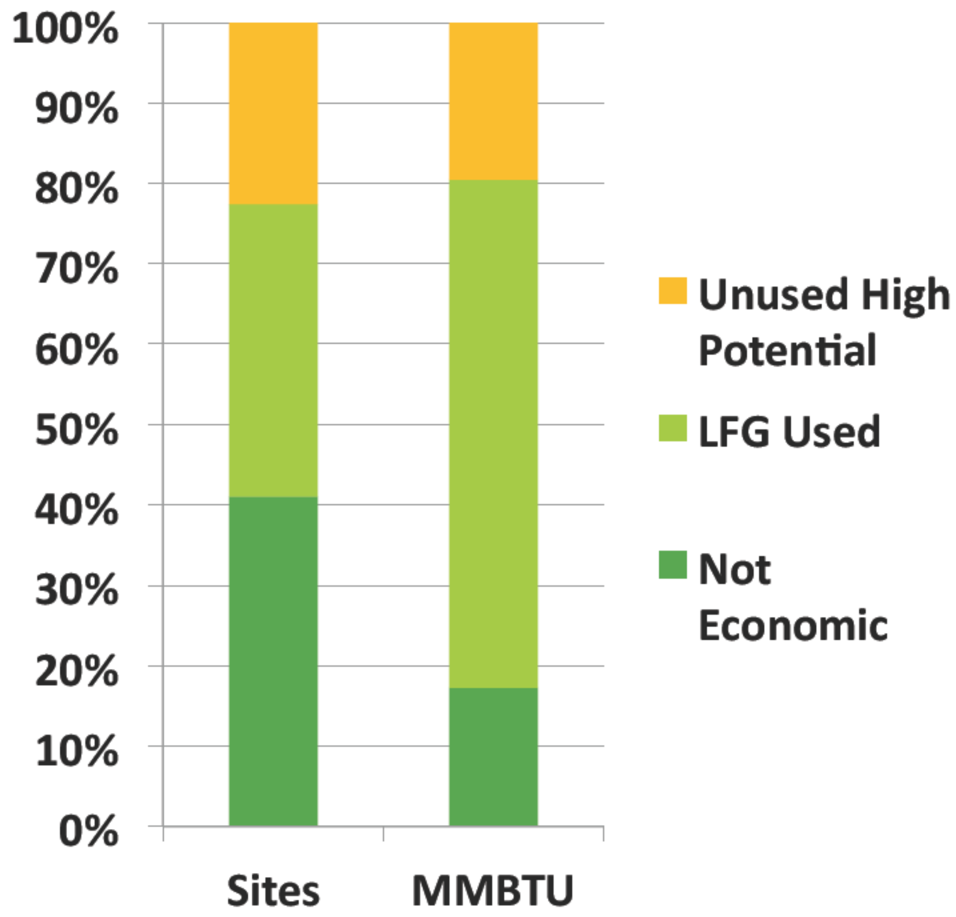


➢ **US Potential = 8.81 Quad / 77 billion GGE**

Unpublished data

WWTP and Landfills offer only limited untapped potential





- 351 untapped, feasible WWTP with 22.4 BCF / 196.5 million GGE potential
- 349 untapped, feasible landfills with 106.4 BCF / 933.6 million GGE potential

Organic fraction of MSW is most challenging

Source Data, Methodology, Assumptions

- EPA's 2011/2012 MSW Facts & Figures: data only at national level
- Up to 55% of MSW likely digestible
- BioCycle/Columbia 2013 survey has state-level data only
- 2011 data by D. Shin
- Organic MSW fraction from landfilled MSW assumed to be 35%: 86.5 million tons per year

Food Waste

47.3%

Paper & Paper Board

33.1%

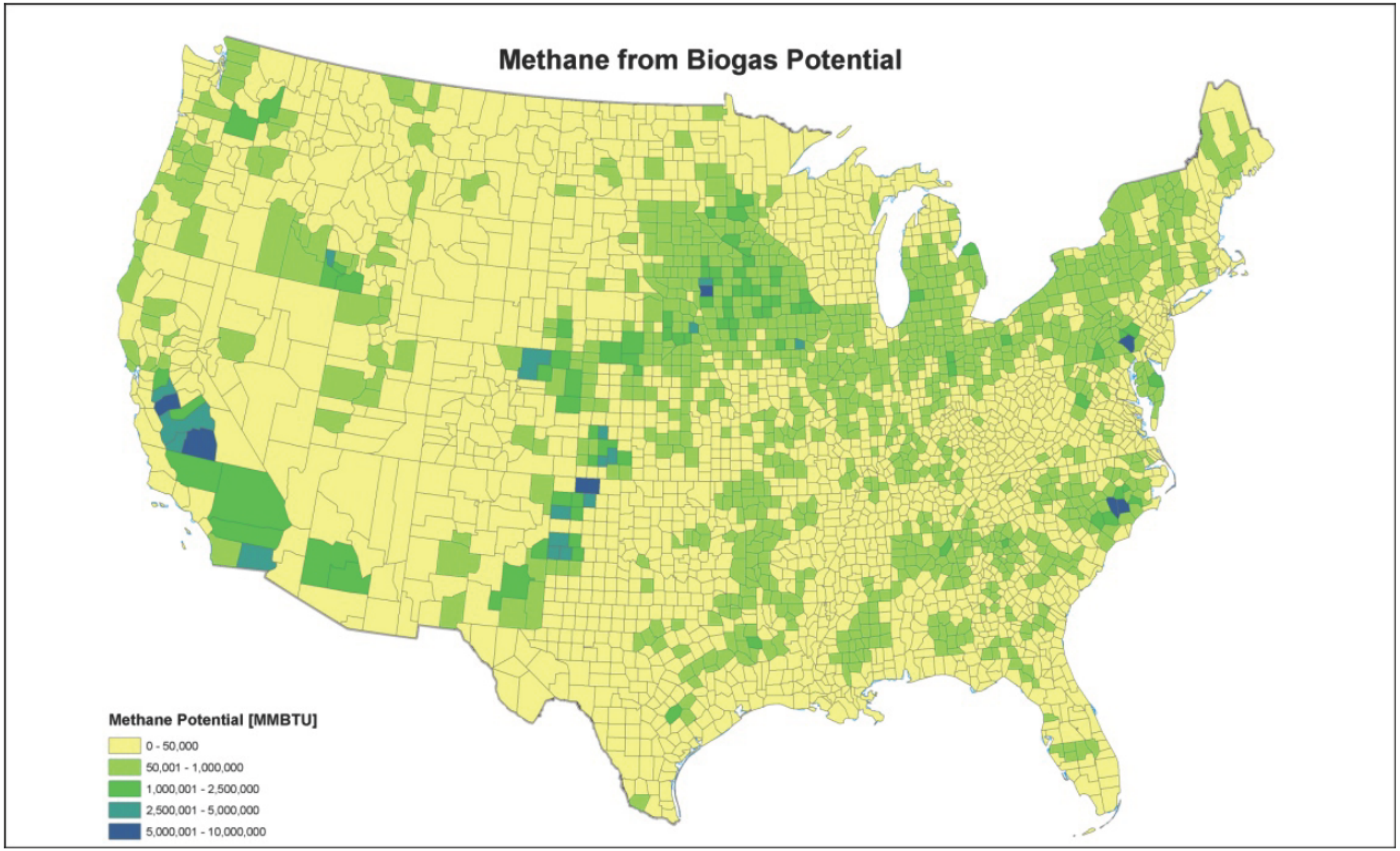
Yard Trimmings

19.6%

- ➢ **US Potential = Only 210.7 BCF / 1,848 million GGE (net)**
- ➢ **Merely 1/10th potential vs. Crop Residues**

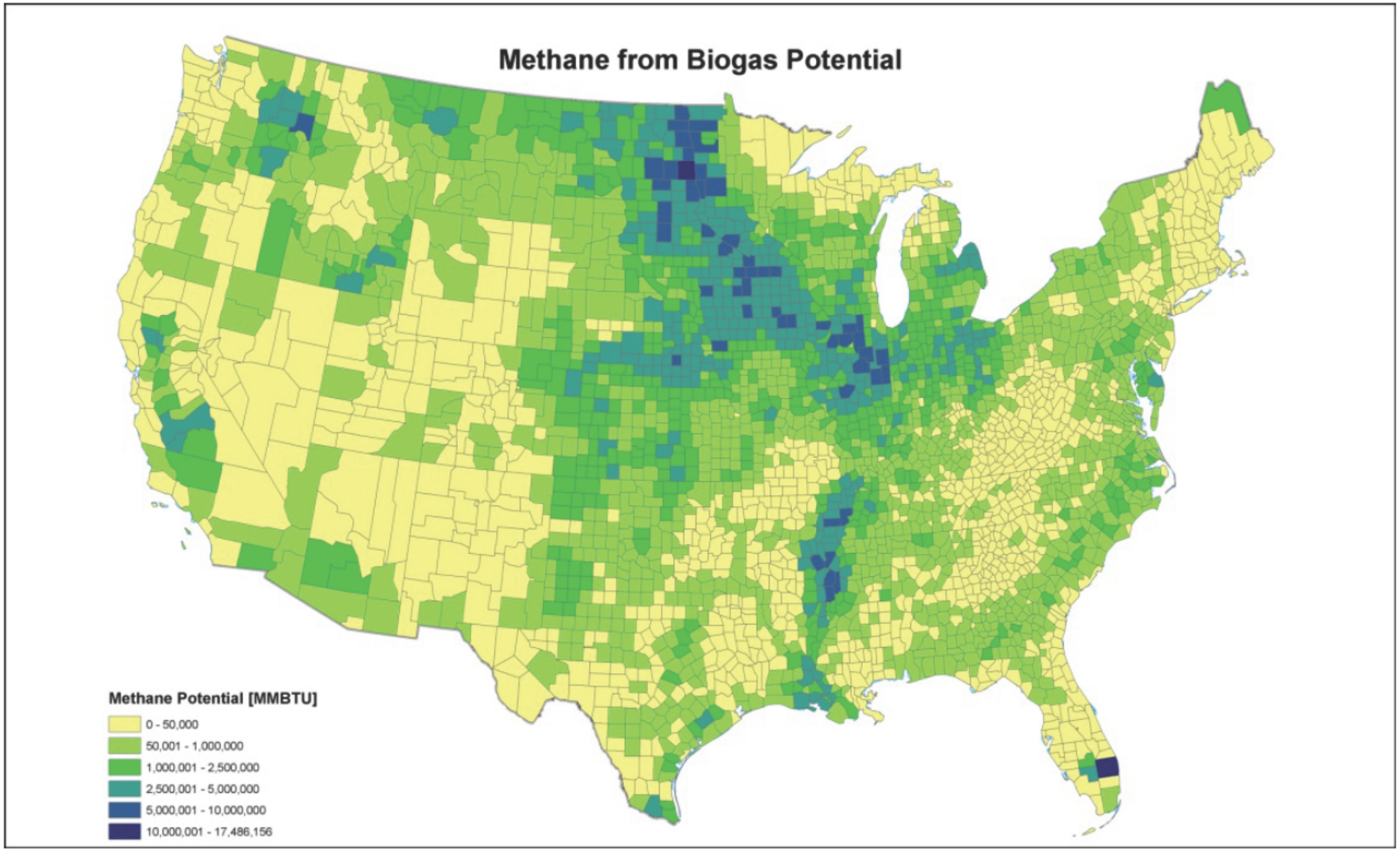
Unpublished data

Biogas potential from manure



- US Potential = 530 BCF / 4.6 billion GGE from 682 million tpy DM
- Significant GHG reduction potential: 247.5 million t CO_2e (3.7% of US_{tot})

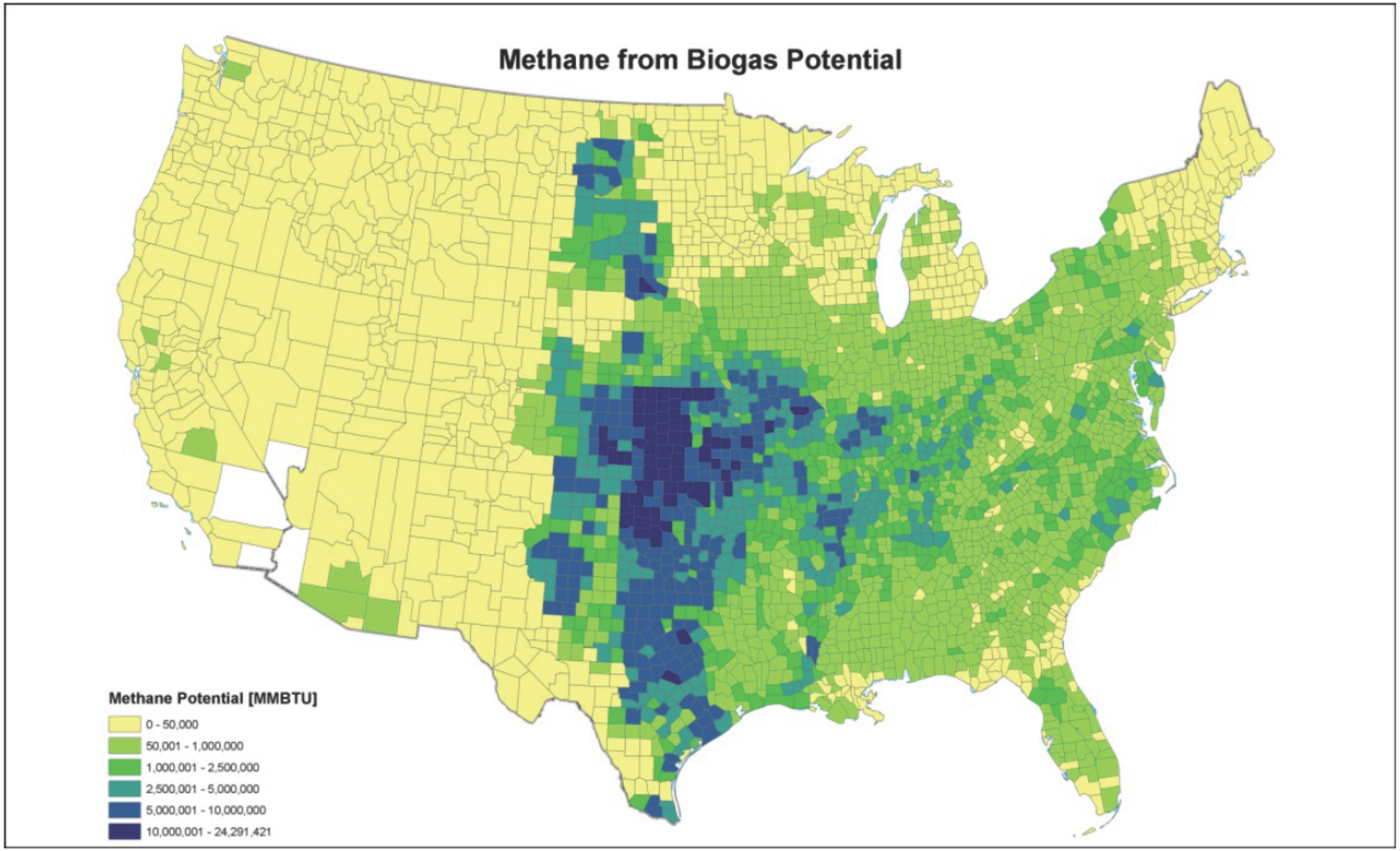
Biogas potential from crop residues



- US Potential = 2,670 BCF / 23 billion GGE from 350 million tpy DM
- Largest readily available untapped pool of feedstock

Unpublished data

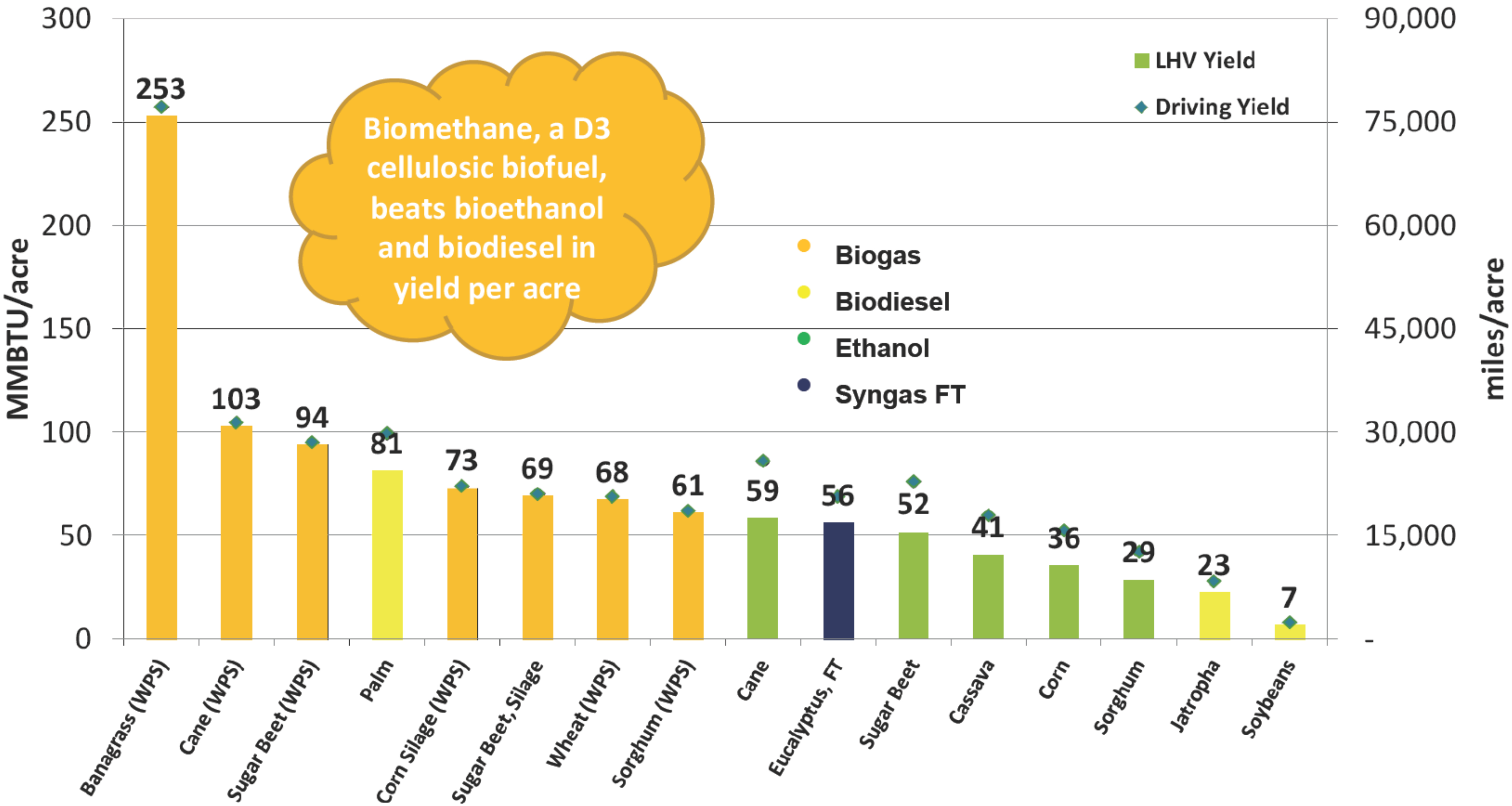
Biogas potential from energy crops



- US Potential = 4,401 BCF / 38.6 billion GGE from 385 million tpy DM (7.5t/ac)
- Largest potential pool of feedstock – 60% Miscanthus, 40% Sorghum

Unpublished data

From crops, the energy yield per acre is highest through biogas



Ideal feedstock characteristics for AD to biogas conversion differ significantly from cellulosic ethanol feedstock criteria

- High specific biogas yield per organic dry matter content
- High fresh matter biomass yield per acre (more than 30t FM/ac)
- **Dry matter content between 20% and 35%**
  - **Malolactic fermentable**
- **Low lignin content (less than 5-6%)**
  - Easy hydrolyzation without the use of external enzyme addition
- Low protein content, **high fat content**
  - Favorable C:N ratio
- Wide, local, existing availability
  - Dual purpose crop that has demand in energy, food and fuel
- Perennial, low water use, drought resistant, low/no till requirement
- Easy harvesting protocol with field shredder or mower
- **Low cost or preferably revenue at digester gate**
- Sugar beet, corn/sorghum silage, energy cane, camelina, bana/napier grass

Key metrics for biogas, CHP, renewable energy production

➢ CapEx for energy AD to electricity:	\$2.7 – \$3.5 / W_{el}
➢ CapEx for organics MSW to biogas:	\$250 – \$500 / t/a
➢ Unsubsidized biogas cost:	\$3.5 – \$7.5 / MMBTU
➢ including crop cost:	\$10 – 18 / MMBTU
➢ Unsubsidized biogas electricity cost:	\$0.10 – \$ 0.15 / kWh
➢ Typical range of biogas plants:	0.5 – 2 MW_{el}
➢ MSW / organic waste plants:	2 – 6 MW_{el}
➢ Large Scale biofuel/biogas plants:	12 – 36 MW_{el}

Economics of CNG from energy crops, crop residues, waste

Case	Food Waste CA	Dairy Manure	Energy Crop	Stover & Manure	Sugar Beet	Ethanol
Feed [t/d]	600	287	730	290	707	6,400
Feed [t/y]	156,000	104791	266,667	105,939	258,000	2,333,333
Biogas [scfm]	1,520	550	3,135	692	1,900	12,300
CNG [GGE/y]	**4,204,927**	**1,520,179**	**8,672,812**	**1,914,542**	**5,257,047**	**33,986,582**
Name Plate [MW]	6.40	2.3	13.5	2.9	8.2	53.0
CapEx [$]	$ 32,000,000	$ 10,200,000	$ 50,000,000	$ 10,200,000	$ 24,100,000	$ 110,000,000
Revenues	CNG	CNG	NG	CNG	CNG	CNG
	$30/t tip fee		$10/t FM crop cost	$50/t FM stover cost	$40/t FM beet cost	$200/t FM DDG cost
Credits	MACRS	MACRS	MACRS	NMTC, MACRS	NMTC, MACRS	NMTC, MACRS
	CNG @2.30 / GGE	CNG @ $14/MMBTU	CNG @ $20/MMBTU	CNG @ $15/MMBTU	CNG @ $20/MMBTU	CNG @ $21/MMBTU
NPV [$]	$ 73,000,000	$ 4,460,000	$ 47,195,000	$ 3,300,000	$ 8,377,000	$ 39,400,000
IRR [%]	35%	15.2%	22%	14.3%	14.8%	15.9%
Methane [$/MMBTU]	**($8.97)**	**$10.85**	**$13.60**	**$11.55**	**$17.08**	**$19.17**
CNG [$/GGE]	**($1.00)**	**$1.21**	**$1.52**	**$1.71**	**2.28**	**2.39**
Carbon Intensity [g CO_2e/MJ]	-15 to -80	13.45				

➢ **Biogas is the cheaper and GHG negative alternative to fossil fuels**

Farmatic US, Inc., unpublished data

Significant economic impact: converting crop residues, organic waste, and manure to biogas

Source	GGE	Scenario	# Plants	CapEx CNG Config.	Jobs
Energy Crops	38.6 bn	Max Yield with BTS2 acreage; 12 MW Plants	5,013	$ 239.3 bn	2.88 mn
Crop Residues	23.4 bn	70% collected; return digestate; 12 MW Plants	3,041	$ 145 bn	1.7 mn
Ethanol Stillage	2.9 bn	All DDGS		$ 14.7 bn	0.18 mn
Biodiesel Glycerin	0.36 bn	All glycerin		$ 1.9 bn	0.02 mn
Organic MSW Fraction	1.8 bn	BioCycle w/ 35% organic	981	$ 21.5 bn	0.26 mn
Manure	4.6 bn	2012 Census Dairy & Feed; 2MW Plants	3,620	$ 28.8 bn	0.35 mn
Total	**71.7 bn**		**12,656**	**$ 451.3 bn**	**5.4 mn**

➢ **With crop residues & energy crops:**
>12,700 plants, $450bn investment, creating 5.4 million jobs

Basis: Average cost per plant = $3.5 / W CapEx or $300/t organic waste treated; 12 jobs per $1 million invested

Unpublished data

What happened in 2014?

- ITC/PTC - expired end of 2013, reactivated for two weeks in 2014
- EPA - rules biogas to be a cellulosic biofuel with D3 RIN, but does not assign RFS2 requirements
- Biogas Roadmap - only marginal, waste driven potential considered

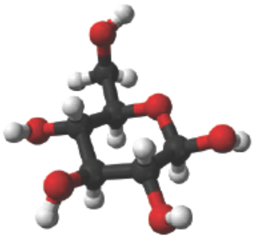
- Crude oil - drops below $50/bbl, natural gas below $2.80/MMBTU, gasoline below $1.80/gal at spot market
- Germany - flip-flops on renewable energy, biogas industry goes Ch. 7/11, players abandon the US

- ARPA-E invests $61 million in 25 projects to convert methane (<2.5mil/proj)

➢ **Biogas 2.0 → needs to be financially self sustainable, at larger, stable, secure margin, through stable take-off partners**

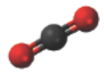
3 Obvious Starting Points to Reformulate Chemical Intermediates

Glucose (Sugar)



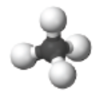
- Agricultural commodity with increasing (high) price and supply limits
- High solubility in water
- Yeast based genetic engineering well established
- IP space crowded
- Biomass deconstruction still challenging

Carbon Dioxide



- Low cost when taken from exhaust
- High solubility in water, requires sparging
- Requires photosynthetic system (plants, algae)
- Light diffusion limiting
- Highly dilute culture requires costly dewatering

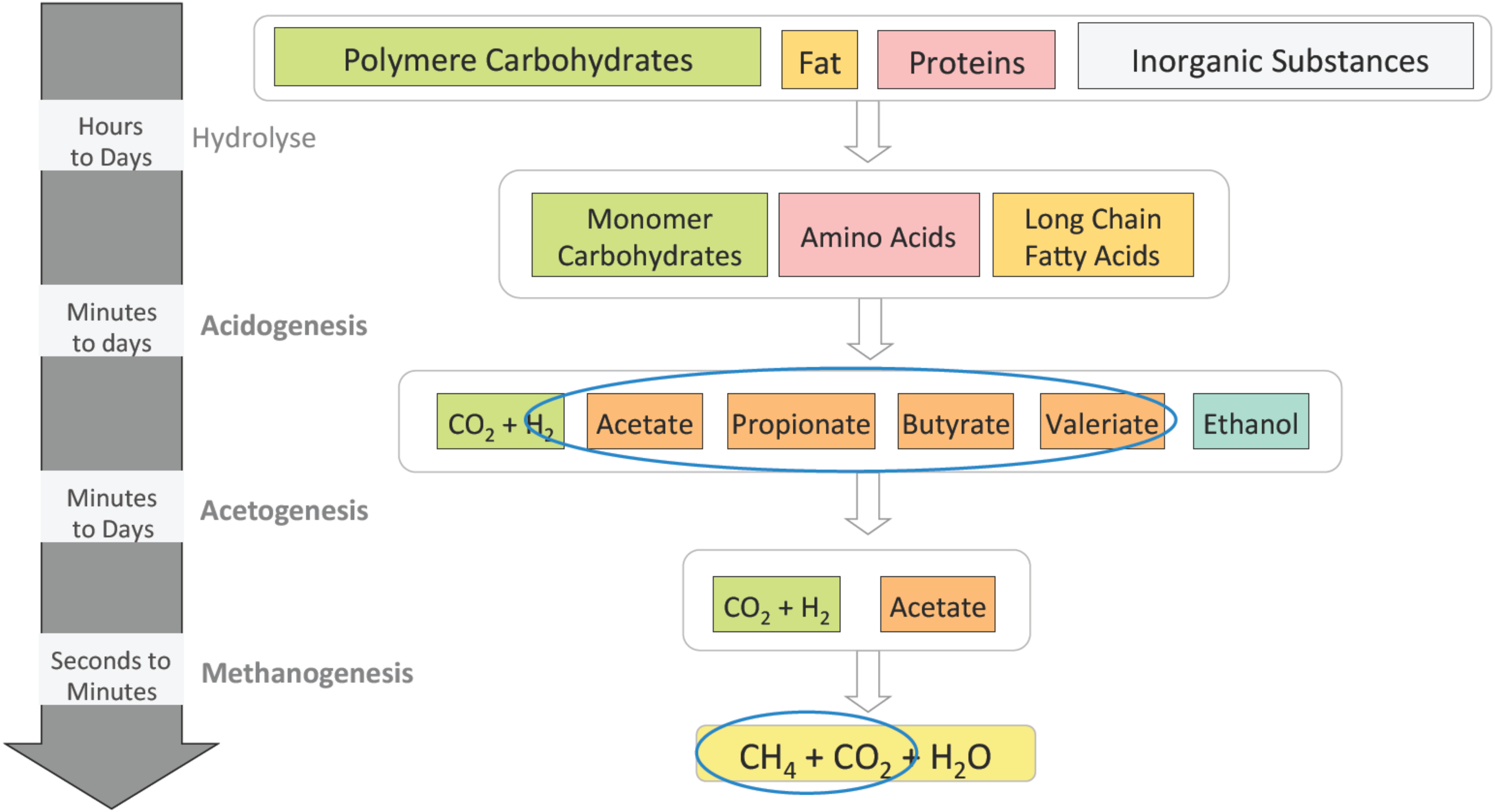
Methane



- Commodity price currently very low, especially from waste
- Low solubility in water, but may not be needed
- Methanotroph biology is only emerging
- Requires different codons, sequences from yeast
- Wide open field, few players

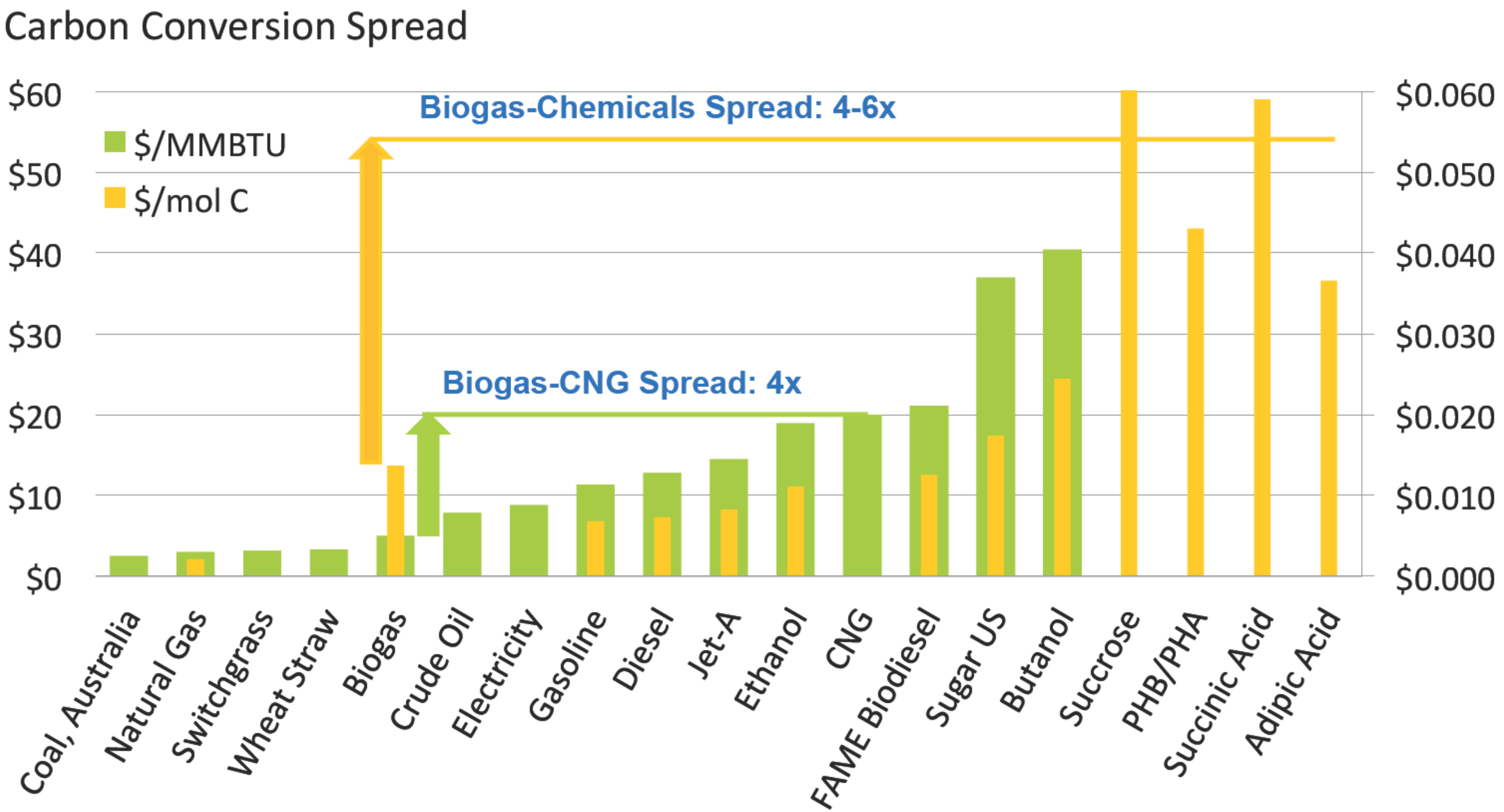
Degradation of Substrates to Biogas

Kinetics



Adapted From: Pind et al: Monitoring and Control aof Anaerobic Reactors 2003

Upgrading biogas: Better spread than sugar-based processes



Take Home

- The US could replace 51% of fossil transportation fuel through renewable biogas (8.81 Quad or 77 billion GGE)
- Biogas from energy crops, crop residues, and waste is cheaper and GHG neg. compared to current fossil fuels
- Upgrading biogas to biointermediates provides a better spread than comparable sugar based processes
- Biointermediates provide a better margin than the fuel alternative
- Methane is a comparatively attractive feedstock from a cost, biology and IP perspective
- A smaller foot print of such biorefineries, their lower substrate need matches the smaller market size/demand of intermediates and works well with the logistics of biomass substrates