Energy Use and Prosperity (US, 1800-1900)
Energy Use and Prosperity (US, 1800-1900)
Energy Use and Prosperity (US, 1800-2000)
The Origin of Breakthrough Energy
CLIMATE IMPACT
We will invest in technologies that have the potential to reduce greenhouse gas emissions by at least half a gigaton.

OTHER INVESTMENTS
We will invest in companies with real potential to attract capital from sources outside of BEV and the broader Breakthrough Energy Coalition.

SCIENTIFIC POSSIBILITY
We will invest in technologies with an existing scientific proof of concept that can be meaningfully advanced.

FILLING THE GAPS
We will invest in companies that need the unique attributes of BEV capital, including patience, judgment by scientific milestones, flexible investment capabilities, and a significant global network.
Breakthrough Landscape of Innovation
Share of total U.S. energy used for transportation, 2017

- Transportation: 29%
- Other: 71%

U.S. transportation energy sources/fuels, 2017

- Gasoline (petroleum): 55%
- Distillates (petroleum): 22%
- Jet fuel (petroleum): 12%
- Natural gas: 3%
- Biofuels: 5%
- Other: 3%

Source: U.S. Energy Information Administration, Monthly Energy Review, Table 2.1, April 2018, preliminary data
Not. Happening.
Assumptions/Stipulations:

Liquid fuels for transportation will be highly persistent;

The planet will mandate zero-carbon fuels;

The planet will adopt the low-cost solution;

Subsidies at scale are not viable;

Infrastructure-compatible solutions are preferred.
Zero-Carbon Liquid Fuels Means Air Capture
Guesstimating the Price of Oil

Avg 1972 – 2018 = $54/bbl

Strong price support at $60/bbl
<table>
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<tr>
<th>Molecule</th>
<th>Concentration</th>
<th>Kinetic Diameter</th>
<th>Dipole Moment</th>
<th>Quadrupole Moment</th>
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<tbody>
<tr>
<td>$\text{N}_2$</td>
<td>78.1%</td>
<td>364 pM</td>
<td>0</td>
<td>N</td>
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<tr>
<td>$\text{O}_2$</td>
<td>20.9%</td>
<td>346 pM</td>
<td>0</td>
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<tr>
<td>$\text{H}_2\text{O}$</td>
<td>0 - 5%</td>
<td>265 pM</td>
<td>1.8546 d</td>
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<td>$\text{CO}_2$</td>
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<td>330 pM</td>
<td>0</td>
<td>Y</td>
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<tr>
<td>$\text{Ar}$</td>
<td>0.93%</td>
<td>340 pM</td>
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Amines Long Known for CO\textsubscript{2} Capture

Robert Roger Bottoms, of Louisville, Kentucky, assignor to the Girdler Corporation, of Louisville, Kentucky, a Corporation of Delaware

United States Patent Office

Process for Separating Acidic Gases

Application filed October 7, 1930. Serial No. 460,018.

This invention relates to the separation of acidic gases from other gases or gaseous mixtures, by means of an absorbent agent. By the term "acidic gases" I mean those gases which in water solution have an acid reaction. 10 but which are released unchanged upon sufficient heating of the water. Carbon dioxide, sulphur dioxide and hydrogen sulphide are the main gases of this type which are present in the gaseous mixtures commonly encountered in industrial operations.

for removing C\textsubscript{2}H\textsubscript{6} and methylene blue and other dyes from removing H\textsubscript{2}S, with alternate oxidation and reduction solid hexamethylenetetramine for removing SO\textsubscript{2}, but so far as I am aware it was not known prior to my invention that certain compounds forming a comparatively small group of the amines possessed the properties of chemically uniting with acidic gases at a comparatively low temperature range, giving up the gas in gaseous form at a higher temperature and at the same time becoming regenerated, and having a low vapor pressure during the absorption stage and also during the heating or gas liberating stage. The possession of these properties of high viscosity and high salt content, with such poor heat transfer properties that the distillation of the amine is accomplished by decomposition. I have found that, by modifying the amine absorption process to include a partial electrolytic purification of the amine solution being returned from the regeneration step to the absorption step, and by maintaining some of the amine, not less than about one half of one percent by weight with respect to the entire solution, in combined form throughout the process, it is possible to prevent accumulation of strong and nonvolatile acids at low cost, of the order of one tenth the cost of maintaining the activity of the solution by addition of fresh amine.

The electrolytic cells employed are of the type in which a permeable partition is interposed between the anode and the cathode, and they are operated in such a manner as to minimise the flow of liquid (as distinct from the flow of ions) through the partitions in either direction.

The improved process is described in the following and is illustrated by the accompanying drawings, in which:

Fig. 1 is a flow diagram illustrating the entire process;

Fig. 2 is a diagram in plan view illustrating the electrolytic purification step; and

Fig. 3 is a cross-sectional view of the electrolytic cells.

Referring to Fig. 1, I is an absorption column provided internally with conventional means for bringing immiscible fluids into contact, such as bubble plates, scraper regeneration columns, or if a liquid is to be the reactant,
Solid-Supported Amine Contactors

Covalent tethering via silane linkage

Physical impregnation

Direct covalent tethering via in-situ polymerization

\( n \) = adsorption capacity (mol/kg)

\( \Delta n \) = working capacity

\( P_{\text{low}} \) to \( P_{\text{high}} \)

humidity swing

Exchange material "inhales" CO₂ when dry

Exchange material "exhales" CO₂ when wet

If exposed to high humidity or wetted directly, the material will release its CO₂
Current: 10.5 GJ·ton\(^{-1}\); long-term: 7.2 GJ·ton\(^{-1}\)
We Have a Target...

$60 \text{ bbl}^{-1} \quad \rightarrow \quad $12.50 \text{ bbl}^{-1} \quad + \quad \text{Kerosene Oil}

$60 \text{ bbl}^{-1} \quad \rightarrow \quad $2.73 \text{ gal}^{-1} \quad + \quad $100 \text{ ton}^{-1}
~97% Theoretical Yield

>95% Theoretical Yield
Where Do We Need to Be?

$0.08 \rightarrow $1.10 \rightarrow $2.73 \text{ gal}^{-1}$
Where Are We Now?

$3.72 \text{ Bu}^{-1}$

$0.12 \text{ lb}^{-1}$

$1.60 \text{ Gal}^{-1}$
Cellulosics?

$1 \text{ Gal}^{-1} \text{ EtOH requires biomass at } <$50 ton$^{-1}$
Does a Viable Low-Cost Feedstock Exist?

Brazilian sugarcane ethanol as an expandable green alternative to crude oil use

Deepak Jaiswal, Amanda P. De Souza, Søren Larsen, David S. LeBauer, Fernando E. Miguez, Gerd Sparovek, Germán Bollero, Marcos S. Buckeridge and Stephen P. Long
Low Cost Renewables?
How Low Cost?

**Assumed CAPEX + OPEX**
- $0.75 \text{ Gal}^{-1}
- $1.25 \text{ Gal}^{-1}

**Implied Max H}_2\text{ Price**}
- $1.34 \text{ kg}^{-1}
- $0.84 \text{ kg}^{-1}
Geologic Hydrogen?
“Far better it is to dare mighty things, to win glorious triumphs, even though checkered by failure, than to rank with those poor spirits who live in the gray twilight that knows not victory nor defeat.”

Theodore Roosevelt, April 1899