Renewable chemistry from biogas: CH_4 and CO_2 as feedstock

Dr. Fabrizio Sibilla, CIB & Krajete GmbH

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Fabrizio Sibilla

- Born & grew up in Metanopoli, MI, (Methane city)
- MSc. In Food Technology at Milano University
- Fellowship in Trieste University (Biocatalysis in organic solvents)
- PhD Student in the Graduated School „BioNoCo“, RWTH-Aachen (Biocatalysis in non conventional media, Enzyme Promiscuity & Metagenomics)
- Post-Doc at RWTH-Aachen in the TMFB Project (Taylor Made Fuels from Biomass, Directed evolution)
- Business Development Manager at Krajete GmbH (A)
- Scientific advisor for the Italian Biogas Council
- Business Development Manager at BSE Engineering Leipzig GmbH (DE)

Krajete GmbH Company Facts

- Established 2012 as “Krajete GmbH” (“Limited Liability Company”)
- Slogan “Learning From Nature.”
- Private owned; > 1 million EUR spent on overall development (funds, own, earned)
- 4 employees (3 PhDs, 1 Dipl.-Ing)
- 2 PhD topics funded, 3 diploma thesis (TU Vienna - biology, JKU Linz - chemistry)
- 6 patents applications (2011 – 2015), new field with almost no prior art
- Assets: 2 benchscale reactors (1 L, 10 L) in Vienna, in steady operation since 2009

  + gas bottle fleet (15 x 50 l) and mobile compressor for sampling of industrial gases,

  Customer pool diversified: **car producers, power producers, international gas organizations, steel companies, biogas companies, machine producers**

Why gases fermenting?

Gases are available all year round as black or green

Methane:

- available all year round from biogas upgrade
- available from Power to Gas plants
- available fossil

Syngas:

- available from various biomasses all year round
- available from steel gases, MSW gasification, fossils

CO_2:

- available from biogas upgrade & ethanol fermentation
- available fossil

Gases or sugars?

Microorganisms need carbon sources

1 ton glucose → 40% C; 53% O; 7% H; it costs 350 €/ton → Carbon atom costs 0,875 €/kg

1 ton CH_4 → 75% C; 25% H; it costs 350 €/ton → Carbon atom costs 0,466 €/kg (circa 2 times less than glucose)

1 ton CO_2 → 27% C; 73% O; it costs 50 €/ton → Carbon atom costs 0,185 €/kg (circa 5 times less than glucose)

Best source of green gases for fermentation? Biogas! (at least in EU)

- AD is Multifeedstock:

– It can use any organic substance available on any agro-ecological distribution area, to convert 70-80% of carbon fixed in chlorophyll photosynthesis into gas

– Avoid MONO-CULTURES that, even though “no-food crops”, are displacing food crops

– Biogas crops can improve farm land rotation and crop diversity

Best source of green gases for fermentation? Biogas! (at least in EU)

- AD is converting biomass to energy in an efficient way on small scale (>500.000 litre diesel equivalent), therefore:

– Applicable to any sized professional farm

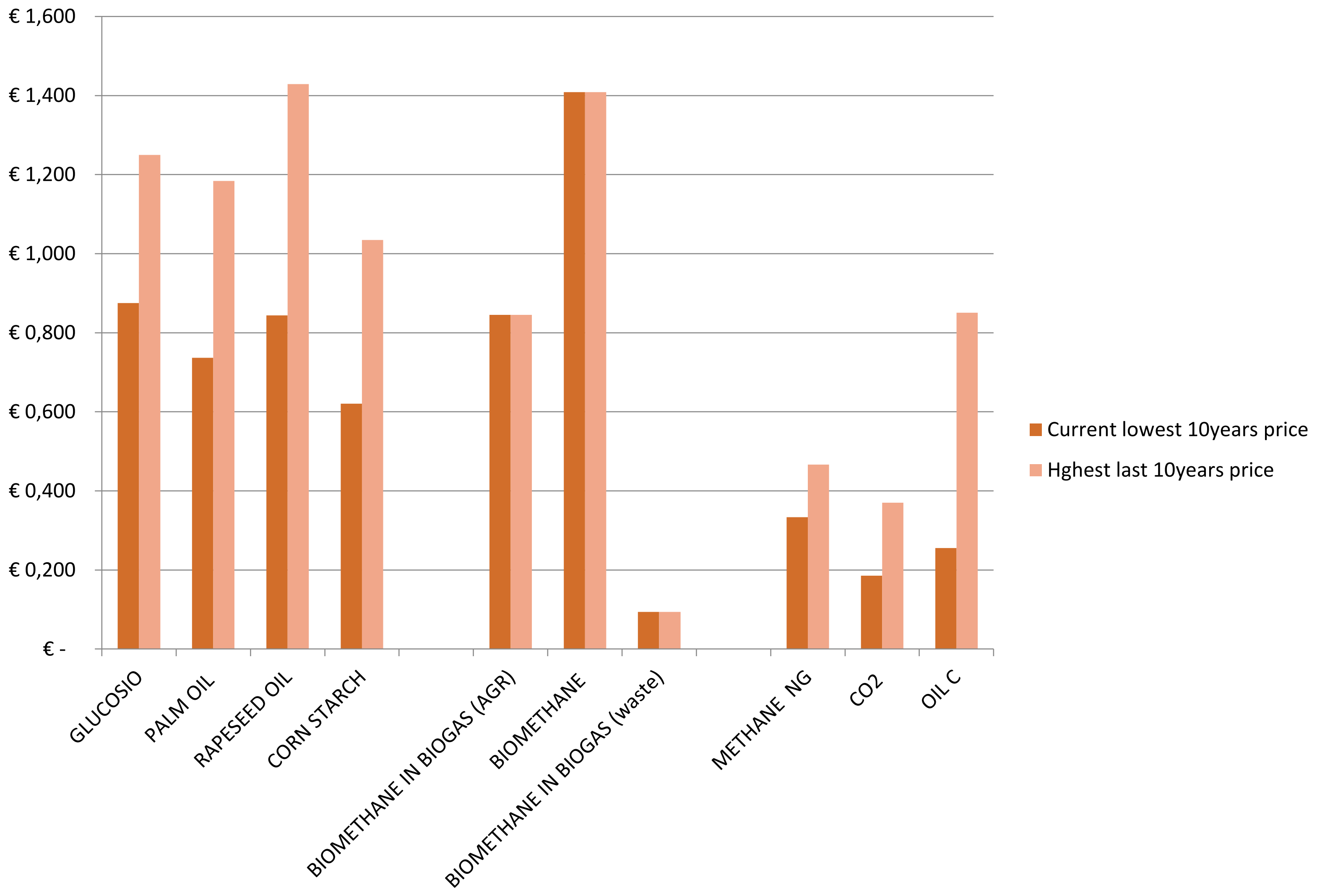
– It can use any biomass and avoid transporting watered (95-70%) biomasses over long distances

- Nutrients cycling:

– By means of the digestate, the undigested carbon and all nutrients (N-P-K micronutrients) may be re-employed on site, sustainably and efficiently, restoring organic fertilization in areas where there is no more breeding and improving efficacy

- With biogas we can dramatically reduce the modern agricultural pollution in the fields and in the stables

To summarize some prices of commodities for fermentation



SWOT Analysis Biogas in EU

	Helpful	Harmful
Internal	**Strenght** Improves economic of farms Protect from price volatilities Generates constant and foreseeable cash flow Allows the farmer to produce his fertilizers and fuel	**Weakness** Access to Credit Learning of new business models Not in every countries possible 2nd or 3rd harvest
External	**Opportunities** Environmental regulations "Renewable fertilizers" Trademark Lowers GHGs emissions from agriculture	**Threats** Fossil fertilizers price lowers Natural gas price lowers Subsidies fully lifted

Scenario di sviluppo del biometano e previsioni di evoluzione della *land efficiency* del biogas italiano al 2030 grazie all'adozione del modello Biogasfattobene®

Estimation methodology and data analysis according to the Italian Biogas Consortium position paper

		2010	2015	2020	2025	2030
Total Biomethane	(Gm^3/year)	0,7	2,2	4,2	5,5	8
UAA Monocrop	(ha)	85.000	200.000	250.000	300.000	400.000
	(ha/Mm^3 $bioCH_4$)	121	91	60	55	50
BioCH4 yield Monocrop	(m_3/ha $bioCH_4$)	6720	6720	6720	6720	6720
LAND EFFICIENCY	(m_3/ha $bioCH_4$)	8.235	11.000	16.800	18.333	20.000
BioCH4 from Monocrop	(Gm^3/year)	0,57	1,34	1,68	2,02	2,69
BioCH4 from integration biomasses	(Gm^3/year)	0,13	0,86	2,52	3,48	5,31
BioCH4 from integration biomasses	%	18	39	60	63	66

2030

8 billion Nm^3 biomethane equivalent
(12% natural gas consumption)

(1) It is possible to produce food AND energy (and biobased materials) via biogas done right «integration biomasses»

The biogas done right integration biomasses

- Double crops before and after a cash crop
- Perennial crops where C3 or C4 aren't deployed
- Livestock effluents
- Agricultural and agroindustrial by products
- (OMW)

The biogas land efficiency

	Etanolo da Mais granella	Biodiesel da Colza	Etanolo da Arundo donax	Biogas da monocolture	Biogas doneright**
N. impianti	1	1	1	27	27
produzione etanolo ton /annui	80.000		80.000	59.200.000	59.200.000
MWh th /annui	586.667	586.667	586.667	586.667	586.667
ton biomassa	239.232	133.333	380.952	538.182	720.000
FCLR ** ha	22.688	35.088	15.238	10.764	2.960
Land efficiency (ha primo raccolto/10GWh th)	**383**	**593**	**257**	**182**	**50**
Moltiplicatore fabbisogno di terra arabile rispetto biogas done right	**8**	**12**	**5**	**4**	**1**
Area agricola (ha) interessata considerando rotazioni e % seminativi	54.019	292.398	25.397	59.798	7.048
***Area interessata Ha sottratta alle produzioni food/feed*	***nel fabbisogno di terreno di primo raccolto (FCLR) andrebbero tolti i crediti derivanti dalla produzione di borlande o pannelli per l'alimentazione zootecnica*			*Nmc di metano equivalenti*	* impianti da 1,0 MWe eq
					*** (50 ha/1Mn Nmc)*

(1) Italian biomethane road map OK

Italian road map

Table 1 – Development scenario for bioCH4 and evolution forecasts for italian bioCH4 production and land efficiency di evoluzione della land efficiency until 2030

			2010	2015	2020	2025	2030
(A)	Biometano totale	(Gm3/anno)	0,70	2,20	4,20	5,50	8
(FCLR)	- SAU primo raccolto	(ha)	85.000	200.000	250.000	300.000	400.000
		(ha/Mm^3 CH_4)	121	91	60	55	50
(C x P)	- Resa primo raccolto	(m^3/ha di CH_4)	6720	6720	6720	6720	6720
(A/FCLR)	LAND EFFICIENCY	(m^3/ha di CH_4)	8.235	11.000	16.800	18.333	20.000
(A - I)	- Biometano da primo raccolto	(Gm^3/anno)	0,57	1,34	1,68	2,02	2,69
(I)	- Biometano da biomasse di integrazione	(Gm^3/anno)	0,13	0,86	2,52	3,48	5,31
(I)	- Biometano da biomasse di integrazione	(%)	18	39	60	63	66

The integration biomass

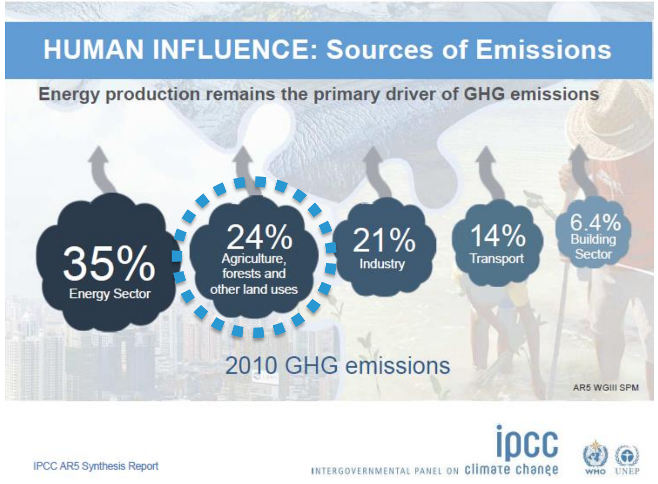
		2030	SAU ha
Obiettivo 2030	**(m3/anno)**	**8.000.000.000**	
- CH4 da primo raccolto	**(m3/anno)**	**2.664.000.000**	
- SAU ha FCLR	(ha)	**400.000**	*400.000*
- Mais - resa CH4	(m3/ha)	**6660**	
- CH4 da Biomasse di integrazione	**(m3/anno)**	**5.336.000.000**	
- di cui da colture	(m3/anno)	2.668.000.000	*892.519*
- di cui da sottoprodotti	(m3/anno)	2.668.000.000	
			1.292.519

CIB Team, 2016 – ***«Considerations about italian «biogasdoneright» potential from agriculture». Methodology, data gathering and analysis in the Italian Biogas Consortium 2016 position paper***

(2) Not only is possible but is desirable

doesn't make sense to produce bioenergy with the current agricultural practices
biogas done right practices help to decarbonize agriculture

AGRICULTURE ITSELF IS RESPONSIBLE FOR 12% OF GLOBAL GHG EMISSIONS

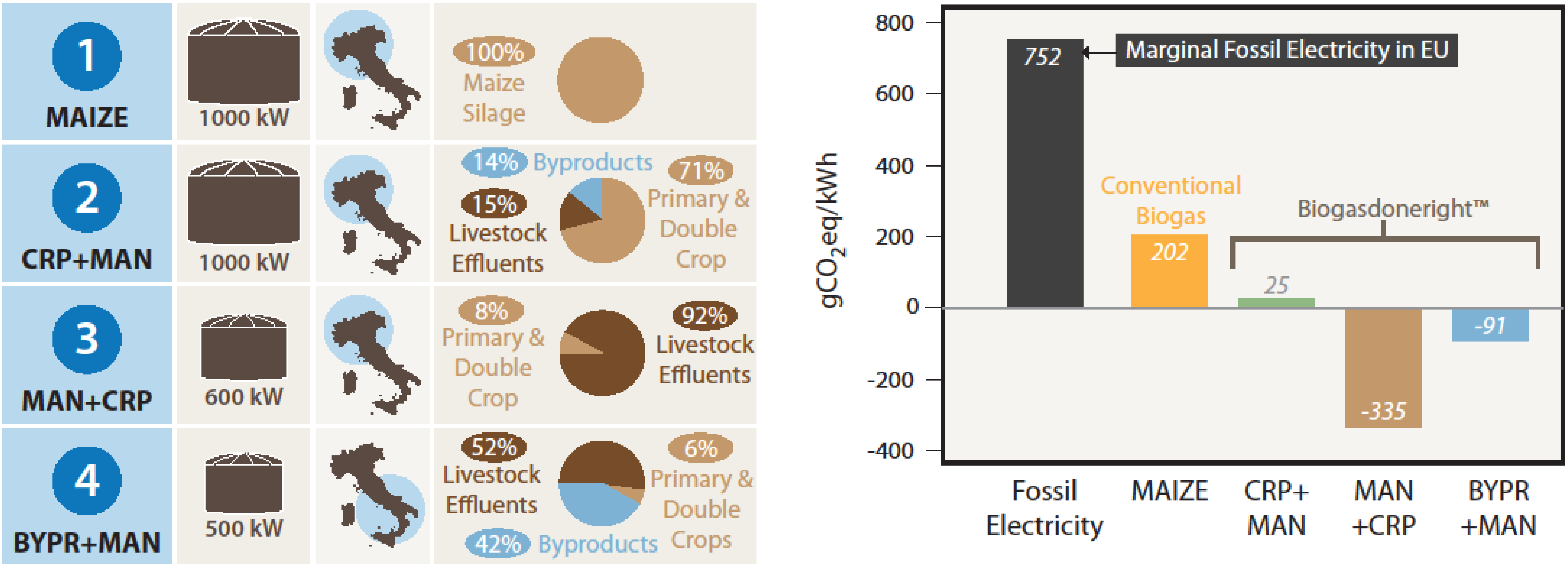


(IPCC mitigation report 2014)

Biogas done right farming practices

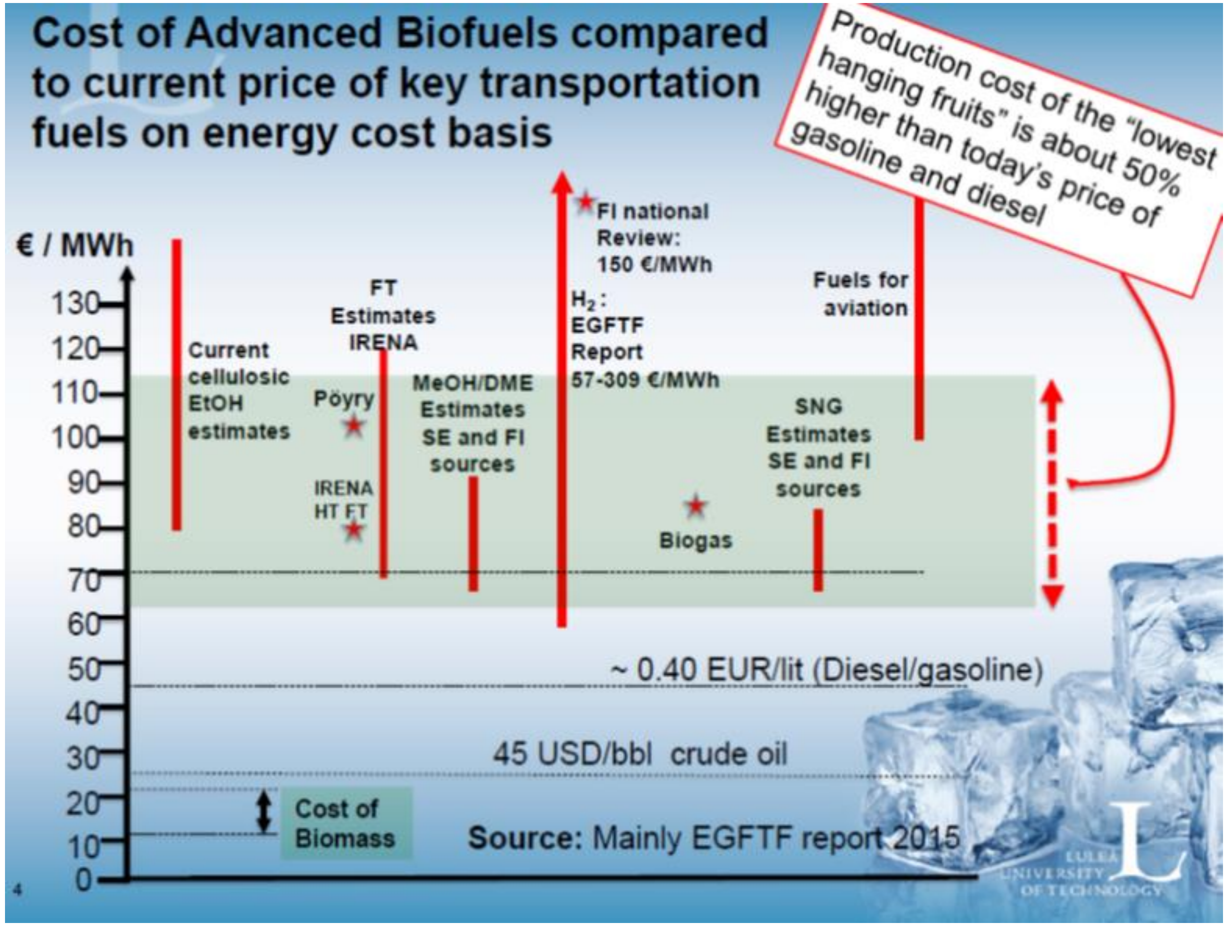
- the organic fertilization, with soil nutrient balance and new machinery avoiding nutrients losses and soil compaction
- the mitigation of emissions from livestock effluents,
- keeping the soil covered the whole year applying new and improved crop rotations with a larger fraction of nitrogen fixing crops,
- the shift from deep plowing to precision farming and minimum tillage agriculture,
- increased share of renewable energy in agriculture
- Etc. etc.

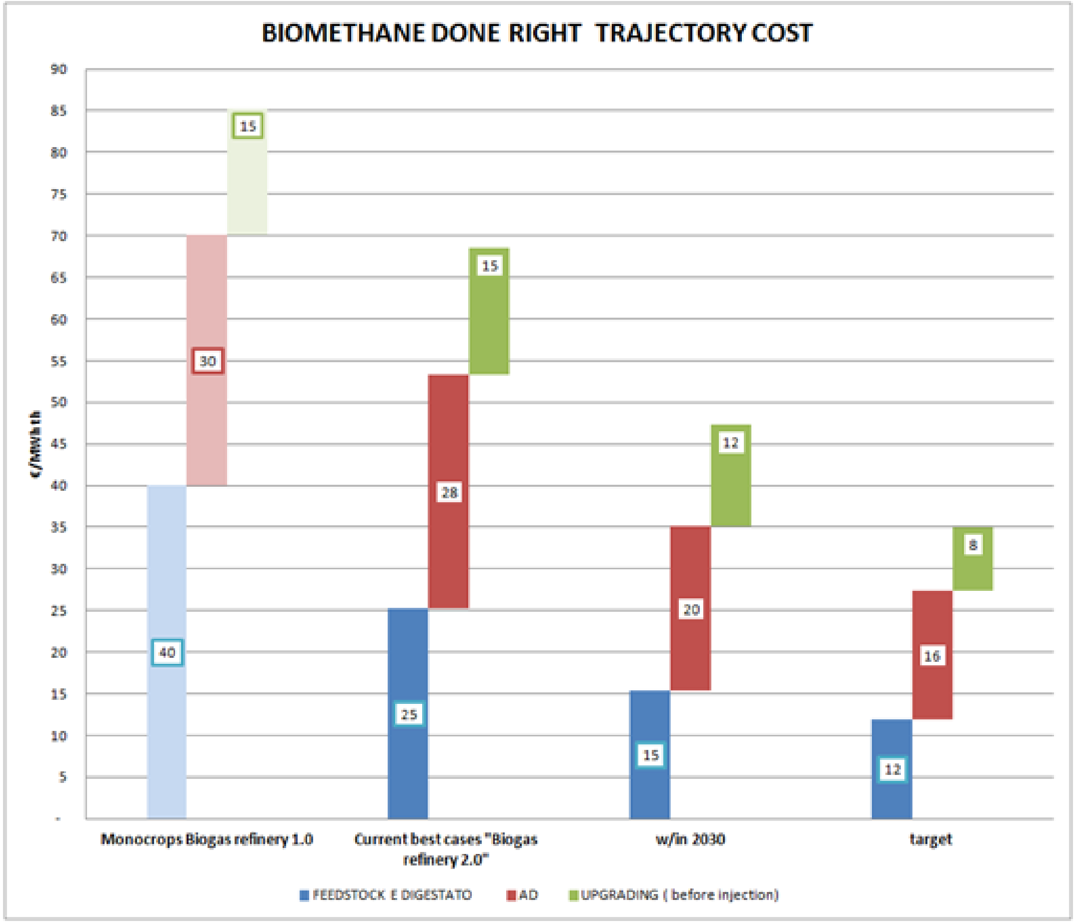
(3) Biogas done right carbon efficiency



Valli and others, "Greenhouse gas emissions of electricity and biomethane produced using the *Biogasdoneright™* system: four case studies from Italy", submitted

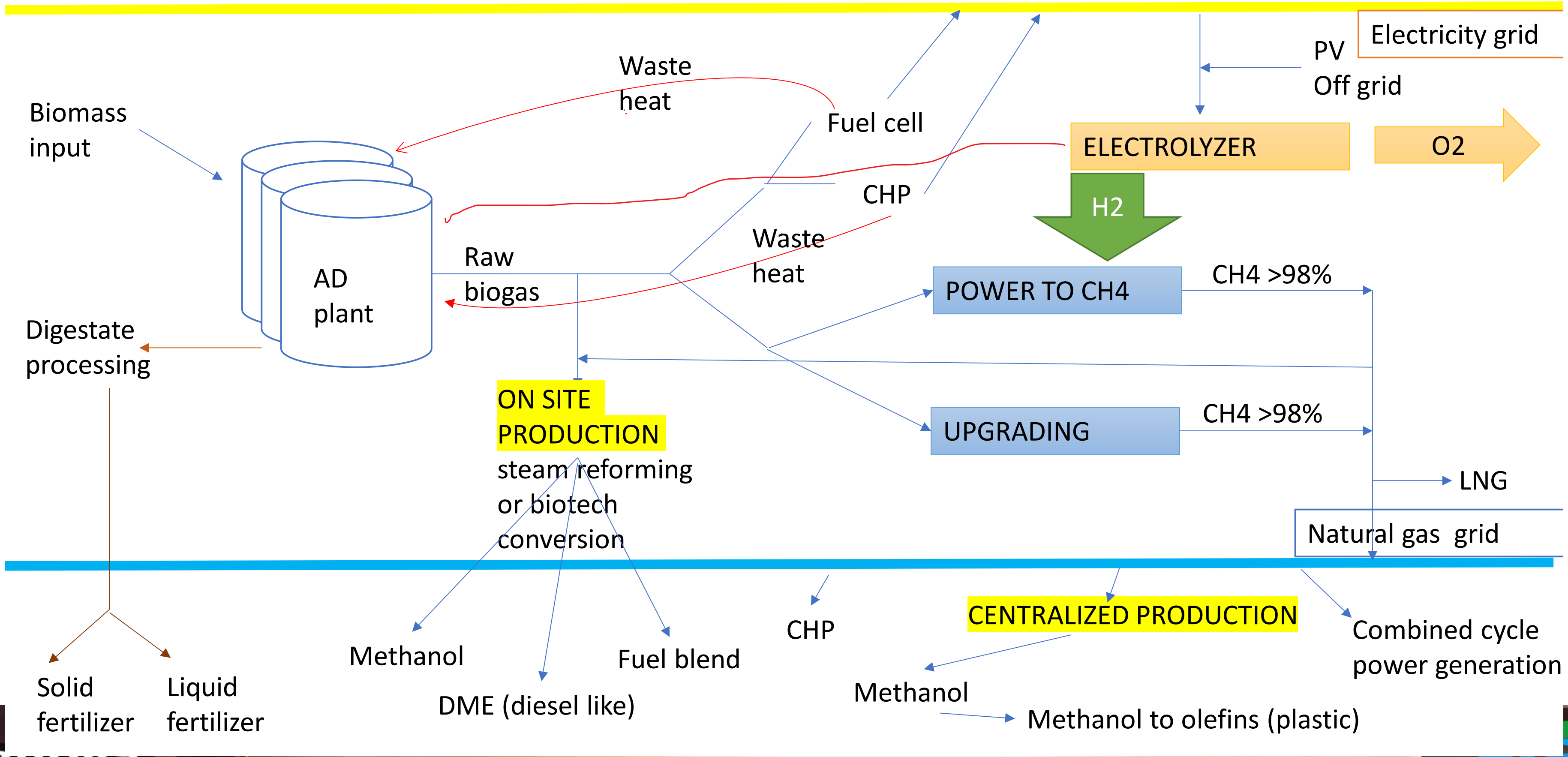
(4) BIOGAS TRAJECTORY COST





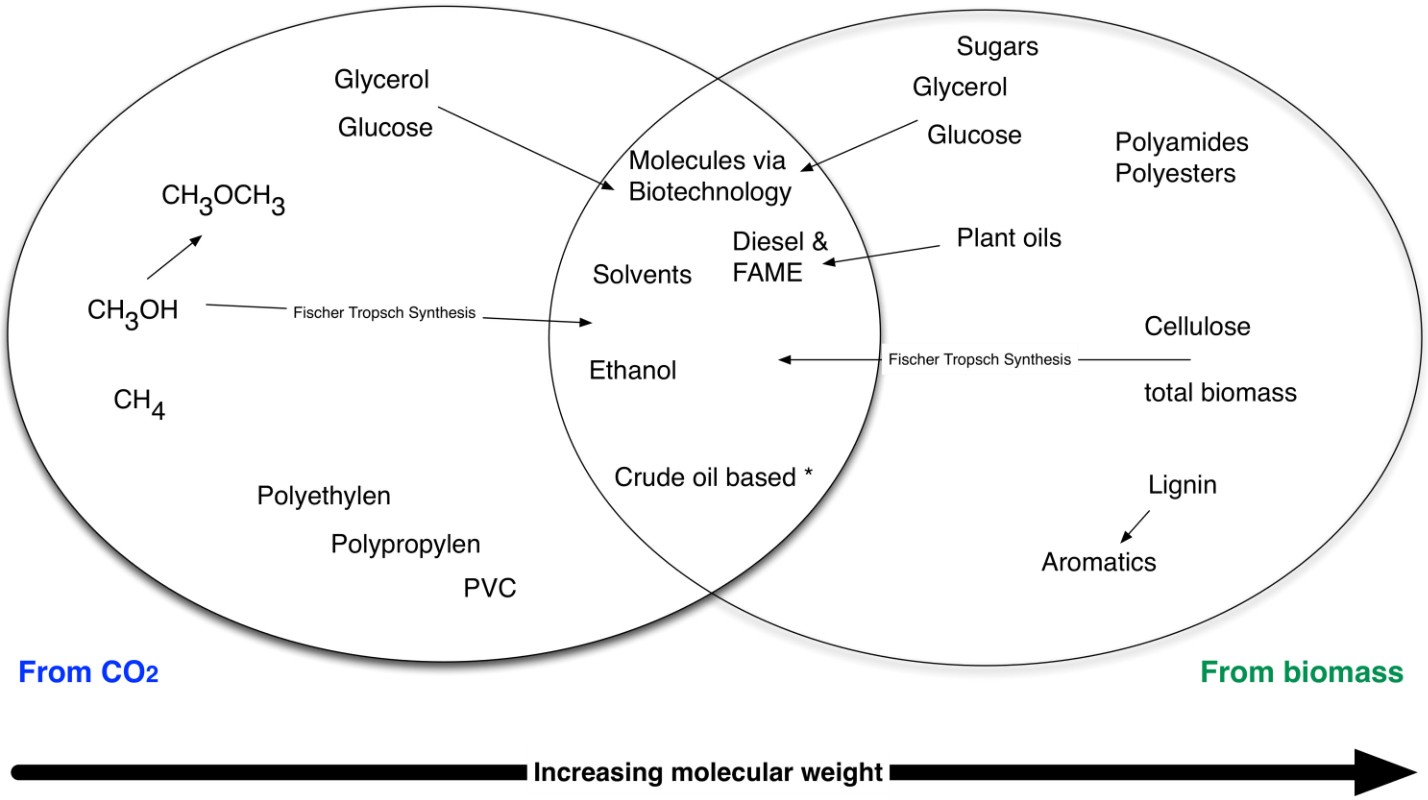
(5) BIOGAS REFINERY VALUE CREATION
THE BIOGAS REFINERY AS A BIOMASS DENSIFICATION CENTER

BIOGAS REFINERY SCHEME : ON SITE AND CENTRALIZED PRODUCTION SCHEME VIA NG GRID



The future carbon sources for the Chemical Industry: CH_4, CO_2, and Biomass – together integrate and complement each other

CH_4 and CO_2 utilization overcome the dogma, that biomass is the only renewable carbon feedstock und it's reducing the pressure on biomass and land substantially



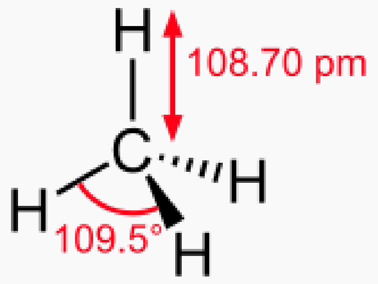
*) Crude oil based: molecules from Fischer Tropsch can be better derived via CH_4 and CO_2 incl. bitumen and asphalt.

Methane

- Well known energy source
- Well known feedstock in industrial chemistry
- Best fossil fuel ever (120 octane number VS 98 of gasoline)
- Does not leave pollution in case of spillage

- 44 times less soluble than CO2 in water
- 4400 less soluble than glucose at 100 g/l

Methane	



Properties	
Molecular formula	CH_4
Molar mass	16.04 g mol^{-1}
Appearance	Colorless gas
Odor	Odorless
Density	0.656 g/L at 25 °C, 1 atm 0.716 g/L at 0 °C, 1 atm 0.42262 g cm^{-3} (at 111 K)[2]
Melting point	−182.5 °C; −296.4 °F; 90.7 K
Boiling point	−161.49 °C; −258.68 °F; 111.66 K
Solubility in water	22.7 mg L^{-1}
Solubility	soluble in ethanol, diethyl ether, benzene, toluene, methanol, acetone
log P	1.09
k_H	14 nmol Pa^{-1} kg^{-1}

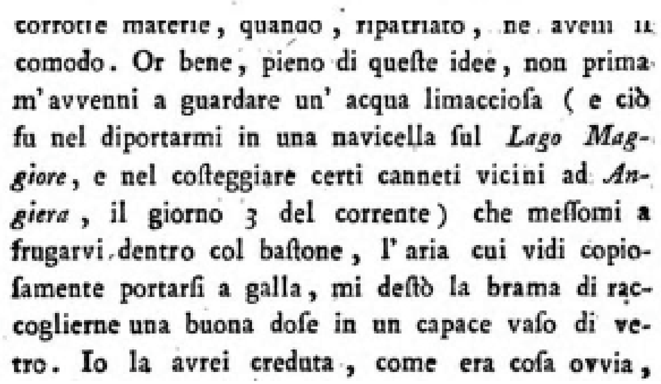
LETTERE
DEL SIGNOR
DON ALESSANDRO VOLTA
PATRIZIO COMASCO, E DECURIONE
REGIO PROFESSORE DI FISICA SPERIMENTALE
REGGENTE DELLE PUBBLICHE SCUOLE DI COMO
MEMBRO DELLA SOCIETA' FISICA DI ZURIGO
E DELL' ACCADEMIA R. DELLE SCIENZE
DI MANTOVA

SULL' ARIA INFIAMMABILE NATIVA DELLE PALUDI.

IN MILANO M. DCC. LXXVII.

NELLA STAMPERIA DI GIUSEPPE MARELLI.
Con licenza de' Superiori.

Ritter:



corrotte materie, quando, ripatriato, ne avessi il comodo. Or bene, pieno di queſte idee, non prima m'avvenni a guardare un' acqua limaccioſa (e ciò fu nel diportarmi in una navicella ſul *Lago Maggiore*, e nel coſteggiare certi canneti vicini ad *Angiera*, il giorno 3 del corrente) che meſſomi a frugarvi dentro col baſtone, l' aria cui vidi copioſamente portarſi a galla, mi deſtò la brama di raccoglierne una buona doſe in un capace vaſo di vetro. Io la avrei creduta, come era coſa ovvia,

Syngas

What is syngas?

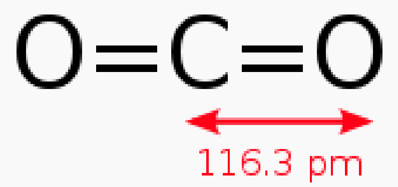
- It is a blend of CO, H_2 and CO_2 in various ratios
- It can be produced from the gasification of coal or biomass and CH_4 steam reforming
- It is used for power generation
- It is used for Fischer-Tropsch synthesis (Gas to Liquids)

CO_2

- Well known „pollutant“
- Carbon source for life on earth through photosynthesis
- Feedstock in many industrial chemistry process
- Many applications in the food industry
- Since 1912 people think on how to use CO2 as feedstock in industrial chemistry[1]

- 70 times less soluble than glucose at 100 g/l

Carbon dioxide

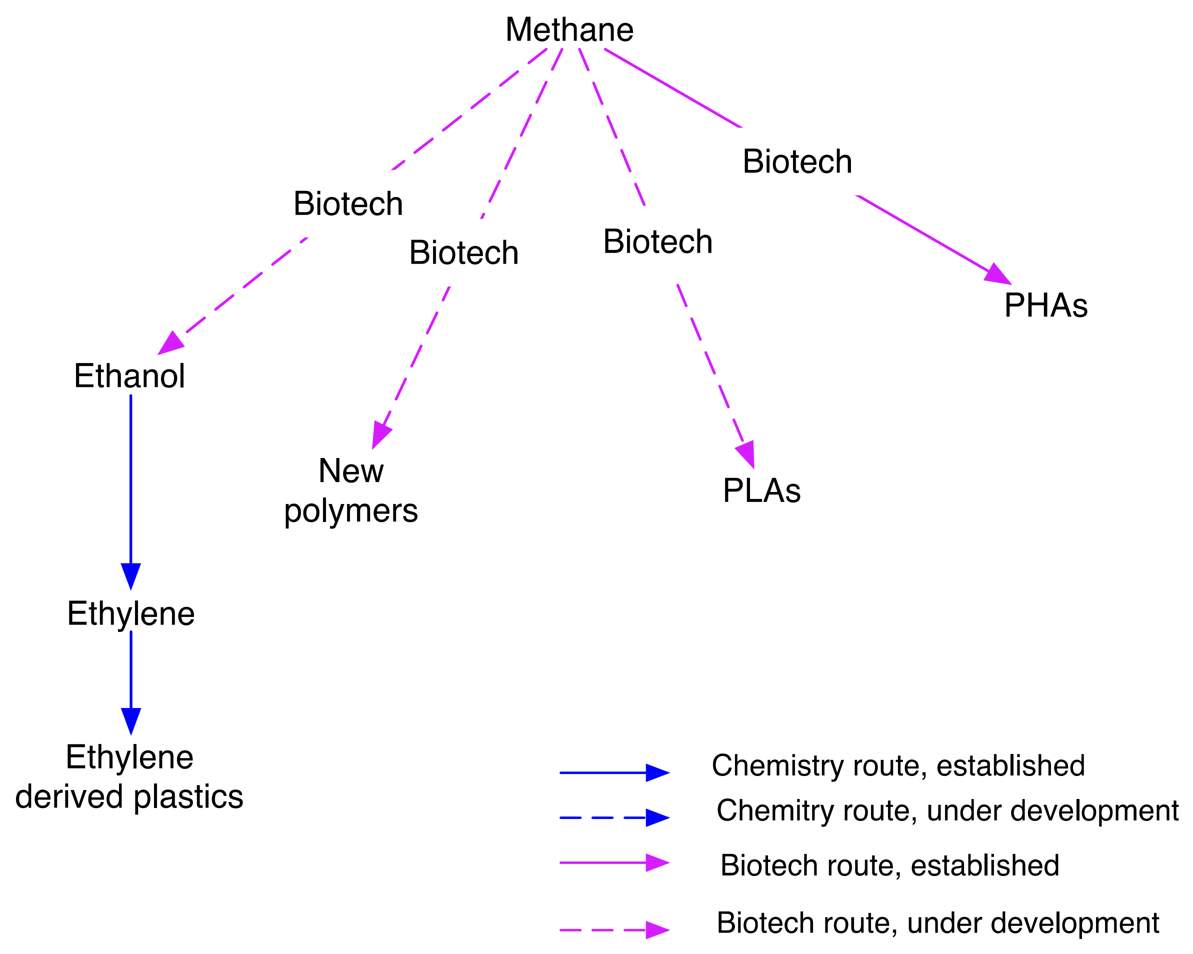


Properties	
Molecular formula	CO_2
Molar mass	44.01 g mol^{-1}
Appearance	Colorless gas
Odor	Odorless
Density	1562 kg/m^3 (solid at 1 atm and −78.5 °C) 770 kg/m^3 (liquid at 56 atm and 20 °C) 1.977 kg/m^3 (gas at 1 atm and 0 °C)
Melting point	−56.6 °C; −69.8 °F; 216.6 K (Triple point at 5.1 atm)
Sublimation conditions	−78.5 °C; −109.2 °F; 194.7 K (1 atm)
Solubility in water	1.45 g/L at 25 °C, 100 kPa
Vapor pressure	5.73 MPa (20 °C)
Acidity (pK_a)	6.35, 10.33
Refractive index (n_D)	1.1120
Viscosity	0.07 cP at −78.5 °C
Dipole moment	0 D

1) The photochemistry of the future. Science 36, 385-394 (1912)

Methane conversion via Biotechnology

- Methane to Polyhydroxyalkanoate (PHA) is already a pre-commercial reality (TRL 6-7)
- Methane to Polylactic acid is currently at R&D stage. The company NatureWorks in US is actively following this route (TRL 3-4)
- Methane to ethanol is already at pre-commercial stage (TRL 7-8 via syngas). From ethanol is easy to go to ethylene and then different options are available for ethylene based plastics
- Very likely in the next years new polymers from biotech use of methane will arise, due to the increased abundance of methane

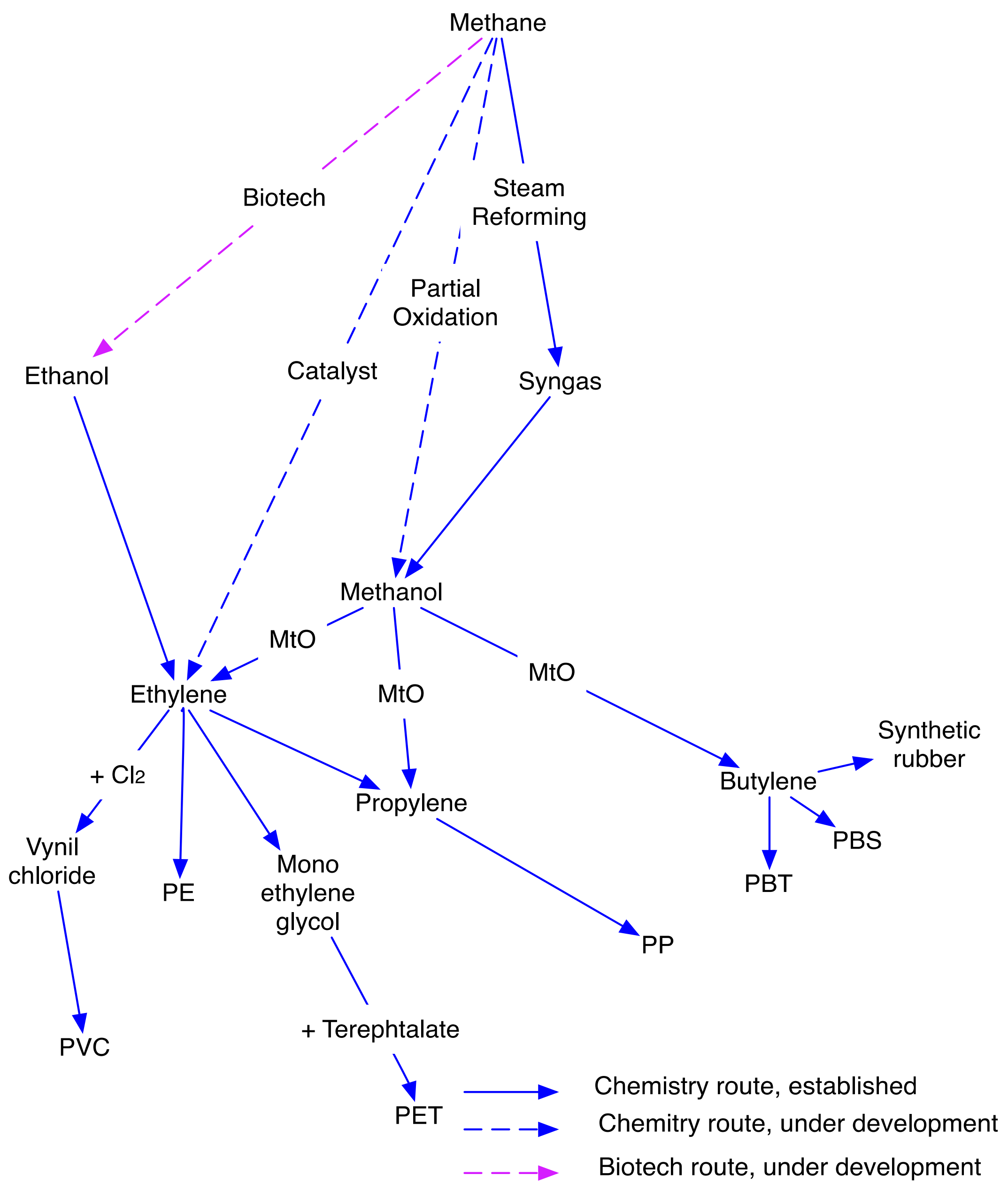


Methane conversion via Chemistry

Multiple options for the conversion of methane via chemistry are already available

- Through syngas and then methanol ethylene, propylene and butylene can be produced. Critical is here the number of steps required (more steps implies higher costs)

- Methane to ethylene in a single step with catalysis is very near to market. This route will open the path from biogas to ethylene based plastics (PE, PET, PP, PVC) as will make ethylene from methane cheaper than with today syngas route



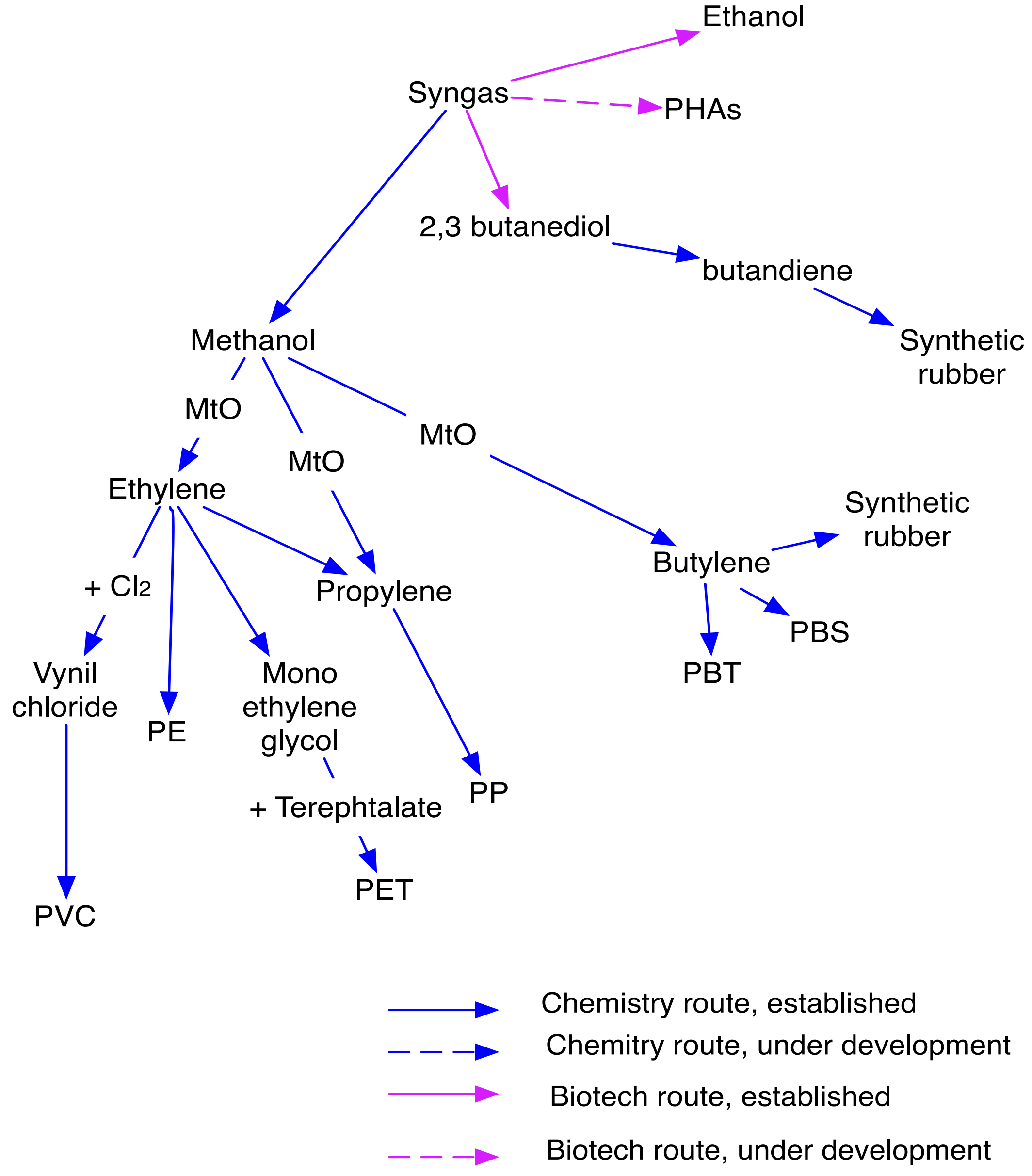
Syngas conversion options

Syngas can be converted:

- to ethanol and 2,3 butanediol via fermentation and then
  ethanol can be then dehydrated to ethylene and open the path to ethylene based plastics

  butanediol can be converted to butandiene and then to synthetic rubbers

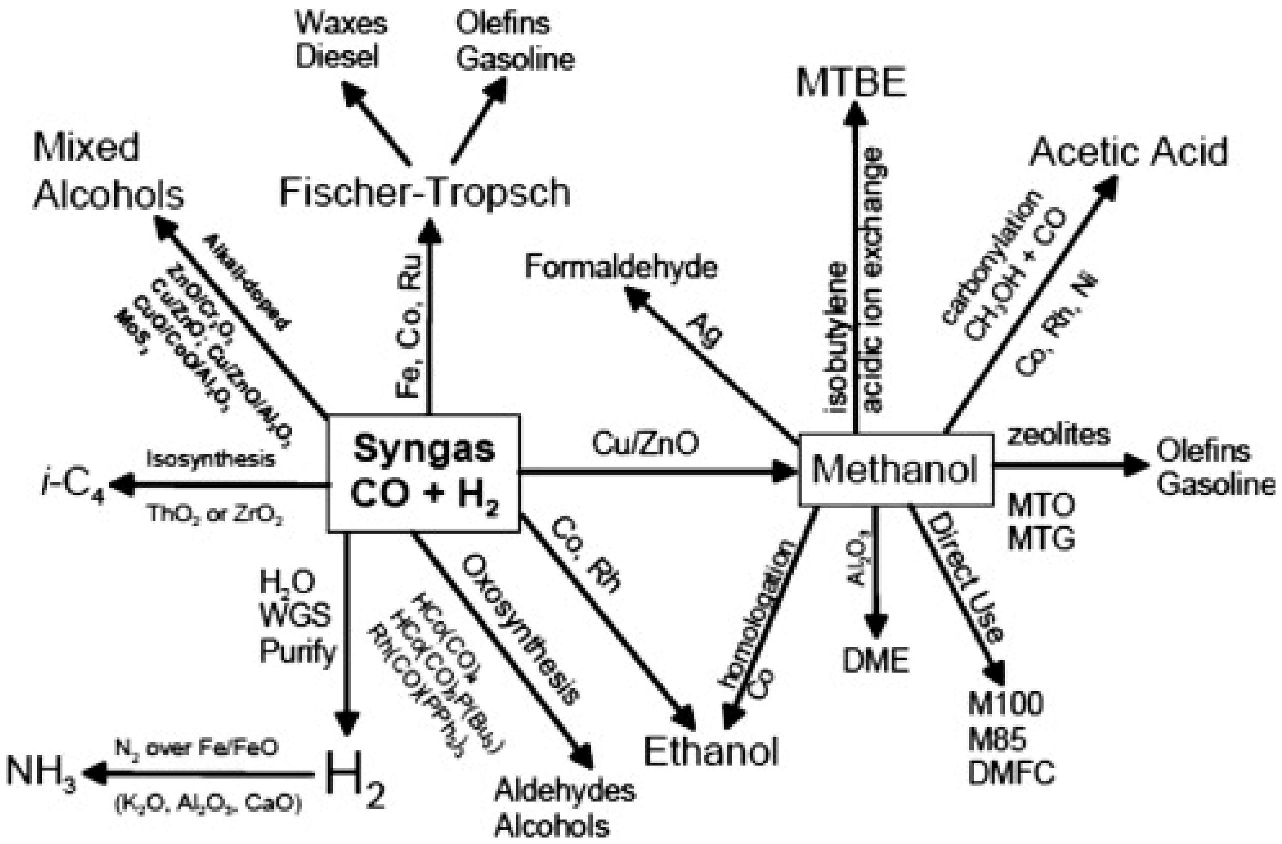
- To methanol via chemistry and then
  Methanol can be converted to olefins (ethylene, propylene and butylene)



Syngas: a versatile intermediate from multiple sources

Syngas can be produced from:

- Biomass
- Municipal solid waste
- Coal
- Natural gas
- Shale gas
- Recycled paper

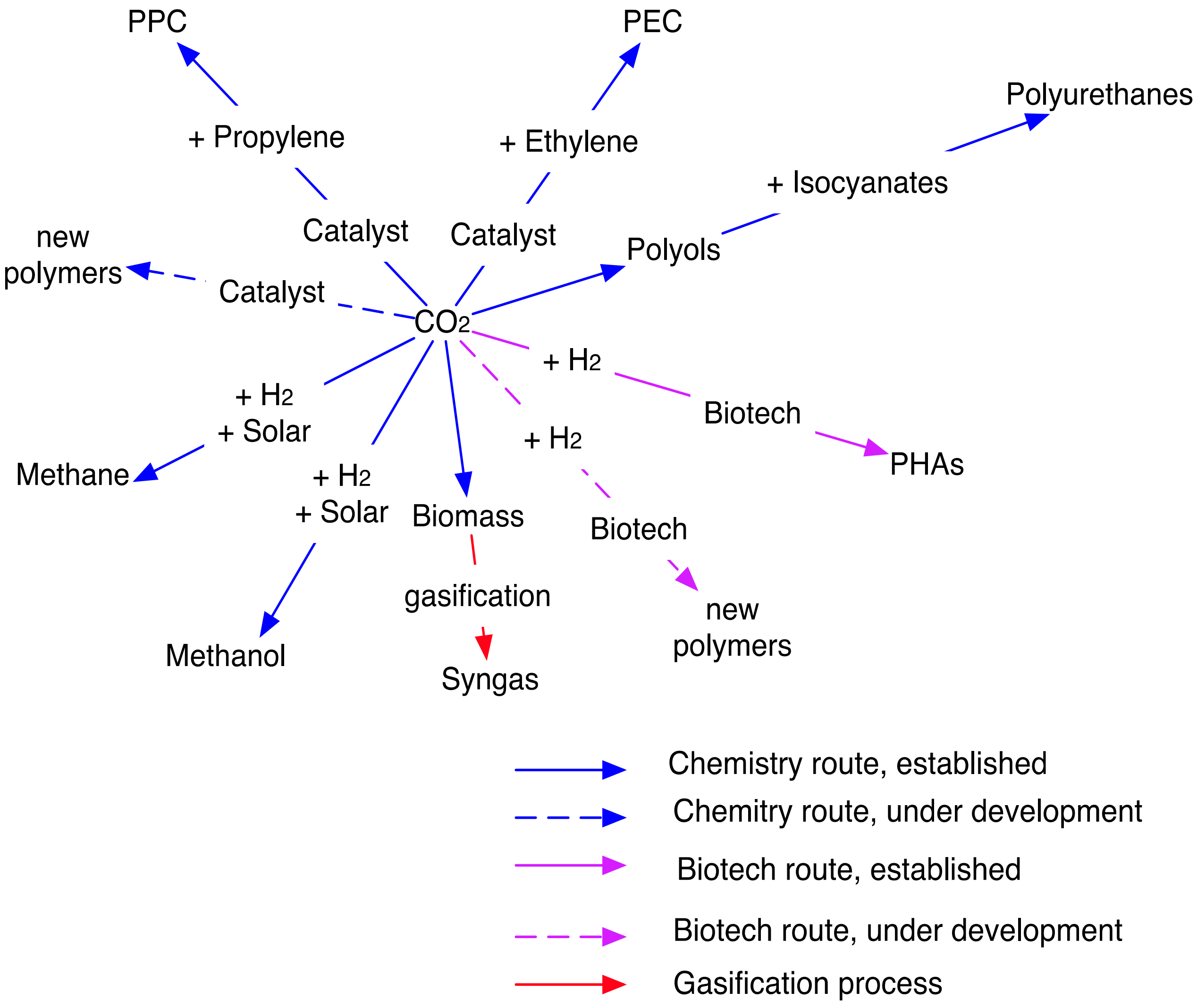


Syngas can be then converted to many useful chemicals

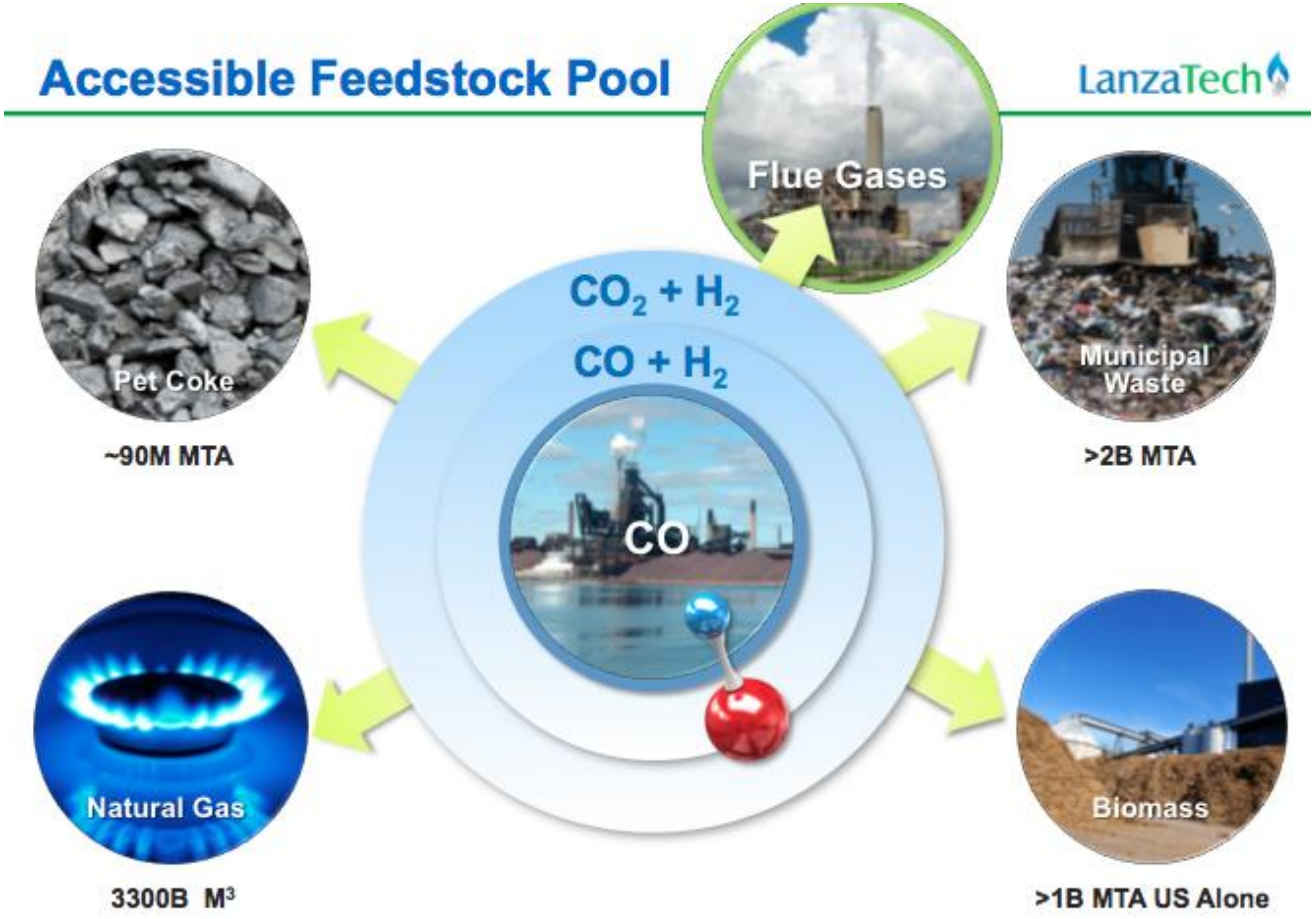
CO_2 conversion to polymers via Biotechnology and Chemistry

CO_2 can be converted:

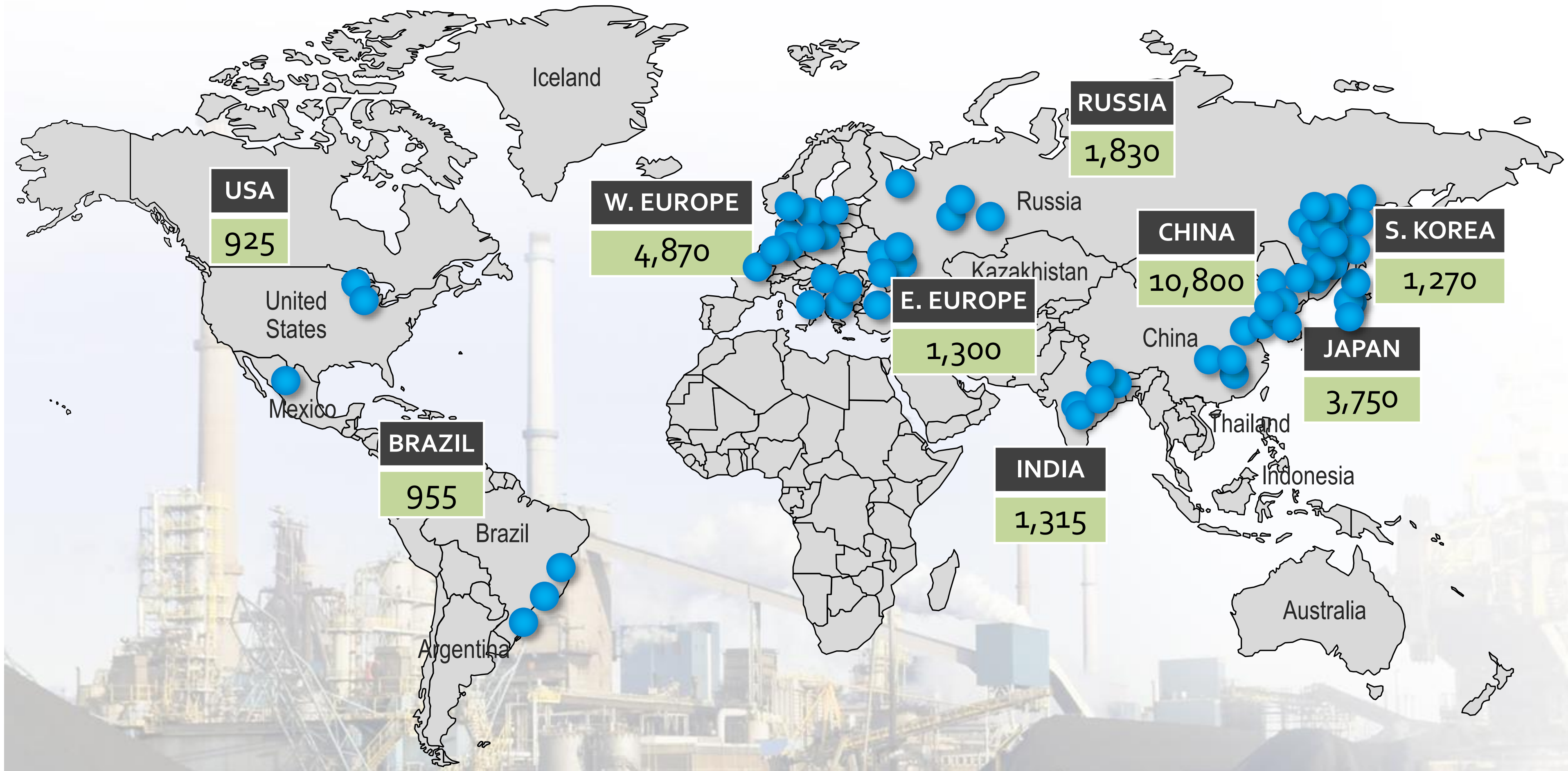
- to polyurethanes, from the company Bayer AG with a process that is already commercial
- to PPC and PEC by Novomer, SK Innovation and other players with processes that is already commercial
- to PHA, by Newlight Technologies with a process that is already commercial
- to all the polymers that are methane or methanol derived, once CO_2 is re-upgraded to these two moleculs with H_2 and renewable energy
- to now polymers that are likely to come as more and more researchers and company are targeting CO_2 as feedstock for polymers and plastics



Lanzatech syngas fermentation



Steel Gases: >110Bn liters Ethanol Capacity

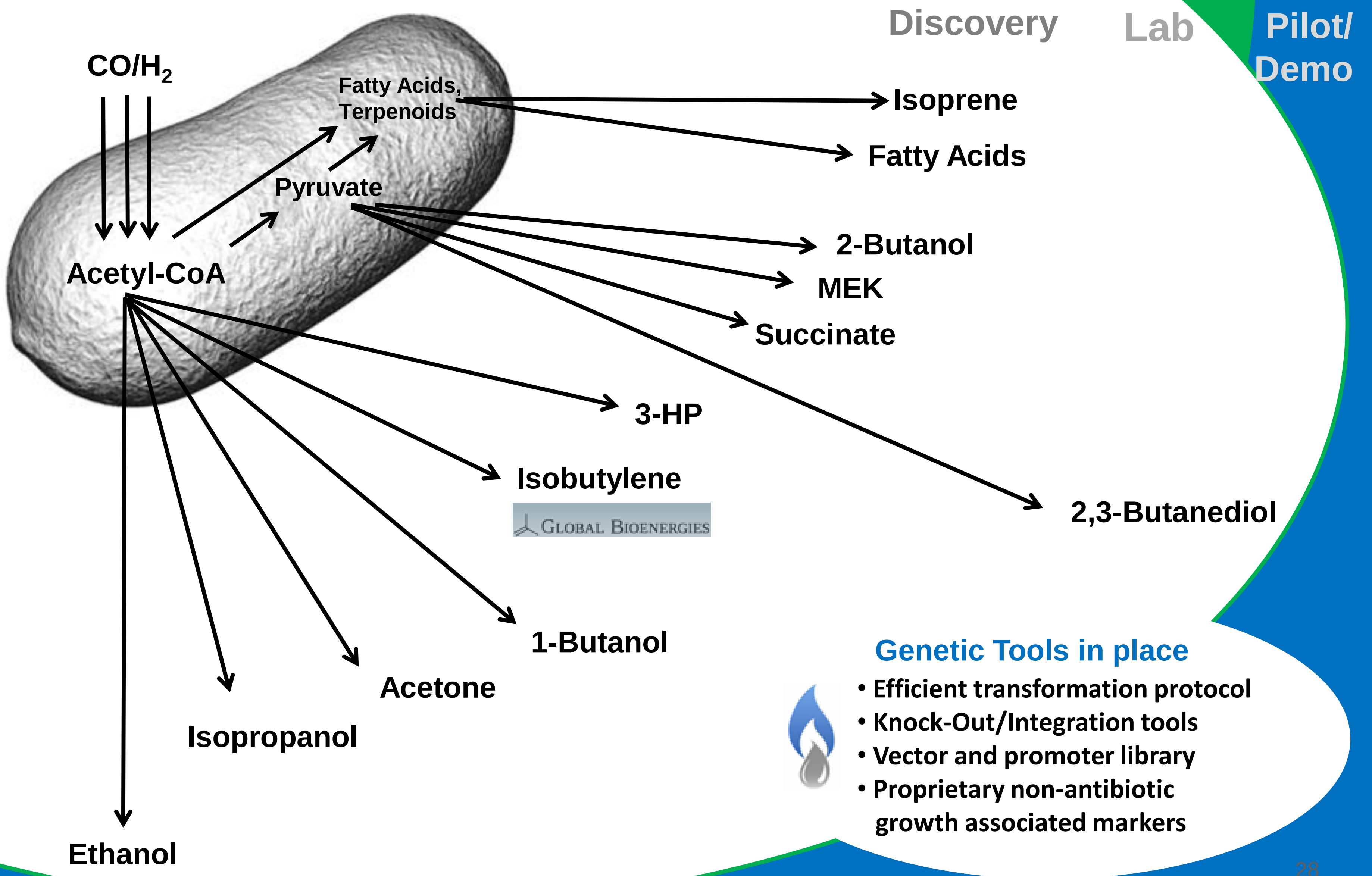


(dark box)	Country
(green box)	Potential Ethanol Production Capacity (MMGPY)
(blue dot)	Steel Mills (>5 MT/year)

TOTAL
27,015 MMGPY

Metabolic Engineering for Fuels/Chemicals

LanzaTech

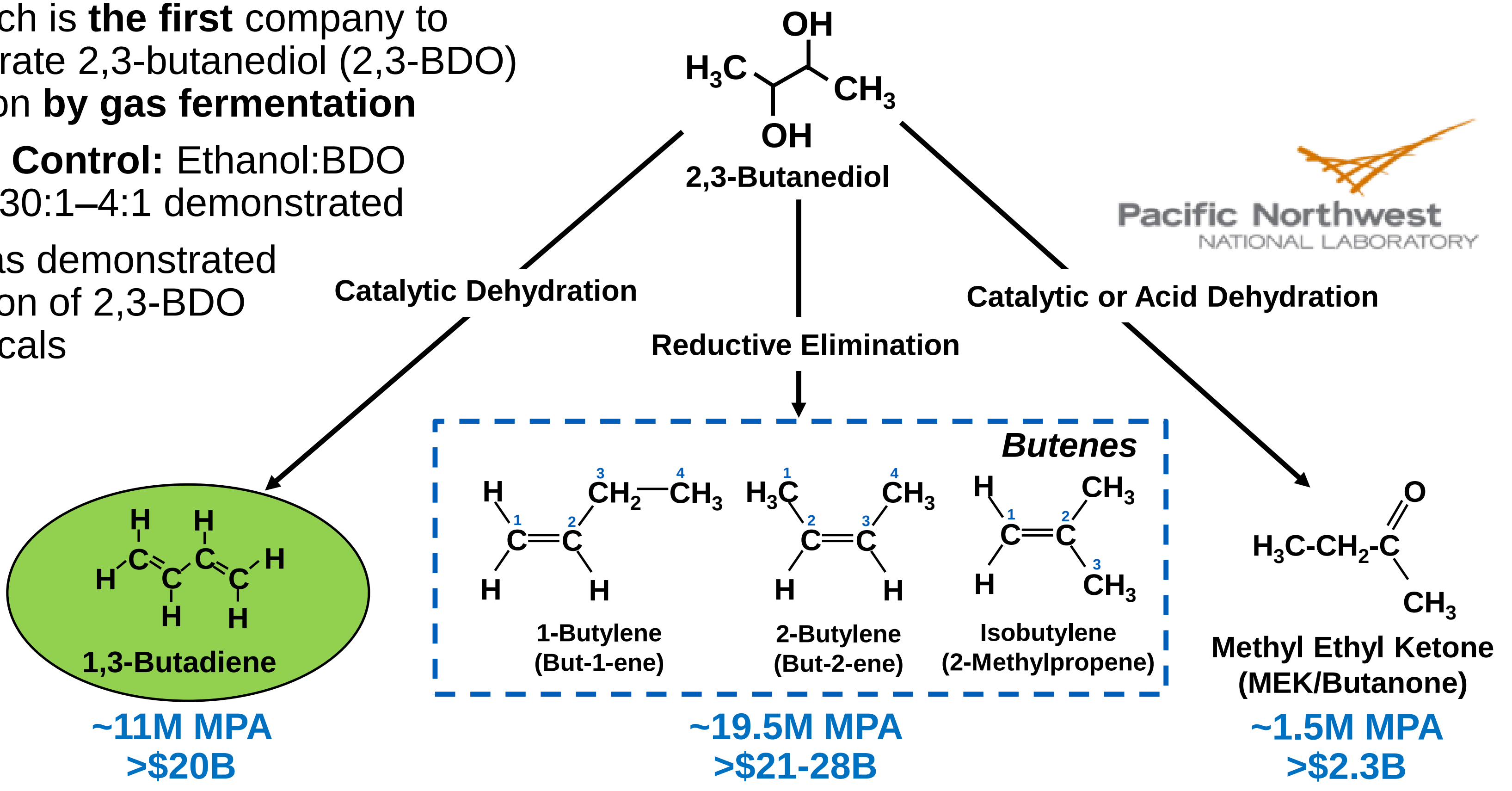


Genetic Tools in place

- Efficient transformation protocol
- Knock-Out/Integration tools
- Vector and promoter library
- Proprietary non-antibiotic growth associated markers

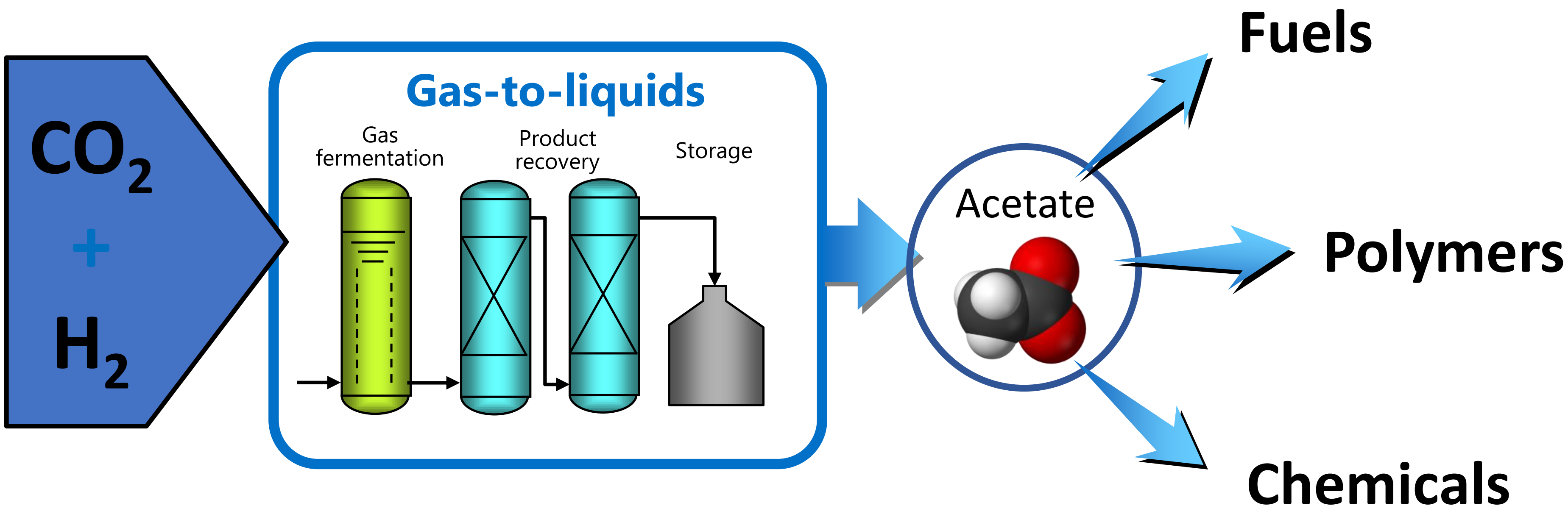
2,3 BDO: A Route to Platform Chemicals

- LanzaTech is **the first** company to demonstrate 2,3-butanediol (2,3-BDO) production **by gas fermentation**
- **Process Control:** Ethanol:BDO ratios of 30:1–4:1 demonstrated
- PNNL has demonstrated conversion of 2,3-BDO to chemicals



Preliminary Screening Demonstrates Technical Feasibility

Using CO_2 as a Carbon Source



***CO_2 uptake and capture** demonstrated*
*in a **<u>continuous</u>** fermentation*

- CO_2 is the carbon source, H_2 is the energy source for product synthesis

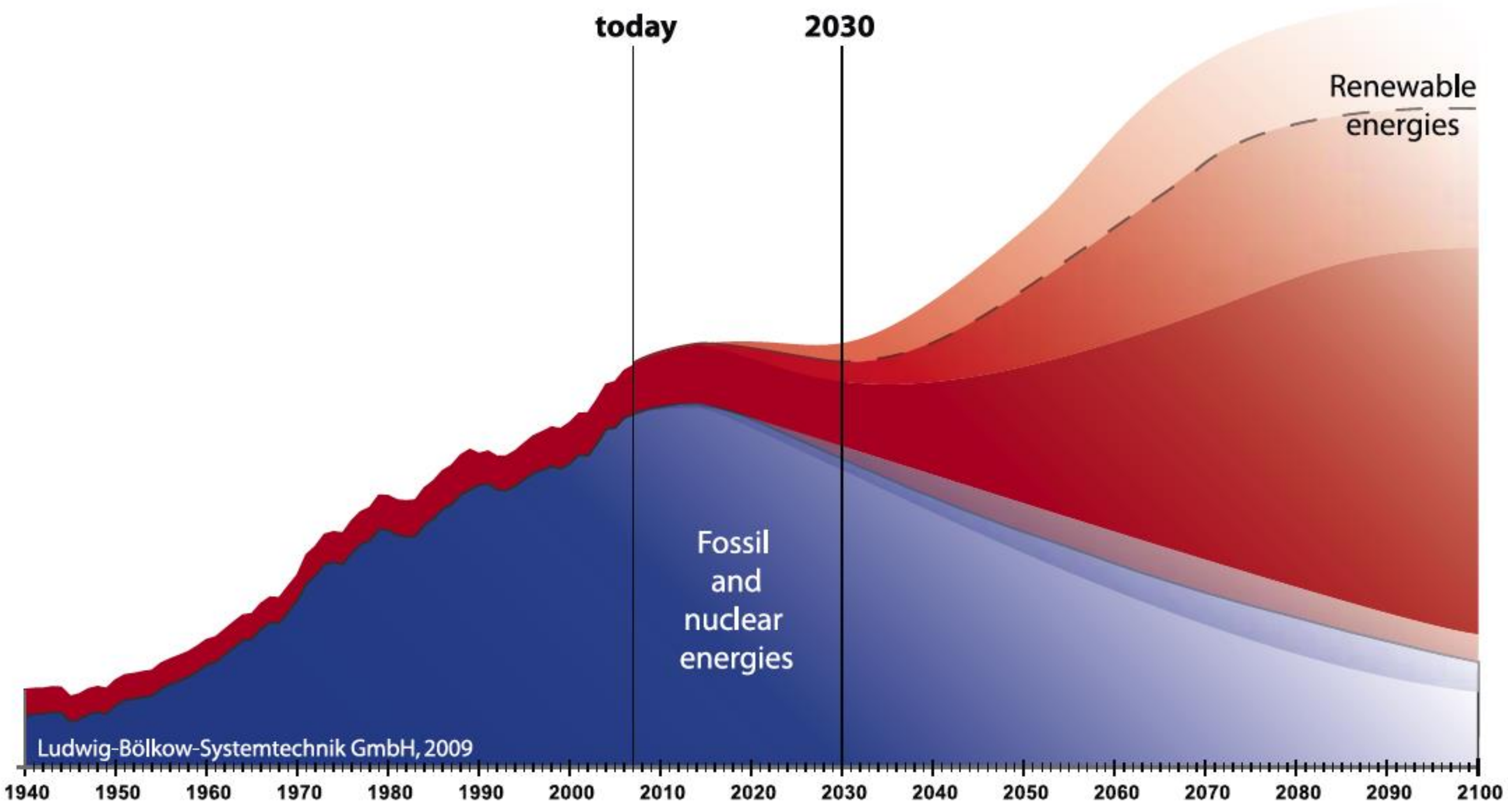
30

Power to Gas at Krajete GmbH: The Origin – Motivation CO_2 Conversion

Today`s problems

- human made (= anthropogenic)

--> CO_2 & Energy Supply



New Approach = "Biomimicry"

- "Biomimicry is the examination of nature to take inspiration from it in order to solve human problems"

Bio Building Block of “Power to Gas”

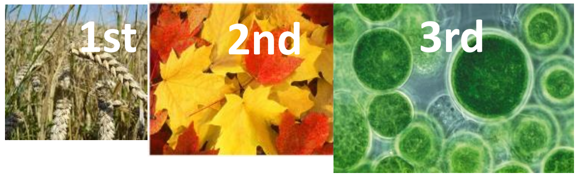
CO_2 + $4\ H_2$ → CH_4 + $2\ H_2O$ - 130 kJ/mol

4 x 3,54 kWh 11,06 kWh efficiency, 78 % max.

Catalyst *“Archaea”*

Process *“Methanogenesis (“Biological Methanation”)*

CO_2 / water — light →



0.1 kg/m³ x h → CH_4

+ H_2 reduction agent !

fast

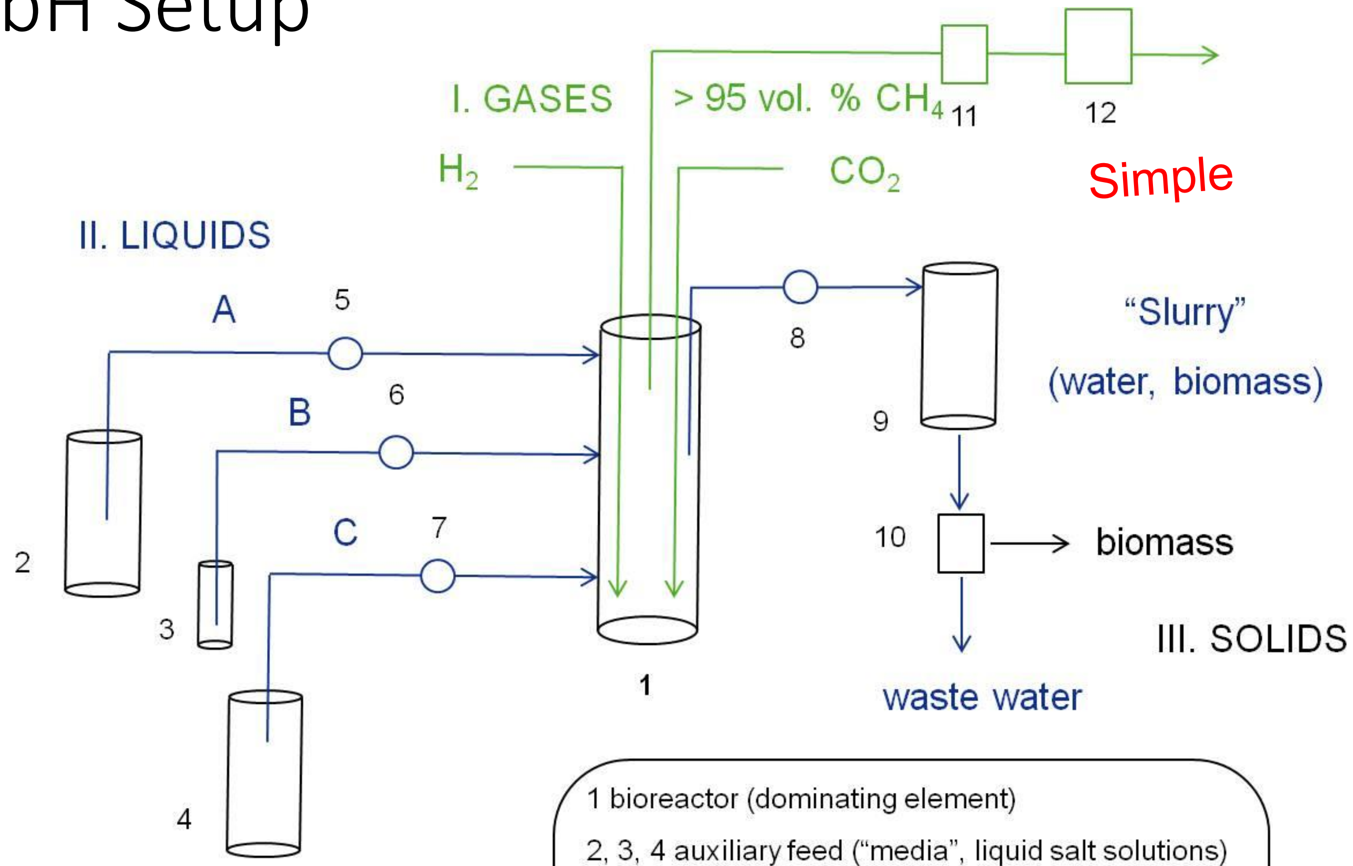
out of “food for fuel”

“Photosynthetic Bypass”

4 th Generation Biofuels

(> 15 kg/m³ x h)

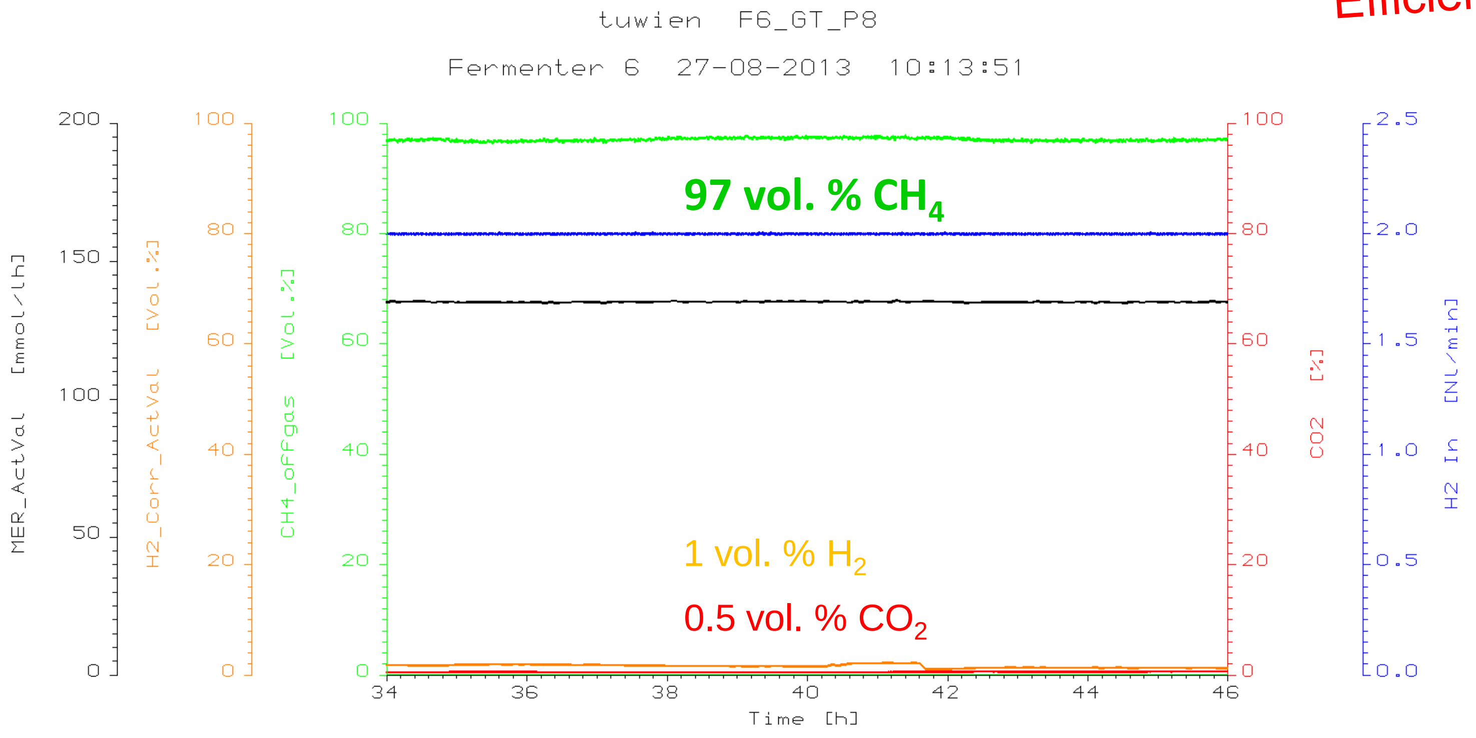
Krajete GmbH Setup

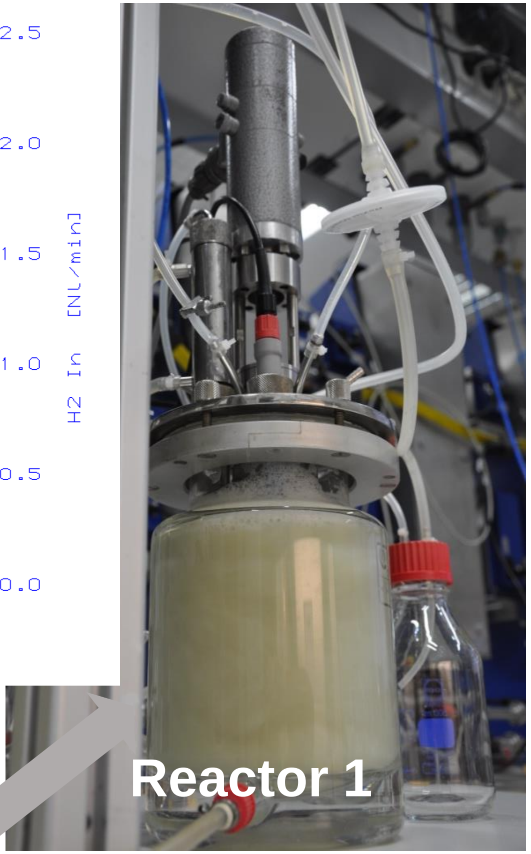


1 bioreactor (dominating element)
2, 3, 4 auxiliary feed ("media", liquid salt solutions)
5, 6, 7 pumps
8 harvest pump
9 vessel
10 separator
11 drying unit (condenser)
12 desulfurization unit (optional)

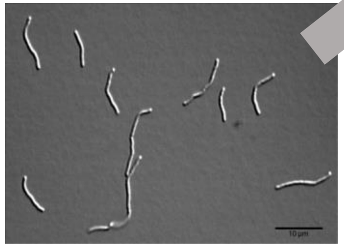
One Step Synthesis = our Route

Efficient





DVGW spec. is 95 vol. % methane

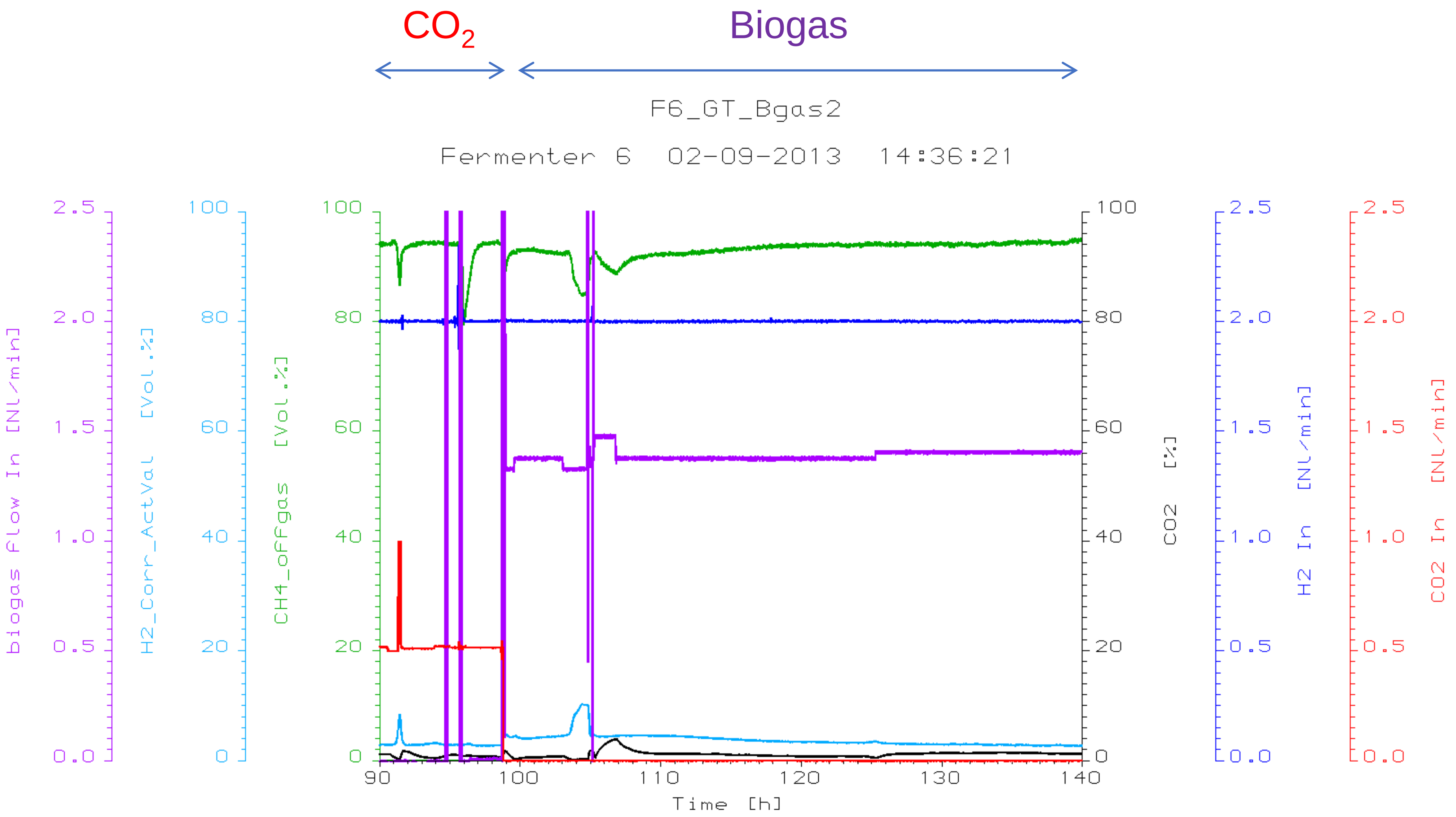


Proof through Gas Sampling & Feasibility – Automobile/Power/Biogas Industry

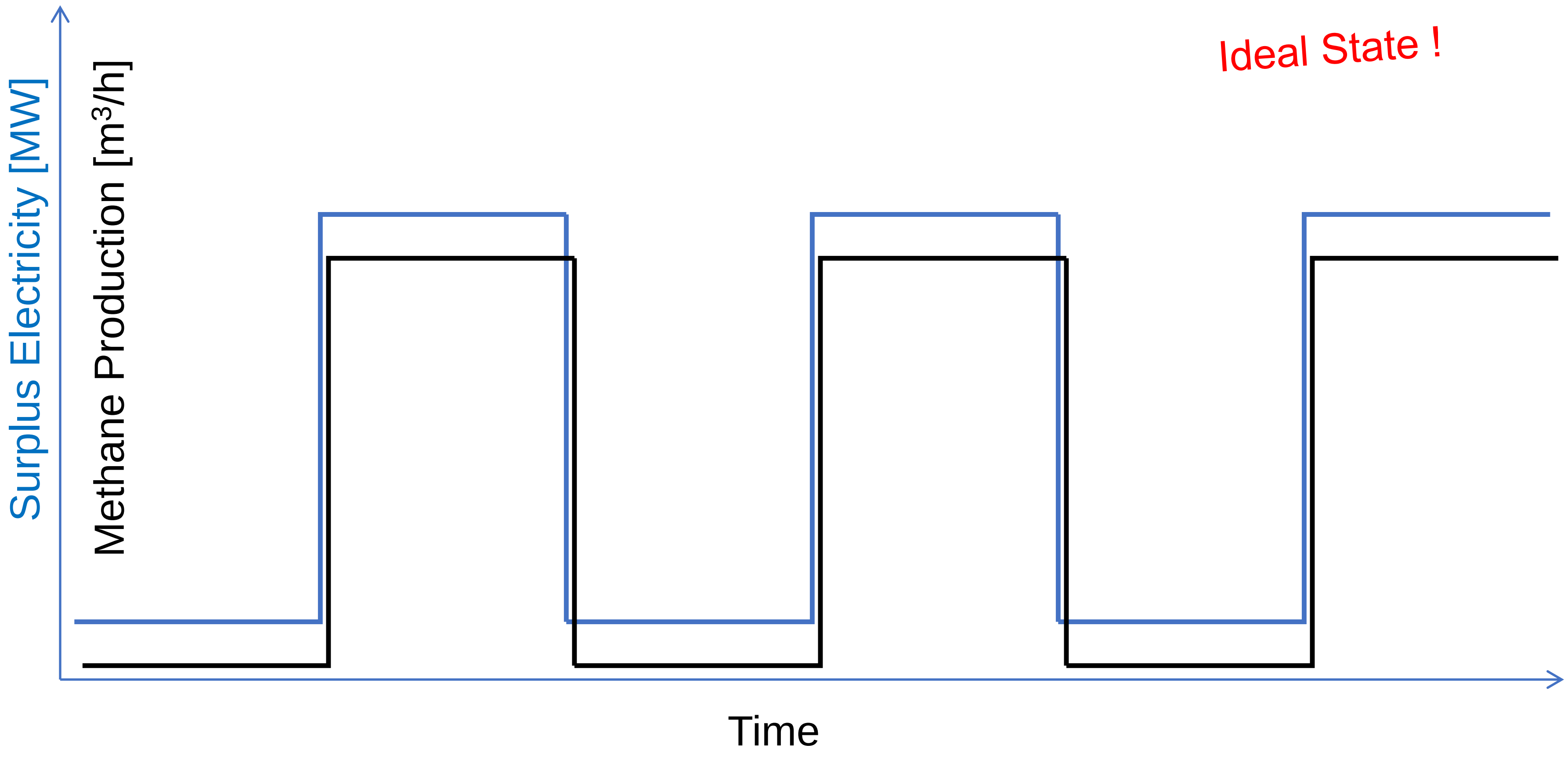
Example Biogas: 3 bottles with 70 - 100 bars were sampled and transported to Vienna

sampled on Aug. 30, 2013

From Biogas to DVGW conform Gas

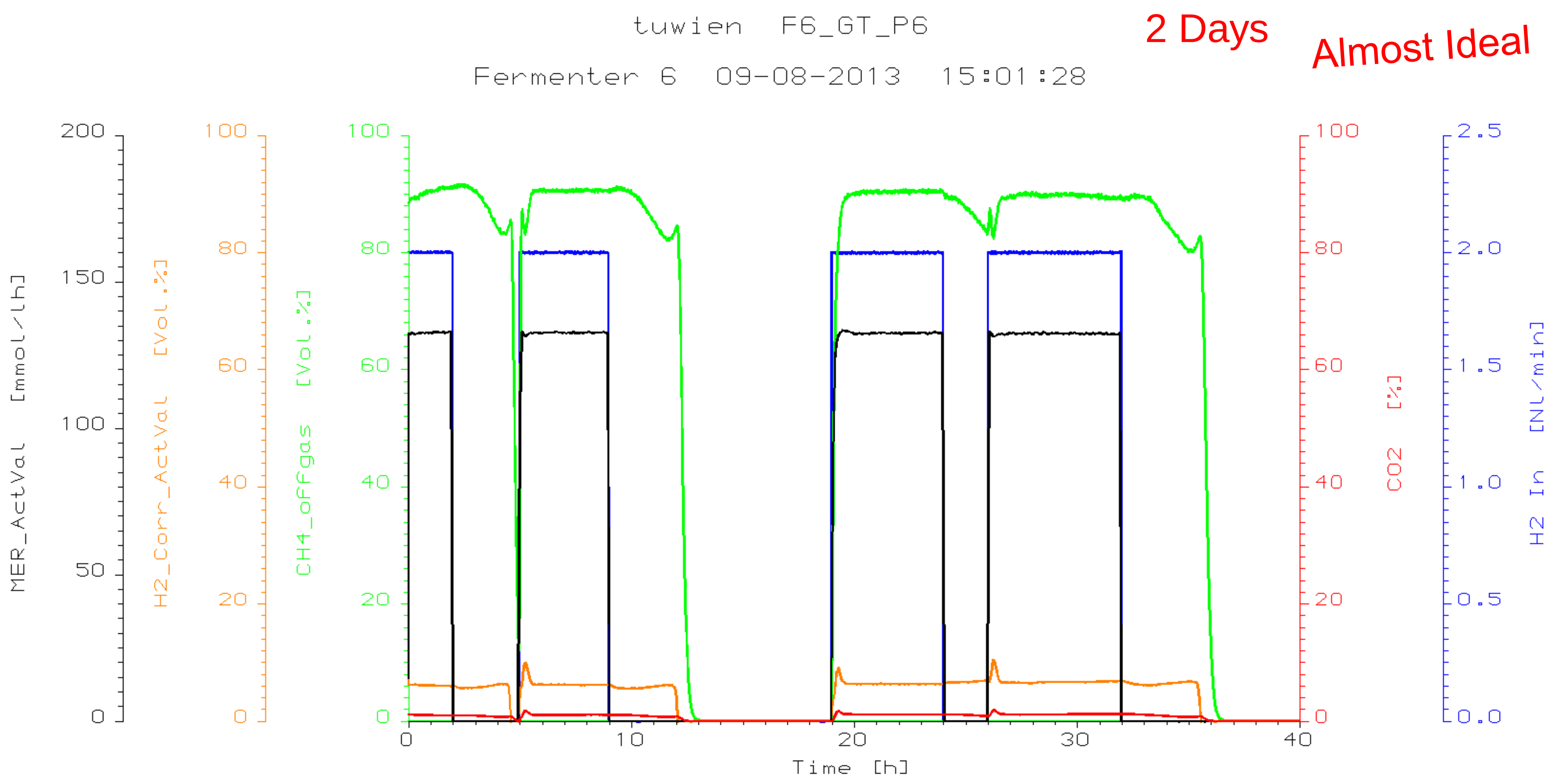


Challenge - Intermittency
How would an ideal Response look ?



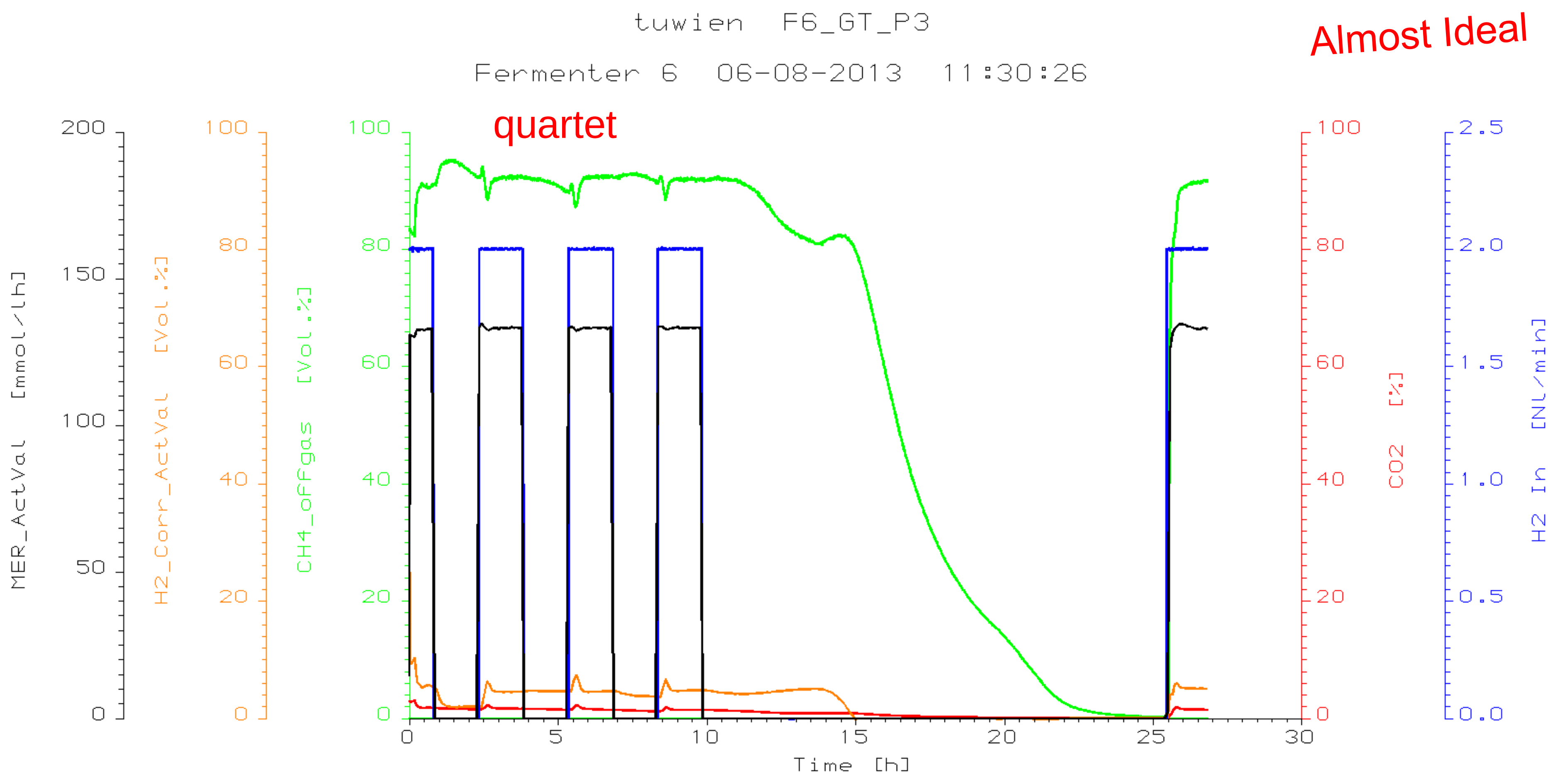
Ideally, methane (energy storage) follows <u>instantly</u> surplus electricity

4. Can we make Natural Gas under "intermittent" Conditions in 1 Step for longer Time ?



1. Fast response to natural gas & reproducible in 1 step !
2. Transitions - complete shutdown !

Can we make Natural Gas under "intermittent" Conditions in 1 Step with frequent Changes ?



1. Fast response to natural gas & reproducible in 1 step !
2. Transitions - complete shutdown, no energy losses

Is Biology fast ?

Conversion = “MER” = “methane evolution rate”

[m^3 CH_4/m^3 suspension x hour]

Very Fast

Volumetric production: >**25** m^3 CH_4/m^3 susp. x hour

Specific production: >2 m^3 CH_4/kg biocatalyst x hour

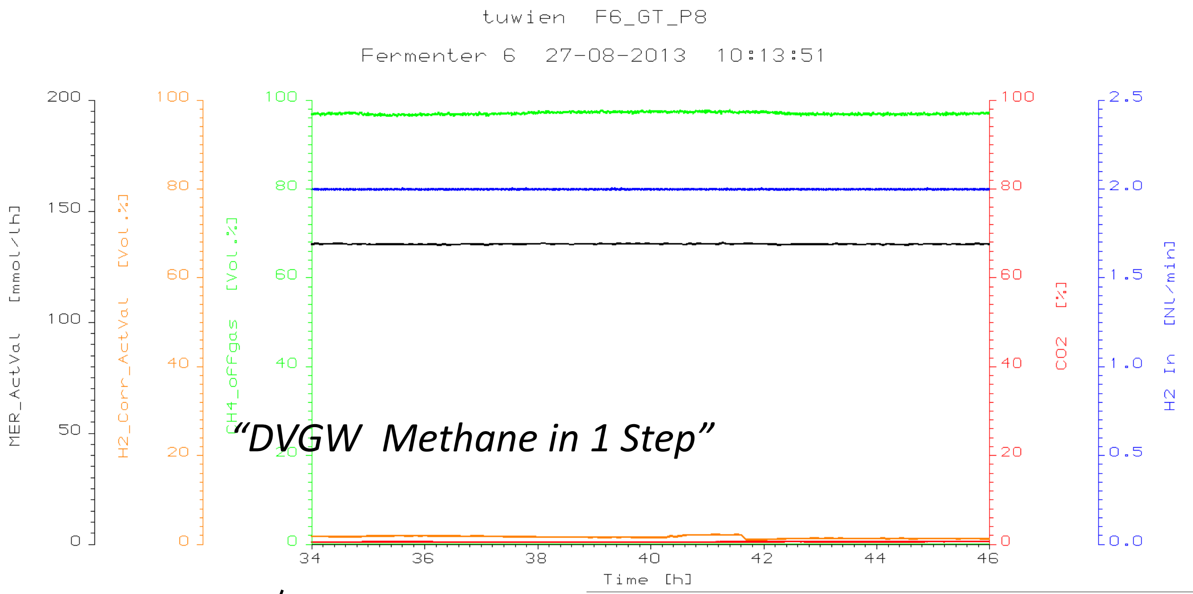
typical biomass concentrations: 5 – 10 g/Liter suspension volume

Process Attributes in a Nutshell

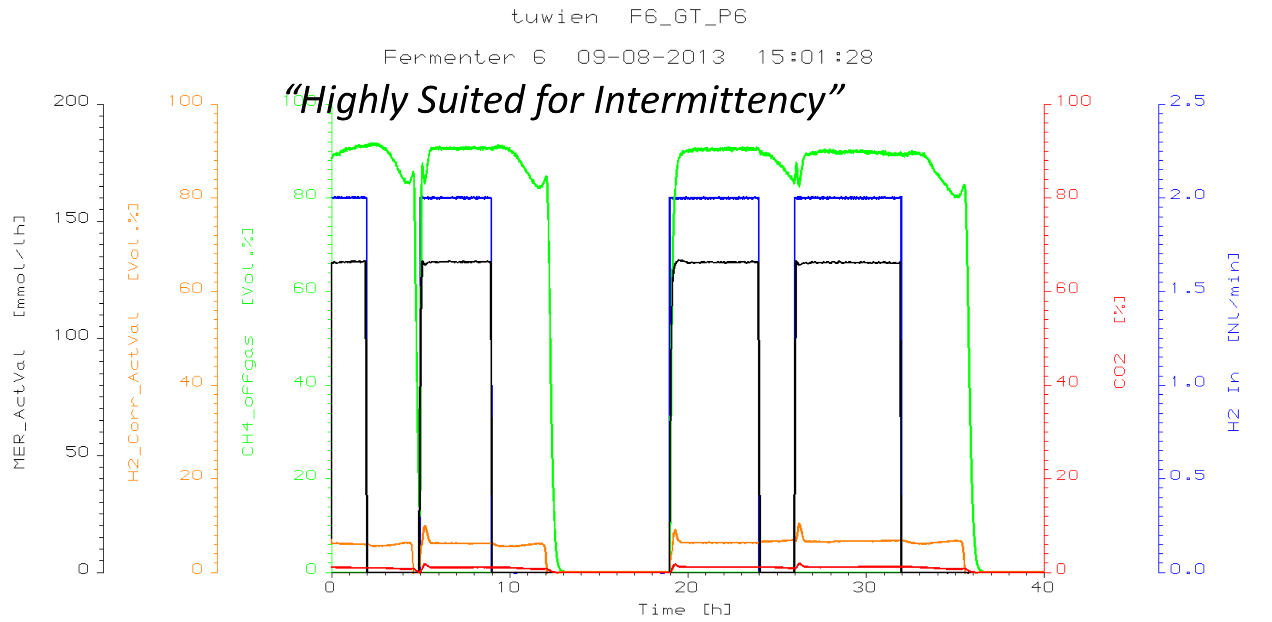
Asset	Parameter	Content	Economic Impact
1	**Energy input**	low, mild conversion at low presure (1 bar) & low T (65 ^oC)	save compressor & heating/cooling elements;
2	**Selectivity & impurity tolerance**	high, microbes extract nutrients from complex mixtures, example black smoker (proof through real gas applications)	save upstream gas processing operating units (e.g. purifier, desulfurization, PSA, amine scrubber)
3	**Stability , Adaptation & Easy Process Control**	high, suited for intermittency, fast response in both directions within 1-2 minutes; adjustment to feedstock, robustness	application feasible, “power to gas” potential, high operability
4	**Conversion**	22 m^3 methane/m^3 bioreactor x hour	lower CAPEX
5	**Catalyst preparation & Image**	easy, from waste ingredients; REACH compliant, sustainable	cheap & independent gas conversion

„Bioprocess is a) simple, b) robust, c) dynamic & d) fast !

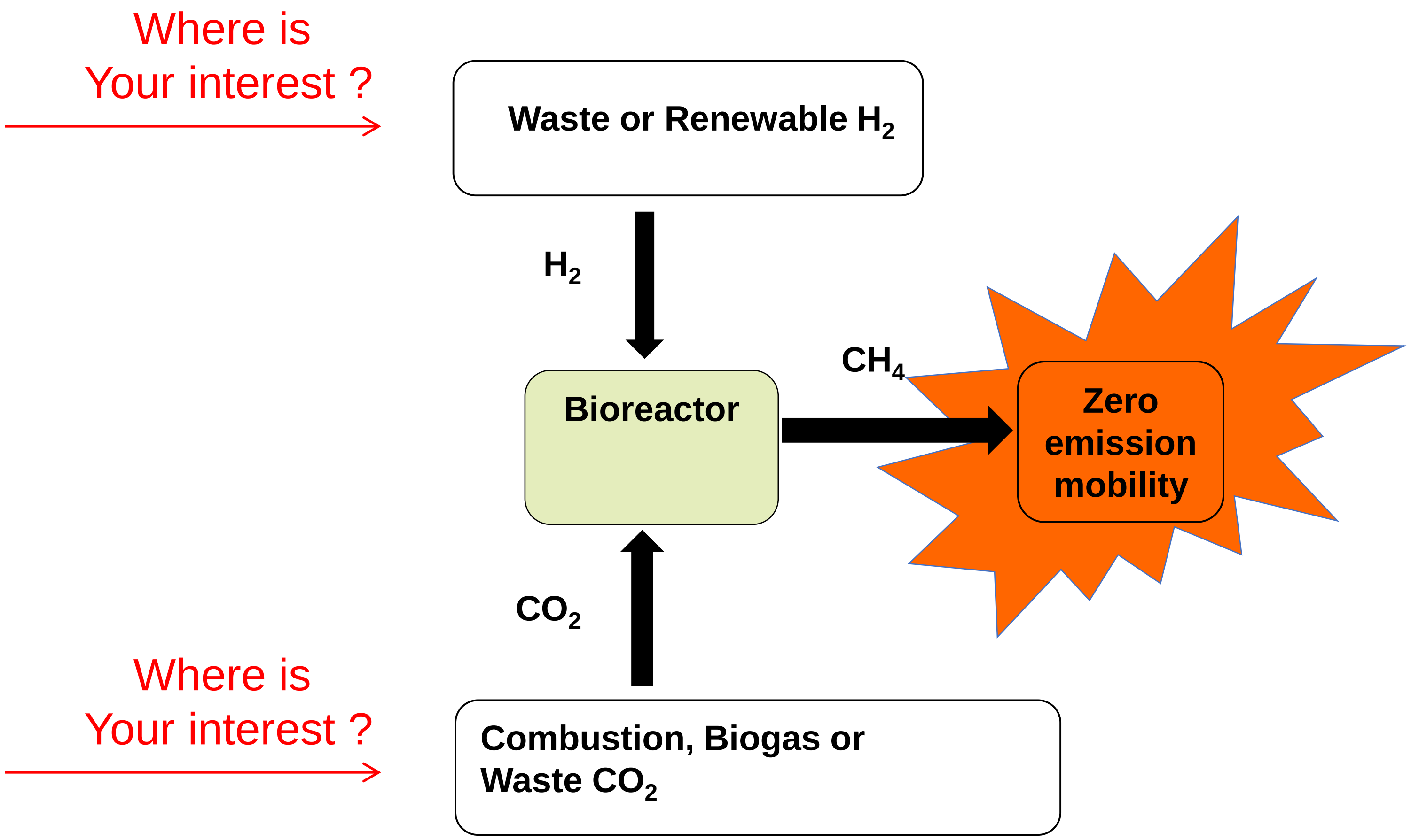
Essence in 2 Key Attributes !



also with Biogas !



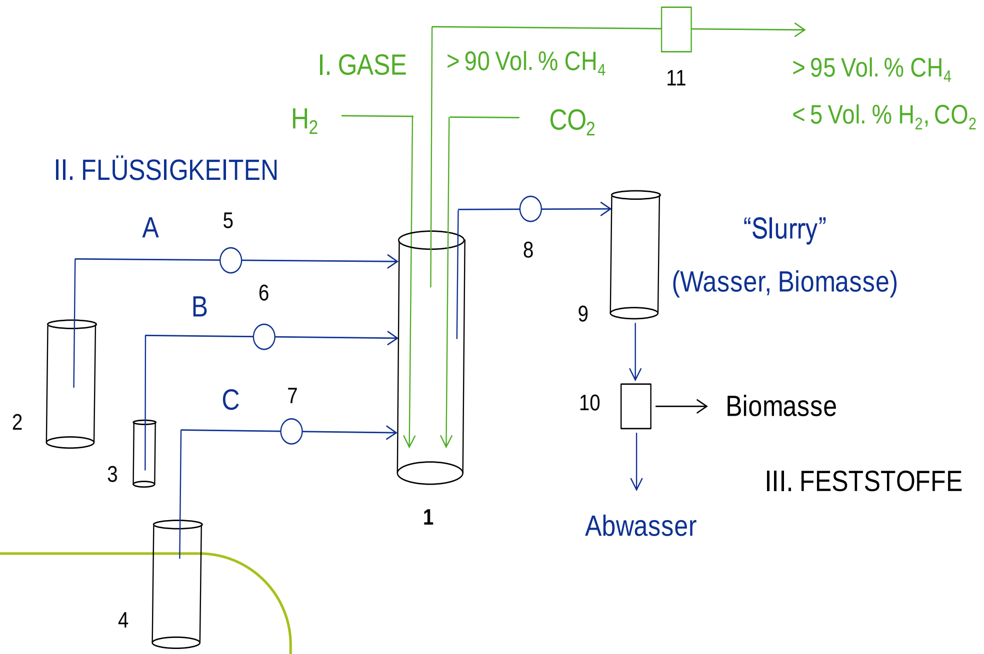
Applications: Efficiency & Power Storage



Example:
1 year / 1 MW electricity via PtG into 500 000 m^3 nat. gas,
sufficient for 1000 cars with 10 000 km/year

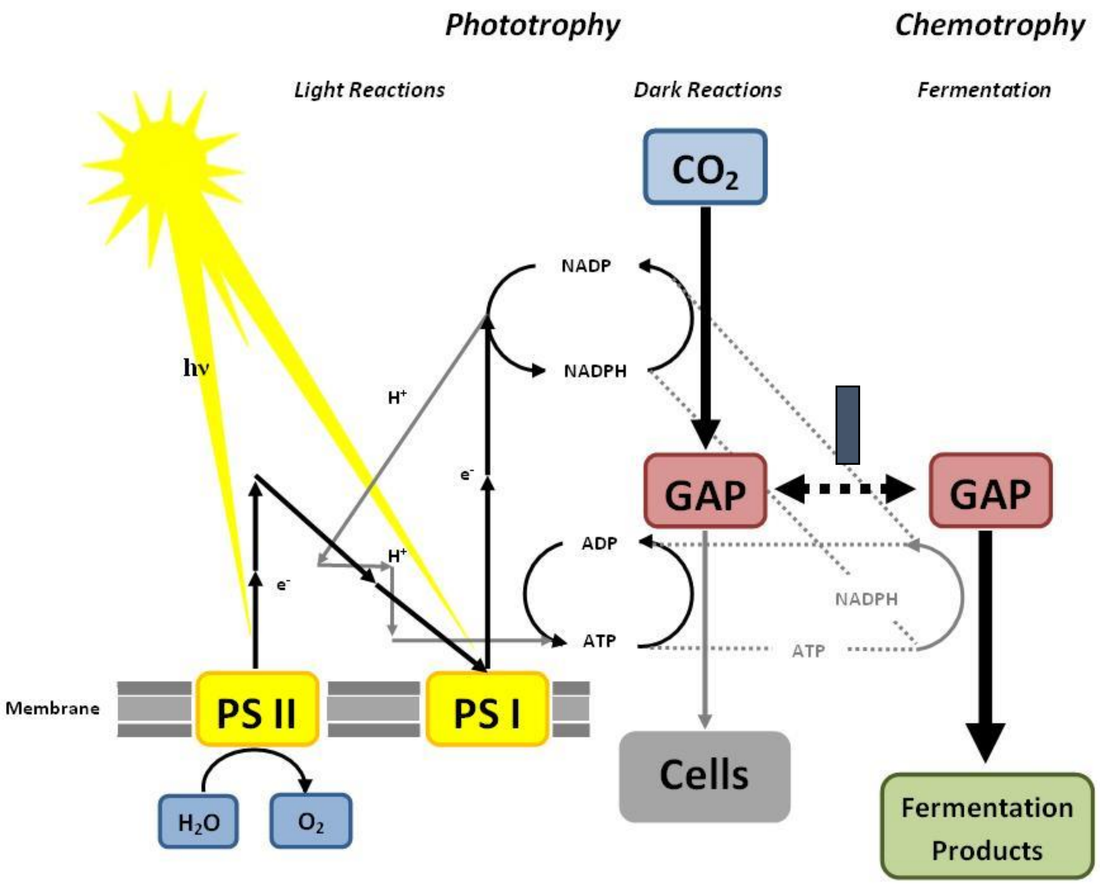
Example: early engineering for car manufacturers

- Study done in cooperation with us
- Inputs from the car manufacturer
- Krajete GmbH delivered 5 detailed reports
- 1 Report based on “Intermittent Power Storage”
- > 250 pages, with 2 concept studies (Pilot & Commercial plant)

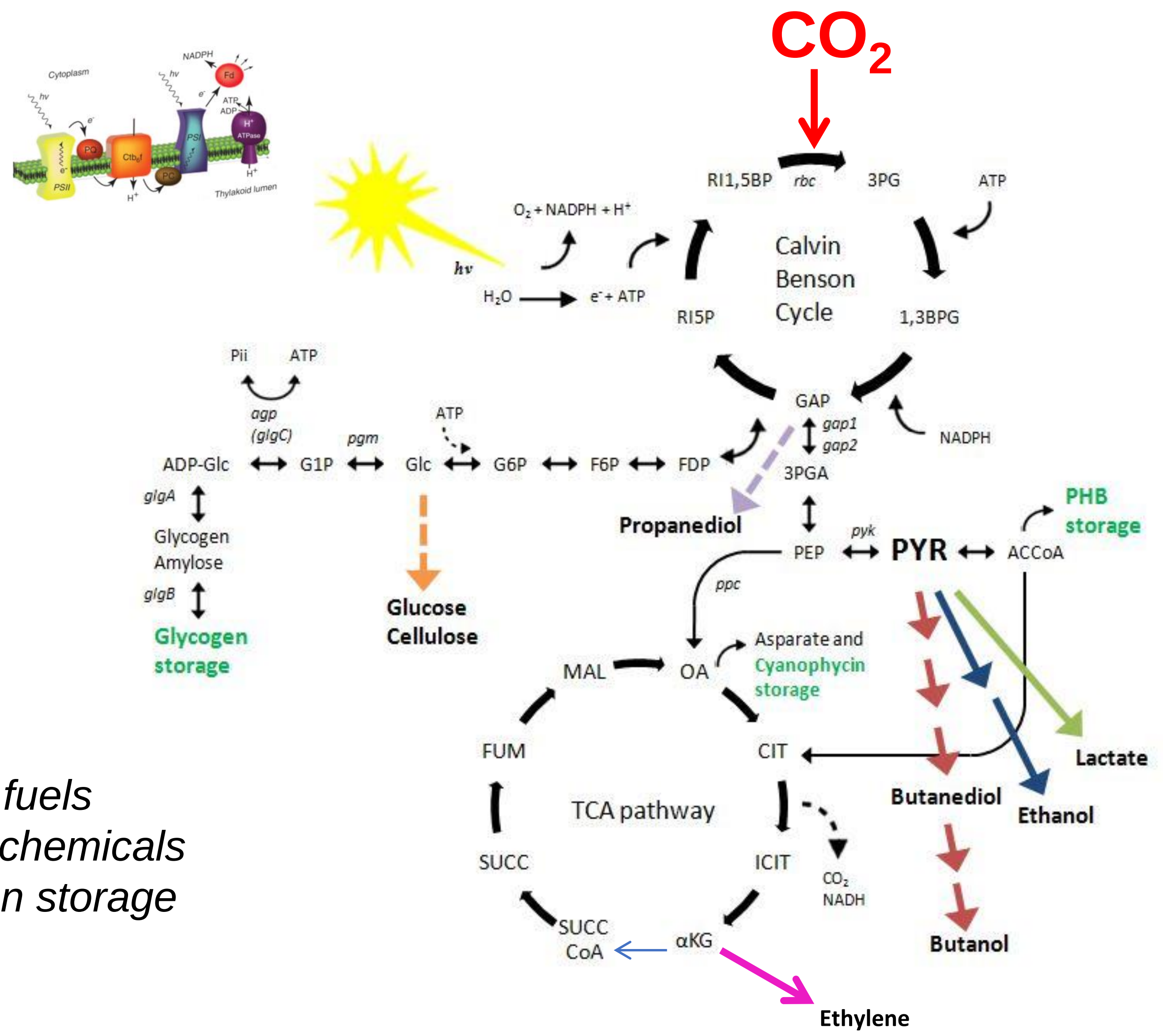


- **Report 1** – Dimension of commercial plant
- **Report 2** – influence of different locations on the pilot and commercial plant
- **Report 3** – Intermittent Power Storage
- **Report 4** – Conceptual Engineering Pilot plant
- **Report 5** – Conceptual Engineering Commercial plant

Photofermentation

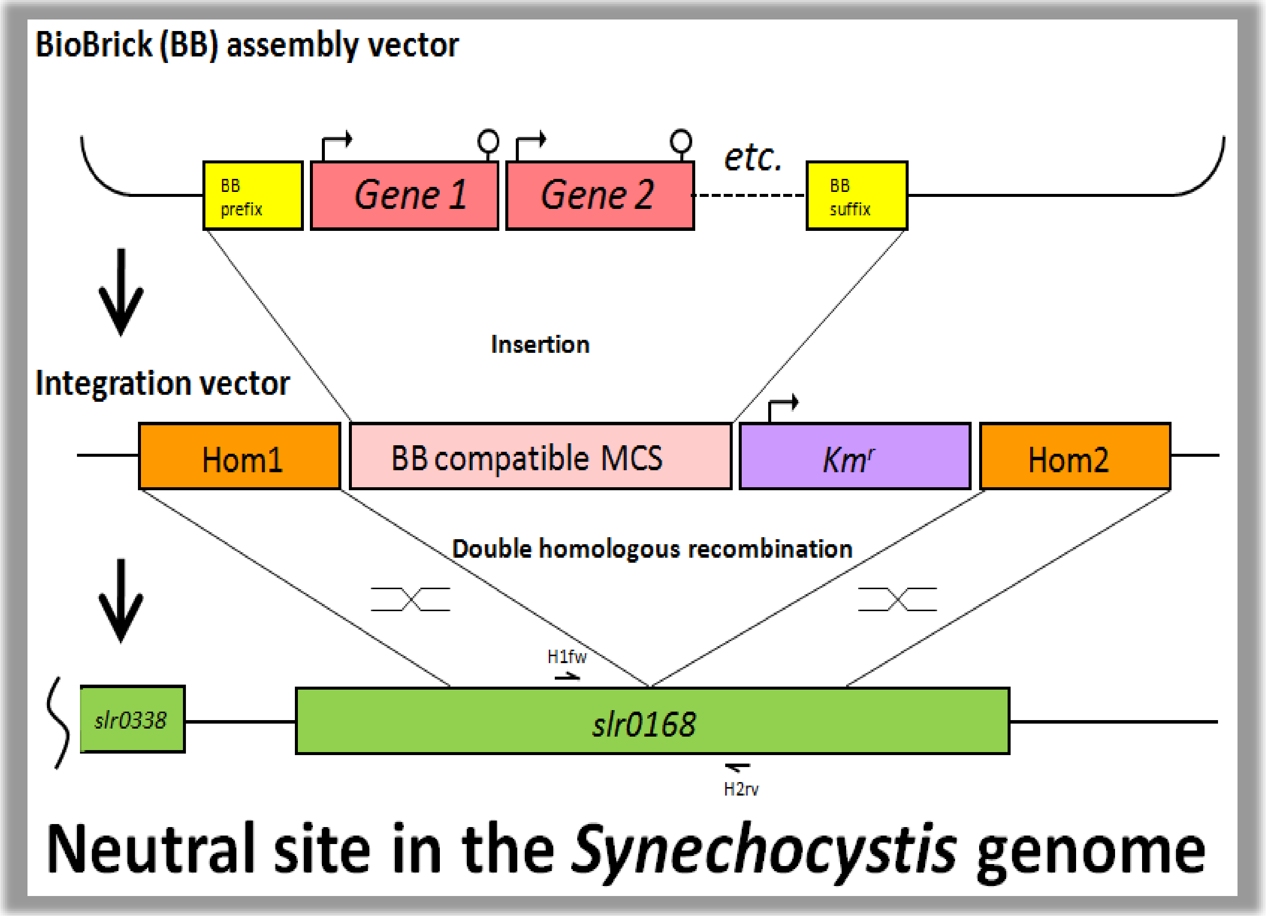


Coupling to cyanobacterial metabolism:



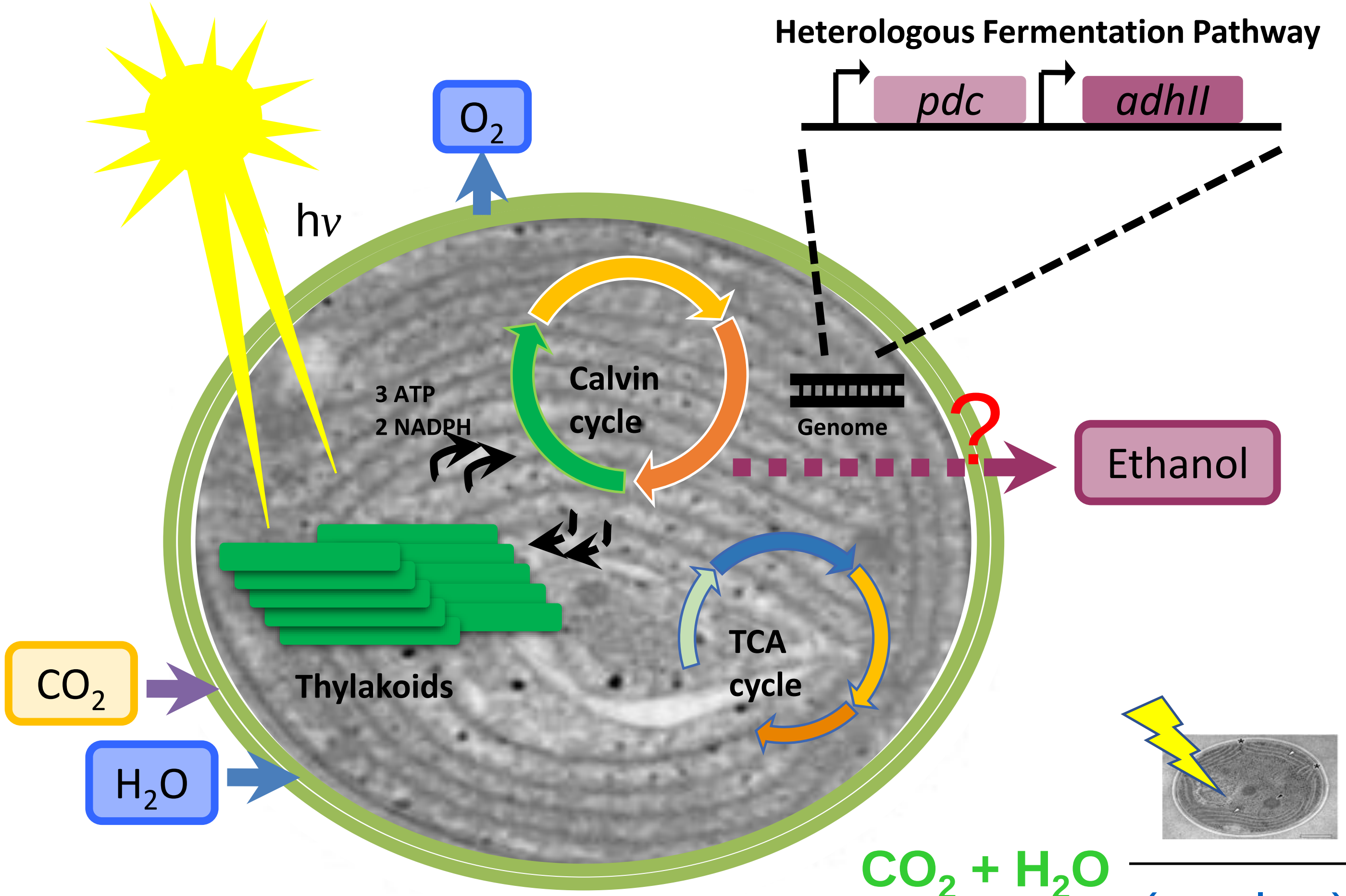
brown, pink: fuels
blue, green: chemicals
green: carbon storage

Engineering with base-pair precision
Photanol (now acquired by Azko-Nobel)



Fourth generation type of process:

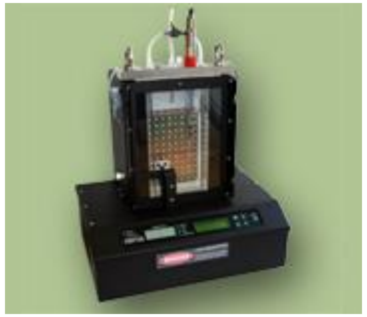
Cyanobacterial cell factories

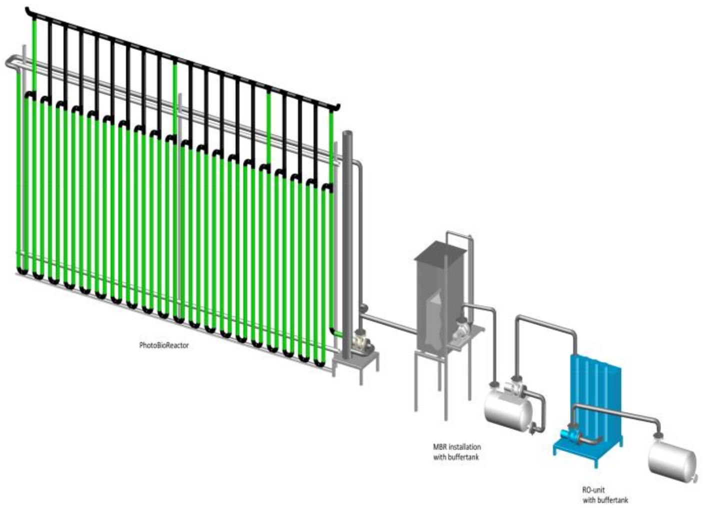


$CO_2 + H_2O \xrightarrow{\text{(catalyst)}} C_2H_6O + O_2$

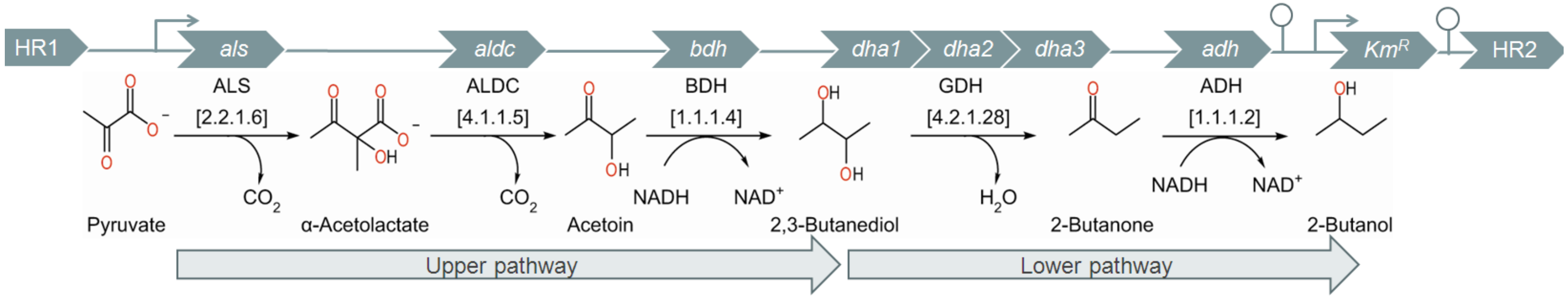
Definition cell factory:
CO_2 partitioning > 50 %

Pilot plant:
(@ Science Park)





Towards 2-Butanol production

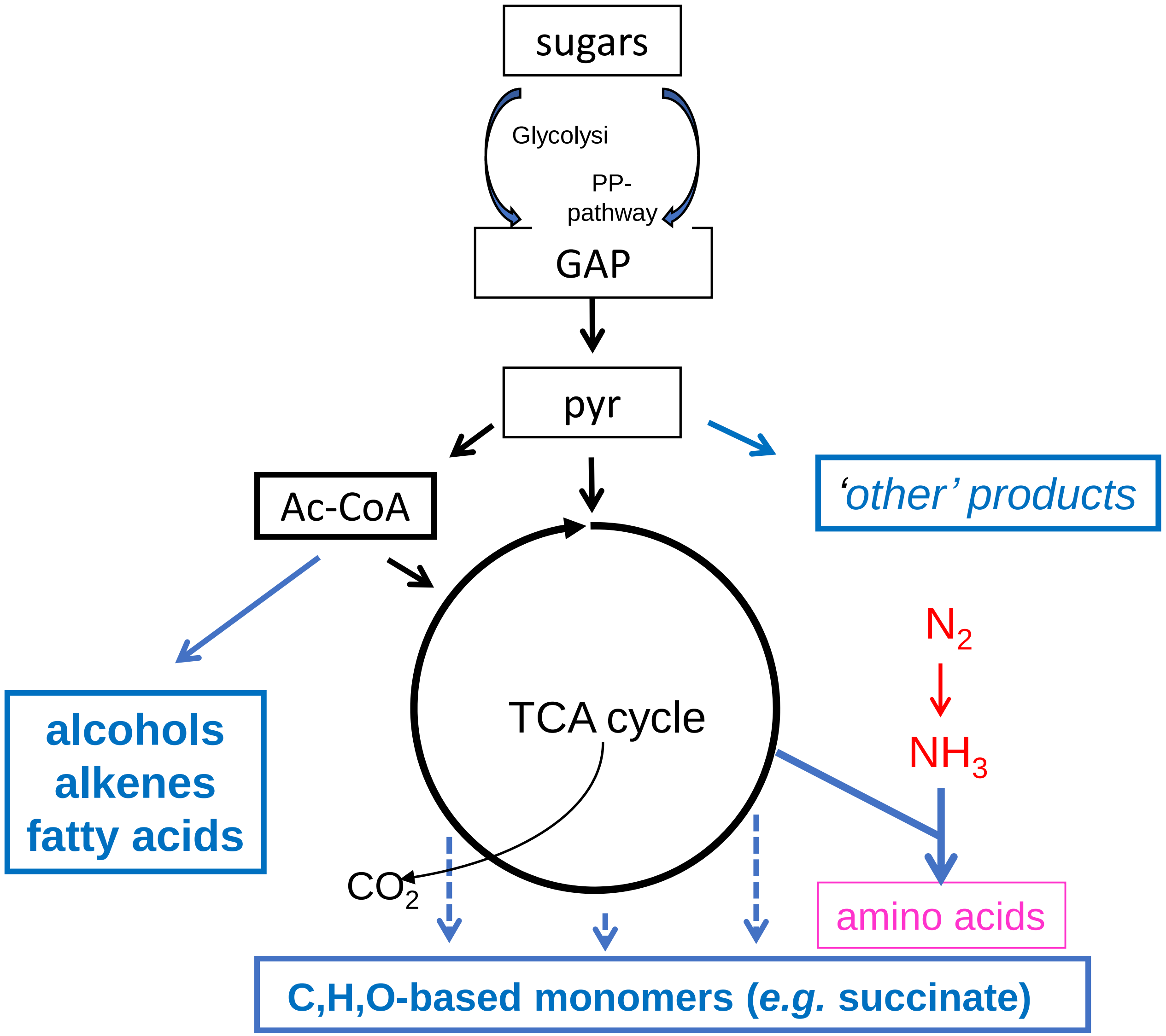


P.E. Savakis, S.A. Angermayr & K.J. Hellingwerf (2013) Synthesis of 2,3-butanediol by *Synechocystis* sp. PCC6803 *via* heterologous expression of a catabolic pathway from lactic acid- and enterobacteria. Metabolic Engineering S1096-7176(13)00092-X

Other products formed from CO_2 with cyanobacteria:

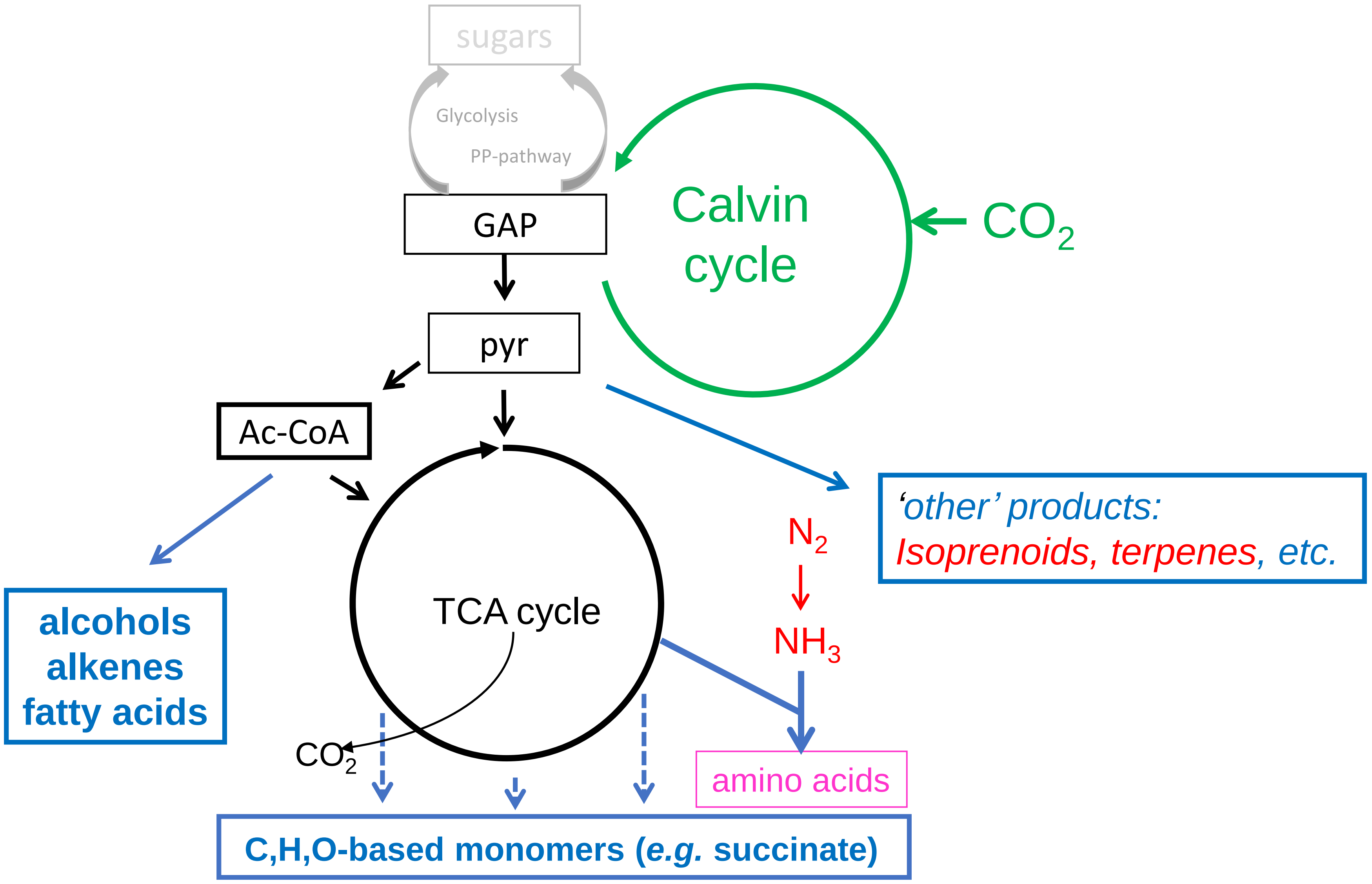
hydrogen, ethanol, ethylene, propanol, acetone, acetoine, *meso*-butanediol, S,S-butanediol, *iso*-butyraldehyde, *n*-butanol, *iso*-butanol, 2-methyl-1-butanol, L-lactic acid, D-lactic acid, glucose, sucrose, isoprene, long-chain alkanes, long-chain alkenes, long-chain fatty acids, long-chain fatty alcohols, etc., → ...

Escherichia coli as a cell factory



PluGbug for sugar

Synechocystis: The new PluGbug: for CO_2



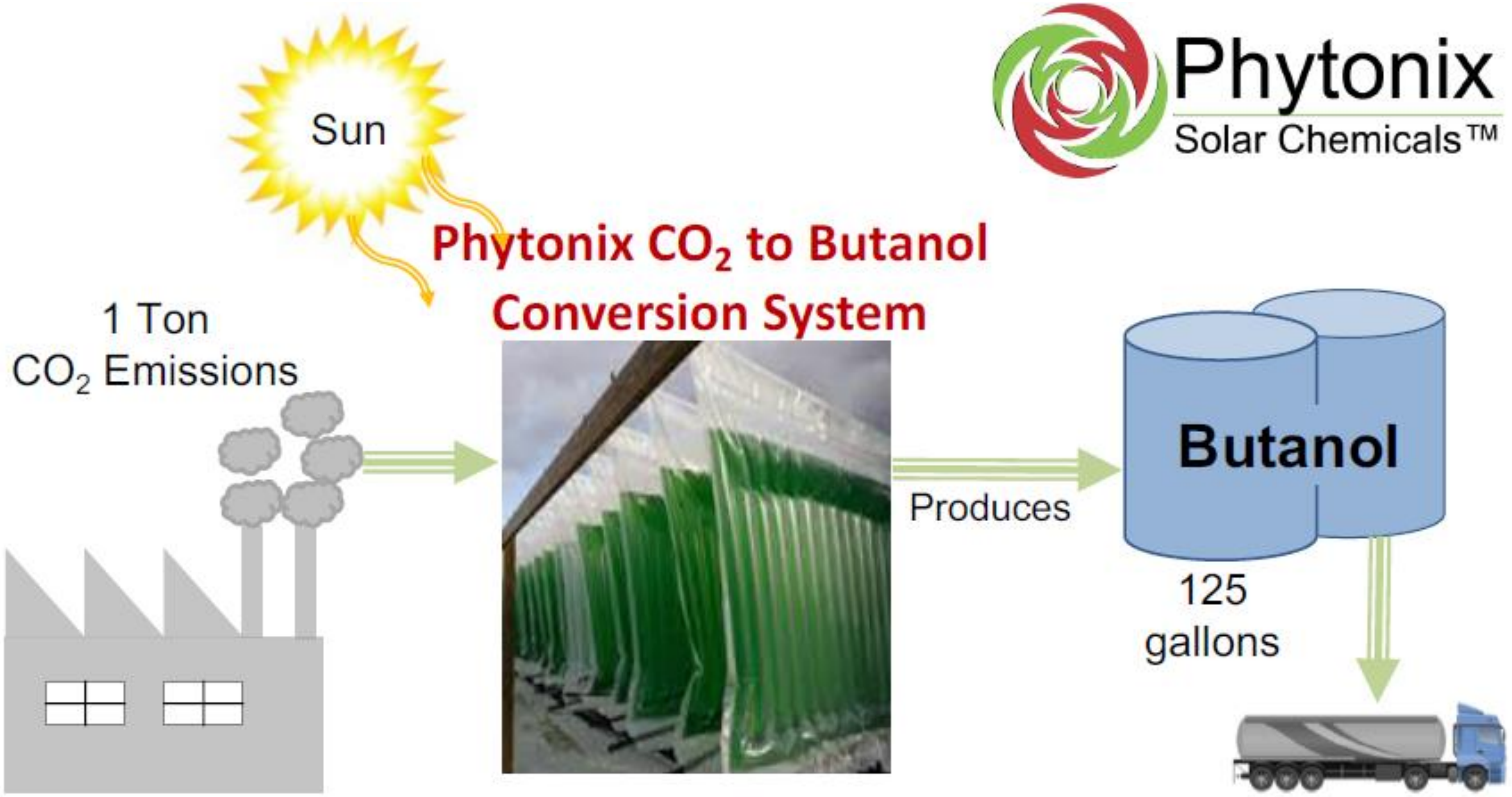
Beyond the 3D approach:

Assuming:
Efficiency of PV-cells: 50 %
Efficiency of LEDs: 70 %
Efficiency conversion 700 nm photons into fuel of 35 %

→ Overall efficiency = 10 %! => 0.1 MW/acre

In other words: A field full of solar panels on non-fertile soil would drive natural photosynthesis more efficiently than plant photosynthesis itself!

CO_2 photofermentation: also Phytonix



Production cost

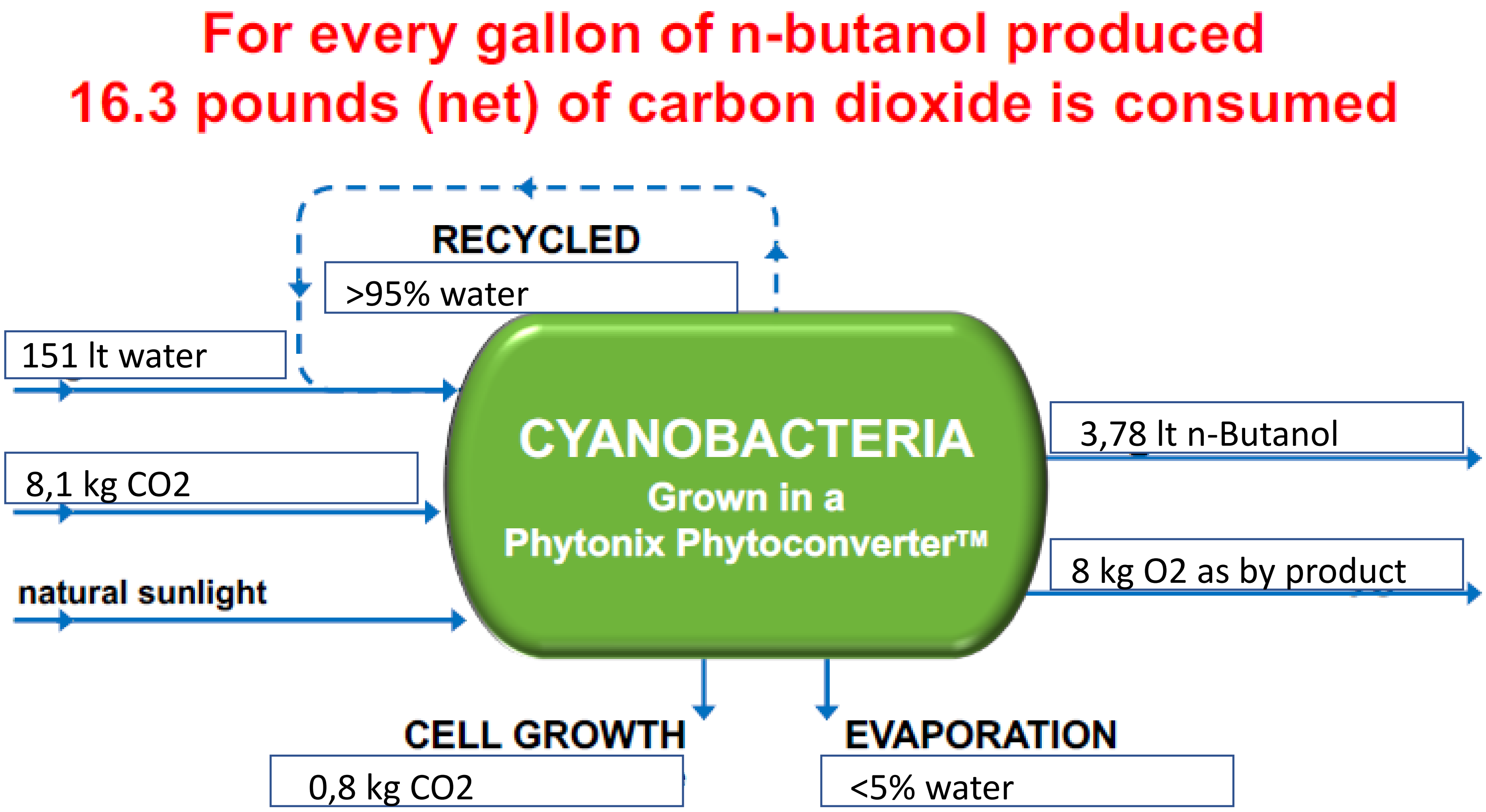
≈ $1.35/gallon

Wholesale Price

≈ $6.00/gallon

High-Value, High-Margin Product

CO_2 photofermentation: also Phytonix



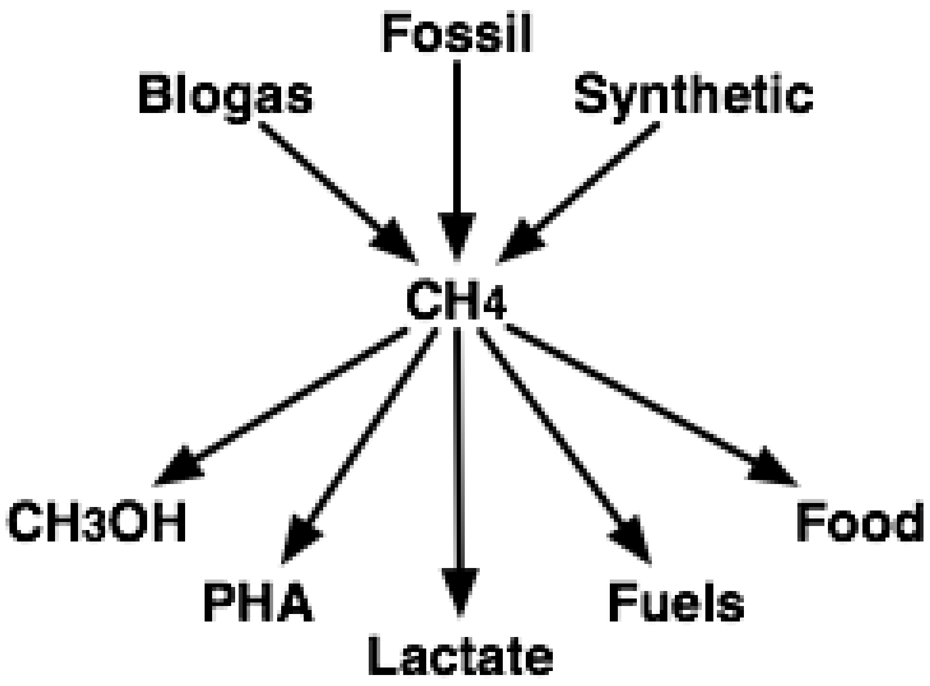
CO_2 photofermentation: also Phytonix

	Small Size Phytonix Plant	Medium Size Phytonix Plant
CAPEX	$14 million	$70 million
Butanol production	2.5 million gal/yr.	25 million gal/yr.
CO_2 feedstock	20,000 tons/yr.	200,000 tons/yr.
Revenue: Butanol @ $6.25/gallon	$15 million/year	$155 million/year
EBITDA	$11 million/year	$115 million/year
EBITDA Payback on Investment	**≈ 1.3 years**	**< 1 year**

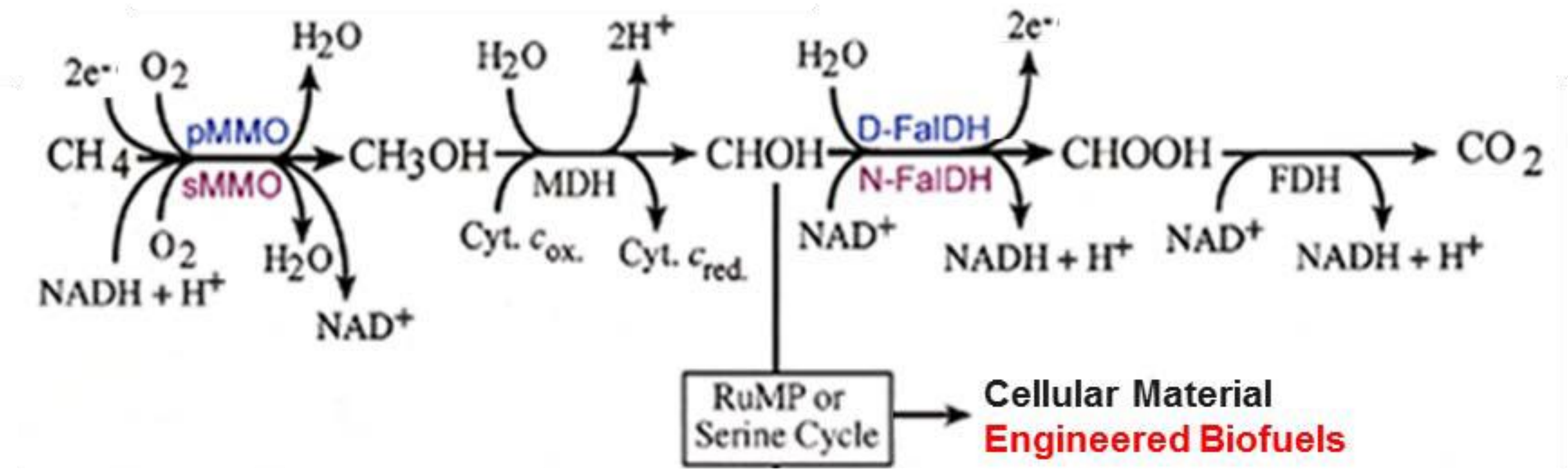
Phytonix plants are scalable and cost-effective at capacities ranging from 500,000 to 500,000,000 gallons/year of n-butanol.

Methane: ideal carbon source

- Cheap
- Available
- Can be green or black
- Flexible
- No capital intensive for preparation



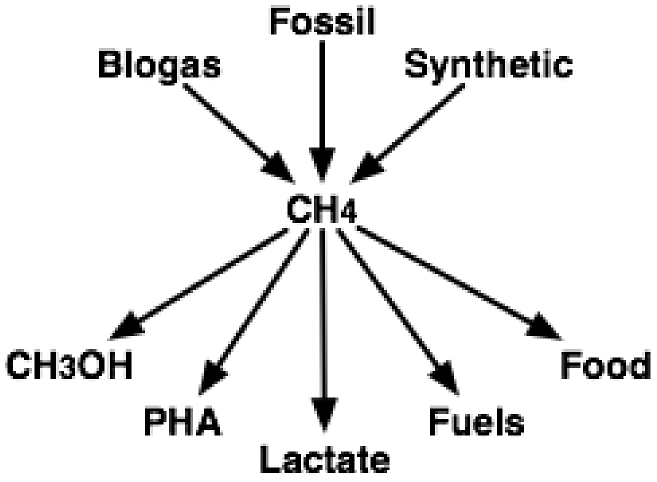
Methane fermentation

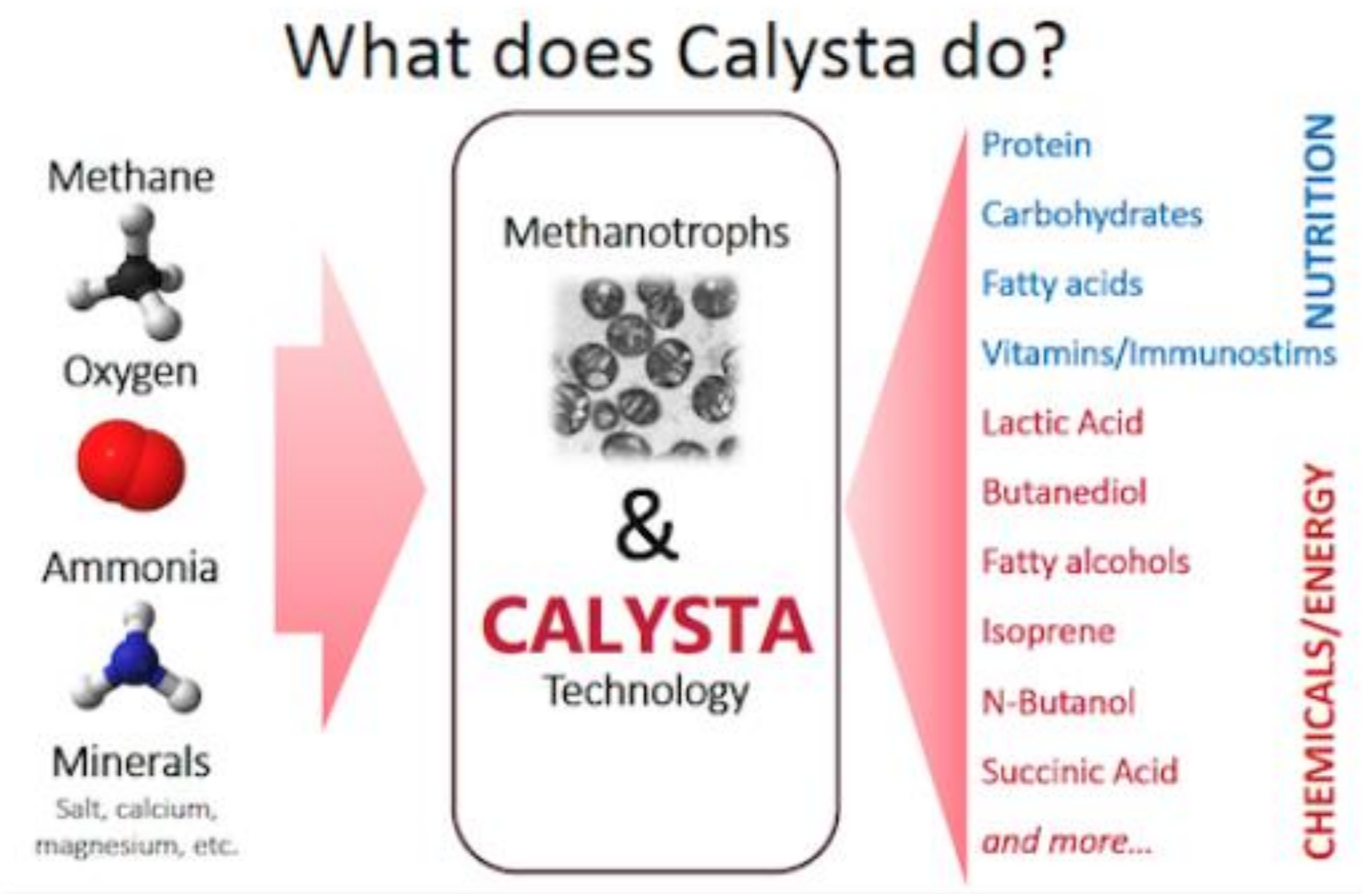


Metric	Algae (Open Ponds)	Methane Fermentation	Biomass Fermentation
Capital Investment	Low	**High**	High
Ease of scale-up	Requires land use	**Good**	Good
Feedstock availability	Mod. (year-round sun)	**Good (nat. gas / biogas)**	Low (food competition)
Feedstock sensitivity	Low	**Low**	High (inhibitors)
Feedstock processing cost	Low	**Low**	High (release sugars)
Downstream processing cost	High (dilute culture)	**Low (dense culture)**	Low (dense culture)
Flexibility to strain selection	Low (open system)	**High (closed system)**	High (closed system)
Water use	High (evaporation)	**Low**	Low

Power to materials

Il Biogas puó essere fermentato come fonte di C invece che il Glucosio

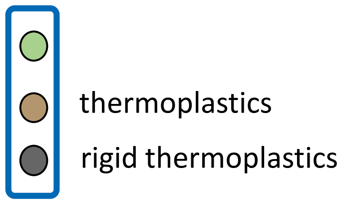


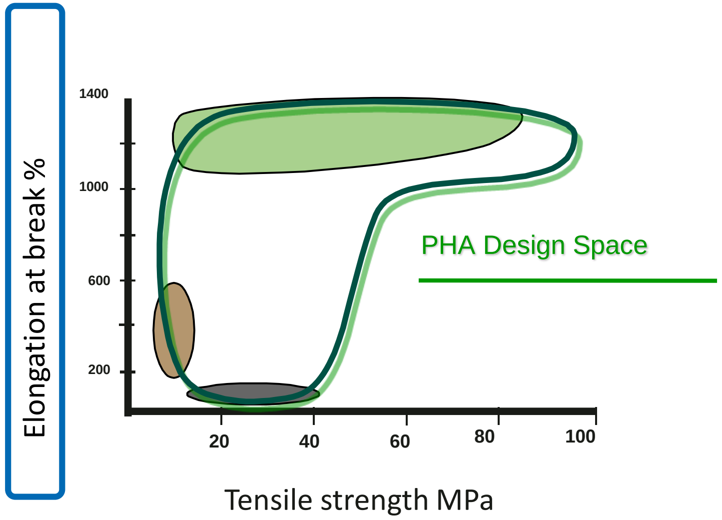

What does Calysta do?
Methane
Oxygen
Ammonia
Minerals
Salt, calcium, magnesium, etc.
Methanotrophs
&
CALYSTA
Technology
Protein
Carbohydrates
Fatty acids
Vitamins/Immunostims
NUTRITION
Lactic Acid
Butanediol
Fatty alcohols
Isoprene
N-Butanol
Succinic Acid
and more...
CHEMICALS/ENERGY

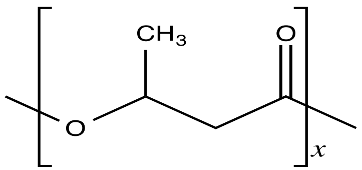
Newlight technologies: biogas to PHA

- PHAs are a family of polymers, all with their own specific characteristics, both, related to their molecular structure and to their thermal, optical and mechanical properties.
- The simplest PHA, called P3HB or sometimes just PHB appears in nature for more than 3 billion years already, but was first isolated and characterized by Lemoigne in 1925
- PHA technology holds great promises, since the potential design space for PHA is very large.

Mechanical Properties







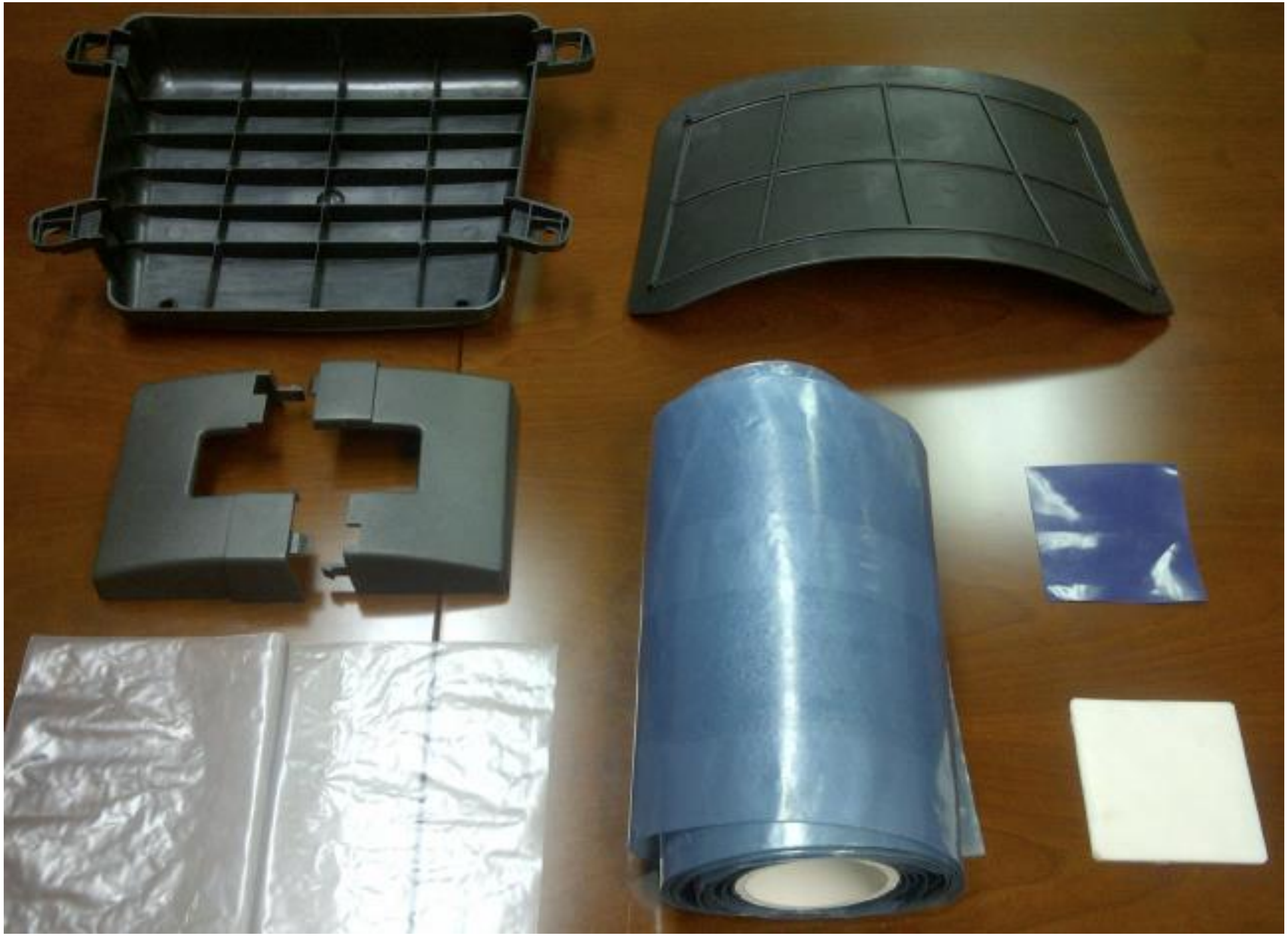
P3HB

Performance

Airflex™

various grades

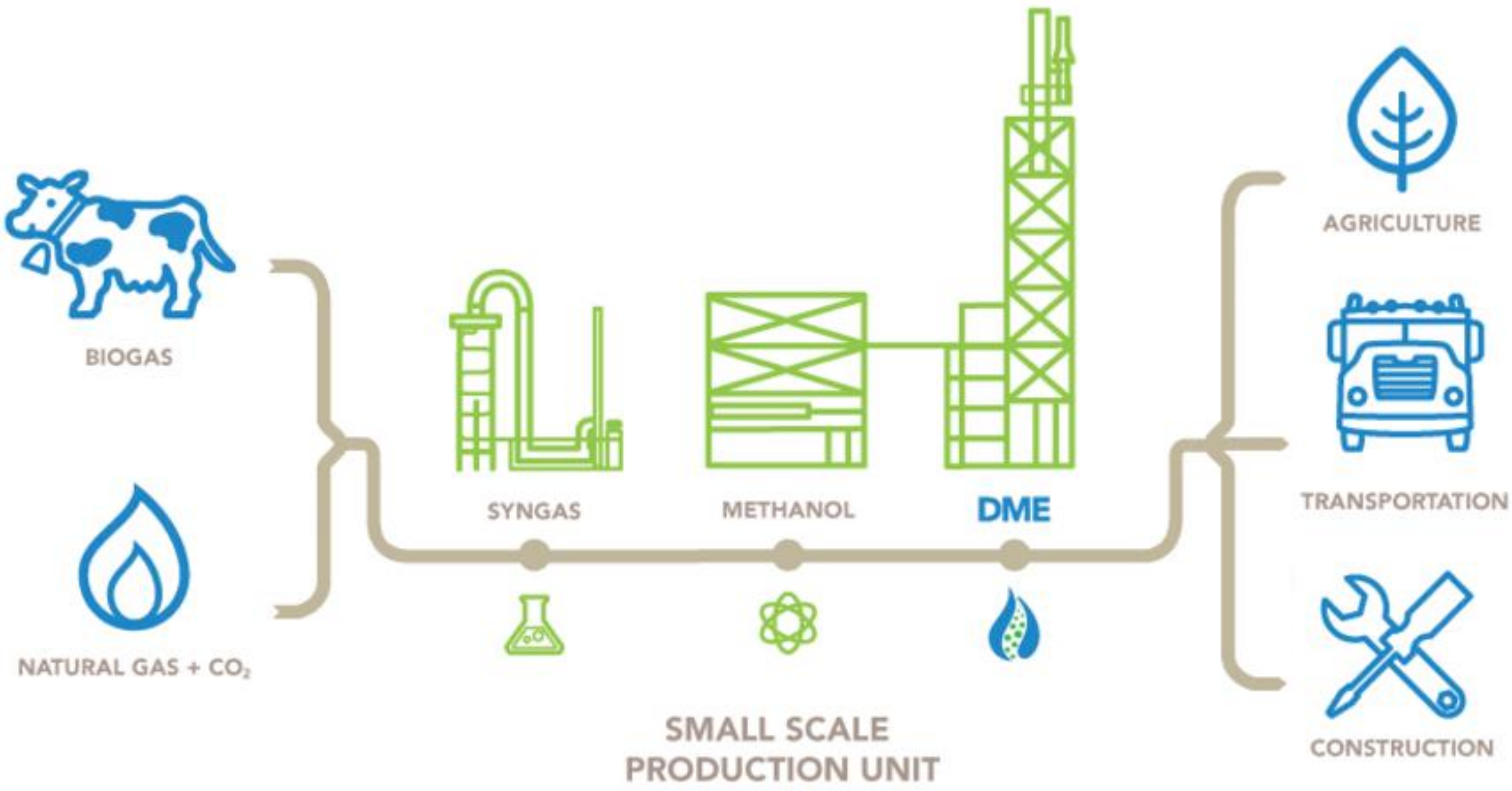
- Tensile Strength: No break
- Flexibility: 648%
- Color / Clarity / Odor: Clear Film
- Thermal & Age Stability: Good
- Molecular Weight: Controlled

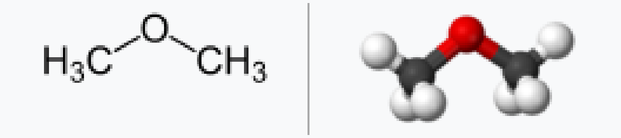


Pellets per fish farming?

BioProtein, Norway

DME: diesel like fuel with LPG tank





Names	
Preferred IUPAC name	
Methoxymethane	
Other names	
Dimethyl ether R-E170 Demeon Dimethyl oxide Dymel A Methyl ether Mether Wood ether	
Identifiers	
CAS Number	115-10-6 ✓

Courtesy of: http://oberonfuels.com/technology/oberon-process/

Biogas to biobutanol: Microvi Biotechnologies

DOE awards Microvi grant for innovative biogas conversion technology

October 16, 2016 | Jim Lane

In California, Microvi has been awarded a grant from the US Department of Energy for a new groundbreaking biocatalytic technology that converts methane and carbon dioxide in biogas into valuable liquid chemicals, the company announced today. The new technology, based on Microvi's MicroNiche Engineering Platform Technology, can convert biogas that is created at facilities like landfills and wastewater treatment plants into important energy chemicals such as biobutanol.

Biogas to Liquids

Table 8. Comparison of the techno-economic analysis of BgTL and other related processes

	BgTL Model	Bechtel,[18]	Tijmensen *et al.*[19]	Hamelinck *et al.*[40]	Larson *et al.*[20]	Swason *et al.*[21]	Bao *et al.*[68]
Feedstock	Biogas	Natural Gas	Poplar	Wood	Switchgrass	Corn Stover	Natural Gas
Feedstock cost ($/tonne)	4 ($/GJ)	N/A	33	38	46	75	44[a]
Plant size (dry tonne/day)	57	8 391	1 741	400MW_{th}	4 536	2 000	21 600
Product	FT liquids	FT liquids	FT liquids	FT diesel	Diesel, gasoline	FT liquids	Synfuels
Cost year	2015	1993	2000	2002	2003	2007	2010
Capital investment (million $)	$96.5	$1842.5	$339	$303.5	$541[b]	$610[c]	$10,800
Product value ($/GGE)	$5.29	N/A	$2.00	$1.92	$1.85	$4.30	$1.41[d]
Product value ($/GGE) 2015	$5.29	N/A	$2.86	$2.73	$2.59	$4.61	$1.44[d]

Note:
a = calculated based on $8/1 000 SCF natural gas price with a density of 0.8 kg/m^3
b = without spare scenario
c = high temperature scenario
d = reported in $/bbl which was converted to $/gal

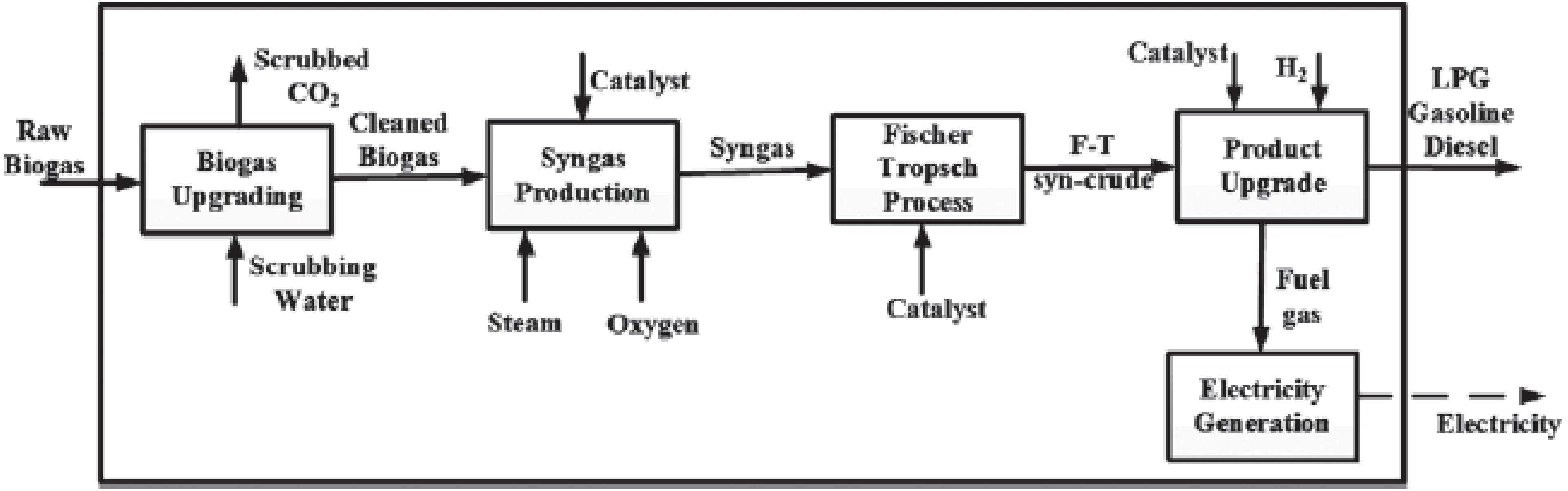


Figure 1. A schematic of a biogas to liquid fuels production technology.

Conclusions

- Is it possible to ferment gases instead of sugar? Yes
- Are gaseous carbon sources cheaper than sugars? Yes
- Are gaseous carbon sources „simpler“ than sugars for their supply chain? Yes
- Is it possible to earn money using gaseous carbon sources or is it an academic curiosity? Yes, it is possible
- Are gaseous carbon sources „easier“ to ferment than sugars? No

- What is needed to enlarge gaseous carbon sources usage in IB? Better mass transfer → Revolutionary reactor design

  Broader products range → higher chance to meet market needs

Bibliography & Further reading

- Process efficiency simulation for key process parameters in biological methanogenesis *doi:10.3934/bioeng.2014.1.53#sthash.AvW4uNDv.dpuf*
- Analysis of process related factors to increase volumetric productivity and quality of biomethane with Methanothermobacter marburgensis *DOI: 10.1016/j.apenergy.2014.07.002*
- Quantitative analysis of media dilution rate effects on Methanothermobacter marburgensis grown in continuous culture on H_2 and CO_2 *DOI: 10.1016/j.biombioe.2011.10.038*
- The changing paradigm in CO2 utilization *DOI: 10.1016/j.jcou.2013.08.001*
- Commercial Biomass Syngas Fermentation doi:10.3990/en5125372
- Rethinking biological activation of methane and conversion to liquid fuels *doi:10.1038/nchembio.1509*
- Techno-economic assessment of biogas to liquid fuels conversion technology via Fischer-Tropsch synthesis *doi: 10.1002/bbb.1758*
- http://www.krajete.com
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- http://phytonix.com/