Climate Change and technical paths to a sustainable future:
How to change the world and be cool

UC Davis Energy Graduate Group
6 October, 2017
Outline of talk

• The risks of climate change: new data
• The rapidly changing landscape of energy
Outline of talk

• The risks of climate change: new data
Global average temperature increased by 1º C since 1970.
This graph shows a “slowdown” in rising temperatures until 2010. The black line shows temperatures as predicted by climate models, and the red line shows actual temperatures. Warming has recently increased, breaking historical records in 2014 and 2015.

*Nature Climate Change* (2016) doi:10.1038/nclimate2938
Why did the climate models miss the energy plateau?

Predicting climate change on a 10-year time frame is difficult. (e.g. details of an *el Niño* and *la Niña*)
Deep Ocean thermal mixing also fluctuates

Argo Float used to measure sea temperature (0 – 2 km deep)
4 year operation, surfaces every 10 days to transmit data
Energy is still conserved! The heat went into heating the oceans.

Global Heat Content anomaly 0 - 2,000 m depth (2006 - 2014)
Are the glaciers melting?
Is the sea level rising?
Are the glaciers melting?
Is the sea level rising?

YES

In the last interglacial period (129,000 to 116,000 years ago), the average temperature was only $\sim 1^\circ C$ warmer than today.

Geological records: the sea level was 6 - 9 meters higher than today. We used to believe would take 1000s of years. We now fear seas could rise 5 meters in < 100 years.

We are at ~ 490 ppm CO$_2$ equivalent today. The U.N. goal is 450 ppm to keep temperature rise to 1$^\circ$ C increase from today’s temperature. We will go over 550 and may go over 600 ppm.

“If you don’t change direction, you will end up where you are heading.”

Lao-Tze (老子)

3/4 of GHG emissions occurred in the last 65 years.
\~ 30\% of GHG emissions is from agriculture, land use and forestry. There is a big opportunity to use CRISPER-Cas systems + high-throughput manipulation of microbial and plant genes to increase productivity, restore soil fertility and sequester carbon.
Outline of talk

• The risks of climate change: new data

• The rapidly changing landscape of energy
Wind energy: $32 - $62 /MWh
Solar utility energy: $46 - $61 /MWh
Gas Combined Cycle: $48 - $78/MWh
Renewable energy costs (L.C.O.E.) at the best sites around the world is likely to achieve 3 ¢/kWh by 2020.

Costs may continue to decline to 2 ¢/kWh by 2030.
Machine Learning can be used to manage electricity distribution, learn patterns of energy use, improve weather predictions and more.

- **Energy Storage**
- **Flexible AC Transmission**
- **Layered real time monitoring and control**
- **HV transmission**
- **Advanced sensors, short-term generation forecasting**
- **Outage detection and management**
- **Distributed generation, demand-side management**
- **Micro-grid management and grid integration**
Energy Storage
Progress in Batteries and other forms of energy storage

Pump water when the wind blows or the sun shines
Chile Solar farm and pumped storage

600 MW solar energy
300 MW pumped storage (@ $1.30/W)
Stanford Energy System Innovations (SESI) project

Thermal storage: Two 5 M gallon cold water tanks, one 2.3-million-gallon hot water tank
The cost of lithium ion batteries for electric vehicles are expected to drop to 10% of the 2006 price.
Yi Cui  
Materials Science Department, Stanford University

Yi and I are seeking a new generation of lithium metal - batteries that may increase the energy density and **charging rate** 4x.
Silicon Anode manufacturing tool (achieving world record results)
Nanoscale Interfacial Materials Design

1 M LiTFSI in DOL:DME w/ 2% LiNO₃

2015 and 2016 forecasts of electric vehicles sales

500% increase in sales estimate in 1 year
By 2032, 100 million EVs on the road?
By 2040, EVs may be 35% of car sales ~ 35 - 40 million EVs/year

Source: Bloomberg New Energy Finance

The gasoline-powered internal combustion engine rapidly replace horse powered vehicles.

New York, 5th Avenue, ~1890s

Detroit, circa 1920

Automobile technology ultimately proved to be superior, but required a oil-gasoline supply chain, paved roads, and other infrastructure.

A serious environmental pollution issue hastened the transition.

The ~160,000 horses in New York in 1880 were producing 3 - 4 millions pounds of horse manure and 40,000 gallons urine a day.
Air pollution
Particulate matter PM$_{2.5}$ (diameter < 2.5 µm) is especially deadly.

1.4 x increase in lung cancer per 10 µg/m$^3$ of PM$_{2.5}$
(The Lancet Oncology 14, 813 - 822 (2013))

The average air in Beijing is ~ 100 µg/m$^3$. Risk of getting lung cancer may be $(1.4)^{10} \sim 29$ x higher.
Nanofiber filtration: 98% filtration of PM$_{2.5}$ with 30% light transmission

Prof Yi Cui and I have started a company to quickly commercialize the production of the filter material that can be used in home and building filters, face masks, coal plants, and vehicle exhaust systems.

Transparent air filter for high-efficiency PM2.5 capture, Chong Liu, Po-Chun Hsu, … Yi Cui, Nature (2015)
A lesson in static electricity

The particle is attracted to where the electric field is strongest
Clean electricity at 2 – 3 ¢/kWh opens up exciting opportunities in electrochemistry
Atomic weight ratio: \( \frac{\text{Li}}{\text{Li}_2\text{CO}_3} = \frac{7}{73.9} = 5.28 \)

\( \Rightarrow \$100,000 / \text{tonne of lithium metal} \)
Trends for Lithium demand

<table>
<thead>
<tr>
<th>Application</th>
<th>Lithium Carbonate Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Phone</td>
<td>3 grams ~ 0.1 oz</td>
</tr>
<tr>
<td>Notebook</td>
<td>30 grams ~ 1.0 oz</td>
</tr>
<tr>
<td>Power Tool</td>
<td>30-40 grams ~ 1.0-1.4 oz</td>
</tr>
<tr>
<td>Hybrid (HEV) 3kWh</td>
<td>3.5 lbs</td>
</tr>
<tr>
<td>Plug-in Hybrid (PHEV) 15 kWh</td>
<td>26 lbs</td>
</tr>
<tr>
<td>Electrical Vehicle (BEV) 25 kWh</td>
<td>44 lbs</td>
</tr>
<tr>
<td>Tesla 85 kWh</td>
<td>112 lbs</td>
</tr>
</tbody>
</table>

The Rise of Electric Cars

By 2022 electric vehicles will cost the same as their internal-combustion counterparts. That’s the point of liftoff for sales.

~ 20M EVs by 2030?

100,000,000 EVs will be sold by 2032. Assuming 30 kWh/EV (30 kg Li$_2$CO$_3$) demand by will be 600,000 metric tons/year.

Sources: Data compiled by Bloomberg New Energy Finance, Marklines
## Lithium Resources

<table>
<thead>
<tr>
<th>Location</th>
<th>Li Amount</th>
<th>Conc.</th>
<th>Price</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral (Spodumene)</td>
<td>16.7 MT</td>
<td>1-4%</td>
<td>6-8 $/kg</td>
<td>Smash, Elution (concentrated chemical, energy-consuming)</td>
</tr>
<tr>
<td>Brines</td>
<td>26.9 MT</td>
<td>0.017-0.15%</td>
<td>2-3 $/kg</td>
<td>Evaporation (Slow, Weather dependence)</td>
</tr>
<tr>
<td>Sea Water</td>
<td>231,000 MT</td>
<td>~1.7 *10^{-5} % (177 ppb)</td>
<td>~80 $/kg ?</td>
<td>Adsorption</td>
</tr>
</tbody>
</table>

9,000 times more Li

From: Camille Grosjean et. al., Renewable and Sustainable Energy Reviews 16 (2012) 1735–1744
**Li Extraction from salt water (Chong Liu, Yi Cui, et al.)**

<table>
<thead>
<tr>
<th>Location</th>
<th>Conc.</th>
<th>Li/Na molar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brines</td>
<td>0.017-0.15%</td>
<td>1/1790 -1/202</td>
</tr>
<tr>
<td>Sea Water</td>
<td>~1.7 *10^{-5}</td>
<td>1/1.86×10^4</td>
</tr>
</tbody>
</table>

### Graphs

- **Graph 1:**
  - **X-axis:** Li / Na Molar Ratio
  - **Y-axis:** Selectivity (%)
  - **Legend:**
    - Prefer Na
    - Prefer Li
    - Brine
  - **Data Points:**
    - Prefer Na: 5.4E-5
    - Prefer Li: 5.01E-4
    - Brine: 0.00405
  - **Selectivity:**
    - ~95%
    - ~100%

- **Graph 2:**
  - **X-axis:** Li/Na Molar Ratio
  - **Y-axis:** 1/1996
  - **Legend:**
    - 1/1996
    - 1/247
Hemoglobin protein in red blood cell carries oxygen to cells. Diffusion of $O_2$ from the lungs to cells is due to the gradient in $O_2$ concentration. 

$CO_2$ is carried by carbonic anhydrase, another protein.

**Alveolus**: 200 µm in diameter
CO\(_2\) reduction to H\(_2\) and CO

“Near world-record CO2 reduction activity performance even with multiple times lower catalyst loading.”
The goal of these companies is to reduce the cost of carbon capture from $70/ton of CO₂ to less than $30/ton.

Capture using structured materials such as MOFs (metal-organic frameworks) (< $30/ton of CO₂)
100% renewable energy will require **carbon recycling**

Captured CO$_2$  $\rightarrow$ CO, H$_2$  $\rightarrow$ liquid hydro-carbon

Carbon-Neutral Energy

- Electrochemical
- Photochemical
- Biochemical
- Thermochemical

H$_2$: Need @ $1.50/kg
Today @ $5/kg

O$_2$
How much does it cost to ship oil anywhere in the world? Answer: $0.02/gallon of gasoline. Oil tankers as transcontinental energy “transmission lines”
Earthrise from Apollo 8 (December 24, 1968)

"We came all this way to explore the moon and the most important thing is that we discovered the Earth.”

Bill Anders, Apollo 8 Astronaut
Ju-Chin Chu
Prof. of Chem. Eng.
Brooklyn Polytechnic

Edith Ju-hwa Chu
Prof. of Chemistry,
Tsinghua Univ.

Ching Chen Li
李靜貞
I was not only ugly, I was the academic black sheep of my family.

- My older brother (Gilbert) went to Princeton, has a Ph.D. in physics from MIT, and an M.D./Ph.D. in medicine from Harvard/MIT. He is Professor of Oncology and Biochemistry at Stanford.

- My younger brother (Morgan) has five degrees including a Ph.D. at the age of 22 from UCLA, an MSL from Yale at 23 and a JD from Harvard at 24. He is one of the most famous patent litigators in the U.S., and was President of the Board of Overseers of Harvard, 2014 - 2015.
At Stanford when the Nobel Prize was announced. (49 yrs old)

Getting a Nobel Prize leveled the playing field in my family.
Future Nobel Laureates who were Ph.D. students at Berkeley in the 1970s

- Mario Molina (Chemistry 1972)
- Kary Mullis (MCB 1973)
- John Mather (Chemistry 1974)
- Tom Cech (Chemistry 1975)
- Steven Chu (Physics 1976)
My advisor and I dropped the test of quantum electrodynamics (QED) to test the Weinberg-Salam-Glashow theory unifying electromagnetic and weak nuclear forces.

The laser I designed was much better than any commercial laser.
With a beginning graduate student, I used my start-up money to build the laser used for her Ph.D. thesis.

When I left Gene’s group, I knew how to build lasers.
Me at 40 (First year at Stanford)
Laser Manipulation of DNA

DNA

Polystyrene sphere

Microscope objective

Cover slip

Water

Microscope slide

Optical manipulation of DNA (1989)

Steve Kron
(U. of Chicago)

Steve Quake
Stanford
Director of Lawrence Berkeley National Laboratory, Professor of Physics, Molecular and Cell Biology (2004 – 2008)
January 2009 – April 2013
end