Net Zero Emissions
Why and How

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Lecture 7

Issues from lecture 6
Negative emissions, CCS, DAC

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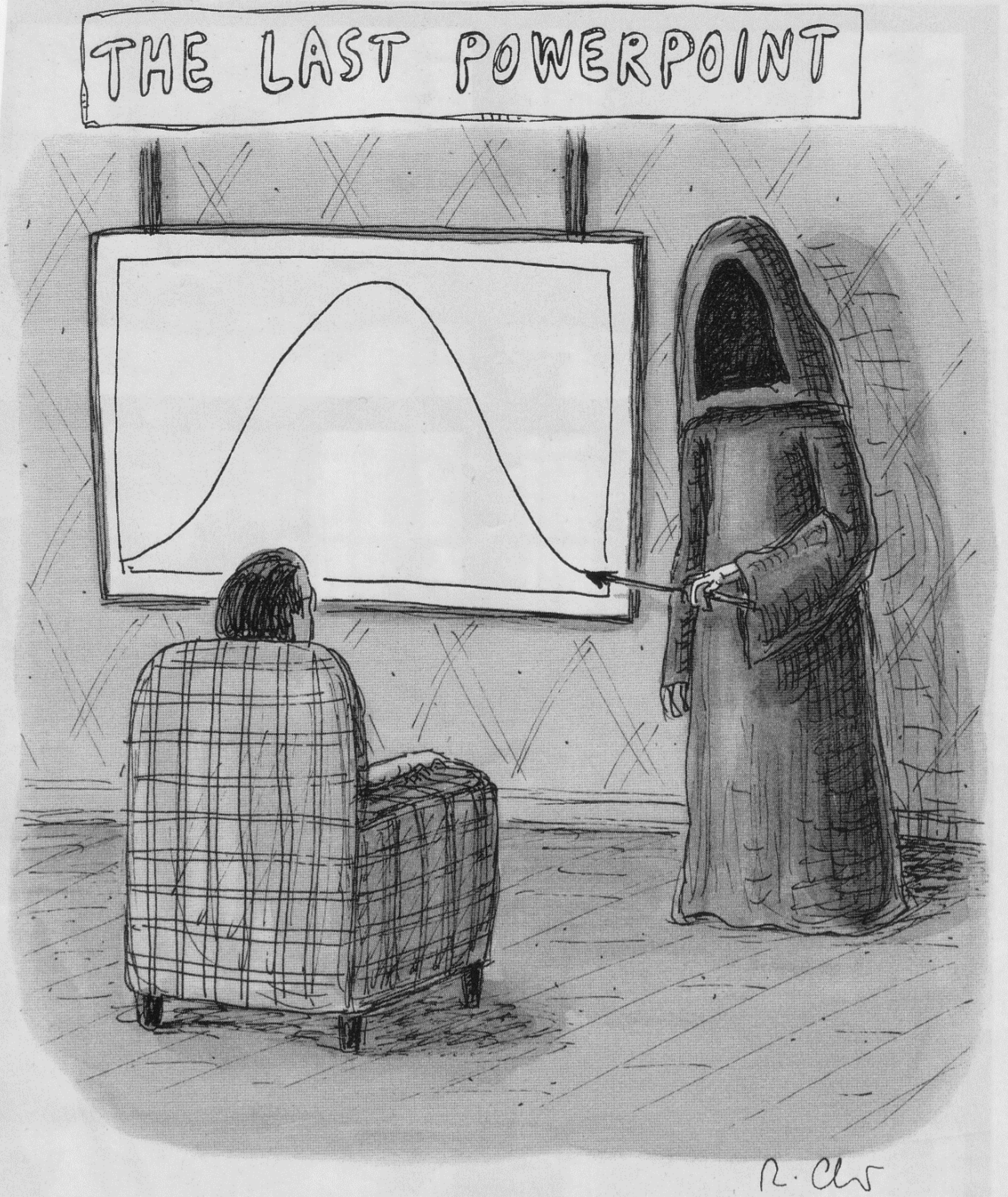
March 16, 2020


THE LAST POWERPOINT

Lecture 7 Outline

- Ground source thermal
- Biomass and biofuels
- Negative emissions
    - Enhanced weathering
    - Afforestation and reforestation see lectures 3&4
    - Ocean-based removal
    - Carbon capture and storage
    - Direct air capture
- Net Zero Emissions Summary [separate document]

Ground Source Geothermal for Heating and Cooling

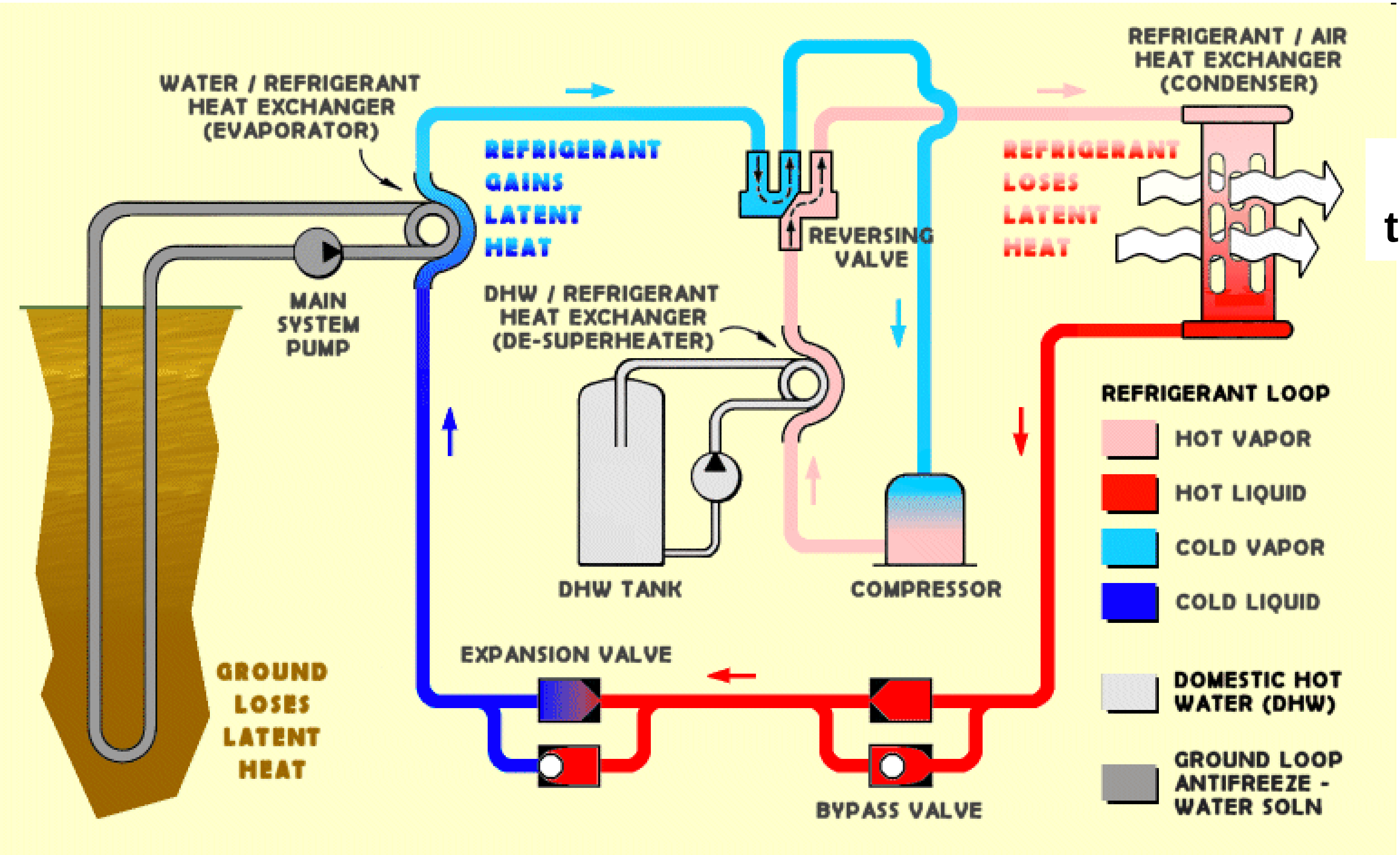
The ground is a renewable energy resource. It is replenished by the energy from the air.

Ground source heat pump

T= 55 F

“Geothermal”

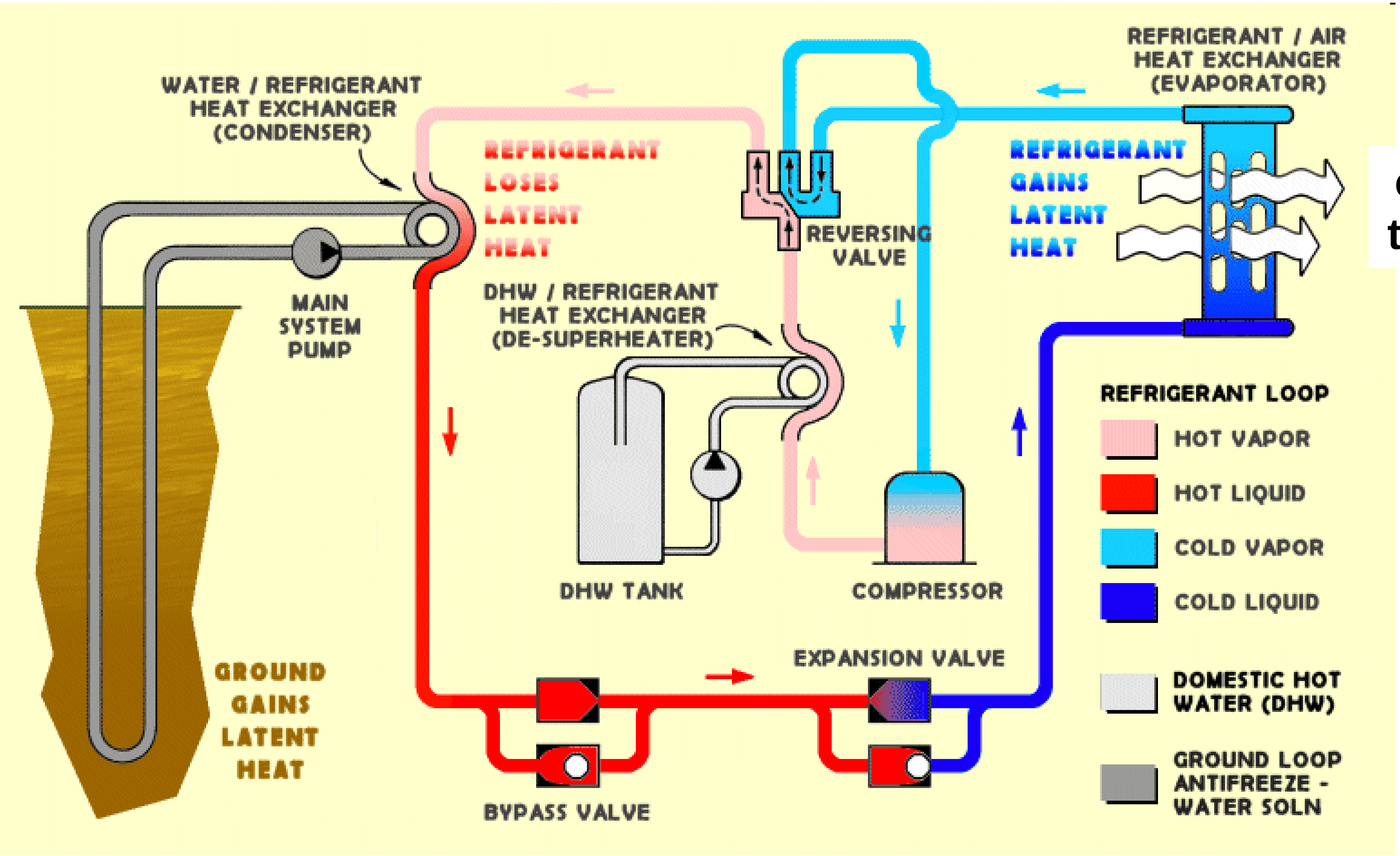
Ground-source (geothermal) heat pump in heating mode



hot air to home

From Geo4VA project, Virginia Department of Mines, Minerals, and Energy

Ground-source (geothermal) heat pump in cooling mode



cold air to home

From Geo4VA project, Virginia Department of Mines, Minerals, and Energy

Ground source heat pump

COP ≈ 2.5

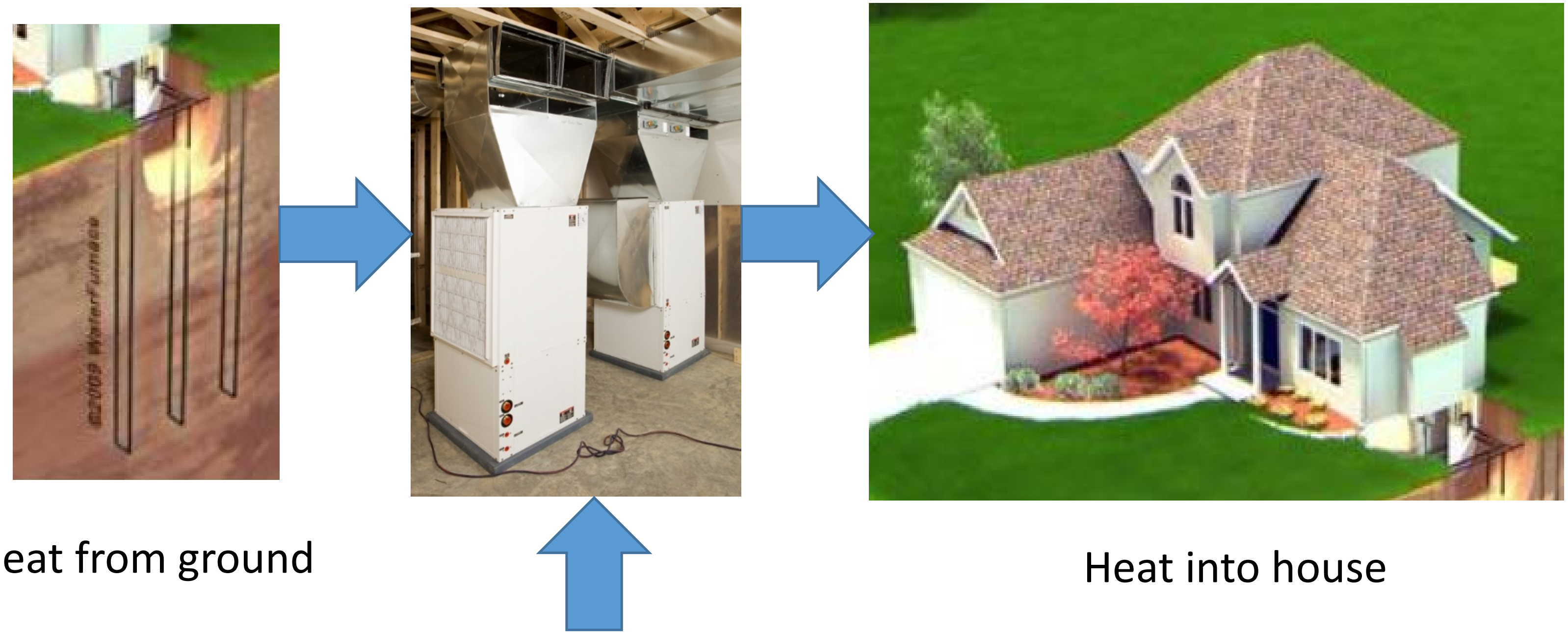
COP ≈ 4

GE heat pump water heater

preheat tank

heat pump

What is COP?
Coefficient of Performance



Heat from ground

Heat into house

Electricity into heat pump

$$\mathrm{COP} = \frac{\text{Heat into house}}{\text{Electricity into heat pump}} = 1.0 + \frac{\text{Heat from ground}}{\text{Electricity into heat pump}}$$

NB COP is greater than 1. Heat from ground is “free.” Electricity cost money.

The Hole Deal, Inc.
Directional Boring & Geothermal
Goodfield, IL

507 W. Illinois Urbana, IL

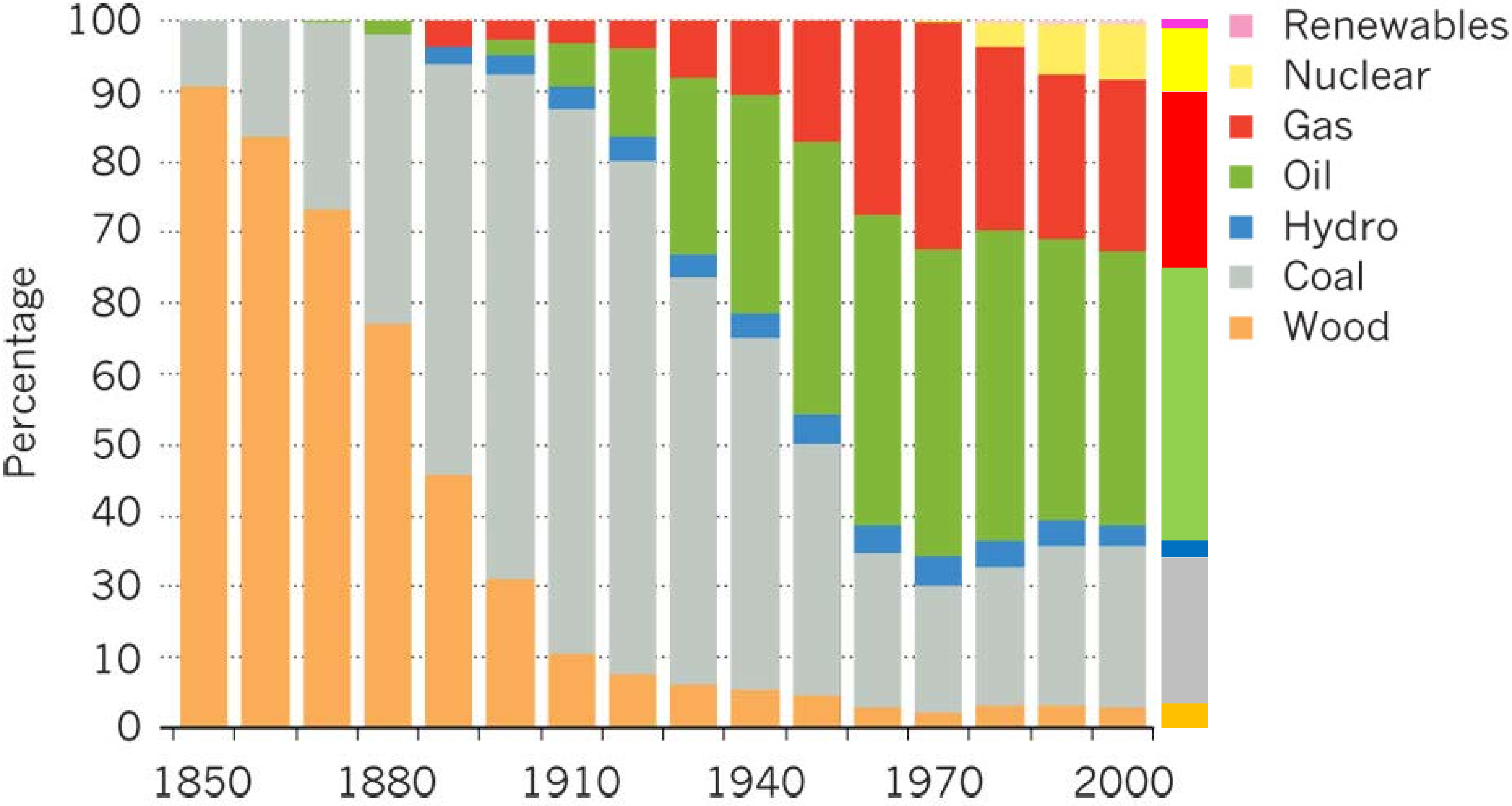
Biofuels and Biomass

Outline

- Primary energy sources: historical and current
- Biomass general considerations
- Renewable fuel standard
- Corn and sugarcane ethanol
- Cellulosic ethanol
- Forest and crop residue
- Biomass and biofuels summary

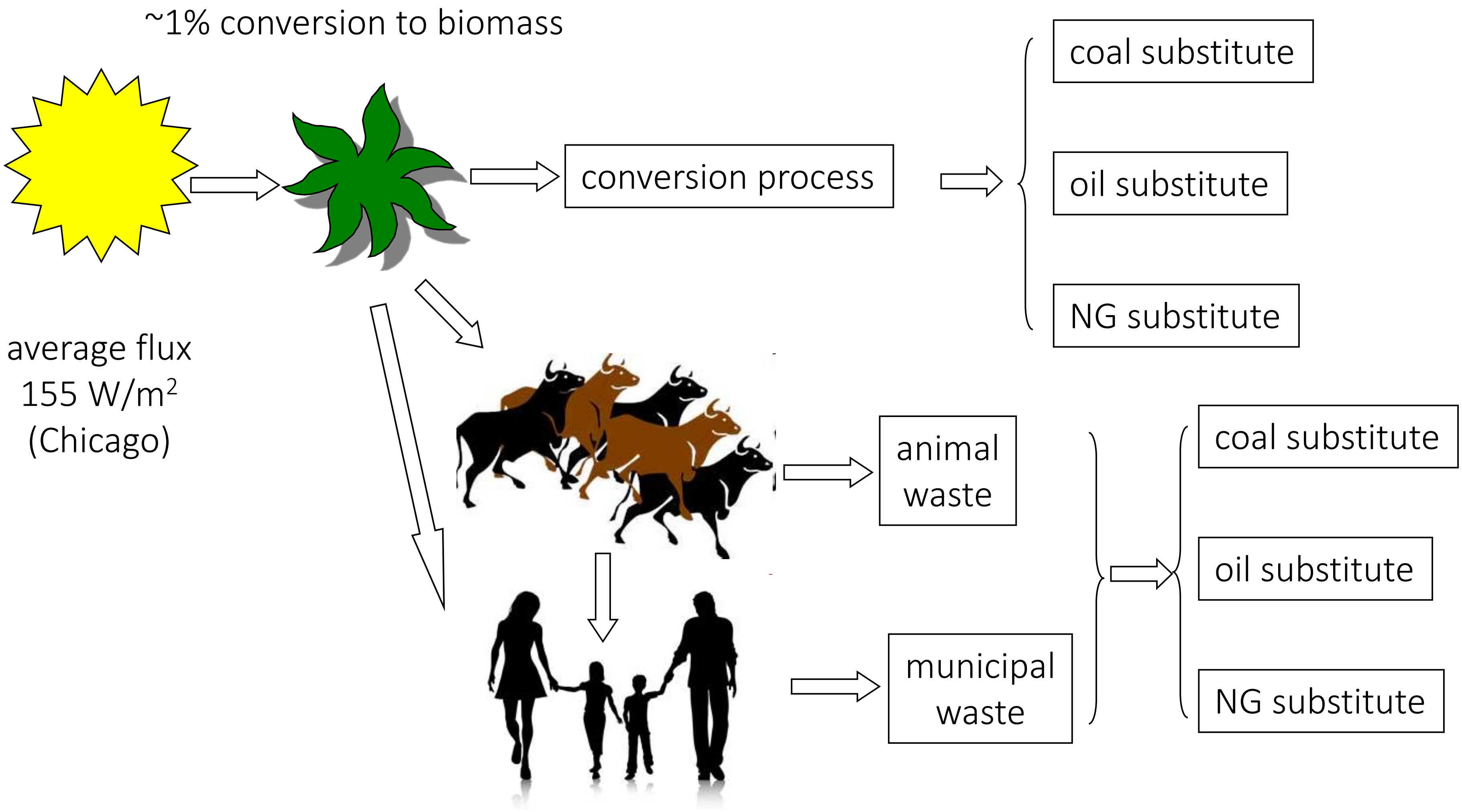
Historical Primary Energy Sources

Energy Transitions in the United States
Chu and Majumdar, Nature 488(2012)294



Biomass in General

Biomass Schematic



~1% conversion to biomass

average flux
155 W/m^2
(Chicago)

conversion process

coal substitute

oil substitute

NG substitute

animal waste

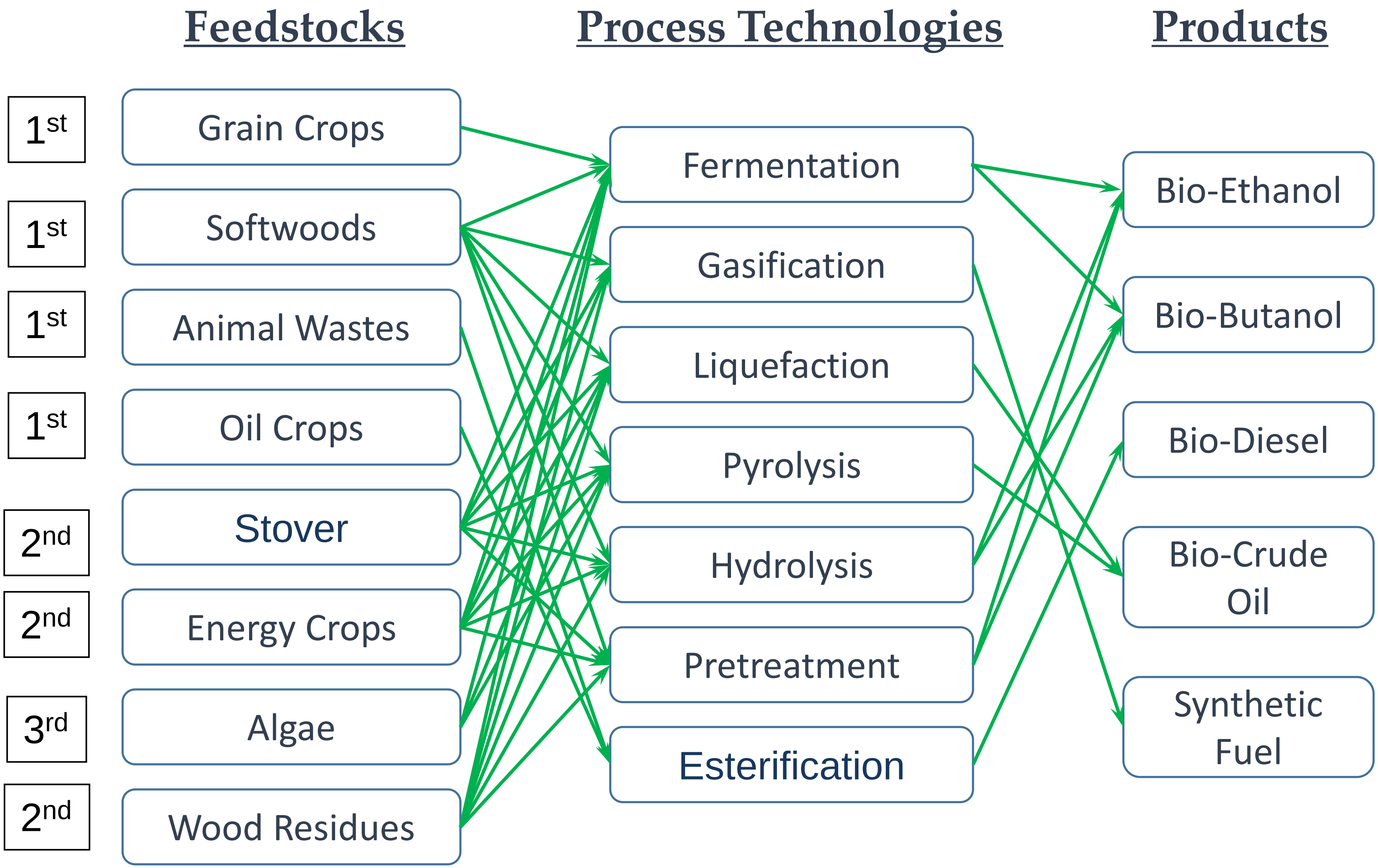
municipal waste

coal substitute

oil substitute

NG substitute

Biofuels Production Processes



Feedstocks

- 1st Grain Crops
- 1st Softwoods
- 1st Animal Wastes
- 1st Oil Crops
- 2nd Stover
- 2nd Energy Crops
- 3rd Algae
- 2nd Wood Residues

Process Technologies

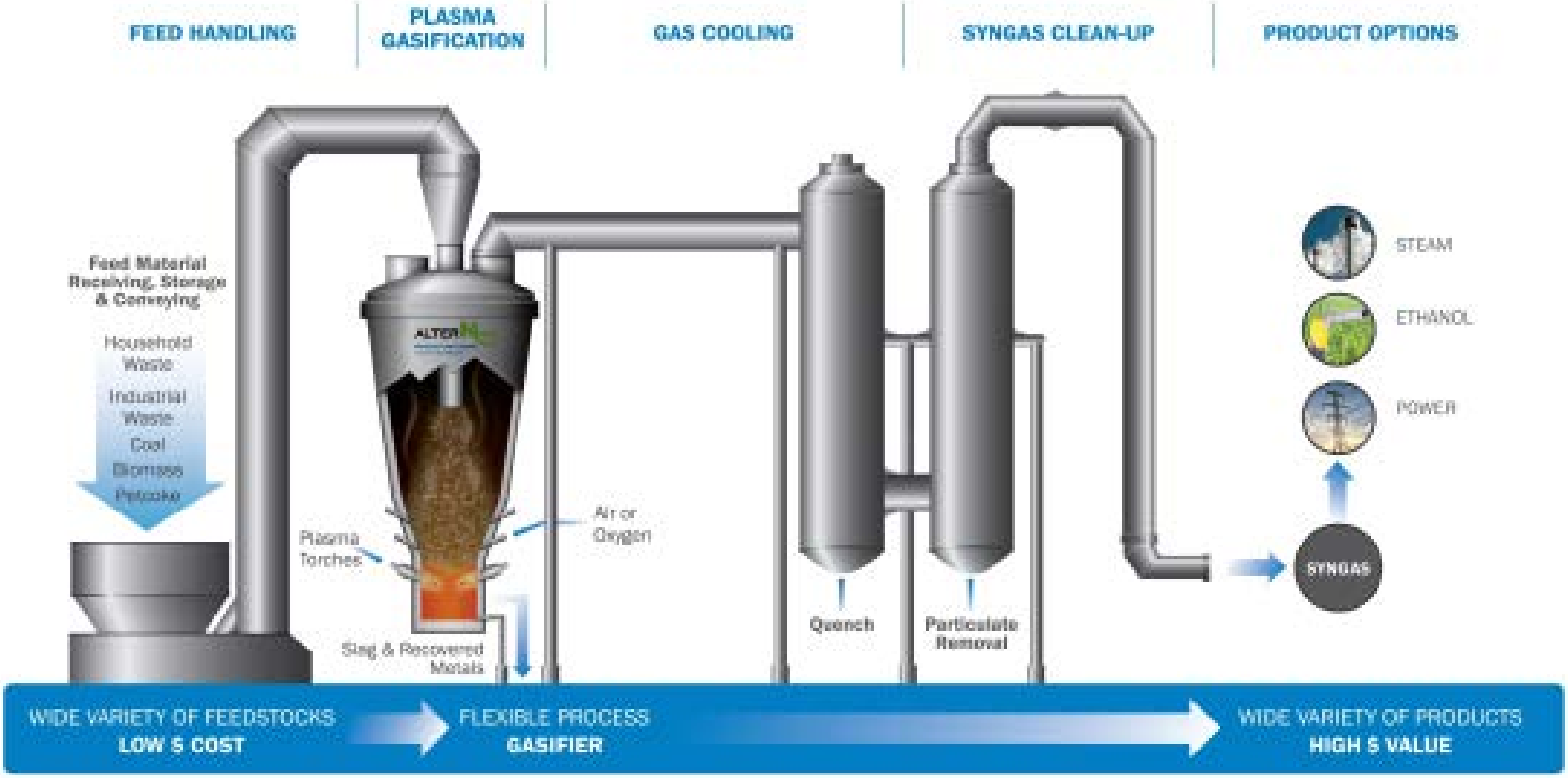
- Fermentation
- Gasification
- Liquefaction
- Pyrolysis
- Hydrolysis
- Pretreatment
- Esterification

Products

- Bio-Ethanol
- Bio-Butanol
- Bio-Diesel
- Bio-Crude Oil
- Synthetic Fuel

1st, 2nd, and 3rd generation of oil substitutes

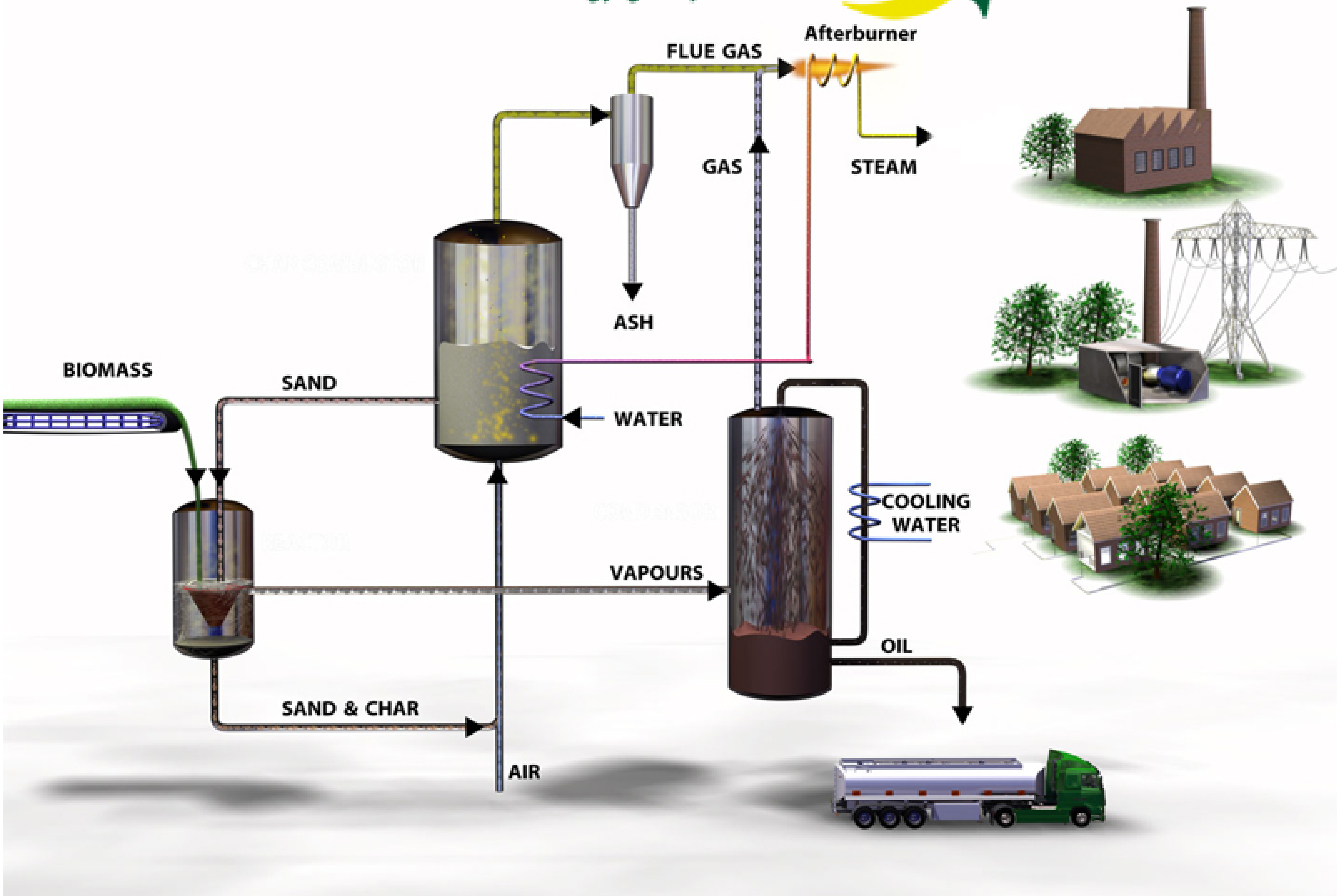
Gaseous Product



See http://wppenergy.com/

Liquid Product

btg
biomass technology group

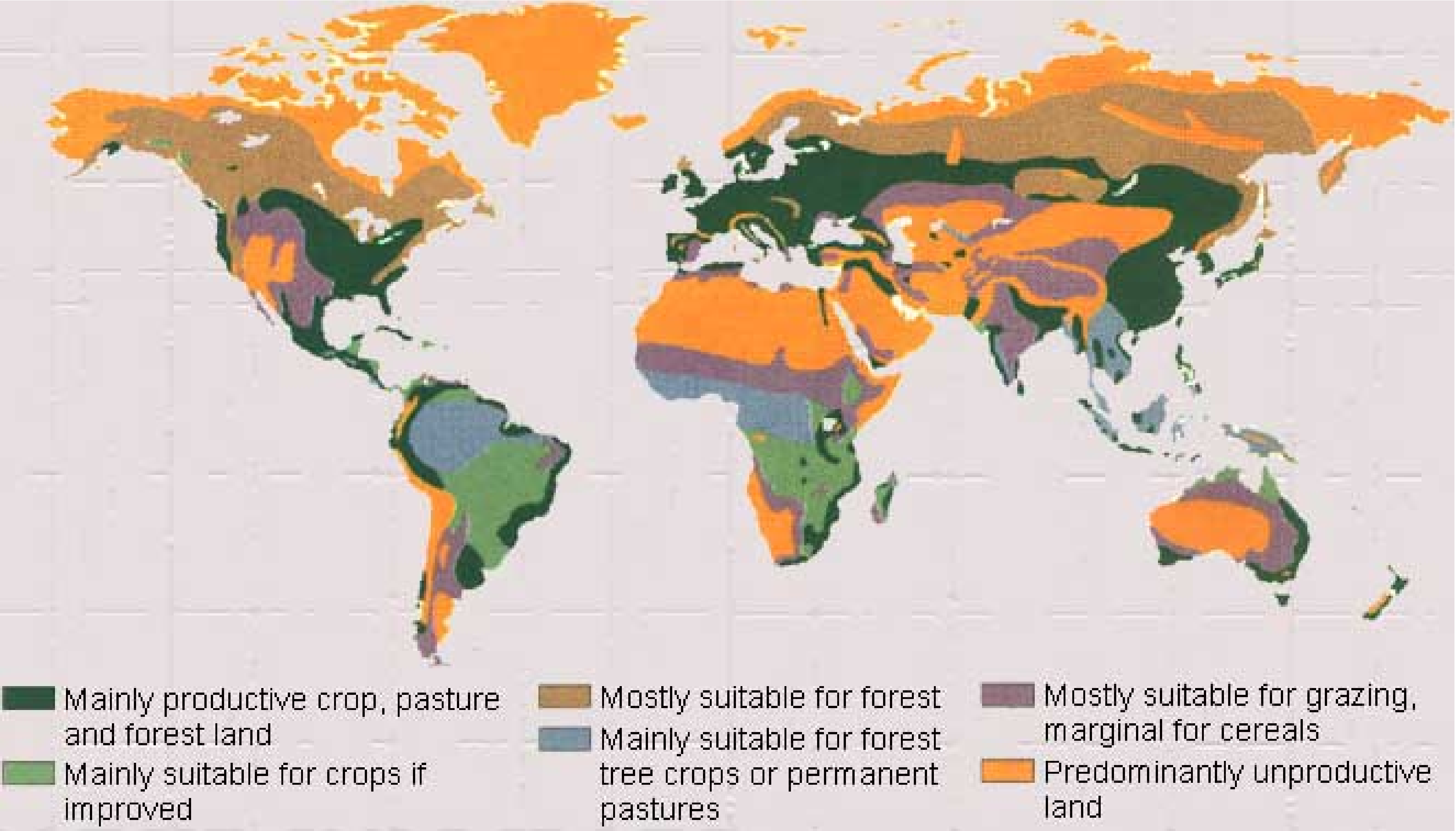


See http://www.btgworld.com/en/rtd/technologies/fast-pyrolysis

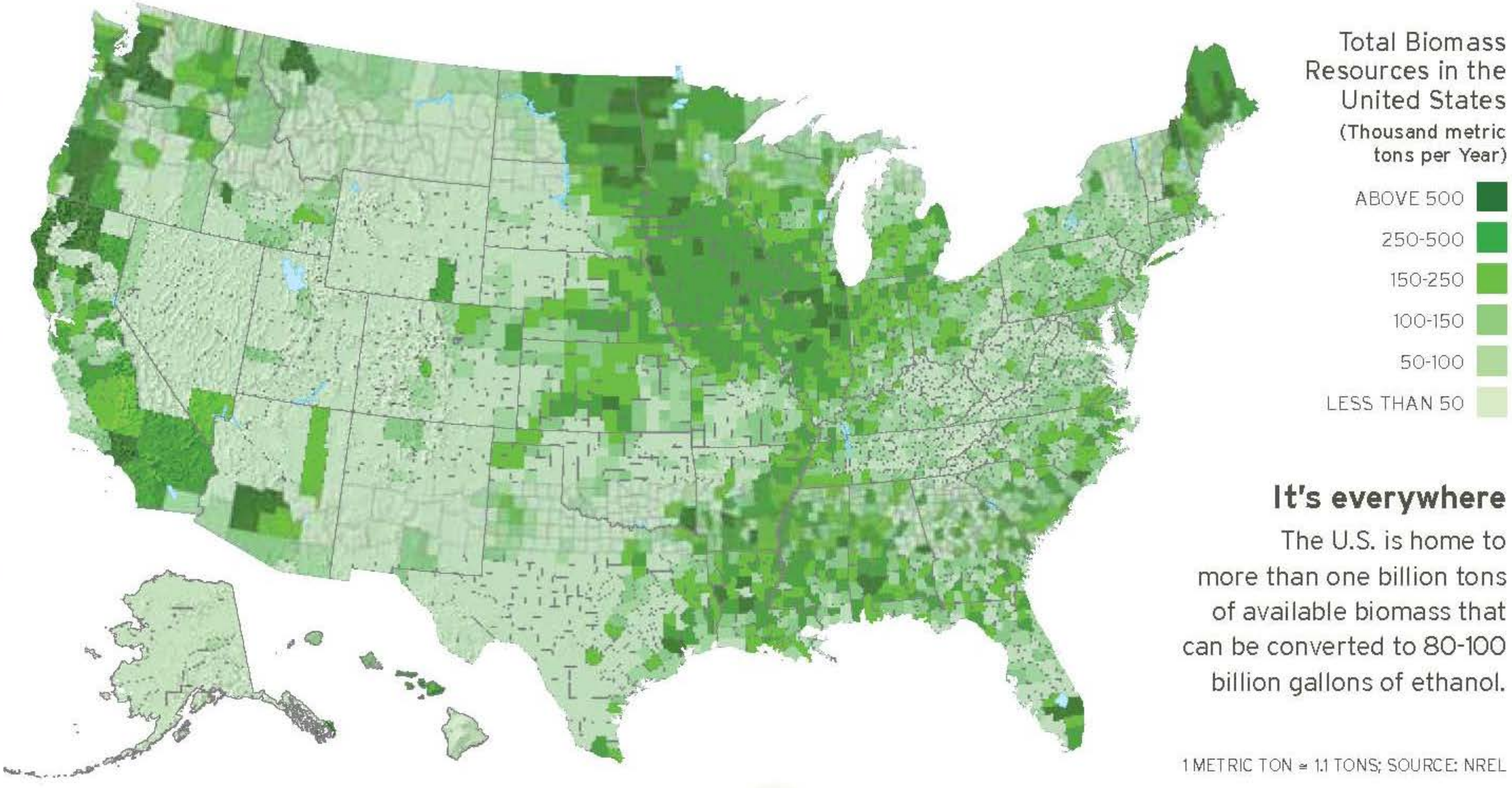
Biomass and Biofuels Comments

- Land area requirement can be large since power density is small.
- Crops may require irrigation.
- Collection of biomass limited by transportation cost.
- Competition for arable exists between food and fuel production.
- Energy is stored and available at harvest.
- Conversion to oil or natural gas substitute can be energy intensive.
- Improvement of plant productivity and conversion efficiency is a very active research field.

Arable and Forest Land of the World



U.S. Biomass Resource



It's everywhere

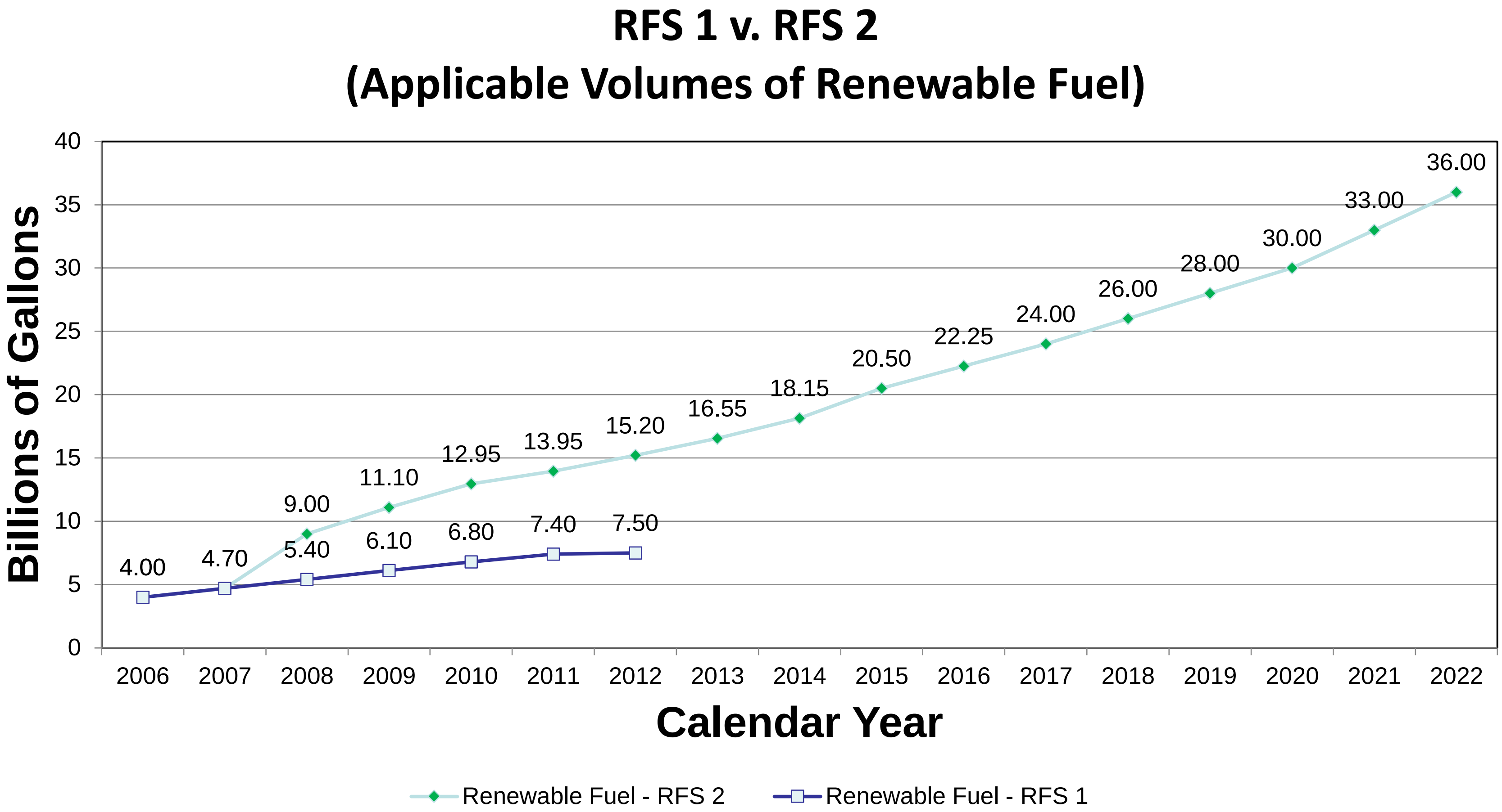
The U.S. is home to more than one billion tons of available biomass that can be converted to 80-100 billion gallons of ethanol.

1 METRIC TON ≅ 1.1 TONS; SOURCE: NREL

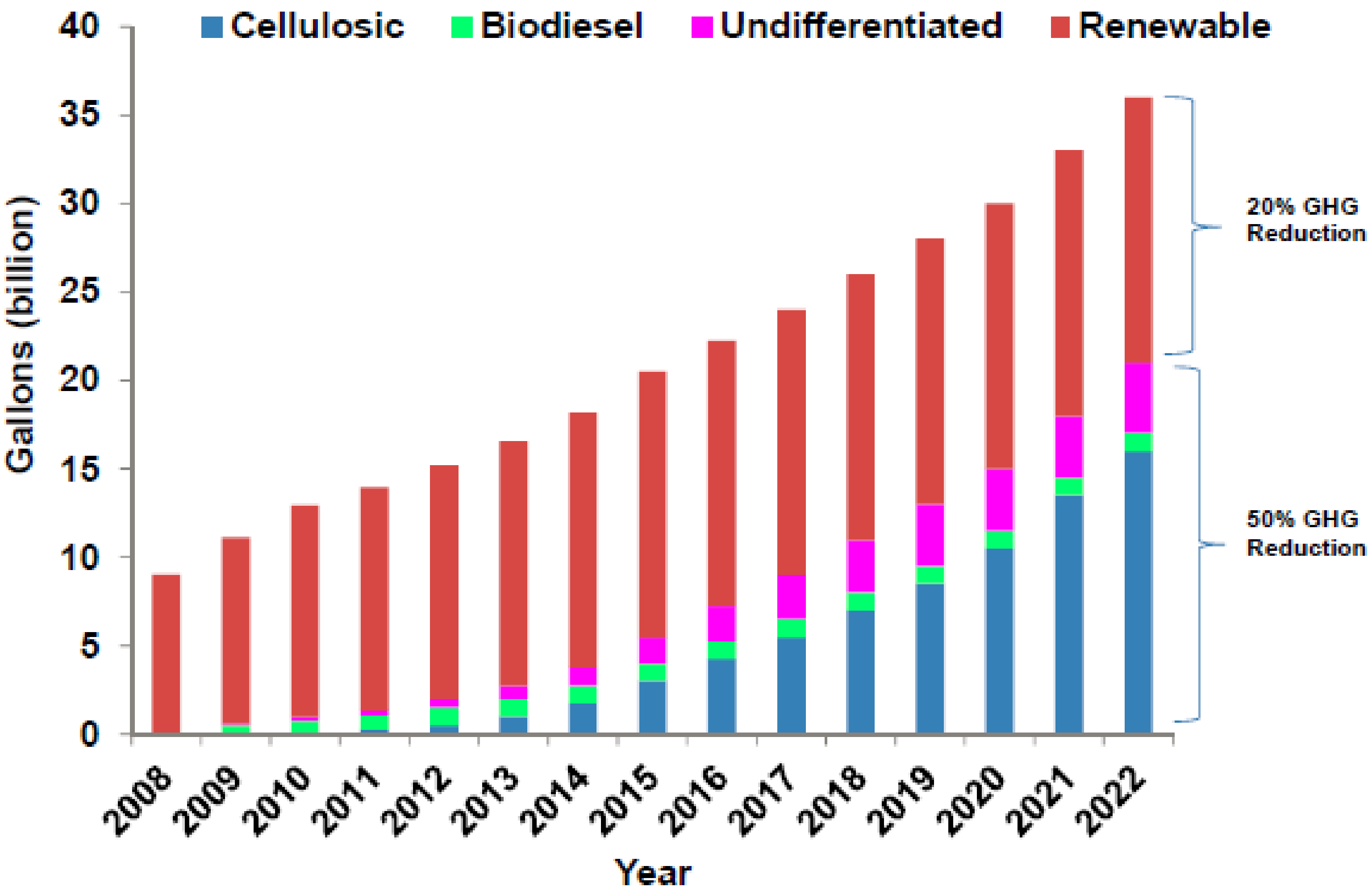
one ton of biomass could yield 80 - 100 gallons of ethanol
80 - 100 billion gallons of ethanol 6.8 - 8.4 quads

Renewable Fuel Standard

Volumetric Requirements of RFS1(2005) and RFS2(2007)



2018 U.S. gasoline consumption 143 billion gallons


U.S. Renewable Fuels Standards, 2008-2022

Sugarcane and cellulosic ethanol are favored by the RFS2 and LCFS but must compete with corn ethanol for blending capacity.

Fuel: Corn ethanol D6

- Currently, most ethanol blended is (inexpensive) corn ethanol
- Counts as Conventional biofuel

Fuel: Sugarcane ethanol (mainly from Brazil) D5

- Not cellulosic, but does count as an RFS Advanced biofuel
- Competes for limited ethanol blending capacity

Fuel: Biomass-based diesel D4

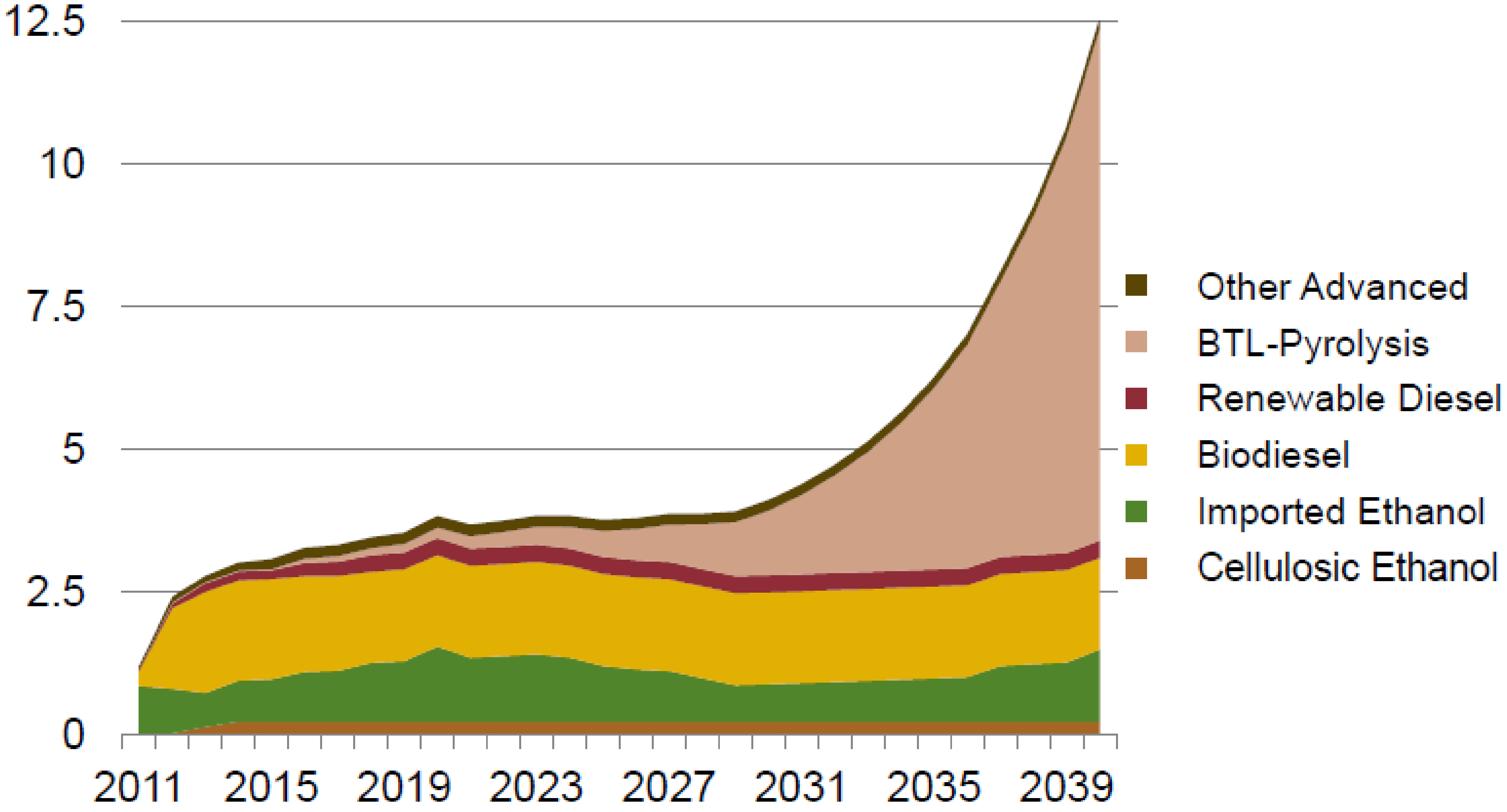
- Not cellulosic, but does count as an RFS Advanced biofuel

Fuel: Cellulosic biofuels D3

- Ethanol or drop-in fuel
- If ethanol, must compete for limited ethanol blending capacity
- Production of biochemicals or electricity may displace cellulosic biofuel production

Consumption of Advanced biofuels

Billion gallons ethanol equivalent



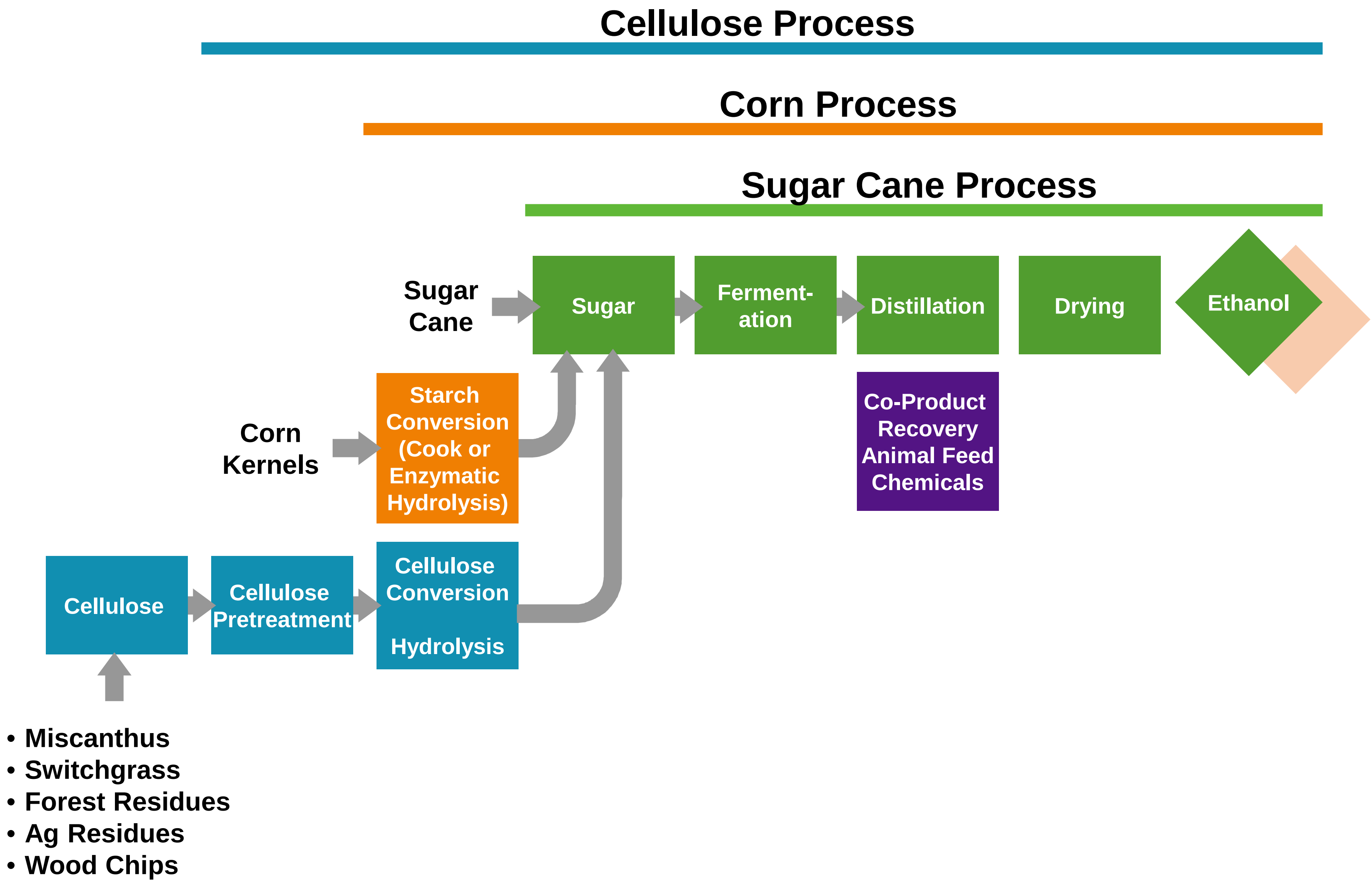
Source: Annual Energy Outlook 2013 Early Release

Ethanol Fuel Blends

- E10 – standard U.S. blend
- E15 – NASCAR Sunoco E15
- E25 – standard Brazil blend
- Flex-fuel vehicle – up to E85
- Indy – E98

Corn, Sugarcane and Cellulosic Ethanol

Ethanol Production Schemes



- Miscanthus
- Switchgrass
- Forest Residues
- Ag Residues
- Wood Chips

Very Basic Chemistry

$$6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2$$

photosynthesis

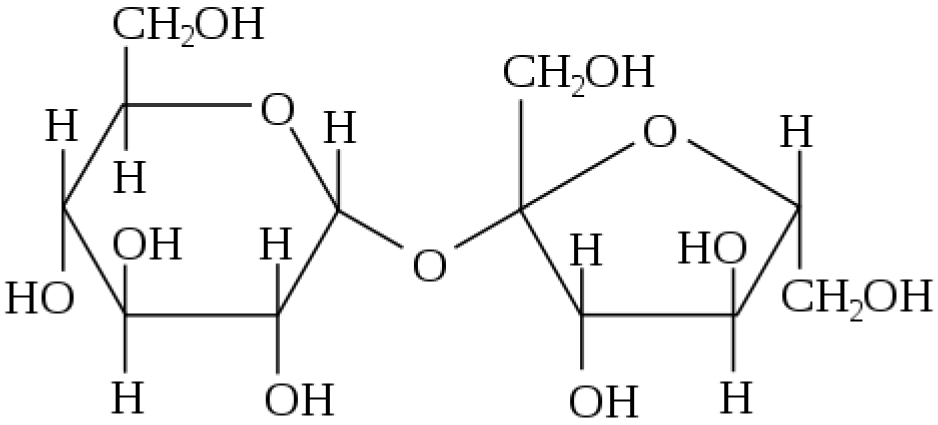
$$C_6H_{12}O_6 \rightarrow +2C_2H_5OH + 2CO_2 + \text{heat}$$

fermentation

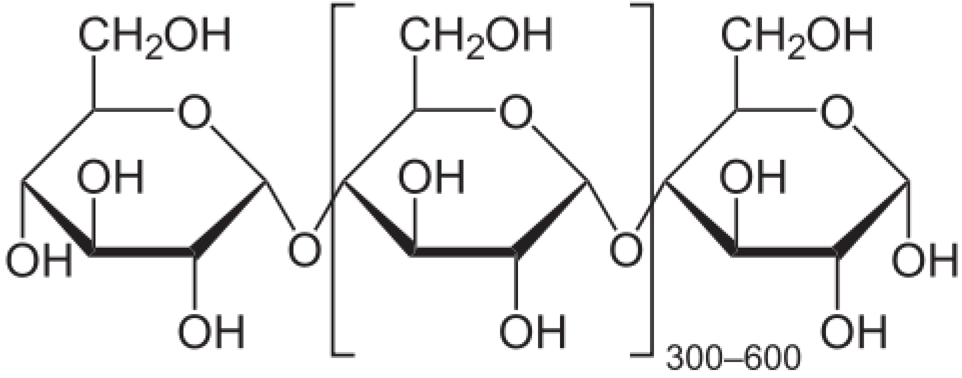
$$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O + \text{heat}$$

combustion

Sugar and Starch



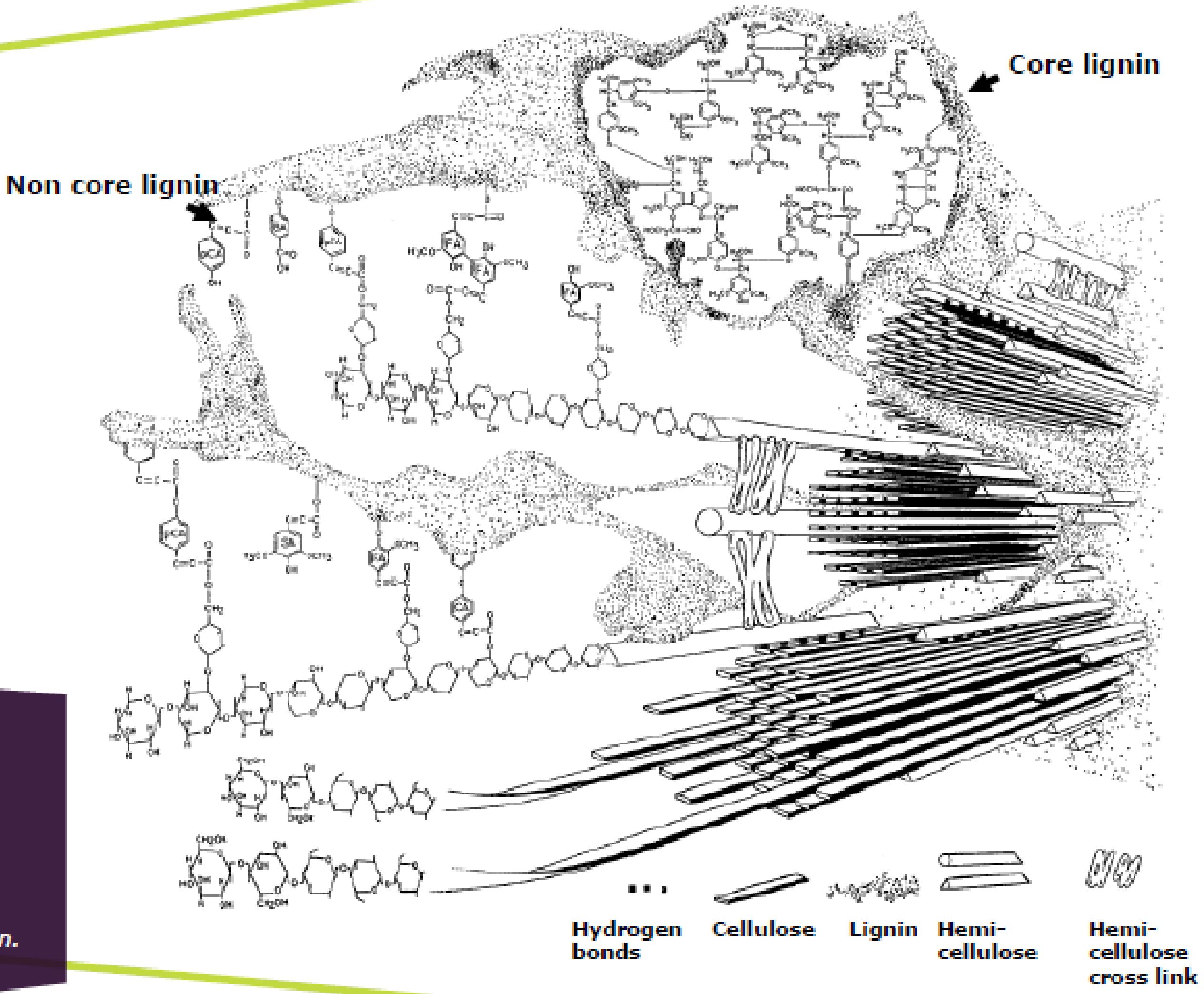
Sucrose: a disaccharide of glucose (left) and fructose (right)



Starch: a polysaccharide of glucose

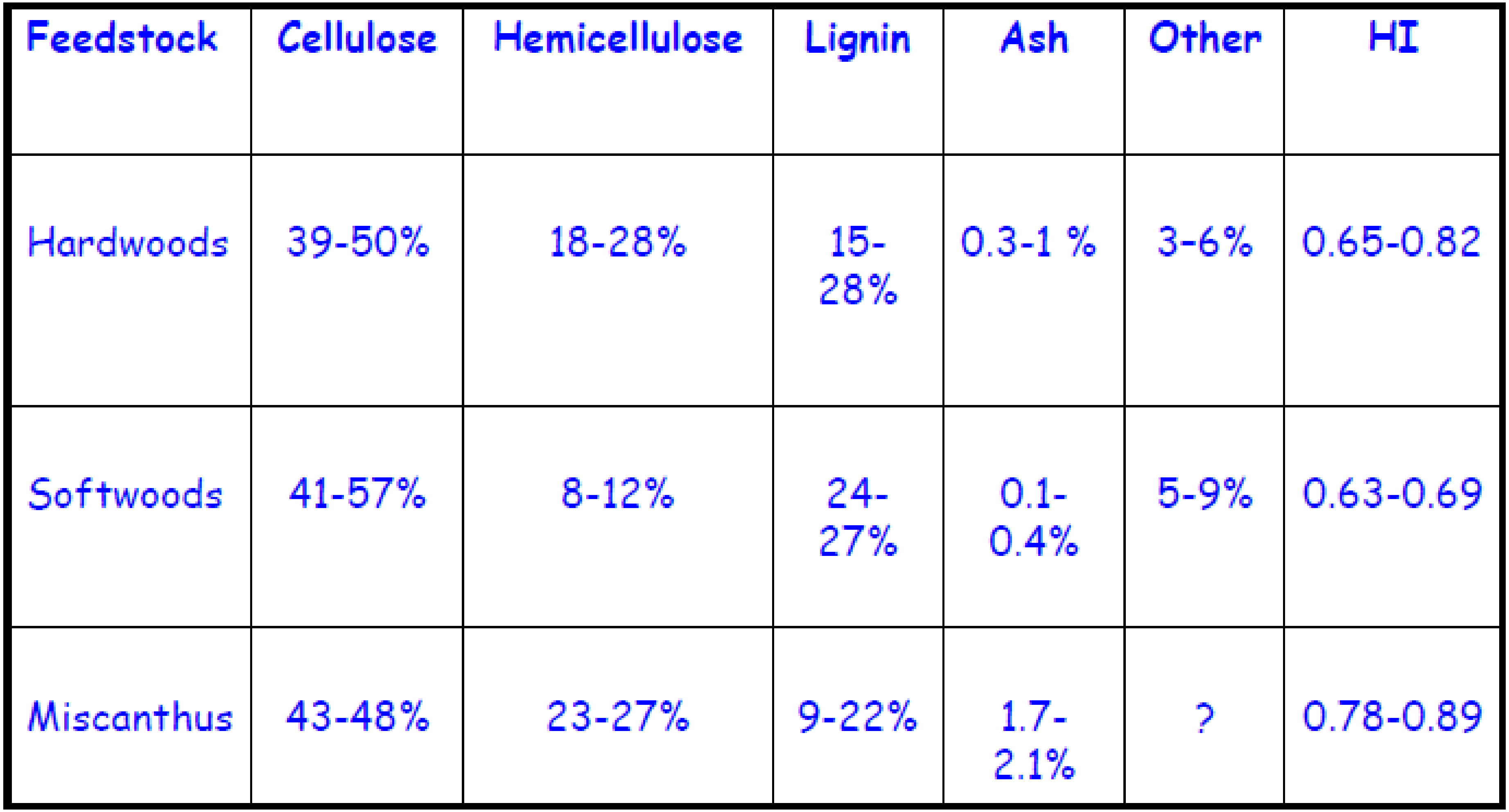
Cell wall model

Lignin
Cellulose
Hemi-cellulose



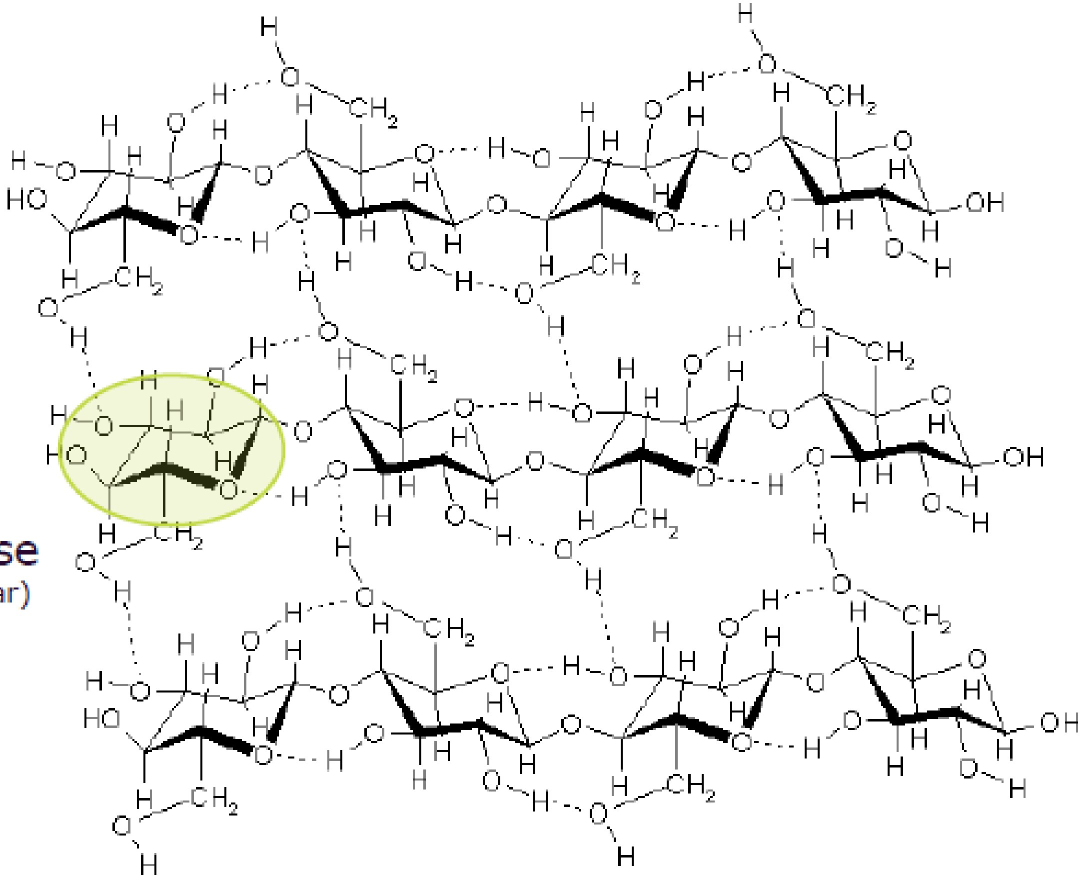
From:
J. Bidlack, M. Malone and R. Benson.
Okla. Acad. Sci., 1992, Vol. 72.

Lignocellulosic Feedstock Harvest Index



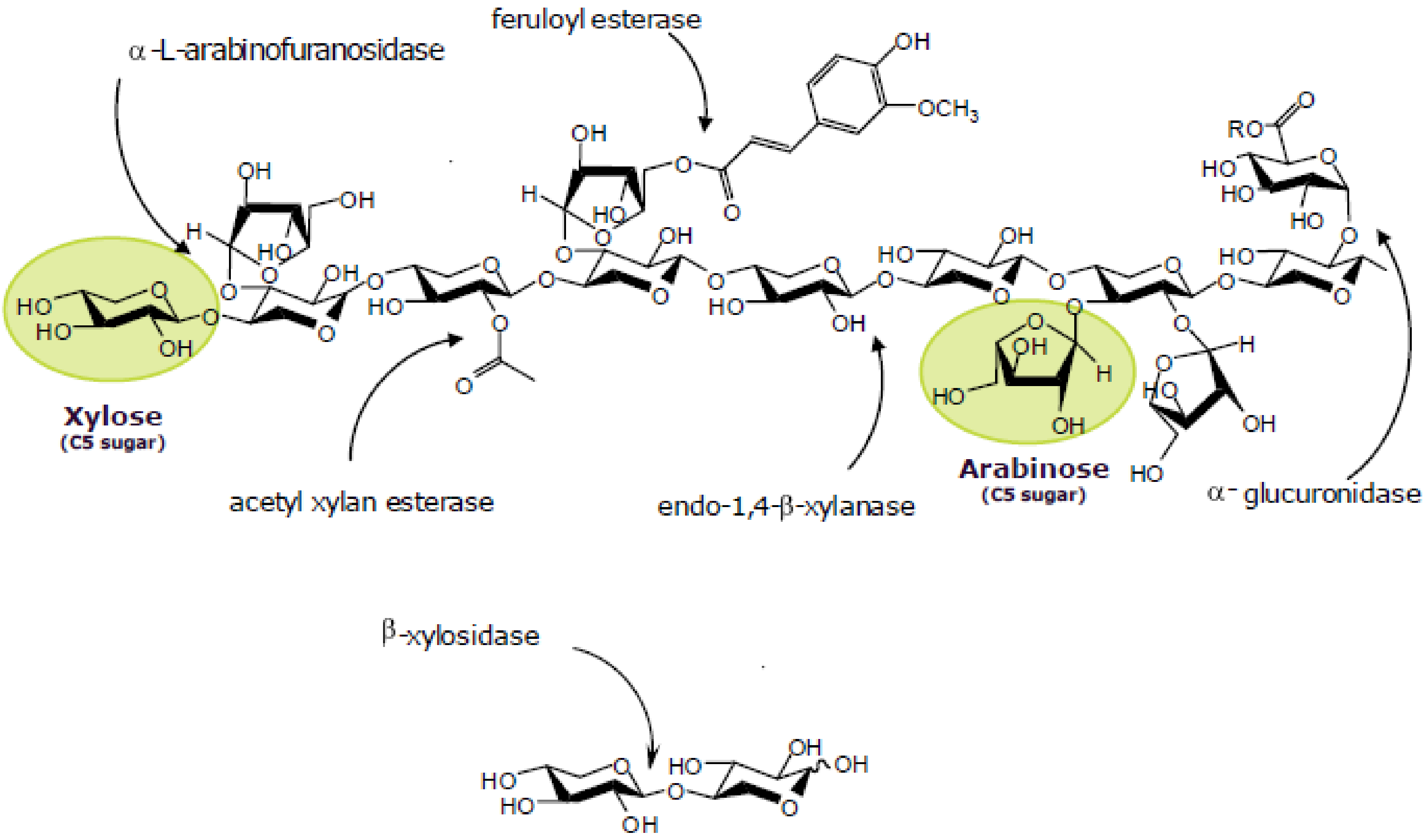
Feedstock	Cellulose	Hemicellulose	Lignin	Ash	Other	HI
Hardwoods	39-50%	18-28%	15-28%	0.3-1 %	3-6%	0.65-0.82
Softwoods	41-57%	8-12%	24-27%	0.1-0.4%	5-9%	0.63-0.69
Miscanthus	43-48%	23-27%	9-22%	1.7-2.1%	?	0.78-0.89

Basic cellulose structure



Glucose
(C6 sugar)

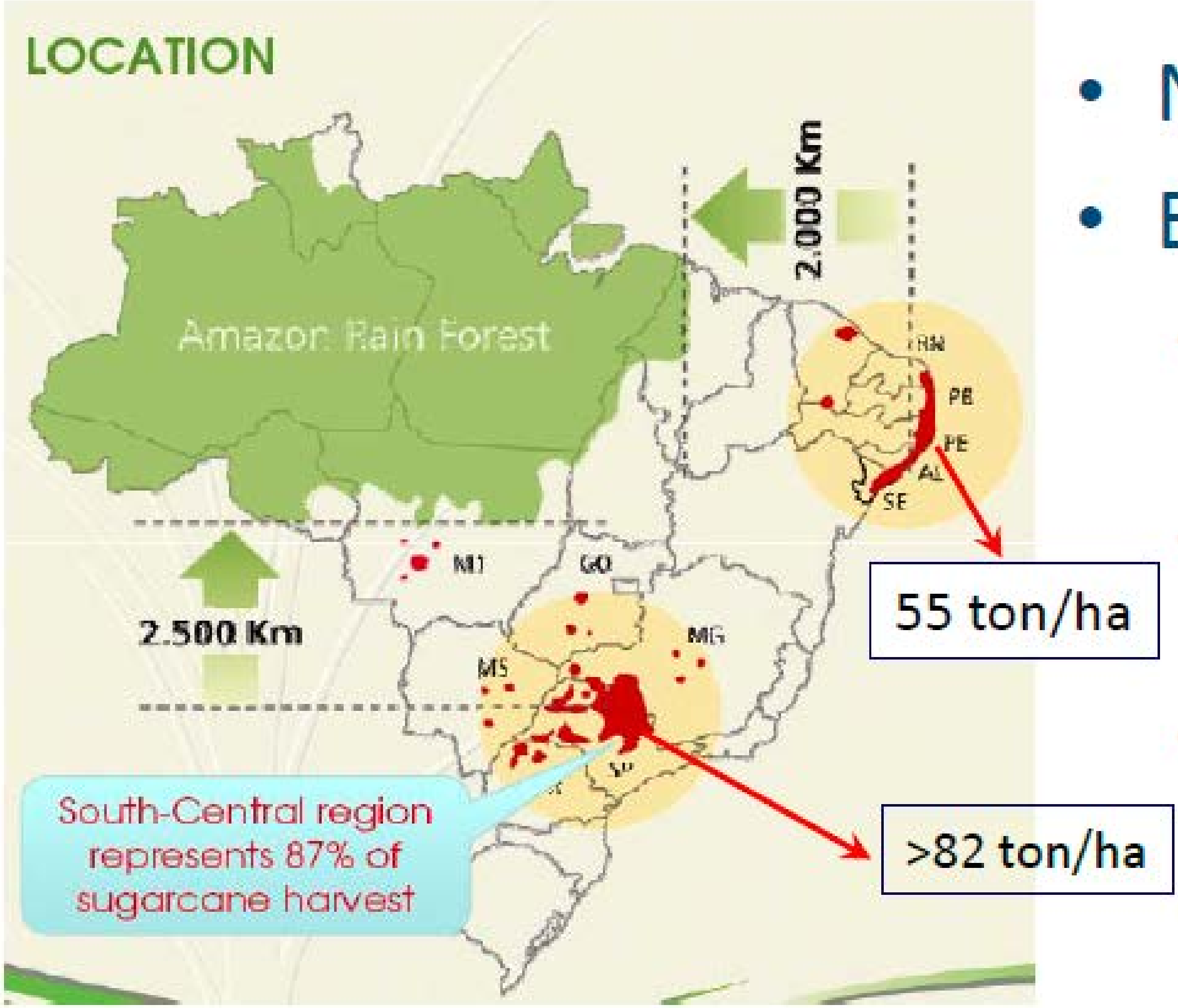
Basic hemicellulose structure



Sugarcane Ethanol

Sugarcane Productivity

Brazilian Sugarcane Locations



South-Central region represents 87% of sugarcane harvest

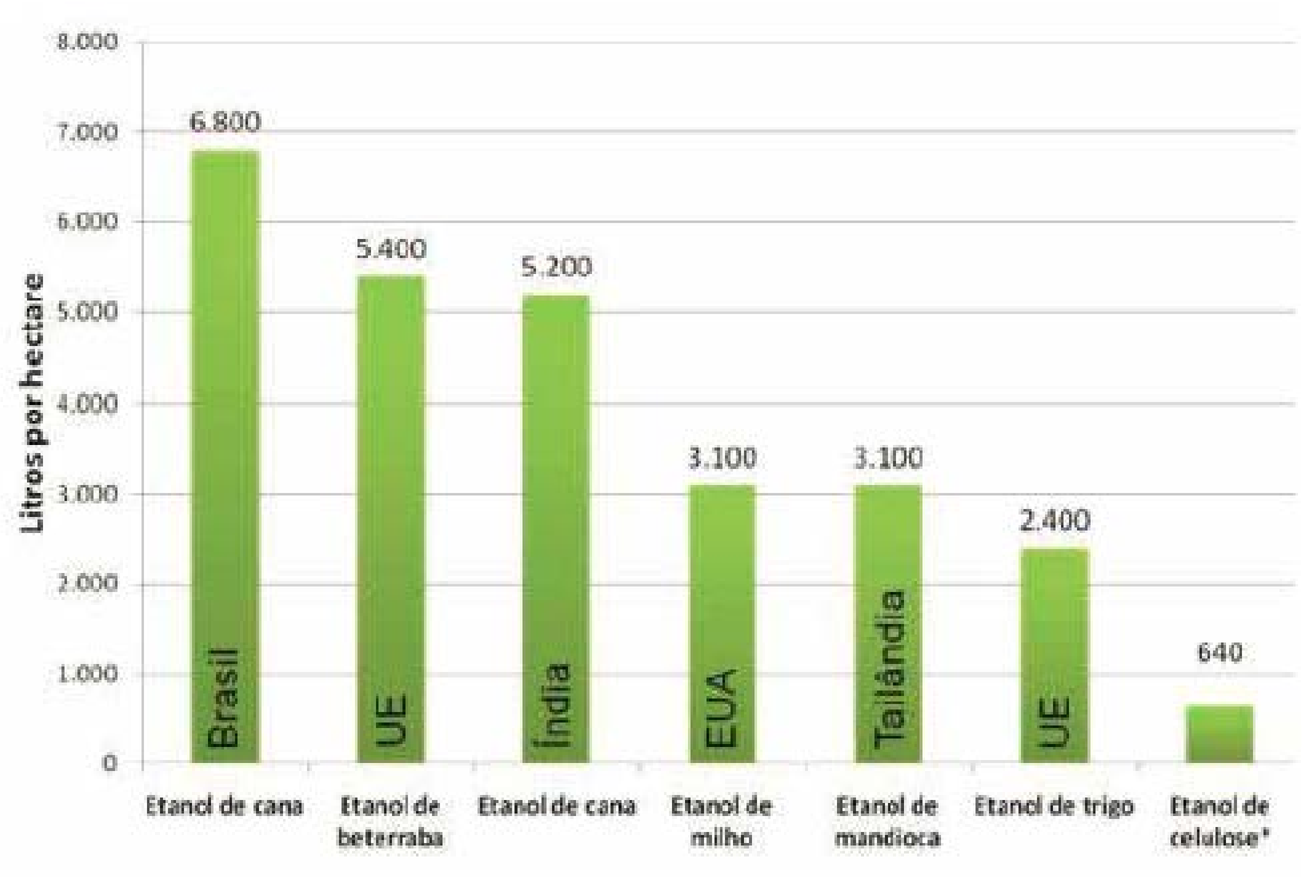
55 ton/ha

>82 ton/ha

- Not in the Amazon
- Best land for cane:
  - Northeast coast
    - Oldest (XVI century)
  - Southeast
    - highest productivity
  - Centralwest
    - main expansion area

22 million acres in sugarcane, 500 million acres in cattle

Corn, Sugarcane, Grass Comparison



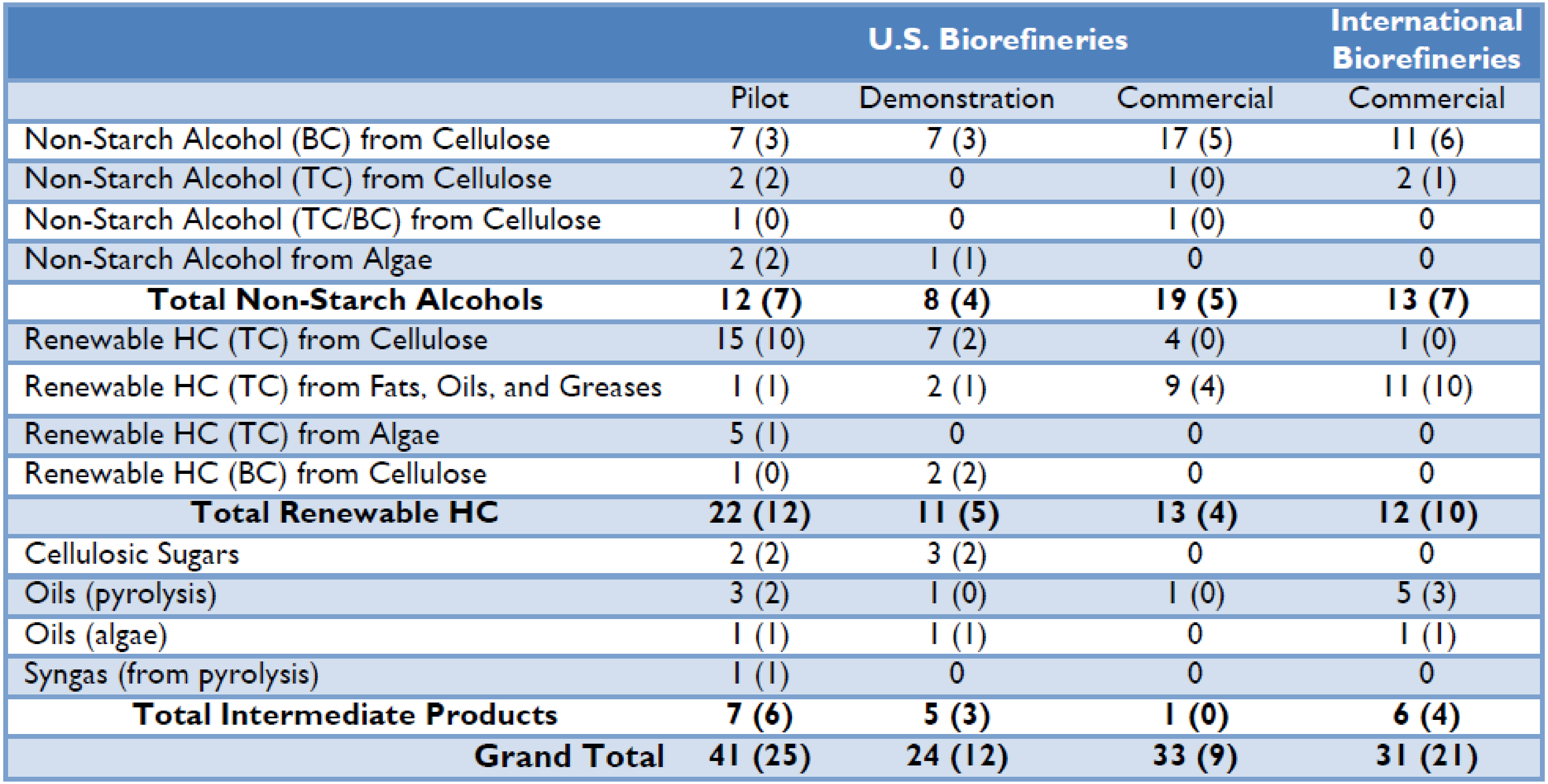
International Energy Agency (2005)

Sugarcane: 39 ton⁄ha (dry stalks and trash)
Miscanthus 29.6 ton⁄ha
Switchgrass 10.4 ton⁄ha
Maize 17.6 t ⁄ ha (total grain plus stover)

(Heaton et al., 2008).

Cellulosic Ethanol

2016 Survey of Biorefinery Projects by Technology and Feedstock Categories



	U.S. Biorefineries			**International Biorefineries**
	Pilot	Demonstration	Commercial	Commercial
Non-Starch Alcohol (BC) from Cellulose	7 (3)	7 (3)	17 (5)	11 (6)
Non-Starch Alcohol (TC) from Cellulose	2 (2)	0	1 (0)	2 (1)
Non-Starch Alcohol (TC/BC) from Cellulose	1 (0)	0	1 (0)	0
Non-Starch Alcohol from Algae	2 (2)	1 (1)	0	0
Total Non-Starch Alcohols	**12 (7)**	**8 (4)**	**19 (5)**	**13 (7)**
Renewable HC (TC) from Cellulose	15 (10)	7 (2)	4 (0)	1 (0)
Renewable HC (TC) from Fats, Oils, and Greases	1 (1)	2 (1)	9 (4)	11 (10)
Renewable HC (TC) from Algae	5 (1)	0	0	0
Renewable HC (BC) from Cellulose	1 (0)	2 (2)	0	0
Total Renewable HC	**22 (12)**	**11 (5)**	**13 (4)**	**12 (10)**
Cellulosic Sugars	2 (2)	3 (2)	0	0
Oils (pyrolysis)	3 (2)	1 (0)	1 (0)	5 (3)
Oils (algae)	1 (1)	1 (1)	0	1 (1)
Syngas (from pyrolysis)	1 (1)	0	0	0
Total Intermediate Products	**7 (6)**	**5 (3)**	**1 (0)**	**6 (4)**
Grand Total	**41 (25)**	**24 (12)**	**33 (9)**	**31 (21)**

Operating projects are in ( ). BC = biochemical, HC = hydrocarbons, TC = thermochemical.

Miscanthus at University of Illinois Experimental Plot

From D. MacKay Sustainable Energy without the Hot Air, Figure 6.10

Beta-Renewables Cellulosic Ethanol Refinery
Crescentino, Italy

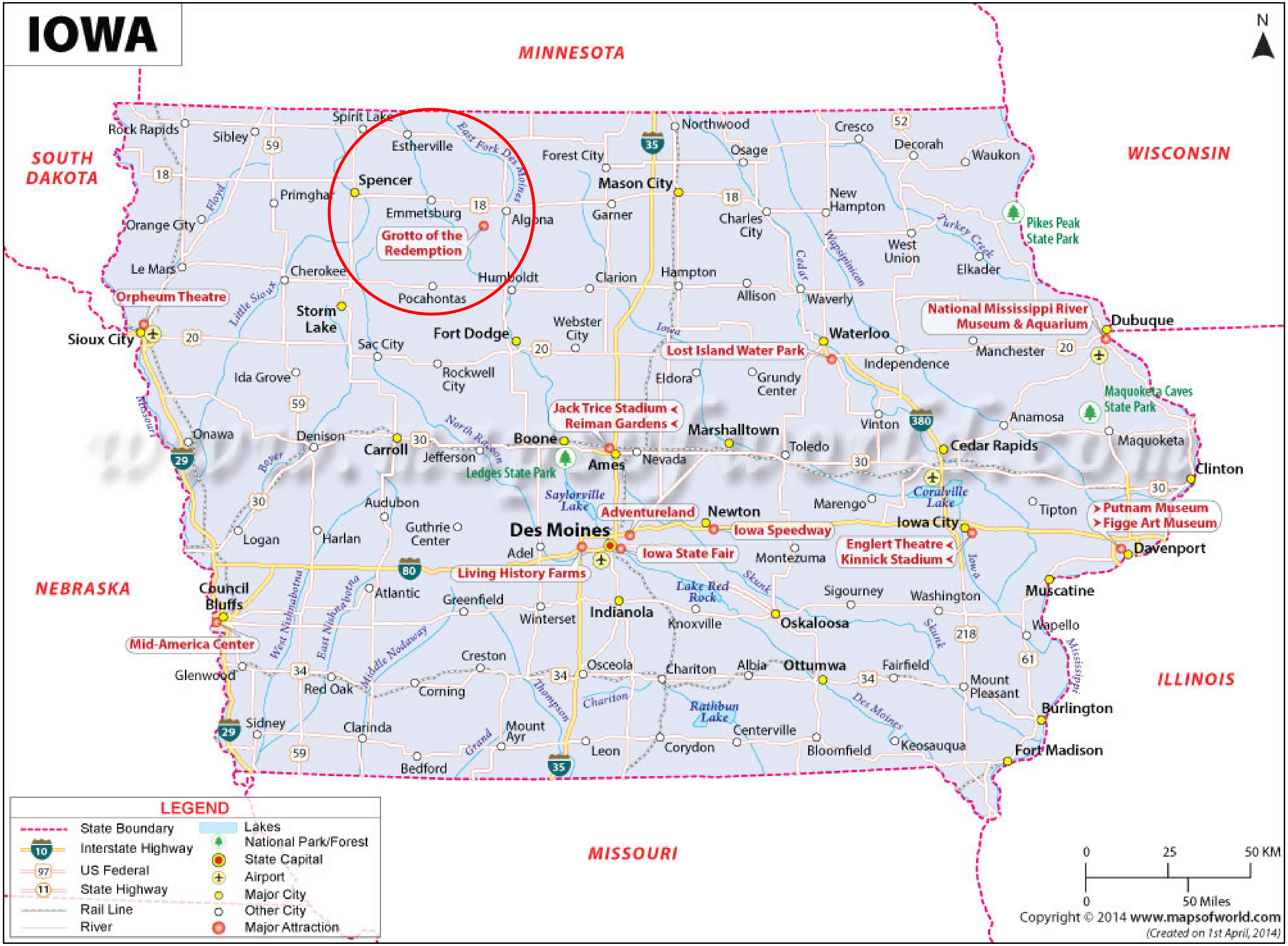
biofuels international

November 1, 2017

World’s 'first' commercial second-generation bioethanol facility 'shuts down'

Advanced Biofuels

Emmetsburg, IA



Copyright © 2014 www.mapsofworld.com
(Created on 1st April, 2014)

Status of Cellulosic Ethanol in U.S.

Company	Project Location	Technology Pathway	Feedstock Category	Capacity [MMGY]	Operational Year [Anticipated]
Abengoa	Hugoton, KS	Biochemical	Crop Residues	23	2015 (idled in 2015)
Ace Ethanol (Sweetwater Energy, Inc.)	Stanley, WI	Biochemical	Corn Kernel Cellulose	3.5	[2017]
Beta Renewables Inc.	Clinton, NC	Biochemical	Dedicated Energy Crops	20	[2017]
Canergy	Brawley, CA	Biochemical	Dedicated Energy Crops	25	[2017]
DuPont	Nevada, IA	Biochemical	Crop Residues	30	2015
Enerkem	Pontotoc, MS	Thermochemical Gasification	Municipal solid waste (MSW)	10	[2020]
Front Range Energy (Sweetwater Energy Inc.)	Windsor, CO	Biochemical	Cellulosic Sugars	3.6	[2017]
INEOS New Planet Bioenergy LLC[a]	Vero Beach, FL	Hybrid Biochemical/Thermochemical	MSW	8	[2016]
Pacific Ethanol (Sweetwater Energy Inc.)	Madera, CA	Biochemical	Corn Kernel Cellulose	3.6	[2017]
POET	Emmetsburg, IA	Biochemical	Crop Residues	25	2015
Quad County Corn	Galva, IA	Biochemical	Corn Kernel Cellulose	3.8	2014
ZeaChem	Boardman, OR	Biochemical	Woody Biomass	22	[2017]

Argus Leader.
PART OF THE USA TODAY NETWORK

April 4, 2019

Sioux Falls-based ethanol producer Poet awarded millions by arbitration panel

Des Moines Register
PART OF THE USA TODAY NETWORK
November 9, 2018

DuPont sells Iowa ethanol plant to German company; it will soon make renewable natural gas

Form **6478**

Department of the Treasury
Internal Revenue Service

Biofuel Producer Credit

▶ **Attach to your tax return.**
▶ **Go to *www.irs.gov/Form6478* for instructions and the latest information.**

OMB No. 1545-0231

2018

Attachment
Sequence No. **83**

Name(s) shown on return	**Identifying number**

	Type of Fuel		(a) Number of Gallons Sold or Used	(b) Rate	(c) Column (a) x Column (b)
1	Reserved for future use	**1**			
2	Reserved for future use	**2**			
3	Biofuel producer credit from partnerships, S corporations, cooperatives, estates, and trusts (see instructions)	**3**			
4	Add lines 2 and 3. Cooperatives, estates, and trusts, go to line 5. Partnerships and S corporations, stop here and report this amount on Schedule K. All others, stop here and report this amount on Form 3800, Part III, line 4c	**4**			
5	Amount allocated to patrons of the cooperative or beneficiaries of the estate or trust (see instructions)	**5**			
6	Cooperatives, estates, and trusts, subtract line 5 from line 4. Report this amount on Form 3800, Part III, line 4c	**6**			

For Paperwork Reduction Act Notice, see separate instructions.

Cat. No. 13605J

New Cellulosic Projects

c&en

September 30, 2018

Clariant bets big on cellulosic ethanol

Chemical maker breaks ground in Romania on $120 million waste-straw-to-ethanol plant

BIOMASS MAGAZINE

September 24, 2018

Cellulosic biorefinery to break ground in North Dakota

New Energy Spirit Biomass Refinery LLC

Current Land Usage for Corn Ethanol and Comparison to Miscanthus

- 2014 total acreage for corn: 83.1 million acres
- 2014 fraction of corn used for ethanol production: 43.7%
- 2014 acreage for corn ethanol production: 36.3 million acres (~11% of all U.S. cropland) to produce 13.8 Ggal
- If miscanthus, 16.9 million acres required (~5.0% of all U.S. cropland)
- Land required for ethanol production from miscanthus smaller

Electricity and Heat from Forest Residue

From MacKay p. 285

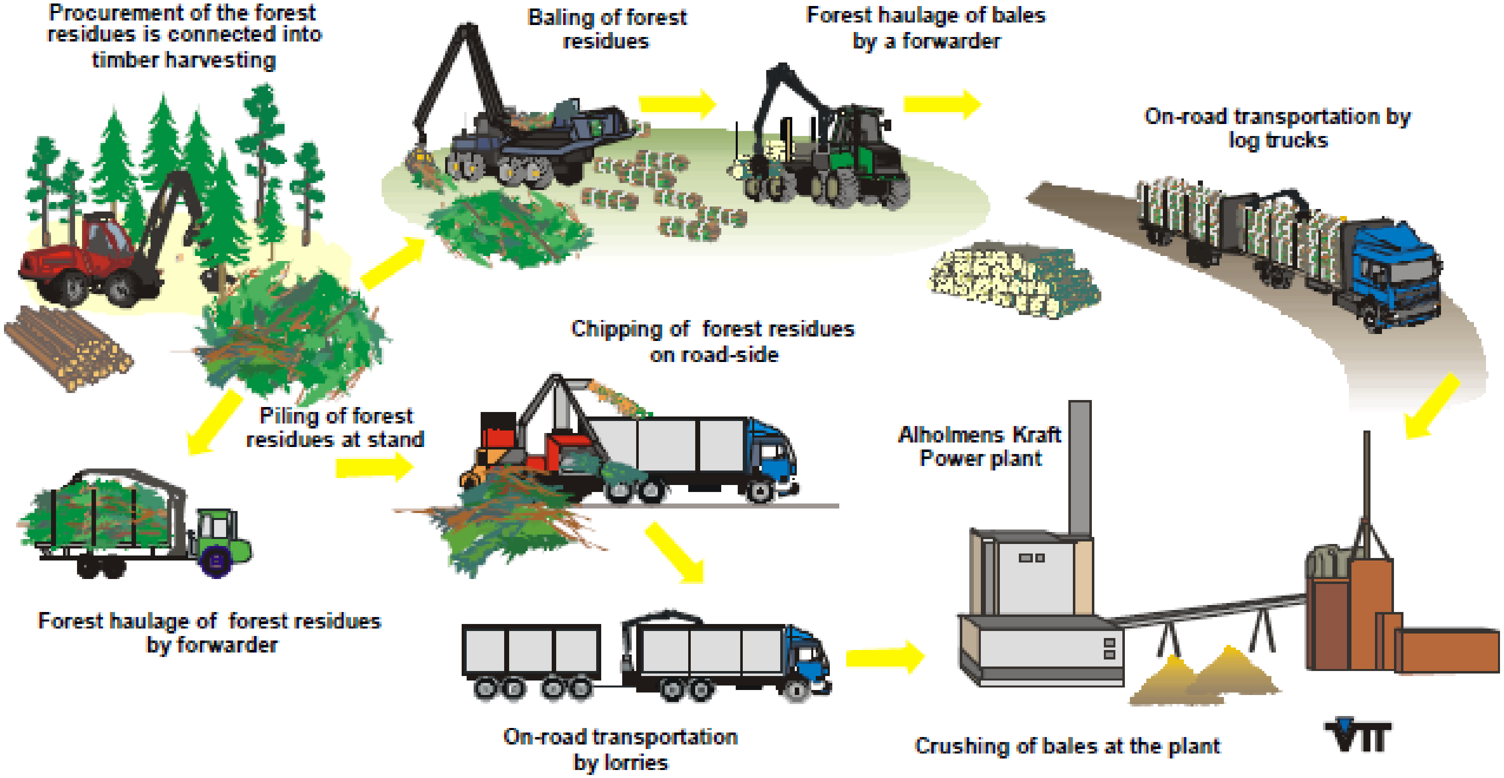
Sustainable crop of woody biomass in northern Europe can produce 0.6 W_t / m^2. For 500 MW_t power plant biomass must be collected from at least a 20 km radius.

World’s Largest Biofuel CHP Plant Alholmens Kraft, Finland

550 MW_t boiler. 240 MW_e. Up to 100 MW_t steam and 60 MW_t district heat.
Approximately, 400,000 tonnes of biomass consumed per year..

From Organisations for the Promotion of Energy Technologies, Finland

Fuel Gathering



Forest fuel supply chain from forest to the plant. VTT Energy.

In 2001 production cost of biomass for up to 80 km transportation distance was 8.2 € / MWh (OPTE, Finland) .

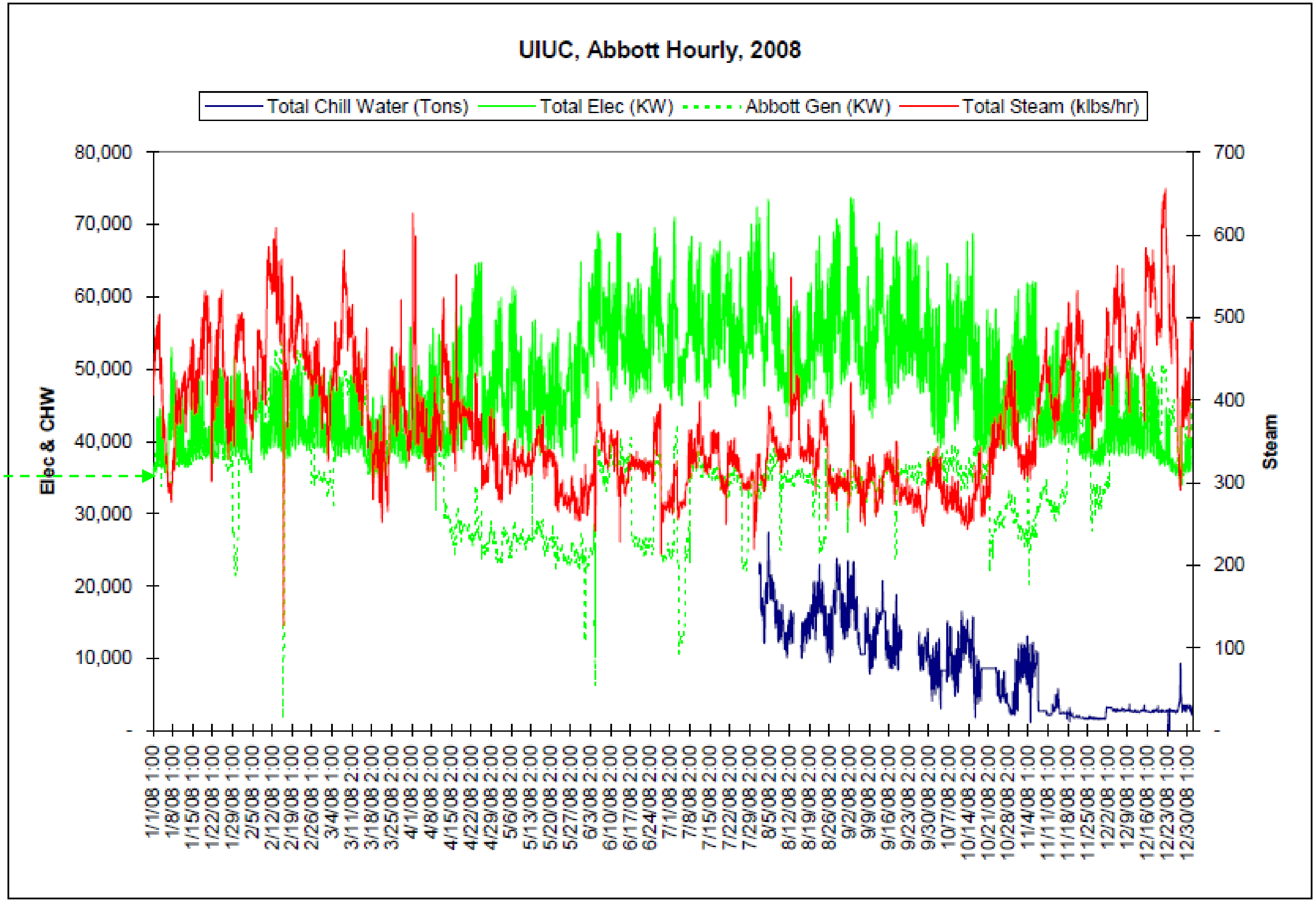
Eastern Illinois University Renewable Energy Center

Fuel: biomass (wood chips), 27,000 tons per year yielding 16 MW_t
Source: Gary Reed presentation at
UIUC Biorefineries Symposium, October, 2010

UIUC Abbott Power Plant

Coal and natural gas fired combined heating, cooling and power production

Abbott Power Generation, 2008



35 MW_e

Figure 3.1-4. Hourly Energy Data from UIUC Central Plants - 2008

Source: “A Study of the Utilities at the University of Illinois,” Science Applications International Corporation, September 2009

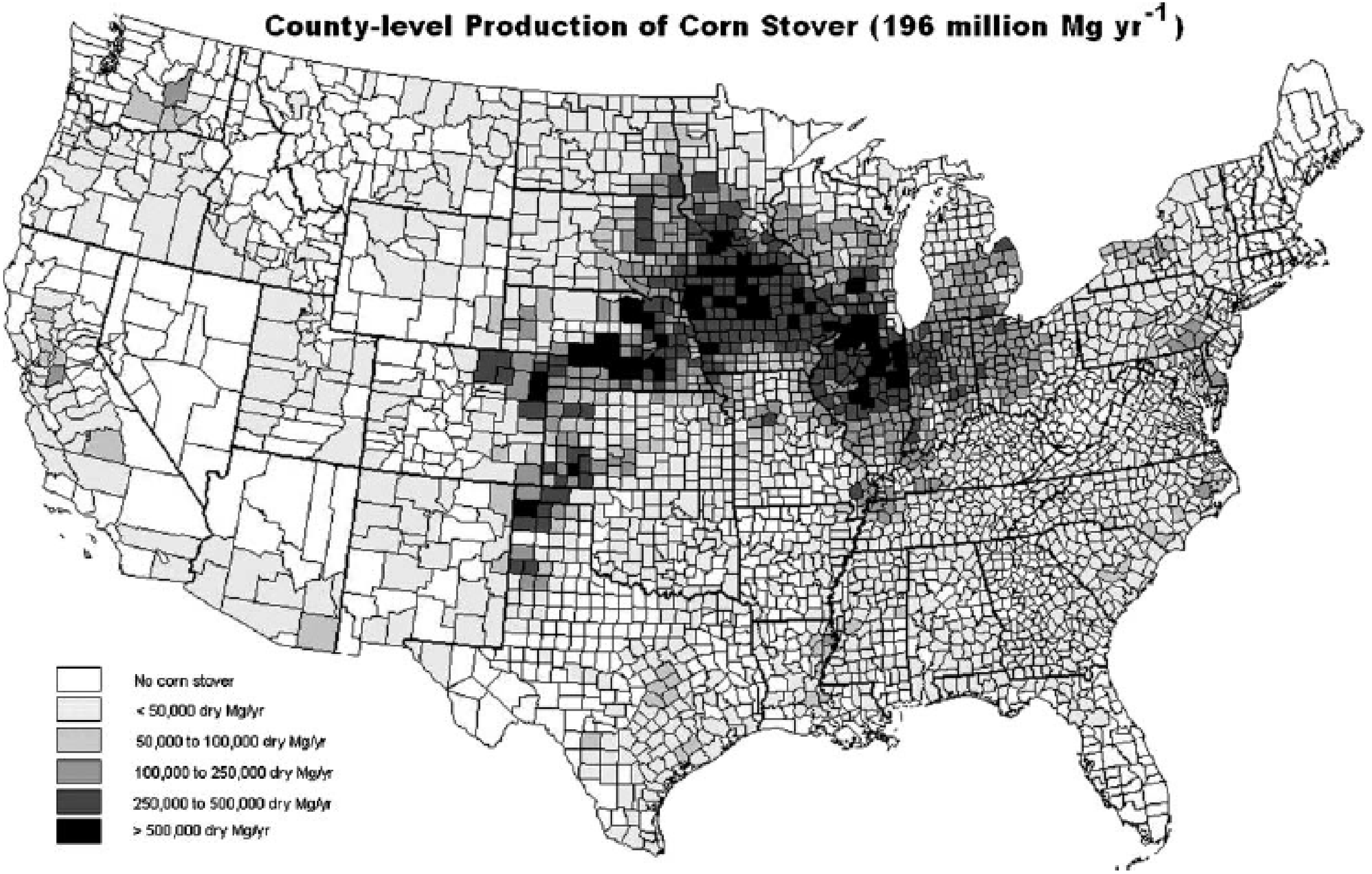


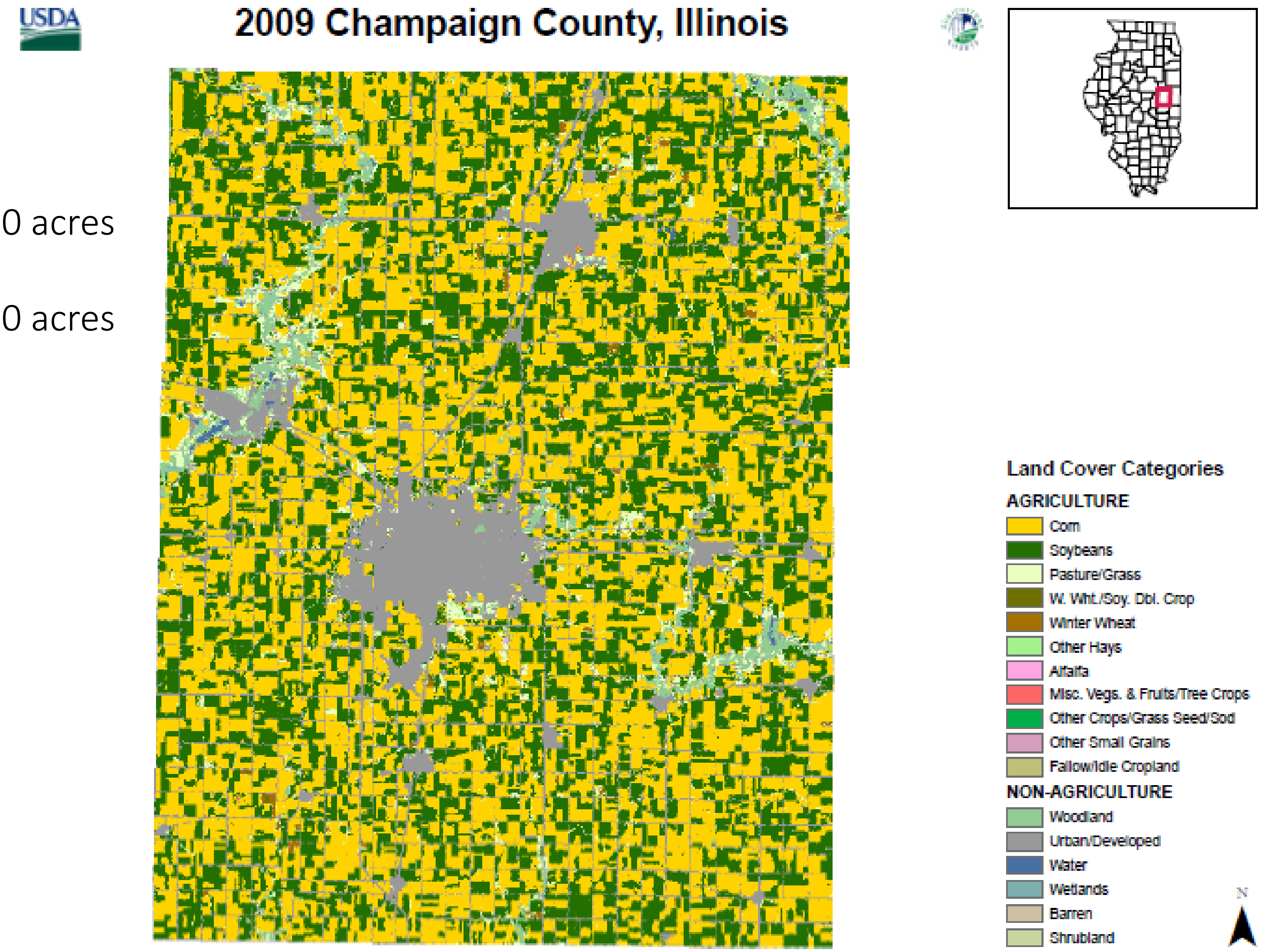
Fig. 5. Annual production of corn stover in the United States. Values were derived as described in text using 1995–2000 corn production statistics from USDA.

from Graham et al., Agronomy Journal 99(2007)1

Champaign County Biomass Potential Sufficient for Abbott?

567,000 acres

307,000 acres
In corn



Abbott Power Calculation

Assume that Abbott requires 180 MW_t

$$\text{corn stover}\left[t/a/y\right]=0.021\times\text{corn yield}\left[bu/a/y\right]$$

$$\text{Champaign County corn production}=180\,bu/a/y$$

$$\text{Champaign County stover production}=3.8\,t/a/y$$

$$\text{energy density of corn stover}=5.3\,kWh/kg$$

$$\text{Champaign County stover production}=0.52\,W/m^2$$

Abbott requires 330,000 tons from 86,000 acres

Abbott could be powered by Champaign County stover.

Other Possible Biomass Examples

- Oil from algae
- Municipal solid waste incineration
- Capture of methane from landfills
- Methane production from animal waste
- Biodiesel production from cooking oil
- Many others

Oil yields from various plants and microalgae in cubic meters per hectare

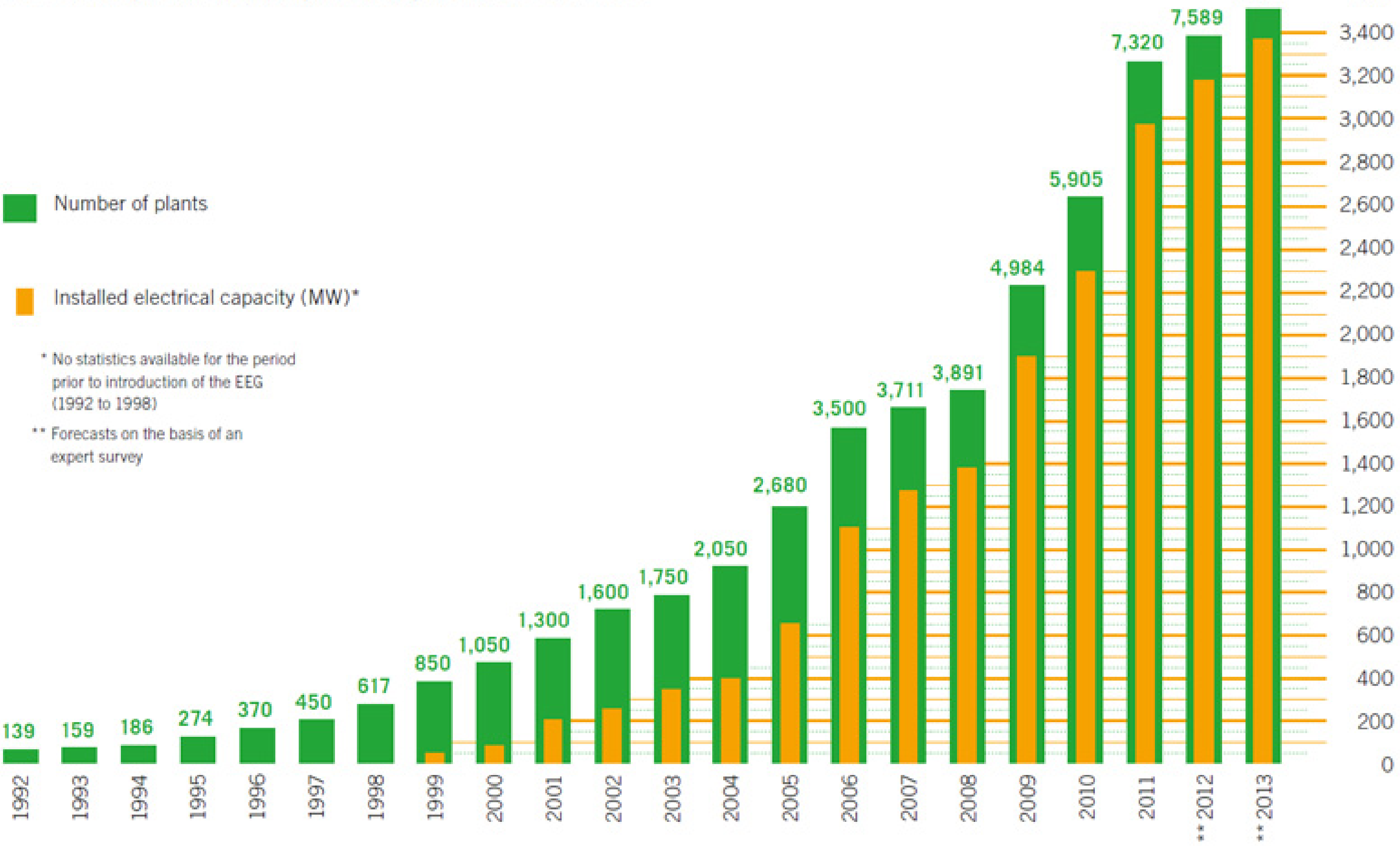
Corn	0.14
Soybeans	0.45
Sunflower	0.95
Canola (Rape)	1.20
Jatropha	1.90
Palm	5.90
Microalgae (30% lipids)	59.0
Microalgae (50% lipids)	98.0
Microalgae (70% lipids)	140.0

Hard Lessons From the Great Algae Biofuel Bubble

Firms That Have Moved Away From Algal Biofuel

- Algae Floating Systems
- Algenol
- Algae Tec
- Algix
- AlgaeLink
- Alga Technologies
- Aquaflow Bionomics (NXT Fuels)
- Aurora Biofuels
- Cellana
- Global Algae Innovations
- GreenFuel Technologies
- Heliae
- LiveFuels
- OriginOil (OriginClear)
- PetroAlgae (Parabel)
- Phycal
- Pond Technologies
- Renewable Algal Energy
- Sapphire Energy
- Seambiotic
- Solix
- Synthetic Genomics
- TerraVia (Solazyme)
- XL Renewables

Use of biogas in Germany: development 1992–2013



* No statistics available for the period prior to introduction of the EEG (1992 to 1998)

** Forecasts on the basis of an expert survey

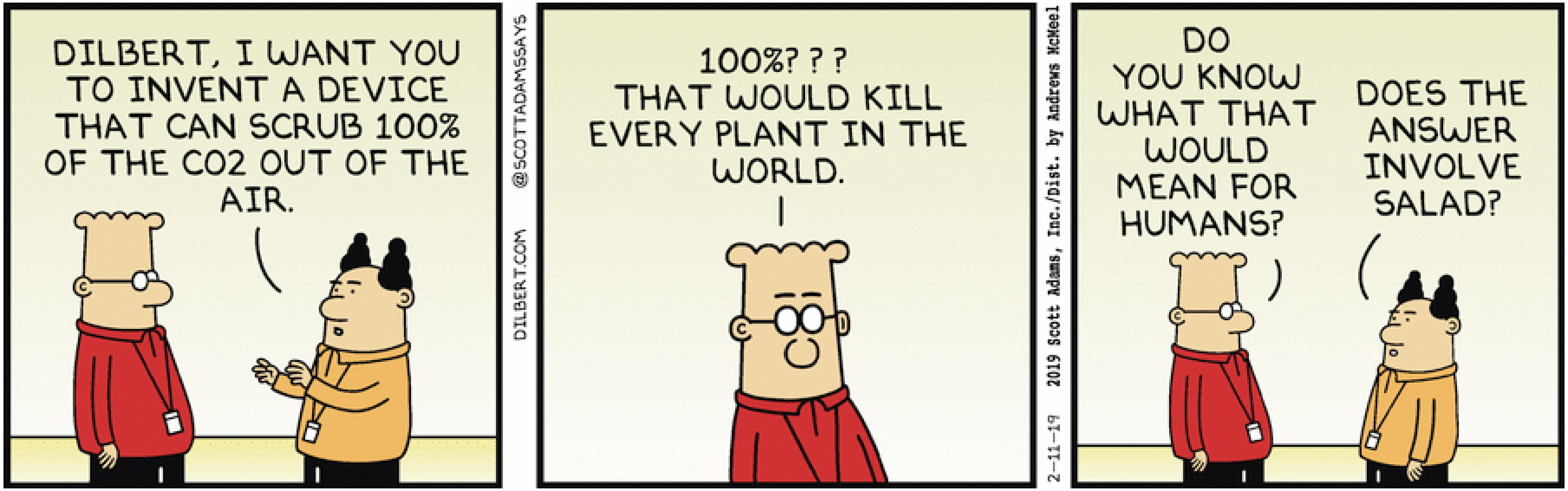
Biomass and Biofuels Summary

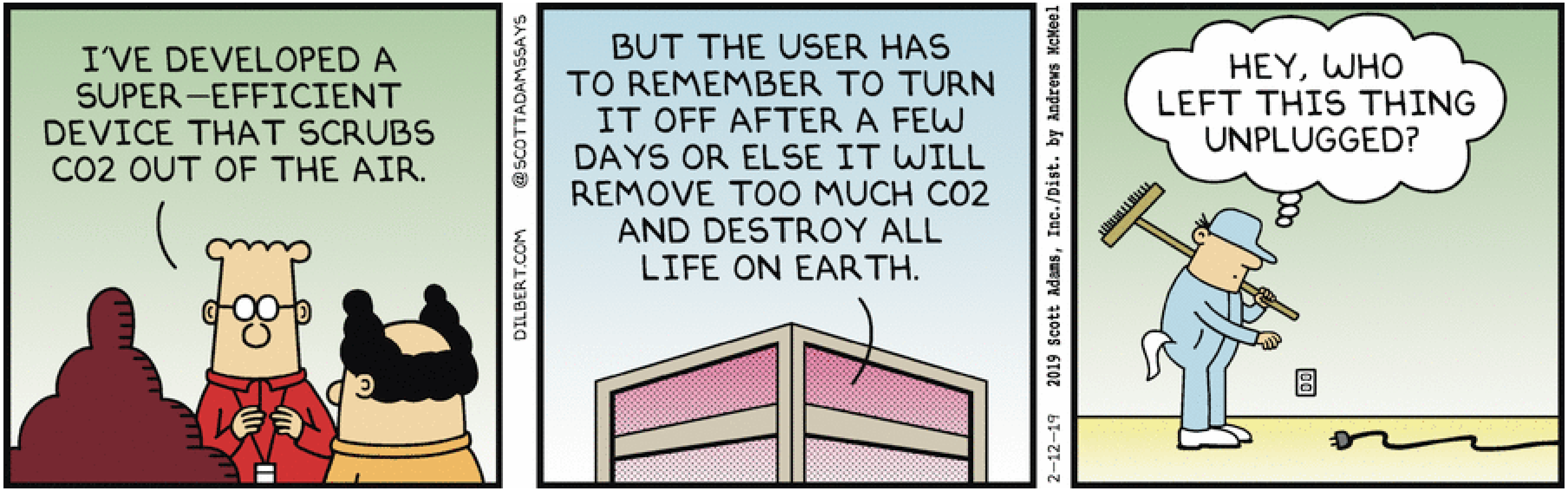
- Significant biomass and biofuel resources both from production and conservation
- Commitment of land required, but marginal land use possible
- Commitment of water required, but drought resistant cultivars exist
- Opportunities for more productive feedstocks and more efficient conversion
- Research to go beyond ethanol promising
- Learn what termites do. Improve on what plants do. Capture more of the sun.

Negative Emissions

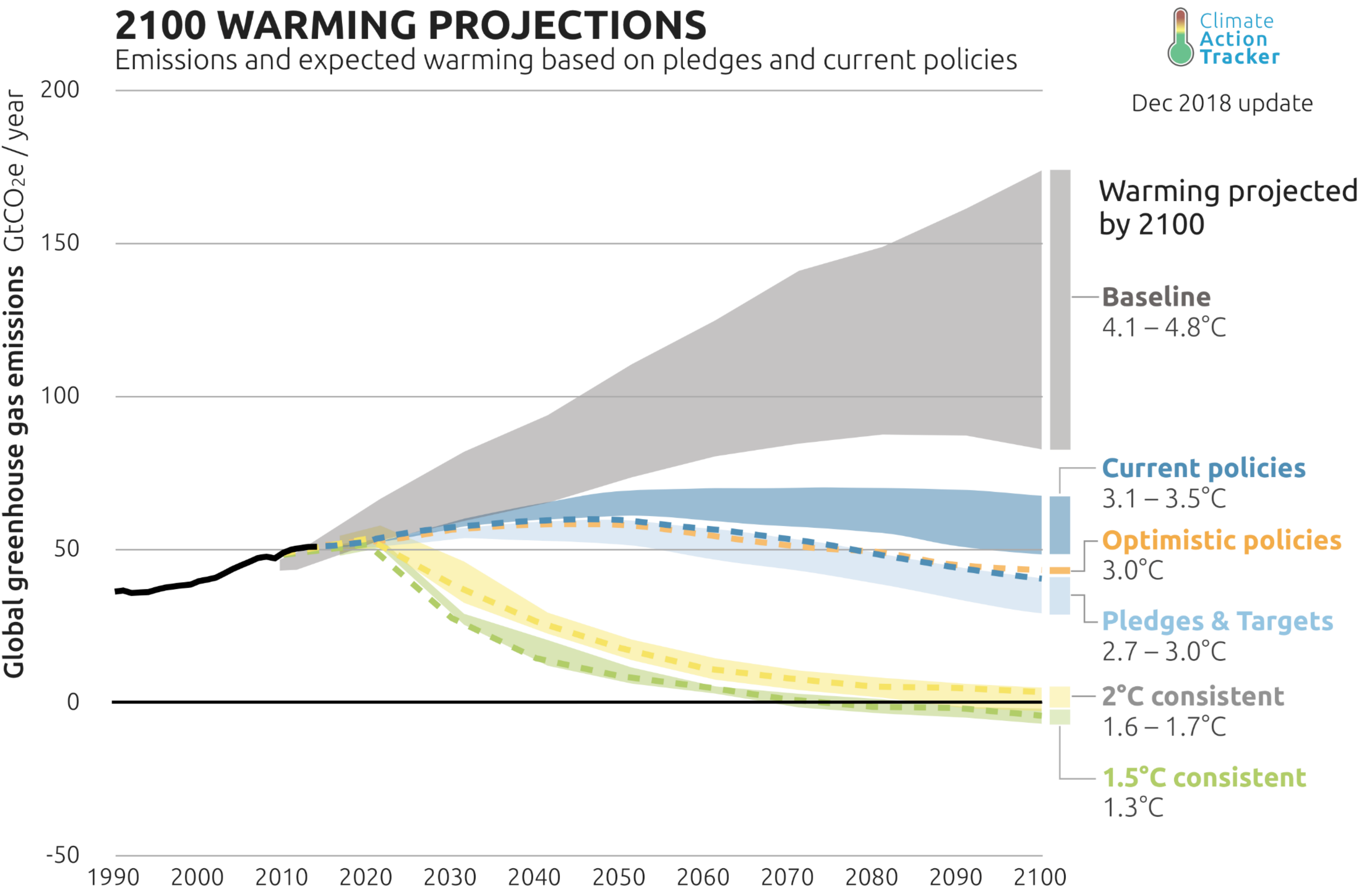
- Why negative emissions?
- Carbon cycle
- Removal of CO_2 from Atmosphere
  - Enhanced weathering
  - Afforestation and reforestation lectures 3&4
  - Ocean-based removal
  - Carbon capture and storage
  - Direct air capture
- Negative emissions summary

Negative Emissions Remove CO_2 from the Atmosphere




I'VE DEVELOPED A SUPER–EFFICIENT DEVICE THAT SCRUBS CO2 OUT OF THE AIR.
DILBERT.COM @SCOTTADAMSSAYS
BUT THE USER HAS TO REMEMBER TO TURN IT OFF AFTER A FEW DAYS OR ELSE IT WILL REMOVE TOO MUCH CO2 AND DESTROY ALL LIFE ON EARTH.
2-12-19 2019 Scott Adams, Inc./Dist. by Andrews McMeel
HEY, WHO LEFT THIS THING UNPLUGGED?

Why Negative Emissions?

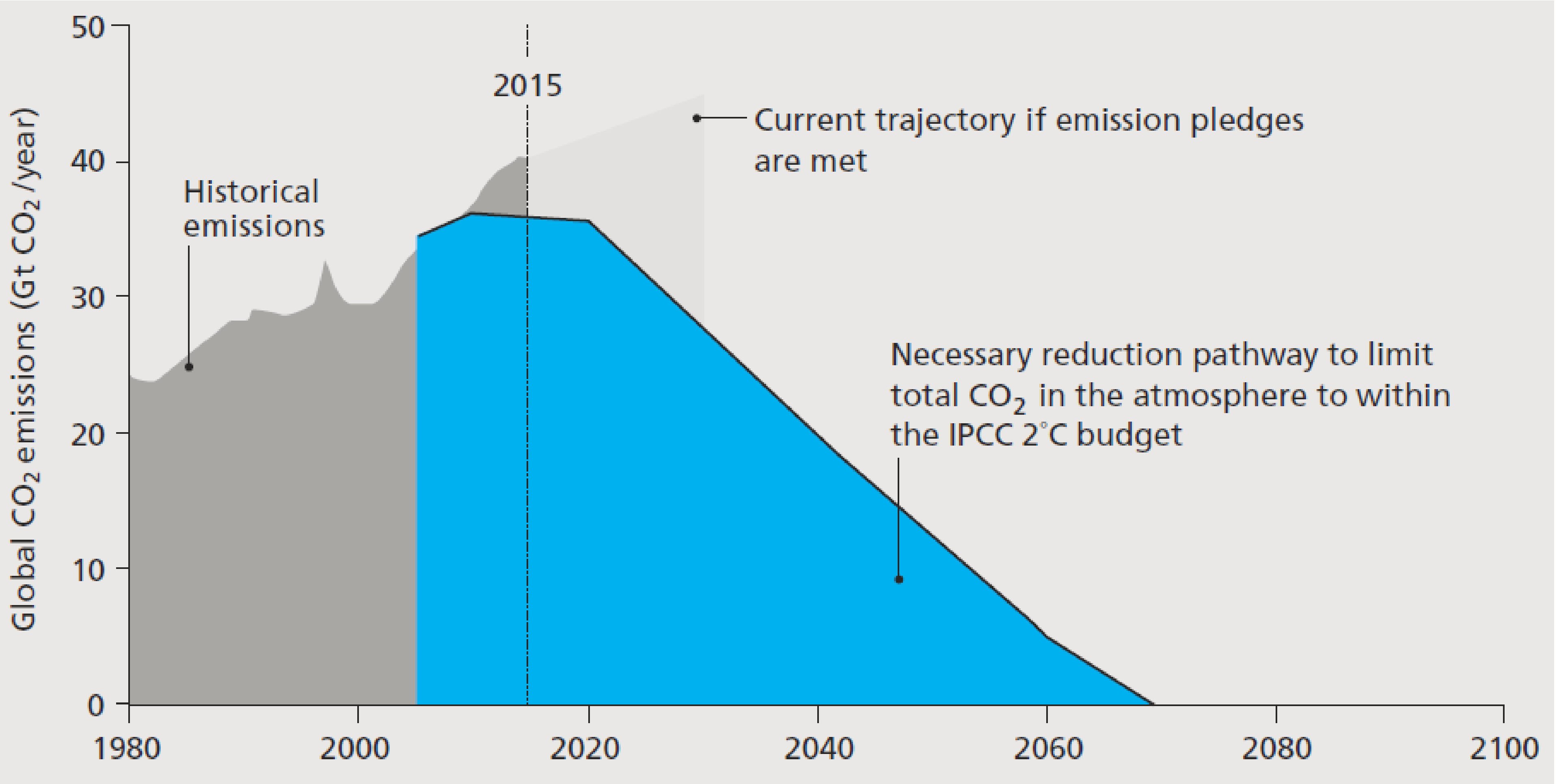


2100 WARMING PROJECTIONS

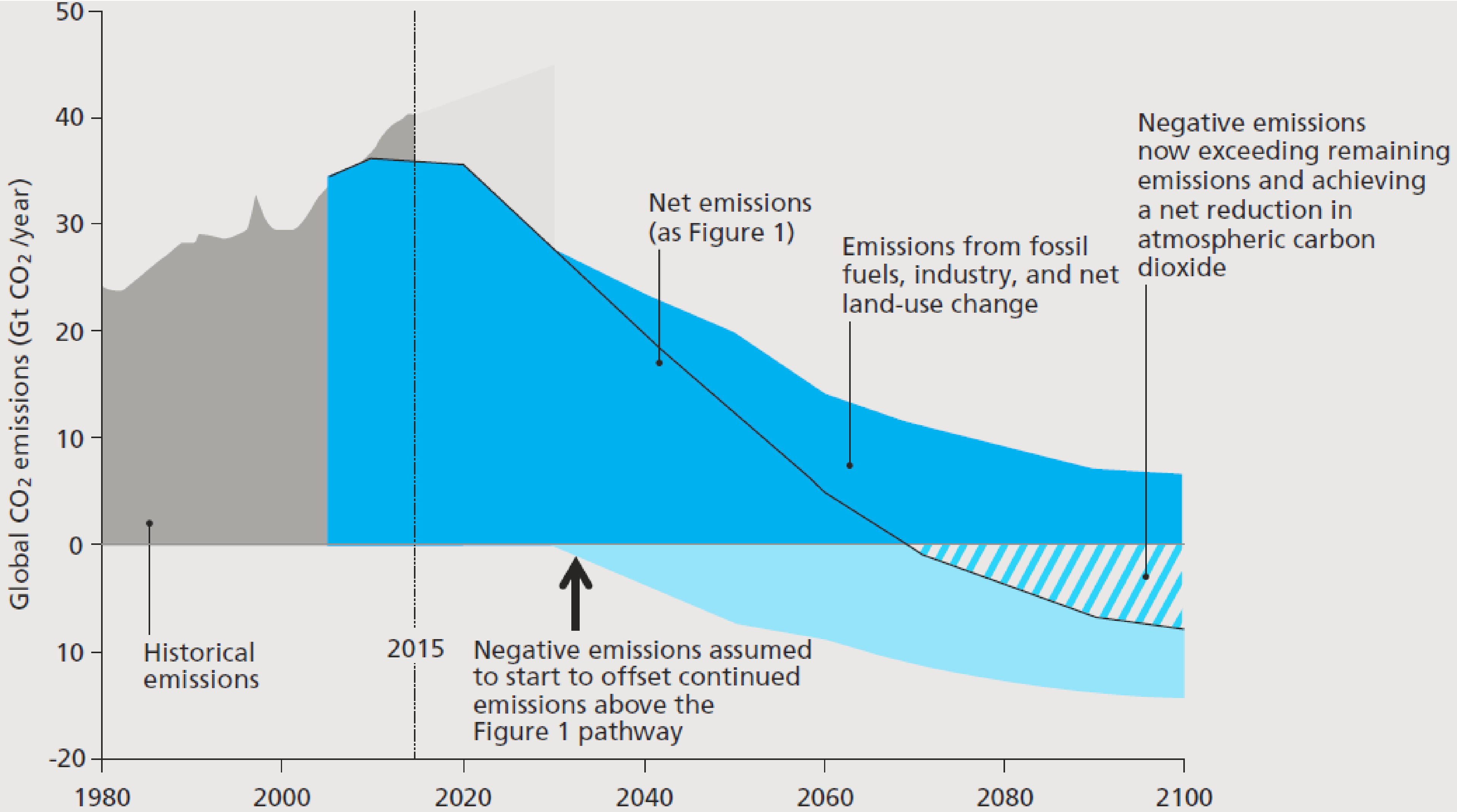
Emissions and expected warming based on pledges and current policies

Dec 2018 update

Emission Pathway to Achieve No More Than 2°C Temperature Rise

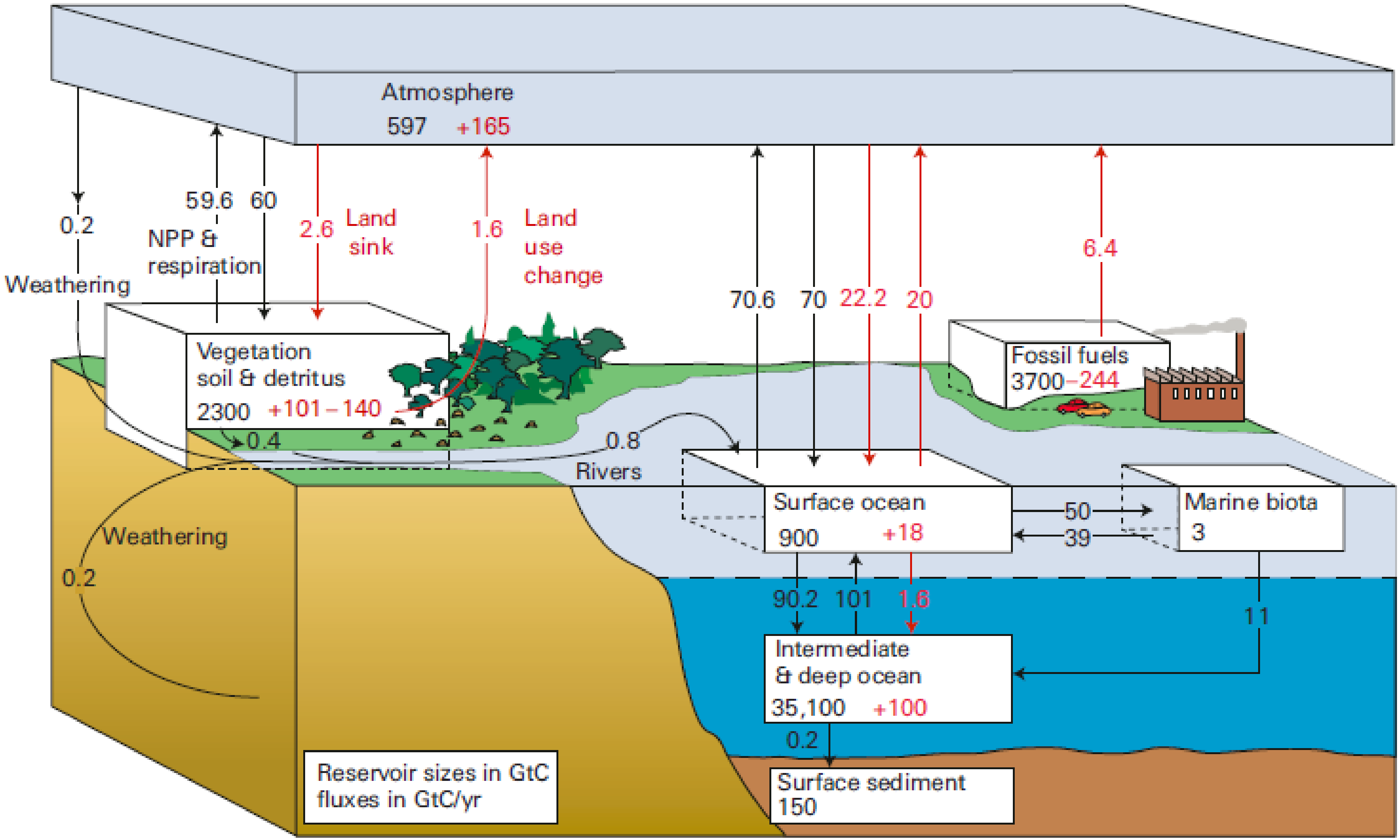


Emission Pathway to Achieve <2°C with Negative Emissions Technology



Carbon Cycle and Keeling Curve

Global Carbon Cycle



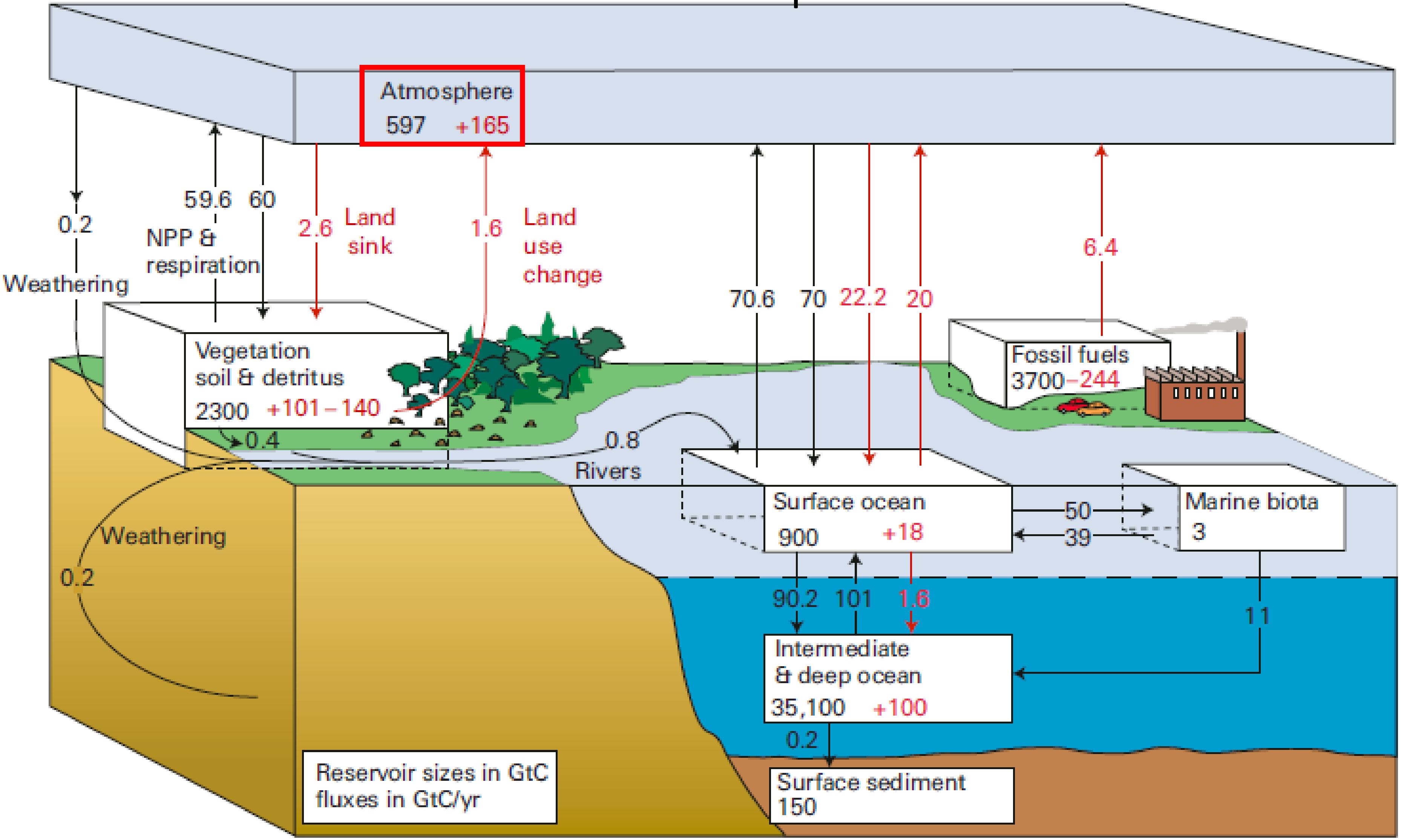
Black numbers pre-industrial steady state. Red numbers additions due to human activity.

How Much CO_2 in the Atmosphere?

How Much CO_2 in the Atmosphere?

- Atmospheric pressure P = 101 kPa
- Mass of atmosphere $M = P\times(4\pi R^2)/g$
  - $101\ \text{kPa} \times (4\pi(6.4 \times 10^6\ \text{m}^2)^2)/(9.8\ \text{N / kg}) = 5.3 \times 10^6\ \text{Gt}$
- GMW of atmosphere 78% O_2, 21% N_2, 1% Ar → 29 g per mole
- Atmosphere contains 1.83×10^{20} moles
- Currently CO_2 at 400 ppm = 7.31×10^{16} moles = 3,220 Gt CO_2
- Pre-industrial CO_2 at 280 ppm 2,250 Gt CO_2
- 970 Gt CO_2 emitted in atmosphere since industrialization

Global Carbon Cycle Modification
Direct Air Capture



Black numbers pre-industrial steady state. Red numbers additions due to human activity.

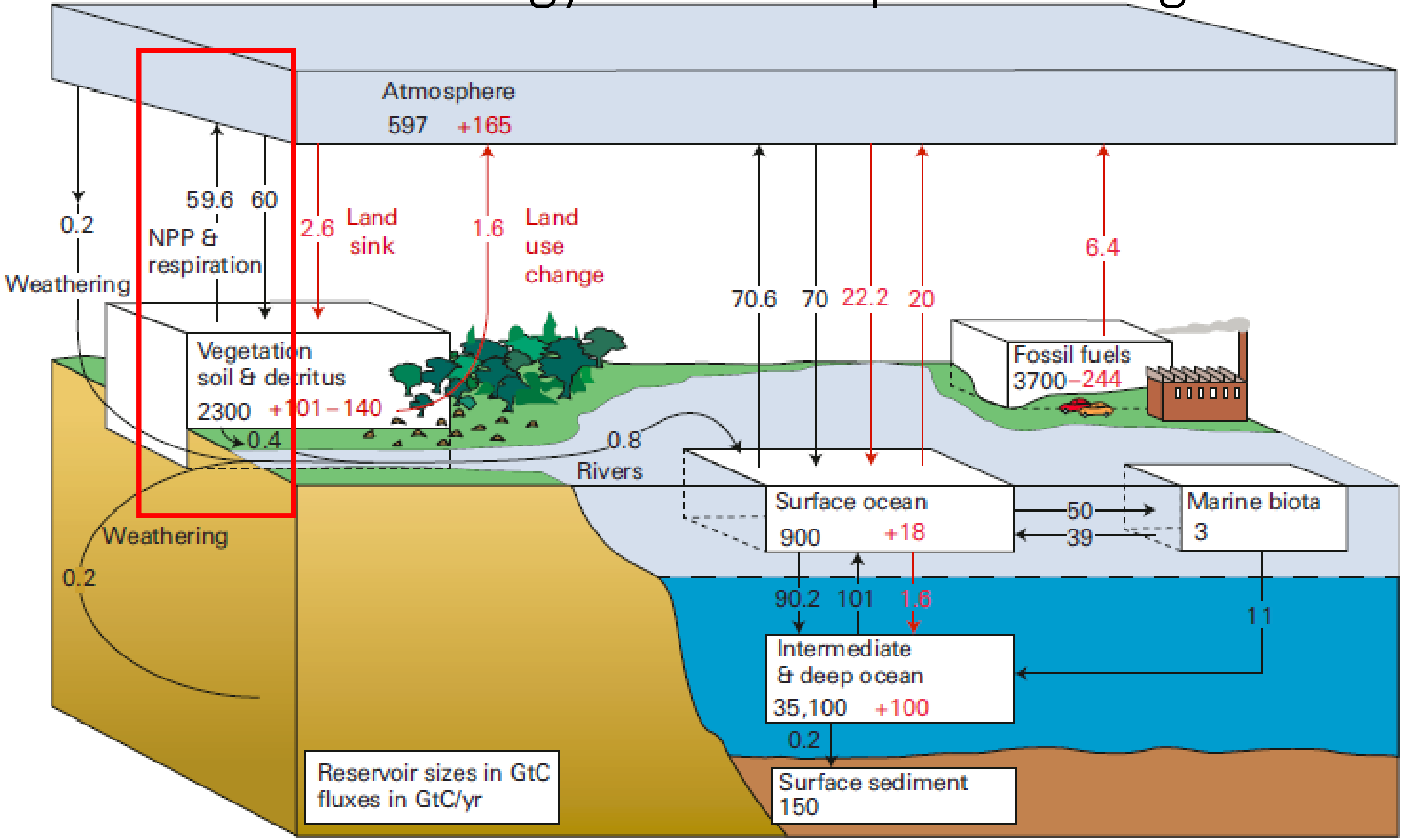
Direct air capture is one possible carbon dioxide removal technology.

How many cubic meters of the atmosphere must be processed to remove one gigatonne of carbon?

Volume of atmosphere for 1 GtC

- Density of air at sea level = 1.225 kg/m^3
- One mole of air = 29 g
  - so air is 42.2 moles/m^3 or 2.54×10^{25} molecules/m^3
- CO_2 concentration 400 ppm
  - So 1.02×10^{22} CO_2 molecules/m^3 = 0.743 g CO_2/m^3 = 0.203 g C/m^3
- 1 Gt = 10^9 tonne = 10^{12} kg = 10^{15} g
  - So 1 GtC in 4.93×10^{15} /m^3 of air
- This volume is equal to area × thickness of 7,000 km × 7,000 km × 10^2 m
- An area of 7,000 km × 7,000 km is approximately the area of Russia, Canada, China, and United States

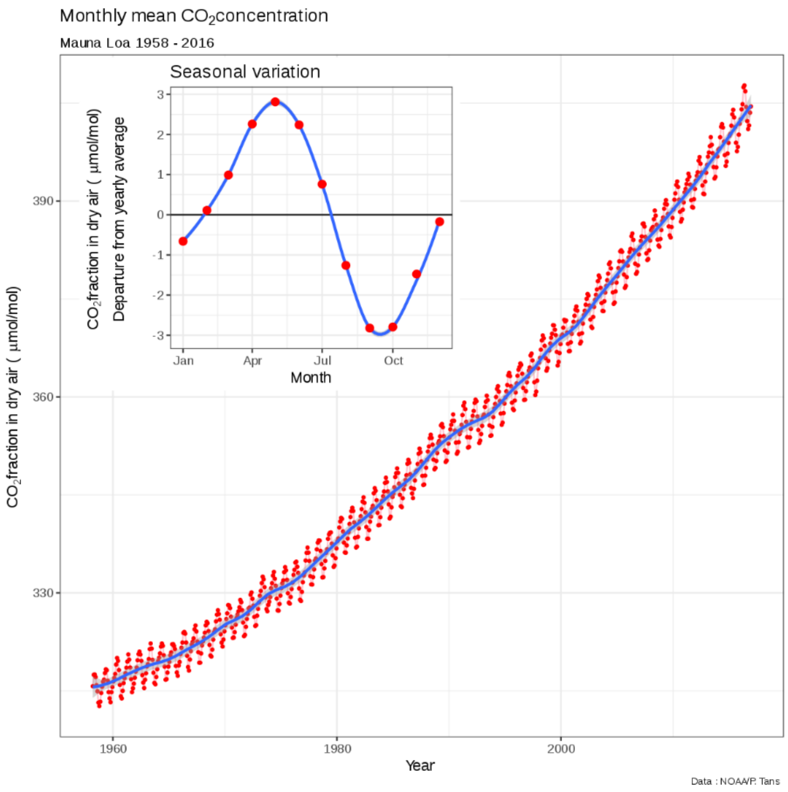
Global Carbon Cycle Modification
Biomass Energy Carbon Capture Storage

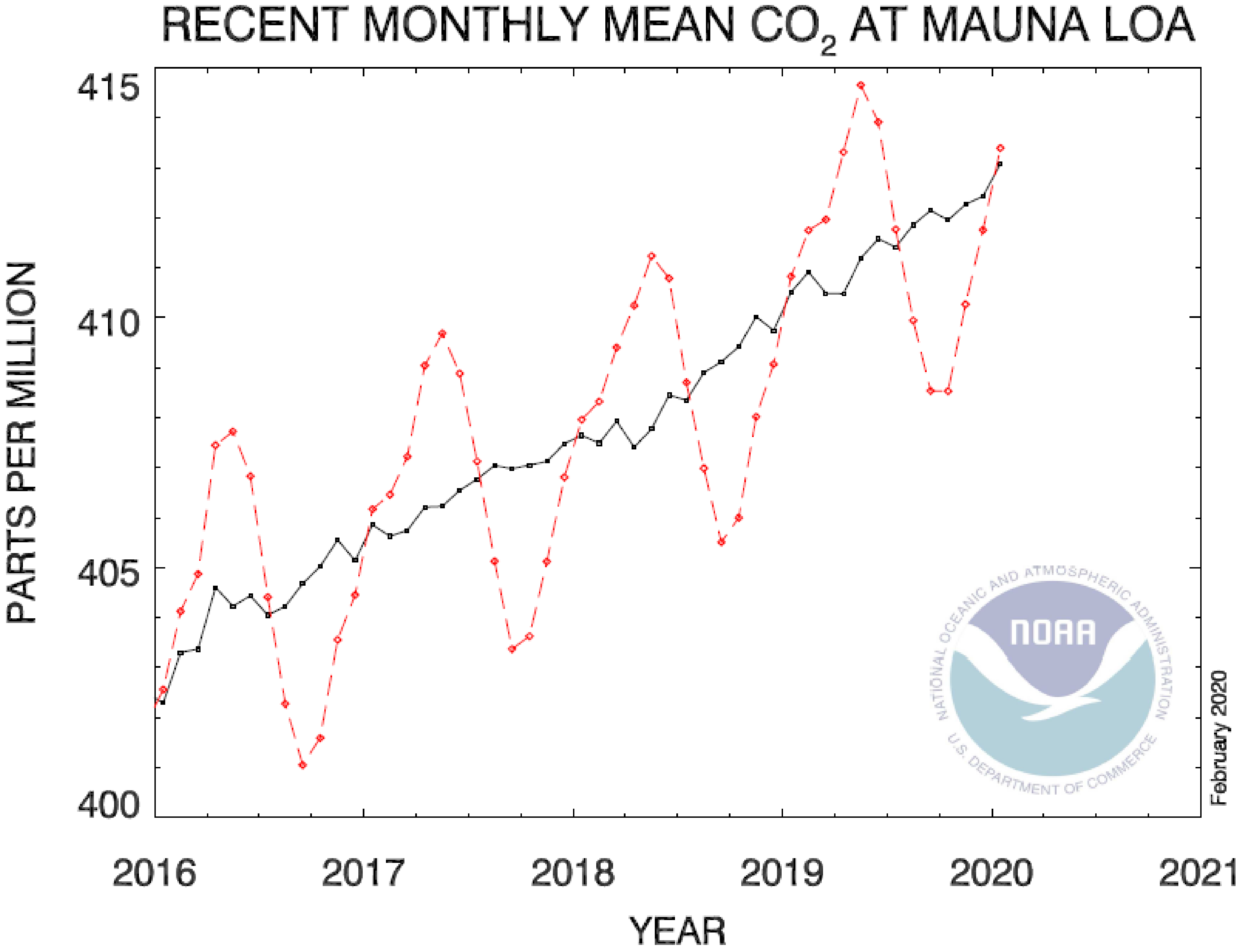


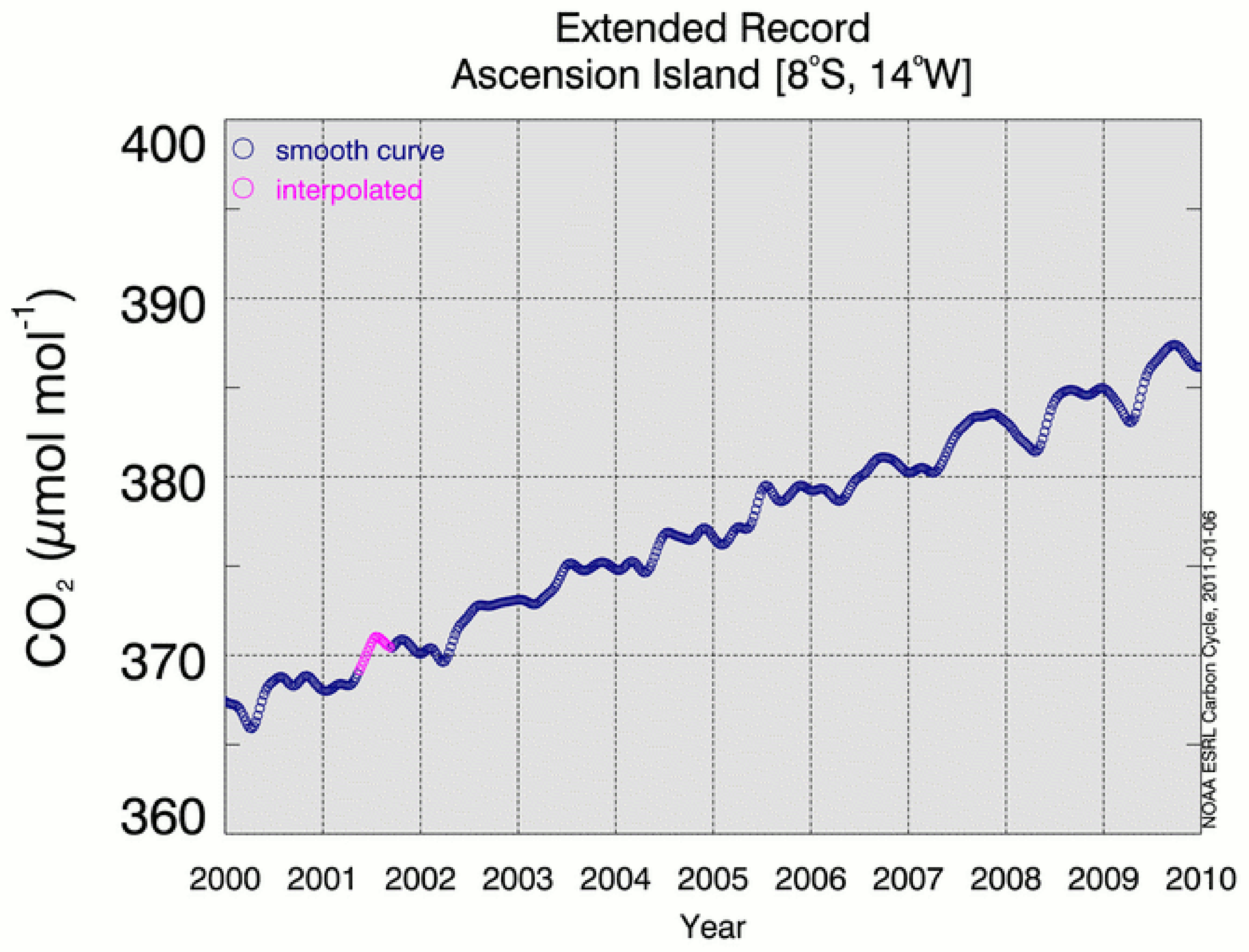
Black numbers pre-industrial steady state. Red numbers additions due to human activity.

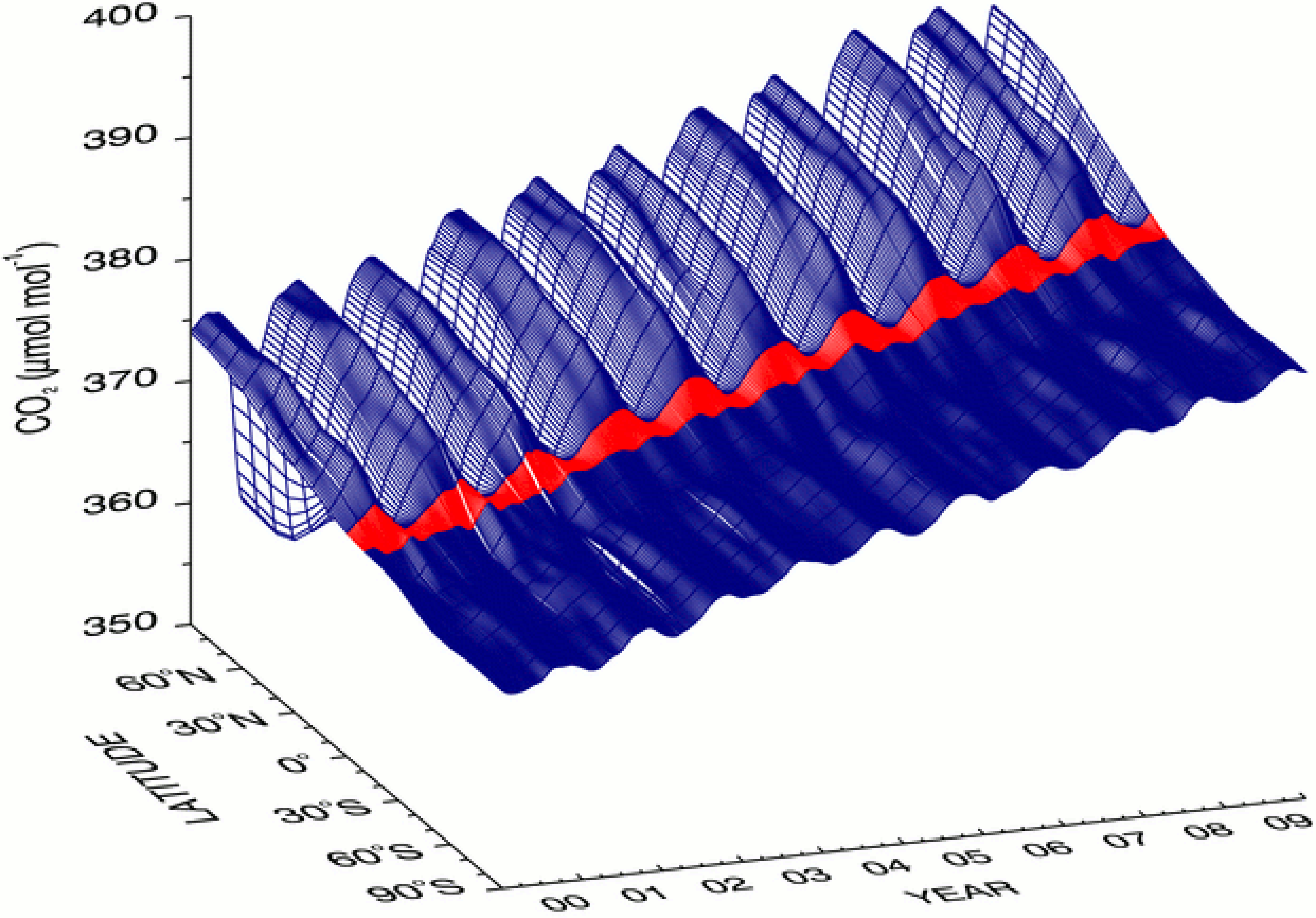
The annual variation shown in the insert is attributed to plant growth and decay.

How many gigatonnes of CO_2 do plants absorb and release in one year?



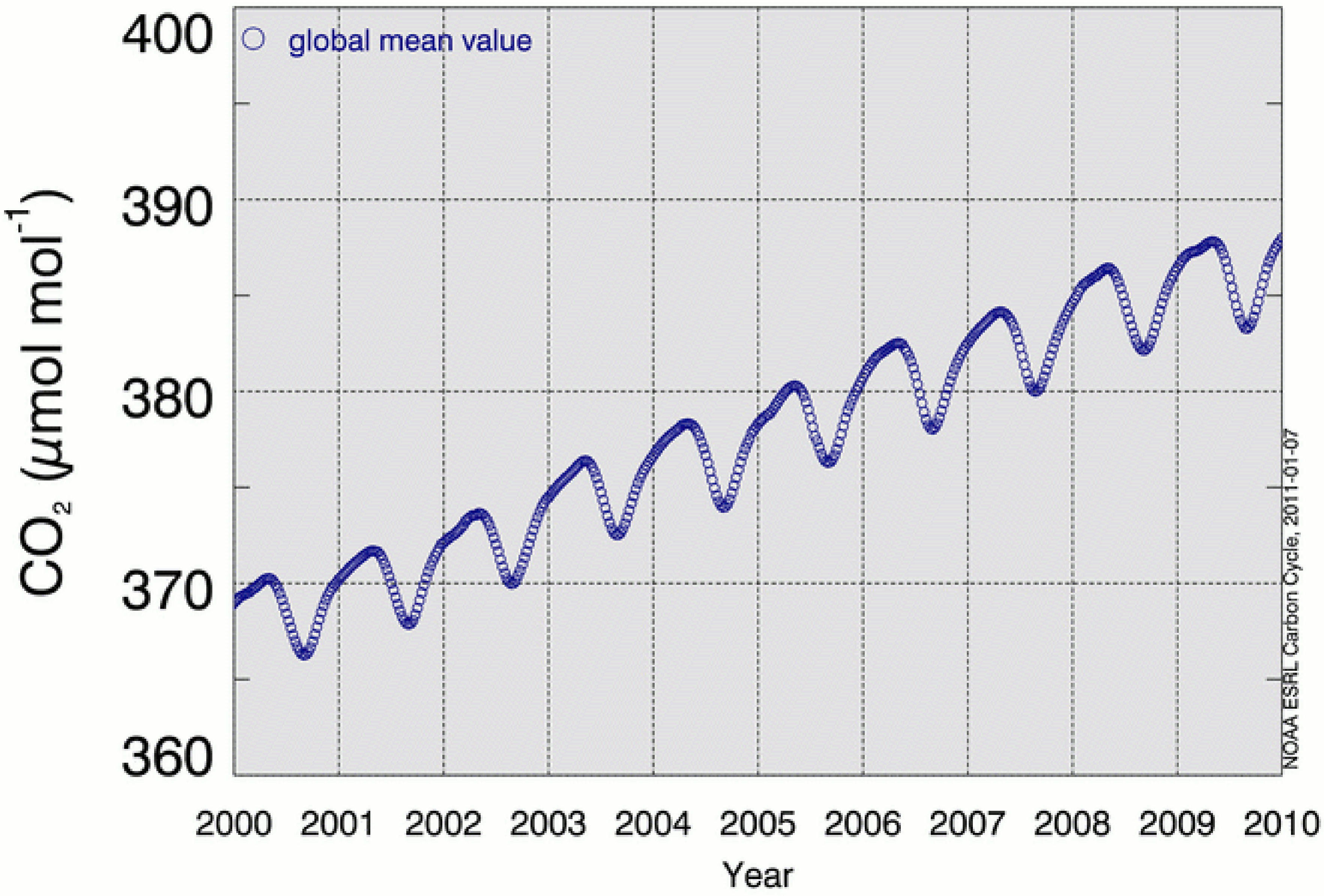

RECENT MONTHLY MEAN CO$_2$ AT MAUNA LOA
PARTS PER MILLION
415
410
405
400
2016
2017
2018
2019
2020
2021
YEAR
February 2020
NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE


Extended Record
Ascension Island [8°S, 14°W]
smooth curve
interpolated
CO₂ (μmol mol⁻¹)
400
390
380
370
360
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Year
NOAA ESRL Carbon Cycle, 2011-01-06



400
390
380
370
360
350
CO$_2$ (µmol mol^{-1})
60°N
30°N
0°
30°S
60°S
90°S
LATITUDE
00
01
02
03
04
05
06
07
08
09
YEAR

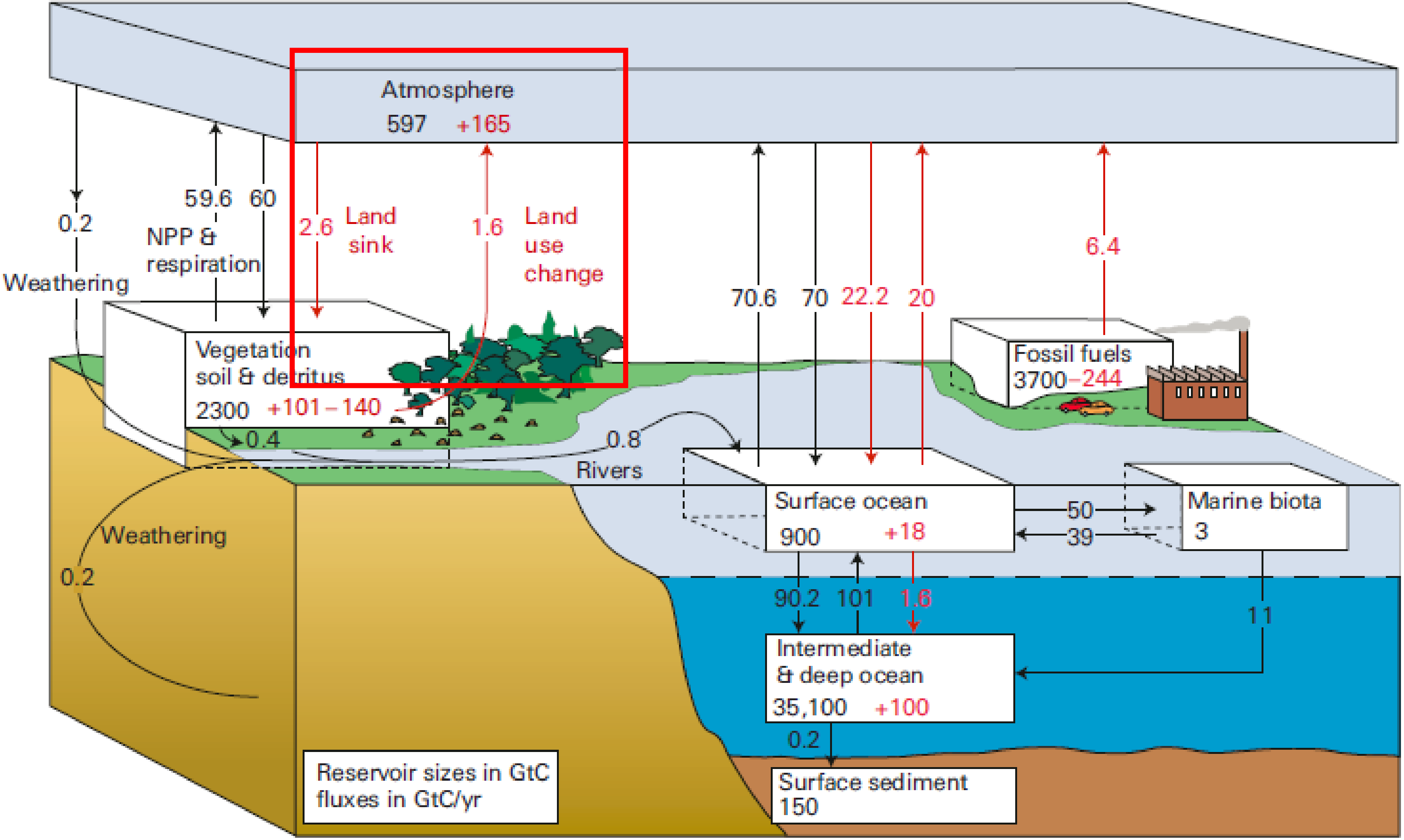
Global Mean Surface Time Series



How many gigatonnes of CO_2 do plants absorb and release in one year?

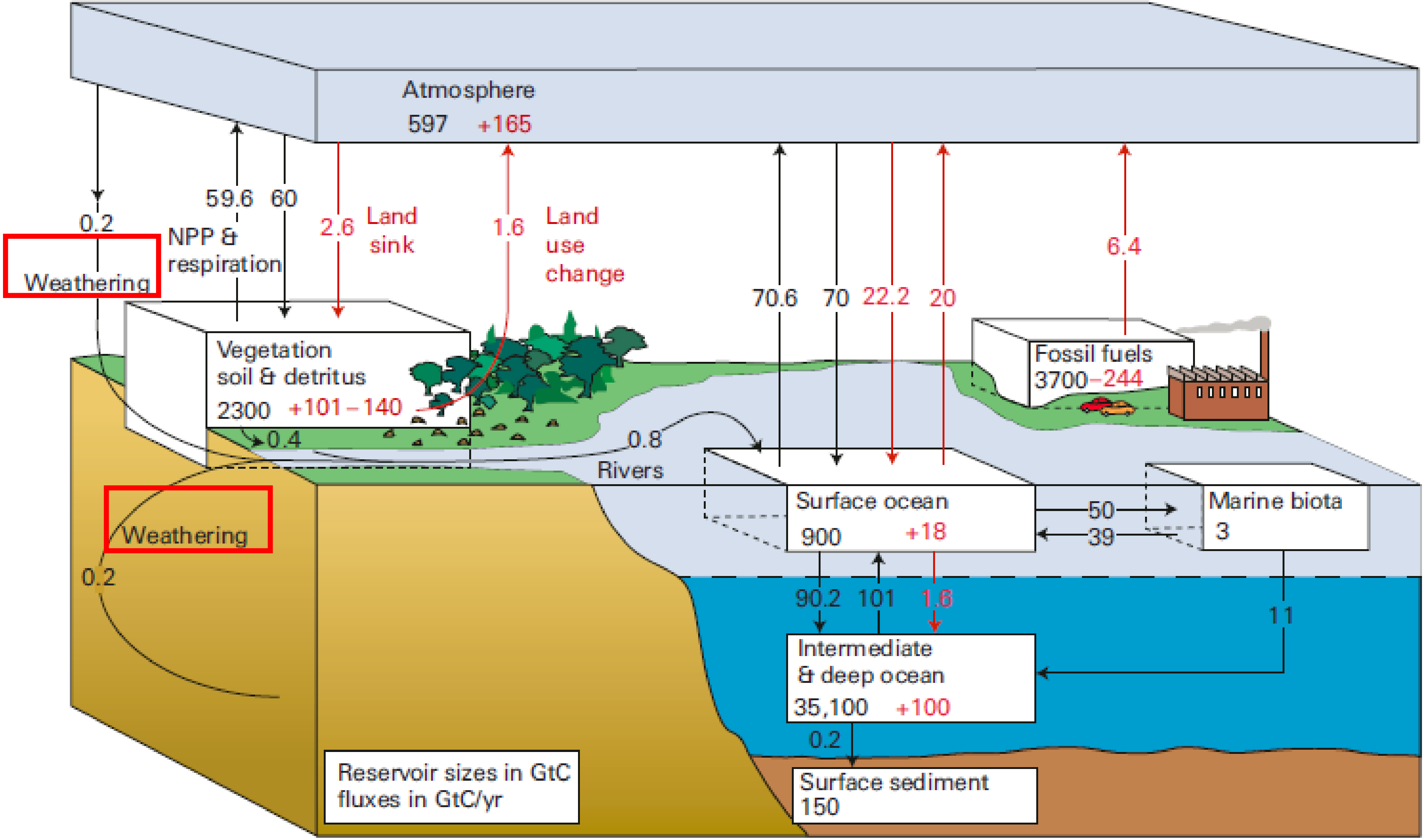
- Peak to peak variation in global average CO_2 concentration is approximately 4 ppm
- Currently CO_2 at about 400 ppm = 3,125 Gt CO_2
- 4 ppm then is 31.2 Gt CO_2
- Slope is approximately 2.3 ppm per year, but 25% of emissions are absorbed by the ocean, 28% by plants, and 46% stays in the atmosphere.

Global Carbon Cycle Modification
Afforestation/Reforestation



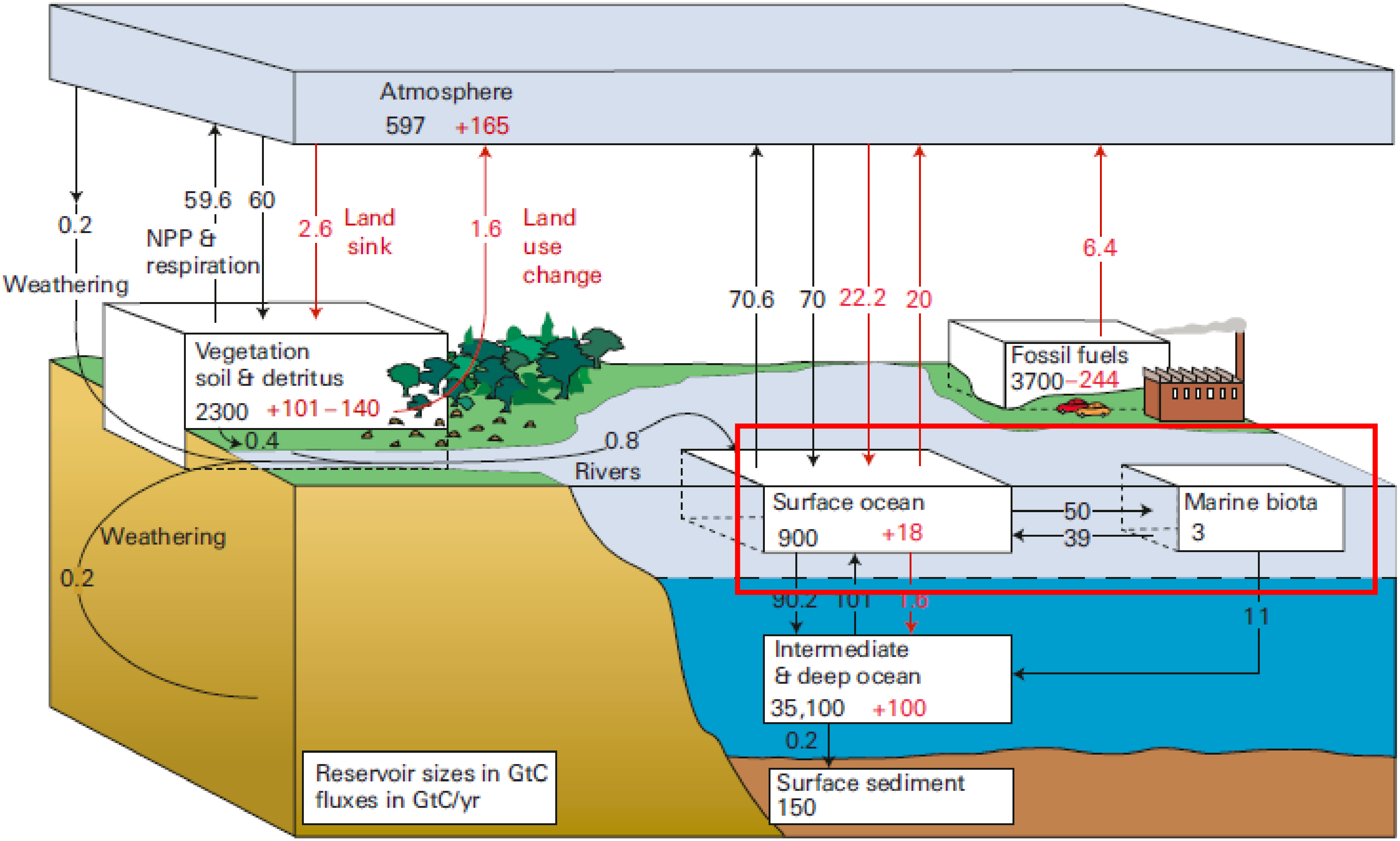
Black numbers pre-industrial steady state. Red numbers additions due to human activity.

Global Carbon Cycle Modification
Enhanced Weathering



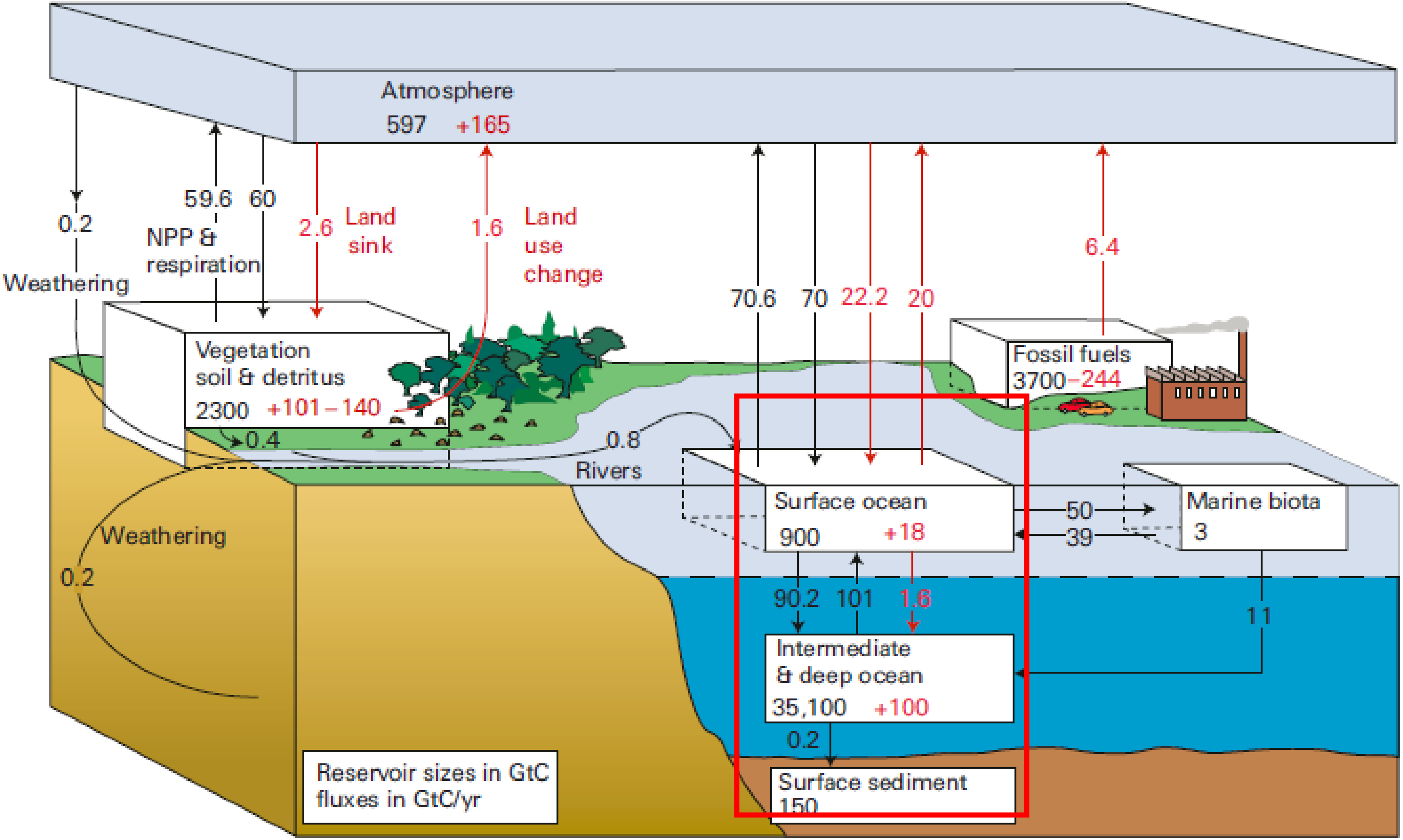
Black numbers pre-industrial steady state. Red numbers additions due to human activity.

Global Carbon Cycle Modification
Ocean Fertilization



Black numbers pre-industrial steady state. Red numbers additions due to human activity.

Global Carbon Cycle Modification
Ocean Upwelling/Downwelling



Black numbers pre-industrial steady state. Red numbers additions due to human activity.

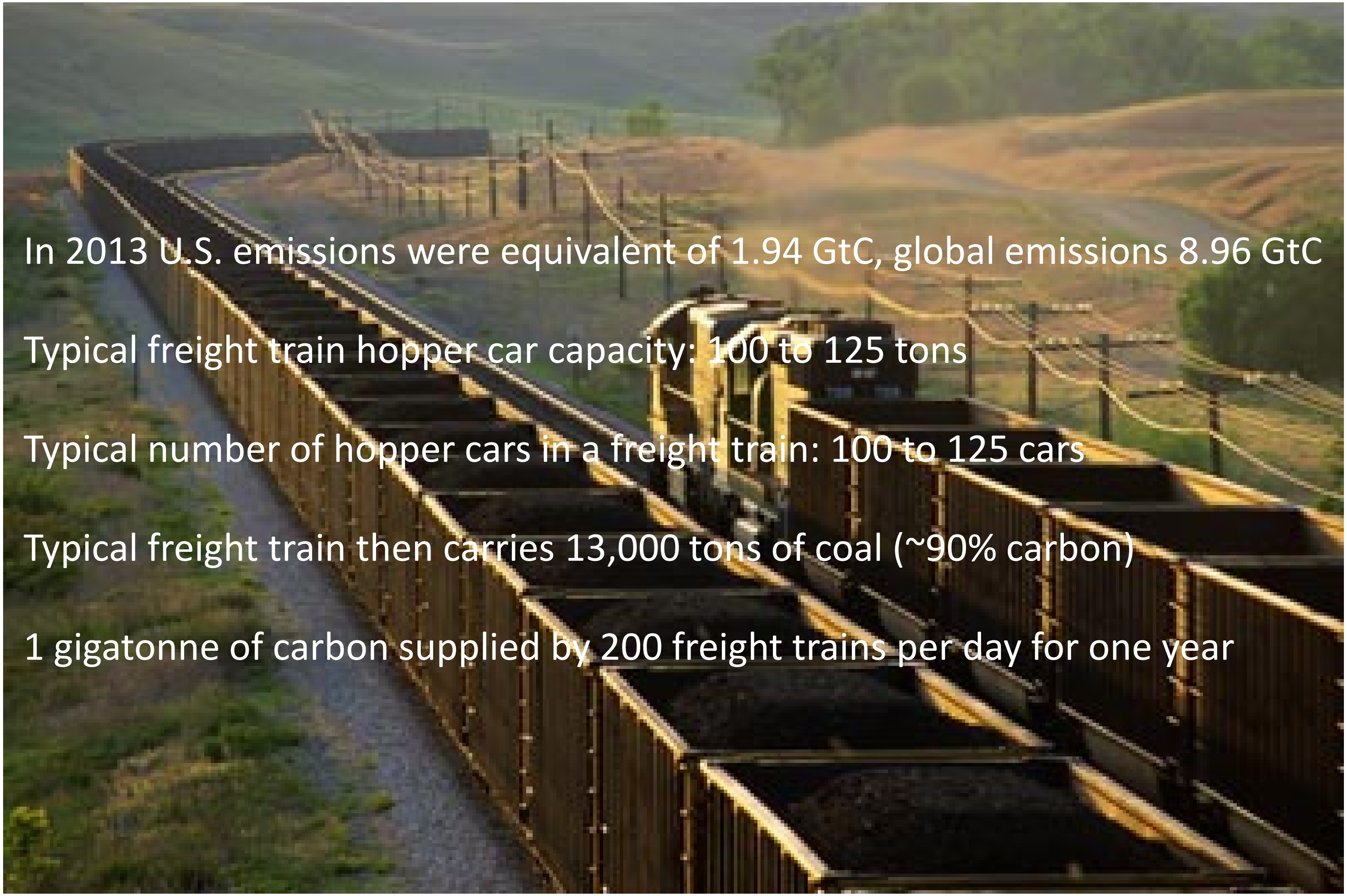
Global Carbon Cycle
natural and anthropogenic

- Gross Primary Production (GPP) of plants material removes 119.6 GtC per year and replaces 120.[0] GtC per year
  - Earth is becoming greener
- Atmosphere interchange with ocean removes 92.2 GtC per year and replaces 90 GtC per year
  - The oceans are becoming more acidic
- Weathering of silicate rock removes 0.2 GtC per year
- Soils sequester 2.6 GtC per year, but land use change replaces 1.6 Gt C per year
- Fossil fuel combustion places 6.4 GtC per year in the atmosphere
- Imbalance between removal from atmosphere, 215.0 GtC per year, and replacement to atmosphere, 218.2 GtC per year, results in increase of CO_2 in atmosphere.
- About one half of CO_2 from combustion ends up in the oceans and about one half in the atmosphere

How Much CO_2 Must Be Removed?

- Current CO_2 concentration ~400 ppm
- To return to 350 ppm, ~350 $GtCO_2$ = 100 GtC must be removed
  - Hansen et al., Target atmospheric CO_2: Where should humanity aim? Atmos. Sci. J. 2(2008)217
- To return to 280 ppm, ~840 $GtCO_2$ = 230 GtC must be removed
  - 280 ppm is pre-industrial level

How Much Is a Gigatonne of Carbon?



In 2013 U.S. emissions were equivalent of 1.94 GtC, global emissions 8.96 GtC

Typical freight train hopper car capacity: 100 to 125 tons

Typical number of hopper cars in a freight train: 100 to 125 cars

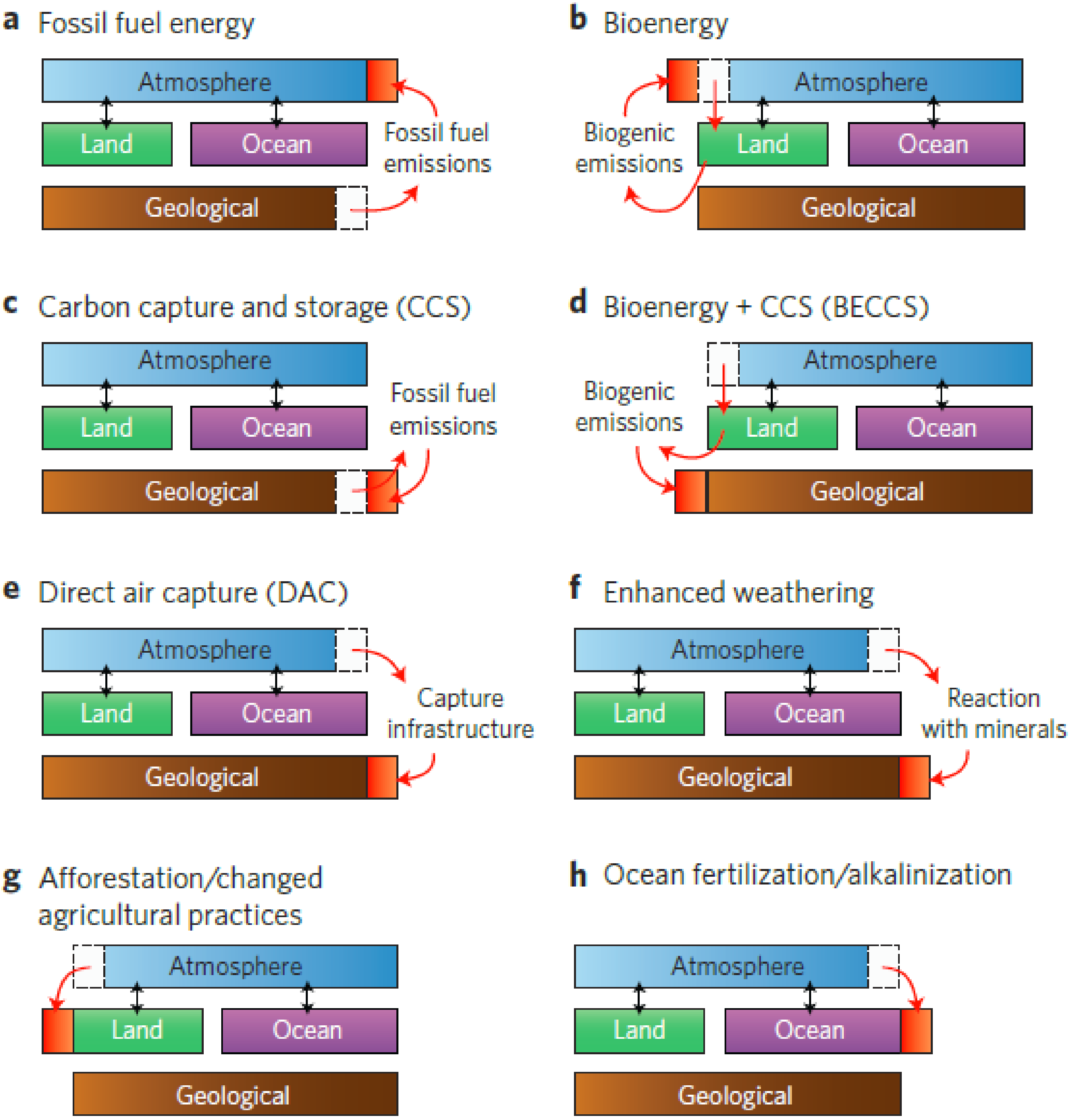
Typical freight train then carries 13,000 tons of coal (~90% carbon)

1 gigatonne of carbon supplied by 200 freight trains per day for one year

Removal of CO_2 from Atmosphere

Carbon Management Options

- Decrease and eliminate fossil fuel consumption
- Increase absorption on land by enhanced weathering
- Increase absorption in ocean by promoting biological activity
- Increase absorption on land by promoting biological activity
- Decrease land use change

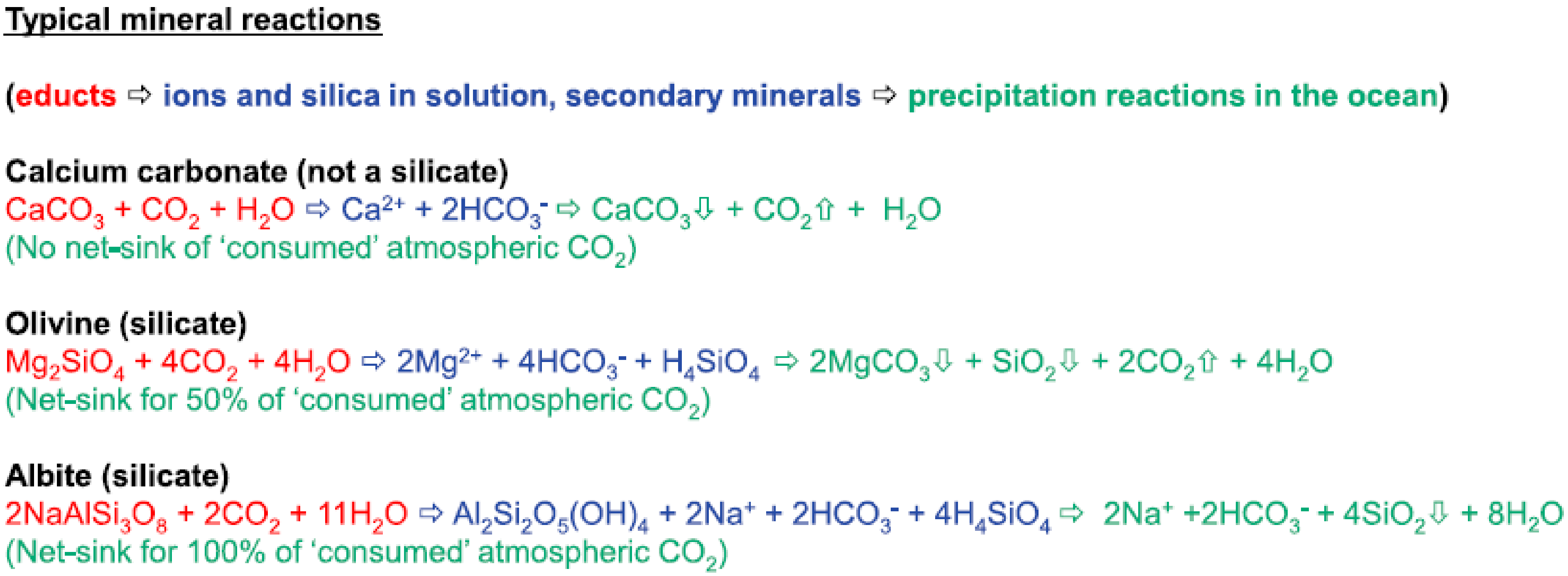

a Fossil fuel energy
Atmosphere
Land
Ocean
Geological
Fossil fuel emissions
b Bioenergy
Atmosphere
Land
Ocean
Geological
Biogenic emissions
c Carbon capture and storage (CCS)
Atmosphere
Land
Ocean
Geological
Fossil fuel emissions
d Bioenergy + CCS (BECCS)
Atmosphere
Land
Ocean
Geological
Biogenic emissions
e Direct air capture (DAC)
Atmosphere
Land
Ocean
Geological
Capture infrastructure
f Enhanced weathering
Atmosphere
Land
Ocean
Geological
Reaction with minerals
g Afforestation/changed agricultural practices
Atmosphere
Land
Ocean
Geological
h Ocean fertilization/alkalinization
Atmosphere
Land
Ocean
Geological

Enhanced Weathering

Crushed Minerals Spread on Land

Enhanced Weathering

Silicate rocks absorb CO_2 allowing eventual formation of carbonites.



Typical mineral reactions

(educts ⇨ ions and silica in solution, secondary minerals ⇨ precipitation reactions in the ocean)

Calcium carbonate (not a silicate)

$CaCO_3 + CO_2 + H_2O \Rightarrow Ca^{2+} + 2HCO_3^- \Rightarrow CaCO_3\downarrow + CO_2\uparrow + H_2O$

(No net-sink of 'consumed' atmospheric CO_2)

Olivine (silicate)

$Mg_2SiO_4 + 4CO_2 + 4H_2O \Rightarrow 2Mg^{2+} + 4HCO_3^- + H_4SiO_4 \Rightarrow 2MgCO_3\downarrow + SiO_2\downarrow + 2CO_2\uparrow + 4H_2O$

(Net-sink for 50% of 'consumed' atmospheric CO_2)

Albite (silicate)

$2NaAlSi_3O_8 + 2CO_2 + 11H_2O \Rightarrow Al_2Si_2O_5(OH)_4 + 2Na^+ + 2HCO_3^- + 4H_4SiO_4 \Rightarrow 2Na^+ + 2HCO_3^- + 4SiO_2\downarrow + 8H_2O$

(Net-sink for 100% of 'consumed' atmospheric CO_2)

Theoretical limit for CO_2 removal by olivine is 1.25 kg of CO_2 per kg of olivine.

Land Use Change
See Net Zero Emissions lecture 3

Removal of CO_2 from Atmosphere
Afforestation and Reforestation

See Net zero emissions lectures 3 and 4

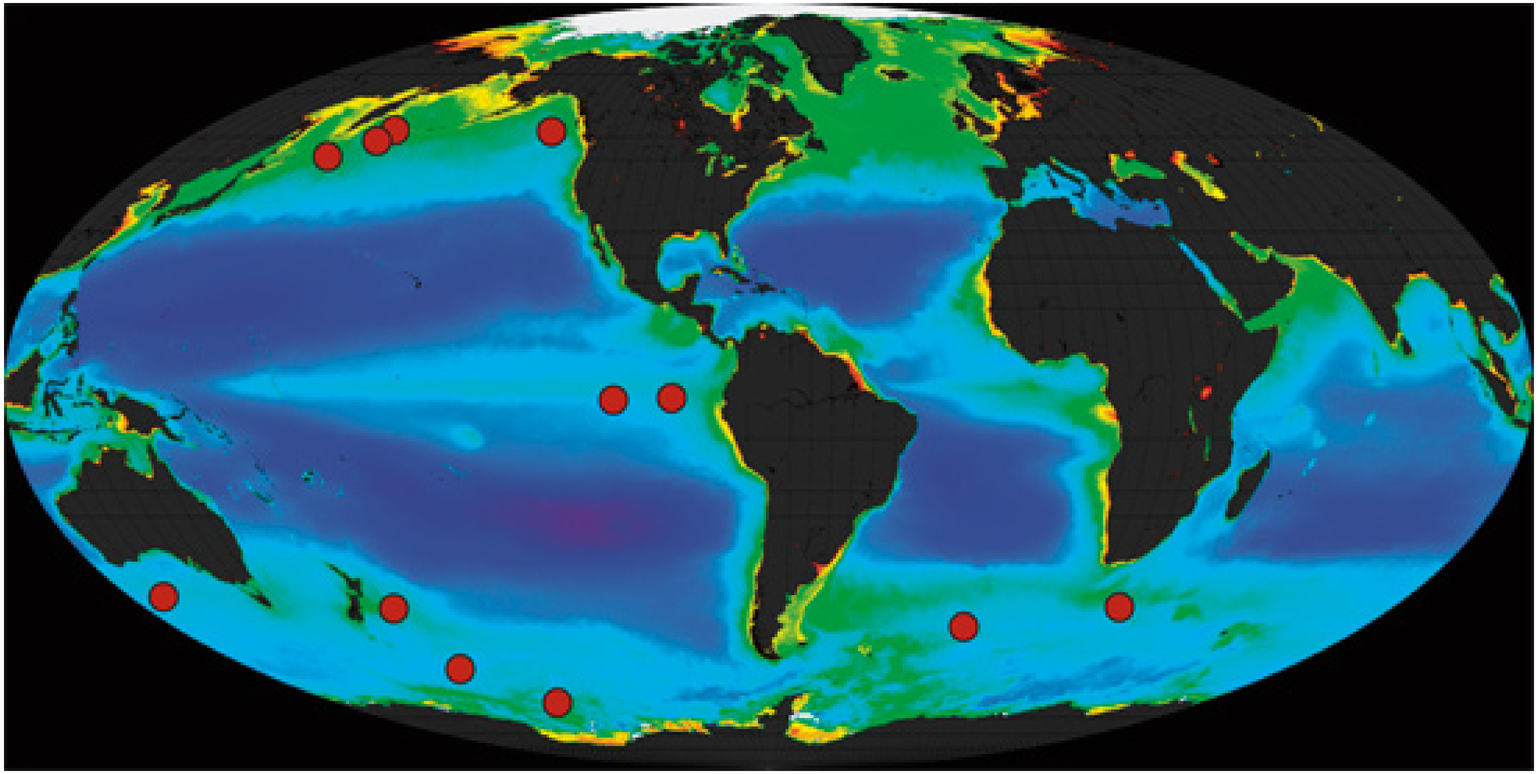
Removal of CO_2 from Atmosphere
Ocean Surface Fertilization

Iron Hypothesis
John Martin, Nature 331(1988)341

"Give me a half tanker of iron, and I will give you an ice age."

Low phytoplankton populations indicated by purple shaded areas on map despite adequate sunlight and nutrients.

Ocean Fertilization Experiment Sites



“Small-scale open ocean experiments (*red dots*) have shown that iron additions do indeed result in phytoplankton blooms, thereby drawing carbon dioxide out of the atmosphere and into the ocean.”

The New York Times

October 18, 2012
A Rogue Climate Experiment Outrages Scientists

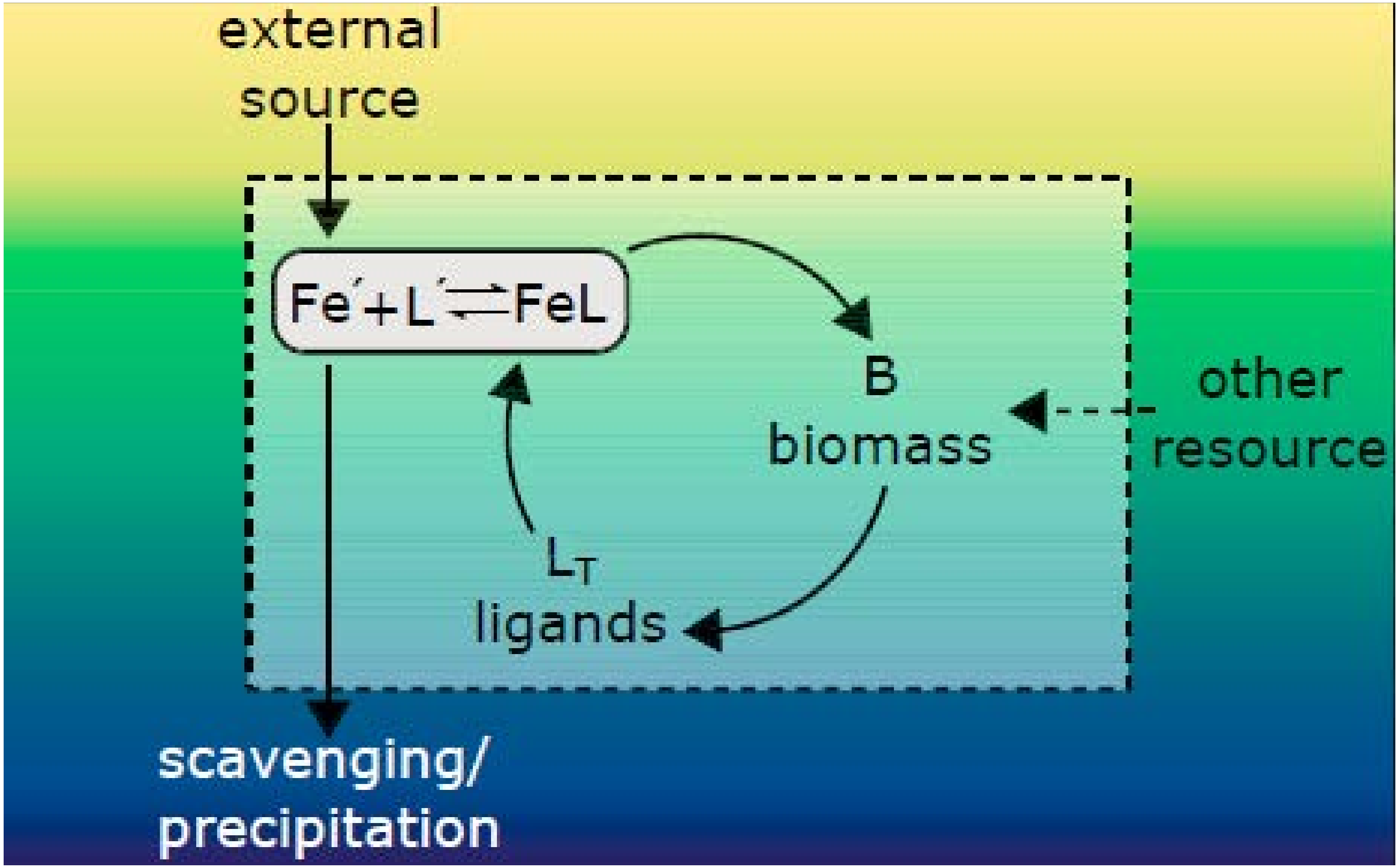
“A California businessman chartered a fishing boat in July, loaded it with 100 tons of iron dust and cruised through Pacific waters off western Canada, spewing his cargo into the sea in an ecological experiment that has outraged scientists and government officials.”

PNAS
Proceedings of the
National Academy of Sciences
of the United States of America

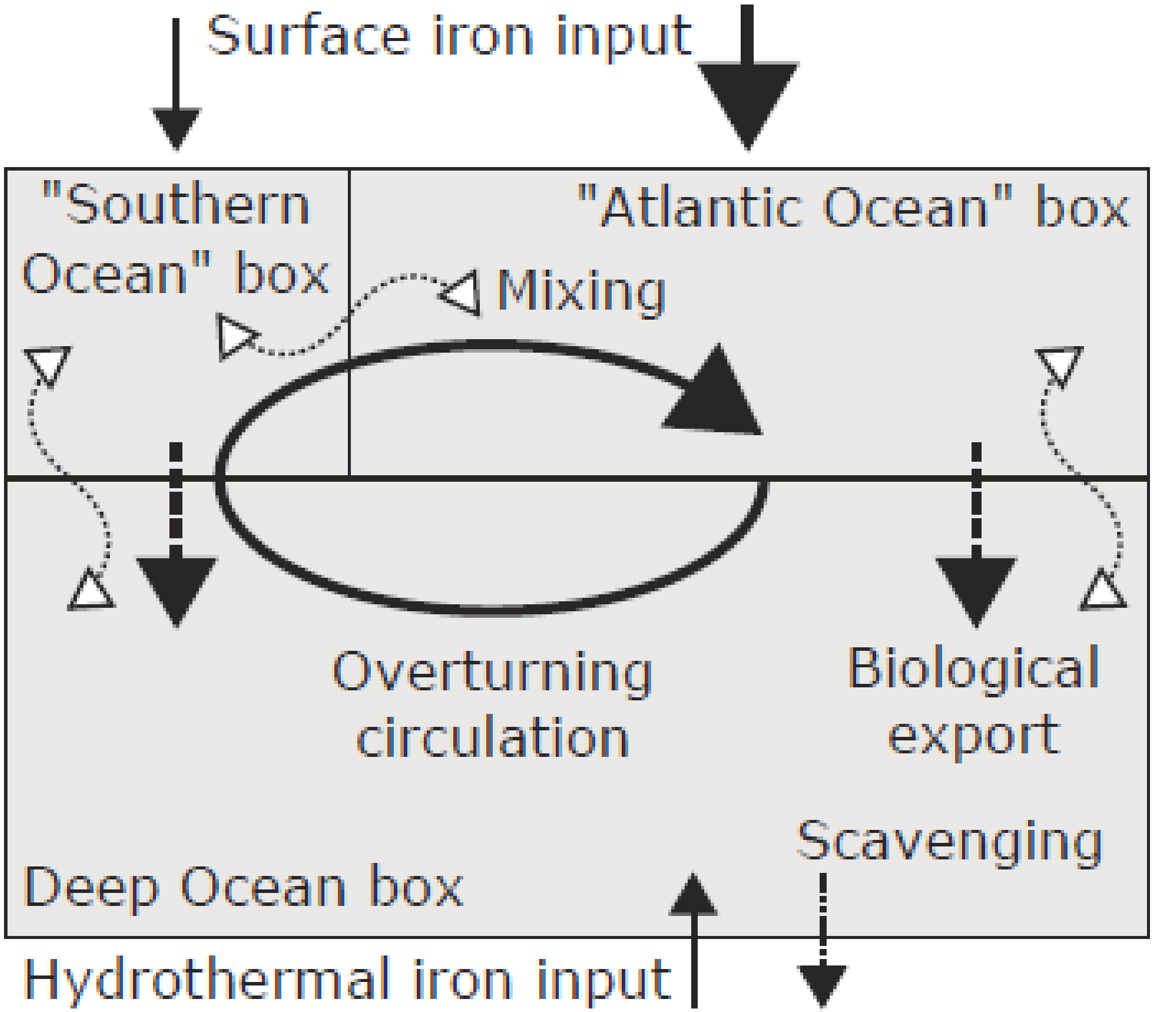
January 22, 2020

Microbial feedbacks optimize ocean iron availability

Schematic of the “ligand–iron–microbe” feedback



Schematic of the idealized three-box ocean biogeochemistry model.

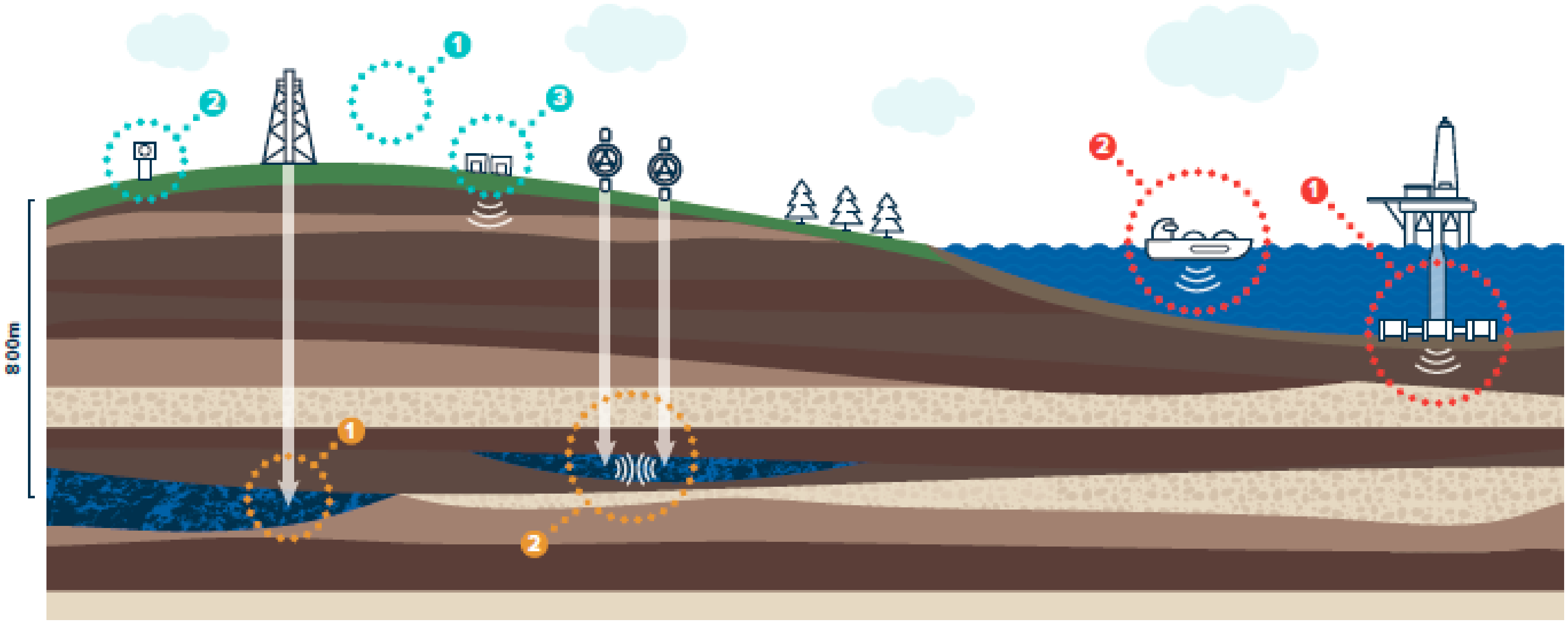


Significance of Global and Local Feedback Loops

Marine microbe growth is limited by iron over about half of the global ocean surface. Dissolved iron is quickly lost from the ocean, but its availability to marine microbes may be enhanced by binding with organic molecules which, in turn, are produced by microbes. We hypothesize this forms a reinforcing cycle between biological activity and iron cycling that locally matches the availability of iron and other nutrients, leading to global-scale resource colimitation between macronutrients and micronutrients, and maximizing biological productivity. Idealized models support this hypothesis, depending on the specific relationships between microbial sources and sinks of organic molecules. An evolutionary selection may have occurred which optimizes these characteristics, resulting in “just enough” iron in the ocean.

Removal of CO_2 from Atmosphere

Carbon Capture and Sequestration



1 **ATMOSPHERE**

- AIRBORNE EM
- AIRBORNE SPECTRAL
- SATELLITE INTERFEROMETRY

2 **SURFACE**

- EDDY COVARIANCE
- SURFACE GAS FLUX
- SOIL GAS CONCENTRATIONS
- GROUND WATER CHEMISTRY

2 **SURFACE**

- 2D/3D SURFACE SEISMIC
- LAND EM/ERT
- SURFACE GRAVIMETRY
- TILTMETERS

1 **SUB-SURFACE**

- DOWNHOLE FLUID CHEMISTRY
- DOWNHOLE PRESSURE
- DOWNHOLE TEMPERATURE
- GEOPHYSICS LOGS

2 **SUB-SURFACE**

- CROSS-HOLE EM
- CROSS-HOLE ERT
- CROSS-HOLE SEISMIC
- MICROSEISMIC
- VERTICAL SEISMIC PROFILING
- WELL GRAVIMETRY

1 **OFFSHORE**

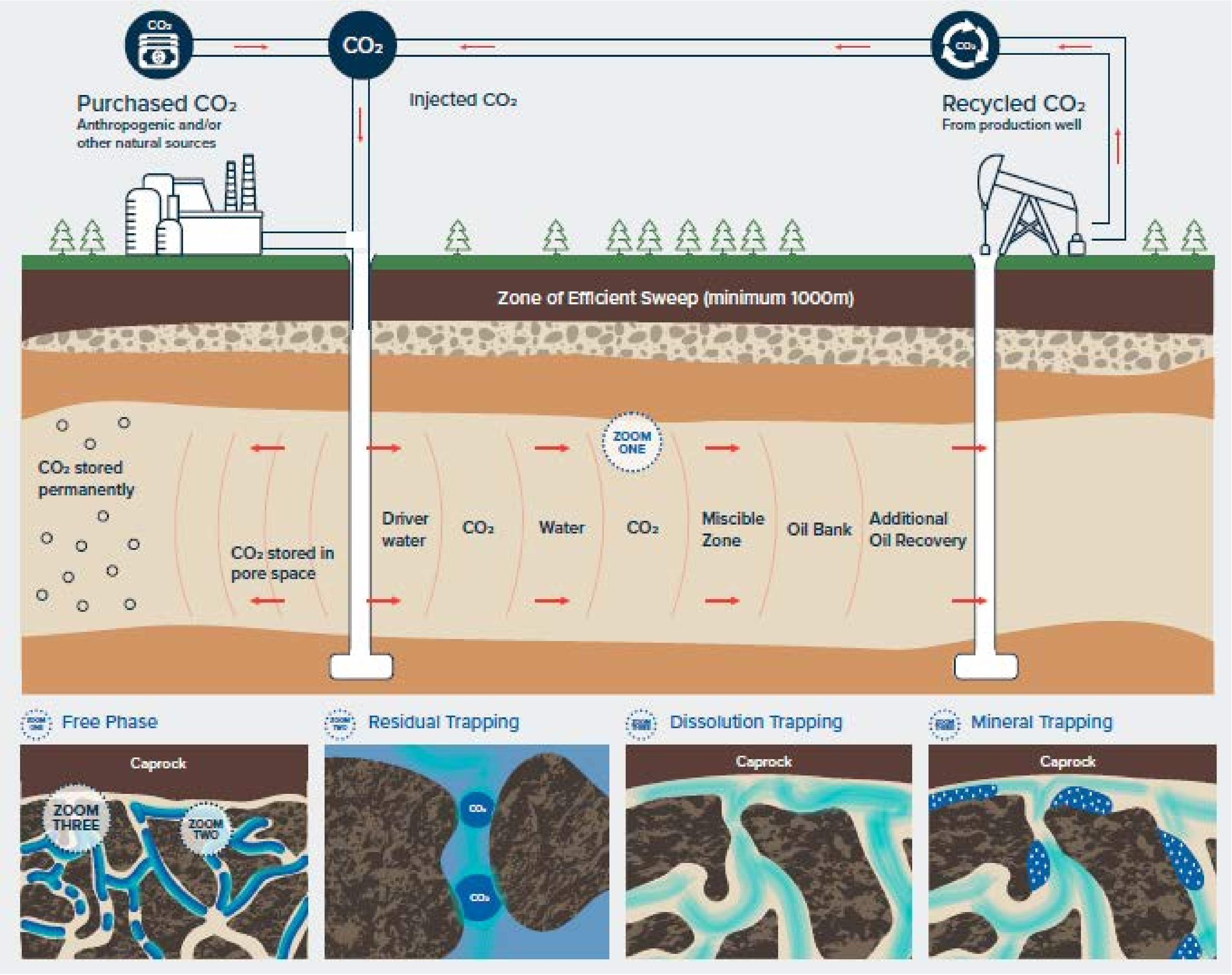
- BOOMER/SPARKER PROFILING
- BUBBLE STREAM DETECTION
- MULTI-ECHO SOUNDINGS
- SIDESCAN SONAR

2 **OFFSHORE**

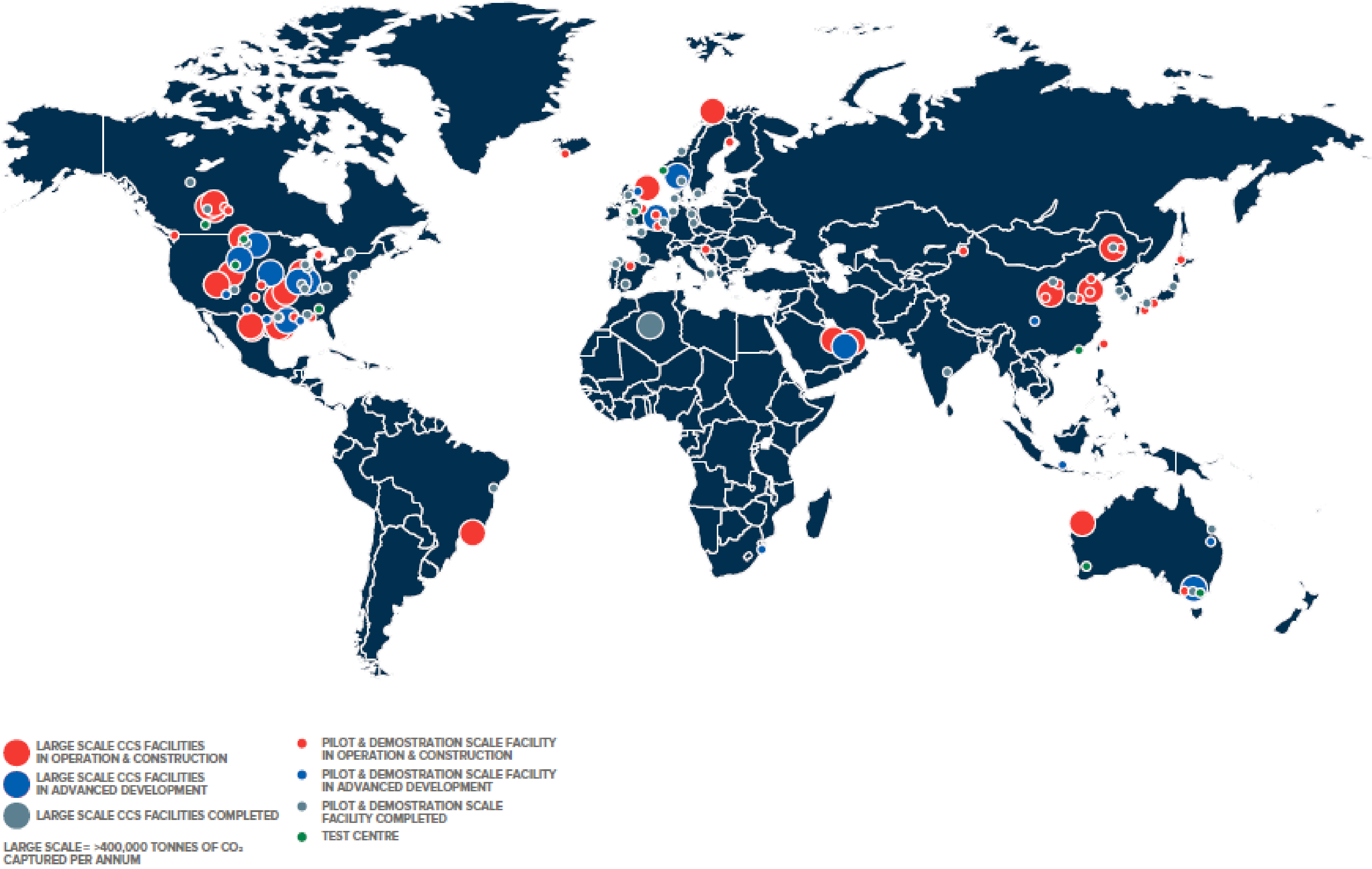
- SEABOTTOM GAS SAMPLING
- SEAWATER GEOCHEMISTRY
- SEABOTTOM SEISMIC
- SEABOTTOM EM

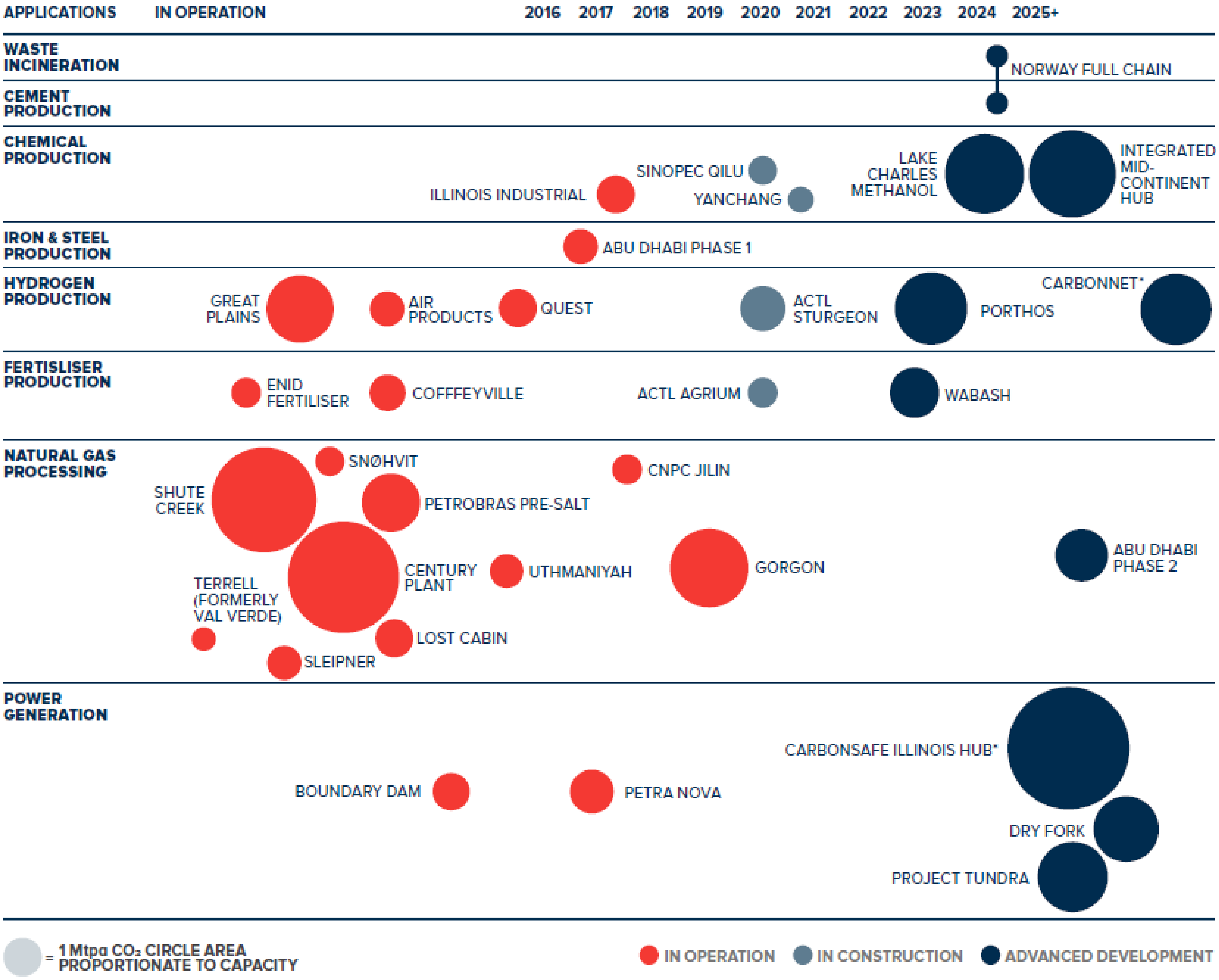
EM ELECTROMAGNETIC

ERT ELECTRICAL RESISTANCE TOMOGRAPHY

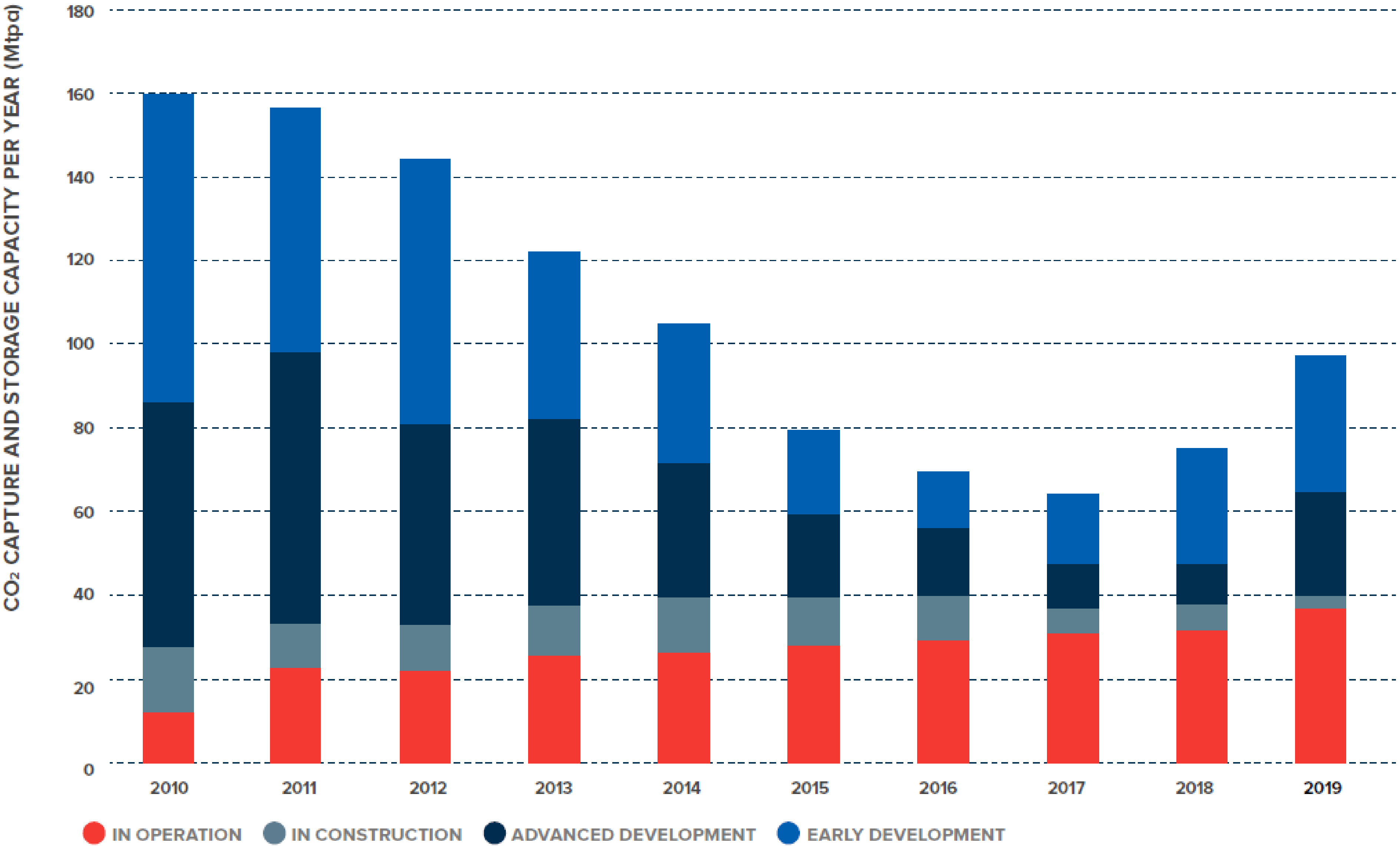

CO₂
Purchased CO₂
Anthropogenic and/or other natural sources
Injected CO₂
Recycled CO₂
From production well
Zone of Efficient Sweep (minimum 1000m)
ZOOM ONE
CO₂ stored permanently
CO₂ stored in pore space
Driver water
CO₂
Water
CO₂
Miscible Zone
Oil Bank
Additional Oil Recovery
Free Phase
Residual Trapping
Dissolution Trapping
Mineral Trapping
Caprock
ZOOM THREE
ZOOM TWO
CO₂
CO₂
Caprock
Caprock

Large Scale CCS Sites (2019)

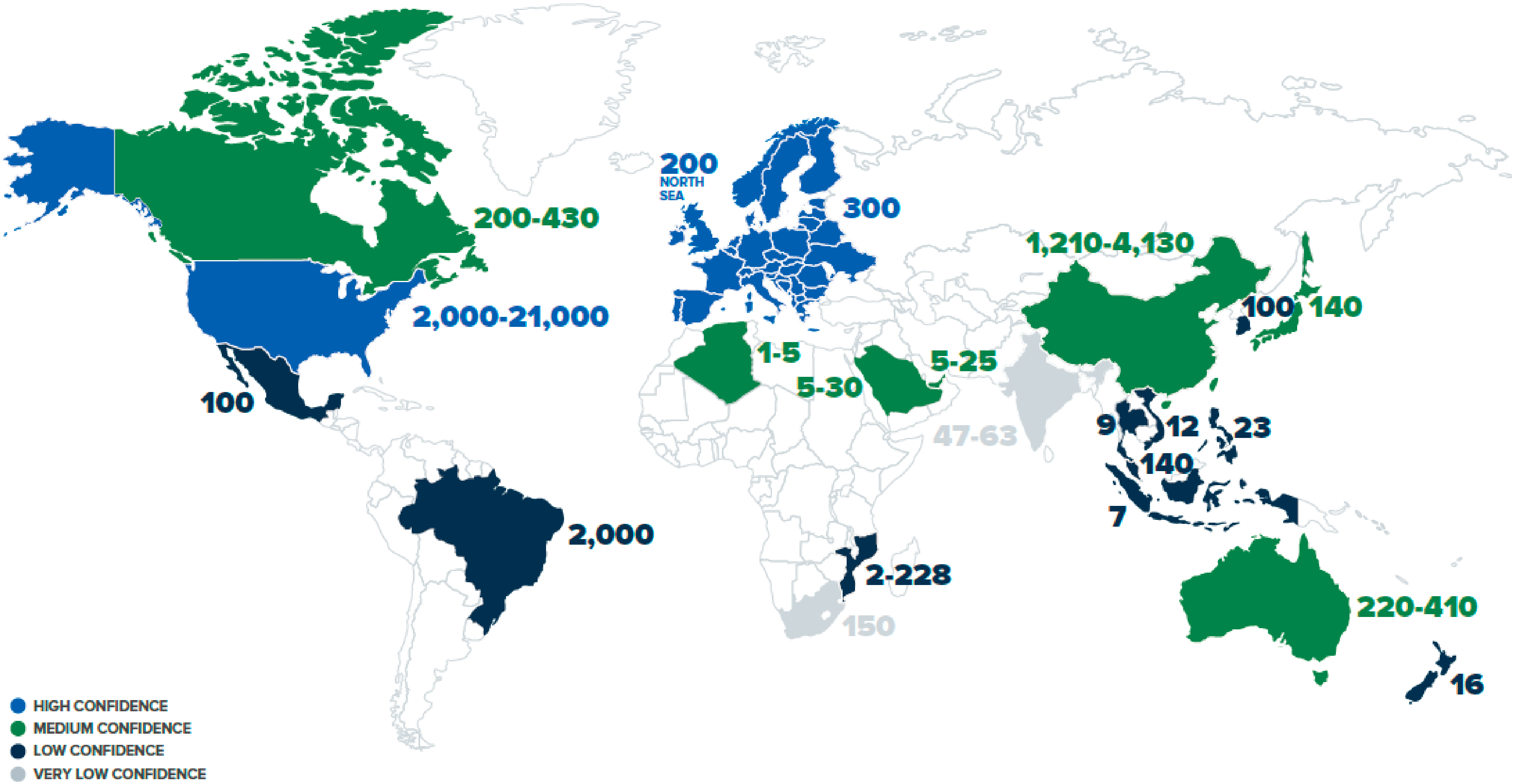



APPLICATIONS
IN OPERATION
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025+
WASTE INCINERATION
NORWAY FULL CHAIN
CEMENT PRODUCTION
CHEMICAL PRODUCTION
SINOPEC QILU
ILLINOIS INDUSTRIAL
YANCHANG
LAKE CHARLES METHANOL
INTEGRATED MID-CONTINENT HUB
IRON & STEEL PRODUCTION
ABU DHABI PHASE 1
HYDROGEN PRODUCTION
GREAT PLAINS
AIR PRODUCTS
QUEST
ACTL STURGEON
PORTHOS
CARBONNET*
FERTISLISER PRODUCTION
ENID FERTILISER
COFFFEYVILLE
ACTL AGRIUM
WABASH
NATURAL GAS PROCESSING
SNØHVIT
SHUTE CREEK
PETROBRAS PRE-SALT
CNPC JILIN
TERRELL (FORMERLY VAL VERDE)
CENTURY PLANT
UTHMANIYAH
GORGON
ABU DHABI PHASE 2
LOST CABIN
SLEIPNER
POWER GENERATION
CARBONSAFE ILLINOIS HUB*
BOUNDARY DAM
PETRA NOVA
DRY FORK
PROJECT TUNDRA
= 1 Mtpa CO_2 CIRCLE AREA PROPORTIONATE TO CAPACITY
IN OPERATION
IN CONSTRUCTION
ADVANCED DEVELOPMENT

Global CCS Capacity 2010-2019



Geological Storage Resource (Gt)

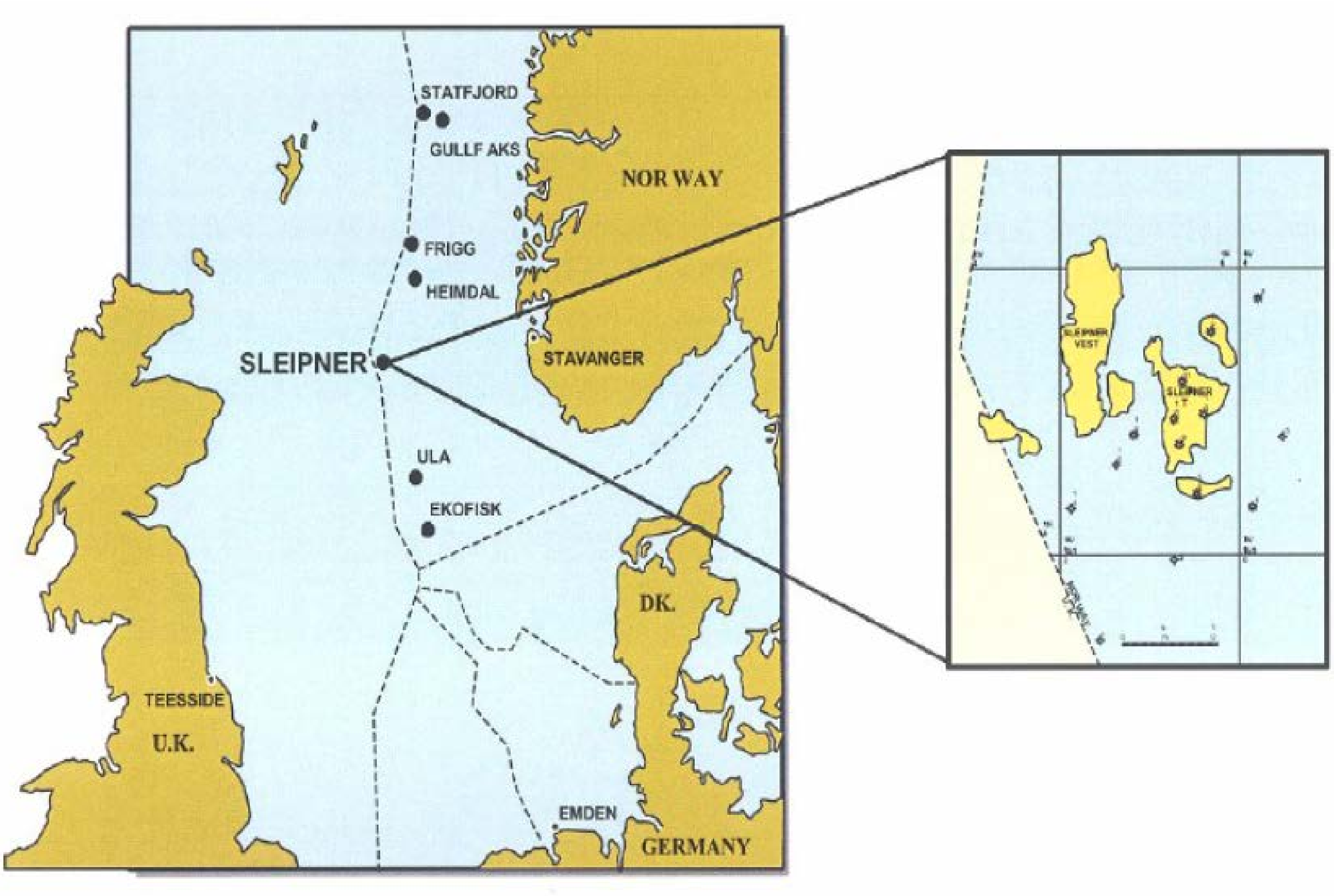


Is Gigatonne CO_2 Storage Possible?

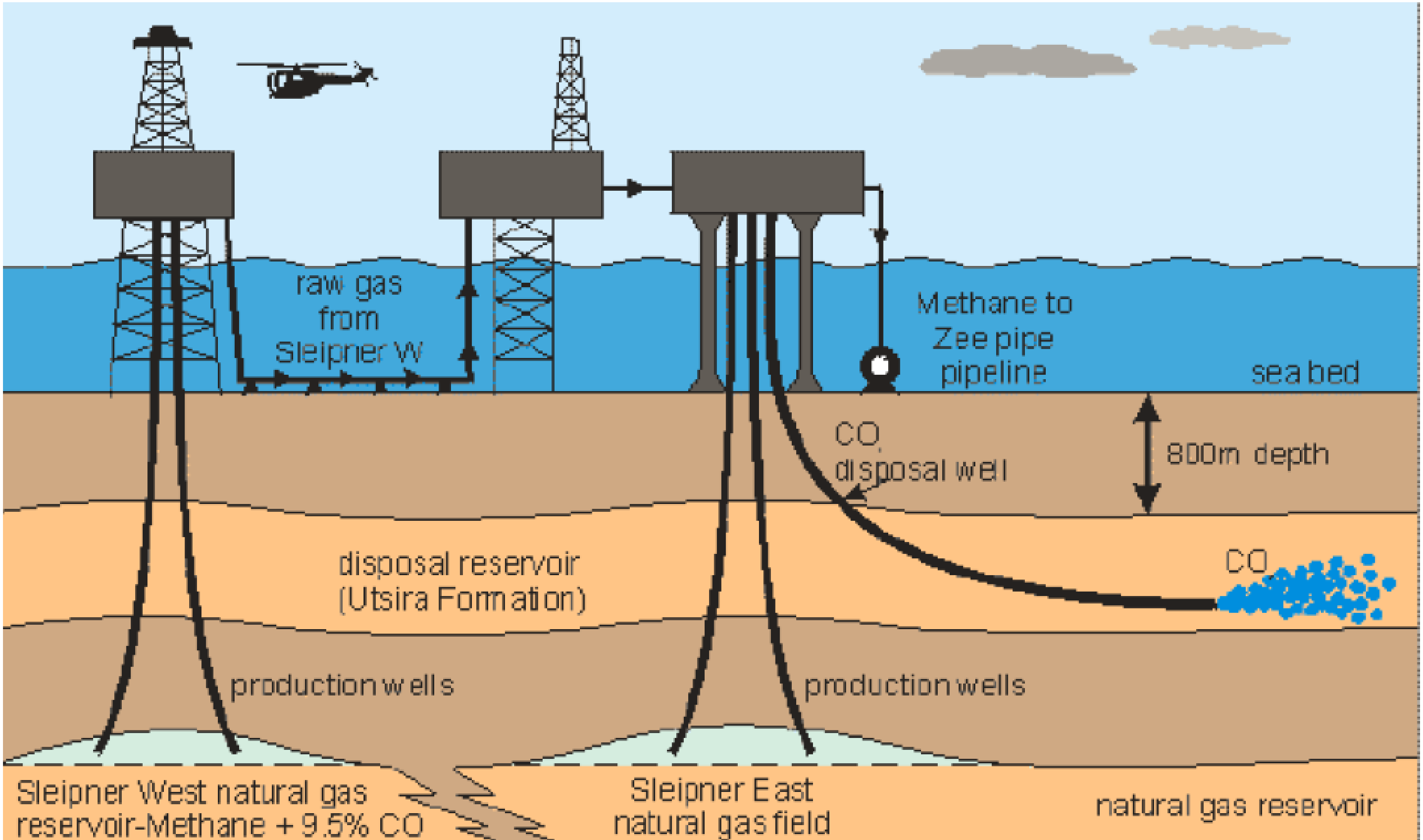
- IPCC pathways model up to 1,200 Gt CO_2 storage by 2100
- 2019 25 Mt CO_2 sequestered from power and industry
- 2019 38 Mt CO_2 sequestration capacity
- IEA forecast 30-60 storage sites per year to 2050
- 350 gas and oil fields were developed annually in the peak development period (2000-2010)
- 20% of available rigs could drill storage sites
- IEA forecast 2.3 $GtCO_2$ per year required until 2060 – double the rate of oil and gas industry in last century

Successful Sequestration of CO_2
The Sleipner North Sea Gas Field

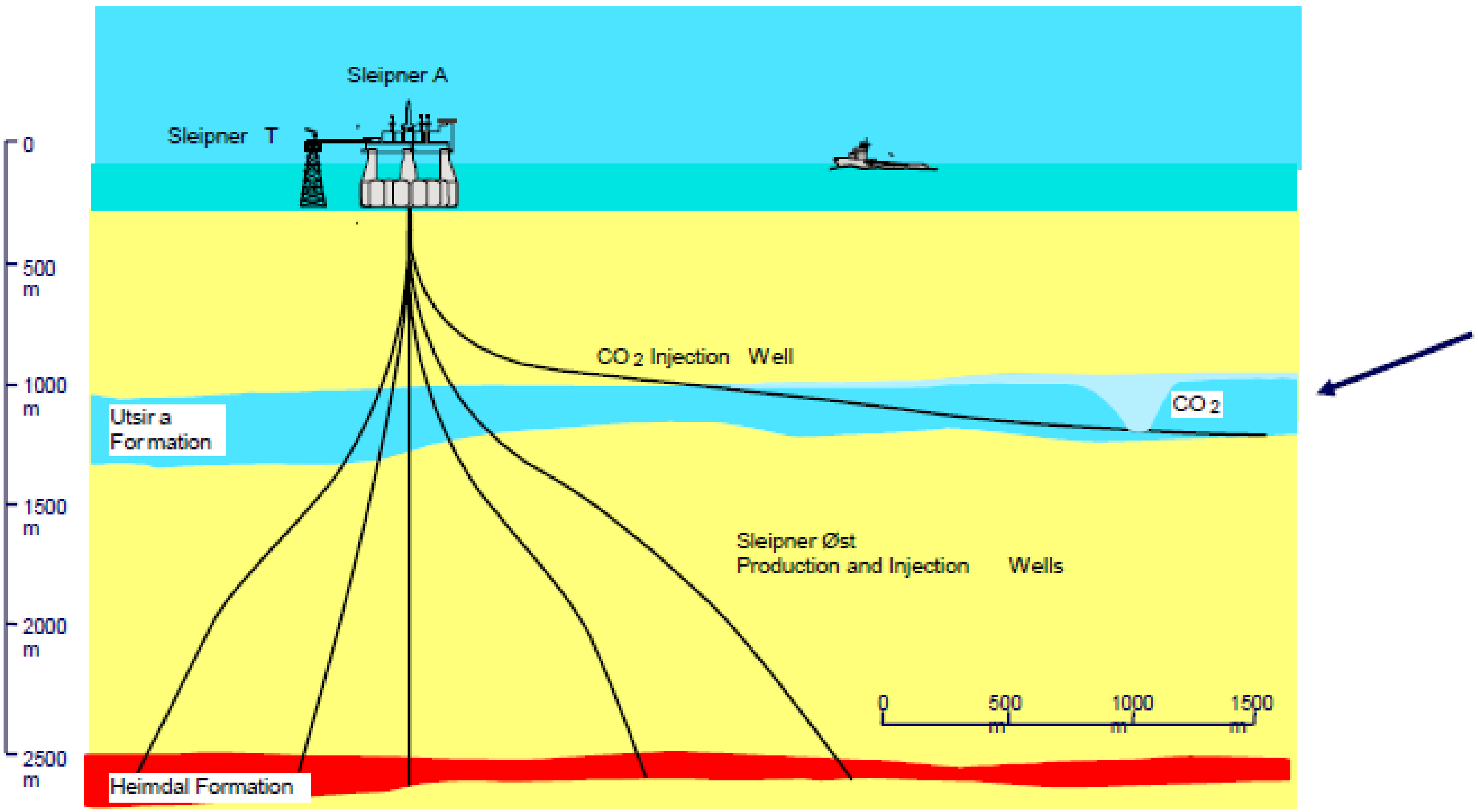
Location of Sleipner Gas Field



Schematic of Sleipner Platforms, Production and Disposal



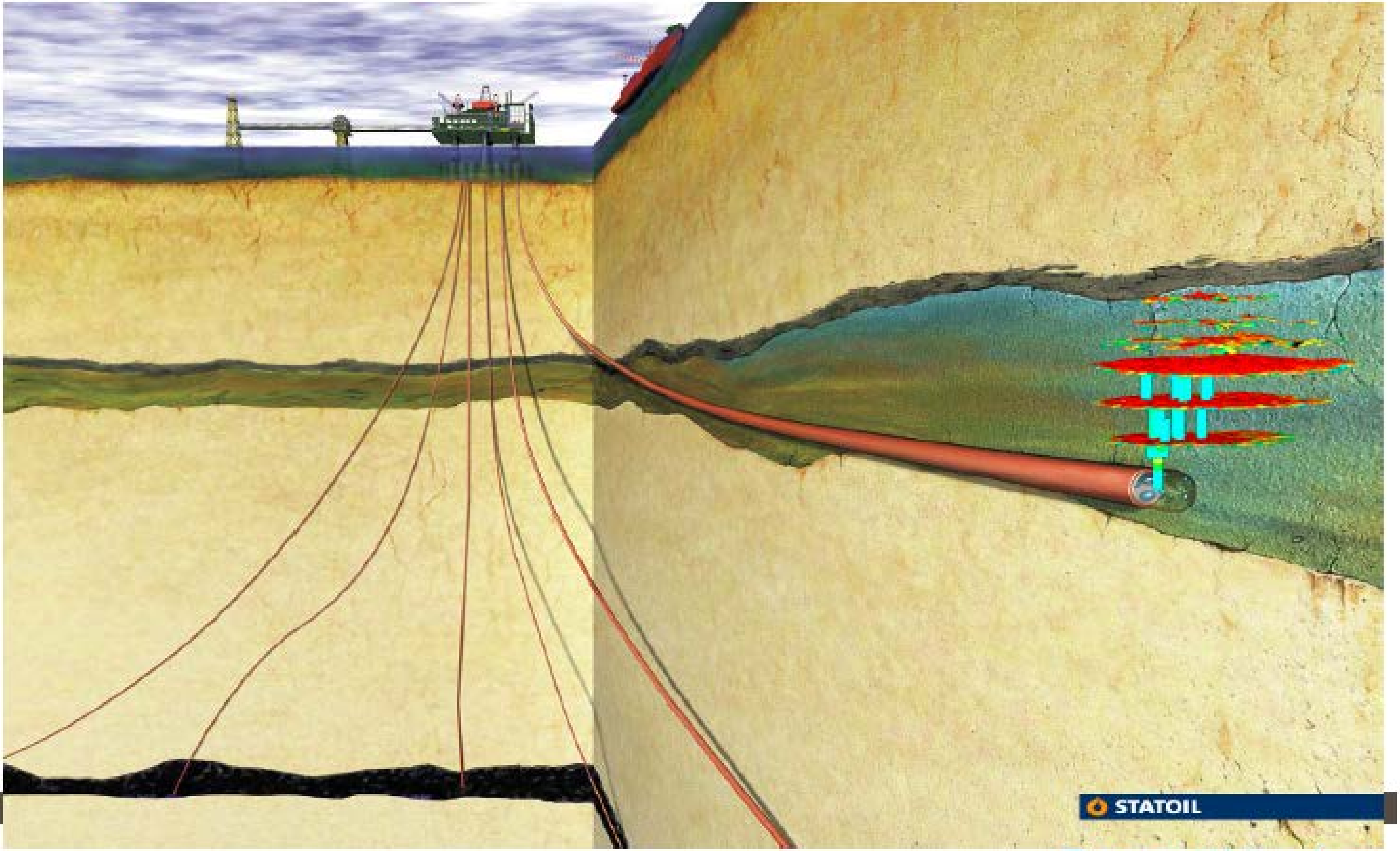
CO2 Injection Well in "Utsira"



The Sleipner field – CO2 Treatment and Injection

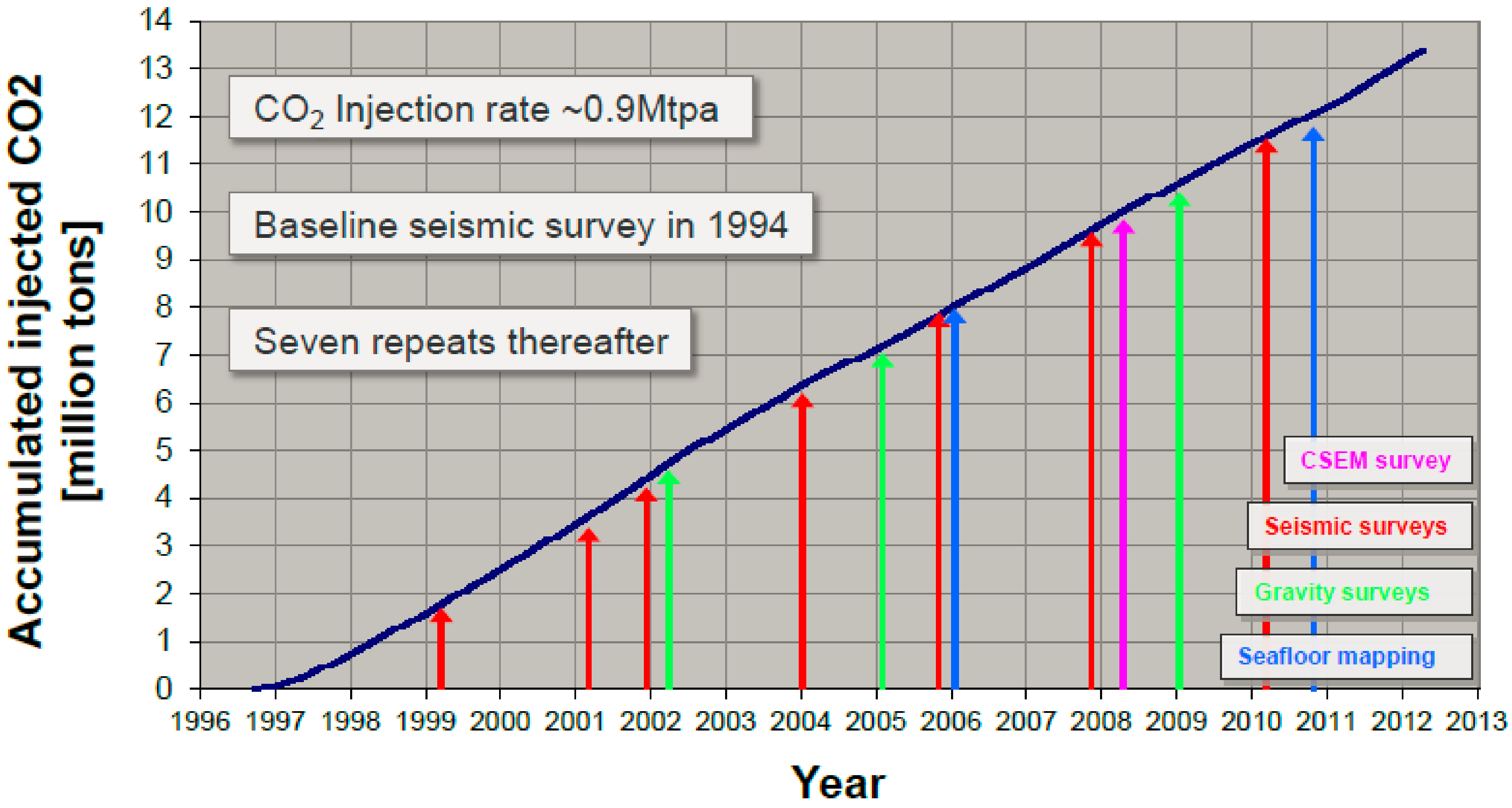
StatoilHydro

Sleipner CO2 Injection



StatoilHydro

Cumulative CO_2 injection to date

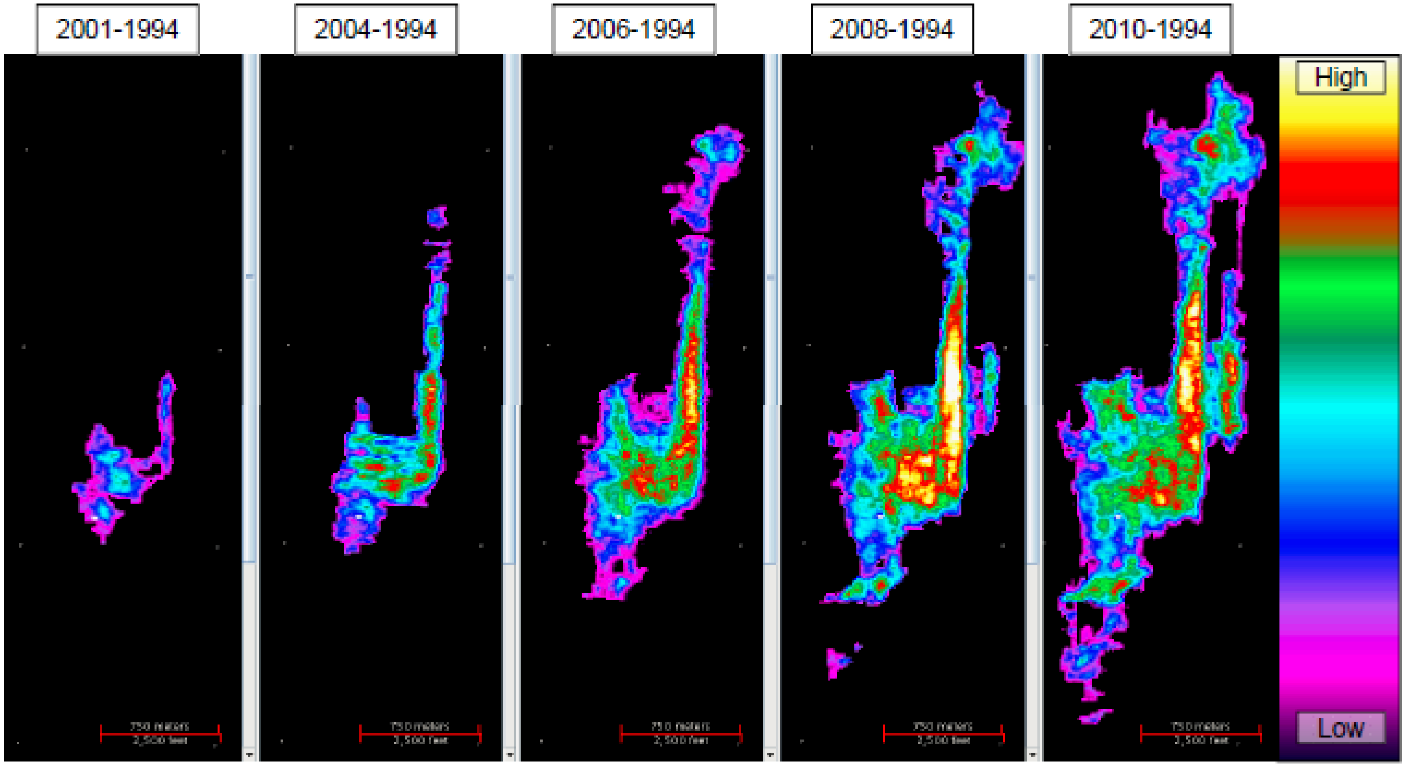


CO_2 Injection rate ~0.9Mtpa

Baseline seismic survey in 1994

Seven repeats thereafter

Development of CO_2 Plume



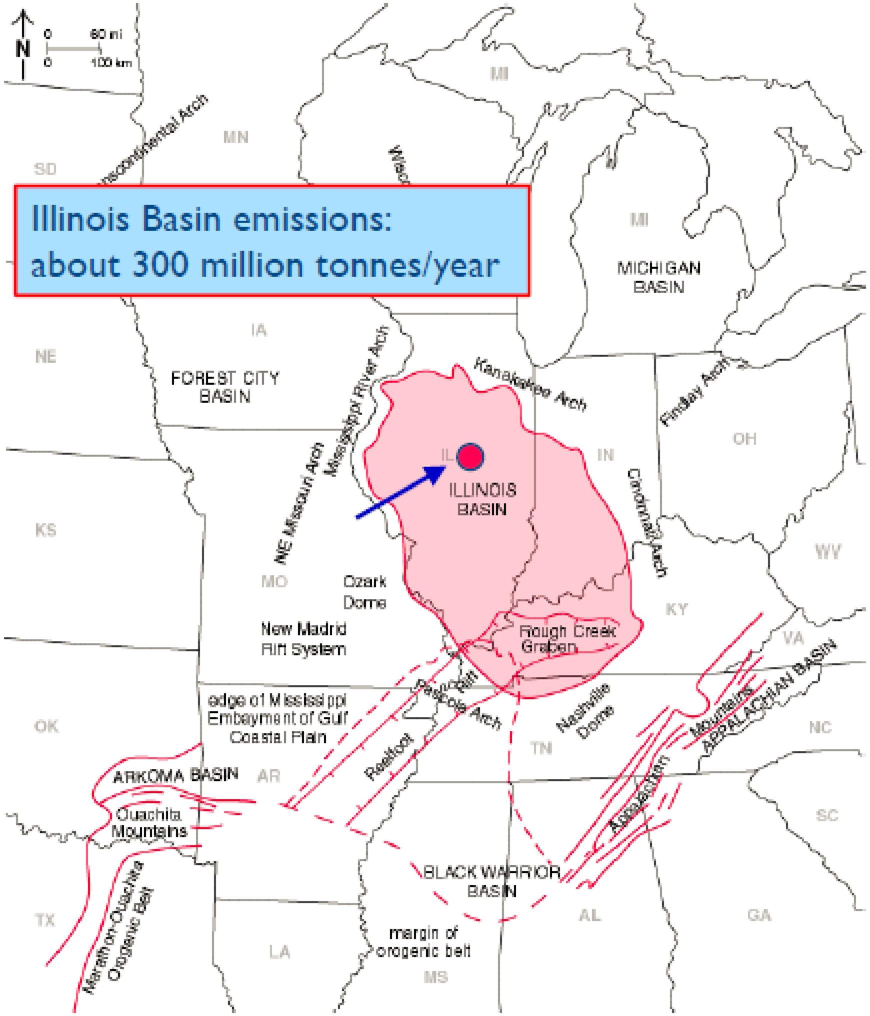
Seismic time-lapse monitoring shows that CO_2 stays in place in the Utsira Fm at Sleipner and gives a detailed description of where the CO_2 is

Furre & Eiken, 2012

The Illinois Basin - Decatur Project
Midwest Geological Sequestration Consortium

CO$_2$ Sequestration Demonstration

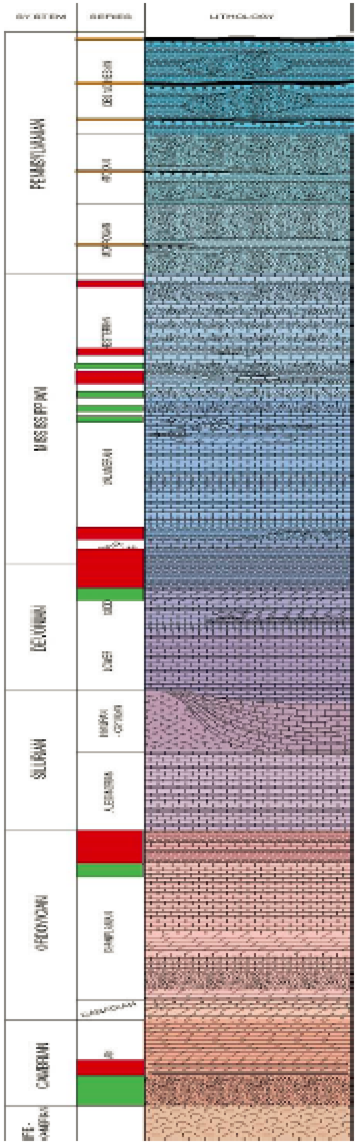
Illinois Basin – Decatur Project Scope



Illinois Basin emissions:
about 300 million tonnes/year

A collaboration of the Midwest Geological Sequestration Consortium, the Archer Daniels Midland Company (ADM), Schlumberger Carbon Services, and other subcontractors to inject 1 million metric tons of anthropogenic carbon dioxide at a depth of 7,000 +/- ft (2,000 +/- m) to test geological carbon sequestration in a saline reservoir at a site in Decatur, IL

Illinois Basin Stratigraphic Column



Pennsylvanian coal seams

New Albany Shale

back-up seals

Maquoketa Shale

St. Peter Sandstone

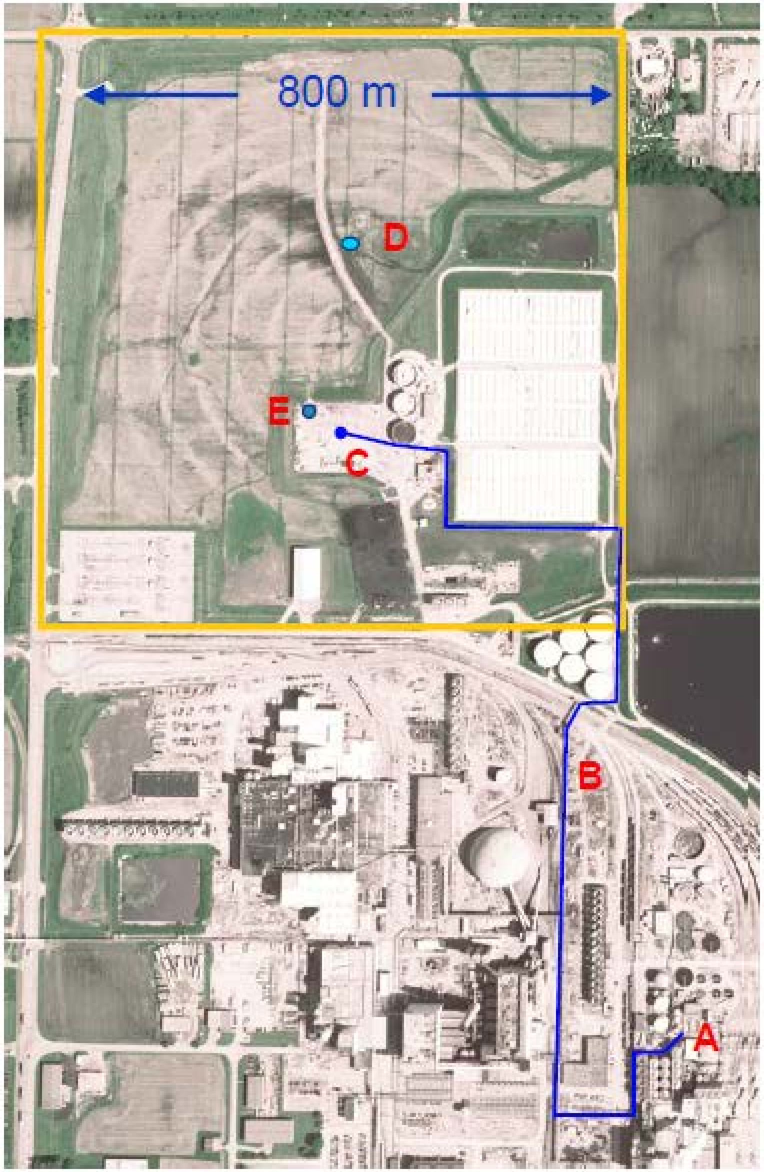
Eau Claire Shale seal

Mt. Simon Sandstone reservoir

Mount Simon Storage Capacity:
11 (E=0.4%) to 150 (E=5.5%) billior metric tons

Illinois Basin – Decatur Project Site

(on ADM industrial site)



A Dehydration/ compression facility location

B Pipeline route (1.9 km)

C Injection well site

D Verification/ monitoring well site

E Geophone well

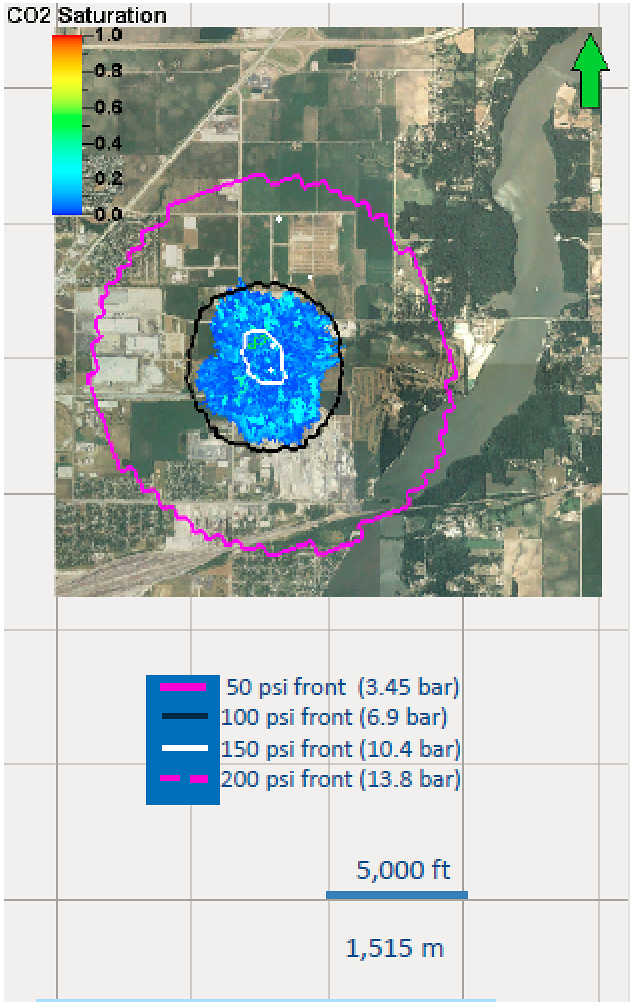
Operational Injection: 17 November 2011

- IBDP fully operational 24/7
- IBDP is the first 1 million tonne carbon capture and storage project from a biofuel facility in the US
- Injection through November 2014
- Intensive post-injection monitoring under MGSC through November 2017

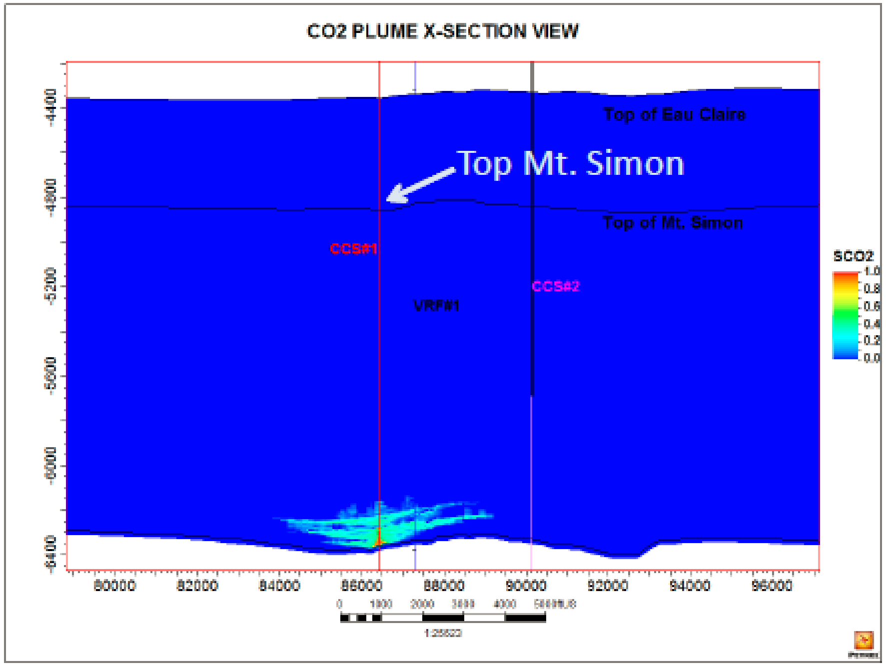
Cumulative Injection
(10 November2014):
984,000 tonnes

IBDP Modeled Plume Configuration

January 2014

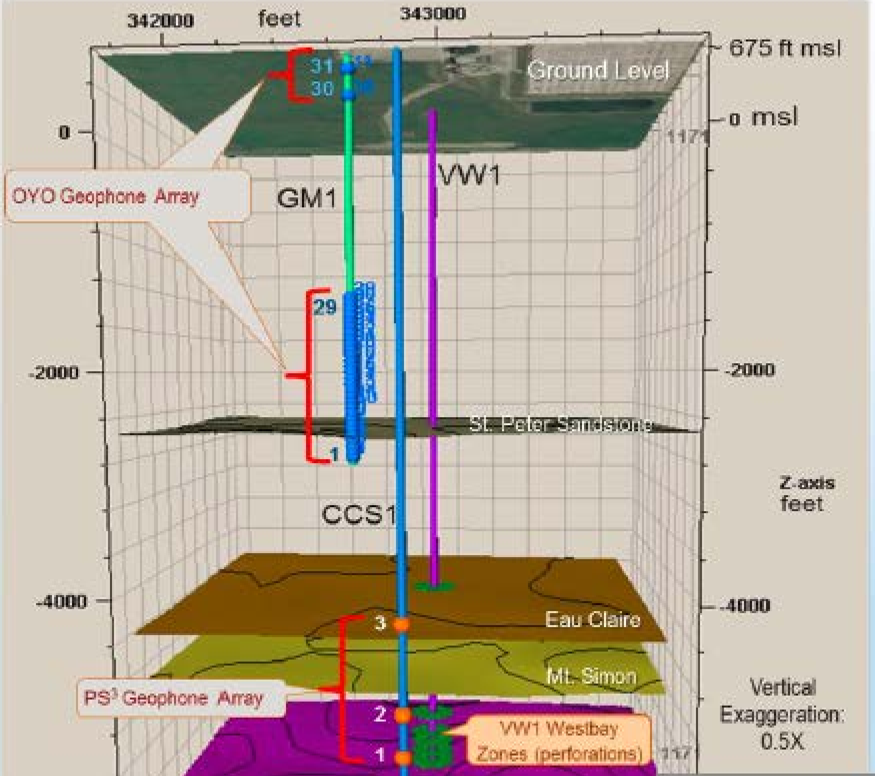


S1. No No-flow Boundaries



from Schlumberger Carbon Services

Microseismic Events Began in January 2012

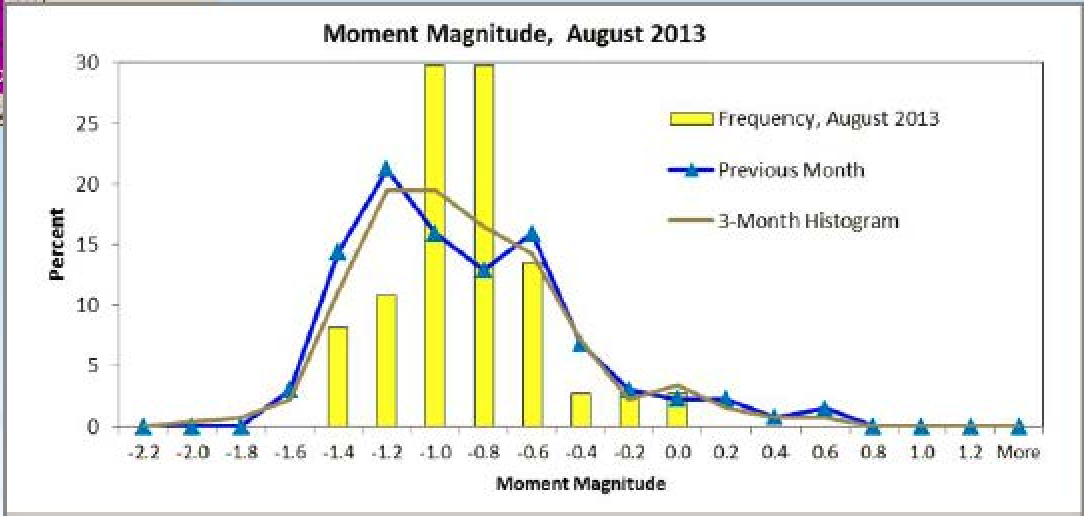


- June-August 2013: average 89 located events/month
- Mean moment magnitude = -0.98
- Max. event for three months: +0.25

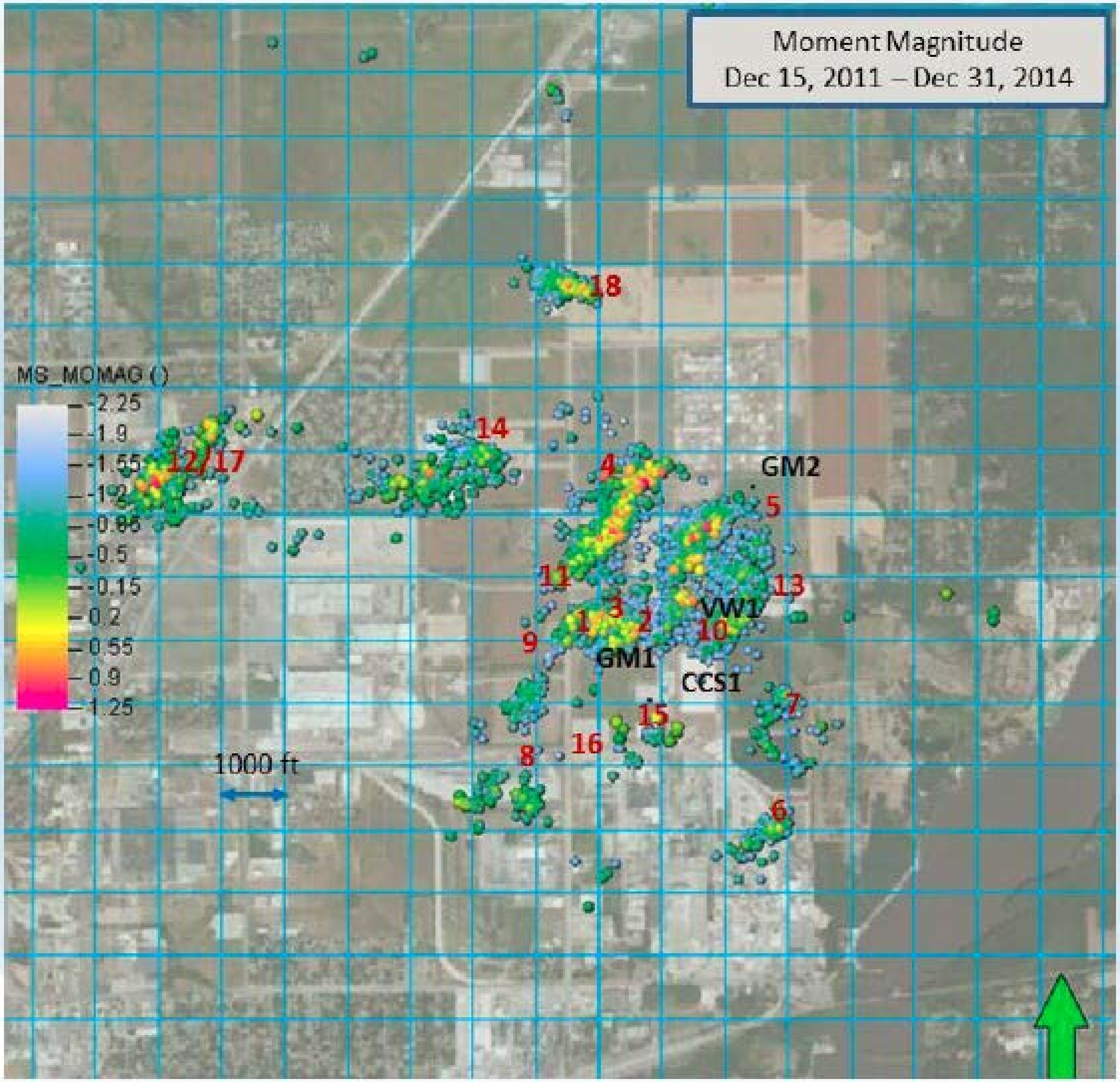
- Recent max event = +1.02 in September 2013

December 2014:
- Peak frequency at -1.2
- Peak MM at -0.05

from Schlumberger Carbon Services

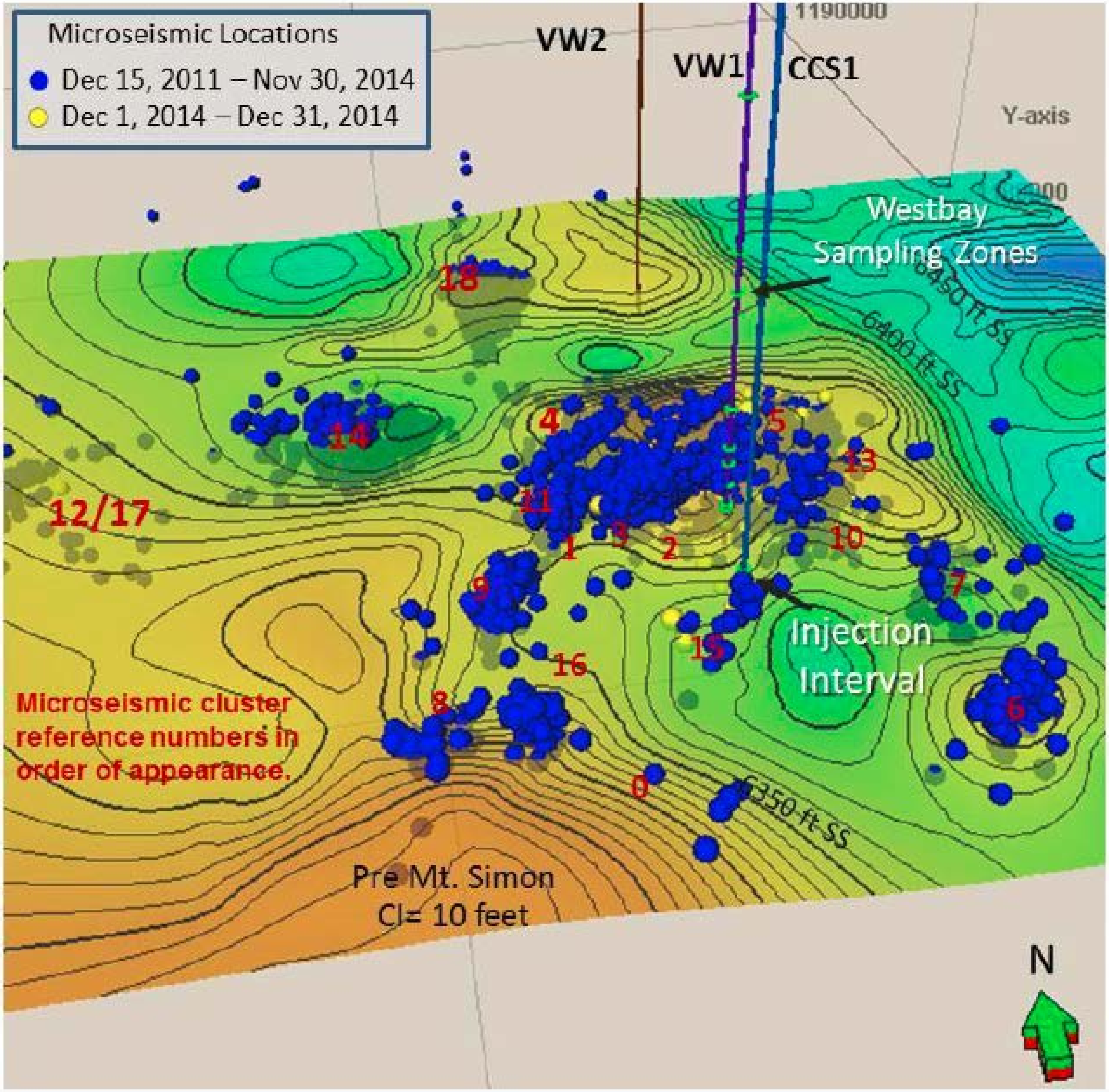


Microseismic Cluster Activity:
Cluster Locations in Relation to Surface Features



Moment Magnitude
Dec 15, 2011 – Dec 31, 2014

from Schlumberger
Carbon Services

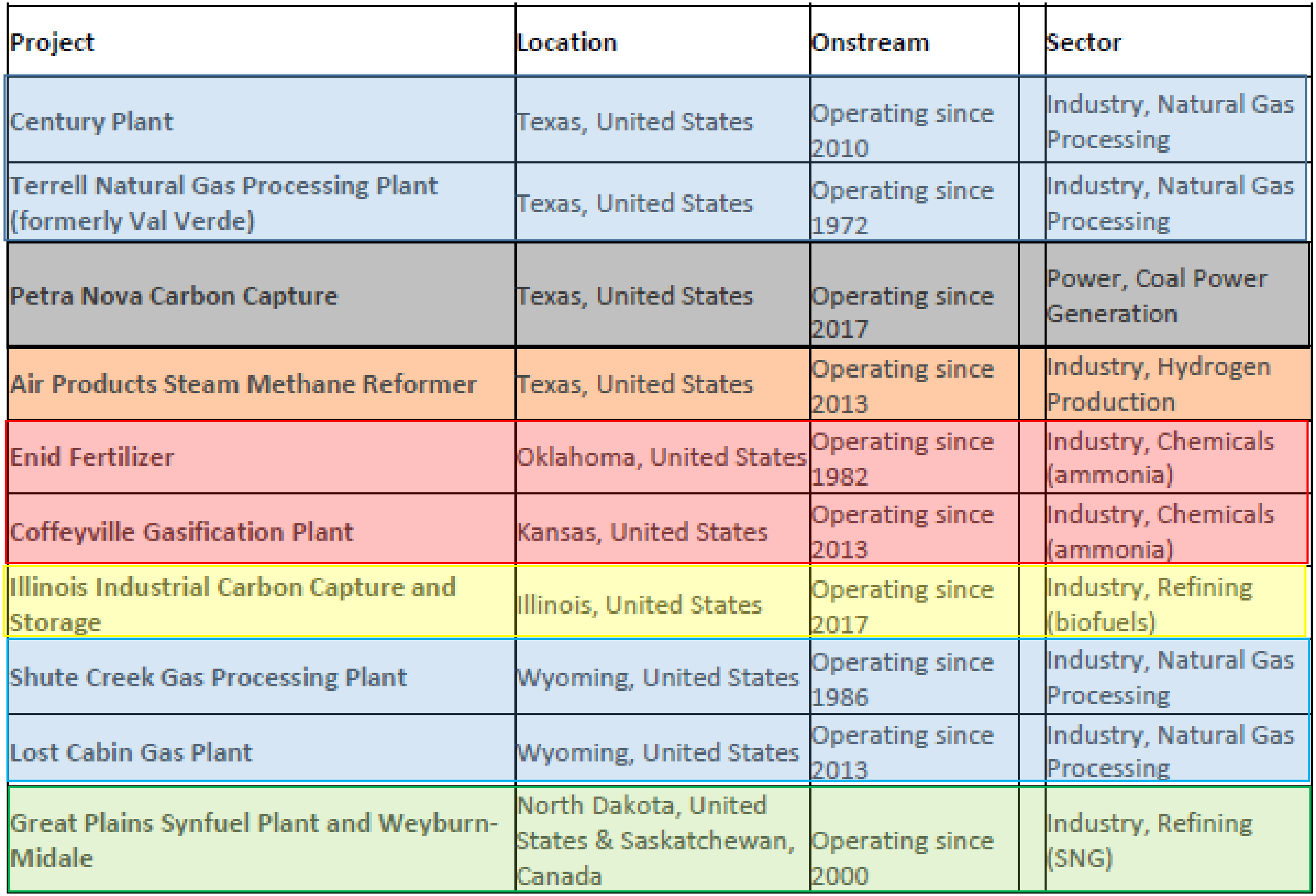


Microseismic Cluster Activity: Relationship to Basement Structure

from Schlumberger Carbon Services

Variety of Carbon Capture Applications Examples from U.S. Projects

Some U.S. Carbon Capture Projects



Project	Location	Onstream		Sector
Century Plant	Texas, United States	Operating since 2010		Industry, Natural Gas Processing
Terrell Natural Gas Processing Plant (formerly Val Verde)	Texas, United States	Operating since 1972		Industry, Natural Gas Processing
Petra Nova Carbon Capture	Texas, United States	Operating since 2017		Power, Coal Power Generation
Air Products Steam Methane Reformer	Texas, United States	Operating since 2013		Industry, Hydrogen Production
Enid Fertilizer	Oklahoma, United States	Operating since 1982		Industry, Chemicals (ammonia)
Coffeyville Gasification Plant	Kansas, United States	Operating since 2013		Industry, Chemicals (ammonia)
Illinois Industrial Carbon Capture and Storage	Illinois, United States	Operating since 2017		Industry, Refining (biofuels)
Shute Creek Gas Processing Plant	Wyoming, United States	Operating since 1986		Industry, Natural Gas Processing
Lost Cabin Gas Plant	Wyoming, United States	Operating since 2013		Industry, Natural Gas Processing
Great Plains Synfuel Plant and Weyburn-Midale	North Dakota, United States & Saskatchewan, Canada	Operating since 2000		Industry, Refining (SNG)

Natural gas processing
Fertilizer production

Coal power plant

Ethanol plant

Hydrogen production
Syngas plant

Policy Incentives for CCUS - 45Q tax credits

"Technology push" through R&D is matched with "market pull" through financial incentives

	Threshold by Facility Type (ktCO$_2$/y)			Credit in 2026 ($/t)
	Power Plant	Industrial Facility	Direct Air Capture	
Dedicated Storage	500	100	100	50
EOR	500	100	100	35
Utilization	25	25	25	35

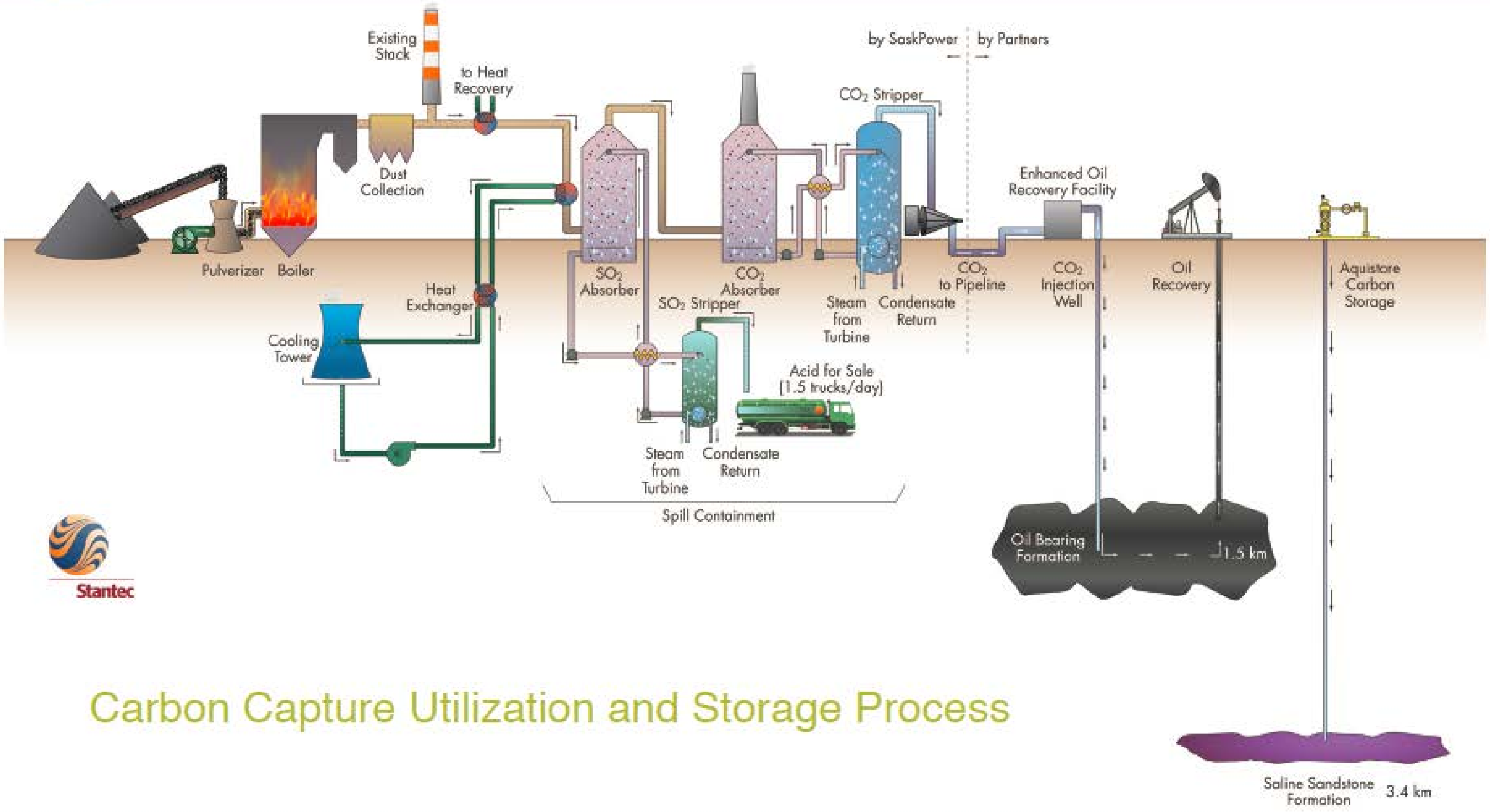
Source: McCoy, 2018

- **Credit available to qualified facilities for 12 year period**
- **Defines qualified Carbon Oxides (CO or CO$_2$)**
- **Measured at point of capture and verified at the point of disposal/injection/use**
- **Qualified facilities:**
    - 1) Construction must begin by Jan 1, 2024;
    - 2) Original planning and design includes carbon capture equipment
- **Credit can be claimed by owner of capture equipment or transferred to disposal/use entity**

CCS Power Plant Projects

Boundary Dam Integrated Carbon Capture and Storage Demonstration Project

Boundary Dam Integrated Carbon Capture and Storage Demonstration Project



Stantec

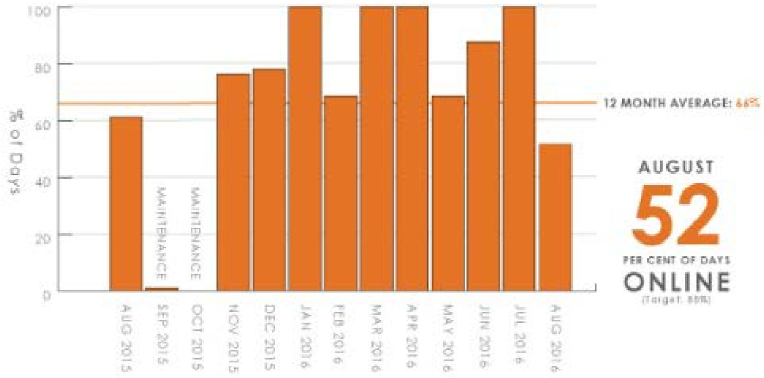
Carbon Capture Utilization and Storage Process

SaskPower Boundary Dam

BOUNDARY DAM UNIT #3

AUGUST 2016

TIME ONLINE



AUGUST

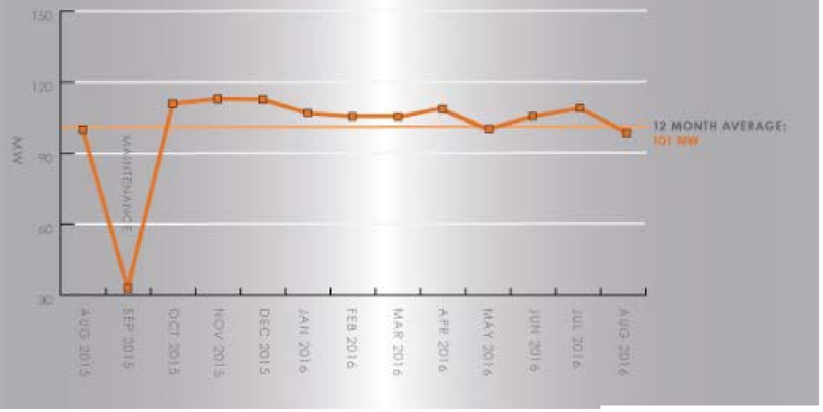
52

PER CENT OF DAYS

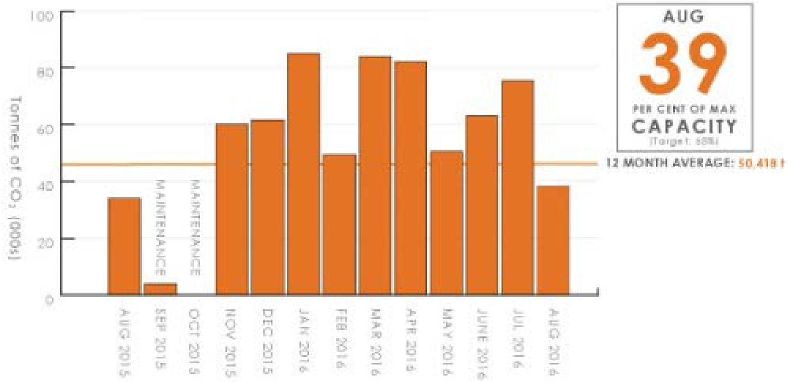
ONLINE

(Target: 85%)

POWER PRODUCED



VOLUME CAPTURED



AUG

39

PER CENT OF MAX

CAPACITY

(Target: 60%)

In August, the daily average of CO_2 captured by Unit #3

PEAKED AT 2,645 TONNES

1,067,000 TONNES

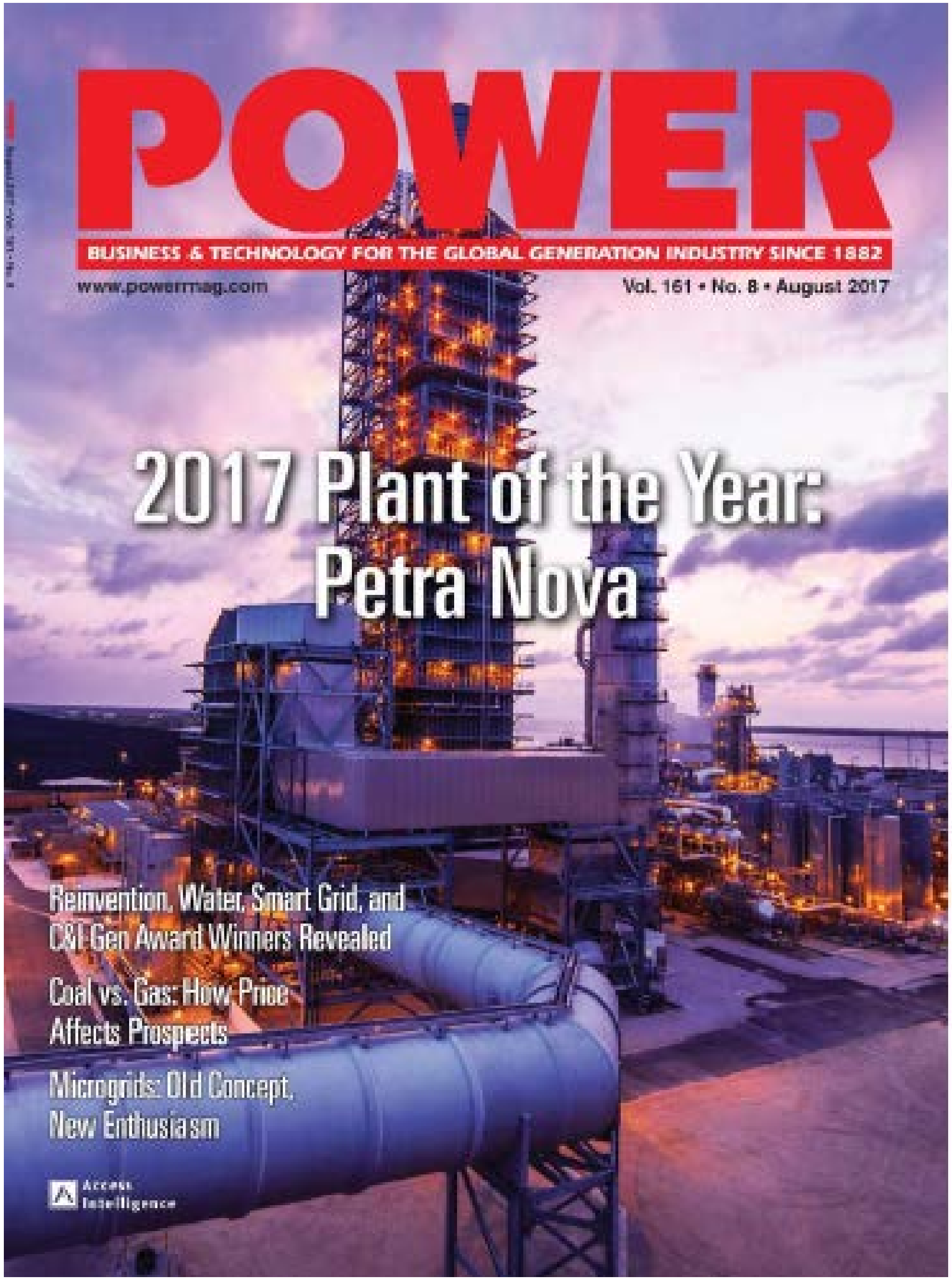
captured since operational start-up

2014: 113,600 t

2015: 426,100 t

2016: 527,000 t

Petra Nova



POWER

BUSINESS & TECHNOLOGY FOR THE GLOBAL GENERATION INDUSTRY SINCE 1882

www.powermag.com
Vol. 161 • No. 8 • August 2017

2017 Plant of the Year: Petra Nova

Reinvention, Water, Smart Grid, and C&I Gen Award Winners Revealed

Coal vs. Gas: How Price Affects Prospects

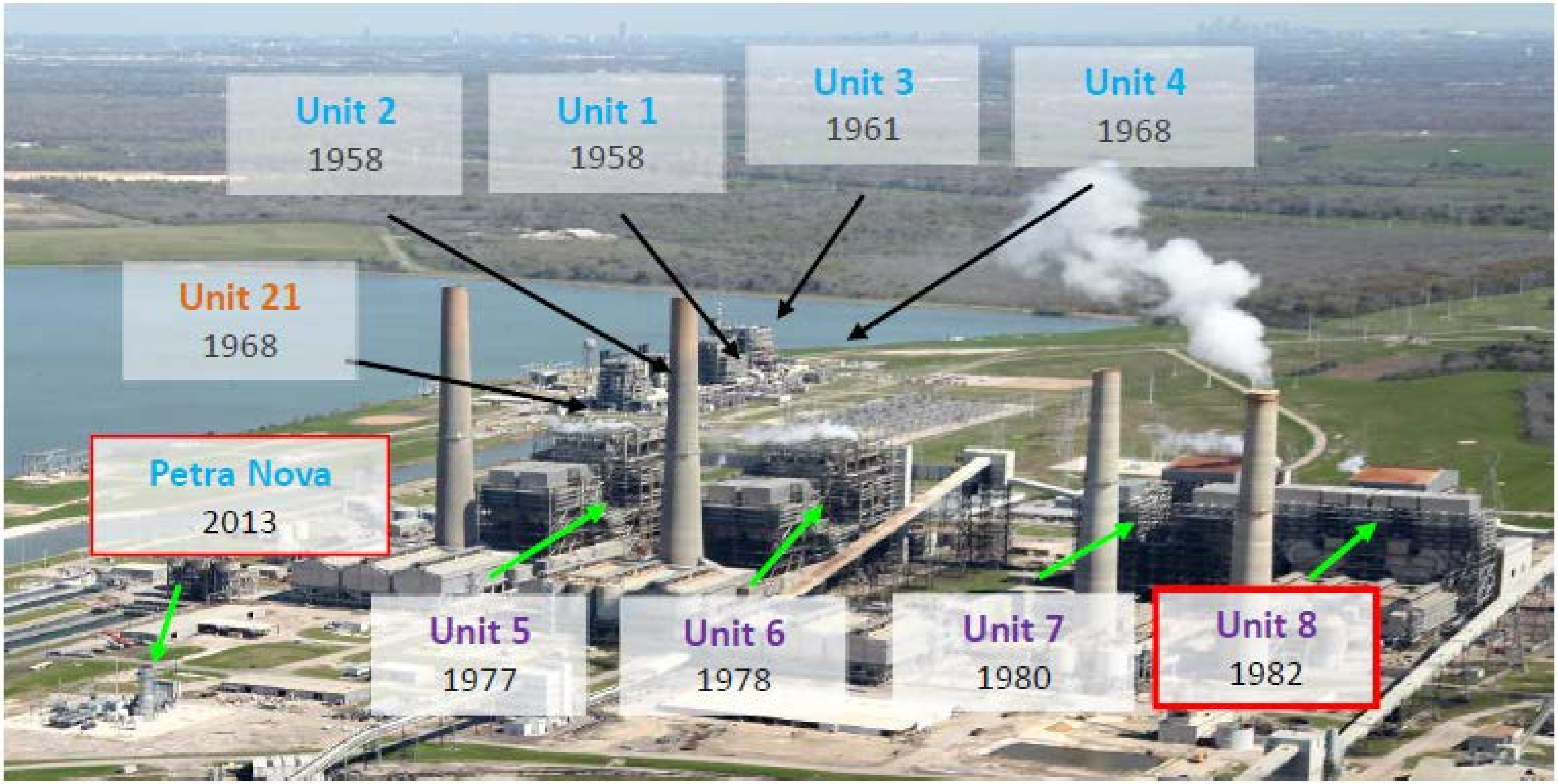
Microgrids: Old Concept, New Enthusiasm

Access Intelligence

Achieved Commercial Operation on December 29, 2016 on time and on budget

A total of 1,000,000 short tons of CO2 captured in October 2017

NRG Energy, Inc. W.A. Parish Power Plant



Coal Generation Unit : *c.a.* 2,500 MW (Unit 5-8)

Gas generation Unit : *c.a.* 1,200 MW (Unit 1-4、Unit 21(diesel) *, Petra Nova)

*Starter uni

Carbon Capture System Site Layout

- **Flue Duct** – Transports flue gas from Unit 8 to Petra Nova
- **Quencher** – SO$_2$ polishing scrubber and flue gas cooler
- **Absorber** – Amine solvent captures the CO$_2$ molecules - remaining flue gas goes out absorber stack
- **Regenerator** – Steam is introduced to separate the CO$_2$ from the amine solvent, CO$_2$ exits the top of the regenerator, solvent is recirculated to either the absorber or filtering process
- **Compressor** – compresses the CO$_2$ to up to 1,900 psi
- **CO$_2$ Pipeline** – transports the CO$_2$ to the TCV Pipeline
- **Cogeneration** – provides steam and power to the CCS facility

Levelized Cost of CO_2 Capture at Coal Fired Power Plants

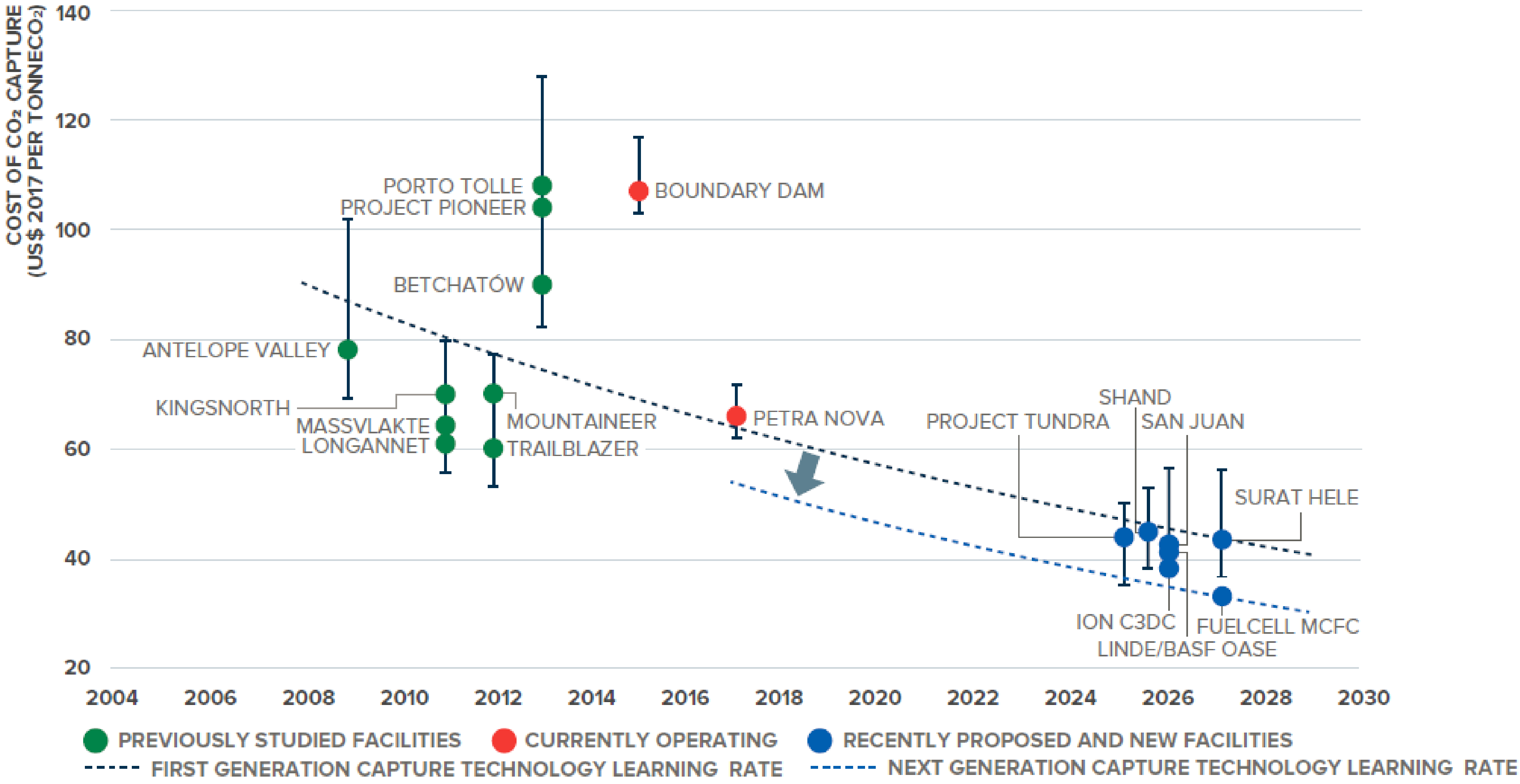
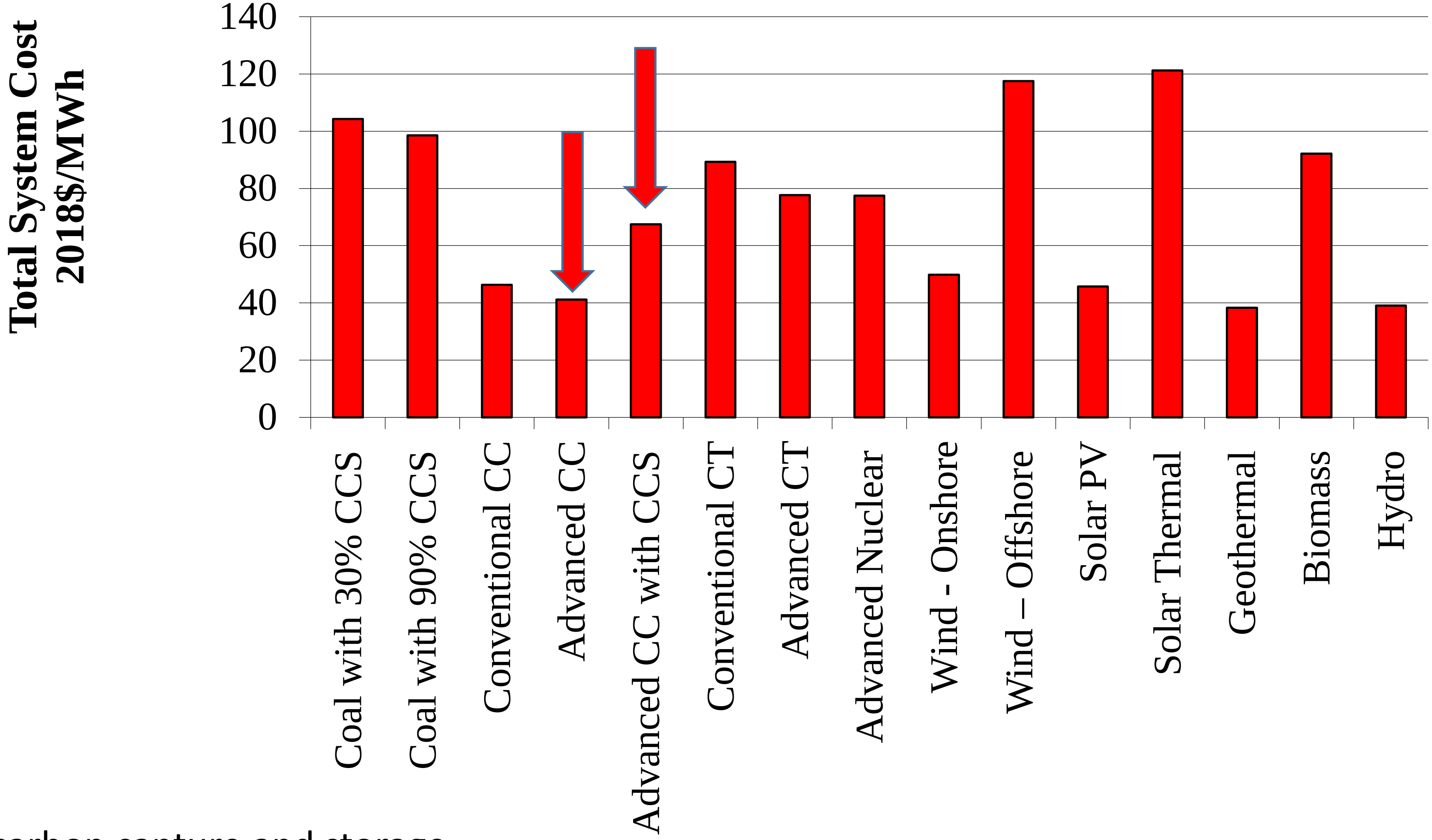


FIGURE 8 LEVELISED COST OF CO_2 CAPTURE FOR LARGE SCALE POST-COMBUSTION FACILITES AT COAL FIRED POWER PLANTS, INCLUDING PREVIOUSLY STUDIED FACILITIES[VII]

Comparison of the Cost of New Electrical Generation in U.S.

Levelized Total System Cost of New Generation Resources, 2023

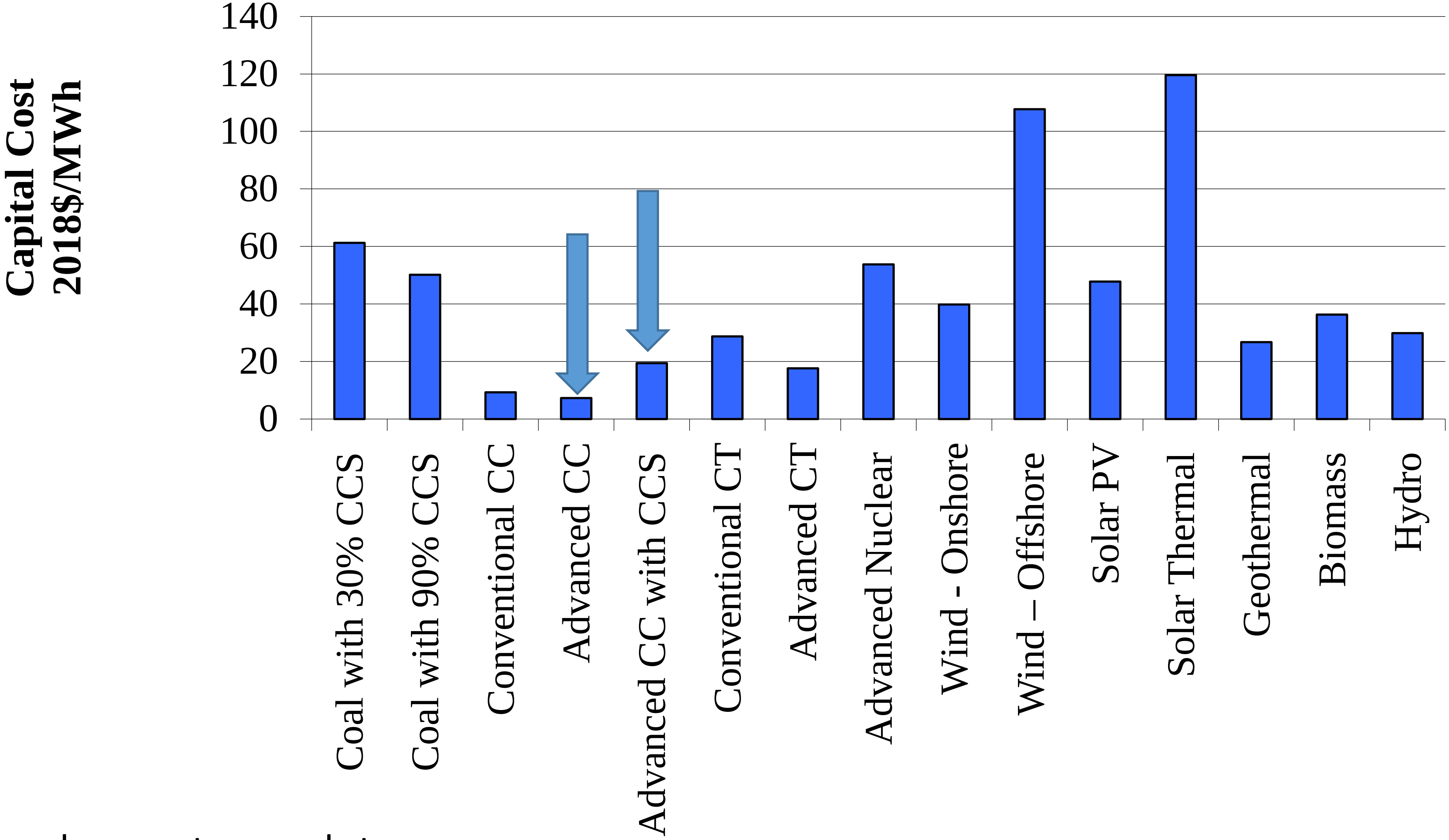


CCS: carbon capture and storage

CC: combined cycle

CT: conventional turbine

Capital Cost of
New Generation Resources, 2023

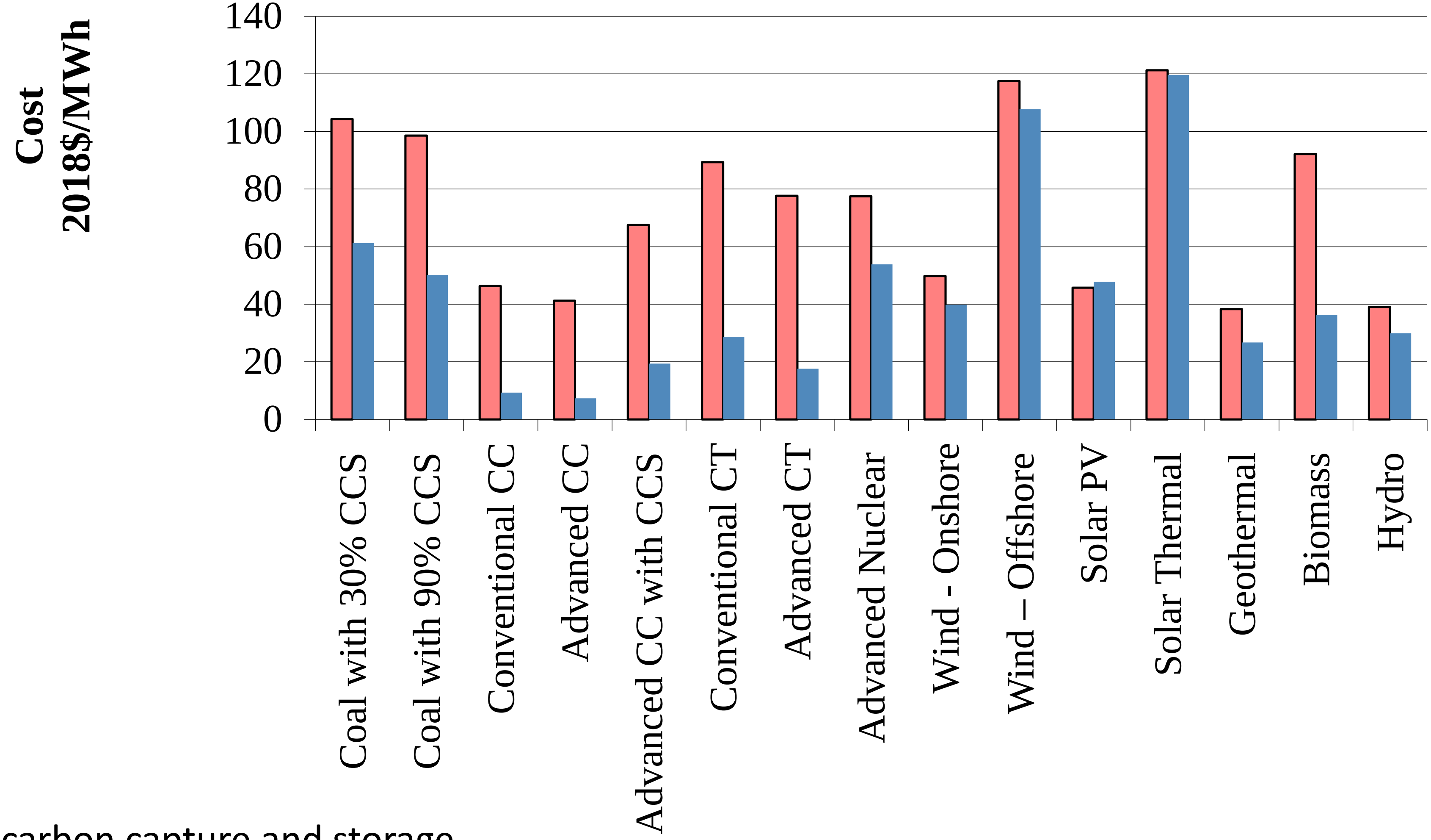


CCS: carbon capture and storage

CC: combined cycle

CT: conventional turbine

Total System Cost Capitol Cost Comparison of New Generation Resources, 2023



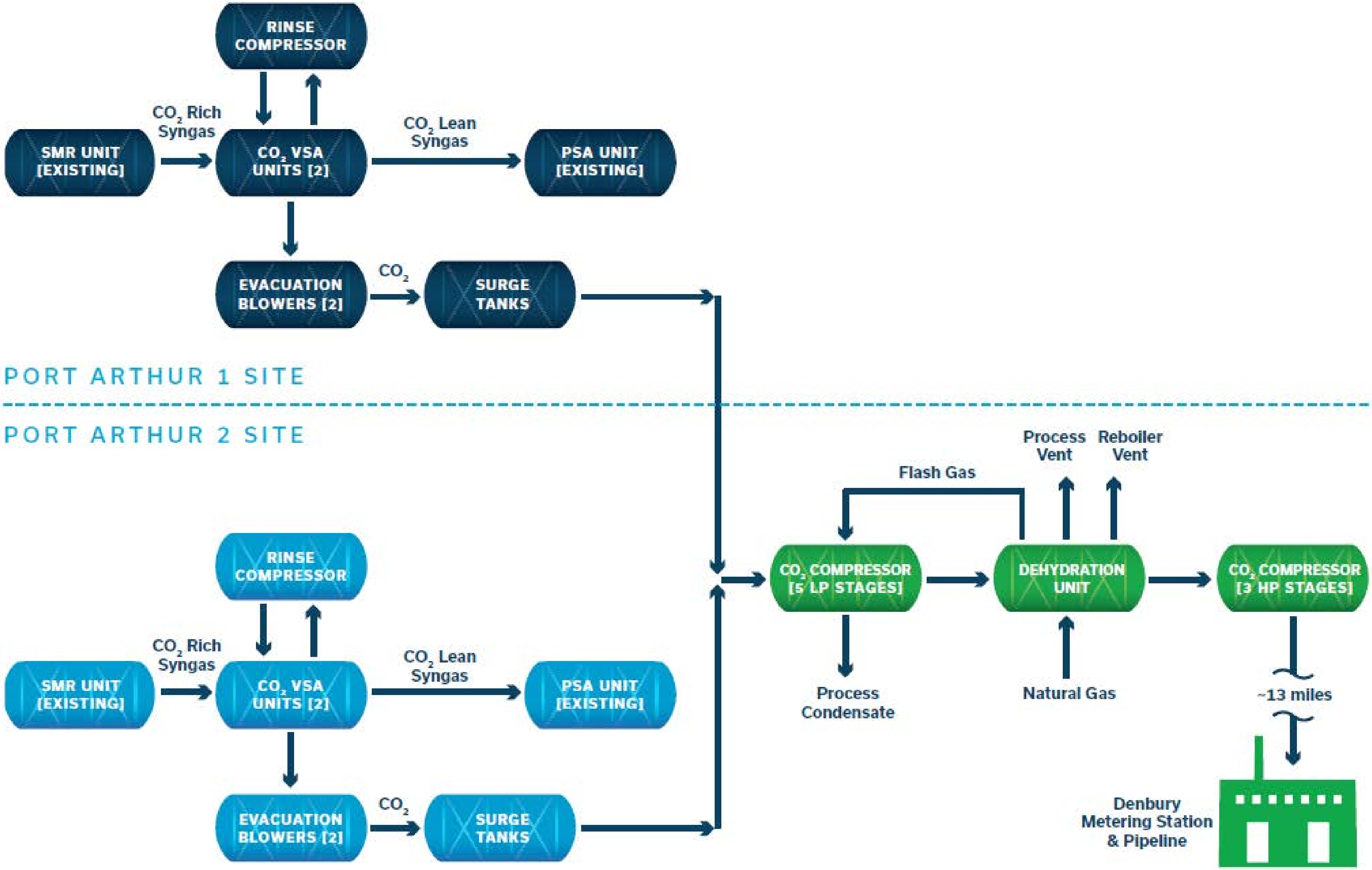
CCS: carbon capture and storage

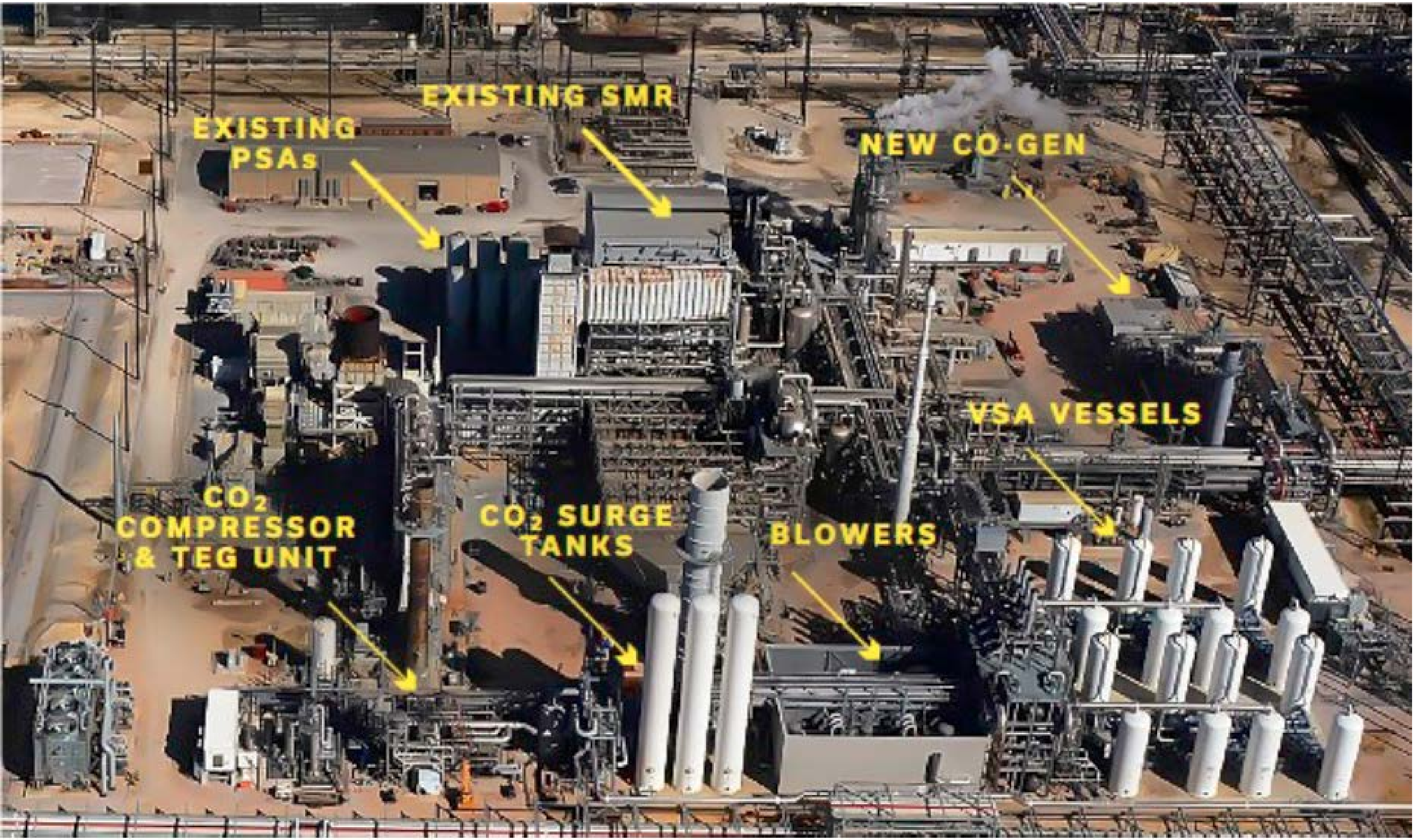
CC: combined cycle

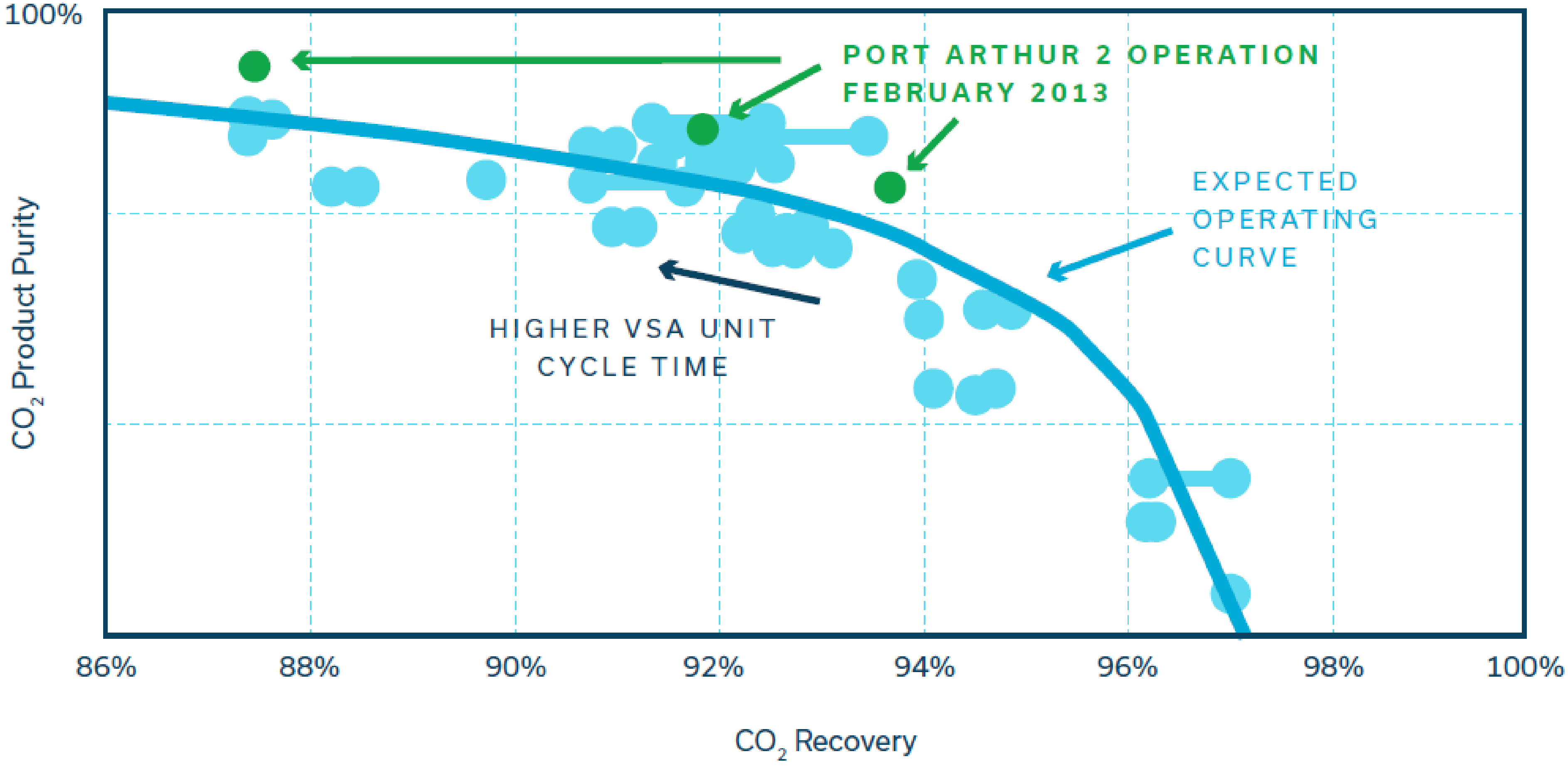
CT: conventional turbine

Carbon Capture at Hydrogen Production Facility

Port Arthur TX SMR with CCUS


RINSE COMPRESSOR
CO$_2$ Rich Syngas
SMR UNIT [EXISTING]
CO$_2$ VSA UNITS [2]
CO$_2$ Lean Syngas
PSA UNIT [EXISTING]
EVACUATION BLOWERS [2]
CO$_2$
SURGE TANKS
PORT ARTHUR 1 SITE
PORT ARTHUR 2 SITE
RINSE COMPRESSOR
CO$_2$ Rich Syngas
SMR UNIT [EXISTING]
CO$_2$ VSA UNITS [2]
CO$_2$ Lean Syngas
PSA UNIT [EXISTING]
EVACUATION BLOWERS [2]
CO$_2$
SURGE TANKS
Flash Gas
Process Vent
Reboiler Vent
CO$_2$ COMPRESSOR [5 LP STAGES]
DEHYDRATION UNIT
CO$_2$ COMPRESSOR [3 HP STAGES]
Process Condensate
Natural Gas
~13 miles
Denbury Metering Station & Pipeline


EXISTING SMR
EXISTING PSAs
NEW CO-GEN
VSA VESSELS
CO_2 COMPRESSOR & TEG UNIT
CO_2 SURGE TANKS
BLOWERS


100%
CO2 Product Purity
PORT ARTHUR 2 OPERATION
FEBRUARY 2013
EXPECTED
OPERATING
CURVE
HIGHER VSA UNIT
CYCLE TIME
86%
88%
90%
92%
94%
96%
98%
100%
CO2 Recovery

Pre-Combustion Capture Project

NATIONAL CARBON
CAPTURE CENTER

Engineering
Clean Coal Technology

CARBON CAPTURE

INTERNATIONAL TEST CENTER NETWORK

The New York Times

July 5, 2016

Piles of Dirty Secrets Behind a Model ‘Clean Coal’ Project

“Kemper coal plant [Kemper County, MS] is more than two years behind schedule and more than $4 billion over its initial budget, $2.4 billion, and it is still not operational.’

THE WALL STREET JOURNAL.

May 4, 2016

Southern’s Clean-Coal Woes Mount

Kemper facility in Mississippi now faces SEC investigation on top of skyrocketing costs

The New York Times

ROOM *for* DEBATE

Clean Coal, or a Dirty Shame?

- Arguing that we can handle the climate challenge with renewables alone is a very risky proposition. Develop a portfolio of low-carbon energy options.
- We cannot afford further investment in a pipe dream that distracts us from developing real solutions and technologies for climate change.
- Nations are still building coal plants and the U.S. is still building gas plants. Unless we do something, these plants will put billions of tons of pollution into the air.
- There are no requirements for how long the carbon dioxide must remain below ground, who owns it, who is liable for leakage.

Bloomberg
Business

February 5, 2015

FutureGen's Demise Shows Carbon Capture for Coal Faces Woes

Artist's rendering of the proposed FutureGen plant (FutureGen Alliance)

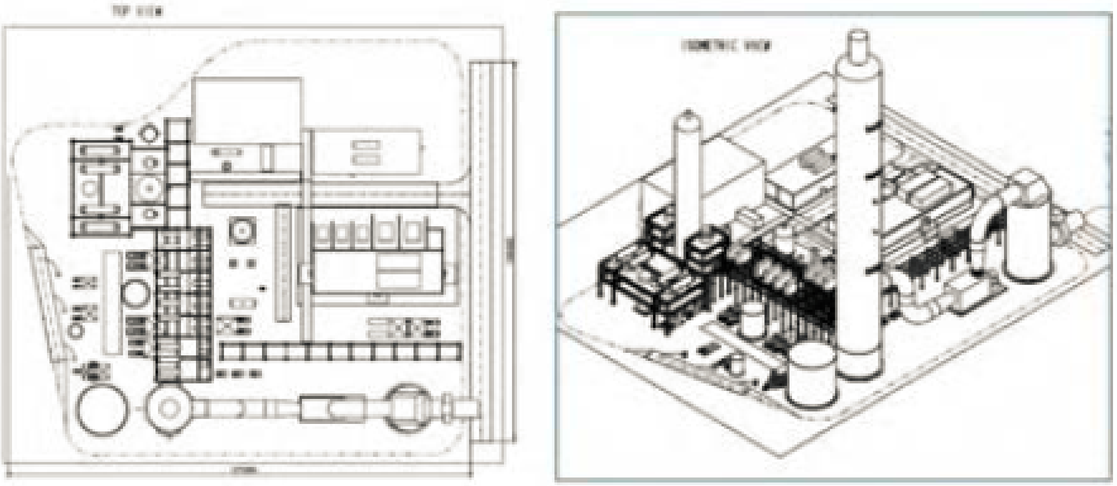
Total capital cost is ~$1.65 billion ($ 1 billion from DOE and the rest is from the private sector); Construction to start in 2014 and operations to begin in 2017

Clean Technologies by Linde

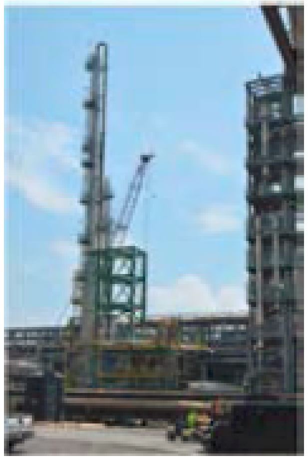
Krish R. Krishnamurthy
iSEE Congress
Champaign, IL
September 14, 2016

CAPTURING CARBON FROM ABBOTT POWER PLANT

PHASE 1 COMPLETED & PHASE 2 PROPOSAL IN EVALUATION BY DOE/NETL FOR 15 MWe CAPTURE FACILITY



Layout of Linde's 15 MWe Carbon Capture Plant at UIUC



Linde 1.5 MWe Capture Plant at National Carbon Capture Center

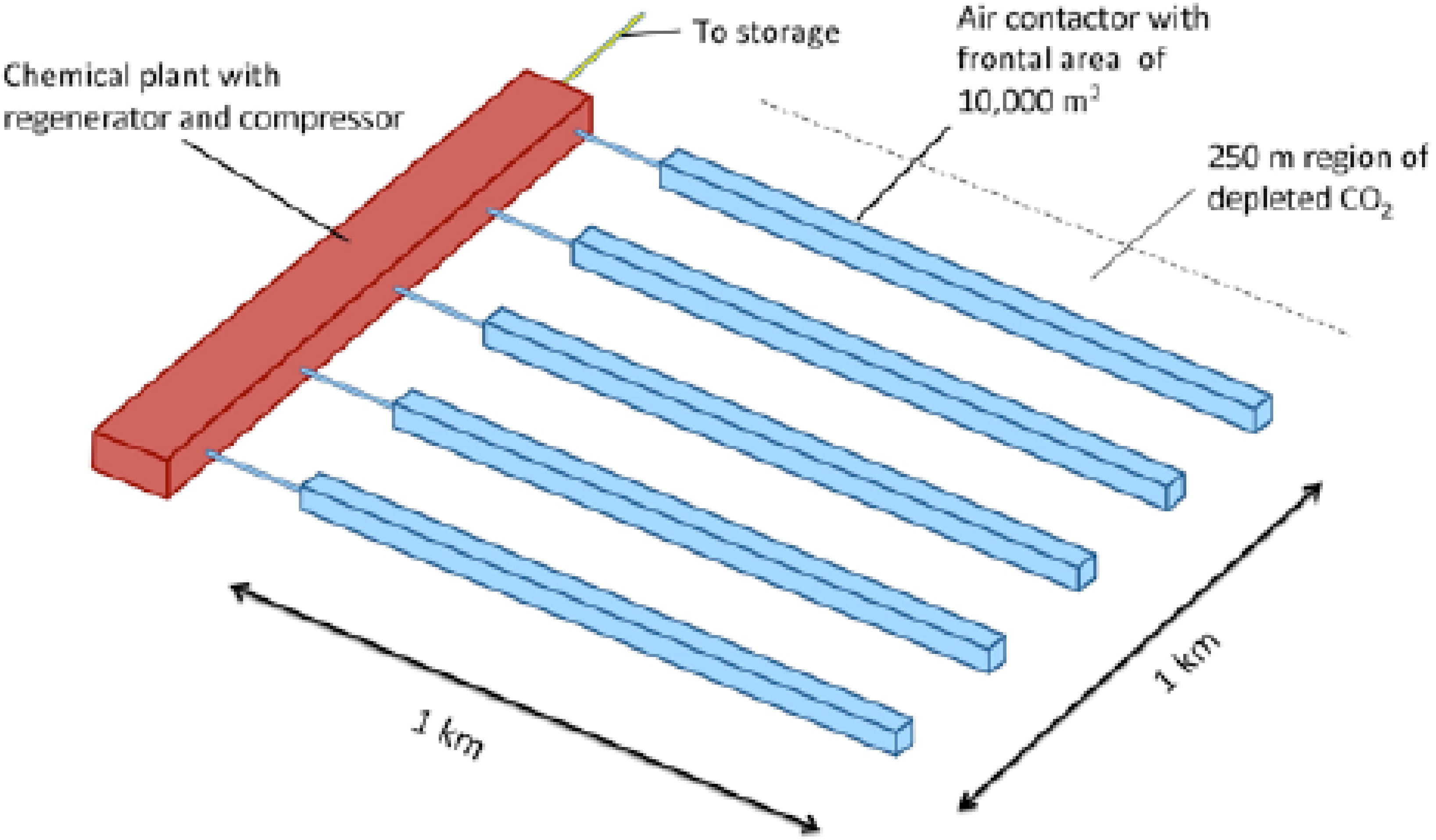
- Strong Illinois team led by University: University of Illinois, Linde, BASF, Affiliated Engineers, ACS
- Vigorously Tested, Proven, and Matured Carbon Capture Technology from Linde/BASF
- Phase 1 (Project Definition and {Pre-FEED)
- Phase 2 (build & test) is a $75 Million project; Phase 2 proposal submitted March 31, 2016
- Syndicated public / private partnership for Phase II with $58.5 Million from DOE/NETL and the remaining from the University and private sector companies
- Phase 3 plans by University to set up a CO2 utilization Research Center

CCS Summary

- Sequestration in saline aq**u**ifers demonstrated
- Techniques exist to monitor CO_2
- Various capture technologies also exist
- SaskPower and Petra Nova demonstration projects appear successful
- FutureGen 2.0 was cancelled
- Kemper County project a failure
- Capture technology successful in other applications, e.g. hydrogen production, fertilizer production with use in EOR
- Wide-spread adoption of CCS appears possible
- But, is the gigatonne scale possible?
- But, should there be continued use of fossil fuels?

Removal of CO_2 from Atmosphere
Direct Air Capture

Schematic Representation of 1Mt CO_2 per year Direct Air Capture Facility



	Post-Combustion Capture DOE/NETL Study	Direct Air Capture APS Study
CO_2 captured tons per year	2,790,000	1,000,000
Total capital cost M$	$500	$2,200
Capital cost $ per ton CO_2 captured	$22	$260
Operating cost $ per ton CO_2 captured	$40	$170
Total cost $ per ton CO_2 captured	$62	$430
Total cost $ per ton CO_2 avoided	$80	$620

Start-Up Companies in Direct Air Capture

Carbon Engineering

Industrial-scale capture of CO_2 from ambient air

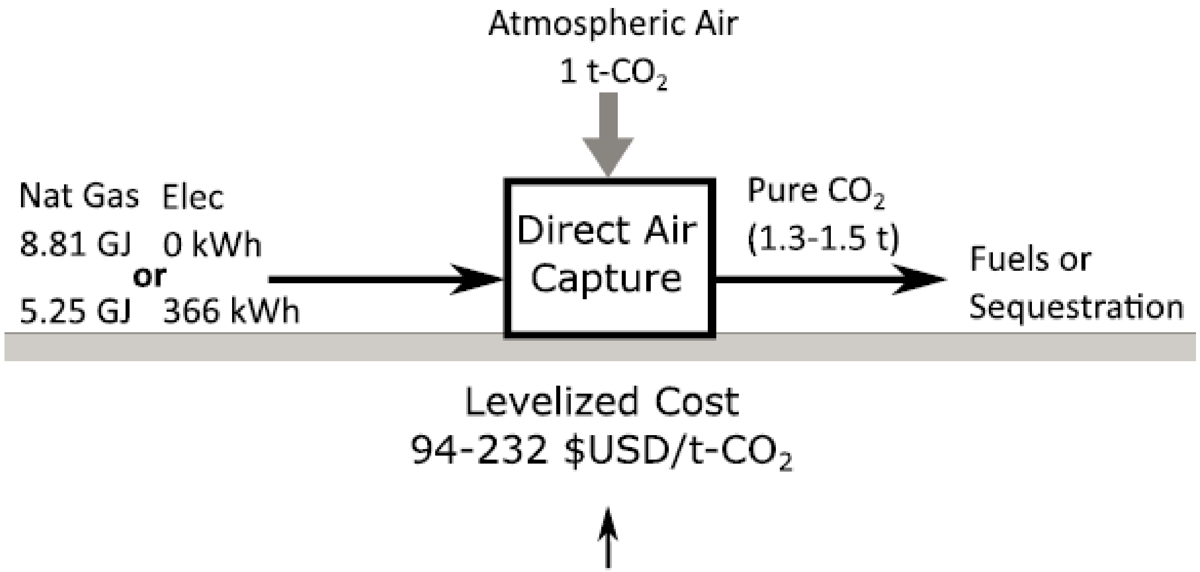
kilimanjaro energy

global thermostat

a carbon negative solution

CLIMEWORKS

Process for Capturing CO$_2$ from the Atmosphere
D. W. Keith et al., Joule 2(2018)1573



Atmospheric Air
1 t-CO$_2$

Nat Gas Elec
8.81 GJ 0 kWh
or
5.25 GJ 366 kWh

Direct Air Capture

Pure CO$_2$
(1.3-1.5 t)

Fuels or Sequestration

Levelized Cost
94-232 \$USD/t-CO$_2$

Process simulation & EPC cost estimate

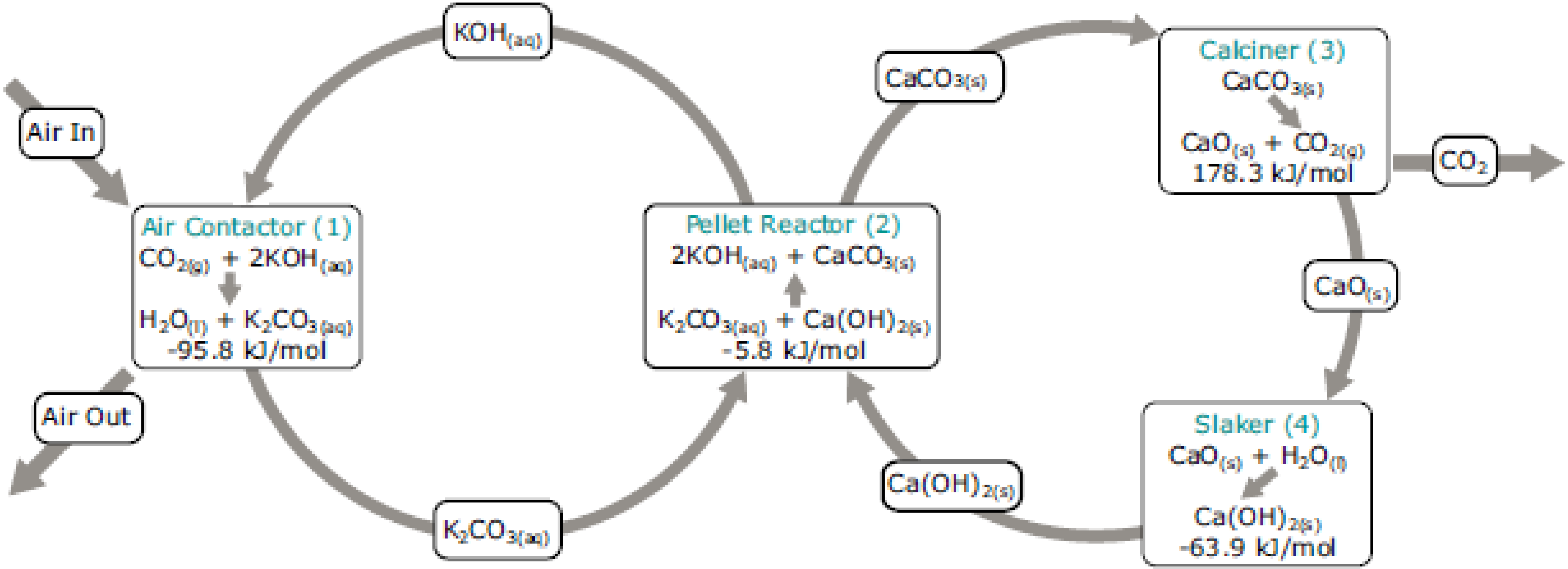
Pilot plant performance data

Commercial scale reference design

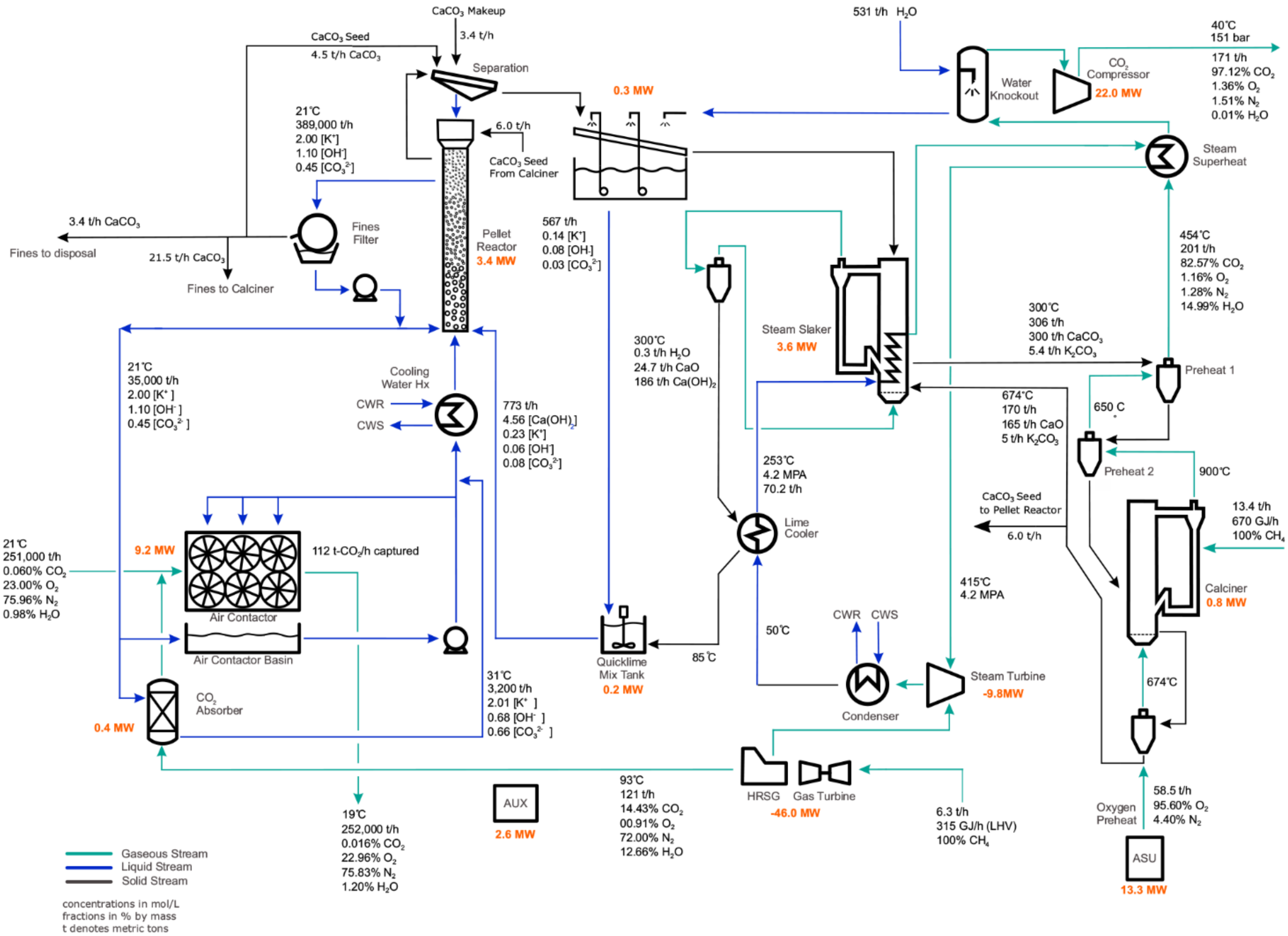
Carbon Engineering Pilot Plant Operation in 2015

Carbon Engineering Commercial Scale Design

Carbon Engineering Chemistry



Carbon Engineering Process Schematic



$CaCO_3$ Makeup
3.4 t/h

$CaCO_3$ Seed
4.5 t/h $CaCO_3$

Separation

21°C
389,000 t/h
2.00 [K^+]
1.10 [OH^-]
0.45 [CO_3^{2-}]

6.0 t/h
$CaCO_3$ Seed
From Calciner

0.3 MW

531 t/h H_2O

Water
Knockout

CO_2
Compressor
22.0 MW

40°C
151 bar
171 t/h
97.12% CO_2
1.36% O_2
1.51% N_2
0.01% H_2O

Steam
Superheat

3.4 t/h $CaCO_3$
Fines to disposal

21.5 t/h $CaCO_3$
Fines to Calciner

Fines
Filter

Pellet
Reactor
3.4 MW

567 t/h
0.14 [K^+]
0.08 [OH^-]
0.03 [CO_3^{2-}]

454°C
201 t/h
82.57% CO_2
1.16% O_2
1.28% N_2
14.99% H_2O

Steam Slaker
3.6 MW

300°C
306 t/h
300 t/h $CaCO_3$
5.4 t/h K_2CO_3

Preheat 1

300°C
0.3 t/h H_2O
24.7 t/h CaO
186 t/h $Ca(OH)_2$

21°C
35,000 t/h
2.00 [K^+]
1.10 [OH^-]
0.45 [CO_3^{2-}]

Cooling
Water Hx
CWR
CWS

773 t/h
4.56 [$Ca(OH)_2$]
0.23 [K^+]
0.06 [OH^-]
0.08 [CO_3^{2-}]

674°C
170 t/h
165 t/h CaO
5 t/h K_2CO_3

650°C

Preheat 2

900°C

253°C
4.2 MPA
70.2 t/h

Lime
Cooler

$CaCO_3$ Seed
to Pellet Reactor
6.0 t/h

13.4 t/h
670 GJ/h
100% CH_4

21°C
251,000 t/h
0.060% CO_2
23.00% O_2
75.96% N_2
0.98% H_2O

9.2 MW

Air Contactor

112 t-CO_2/h captured

Air Contactor Basin

415°C
4.2 MPA

Calciner
0.8 MW

50°C

CWR CWS

85°C

Quicklime
Mix Tank
0.2 MW

31°C
3,200 t/h
2.01 [K^+]
0.68 [OH^-]
0.66 [CO_3^{2-}]

Steam Turbine
-9.8MW

Condenser

674°C

CO_2
Absorber
0.4 MW

HRSG
-46.0 MW

Gas Turbine

93°C
121 t/h
14.43% CO_2
00.91% O_2
72.00% N_2
12.66% H_2O

6.3 t/h
315 GJ/h (LHV)
100% CH_4

Oxygen
Preheat

58.5 t/h
95.60% O_2
4.40% N_2

AUX
2.6 MW

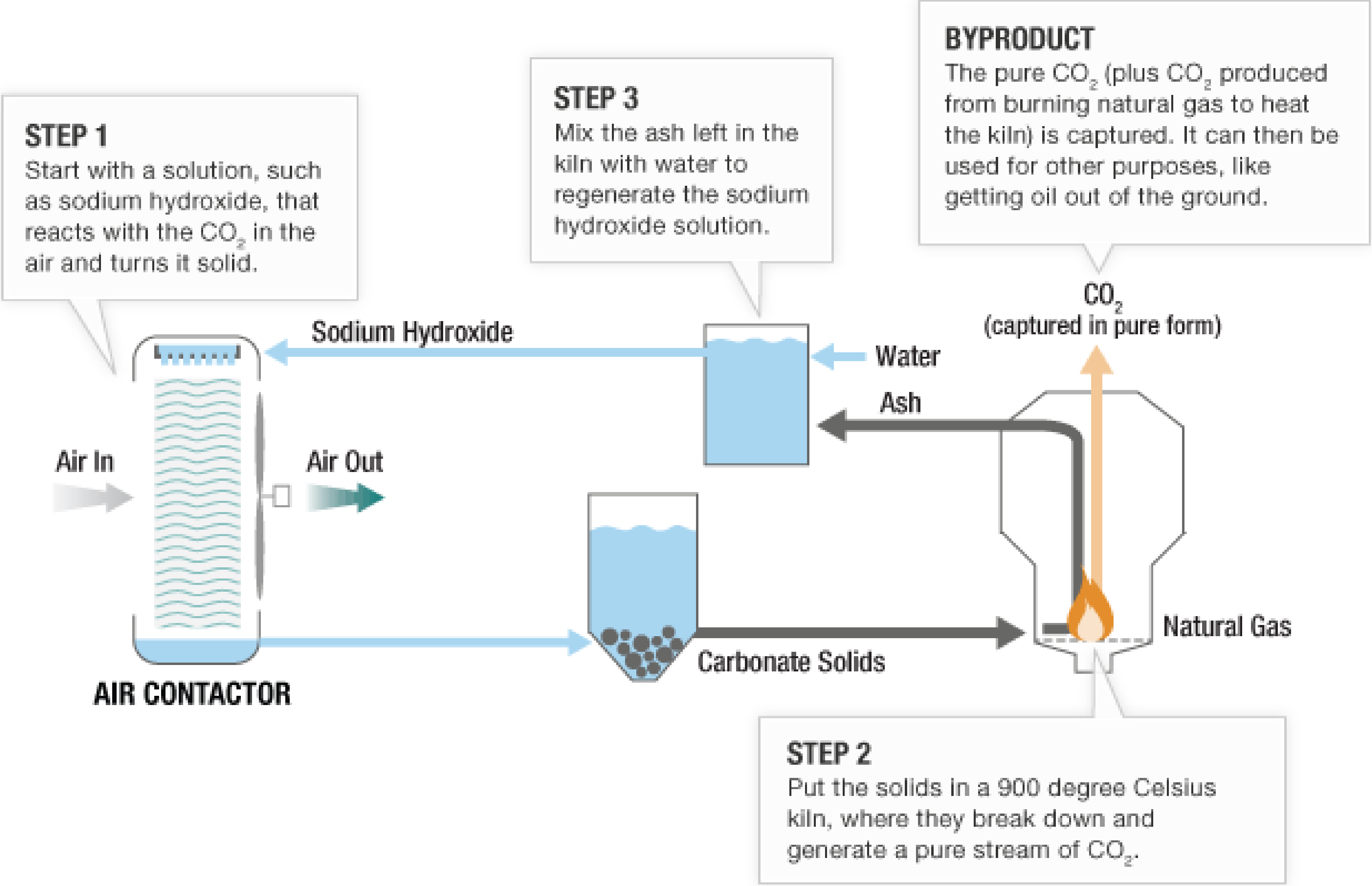
19°C
252,000 t/h
0.016% CO_2
22.96% O_2
75.83% N_2
1.20% H_2O

ASU
13.3 MW

Gaseous Stream
Liquid Stream
Solid Stream

concentrations in mol/L
fractions in % by mass
t denotes metric tons

Carbon Engineering Process Simplified



STEP 1
Start with a solution, such as sodium hydroxide, that reacts with the CO_2 in the air and turns it solid.

STEP 3
Mix the ash left in the kiln with water to regenerate the sodium hydroxide solution.

BYPRODUCT
The pure CO_2 (plus CO_2 produced from burning natural gas to heat the kiln) is captured. It can then be used for other purposes, like getting oil out of the ground.

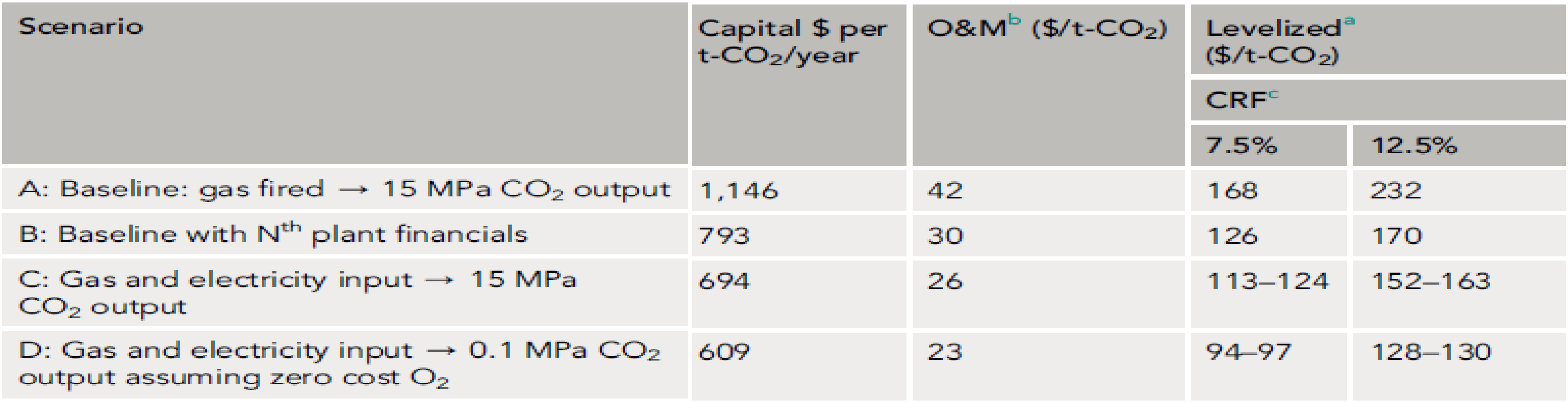
STEP 2
Put the solids in a 900 degree Celsius kiln, where they break down and generate a pure stream of CO_2.

H. Rickover (1953)
“the academic” versus “the practical”

An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose ("omnibus reactor"). (7) Very little development is required. It will use mostly “off-the-shelf” components. (8) The reactor is in the study phase. It is not being built now.

On the other hand, a practical reactor plant can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It is requiring an immense amount of development on apparently trivial items. Corrosion, in particular, is a problem. (4) It is very expensive. (5) It takes a long time to build because of the engineering development problems. (6) It is large. (7) It is heavy. (8) It is complicated.

Carbon Engineering Cost Estimates



Scenario	Capital $ per t-CO_2/year	O&M[b] ($/t-$CO_2$)	Levelized[a] ($/t-$CO_2$)	
			CRF[c]	
			7.5%	12.5%
A: Baseline: gas fired → 15 MPa CO_2 output	1,146	42	168	232
B: Baseline with N^{th} plant financials	793	30	126	170
C: Gas and electricity input → 15 MPa CO_2 output	694	26	113–124	152–163
D: Gas and electricity input → 0.1 MPa CO_2 output assuming zero cost O_2	609	23	94–97	128–130

Capital cost 1 $MtCO_2$ per year 1st plant $1,127 M, Nth plant $780 M
Levelized cost $94 - $232 per tCO_2

Negative Emissions Summary

- Carbon burden in the atmosphere has increased by 230 Gt compared to pre-industrial times
- For comparison global coal production in 2015 was approximately 8 Gt.
- Enhanced weathering requires massive mining operations.
- Afforestation and reforestation in tropics could sequester CO_2, but significant land required.
- Ocean-based removal experiments have had some success.
- Bioenergy plus carbon capture and sequestration requires CCS, which has had limited success.
- Direct air capture appears feasible.
- Currently, there is no policy or economic incentive to remove carbon from the atmosphere.

Net Zero Emissions Summary [separate document]