Re-Designing Metabolic Infrastructure for Carbon Management

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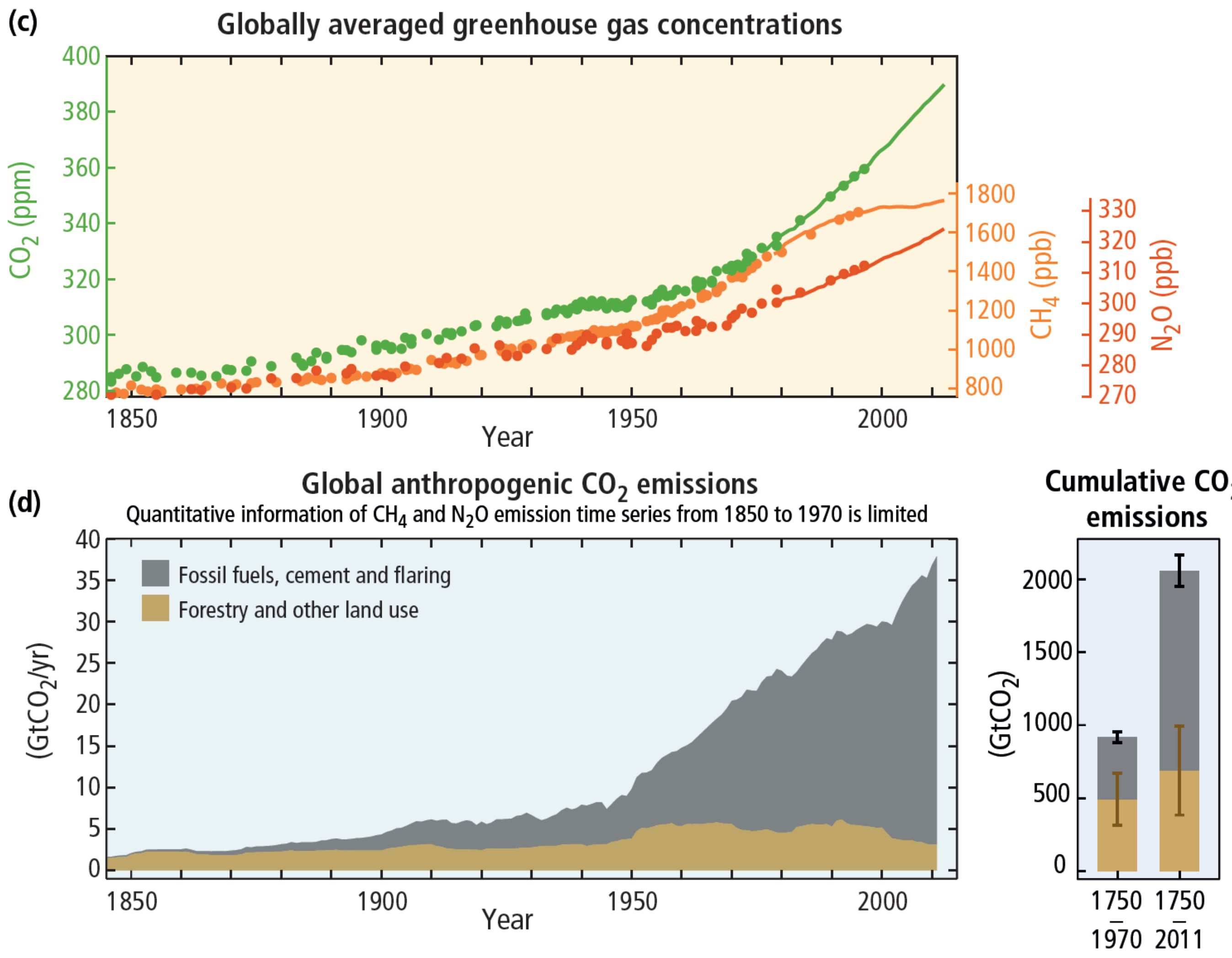
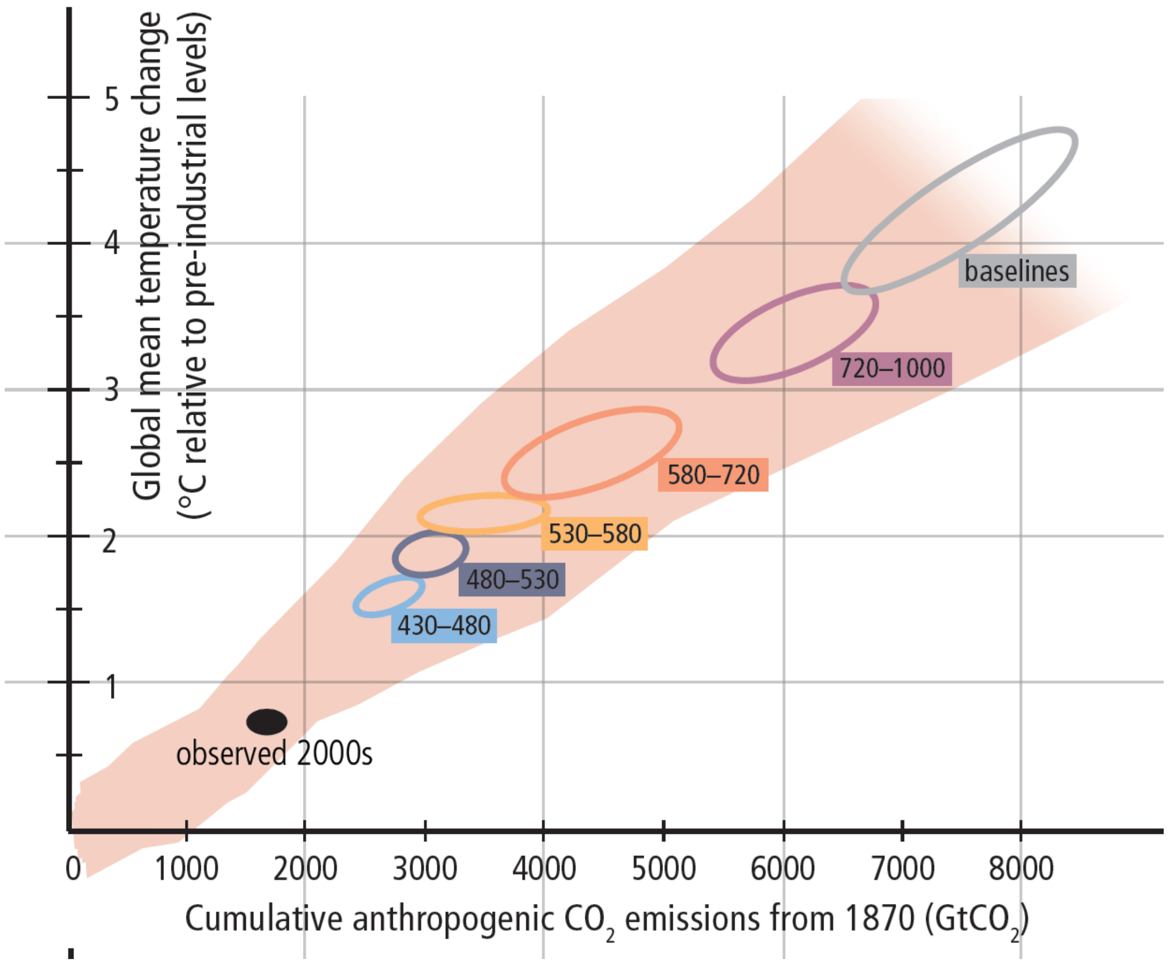
IPCC Climate Change 2014 Synthesis Report

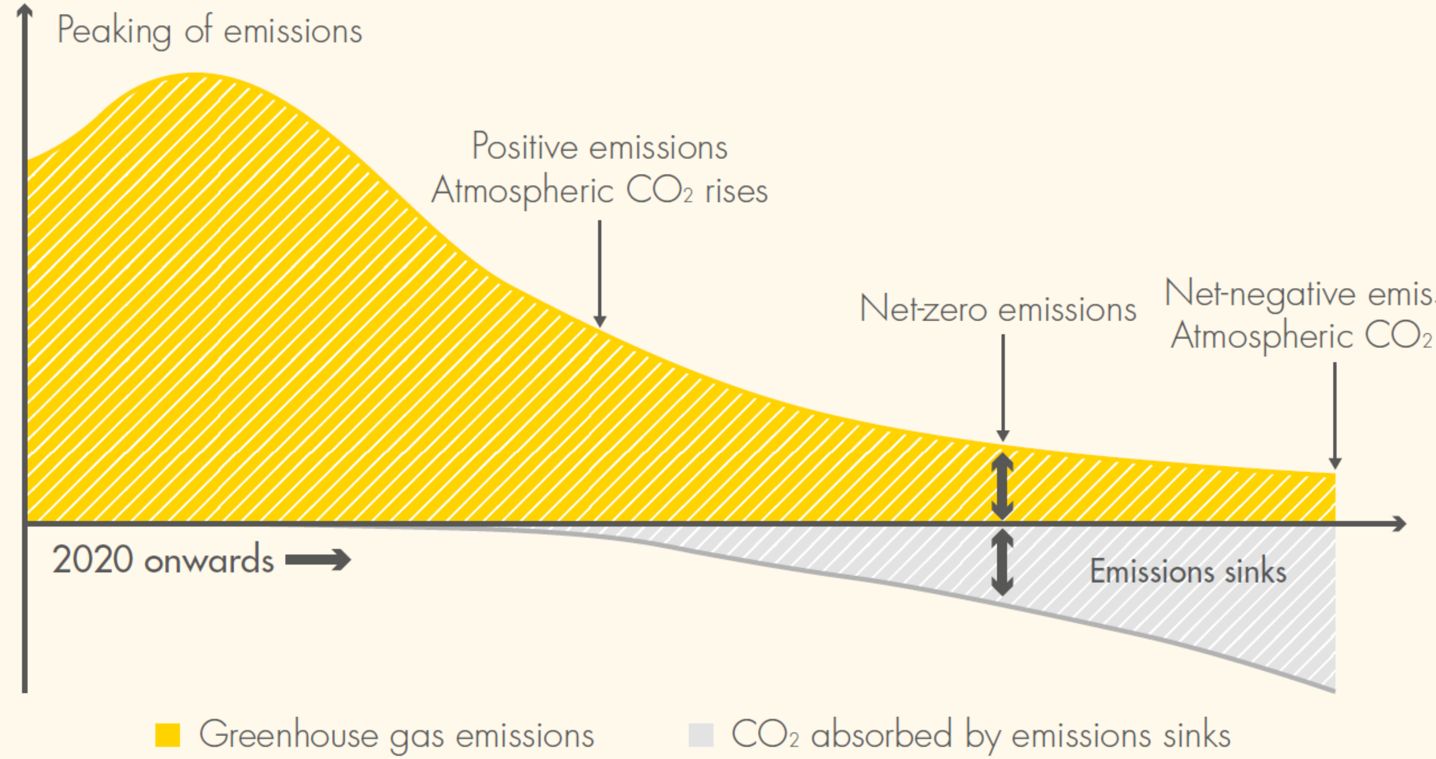


IPCC Climate Change 2014 Synthesis Report

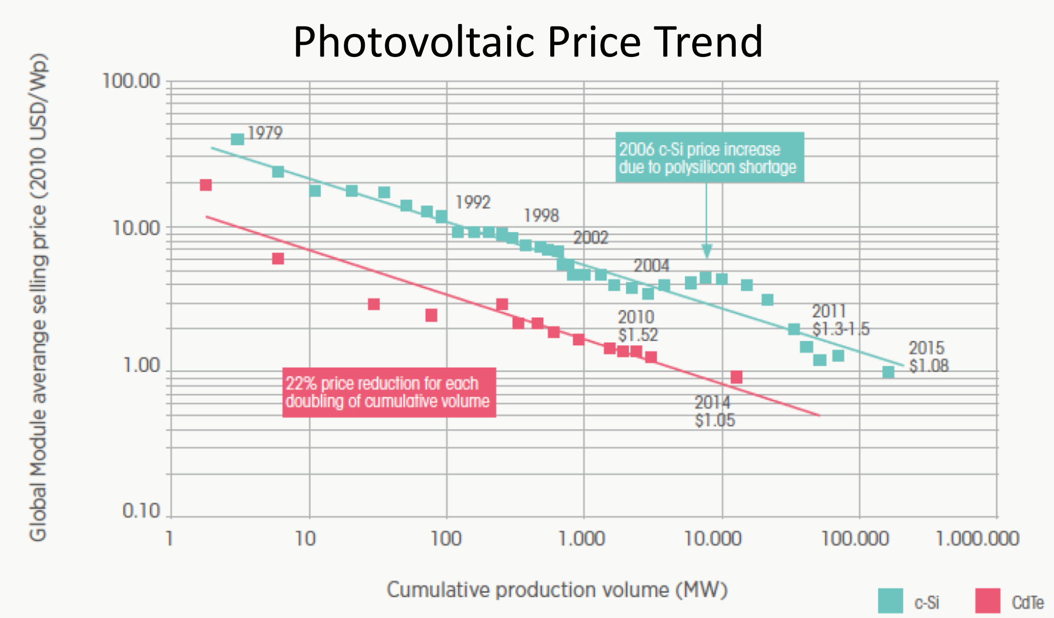
Risk from climate change depends on cumulative CO2 emissions



THE PARIS AGREEMENT CALLS FOR AN EARLY PEAK IN EMISSIONS, THEN A DECLINE TO NET-ZERO EMISSIONS DURING THE SECOND HALF OF THE CENTURY



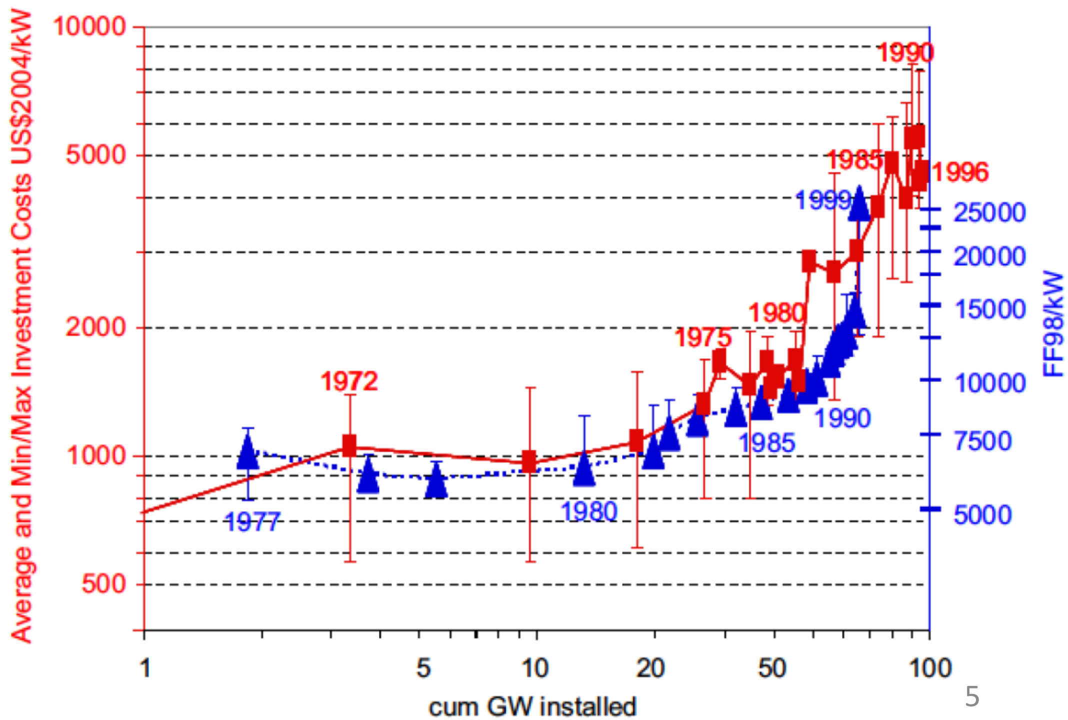
Source: Shell schematic



Wp = Watt peak capacity

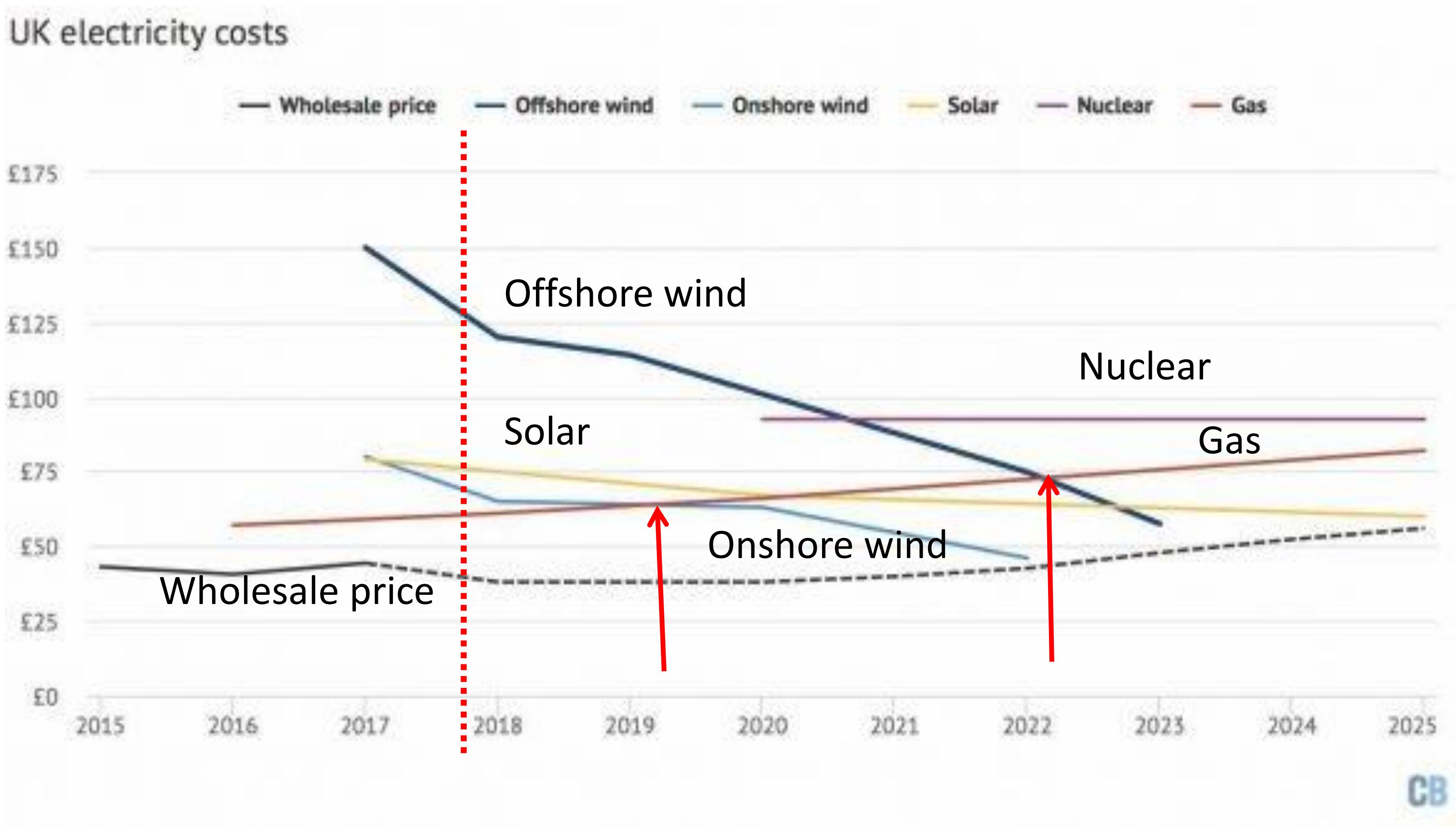
Learning or experience curves of photovoltaic (PV) modules made from crystalline-Si and CdTe (IRENA, 2012).

Cost of nuclear plants ($/kW) in the US and France (Grubler, 2010)



SEAB CO2 Utilization Task Force 2016

UK auction reveals offshore wind cheaper than new gas

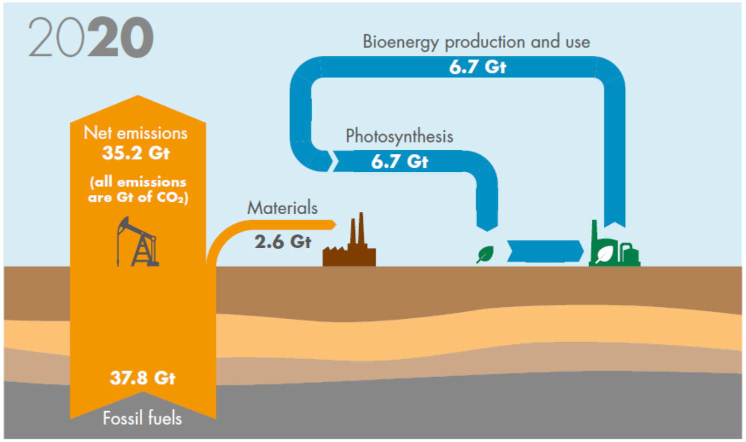


https://www.carbonbrief.org/analysis-uk-auction-offshore-wind-cheaper-than-new-gas

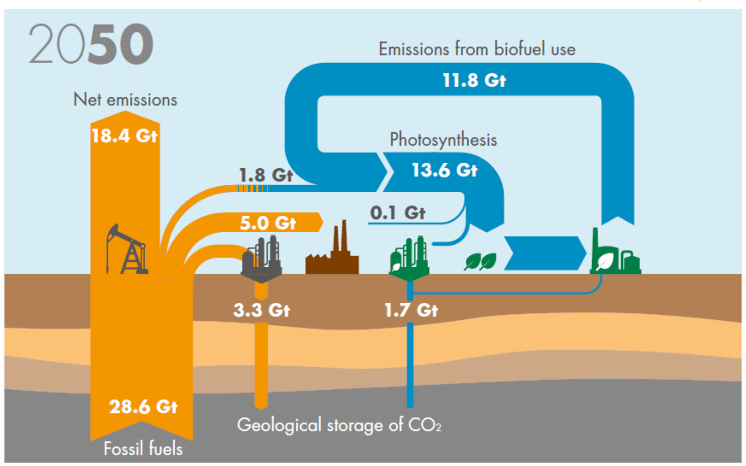
Shell SKY Scenarios

THE EVOLVING ENERGY SYSTEM CO_2 BALANCE SHEET IN **SKY**

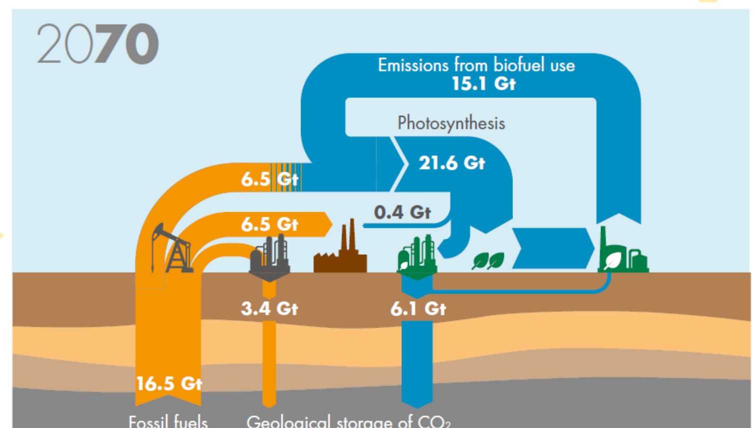
Fossil fuel production · CCS · Biofuel production · Bioenergy with CCS · Carbon in products · Growing biomass



Today, most carbon in fossil energy production is burned and emitted to the atmosphere, while the CO_2 absorbed by wood and other plants used for energy is also returned to the atmosphere.

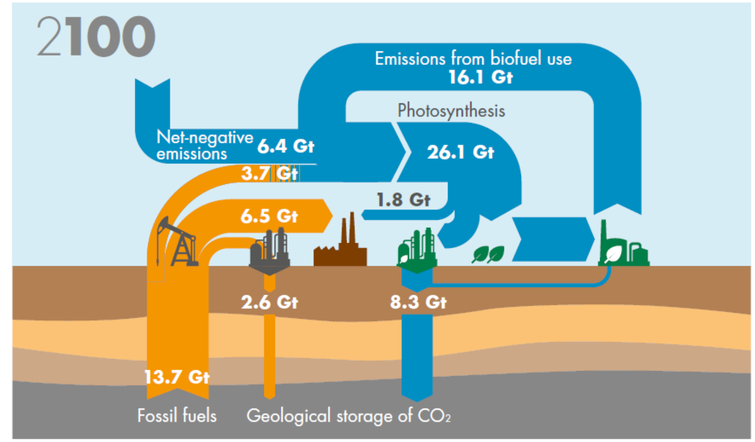


In Sky, in 2050, the storage of CO_2 is rapidly scaling up. There are equal contributions from the embedded carbon in materials production and CCS. Fossil energy CCS leads the way, but bioenergy CCS (BECCS) is close behind.



Note: The numbers do not add up exactly in 2070 owing to rounding up of data.

In Sky, in 2070, the energy system has achieved net-zero emissions. Fossil energy production is less than half today's level. Alongside direct CCS and the use of carbon for materials, the remaining fossil energy emissions are fully offset by captured CO_2 from an expanded bioenergy system.



In Sky, at 2100, the bioenergy system has reached its resource base limit and is twice the size of the fossil energy system in CO_2 terms. The active management of CO_2 means that the total energy system is providing a drawdown of CO_2 from the atmosphere.

Biological Carbon Capture and Utilization

- Avoid CO_2 release during fermentation

Bogorad et al. Nature 2013, Lin et al. PNAS 2018

Conventional Fermentation: Sugar → alcohol + CO2
Reductive Fermentation: Sugar + Reducing agent → alcohol

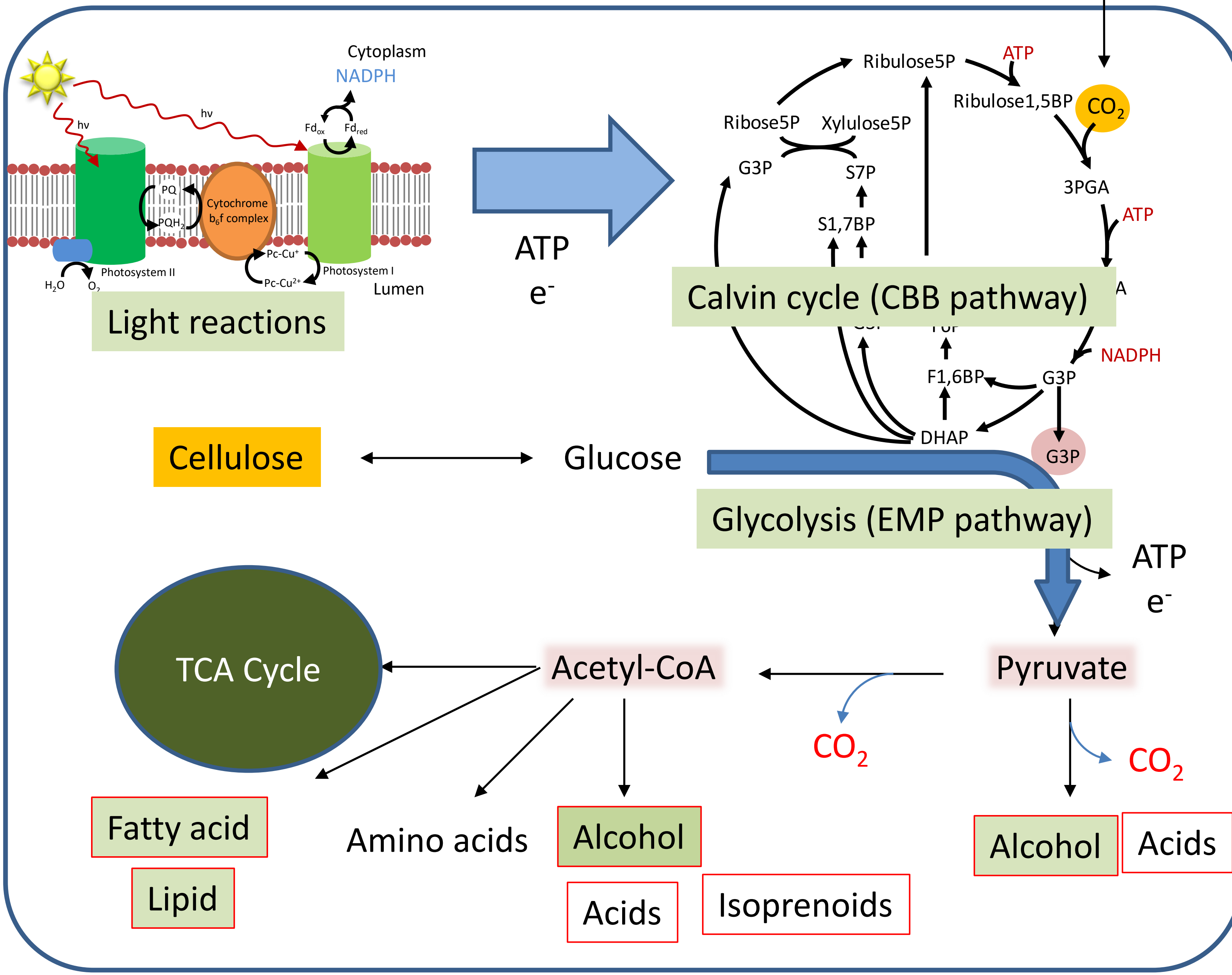
- Increase CO_2 fixation by photosynthesis

Yu et al. Nature Comm. 2018

- Develop non-photosynthetic CO_2 fixation

Li et al. Science 2012

Pathways to Life

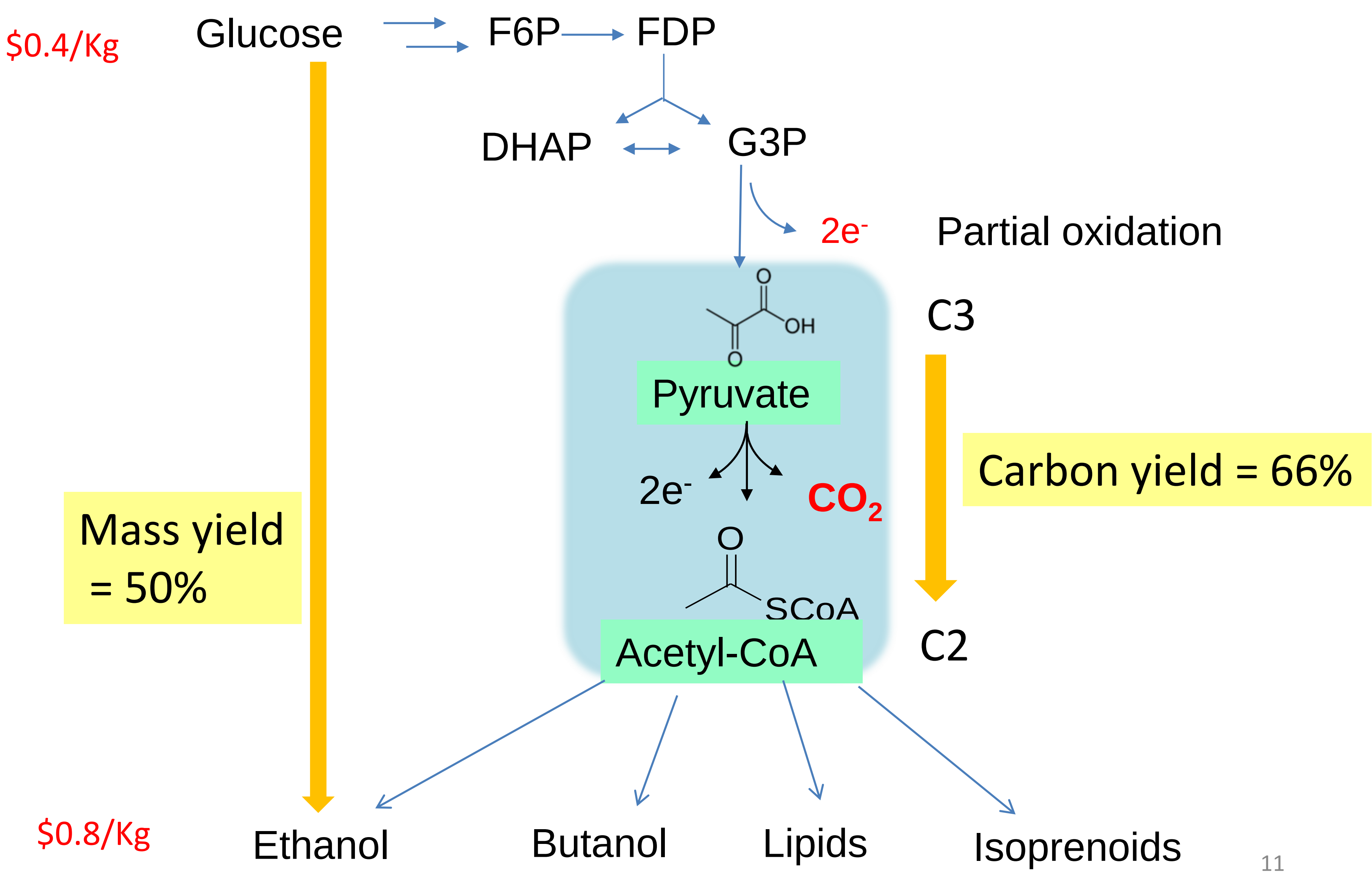


Theoretical Energy and Mass Yields

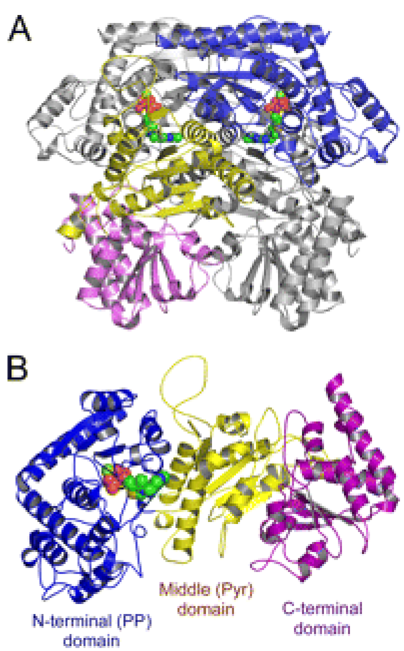
		energy %	mass %
$C_6H_{12}O_6 \rightarrow 2C_2H_6O + 2\,CO_2$			
2540	2 x 1235 kJ/mol	97.24%	51%
$C_6H_{12}O_6 \rightarrow C_4H_{10}O + 2\,CO_2$			
2540	2455 kJ/mol	96.6%	41%
$2\,C_6H_{12}O_6 \rightarrow C_7H_{16} + 4CO_2 + CO$			
2x 2540	4543 kJ/mol	89.4%	27%

Jet fuel

Oxidative Glycolysis
Embden-Meyerhof-Parnas (EMP) pathway



Non-oxidative Glycolysis (NOG)

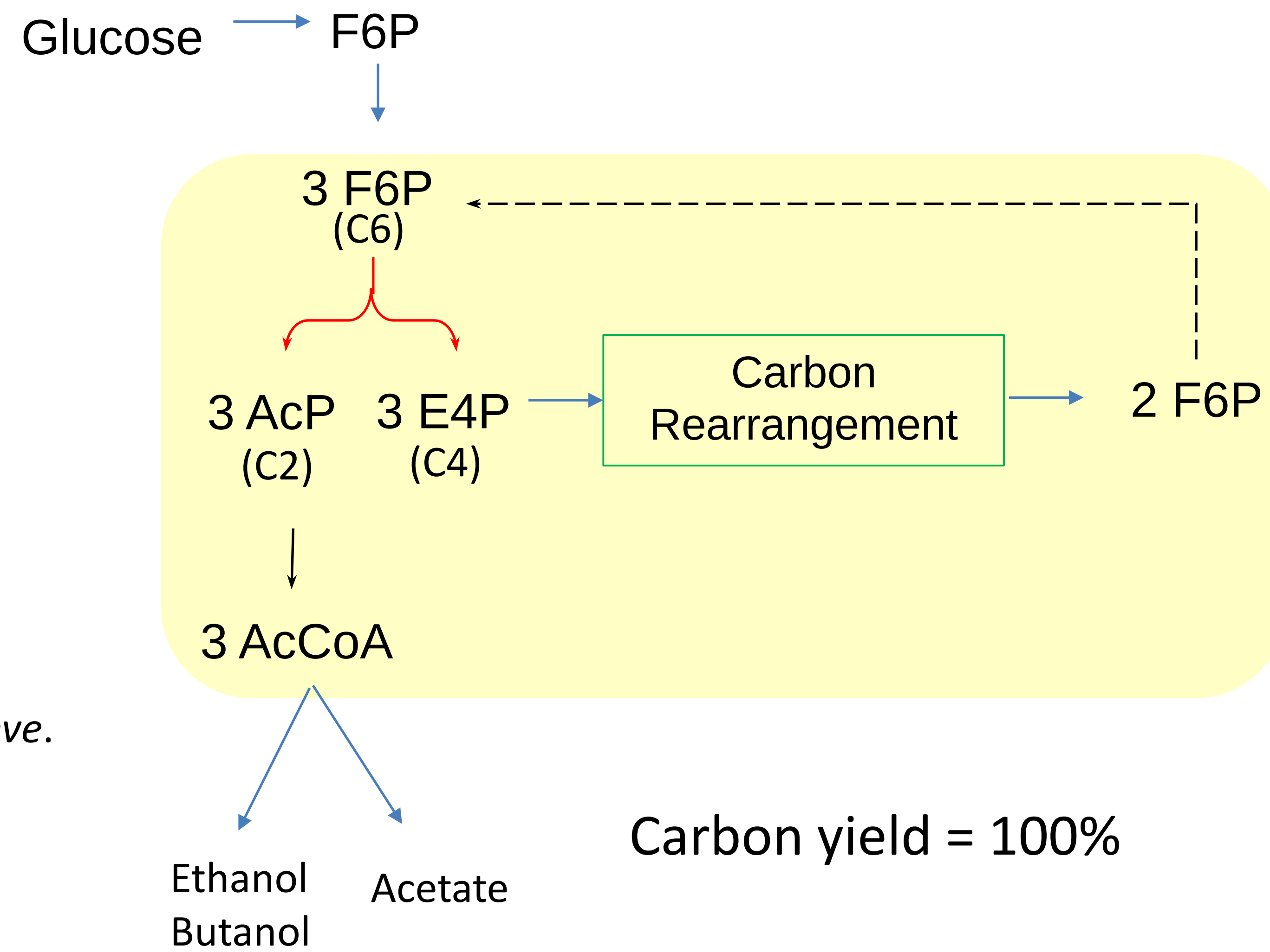


Bifidobacterium breve.

Phosphoketolase

F6P → AcP + E4P

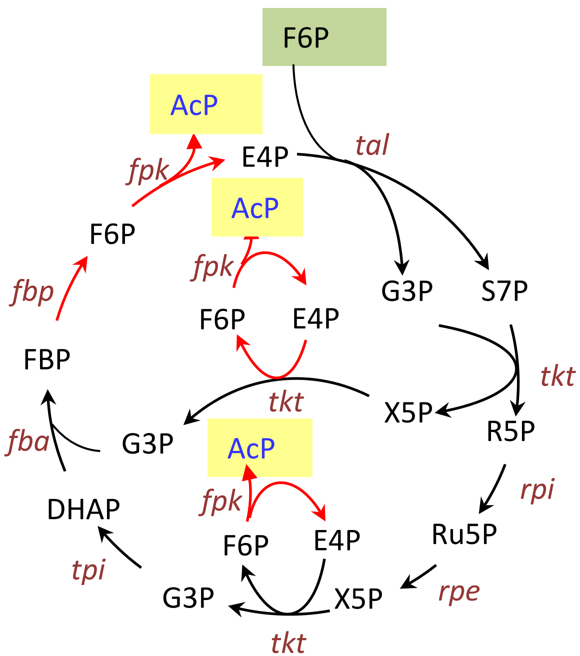
X5P → AcP + G3P



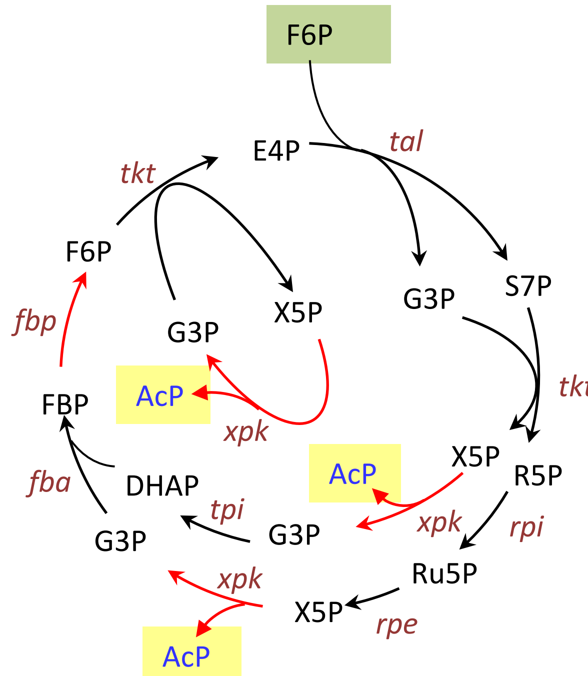
Carbon yield = 100%

Two Modes of Non-Oxidative Glycolysis (NOG)

F6P phosphoketolase
F6P → AcP + E4P



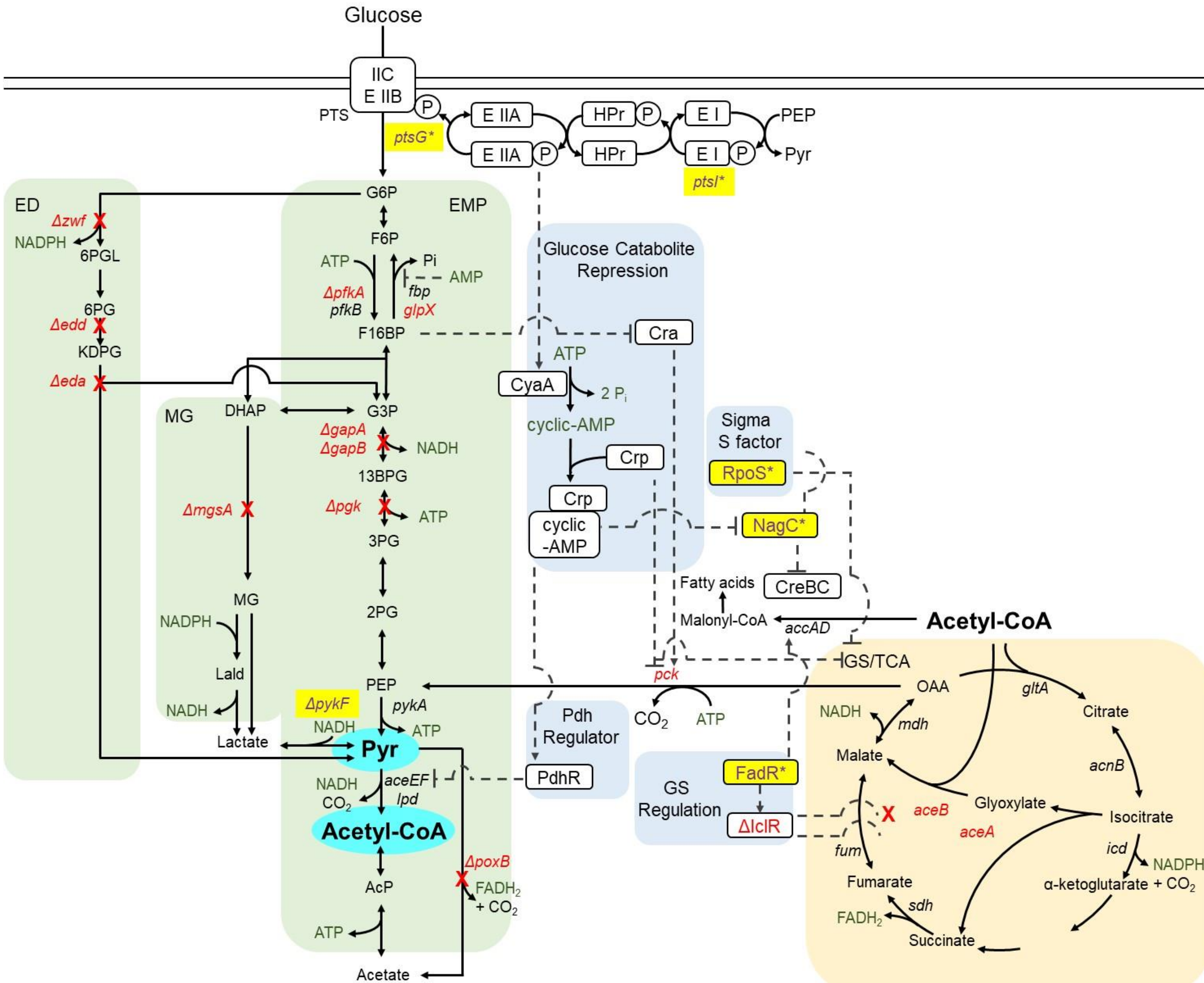
X5P phosphoketolase
X5P → AcP + G3P



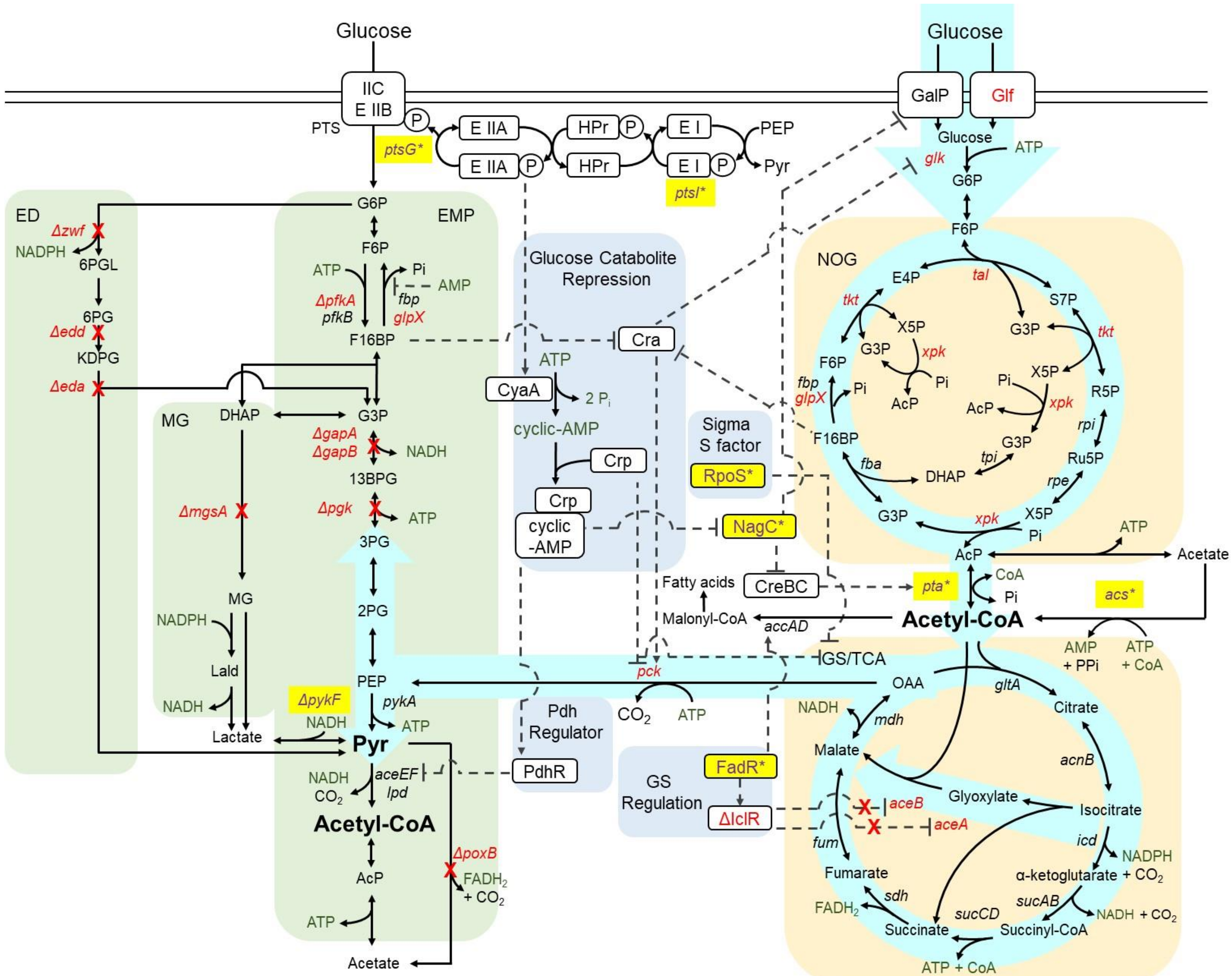
Net reaction: F6P → 3 AcP

Bogorad et al. Nature 2013

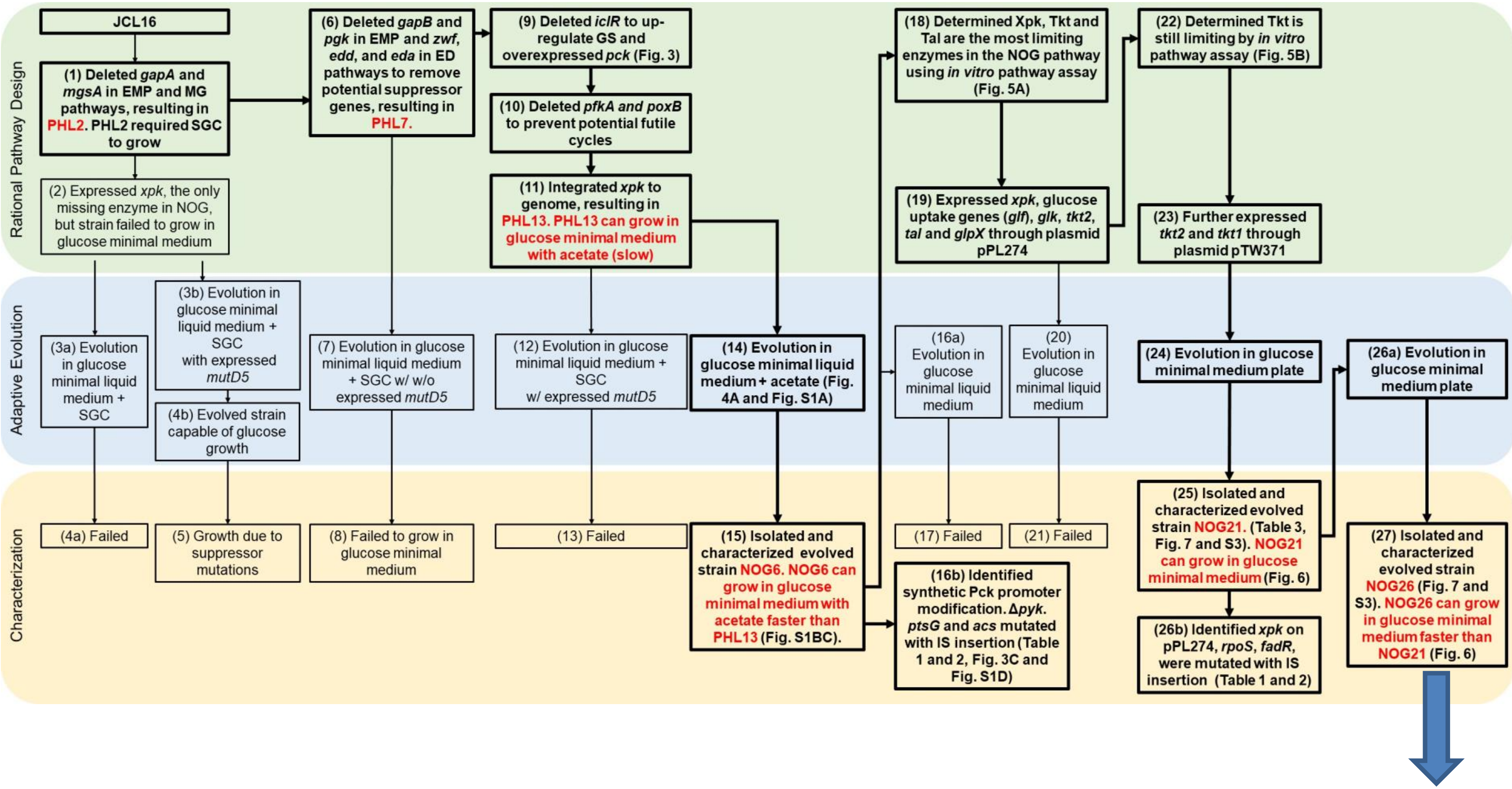
Construction and Evolution of an NOG *E. coli* strain



Construction and Evolution of an NOG E. coli strain



Lin et al. PNAS 2018



Improved growth

Lin et al. PNAS 2018

Economy of oxidative and non-oxidative glycolysis for making ethanol

Traditional fermentation

$$1.5\ C_6H_{12}O_6 \rightarrow 3C_2H_6O + 3\ CO_2$$

sugar price = \$0.4/Kg

ethanol price = \$0.75/Kg

http://www.nasdaq.com/markets/sugar.aspx

(Formate)

NOG

$$C_6H_{12}O_6 + 6\ \text{“}H_2\text{”} \rightarrow 3\ C_2H_6O + 3\ H_2O$$

$$1.5\ CH_4 + 3\ H_2O \rightarrow 1.5CO_2 + 6\ H_2$$

When

$$\frac{\text{sugar price}}{\text{H2 price}} > \frac{12}{90}\ (= 0.133)$$

Then it makes sense to use NOG + H2.

H2 price < \$3/Kg

Reductive Fermentation
(H_2-assisted CO_2 fixation)

Traditional fermentation

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2\,CO_2$$

$$+ \quad 6\,H_2 + 2CO_2 \rightarrow C_2H_5OH + 3\,H_2O$$

NOG: Reductive fermentation

$$C_6H_{12}O_6 + 6\,H_2 \rightarrow 3\,C_2H_5OH + 3\,H_2O$$

CO_2 Saving

Non-oxidative (NOG) $C_6H_{12}O_6 + 6\ H_2 \rightarrow 3\ C_2H_5OH + 3\ H_2O$

Methane steam reforming $1.5\ CH_4 + 3\ H_2O \rightarrow 1.5CO_2 + 6\ H_2$

$C_6H_{12}O_6 + 1.5\ CH_4 \rightarrow 3\ C_2H_5OH + 1.5\ CO_2$

Traditional Fermentation $1.5\ C_6H_{12}O_6 \rightarrow 3\ C_2H_5OH + 3\ CO_2$

Methane upgrading

Traditional Fermentation
+

$$C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2$$

Methane upgrading

$$0.5\ CO_2 + 1.5\ CH_4 \rightarrow C_2H_5OH$$

NOG
+
Steam Reforming

$$C_6H_{12}O_6 + 1.5\ CH_4 \rightarrow 3\ C_2H_5OH + 1.5\ CO_2$$

Natural gas price ~ \$3/mmBTU, Ethanol price ~\$0.8/Kg

$$\frac{\text{Price of 1 mol of C2H5OH}}{\text{Price of 1.5 mol of CH4}} = 9.6$$

Methane upgrading

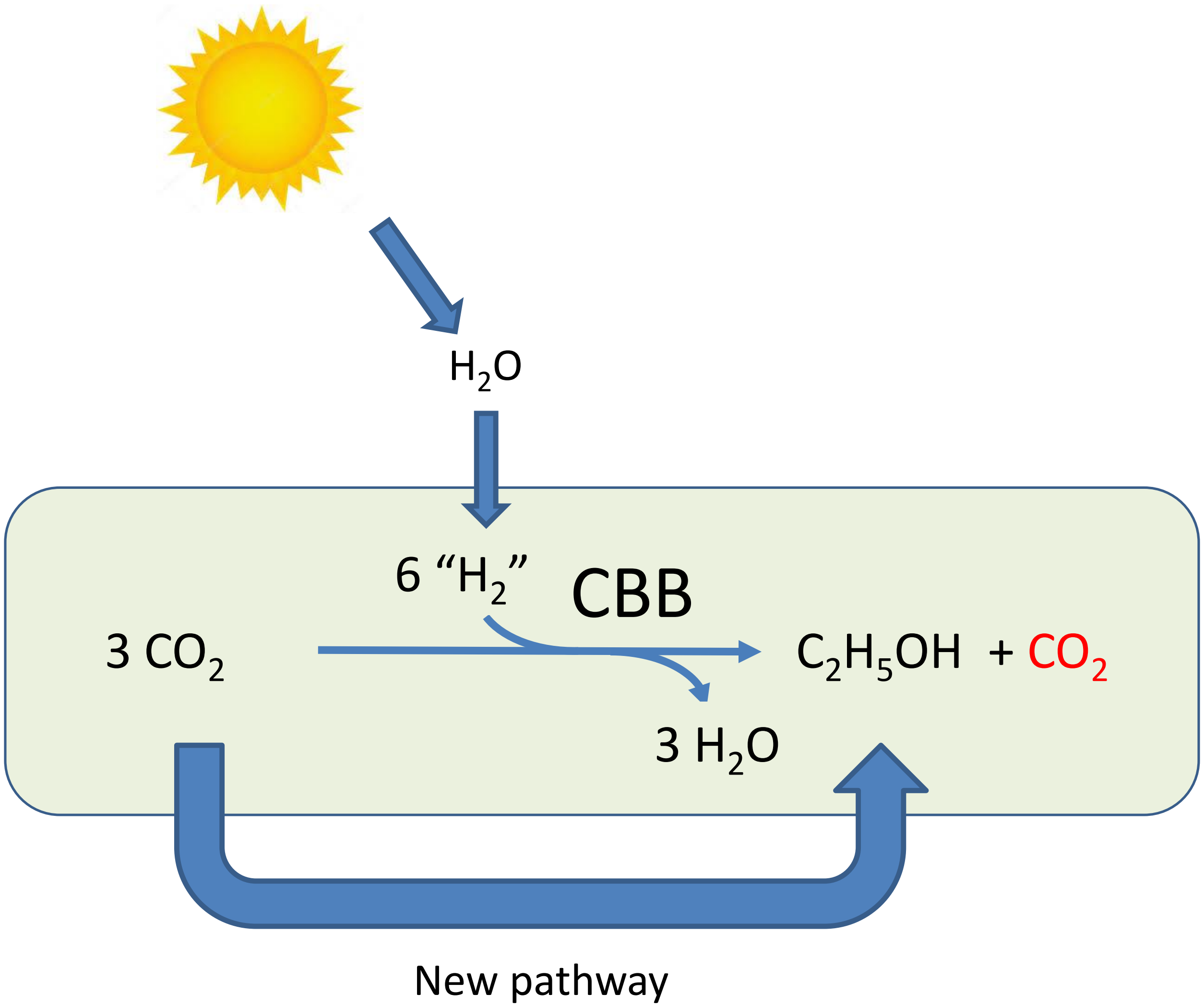
Reactions	ΔG^o (kJ/mole)	Energy* efficiency	Carbon# yield	Comment
1) $C_6H_{12}O_6$ --> 2 C_2H_6O + 2 CO_2	-228.4	0.97	66.70%	Current fermentation
2) 0.5 CO_2 + 1.5 CH_4 --> C_2H_6O	100.05	1.03	133%	Proposed Methane upgrading (ΔG^o >0)
3) = 1)+2) $C_6H_{12}O_6$ + 1.5 CH_4 --> 3 C_2H_6O + 1.5 CO_2	-128.35	0.99	80%	Proposed reductive fermentation
4) $2CH_4 + O_2$--> C_2H_6O+ H_2O	-309.1	0.77	100%	REMOTE

*Energy efficiency is calculated from the lower heating value (LHV) of combustion of products divided by the LHV of the reactants.

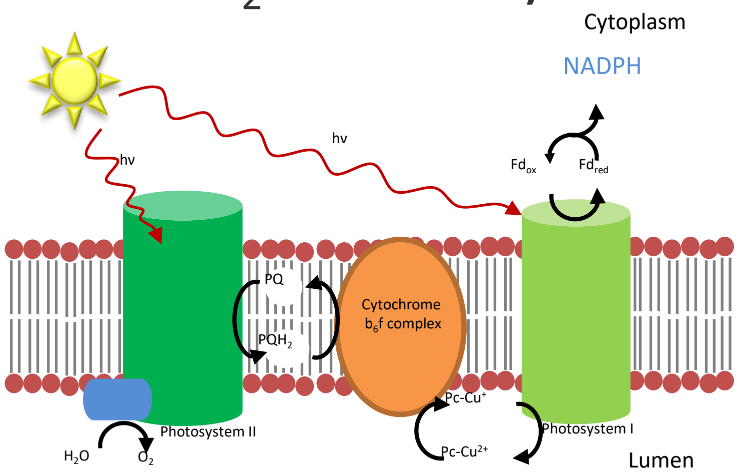
! ΔG_f^o and ΔH^o_{LHV} values were taken from Table 2

Carbon yield calculation does not include CO_2.

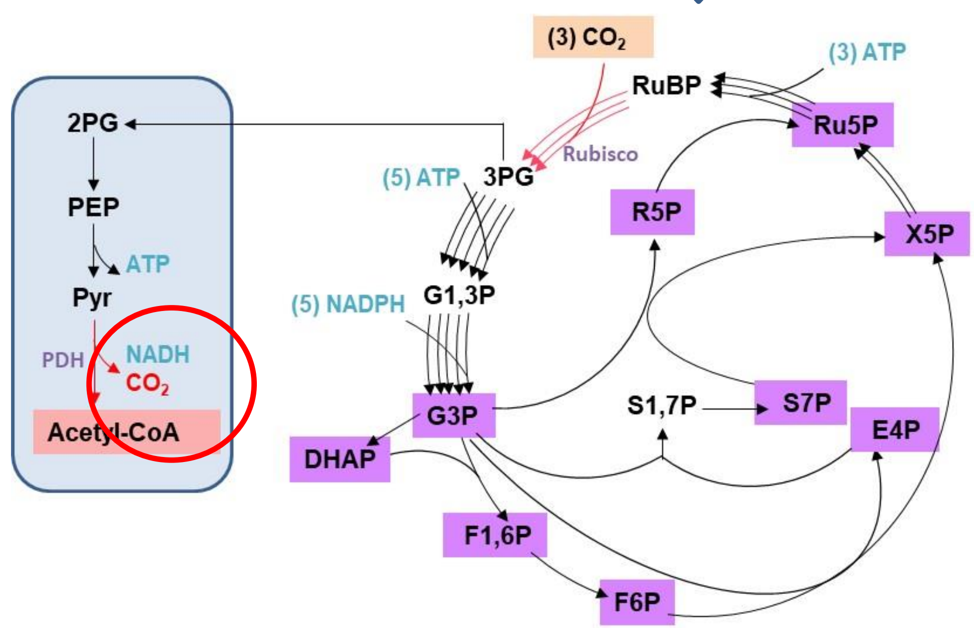
Augmented CO_2 fixation



CO_2 fixation by Calvin-Benson-Bassham (CBB) cycle



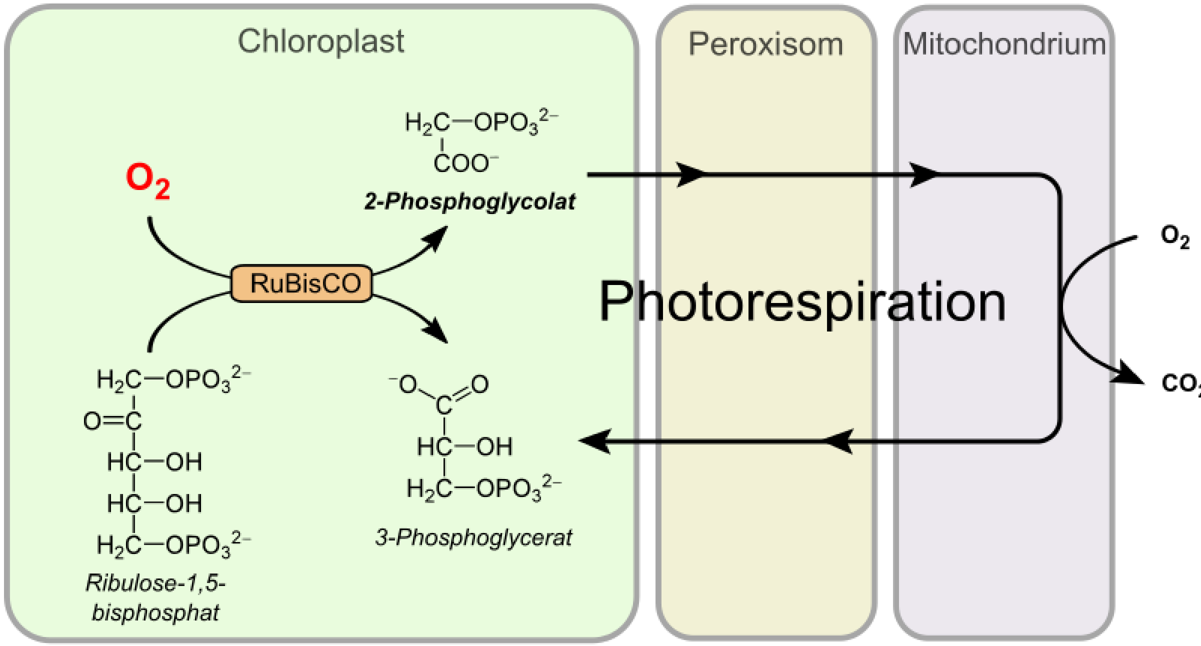
ATP, NADPH



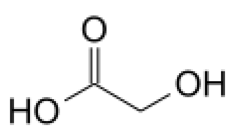
$$3CO_2 \rightarrow 1 \text{ pyruvate}$$

$$3CO_2 \rightarrow 1 \text{ Acetyl-CoA} + CO_2$$

Photorespiration



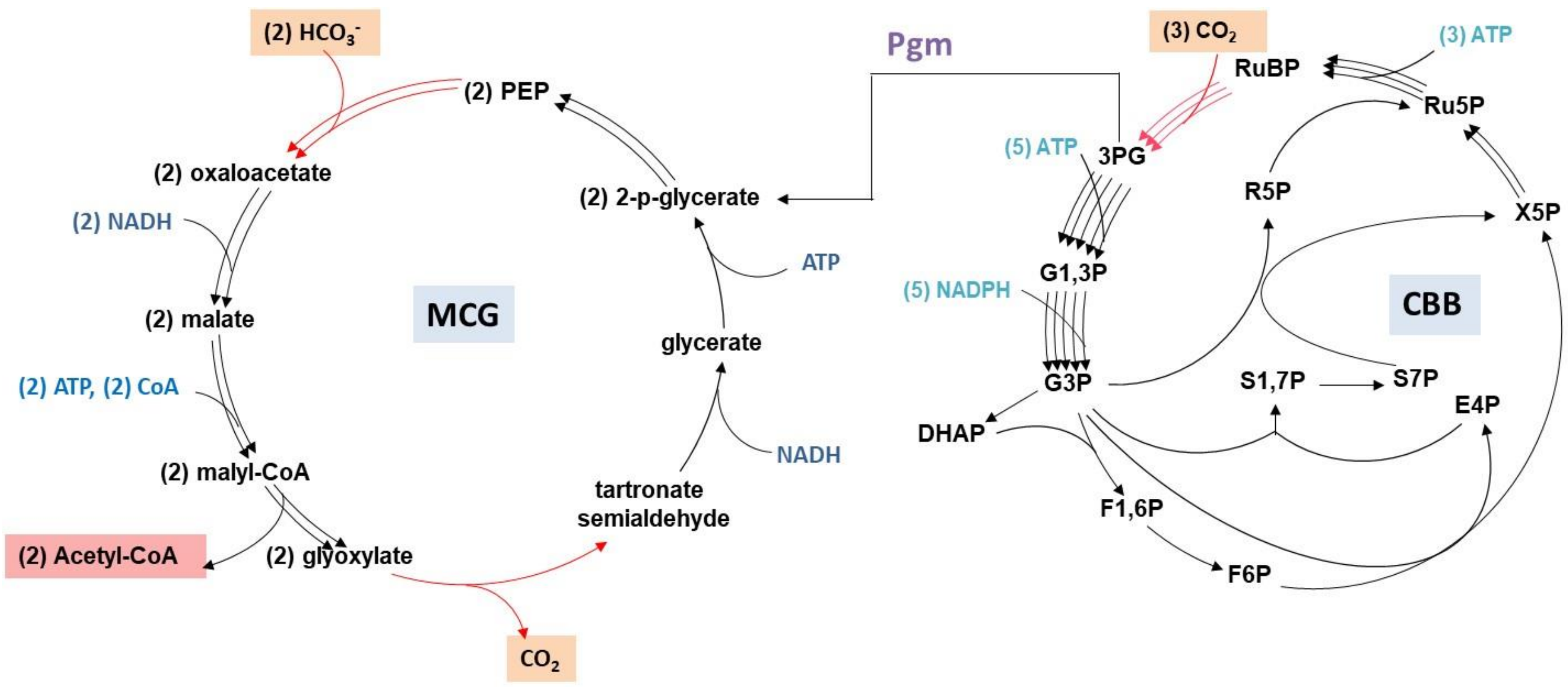
From Wikipedia

2 

2 Glycolate

? → Acetyl-CoA + 2 CO_2

MCG augments CBB pathway



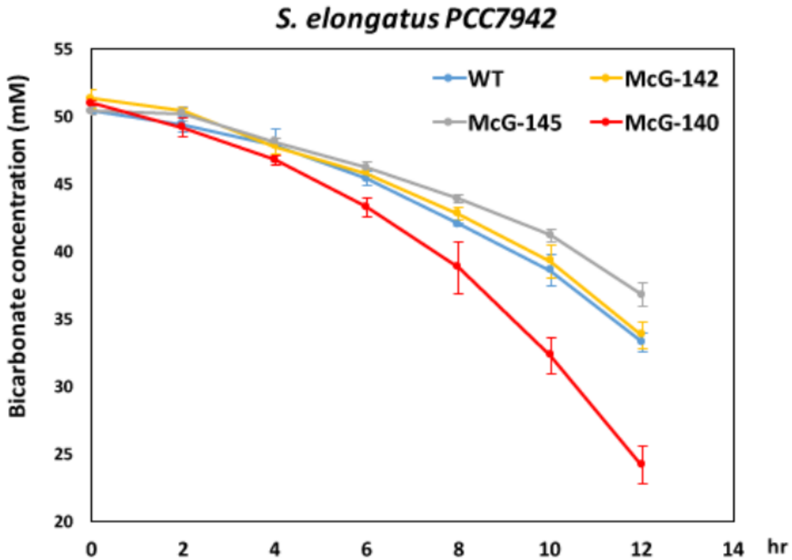
Per Ac-CoA Synthesis from CO_2	NAD(P)H consumption	ATP consumption	Rubisco turnover	The theoretical carbon yield
CBB+ PDH	4	7	3	66% (Ac-CoA/C3)
CBB+ NOG	4	6	2	100% (1.5 Ac-CoA/C3)
CBB+ MCG	4	5.5	1.5	100% (2 Ac-CoA/C3+C1)

Table 2 Comparison of ATP/NADH consumption and carbon yield among different pathways in assimilation of glycolate to produce acetyl-CoA

Per Ac-CoA synthesis from glycolate	NAD(P)H consumption	ATP consumption	The theoretical carbon yield
Native photorespiration pathway[41]	0	0	50% (1 Ac-CoA/2 glycolate)
The bacterial glycolate assimilation route[41]	−2	0	50% (1 Ac-CoA/2 glycolate)
The MCG pathway	1	2	100% (1 Ac-CoA/1 glycolate)

The MCG pathway can convert one glycolate to produce one acetyl-CoA without net carbon loss. The bacterial glycolate assimilation route converts two glycolate to only one acetyl-CoA

MCG in S. elongates increased CO_2 fixation



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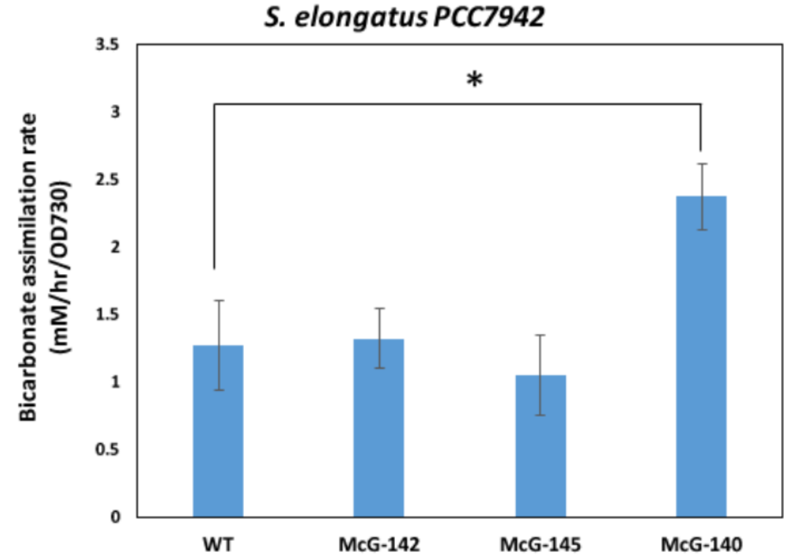
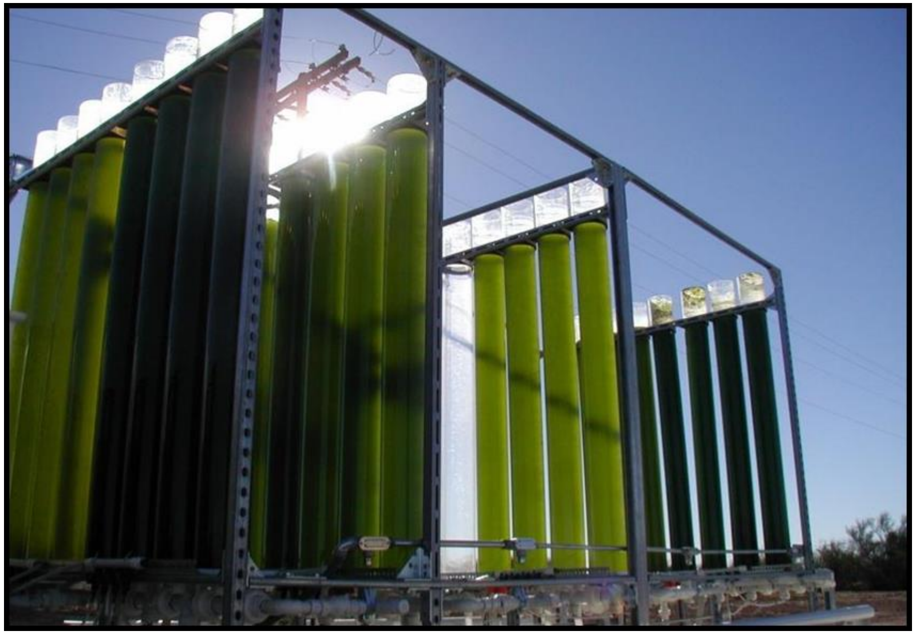
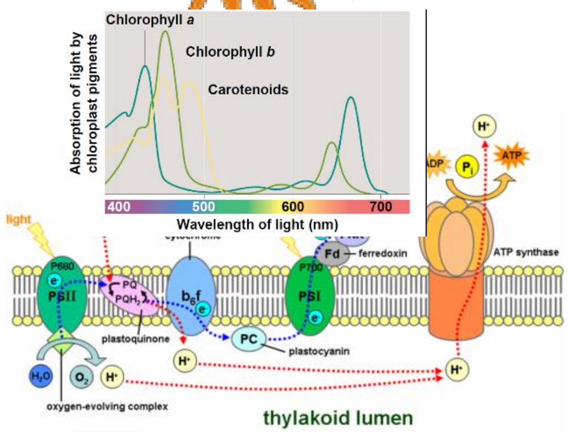


Challenges of Algae and cyanobacteria: Photobioreactor is expensive



Decouple Light and Dark Reactions

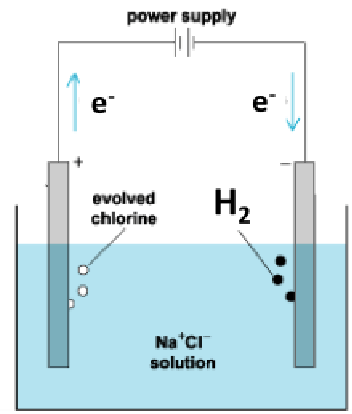
Light Reactions



PV

e^-

Electrochem



NADPH ATP

Calvin Cycle

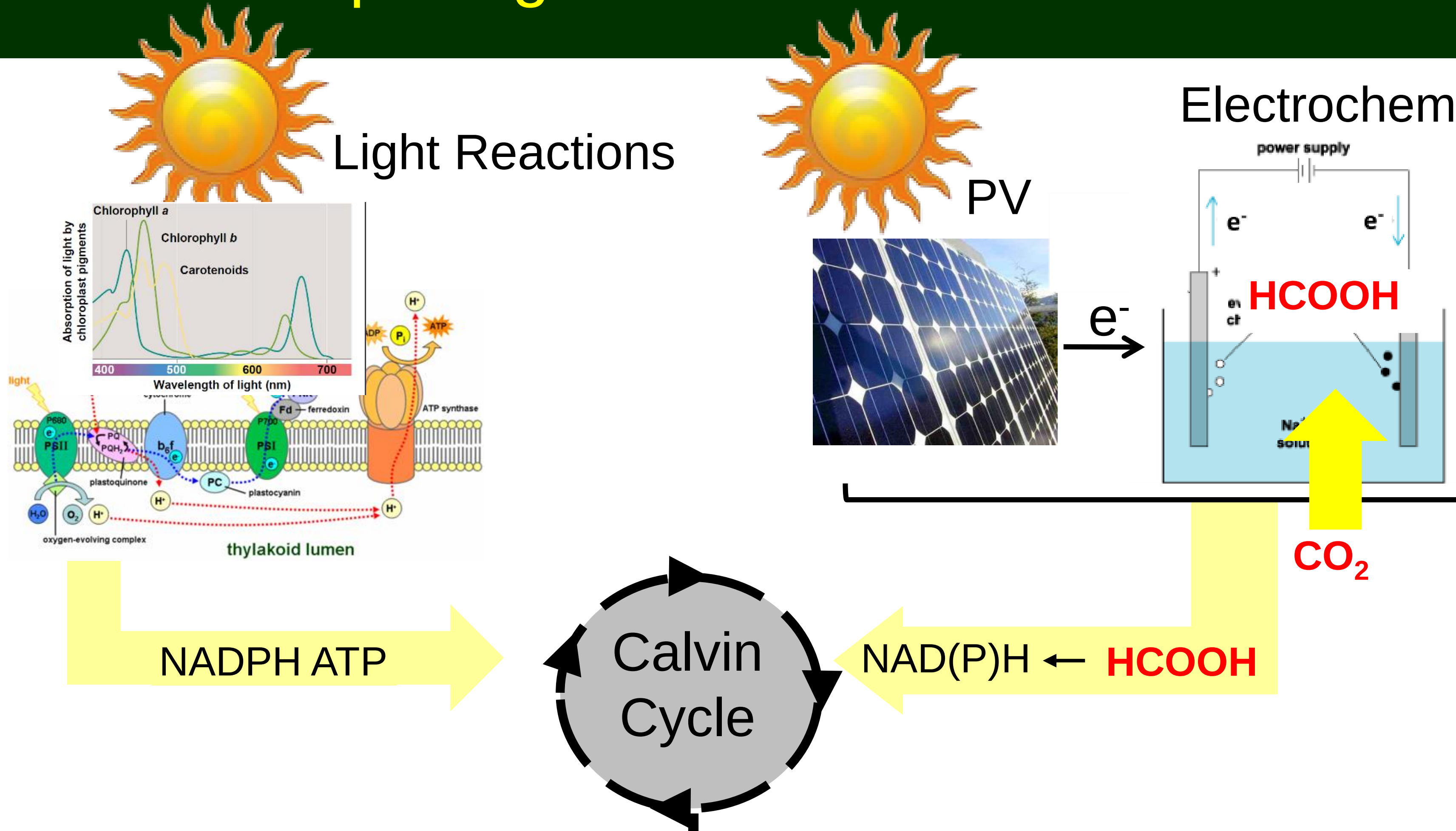
NAD(P)H ← H_2

Biofuel

Energy efficiency
0.3 % (practical)
5.7% (theoretical)

Energy efficiency
2.9% (practical)
9% (theoretical)

Decouple Light and Dark Reactions



Biofuel

Energy efficiency
0.3 % (practical)
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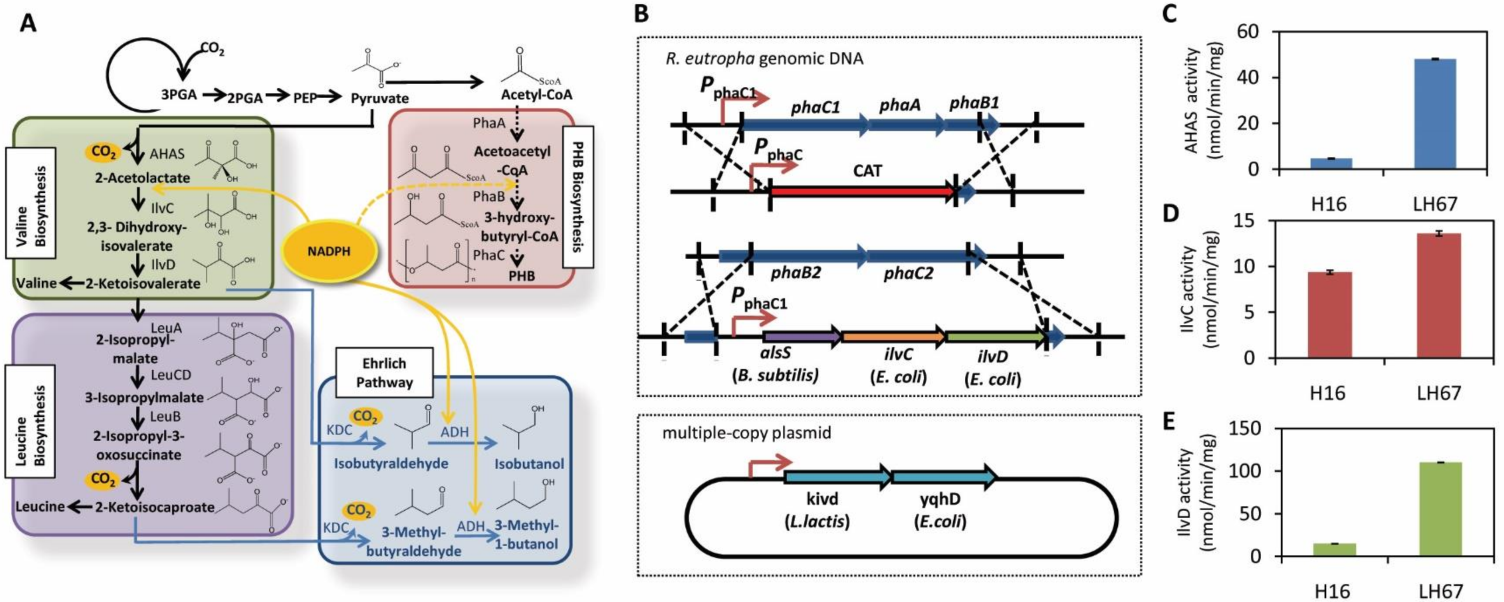
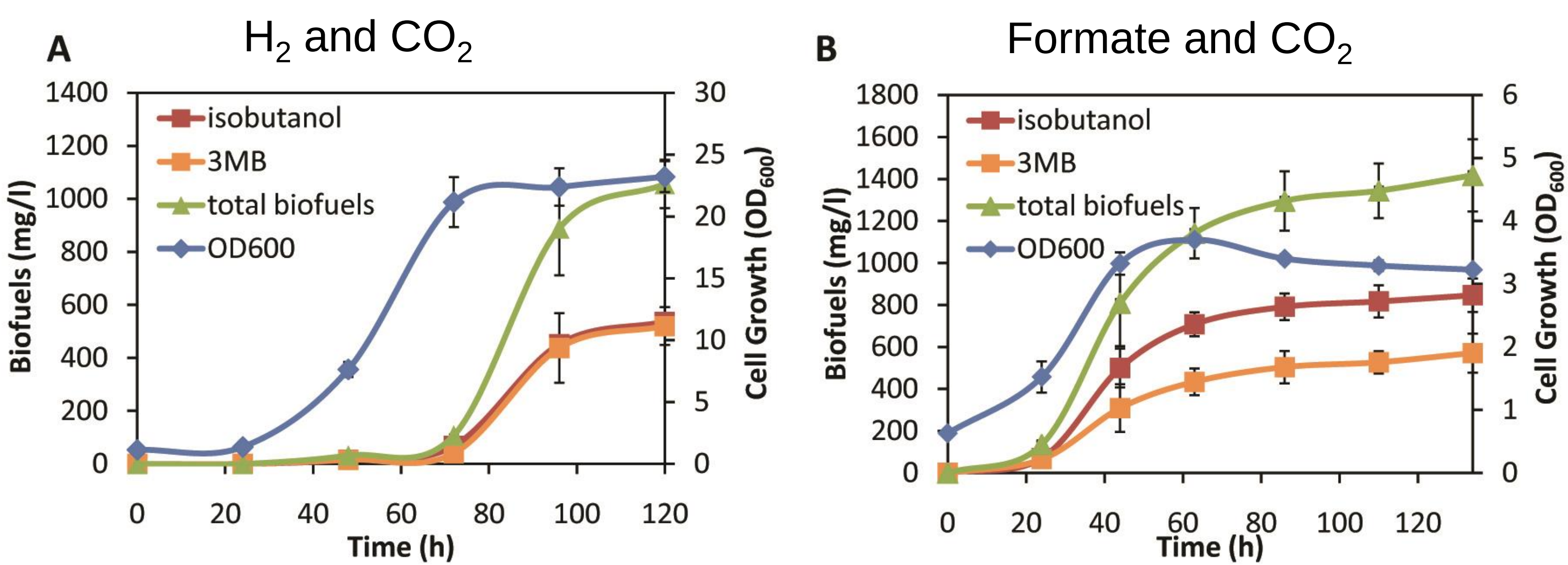


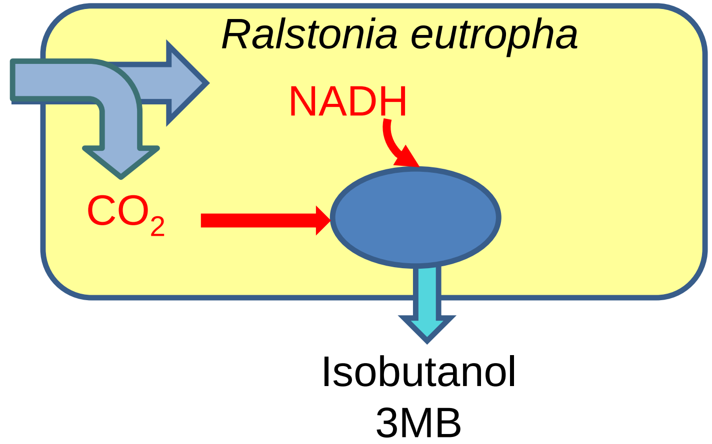


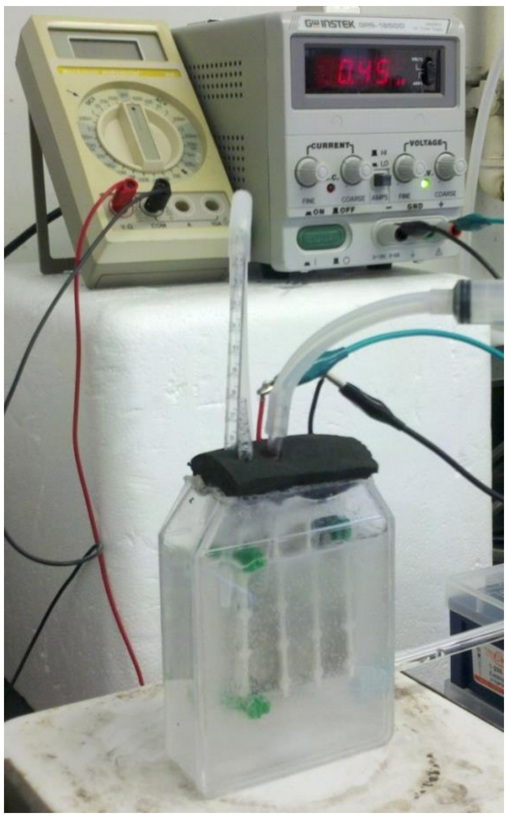
Li et al. Science 2012

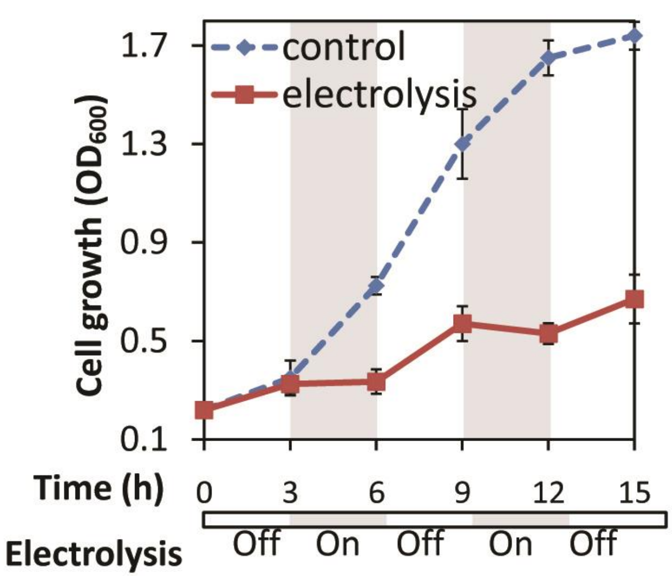
Electricity-powered CO_2 fixation for Isobutanol synthesis

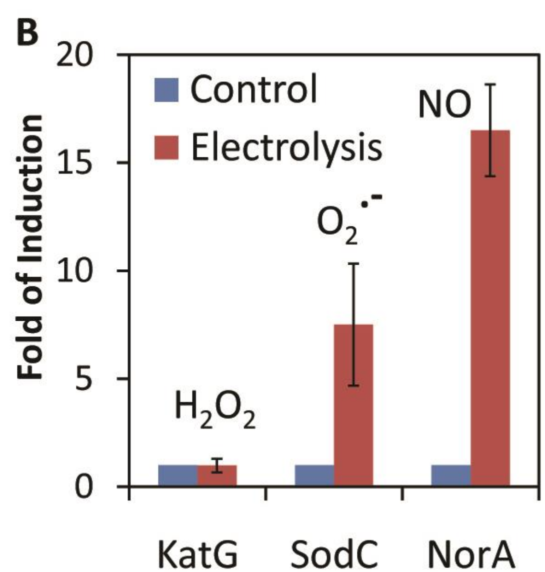
Cathode: $CO_2 + 2e^- + 2H^+ \xrightarrow{In} HCOOH$

Anode: $H_2O \xrightarrow{Pt} \frac{1}{2} O_2 + 2e^- + 2H^+$





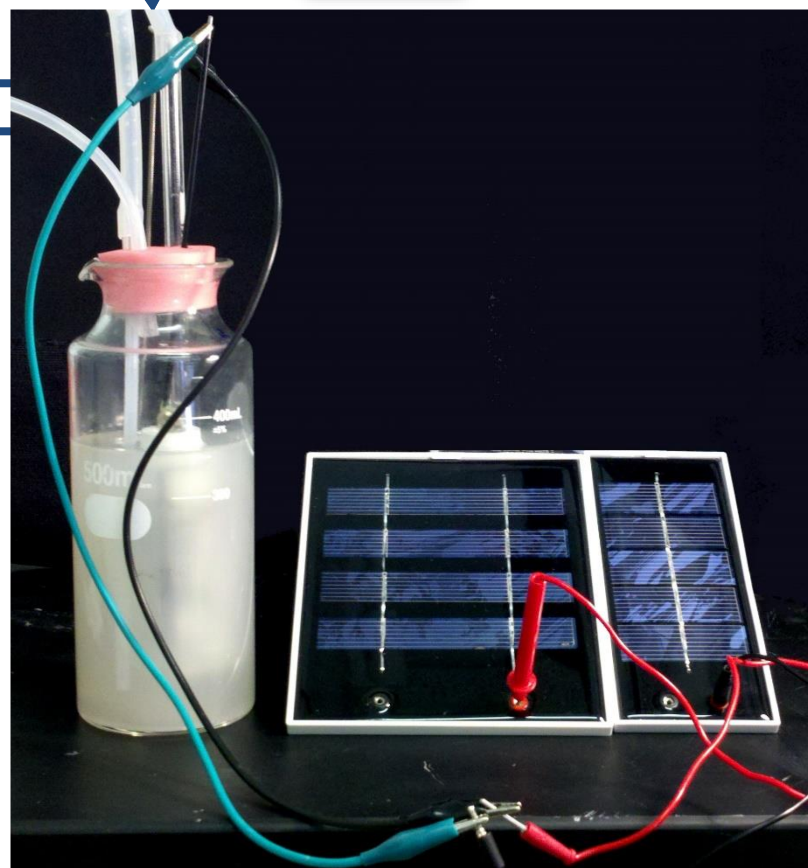




Li et al. Science 2012

Integrated Electro-microbial fuel Production

CO_2



OR

Gasoline substitutes

Thank you.