

Optimizing Geoengineering schemes for CO₂ Capture from Air

Putting together ideas from:

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Denis BONNELLE, F. Jeffrey MARTIN,
William L. KUBIC, John HOLBROOK,
et al (and many others...)*

by Renaud de_RICHTER

CO₂ Capture from Air

*Air capture is (arguably) a form of **geoengineering** because it directly modifies the biosphere and would be implemented with the aim of counterbalancing other human actions*

2000: Keith, D.W., Geoengineering the Climate: “History and Prospect”. *Ann. Rev. Energy and Environ.*, **25**, 245-284

Air extraction is an appealing concept, because it separates the source from disposal. One could collect CO₂ after the fact and from any source
Air extraction could reduce atmospheric CO₂ levels without making the existing energy or transportation infrastructure obsolete. There would be no need for a network of pipelines shipping CO₂ from its source to its disposal site. The atmosphere would act as a temporary storage and transport system.

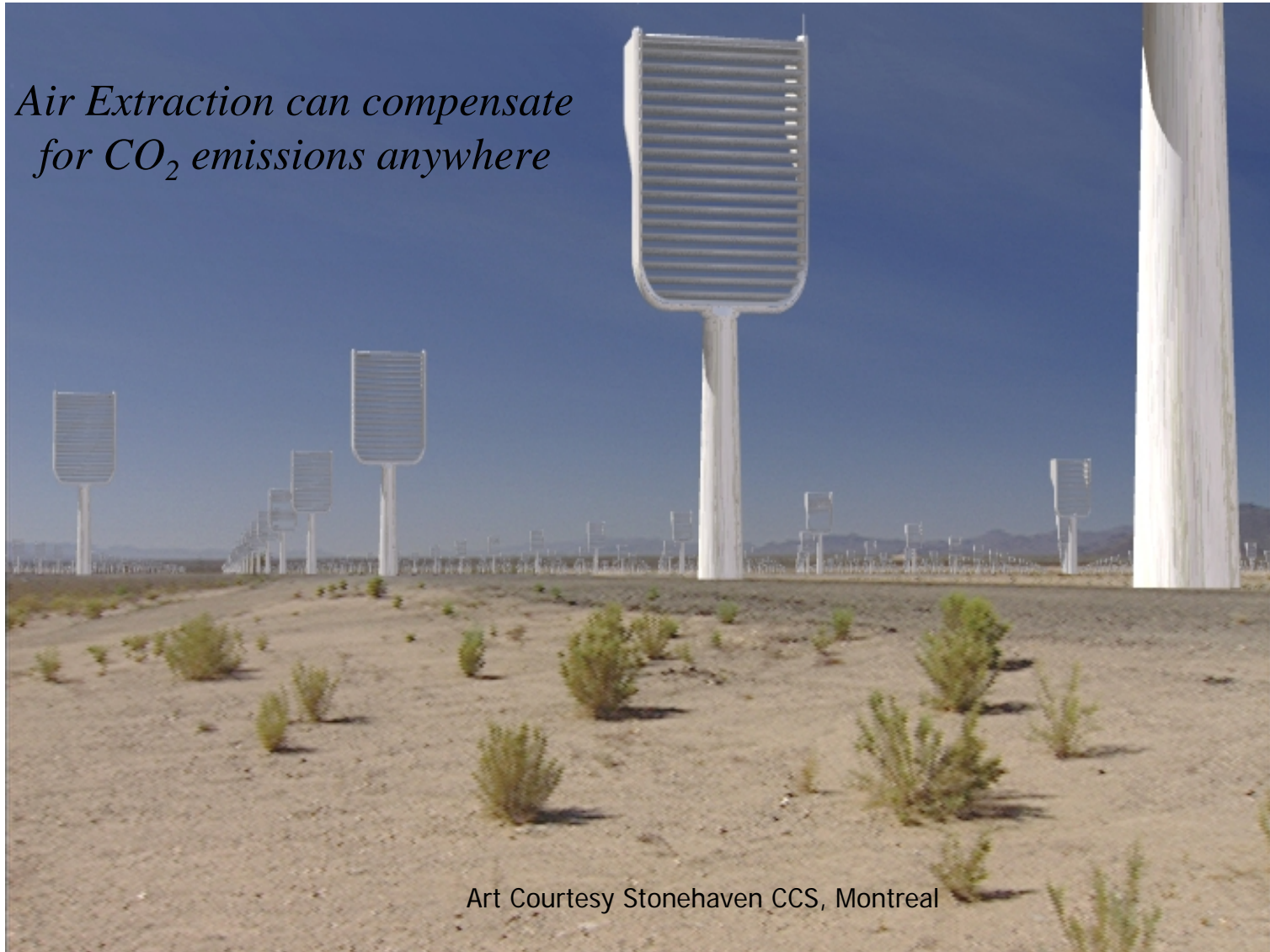
2001: Elliott, S., Lackner K.S. et al., Compensation of atmospheric CO₂ build-up through engineered chemical sinkage. *Geophysical Research Letters*, **28**, 1235-1238

2003 LACKNER

Air capture with synthetic trees

*Air Extraction can compensate
for CO₂ emissions anywhere*

*250,000
“synthetic trees”
worldwide would
be needed
to soak up the
22 billion tones
of CO₂ produced
annually*

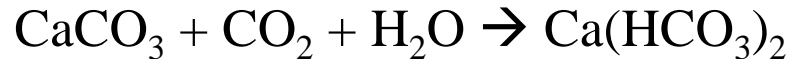
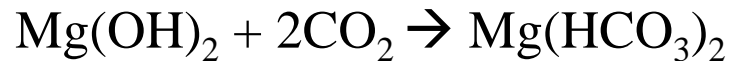
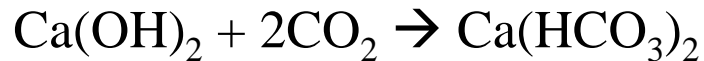
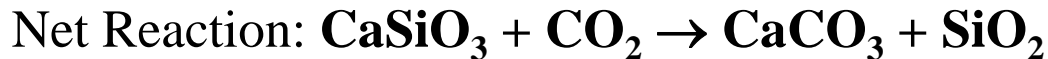
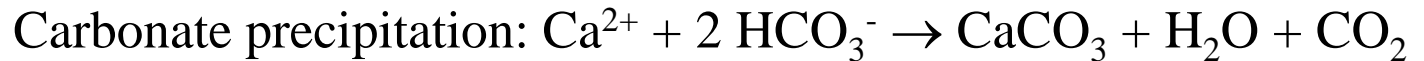


Art Courtesy Stonehaven CCS, Montreal

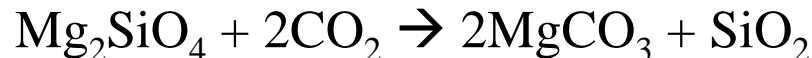
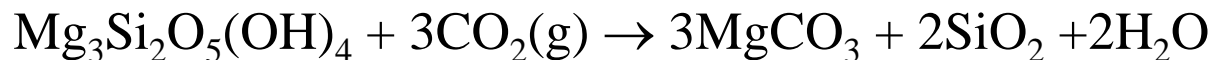
Some ideas for CO₂ Capture from Air

In recent years, carbonation of magnesium- and calcium- based silicates has emerged as a potential option for mitigation of the global climate change by storing carbon dioxide (CO₂) as inert carbonates.

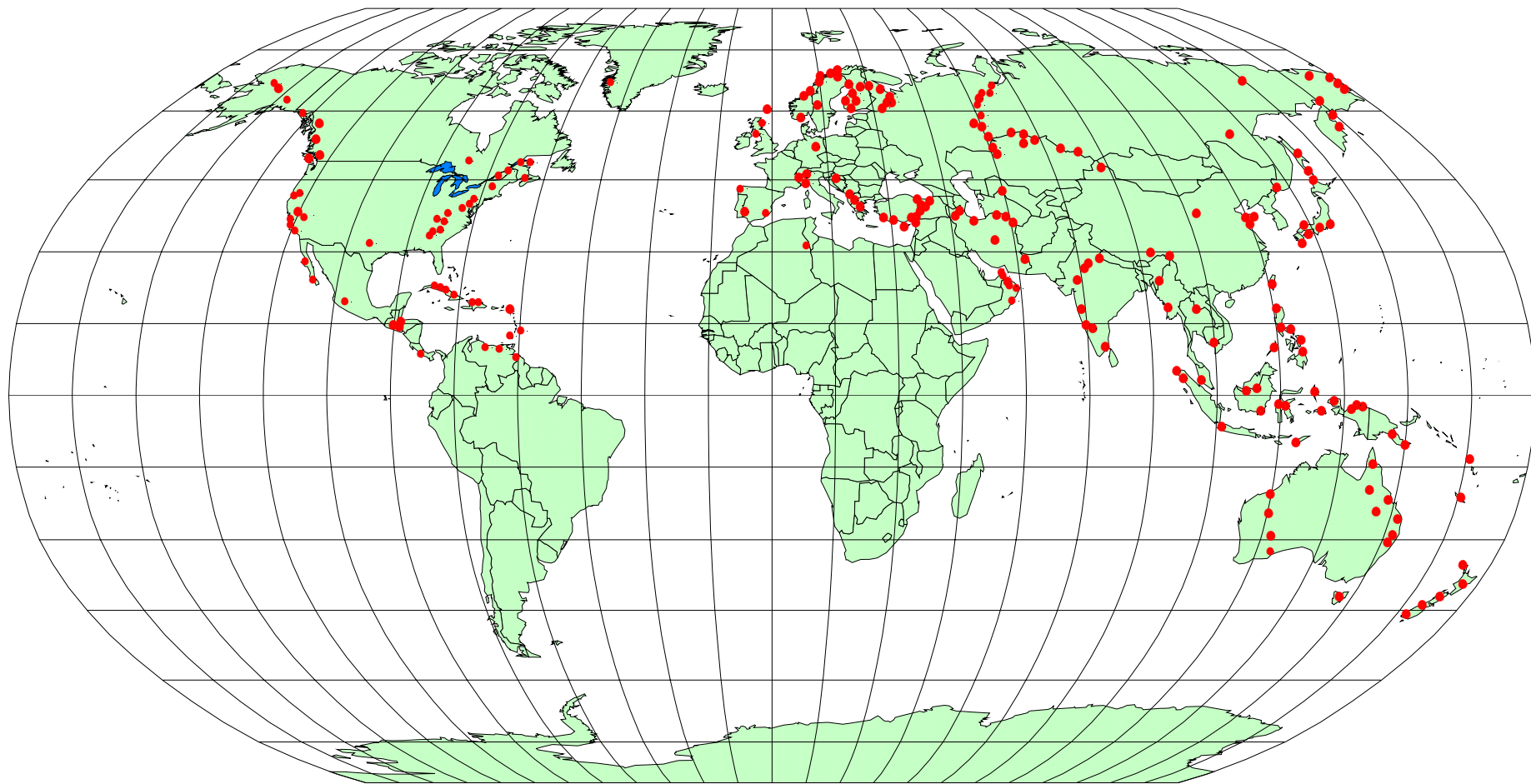
Silicate Mineral Weathering: based on dissolution of calcium silicate minerals



Serpentine Mg₃Si₂O₅(OH)₄ and Olivine Mg₂SiO₄ are the most abundant Mg-silicates



1997 LACKNER **Carbonation of magnesium silicates**
Peridotite and Serpentinite Ore Bodies



Magnesium resources far exceed world fossil fuel supplies

Air capture by increasing ocean alkalinity

2007 HOUSE and colleagues propose building hundreds of special water treatment facilities worldwide that would remove hydrochloric acid from the ocean by electrolysis and neutralize the acid through reactions with silicate minerals or rocks. ... *About 700 plants could offset 15% of all CO₂ emissions...*

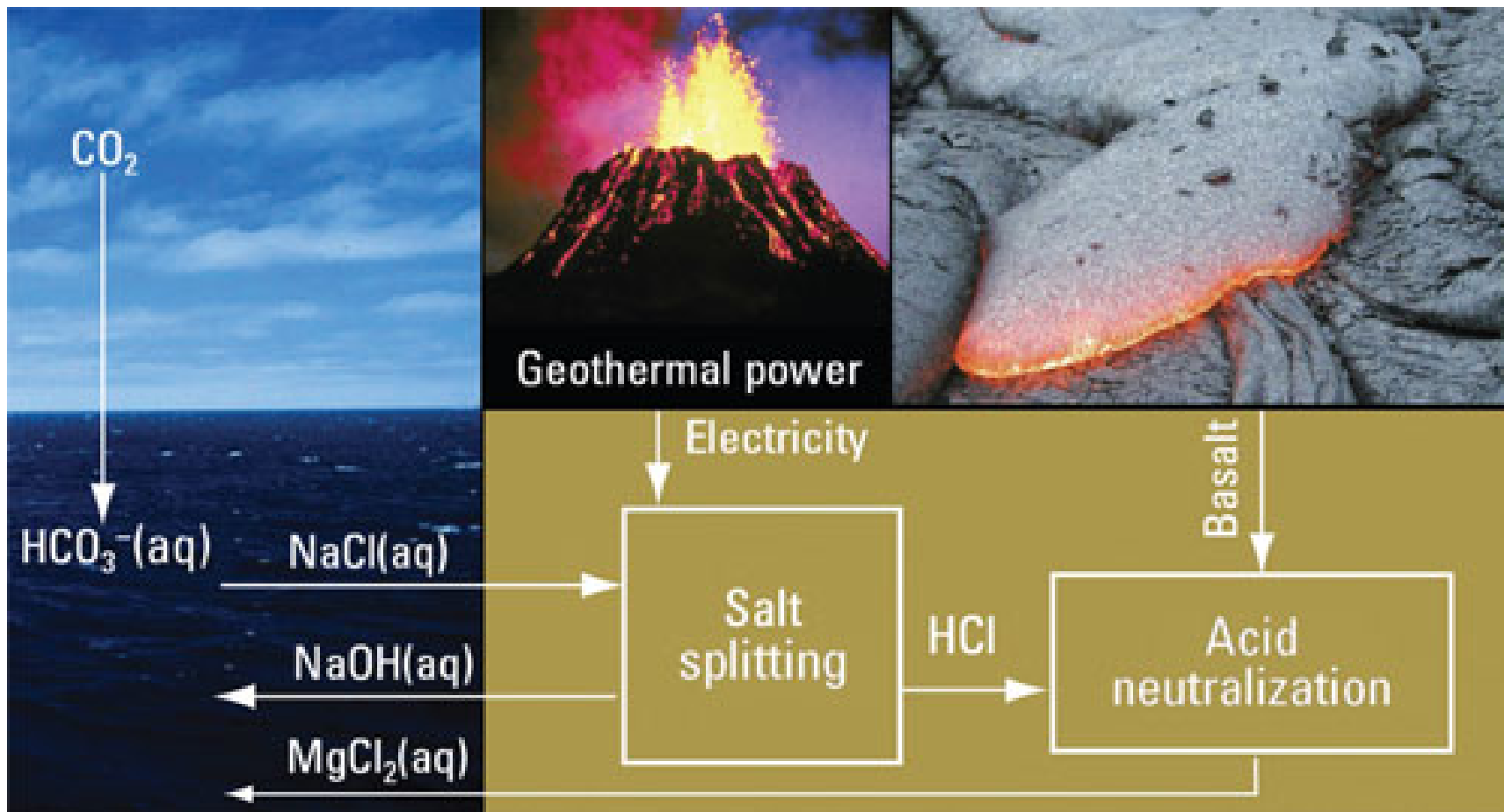


Illustration depicts how the oceans could be used as a giant carbon dioxide collector 6

2007 HOUSE

Remove HCl from the ocean

The idea is that as CO_2 is a weak acid the kinetics of reaction with alkaline rocks is very slow. But the strong acid HCl is readily neutralized by various silicate rocks. For example with the mineral enstatite (MgSiO_3) the dissolution reaction is spontaneous and exothermic: $2\text{HCl}(\text{aq}) + \text{MgSiO}_3(\text{s}) \rightarrow \text{MgCl}_2(\text{aq}) + 2\text{SiO}_2(\text{s}) + \text{H}_2\text{O}(\text{l})$

The kinetics of silicate rock dissolution are highly dependent on pH and temperature, then the heat generated will accelerate the reaction kinetics because the dissolution process is thermally activated.

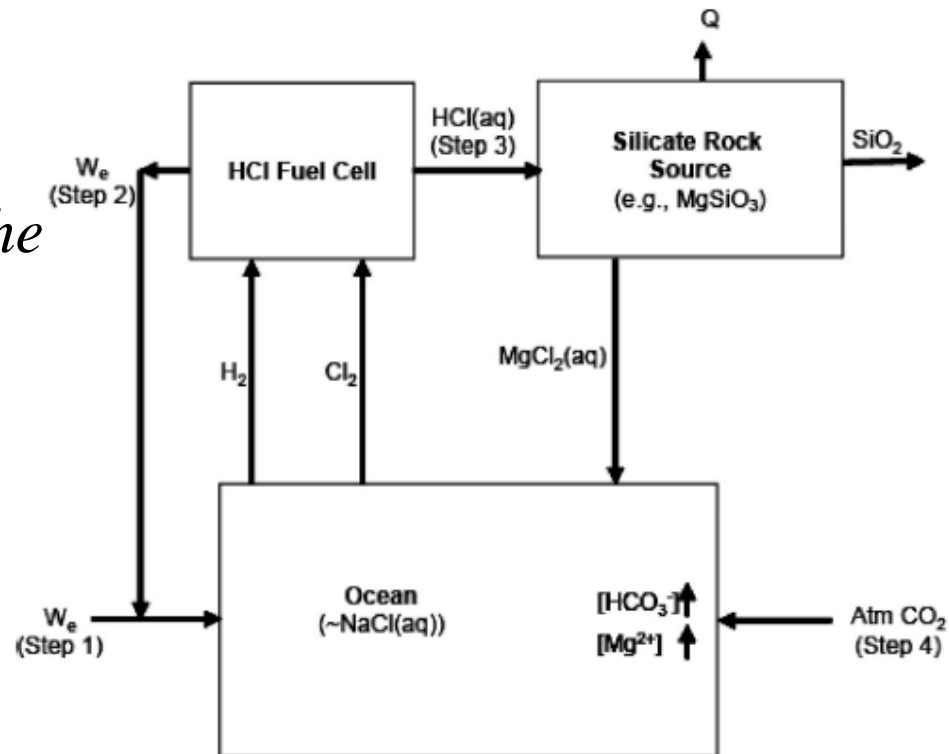


FIGURE 1. Diagram showing carbon dioxide sequestration via the removal and neutralization of hydrochloric acid from the ocean. Magnesium has been used to represent any metal found in silicate rocks. W_e represents electrical work and Q represents heat.

Can this scheme be optimized?

House's idea is, in principle, scalable but among some problems or drawbacks reported by House himself:

- **Engineering Difficulties and Scale Limitations.** *“The process must overcome several technical hurdles before it can offset an appreciable quantity of CO₂ emissions. The magnitude of the CO₂ problem is daunting, and offsetting even 15% of global emissions by electrolysis of seawater would be a serious task. To offset 15% of annual carbon emissions (3.7 Gt CO₂ or 1 Gt of carbon), 10¹⁴ moles of HCl would have to be removed from the ocean and neutralized per year. Seawater would have to be separated into acid and base at a global volumetric flow rate of 6000 m³/s. Large sewage treatment facilities have a capacity of 60 m³/s. Thus, capturing and storing 3.7 Gt of CO₂ annually by the process we discuss would require 100 plants with a volumetric flow capacity similar to that of large sewage treatment facilities.”*
- *The process uses a lot of electricity; if coal is burned to generate that power, the whole process saves less CO₂ than could have been reduced by replacing one coal-burning power plant with a plant run on carbon-free renewable energy like geothermal energy.*
- *Around the plant you would get a very basic solution, which could contain chlorinated by-products that could harm sea life locally.*
- *The need to use more concentrated NaCl solutions for electrolysis (than sea water)...*

All these questions will be seen later on this presentation

Another possible limitation:

- Kurt House, Michael Aziz and Daniel Schrag publication includes an HCl fuel cell which transforms H₂ and Cl₂ into HCl, which is then neutralized by alkaline rocks. But this kind of fuel cell needs platinum to work. The billions tons of Cl₂ that will be generated will require huge amounts of Pt, which are not available and would be very expensive.

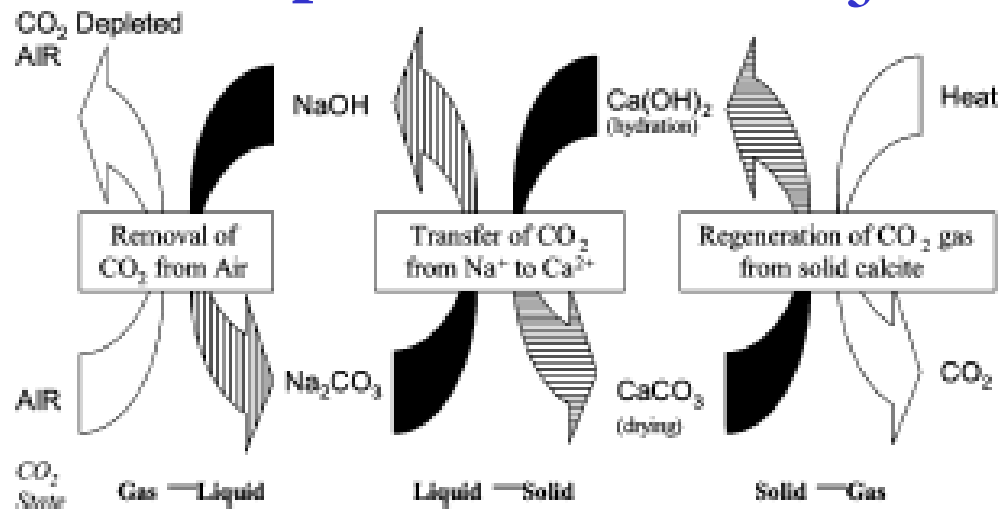
A possible solution:

- Why not keeping H₂ for other uses and take advantage of the reaction of chlorine with water and light?
Exposed to bright sunlight, the Chlorine is decomposed and a solution of hydrochloric acid remains
$$\text{H}_2\text{O} + \text{Cl}_2 \rightleftharpoons \text{HCl} + \text{HClO}$$

The hydrochloric acid, HClO, is not very stable and the solution readily decomposes, especially when exposed to sunlight, yielding Oxygen: $2 \text{HClO} \rightleftharpoons 2 \text{HCl} + \text{O}_2$

Can we find some value to the products and by-products?

- chlorine is used for the extraction of gold from its ores
- chlorination of FeO and MgO is possible
- HCl can be used for platinum, palladium, and rhodium extraction/purification
- sodium hypochlorite has many uses and with the increasing number of floods it's use as disinfectant may increase



Schematic overview of air capture including Air Separation Unit (ASU).

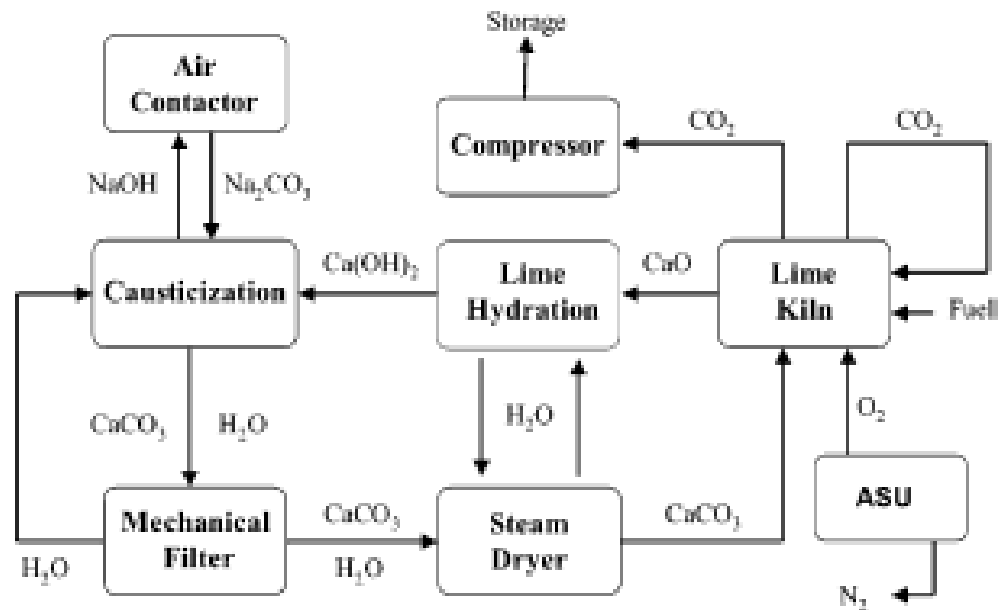


FIGURE 2. Overview of air capture process.

2005: STOLAROFF/KEITH

Air Capture with CaO / Ca(OH)_2 / NaOH

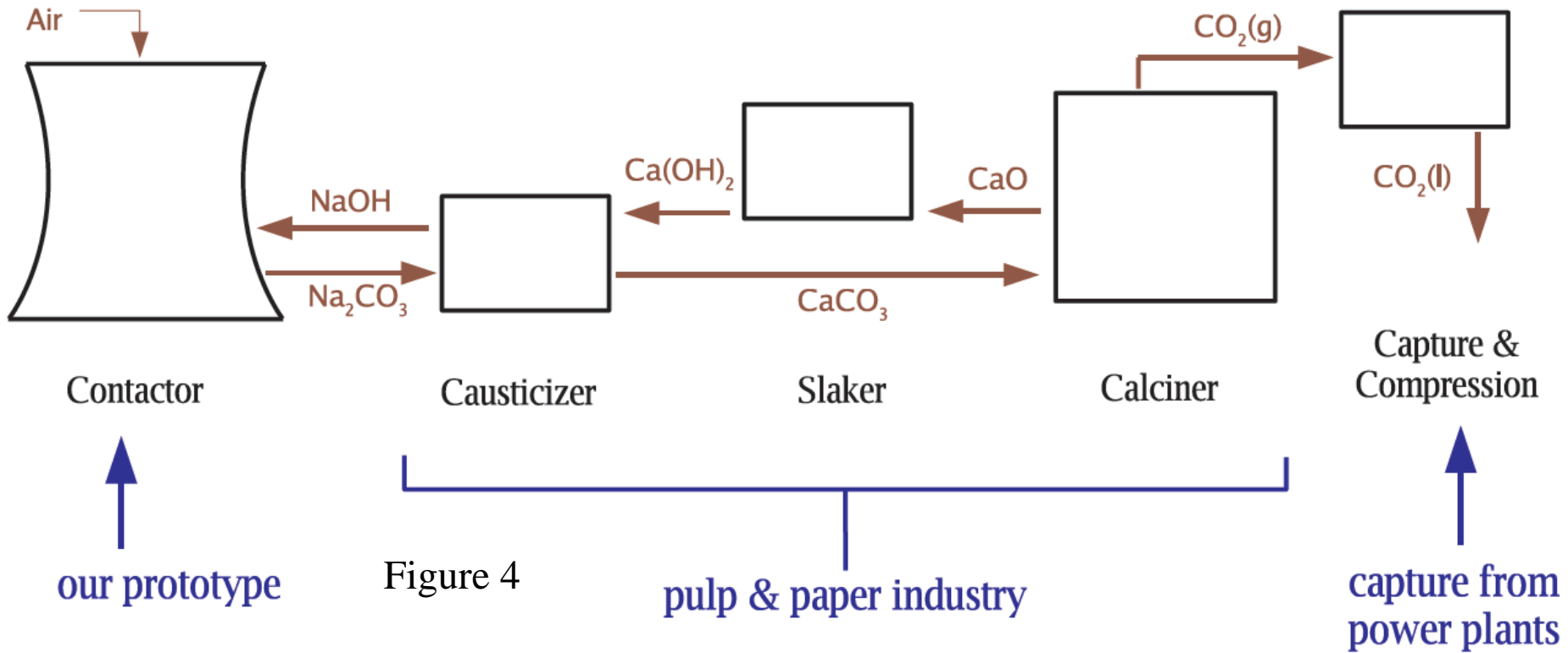


Figure 4

pulp & paper industry

capture from power plants

... a causticizer and calciner nearly identical to those widely in use, an amine capture and compression system nearly identical to those currently in use, and a spray tower capture unit very much like a power plant cooling tower. The sole novelties would be efficient heat integration allowing low grade waste heat from the calcination and slaking system to be used for regeneration of the amines, and the addition of a heat exchanger to allow the contactor and causticizer to operate at different temperatures.

Air capture with sodium hydroxide

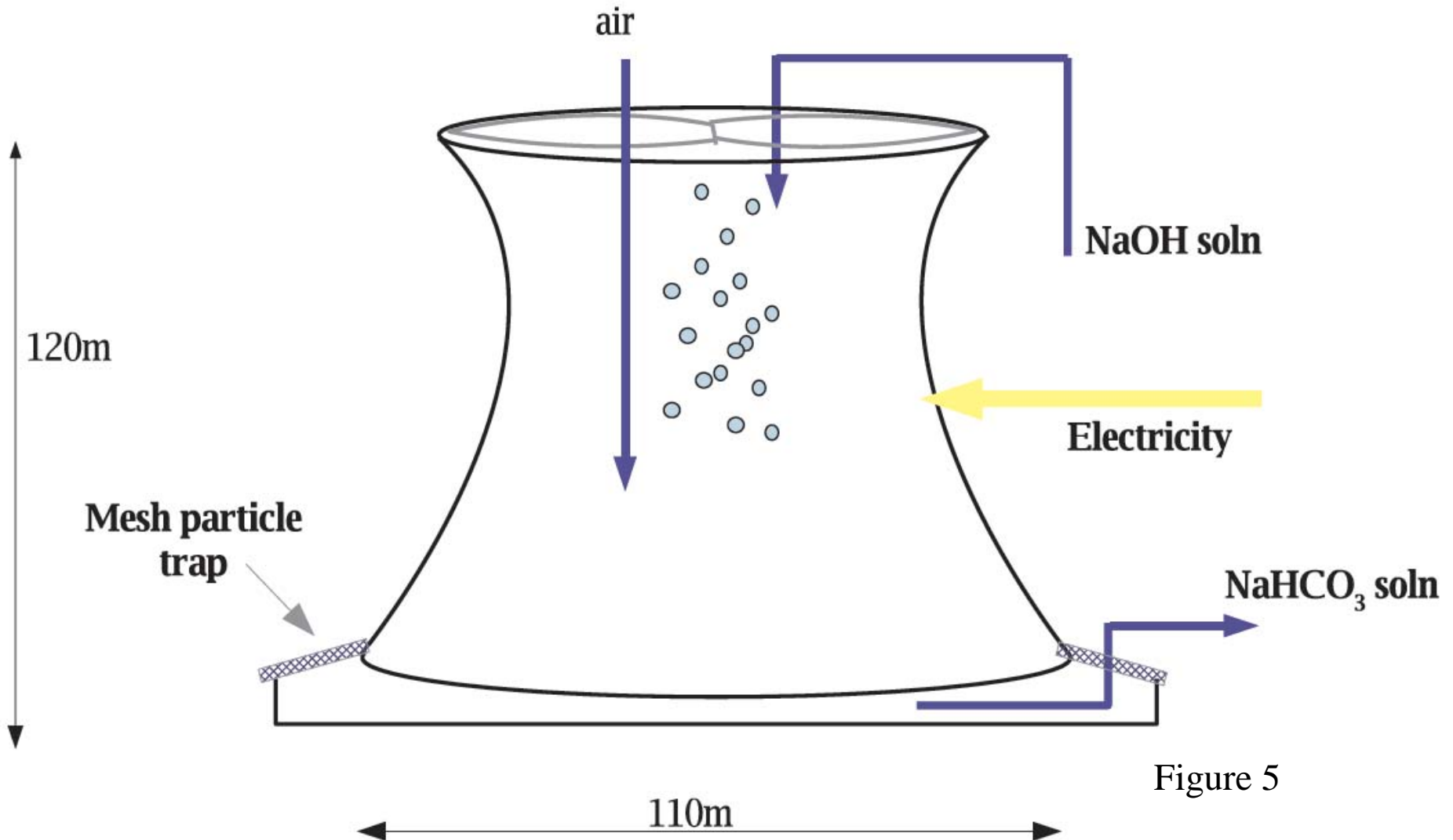


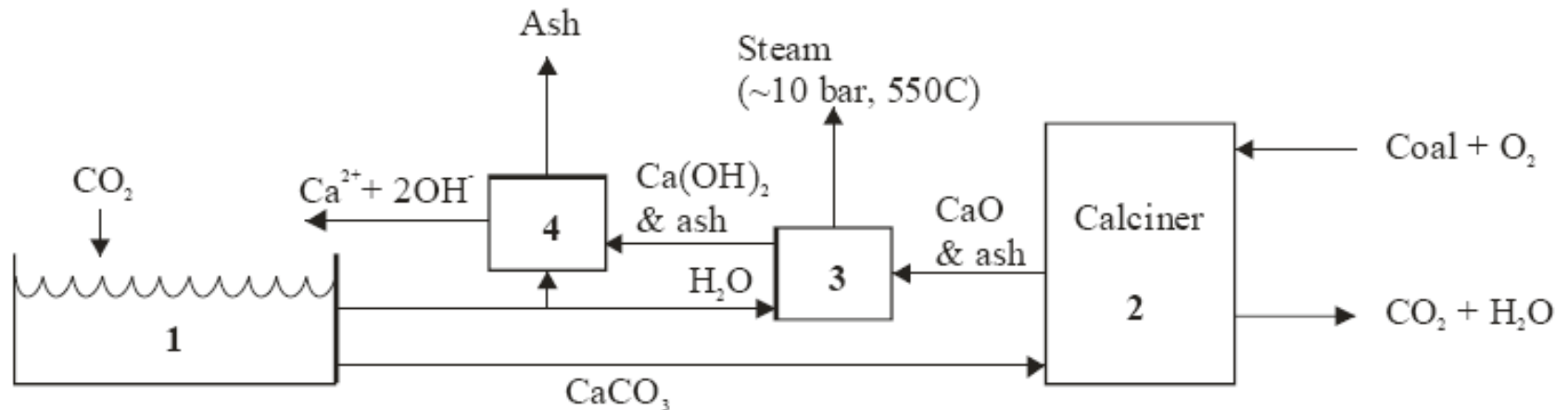
Figure 5

2003 LACKNER **Air capture with calcium hydroxide**

Lackner et al. and Elliott et al. have proposed a direct CO_2 capture system using calcium hydroxide. Figure 1 shows a schematic diagram of such a system.

Aqueous **calcium hydroxide** $\text{Ca}(\text{OH})_2$ is used as a sorbent for CO_2 producing calcium carbonate CaCO_3 .

The carbonate is then heated in a closed vessel producing CaO and CO_2 . Finally, the CaO is returned to the water regenerating the sorbent and producing heat.



		kJ/mol-C	GJ/tC
1.	$\text{CO}_2(\text{g}) + \text{Ca}^{2+} + 2\text{OH}^- \rightarrow \text{CaCO}_3(\text{s}) + \text{H}_2\text{O}(\text{l})$	-96	-8
2.	$\text{CaCO}_3(\text{s}) \rightarrow \text{CaO}(\text{s}) + \text{CO}_2(\text{g})$	179	15
3.	$\text{CaO}(\text{s}) + \text{H}_2\text{O}(\text{l}) \rightarrow \text{Ca}(\text{HO})_2$	-65	-5
4.	$\text{Ca}(\text{HO})_2 \rightarrow \text{Ca}^{2+} + 2\text{OH}^-$	-17	-1

Figure 6 : Air capture with calcium hydroxide.

2007: MARTIN / KUBIC:

Air capture with K_2CO_3

Green Freedom™ concept making gasoline with CO_2 from air with nuclear energy

*CO_2 is readily absorbed into a **potassium carbonate** solution... to form bicarbonate...
Green Freedom™'s carbonate scrubbing process can process production quantities
of air and capture >95% of the carbon dioxide on a single pass*

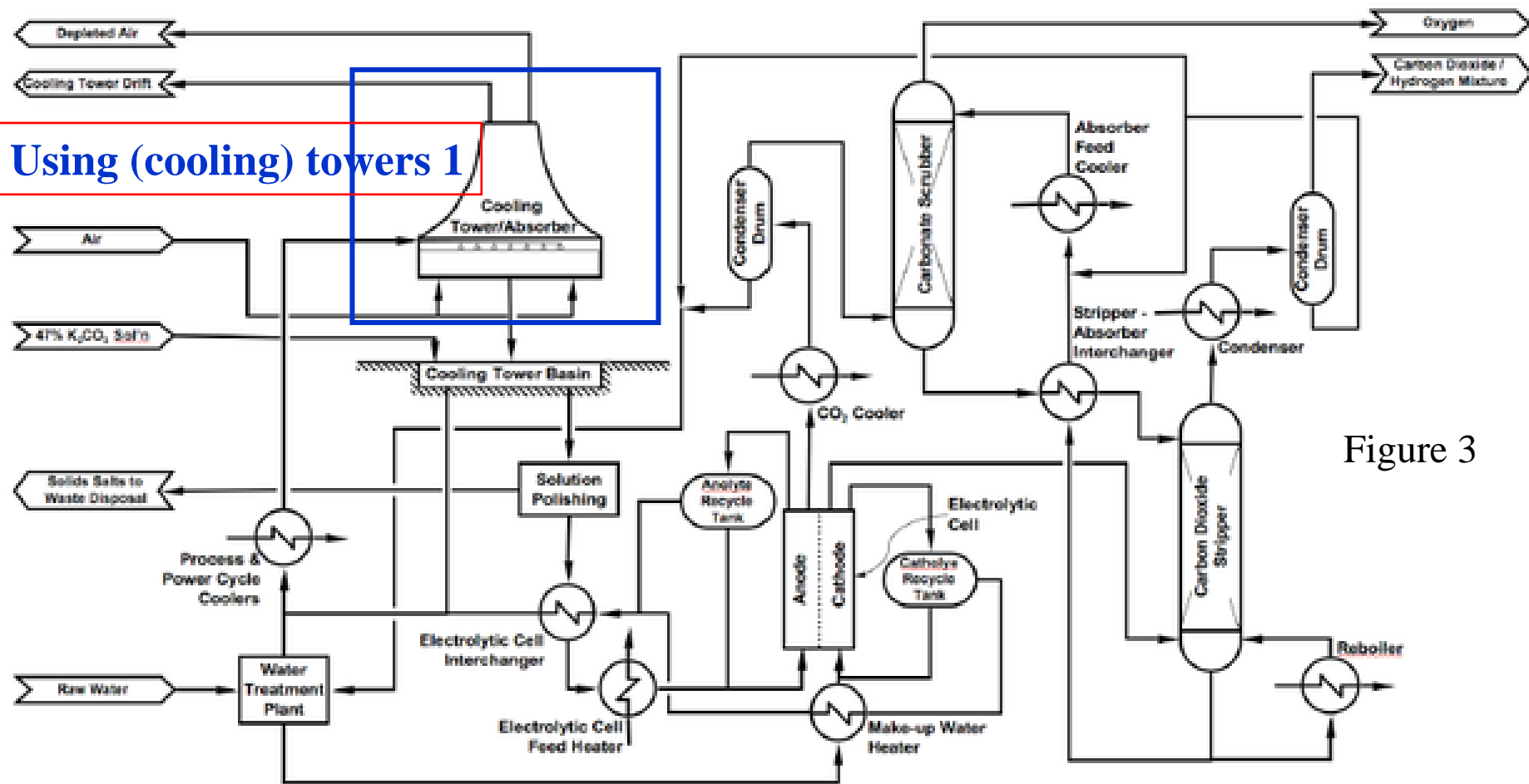


Figure 3



2005 KEITH

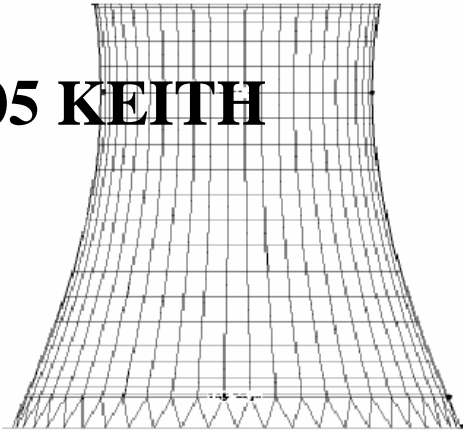


Figure 7

TABLE B.2
NaOH spray tower air capture unit: key parameters

Parameter	Value	Motivation
Tower diameter	110 m	Equal to cooling tower
Tower height	120 m	Equal to cooling tower
Air velocity	2 m/s	Reasonable value ^a
CO ₂ capture efficiency from air	50%	Reasonable value ^b
Mean drop diameter	0.7 mm	Spray distribution from a hollow-cone spray nozzle
NaOH concentration in solution	3–6 mol/l	Adjusted to minimize evaporative loss based on local climate.
Carbonate captured per pass ^b	0.2 mol/l	Based on numerical model of falling drops
Solution flow rate	1 m ³ /s	Fixed by above parameters
Pressure drop across tower ^b	22 Pa	Based on numerical model of falling drops; excludes wall friction.
Electricity use	1.4 MW	Based on 75% fan and 85% pump efficiency
Carbon capture rate	76000 tC/yr	Fixed by above parameters
Capital cost ^c	\$12 million	(Cooling tower cost) × 1.5 ^c
Operation and maintenance cost	400,000 \$/yr	Conservative guess

^aThe air velocity trades off higher CO₂ throughput, i.e. lower capital cost, with increased fan energy (since fan energy goes as the square of velocity). While this value is not optimized, it falls in the likely range of the optimal value since capital costs balloon for air speeds much below this, and fan electricity costs dominate for values much above this.

^bThe capture efficiency trades off higher CO₂ throughput, i.e. lower capital cost, with increased solution pumping. Because higher efficiencies require exponentially more energy to achieve, but low efficiencies drive up capital costs, 50% is in the likely optimal range.

^cThe contactor has additional cost over a cooling tower of fans and some liquid-handling components.

Using (cooling) towers 2

In the contactor, CO₂ is absorbed into NaOH solution forming sodium carbonate (Na₂CO₃), which is then sent to the "causticizer", where the NaOH is regenerated by addition of lime (CaO) in a batch process.

The resulting CaCO₃ solid is sent to the calciner where it is heated in a kiln to regenerate the CaO, driving off the CO₂ in the process known as calcination.

The CO₂ is then captured from the flue gas by conventional means (such as an amine system), compressed, and sequestered for long term storage.

The net result is that CO₂ is concentrated from atmospheric levels to those required for compression and storage.

The primary inputs are energy, water, and small amounts of Na₂CO₃ and CaCO₃ to make up for losses in the regeneration process

Carbon capture rate: 76,000 tC/yr

*If CO₂ capture efficiency 50%
as stated by the authors*

2001: LACKNER

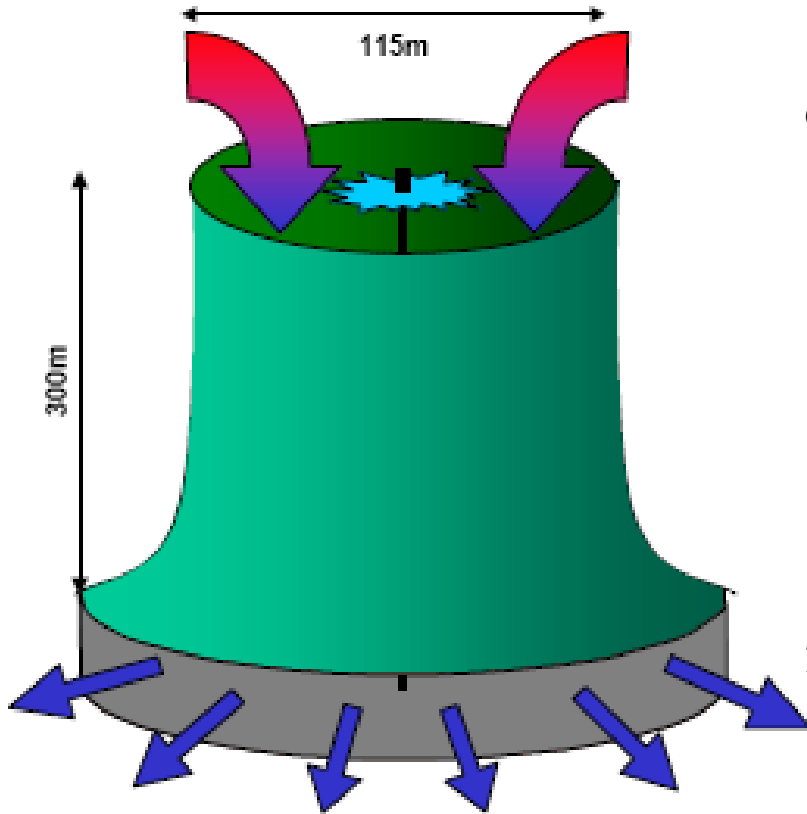


Figure 8: Sketch of a convection tower that could either provide electricity or CO₂ capture

Using (cooling) towers 3

Water pumped to the top cools the air, which causes a downdraft inside the tower.

The tower has a 10,000 m² opening.

Cooling the air to the degree possible in a desert climate would cause in the absence of obstructions a downdraft in excess of 15m/s generating a flow of nearly 15 km³ of air per day through the tower.

The air leaving at the bottom could drive wind turbines or flow over CO₂ absorbers.

*Based on the volumes of air flowing and the potential energy of the cold air generated at the top of the tower, **the tower could generate 3 to 4 MW of electricity** after pumping water to the top.*

The same airflow would carry 9,500 tons of CO₂ per day through the tower.

This CO₂ flow equals the output of a 360 MW power plant. The CO₂ flux is also equivalent to the CO₂ output of the vehicle fleet of a city of 700,000 people, indicating the usefulness of the concept for dealing with emissions from the transportation sector.

Carbon capture rate: 945,000 tC/yr

If CO₂ capture efficiency 100%

Some improvements needed for optimisation

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At this stage of the reflexion, comes the idea that in order to optimise this Keith – Lackner process, maybe it can be coupled with House proposal
So we are seeking favourable actions on several points simultaneously:

- Satisfy energy needs and supply
- Satisfy raw materials needs and supply
- Have an huge air flow in order to get significant amounts of CO₂
- Perform an efficient contact between CO₂ and the alkali

The logical questions are:

- Why not trying to exploit an energy production system for at the same time: * CO₂ capture and *energy production?
- Which one should we try to use?
- Did some energy production plants already have **cooling towers**?

Maybe the Green Freedom concept has found one! But it uses **nuclear** power and doesn't need the House proposal to function...

So, can a renewable energy production system satisfy all needs?

▣  YES! In fact Lackner already gave the answer...

2001: LACKNER

*Some years ago a wind energy technology was suggested (Bishop, J.E., Wind Tower May Yield Cheap Power, in Wall Street Journal. June 9, 1993): inside a large tower, water is pumped to the top, where it cools the air by evaporation. The cold air, being denser, would cause a downdraft inside the convection tower. The potential energy of the air falling down is eight times larger than the potential energy of the water that has to be pumped up. The air flows through the lightweight tower structure and escapes at the bottom where its kinetic energy is harnessed by wind turbines. ... **Such a tower would be much more efficient at extracting CO₂ rather than kinetic energy.***

We are not advocating this specific design for CO₂ capture, it shows once again that the physical structure required to capture the CO₂ is not going to drive the cost of the process.

There are a number of different design options, and further work will have to tell which ones are most advantageous.

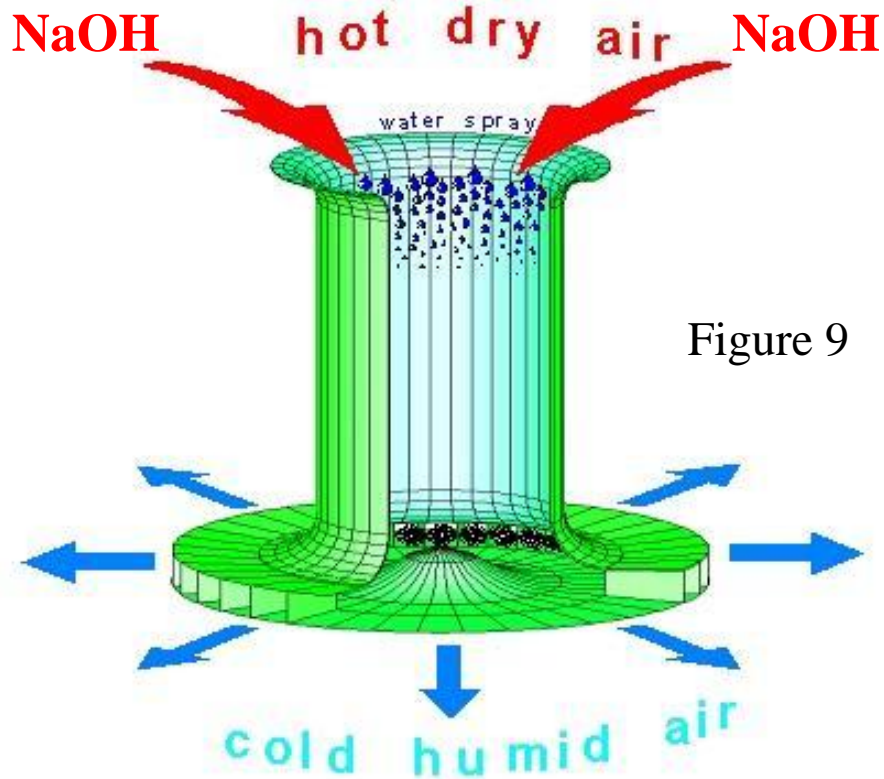
As a matter of fact, the concept described by Lackner in 2001 is called an “**Energy Tower**” [http://en.wikipedia.org/wiki/Energy_tower_\(downdraft\)](http://en.wikipedia.org/wiki/Energy_tower_(downdraft)).

The "Energy Tower" concept has been developed at the Technion Institute in Israel by Prof. Dan ZASLAVSKY and Rami GUETTA

http://physicaplus.org.il/zope/home/en/1124811264/1137833043_en

From 1980 to 2008 ZASLAVSKY Energy Tower

http://physicaplus.org.il/zope/home/en/1124811264/1137833043_en



Using (evaporation) towers 4 2008 de_RICHTER

With a 300 m diameter:

The tower has a 70,000 m² opening

The air speed is 15m/s, generating a flow of nearly 90 km³ of air per day through the tower

There are 0.75g CO₂ in 1m³ of air
(68,000 tCO₂ in 90 km³ of air)

1130 GWh of electricity are produced annually at very low cost (3 to 5 cts/kWh)

The by-product of the energy tower is NaCl salt which by electrolysis can give NaOH (+ H₂ and Cl₂ then transformed into HCl and then neutralized by magnesium alkali rocks)

The electricity cost vs tower dimensions show an optimum for a **140 MW** tower, 800m high and 300m diameter

Carbon capture rate: 6,800,000 tC/yr

<http://www.eng.tau.ac.il/~kribus/irec-2007/papers/Zaslavsky-R07-02.pdf>

If CO₂ capture efficiency 100%

and more than 13 million tC/yr if Na₂CO₃ is sent back to the ocean

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The ZASLAVSKY - GUETTA “Energy Tower” of 300 to 400m diameter provides at the same time:

- a huge air flow: 90 km³/day or 190 km³/day
- electricity: 140 MW or 310 MW
- NaCl to produce NaOH in order to capture almost 25 Mt CO₂/yr
- the H₂ and Cl₂ by-products can allow a chemical industry to develop
- the HCl produced can be neutralized by basalt and silicate alkaline rocks located in the immediate neighbor of the “Energy Tower”
- and much more: cold humid air, low altitude clouds, irrigation, algae for bio-diesel / bio-ethanol, aquaculture, (albedo modification?), etc.

This, answers questions arising from House process (slide 8)

With NaOH, for one mole of CO₂ captured, one mole of Cl₂ is produced: ie if we remove 22 billion tons CO₂ annually we have to deal with 35 billion tons Cl₂/yr or 36 billion tons HCl/yr.

But, since from 1 to 3 TWh of power are available annually from one single “Energy Tower”, **why using NaOH and why not NH₃?**

Not only the “Energy Towers” allow to simultaneously meet all the favourable actions seen previously, but they also permit to:

- Realise the fragmentation of huge amounts of water into an even more gigantic number of droplets, which is necessary to optimize the material transfer (droplet breakage, dispersion and then evaporation), a phenomenon necessary but costly
- And at the same time gives an opportunity to succeed an efficient thermal transfer useful for the production of renewable energy
- Perform scale economies and increases the tons of CO₂ captured

Zaslavsky and Guetta have performed many studies, in order to bring the water in a desert, calculate the costs (depending on altitude and distance from sea) of pumping water, channels or pipes.

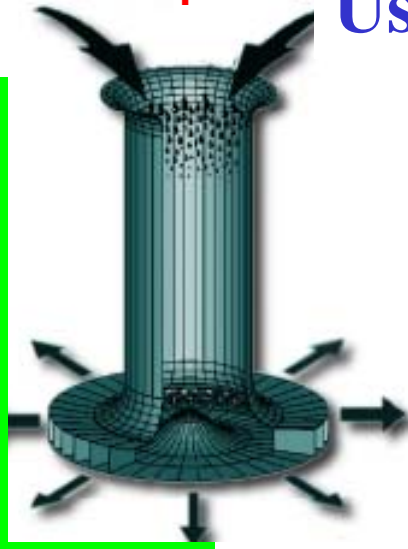
There are still some issues to be resolved later: like how to pool geometrically between energy towers and other possible things like a chlor alkali plant, or an ammonia facility.

Other possible scale economies maybe performed by establishing an "ammonia pipeline chain" with its various properties and uses: strong base to capture CO₂, energy vector easy to transport in liquid form and to convert into H₂ upon arrival, nitrogen available for agriculture or aquaculture as alternatives...

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Using (evaporation) towers 5



Input parameters (a) and state variables(b) of the ETP model with example values

	Input parameter	Unit	Value
1	Height of site above water source	[m]	80
2	Distance between site and water source	[km]	50
3	Air temperature at the top of the ET	[K]	283.15
4	Air relative humidity at the top of the ET	[%]	30
5	Air pressure at the top of the ET	[hPa]	820
	State variable	Unit	Value
1	Total pumping head	[m]	1445
2	Energy gain due to air cooling (E_C)	[Pa]	428.5
3	Energy gain due to the droplets drag effect (E_r)	[Pa]	27
4	pumping energy (E_p)	[Pa]	126.8
5	Net Energy (E_{net})	[Pa]	318
6	Energy losses (E_{loss})	[Pa]	102
7	Net power	[MW]	311.5
8	Gross power	[MW]	550
10	Air velocity at the ET's bottom	[m/s]	17.8
11	Water discharge	[ton/s]	14.2

Figure 10

values calculated for an ET of 1200m height and 400m diameter

**Carbon capture rate:
14,000,000 tC/yr**

If CO₂ capture efficiency 100%, only 1600 "Energy towers" worldwide would be needed to soak up the 22 billion tones of CO₂ produced annually

With a 400 m diameter:
The tower has a 125,000 m² opening
Electricity production is 2700 GWh annually at very low cost: 2.5 cts/kWh
Air velocity is almost 18m/s

Air flow is nearly 190 km³ / per day
There are 143,000 tCO₂ in 190 km³ air
If part of the electrical power is used to produce ammonia NH₄OH to capture CO₂
The by-product of this Energy Tower will be ammonium carbonate (NH₄)₂CO₂ salt which under pressure by the Bosch-Meiser process gives UREA: H₂N-CO-NH₂

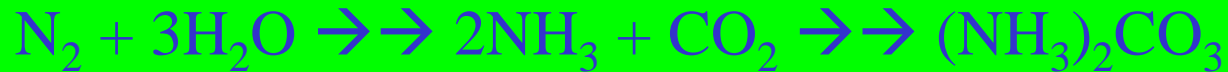
The fertilizer obtained can be used to sequester more carbon and help green the Sahara and other deserts

Why Ammonia?

2008 BONNELLE*

(* personal communication)

- Ammonia (a strong base) can be produced from (neutral) Air and Water (Haber Bosch process) and then capture the weak acid CO₂:

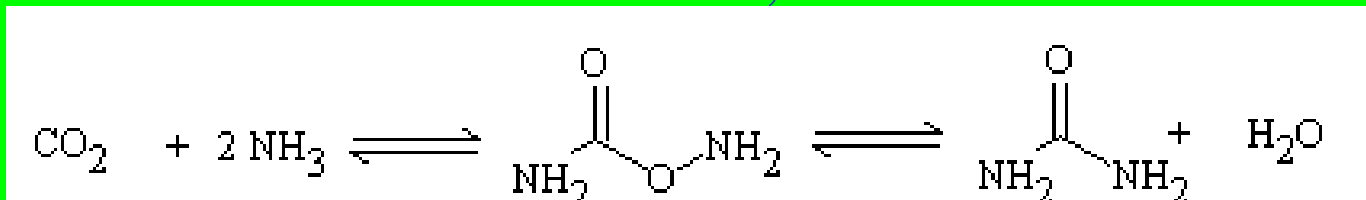


- While the global scheme proposed from salt is to capture one mole of weak acid by producing two moles of a strong one:



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- Sodium chloride electrolysis is more expensive and technically difficult than ammonia synthesis
- By the Bosch-Meiser Urea Process, fertilizers can be made:



- Agriculture can be developed, allowing “natural” C sequestration
- Ammonium nitrate NH₄NO₃ (the preferred nitrogen source of fertilizers), can eventually be made. It is a highly water-soluble salt

Advantages of these 2 schemes for CO₂ capture from air

- Previous schemes from Lakner, Keith et al, consume energy to work, these ones **produce energy** and allow the capture of 100 times more CO₂;
- No sorbent material, no costly and laborious regeneration;
- The biggest benefits are likely to be improved conditions for agriculture in dry parts of warm deserts all over the world;
- Spin off benefits for countries directly involved include: energy production, selling CO₂ credits, regional cooling and humidifying impacts, employment creation, enhancing development possibilities: bio-diesel from algae, water desalinisation by reverse osmosis, agriculture, chlor alkali industry...
- Involves much less risk, pollution and spending than would be required by other possible global CO₂ capture & long term sequestration strategies
- As this scheme involves working with sea water, desert and clouds, the impacts do not depend on political decisions about CO₂ emissions, nor on an international agreement to allow performing this geoengineering scheme
- No pure CO₂ stream to collect and then to sequester...
- Producing low altitude clouds (and, if harmless proved, increasing sand albedo by on the spot disposal of the mineral NH₃ or Mg carbonates;); etc.

2007 KEITH Carbon Management: Location vs Mechanism

		Location		
		Land Surface	Ocean	Geosphere
Mechanism	Biological	Enhancing carbon content of soils Afforestation	Fertilization to accelerate biological pump	Use of anaerobic biological reactions to reduce CO ₂ to CH ₄ in strongly reducing environments.
	Chemical	Industrial production of stable carbonates	Acceleration of CaCO ₃ dissolution Addition of alkalinity	Subsurface dissolution of carbonates or silicates by brines acidified by injected CO ₂ .
	Physical	NaCl electrolysis or Ammonia synthesis and CO ₂ capture from air by NaOH or NH ₃ in “Energy Towers” located in deserts	Formation of ‘lakes’ of liquid CO ₂ .	Physical confinement of gas phase CO ₂ in underground formations.

2008 de_RICHTER **Some technical details**

- The Energy Tower works with sea water! So a by-product is NaCl.
- ZASLAVSKY's and GUETTA's team has studied a precipitation process of the brine spray by electrostatic coalescence.
A small water excess sprayed at the top of the tower will recover most of the salt, in order to send it back to the sea (or to a new lake) by a second channel. An electrostatic dust collector may be possible.
- In order to start addressing the ocean thermal expansion and sea level rise, consider sending this extra water and salt to some of the places in earth below mean sea level

http://en.wikipedia.org/wiki/List_of_places_on_land_with_elevations_below_sea_level

- In the CO₂ capture process by NaOH, while HCl is neutralized on land by alkaline Mg rocks, the sodium carbonate Na₂CO₃ produced can be sent back to the sea with the excess NaCl, and more CO₂ can be captured in the ocean by its transformation into 2NaHCO₃.
It can also be sent to a new lake in a depression.
- An HCl and Cl₂ chemistry can be developed
- Extraction of gold, platinum, palladium may be possible...

Some technical details

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- In the CO_2 capture process by NH_4OH , the ammonium carbonate $(\text{NH}_4)_2\text{CO}_3$ can easily be separated from NaCl by sublimation, and then transformed into urea $(\text{NH}_2)_2\text{CO}$.
- Urea is produced on a scale of 100,000,000 tons per year worldwide (wikipedia)
Urea has the highest nitrogen content of all solid nitrogenous fertilizers in common use (46.4%). Therefore, it has the lowest transportation costs per unit of nitrogen nutrient.
- Urea can be produced as prills, granules, flakes, pellets, crystals; but as urea is highly soluble in water, it is therefore also very suitable for use in fertilizer solutions.
- Urea can also be used to **capture NOx** from combustion motors and has many other uses
- Additional calcium ions can be sent to the ocean, allowing plankton with calcium carbonate skeleton to regenerate and consume CO_2
- Ammonia can be stored and transported in MgCl_2 and then released at 300°C (ammonia fuel cell) to be used as carbon free energy.

Some technical details

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If HCl is neutralized by MgO basalt rocks, a metal extraction industry can be considered.
Magnesium hydride and Mg chloride are hydrogen and ammonia storage and delivery materials.

Figure 1

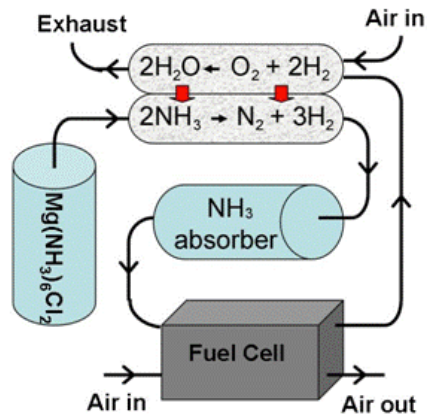
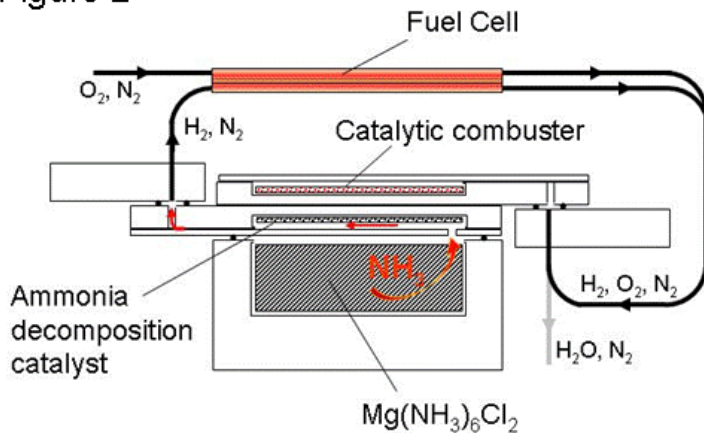
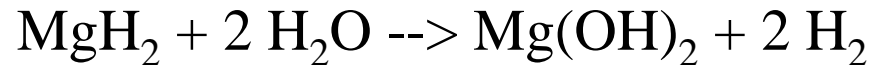


Figure 2



Hydrogen Storage Properties in Magnesium Hydride MgH_2 see work from Biocoke Lab. in collaboration with professor T. Akiyama from Hokkaido university: at only 75°C



$\text{Mg}(\text{NH}_3)_6\text{Cl}_2$, has been proposed as a solid ammonia or hydrogen storage and delivery material. *J. Am. Chem. Soc.*, 128 (1), 16 -17, 2006. Patent WO/2006/012903.

Ammonia can also be used as fuel

- *Ammonia is the only practical (viable?) liquid fuel that can be made from water, air, and renewable energy*
- *Energy dense*
- *Clean burning direct fuel: no carbon*
- *Excellent hydrogen carrier*
- *Widespread use/experience (#2 chemical)*
 - *US consumes 20 million tons per year*
 - *130 million tons produced annually worldwide*
- *Exists as liquid at moderate pressure/temperature Transmission and firming storage for renewables*
- *Large existing market and delivery infrastructure*
- *Ammonia pipelines ~3000 miles currently used*
- *No corrosion or embitterment problems*
- *Approximately 4.5 million tons of large-tank ammonia storage*

Zero-Emission Combustion

- *Only hydrogen and ammonia burn without emitting greenhouse gases (contain no carbon)*
- *Also, no CO, SO_x, or NO_x*
- *Hydrogen combustion--*



(water only combustion product)

- *Ammonia combustion--*



(nitrogen and water only combustion products)

- *The Ammonia Cycle can be totally carbon-free, starting with water and nitrogen and ending with water and nitrogen*
- *Can be made from water + air +renewable energy*

Relevant Ammonia Properties & Safety

- *Fuel is same as fertilizer, NH₃, anhydrous ammonia*
 - *18% hydrogen by weight*
 - *Liquid at >125 psi at room temperature*
 - *About half energy density of gasoline, by volume (HHV)*
 - *About 50% more energy dense than LH2 **
 - *At point of use can be used as direct fuel or cracked to provide GH2 ***
 - * *LH2: Liquid Hydrogen / ** GH2: Gaseous Hydrogen*
 - *Inhalation hazard, so must be handled with respect*
 - *Millions of tons are stored, transported, and handled every year with an excellent safety record*
 - *Not corrosive*
 - *Not explosive nor highly flammable*
 - *Can be stored at moderate pressures*
 - *Safer than gasoline or propane*
 - *Lighter than air*
 - *Trapped by water*
 - ***Not a greenhouse gas***
- ***Lighter than air gas for inflatable reactors or for sending balloons to the stratosphere with sulphur?***

**POTENTIAL EXTRA BENEFITS
OF THE “ENERGY TOWER” CONCEPT**

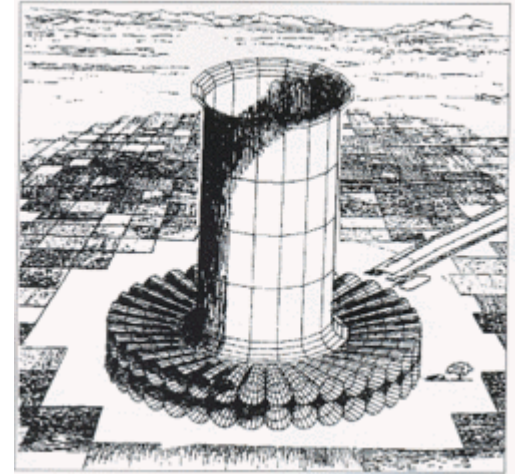
2007 ZASLAVSKY

"We can produce cheap desalinated water, we can irrigate the desert, we can produce bio-fuel, we can boost aquaculture," Zaslavsky recites.

<http://www.unenergy.org/index.php?p=1> 69 Energy-Tower

His team estimates the running costs of the electricity for this project at 2.5 cents per kilowatt-hour, less than a third of the cost of electricity in Israel today, and far cheaper than any mooted alternative such as solar, hydro-electric or wind power.

Such promise might be enough to convince anyone of the technology's merits.



*The team has calculated that **the energy towers may actually be able to reverse the mechanism of global warming.***

"Hadley Cell Circulation" is a natural process whereby the earth cools itself. This naturally happens mostly over the equator, where air is already humid but if we find a way to humidify desert air, this global cooling process can occur over desert latitudes too. And the energy towers work by doing exactly that. The Energy Tower could expand the effects of this global cooling process.

Comments

REUTERS Oct 9, 2007: *Egypt is slowly greening the sand that covers almost all of its territory as it seeks to create more space for its growing population.*

*With only five percent of the country habitable, almost all of Egypt's 74 million people live along the Nile River and the Mediterranean Sea. ... Egypt's population is expected to double by 2050. ... The government is keen to encourage people to move to the desert by pressing ahead with an estimated **\$70 billion** plan to reclaim 3.4 million acres of desert over the next 10 years.*

<http://www.reuters.com/article/inDepthNews/idUSL2651867020071009>

Guetta and Zaslavsky have studied various locations and calculated for each one the profitability of the system: an Energy Tower (1200m x 400m) costs nearly **\$1 billion**

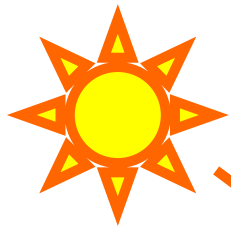
Is a tower of 1200m difficult to build? It's only an empty chimney! Architects build skyscrapers with floors, elevators, water, electricity, gas and many fluids going up and down. The Burj Dubai building in Dubai is already 900m high and a 1600m skyscraper the "Mile High Tower" is planned in Jeddah (Saudi Arabia) http://en.wikipedia.org/wiki/Mile_High_Tower

2007 ZASLAVSKY

December 2007 ... *its inventors claim energy towers could easily produce between 15 and 20 times the total electricity the world uses today. Not only that, it could also be used as a desalination device and may be able to reverse the effects of global warming*

<http://www.unenergy.org/index.php?p=1> **69 Energy-Tower**

http://inventorspot.com/articles/energy_tower_power_15_earths_9102



What about clouds?

Some reflection

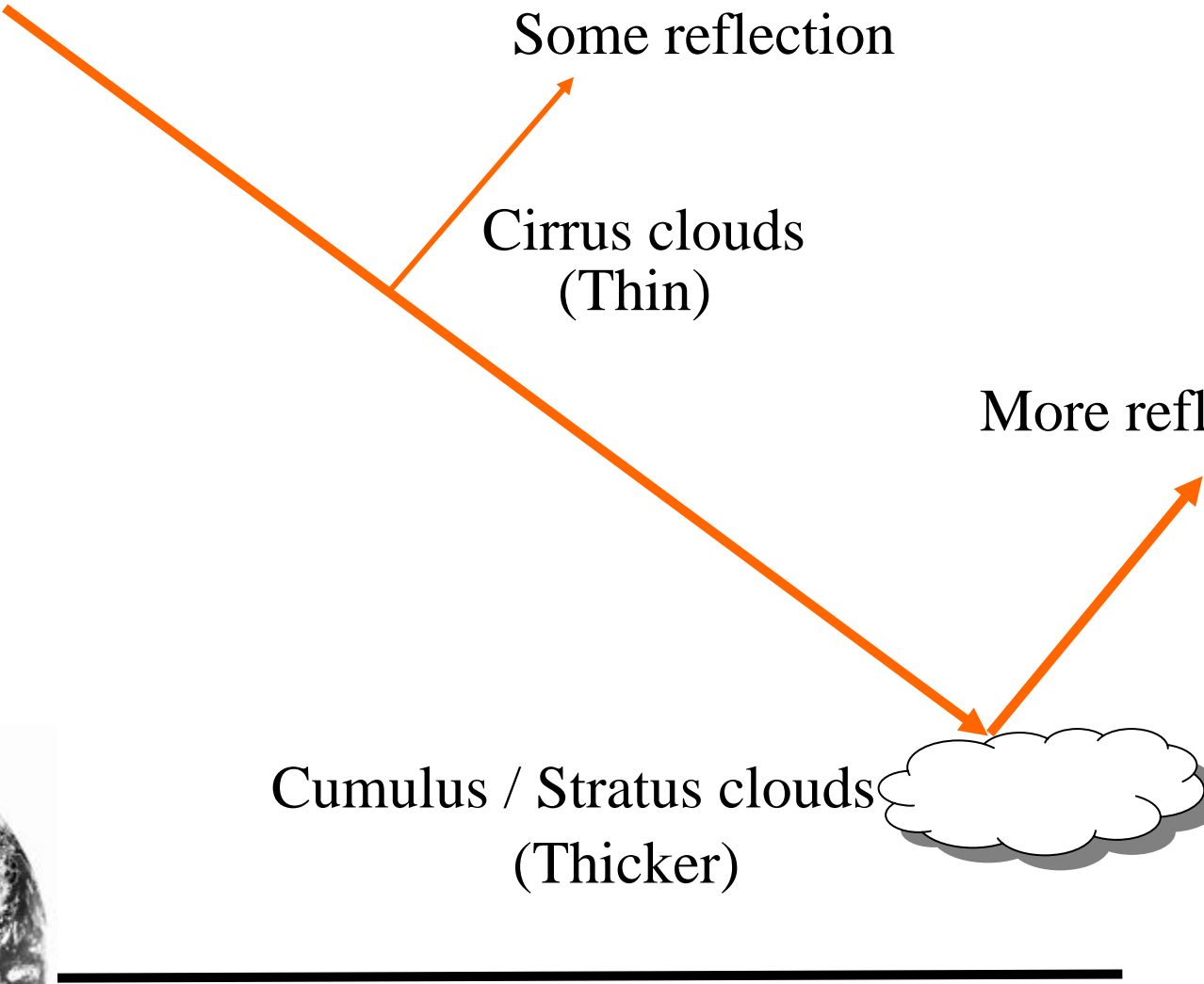
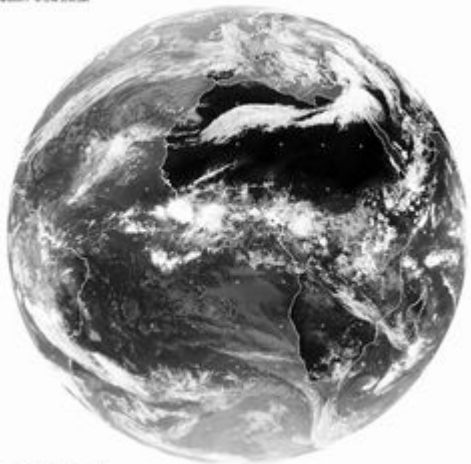
Cirrus clouds
(Thin)

More reflection

10 km

Altitude

Cumulus / Stratus clouds
(Thicker)



Cooling effect due to Clouds

2006 LATHAM / SALTER

propose controlled enhancement of the albedo and longevity of low-level maritime clouds by a spray of very fine sea water that is carried by turbulent mixing up into clouds, brightening their albedo

Latham has pointed out that low level clouds are quite good reflectors and their reflectivity can be increased by exploiting the well-known Twomey effect. This says that clouds with large numbers of small drops have a higher albedo than ones with a smaller number of large drops. The clouds can also have greater longevity.

*But cloud drops cannot form without a small starting seed known as a cloud condensation nucleus. There are somewhere between **1000 to 5000/cm³** of these nuclei in over land air masses.*



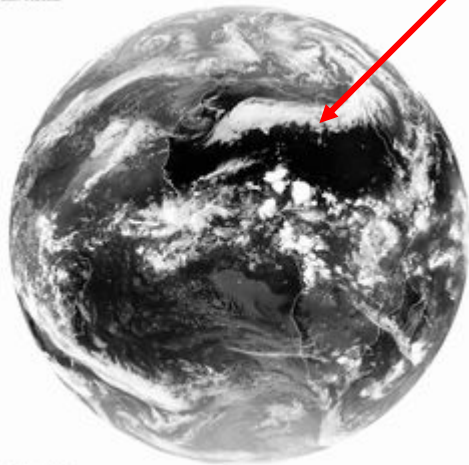
Cooling effect due to Clouds

In deserts, sand dust will increase considerably the number of available condensation nucleus.

After CO₂ capture, at the bottom of an “Energy Tower” some sodium or ammonium bicarbonate will come out mixed in the humid air, producing high albedo clouds.



**Sahara
rainy clouds**



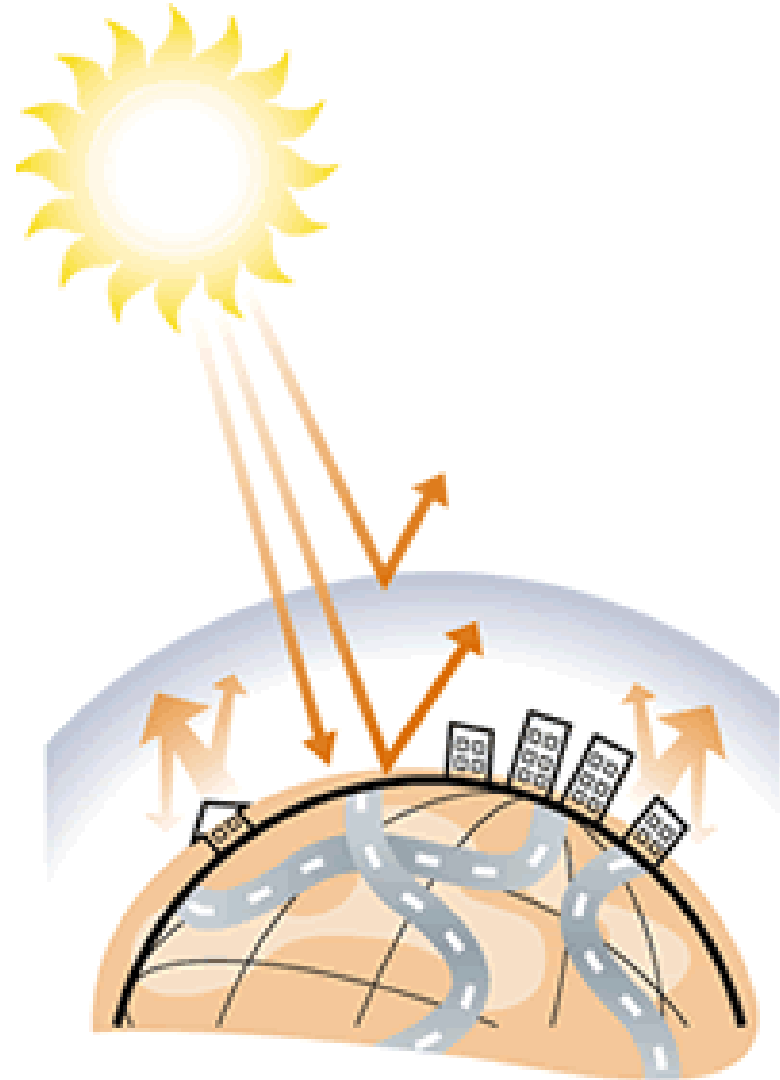
A cooling effect begins as soon as the cloudiness increases. This means that increased low altitude cloud cover can have an immediate and sustained cooling effect.

Cooling effect due to Evaporation

The operating principle of the “Energy Towers” is based on cooling the air!

Several teams (2007 Bonfils / Kueppers) have demonstrated that *irrigation has a cooling effect, masking somewhat the extent of global warming:*

“In California, irrigation expansion has had a large cooling effect on summertime average daily daytime temperatures (-0.14 °C to -0.25 °C per decade), which corresponds to an estimated cooling of -1.8 °C to -3.2 °C since the introduction of irrigation practices”



“Energy Towers” opposed to “urban heat islands”?

There is no single solution to global warming.

In this document complementary geoengineering techniques have been proposed, as synergies and scale economies have been found.

As far as we work on a **big enough scale** “Energy Towers” can capture **all** CO₂ from air... by at least two processes NaOH and NH₃.

Only 1600 “Energy towers” worldwide would be needed to soak up the 22 billion tones of CO₂ produced annually...

And at the same time:

- green electricity can be produced
- and/or “carbon free” fuel: for ammonia or hydrogen economy

Some other extra benefits can be expected:

- drastically reducing the prices of ammonia fertilizers, chlor-alkali raw materials, metals...
- increasing humidity and albedo of low altitude clouds
- no deleterious effect such as ozone depletion, or acid rains

2008 de_RICHTER **Conclusions (2)**

Some other extra benefits may be expected, but research is needed:

- stop ocean acidification and sea level rise (to be further studied)
- provide various cooling effects,
- greening the deserts, feeding humankind, etc.

As the countries that will apply this geoengineering scheme will become carbon neutral, international and political cooperation, agreement and acceptance might not be required.

On the contrary, those countries will deserve winning tradable CO₂ emission permits (green certificates).

At the same time they will reach an energetic independence, enter in the H₂ or NH₃ economy and help the others by providing new fuels.

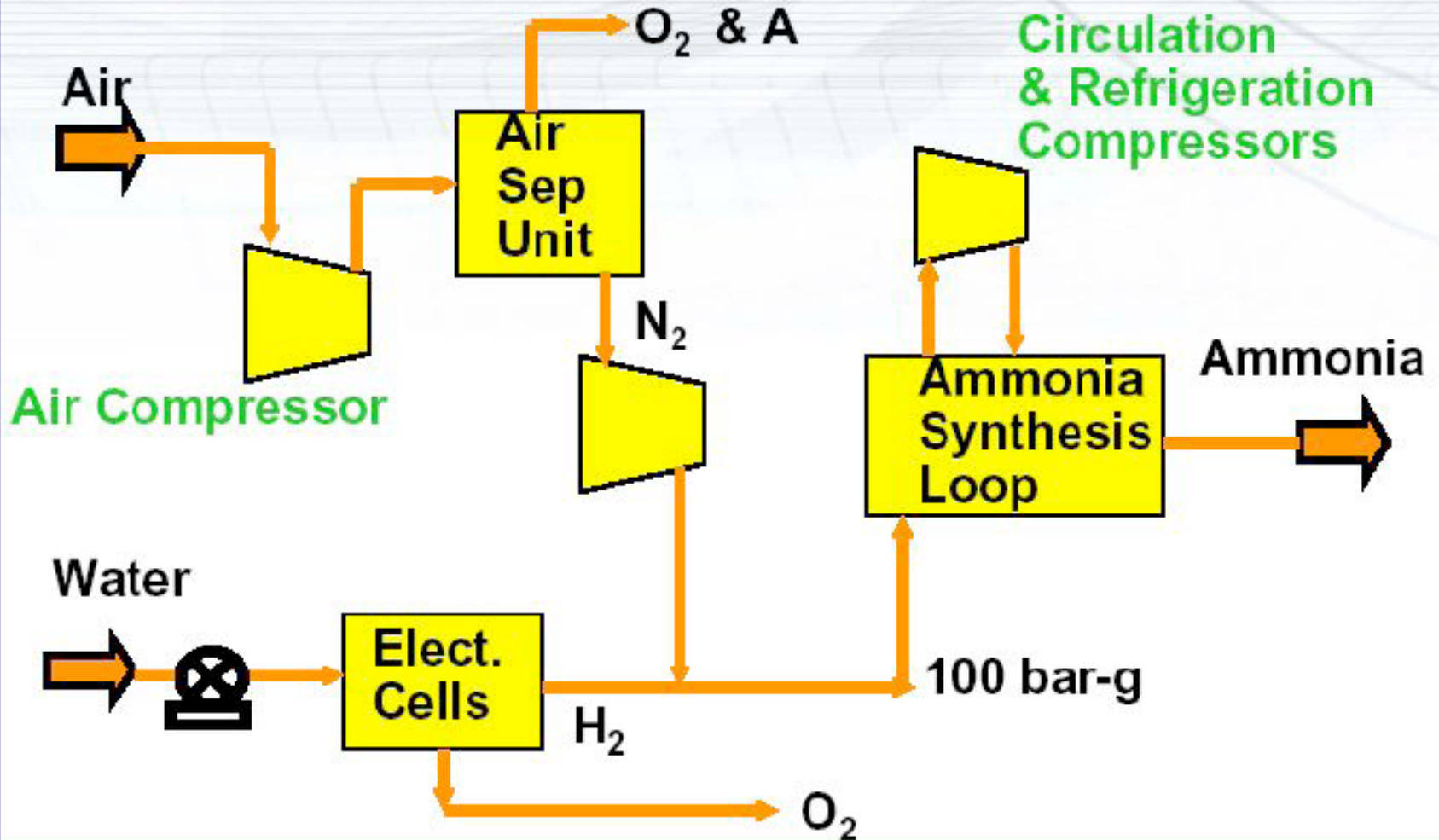
But international funding is more than ever needed to build the first 'Carbon Capture Towers', as initial investment is high.

International scientific cooperation is also needed for pooling R&D.

To start it would be better to concentrate initial efforts in certain parts of the **arid** zones already proposed by Zaslavsky & Guetta.

Ammonia from Water Electrolysis

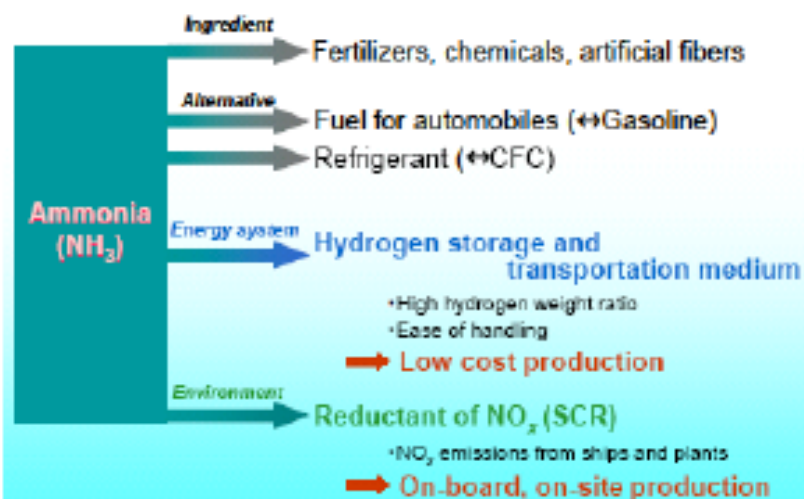
Conceptual Process Scheme



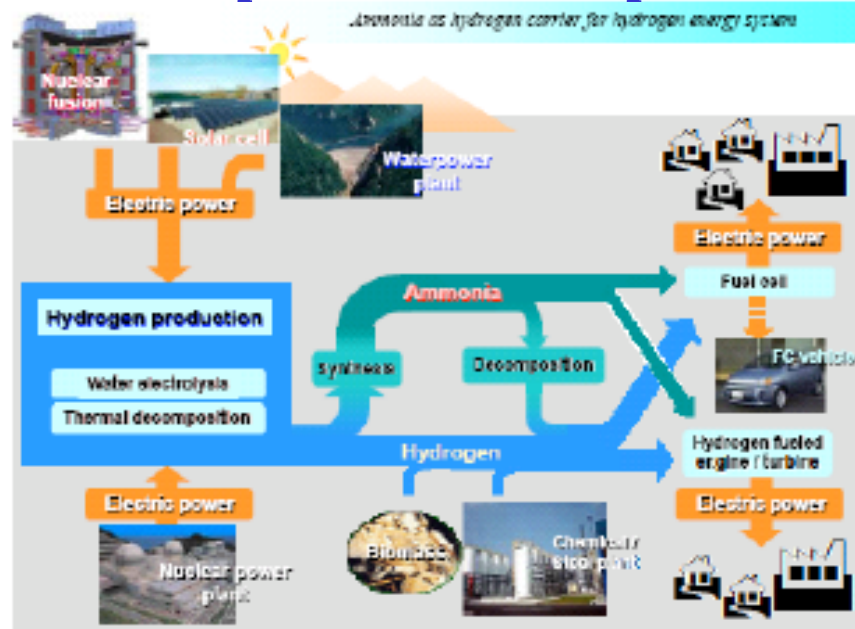
Hydrogen Energy System Coupled with Ammonia Economy

www1.doshisha.ac.jp/~ene-cent/research/example/ammonia_en.pdf

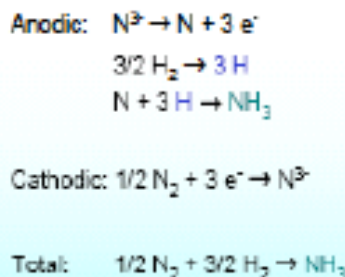
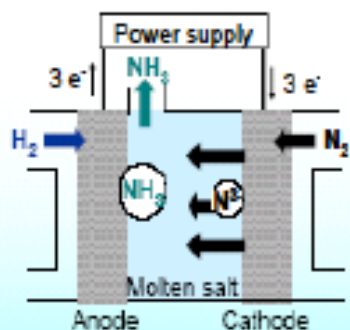
Various uses of Ammonia



Ammonia as hydrogen carrier for hydrogen energy system



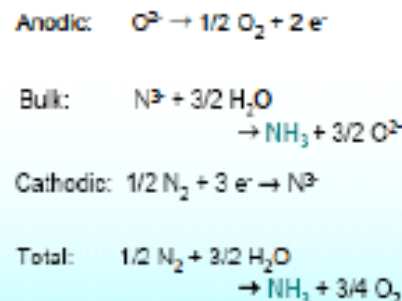
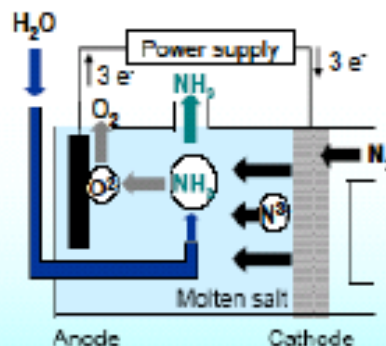
Electrolytic synthesis of ammonia under atmospheric pressure



Principle of electrolytic synthesis of NH₃ from H₂ and N₂ under atmospheric pressure.

Theoretical electrolysis voltage
0.054 V at 800 K

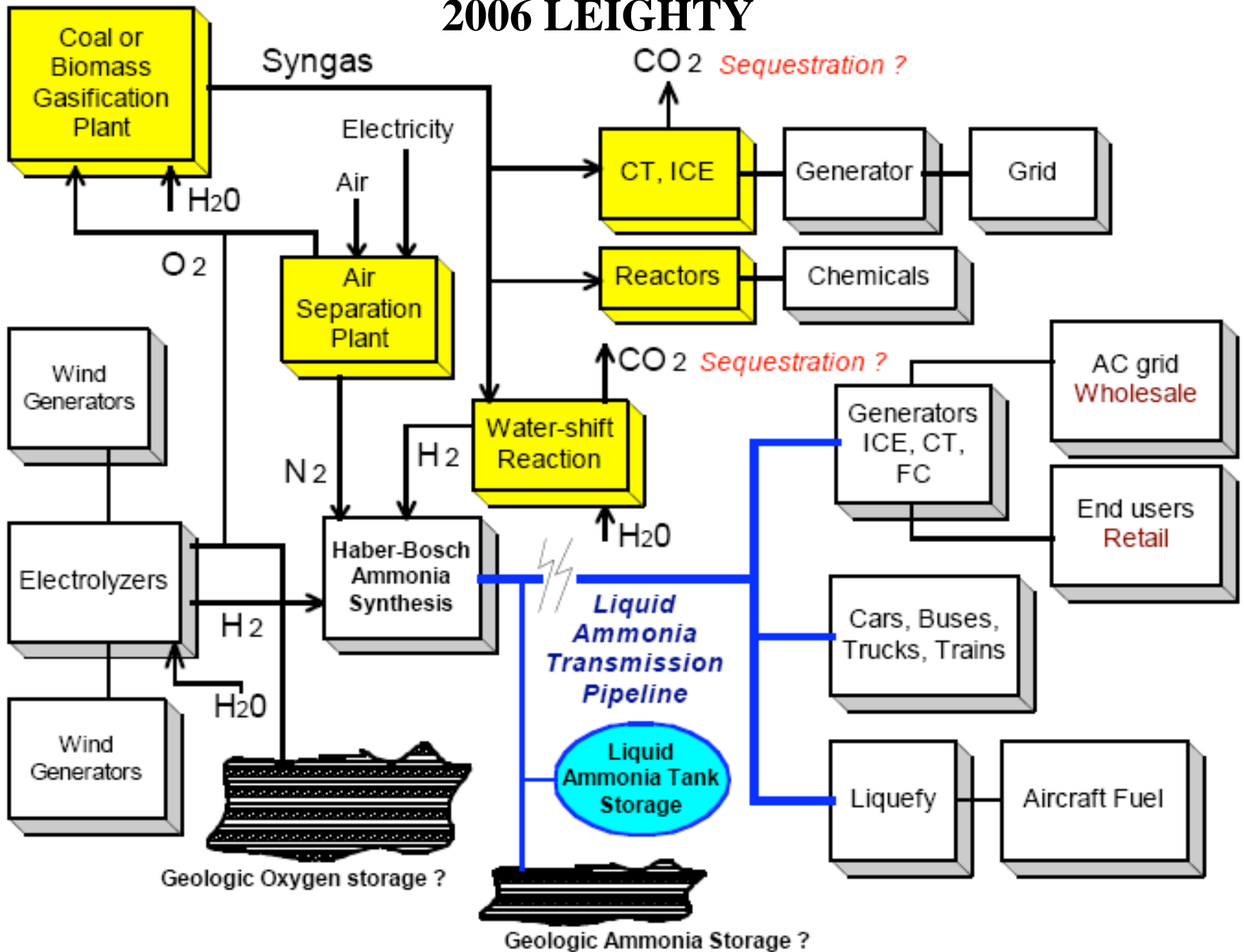
Electrolytic synthesis of ammonia from H₂O and N₂



Principle of electrolytic synthesis of NH₃ from H₂O and N₂

Theoretical electrolysis voltage
1.17 V at 800 K

2006 LEIGHTY



Addendum

“Energy Towers” are **downdraft** solar towers [http://en.wikipedia.org/wiki/Energy_tower_\(downdraft\)](http://en.wikipedia.org/wiki/Energy_tower_(downdraft))

Similar ideas are developed on **updraft** solar towers http://en.wikipedia.org/wiki/Solar_updraft_tower

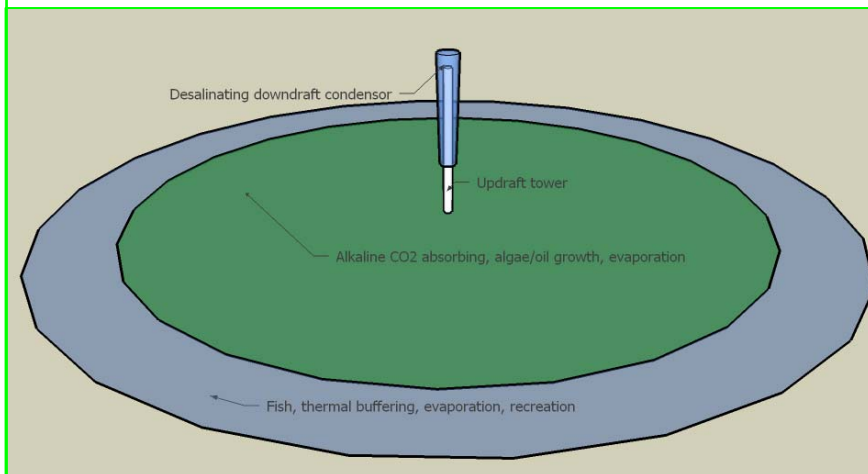
2007 BONNELLE D. “New meteorological reactors: a solution for geoengineering and cost-effective renewable energy production, at the same time”

This article describes three projects which, at the same time, have a geoengineering effect and produce renewable energy at reasonable prices, thus fight both the effects of past CO2 emissions and the need for new emissions.

http://groups.google.com/group/geoengineering/browse_thread/thread/69df204c4fd0a2e6/e8baca94c2c5a5?hl=en&lnk=gst&q=bonnelle#e8baca94c2c5a5 (may 3, 2007)

2006 BOWERY J.A., “Brief Proforma for a Solar Updraft Tower Algae Biosphere”, http://www.geocities.com/jim_bowery/sutabs.html

Something which would further enhance the value of the solar updraft tower power structure is to use the greenhouse area for algae ponds to add biodiesel, water, fish and salt production to the production of electricity normally envisioned.



Another possibilities (yet unexplored)

2008 de_RICHTER

This ideas have not yet been carefully studied and may have positive feedbacks, so more work is still necessary before validation.

Building a plankton economy?

- Wherever in the world the «Energy Towers» will be built, they will need sea water to work. The carbon dioxide captured from the atmosphere can feed plankton and algae.

Algae have emerged as one of the most promising sources for **bio-fuel** production, for 7 main reasons:

- (1)The yields of **bio-diesel** from algae are one order of magnitude higher than those for traditional oilseeds
- (2)Algae can be grown in sewages and next to power-plant smokestacks where they “eat” CO₂
- (3)There are also several projects of algae **bio-ethanol** in Taiwan, Japan and other countries
<http://www.jedi.org/ronbun/file/32.doc>
- (4)Algae can even produce **bio-hydrogen**: "Potential for hydrogen production with ... Chlamydomonas", Proc. Natl. Acad.Sci USA (2007) 105, 17548-17553, <http://www.pnas.org/cgi/content/abstract/104/44/17548>
- (5)Everything can be used in the algae: after death it can be digested into **bio-gas** (methane, carbon dioxide, and the fertilizer needed to grow more algae). The **bio-methane** is a renewable natural gas.
- (6)The remaining material (equivalent of inert peat) can be compacted and then be burnt to produce energy in a cogeneration plant (combining electricity and heat production).
- (7)Algae can grow in places away from the farmlands & forests, thus minimising the damages caused to the eco- and food chain systems. For instance in temporary storage lakes of sea water for “Energy Towers”. The nitrogen derivatives produced by the “Energy Tower” process, can also help feed the algae or plankton. Algae can also be used for protein production and as human food (high lipid or polysaccharide content).

Terrestrial albedo enhancement:

- Releasing white carbonate salts (Ammonium, Mg...) may provide an easy way of changing land surface albedo in some parts of the world. This can contribute to a “Solar Radiation Management Project” enhancing the albedo more efficiently than white roofs on cities. But one must be very careful, not to produce detrimental effects such as soil salinisation: the goal is to increase soil fertility, not the opposite! It must also be previously verified that there will be no effects on potentially close aquifers and ecosystems

Increasing surface reflectivity of the desert

The Egyptian **black** sahara (the well called) looks like a good candidate option for the first experimental “Energy Tower”

As salts like Na_2CO_3 , $(\text{NH}_4)_2\text{CO}_3$, MgCl_2 , CaCl_2 , and many other salts are

white...



Humid air, wind and the atmosphere may act as a transport system for the Mg or NH_4 bicarbonates released at the bottom of Energy Towers...



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Thanks for your attention

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