Running the World on Renewables:
Energy Sustainability with
God on our side?

Santa Clara University

22 October 23

Bill Leighty
The Leighty Foundation
wleighty@earthlink.net
"Philosophers, like vegetables, are profoundly influenced by their environment."

E. A. J. Johnson

Some Origins of the Modern Economic World

1936
Rad’i cal  adj.

1. a) of or from the root or roots; going to the foundation or source of something fundamental; basic
Aldo Leopold

1887 - 1948
There are two spiritual dangers in not owning a farm:

One is supposing that breakfast comes from the grocery;

The other is supposing that heat comes from the furnace.

*Aldo Leopold, “A Sand County Almanac”*
1958: NE Iowa Science Fair, SCI, 9th grade
Mendenhall Glacier, Juneau, AK
June ‘71
Mendenhall Glacier, Juneau, AK
10 October 10
Rapid climate change

Spruce bark beetle kill, Alaska
Spruce bark beetle kill, Alaska
“Drunken Trees” on thawing permafrost
Shishmaref, Alaska
Winter storms coastal erosion
Gold Creek Salmon Bake, end of Basin Road  ’71 – ‘91
"The unleashed power of the atom has changed everything save our modes of thinking and we thus drift toward unparalleled catastrophe."

New York Times
25 May 1946
MUST Run the World on Renewables – plus Nuclear?
Earth’s only source of income: Solar radiation, lunar tides
MUST Run the World on Renewables – plus Nuclear?

- Emergencies:
  - Climate change
  - Ocean acidification
  - Sea level rise
  - Species extinction
- Conservation + efficiency
- GW scale renewables
- Beyond Electricity Grid
- Energy: beyond electricity
- Hydrogen, ammonia, ?
MUST Run the World on Renewables – plus Nuclear?

- Global system
- Indigenous
- Equitable
- Firm: available
- Benign: C-free
- Abundant
- Affordable
- Perpetual:
  - solar
  - geothermal
  - tidal
Comparing the world's energy resources

Where should we invest for the long-haul??

Annual Income

Capital

SOLAR

World energy use

©Richard Perez, et al.

*yearly potential is shown for the renewable energies. Total reserves are shown for the fossil and nuclear “use-them, lose-them” resources. World energy use is annual.
Alaska Applied Sciences, Inc.

560 kW windplant

Palm Springs, CA
**PROJECT:** Complete RE - NH₃ SSAS Storage System

> NH₃ synthesis from RE electricity, water, air (N₂)
> Liquid NH₃ tank storage
> Regeneration + grid feedback
> SCADA instrumentation → UAF - ACEP

SSAS Pilot Plant Demonstration System for AEA EETF Grant

Rev: 6 Mar 11 W. Leighty
Alaska Applied Sciences, Inc.
Thin-shell concrete dome for housing, classroom, clinic, storage:
  46% scale model, proof-of-concept prototype

Alaska villages
Afghanistan development
Haiti rebuilding

Bill Leighty
wleighty@earthlink.net
907-586-1426
206-719-5554 cell
Box 20993
Juneau, AK 99802

Dome form set:
  5/8 sphere

Foundation ring
form set
Dome #1     Juneau, Jan 11     8’ 6” Diameter
Dome #1     Juneau, Jan 11     8’ 6” Diameter
The Leighty Foundation board

- Earth Protection
- 20 co-authored papers: renewables transmission & Storage
6,000 delegates
100 CEO’s
50 energy ministers

22nd World Energy Congress, Daegu, Korea  13 – 17 Oct 13
South Korea President, Mrs. Park Gyeung-He
Christiana Figueres, UN
Kandeh Yumkella, UN
World Energy Trilemma

World Energy Council
15 October 13
2050: Key messages, World Energy Council

1. System complexity increase
2. Efficiency crucial: prevent Demand >> Supply
3. Mostly fossil-source
4. Regional priorities: no “one size fits all”
5. 450 ppm CO2 target: Very high C tax?
6. Low-carbon future:
   1. Renewables
   2. CCUS: carbon capture, utilization, storage
   3. Consumer behavior change
7. Greatest uncertainties:
   1. CCUS
   2. Solar energy cost
   3. Storage
8. Balance: difficult choices
9. Markets: investments + regional integration
10. Policy: energy and carbon markets must work and deliver
CCS: Carbon Capture and Storage

CCUS: Carbon Capture Utilization and Storage
Emerging economies dominate energy production growth...

Primary energy production

Billion toe

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<tr>
<th>Year</th>
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<th>OECD</th>
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<td>3</td>
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Primary energy production

Billion toe

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<th>Region</th>
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<tr>
<td>S&amp;C America</td>
<td>Green</td>
</tr>
<tr>
<td>N. America</td>
<td>Orange</td>
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<td>Yellow</td>
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<td>Africa</td>
<td>Brown</td>
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Energy Outlook 2030

© BP 2013
Energy demand growth is matched by supply...

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<tr>
<td>Billion toe</td>
<td>2030 level</td>
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<tr>
<td>2011</td>
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<tr>
<td>11</td>
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<tr>
<td>16</td>
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<td>13</td>
<td>Non-fossil</td>
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<td>Tight Other</td>
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<td>Shale</td>
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<td></td>
<td>Hydro</td>
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<td></td>
<td>Nuclear</td>
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</tbody>
</table>

*Includes biofuels

Energy Outlook 2030

© BP 2013
Electricity gains in all sectors...

Electricity share of final consumption

- Industry
- Transport
- Other

World power generation

- Renewables
- Hydro
- Nuclear
- Coal
- Gas
- Oil

Energy Outlook 2030
The fuel mix for power generation diversifies...

Growth of fuel inputs to power

Shares of power output

Billion toe


1970 1990 2010 2030

Energy Outlook 2030

© BP 2013
Energy demand growth drives carbon emissions...

**CO₂ emissions and primary energy**

- Emissions from energy use
- Primary energy (RHS)

**Growth of CO₂ emissions**

- 1970-1990
- 1990-2010
- 2010-2030

---

*Energy Outlook 2030*
Conclusion

- Economic growth needs energy
- Competition and innovation are the key to meeting this need
  - energy efficiency
  - new supplies
- Energy security and climate change remain challenges
Annual Global CO₂ Emissions, GT/year

IPCC Categories (CO₂ – eq):
- 445–490 ppm
- 535–590 ppm
- 710–855 ppm
- 855–1130 ppm

Note: Assumes over the long term that non-energy CO₂ emissions from industry, agriculture, and land use are reduced to insignificant levels in Jazz and Symphony.
Uncertainty Increases with Time: Simply Extrapolate?
Scenarios  Dangers

• Extrapolation  *ad absurdum*
• Wrong
• Fate: experts, logical
• Frightening
• Absurd
• Unacceptable
• Motivating
• Guiding
Refugees, not new energy plants

5 meter sea level rise by 2100: high CO2 emissions
Calibrate: CO₂ problem

- Heat-trapping "greenhouse gases" (GHG’s)
- Carbon dioxide (CO₂) most abundant
- Climate forcing
- Rapid global warming and climate change
- Ocean acidification
Ocean Acidification

How will changes in ocean chemistry affect marine life?

CO₂ absorbed from the atmosphere

CO₂ + H₂O + CO₃²⁻ → 2 HCO₃⁻

carbon dioxide  water  carbonate ion  2 bicarbonate ions

Consumption of carbonate ions impedes calcification
This graph shows the correlation between rising levels of carbon dioxide (CO₂) in the atmosphere at Mauna
Svante Arrhenius

Sweden

1905
Nobel Prize Chemistry

Proved CO$_2$ is heat-trapping gas in 1896
The Greenhouse Effect

Some solar radiation is reflected by the Earth and the atmosphere.

Some of the infrared radiation passes through the atmosphere, and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower atmosphere.

Solar radiation passes through the clear atmosphere.

Most radiation is absorbed by the Earth's surface and warms it.

Infrared radiation is emitted from the Earth's surface.
1 gallon = 7 lbs

- Gasoline
- Diesel
- Jet

Burned = 20 lbs CO₂

(carbon dioxide)
Earth Surface Temperature °C
Relative to 1980
Atmospheric CO₂ at Mauna Loa Observatory

Scripps Institution of Oceanography
NOAA Earth System Research Laboratory

PARTS PER MILLION

YEAR


320 340 360 380
RECENT MONTHLY MEAN CO₂ AT MAUNA LOA

YEAR

PARTS PER MILLION

2005 2006 2007 2008 2009 2010

375 380 385 390 395
Concentrations of Greenhouse Gases from 0 to 2005

- Carbon Dioxide ($CO_2$)
- Methane ($CH_4$)
- Nitrous Oxide ($N_2O$)
Variations of the Earth’s surface temperature for...

- The past 140 years (global)
- The past 1000 years (Northern Hemisphere)

140 years: global
1,000 years: northern hemisphere
(d) Temperature change


- Several models all SRES envelope

- Model average all SRES envelope

- Bars show the range in 2100 produced by several models
(b) CO₂ concentrations

Scenarios
- A1B
- A1T
- A1FI
- A2
- B1
- B2
- IS92a

Year

2000 2020 2040 2060 2080 2100
Geoengineering: Earth repair

- Aerosols
  - Sulfates today, future enhance
  - Saltwater
- Mirrors in space
- Ocean iron fertilization
- Risky: unintended consequences
The Great Plains Wind Resource

Running the World on Renewables:
Alternatives to Electricity for Transmission and Low-cost Firming
Storage of Stranded Renewables as Hydrogen and Ammonia Fuels via Underground Pipelines
What about nuclear?

- Need it?
- Fission or fusion?
- Afford it? Capital, O&M
- Renewable?
- Balance with renewables?
- Dangers
- Many reactors under construction
- Russia major sales push
- Gen IV plants; SMR’s
High Temperature Gas Reactor (HTGR)

Same Problems:
- High plant cost
- Waste disposal
- Accidents
- Insurance
- Proliferation
- Limited fuel
Nuclear Fusion

ITER

International Thermonuclear Energy Reactor

France

2018

first plasma
Running the World on Renewables: Alternatives to Electricity for Transmission, Firming Storage, and Supply Integration for Large-scale, Stranded, Renewable Energy
World Renewable Energy Forum, Denver, May ‘12
Four Stanford Alumni
Denis Hayes
Director, 1979 - 81
SERI (Solar Energy Research Institute)
Now NREL, Golden, CO

Coordinator:
First Earth Day, 1970
Founder:
Earth Day Network
Denis Hayes
Executive Director
Bullitt Foundation, Seattle

“We’re screwed. All the trends are in the wrong direction. But we have to find hope.”

To moderator Ray Suarez.
ASES Conference 2010
“America has the technology and resources to meet all its energy needs while safeguarding the Earth’s climate. The urgent question now is, ‘Do we have the will?’”

“I feel more confident than ever that the power to save the planet rests with the individual consumer.”
Bullitt Center, Seattle
Greenest Commercial Building in the World
“Americans can be counted on to always do the right thing – but only after they have tried everything else.”

Winston Churchill

The dog caught the car.

Dan Reicher
Providing all global energy with wind, water, and solar power (WWS)


Mark Z Jacobson
Stanford Engineering Prof

Mark Delucchi
Institute of Transportation Studies
UC Davis
• We suggest producing all new energy with WWS by 2030 and replacing the pre-existing energy by 2050.
• Barriers to the plan are primarily social and political, not technological or economic.
• Energy cost in a WWS world should be similar to that today.

Mark Z Jacobson
Stanford Engineering Prof

Mark Delucchi
Institute of Transportation Studies
UC Davis
Adequate Renewables

• Run the world; humanity’s needs
• “Distributed” and “Centralized”
• Affordable, benign
• Diverse, synergistic
• Richest are “stranded”
  – Far from markets
  – No transmission
Global Opportunity
Wind Powering America

NW Iowa 190 MW windplant

Diverse!
Geothermal: hot water, surface recharge
“Enhanced”, “Engineered” Geothermal  Mt. Spurr, Alaska
Hot dry rock: flash injected water to steam
Photobiological
Rhodobacter sphaeroides
Algae: 
*Chlamydomonas reinhardtii*

Photo: Tasios Melis, PhD, 
UC Berkeley, USA
Dry Biomass
Wet Biomass: Anaerobic Digester
Concentrating Solar Power (CSP)
Stirling Energy Systems, Inc.

Model solar thermal power plant, NM    Completed May 05
Parabolic Trough
Concentrating Solar Power (CSP)
CA, Spain
Photovoltaic (PV)

Small
Medium
Large
Example: Vision of a bright future

The Silk Road Genesis Project*
*proposed by Sanyo

Vision of solar farms in China along the historic silk road to cover $\frac{1}{3}$ of China’s energy demand in 2030
Currents: Tidal, River, Ocean
"LIMPET", Island of Islay, off Scotland coast

Wave Generation 500 kW

UK

"Limpet": Land Installed Marine Powered Energy Transformer

The Wells Turbines rotate in the same direction regardless of the direction of the air flow. Thus generating irrespective of upward or downward movement of the water column.

Air is compressed and decompressed by the Oscillating Water Column (OWC). This causes air to be forced through the Wells Turbine and is then drawn back through the Wells Turbine.
Oregon State University Conceptual Wave Park

Wave Generation

Magnetic Shaft anchored to sea floor

Electric Coil secured to heaving buoy

Permanent Magnet Linear Generator Buoy

Source: Nicolle Rager Fuller, NSF
Big Island, Hawaii: OTEC: Ocean Thermal Energy Conversion
Hot Dry Rock (HDR) for geothermal-source hot water district heating taps the crust at \( \sim 6,000 \) m depth, at \( \sim 180 \) deg C.

The ubiquitous “geothermal gradient” worldwide is \( \sim 30 \) deg C per 1,000 m depth.
EPB might be used for this, at deep rock temp < 200 deg C, but is probably most economical as a single borehole HDR “well”.
2003: EPB Drilling Full Scale in Granite
311 mm = 12.25”
2006 BIT DESIGN

PROTOTYPE I
MULTIELECTRODE BIT
Calibrate: Energy

World’s largest industry
Slavery in America
Energy Slaves
Lance Armstrong 2002

Peak  500 Watts
Average  250 Watts

3 kWh per day
( 12 hour day )
746 Watts = 1 hp
Kilowatt-hour (kWh):

- Energy = power (Watts) × time (hours)
- 1,000 Watt-hours
- 2.6 million foot-pounds
- 1 Sherpa-week (100 pounds from 3,000 ft to 29,000 ft)
- 3,410 Btu = 640 lbs water heated 5 °F
Energy Slaves

USA:
35 Lance Armstrongs per person working 24/7
DOE-EIA: Estimated 2005 US energy use

Estimated Future U.S. Energy Requirements - 96.8 Quads

- Hydro: 0.94
- Bio/Geo: 3.81
- Wind: 0.06
- Solar: 0
- Nuclear: 7.48
- Coal: 20.83
- Gas: 24.73
- Oil: 38.96

Electricity Generation: 33.91
H2 Production: 0

Useful Energy: 44.76
Rejected Energy: 52.06

Residential: 11.89
Commercial: 8.96
Industrial: 26.36
Automotive: 16.18
Freight: 9.19
Airlines: 2.9

Projection Year 2005
From Year 2005
Efficiency Year 2005
Energy Distribution Year 2005
EIA estimated 2025 energy use

Estimated Future U.S. Energy Requirements - 133.1 Quads

- Hydro: 0.96
- Bio/Geo: 5.94
- Wind: 0.11
- Solar: 0.01
- Nuclear: 7.64
- Coal: 26.89
- Gas: 34.88
- Oil: 56.7

Electricity Generation: 45.74

Residential: 14.09
Commercial: 12.31
Industrial: 34.81
Automotive: 25.83
Freight: 13.18
Airlines: 5.06

Useful Energy: 59.64
Rejected Energy: 73.47
Postponed: Fracked oil & gas
Methane Hydrate (clathrate)

Methane: $\text{CH}_4$

Water ice: $\text{H}_2\text{O}$

- More hydrocarbon than all oil + gas
- Deep seabed
- Inaccessible?
- Methane release?
The Fossil Fuel Age: a “Blink of an Eye” between the First and Second Solar Civilizations.
Titusville, PA

1859

First oil well in USA
The First Solar Civilization

One-fourth of farm’s solar energy harvest to draft animals
The Second Solar Civilization

- Diverse
- Benign
- Renewable
  - Electricity
  - Hydrogen
  - Ammonia
Trouble with Renewables

- Diffuse, dispersed: gathering cost
- Richest are remote: “stranded”
  - High intensity
  - Large geographic extent
- Time-varying output:
  - “Intermittent”
  - “Firming” integration + storage required
- Distributed AND centralized
Trouble with Renewables: Big Three

1. Transmission and gathering
2. Storage: Annual-scale firming
3. Integration
   • Extant energy systems
   • Electricity grid
   • Fuels: CHP, transportation
Trouble with Renewables: Electricity Transmission

• Grid nearly full: who pays?
• Integration
  – Continental energy system
  – Quality
  – Time-varying
• Costly “firming” storage: CAES, VRB, pump hydro
• Low capacity factor (CF) or curtailment
• Overhead vulnerable: God or man
• Underground: only HVDC, 6x cost
• Wide ROW
• NIMBY: delay + cost, site + ROW
• Beyond electricity
Beyond “Smart Grid”

- Primarily DSM
- More vulnerable to cyberattack?
- Adds no physical:
  - Transmission, gathering, distribution
  - Storage
- Next big thing; panacea
- Running the world on renewables?
- Must think:
  - Beyond electricity
  - Complete energy systems
  - ALL energy: Hermann Scheer
“Transmission”

- Electrofuels
- Renewable-source electricity
- Underground pipelines
- Carbon-free fuels: hydrogen, ammonia
- Low-cost storage:
  - $0.10 – 0.20 / kWh capital
- CHP, transport, industrial
- GW scale
Zion, IL
Near Zion nuclear plant, Oct 02
“There’s a better way to do it... Find it”

Thomas Edison
Sunlight from local star

Solar Hydrogen Energy System

Solar Hydrogen System Junior Basic

PEM Electrolyzer

2H₂O + Energy → 2H₂ + O₂

Electrolyzer

H₂

Fuel Cell

2H₂ + O₂ → 2H₂O + Energy

Work

Electricity

O₂
What if we broke down our silos

Integrative Thinking About Electricity and Energy

Source data: National Energy Board secondary energy demand forecast, Rethinking Energy Conservation in Ontario, May 2010 report
Hydrogen and Ammonia Fuels

• Solve electricity’s RE problems:
  – Transmission
  – Firming storage
  – Grid integration: time-varying output
• Carbon-free
• Underground pipelines
• Low-cost storage: < $1.00 / kWh capital
  – Pipelines
  – GH2 salt caverns
  – NH3 tanks
Volumetric Energy Density of Fuels
(Fuels in their Liquid State)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Hydrogen Energy (kWh/LHV)</th>
<th>Carbon Energy (kWh/LHV)</th>
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“Atmospheric” Liquid Ammonia Storage Tank (corn belt)

- 30,000 Tons
- 190 GWh
- $15M turnkey
- $80 / MWh
- $0.08 / kWh
- -33 C
- 1 Atm

’09 ARPA-E “Grids” Goal: $100 / kWh
Humanity’s Goal?

A sustainable, benign-source, equitable, global energy economy
Watch our language!

“Run”

6. Move freely and without restraint
8. Take part in a race or contest
12. Ply between places
19. **Operate or function**
35. **Perform or accomplish**
46. Operate or drive
50. Manage or conduct
...
67.
Watch our language!

- Nuclear weapons
- Sustainable
  - Sustainability
  - Sustainable development
- Environment
  - Environmental
  - Environmentalist
  - Earth protection
- Natural
- Global warming
- Global climate change, rapid climate change
- Stewardship
- Extinction
Poetry's really about what can't be said… when you can't find words for something.”

“Nobody finds words for grief… for love… for lust.”

W.S. Merwin
poet
Humanity’s Goal?

A Benign-source, Sustainable, Equitable, Affordable, Perpetual energy services system
Sustainable

“Meeting our needs without compromising the ability of future generations to meet their own needs”

United Nations Commission on Environment and Development (UNCED)
“Our Common Future”, 1987
Sustain what?

1. Keep in existence; maintain
2. Supply with necessities or nourishment; provide for
3. Support from below; keep from falling or sinking; prop
4. Support the spirits, vitality, or resolution of; encourage
5. Bear up under; withstand

• Economy back on track?
• Get my job back?
• More of the same?
• Lower price of gasoline?
• My grandkids? Seventh generation?
• New Vision, Paradigm, Myth?
“In every deliberation, we must consider the impact on the seventh generation... even if it requires having skin as thick as the bark of a pine.”

— Great Law of the Iroquois
Watch our language: Define

- Power
- Energy
- kW, kWh
- Efficiency
- Conservation
- Transmission
Rad’ical adj.

1. a) of or from the root or roots; going to the foundation or source of something fundamental; basic
Joseph Campbell 1904 - 87

“The Power of Myth”, Bill Moyers

“What Myth are we living?”
MUST Run the World on Renewables – plus Nuclear?

- Emergencies:
  - Climate change
  - Ocean acidification
  - Sea level rise
  - Species extinction
- Conservation + efficiency
- GW scale renewables
- Beyond Electricity Grid
- Energy: beyond electricity
- Hydrogen, ammonia, ?
MUST Run the World on Renewables – plus Nuclear?

- Climate Change
- Demand growth
- Depletion of Oil and Gas
- Only 200 years of Coal left
- Only Source of Income:
  - Sunshine
  - Tides
  - Meteors and dust
- Spend our capital?
CO₂ in the Atmosphere

WE’RE HERE: 385.92 ppm

WE NEED TO GET BELOW: 350 ppm

www.350.org
Total solar: \( \sim 3 \times 10^{14} \) kg / yr

Total wind: \( \sim 3 \times 10^{11} \) kg / yr

Rich, stranded
Resources
YO! AMIGO!!
WE NEED THAT TREE TO PROTECT US FROM THE GREENHOUSE EFFECT!
"We have met the enemy..."
GOTT MIT UNS  "God with Us"
Only the Abrahamic Religions?
There are two spiritual dangers in not owning a farm:

One is supposing that breakfast comes from the grocery;

The other is supposing that heat comes from the furnace.

Aldo Leopold, “A Sand County Almanac”
Doomsday Scenario

• “Hot, Flat, and Crowded” -- T. Friedman
• “Catastrophic climate disruption”
• Ocean acidification
• Rising sea level
• Storms, flood, drought
• Tropical pests and diseases move north
• Peak oil, gas, coal
• Environmental refugees: humans, other
• Species extinction
Doomsday Scenario

- Cannot accept, indulge, acquiesce
- Unfair: species, future generations
- Profane, insult creation-evolution
- Rapture: “Gott mit Uns”
- WWII: amazing
  - Mobilization
  - Sacrifice
“The Structure of Scientific Revolutions” – 1973

- Paradigm
- Paradigm paralysis
- Paradigm shift
Joel Barker:
• The Business of Paradigms
• Paradigm Paralysis
Ilya Prigogine

1977 Nobel Prize, Chemistry

- Surprisingly alive
- Twitchy, searching, self aware
- Self-destruct?
- Self-shaking to higher ground
George Land

- Purpose of all life
- Growth
- Higher, more complex
  - organization
  - individual
“There’s a better way to do it... Find it”

Thomas Edison
New Myth

- Beyond “Gott mit Uns”
- Bigger loyalty, allegiance, patriotism
- Run world on renewables
- Stewardship
- Responsibility: united by threat
- Ethical, moral: fellow species in creation – evolution mystery
Socolow’s Wedges
Renewable electricity and fuels

Stabilization Triangle

- CO₂ capture and storage
- Forests and soils
- Nuclear Fission
- Energy efficiency and conservation
- Fuel switch

2004: 2 GtC/y
2054: 14 GtC/y

7 GtC/y
**Wedges**

**Efficiency & Conservation**
- Increased transport efficiency
- Reducing miles traveled
- Increased heating efficiency
- Increased efficiency of electricity production

**Fossil-Fuel-Based Strategies**
- Fuel switching (coal to gas)
- Fossil-based electricity with carbon capture & storage (CCS)
- Coal synfuels with CCS
- Fossil-based hydrogen fuel with CCS

**Nuclear Energy**
- Nuclear electricity

**Renewables and Biostorage**
- Wind-generated electricity
- Solar electricity
- Wind-generated hydrogen fuel
- Biofuels
- Forest storage
- Soil storage
## Exporting From 12 Windiest Great Plains States

Number of GH2 pipelines or HVDC electric lines necessary to export total wind resource

<table>
<thead>
<tr>
<th>State</th>
<th>Annual Energy Production (TWh)</th>
<th>Nameplate Installed Capacity (MW)</th>
<th>Nameplate Installed Capacity (GW)</th>
<th>6 GW 36” GH2 Hydrogen Pipelines</th>
<th>$ Billion Total Capital Cost</th>
<th>3 GW 500 KV HVDC Electric Lines</th>
<th>$ Billion Total Capital Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texas</td>
<td>6,528</td>
<td>1,901,530</td>
<td>1,902</td>
<td>317</td>
<td></td>
<td>634</td>
<td></td>
</tr>
<tr>
<td>Kansas</td>
<td>3,647</td>
<td>952,371</td>
<td>952</td>
<td>159</td>
<td></td>
<td>317</td>
<td></td>
</tr>
<tr>
<td>Nebraska</td>
<td>3,540</td>
<td>917,999</td>
<td>918</td>
<td>153</td>
<td></td>
<td>306</td>
<td></td>
</tr>
<tr>
<td>South Dakota</td>
<td>3,412</td>
<td>882,412</td>
<td>882</td>
<td>147</td>
<td></td>
<td>294</td>
<td></td>
</tr>
<tr>
<td>Montana</td>
<td>3,229</td>
<td>944,004</td>
<td>944</td>
<td>157</td>
<td></td>
<td>315</td>
<td></td>
</tr>
<tr>
<td>North Dakota</td>
<td>2,984</td>
<td>770,196</td>
<td>770</td>
<td>128</td>
<td></td>
<td>257</td>
<td></td>
</tr>
<tr>
<td>Iowa</td>
<td>2,026</td>
<td>570,714</td>
<td>571</td>
<td>95</td>
<td></td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>Wyoming</td>
<td>1,944</td>
<td>552,073</td>
<td>552</td>
<td>92</td>
<td></td>
<td>184</td>
<td></td>
</tr>
<tr>
<td>Oklahoma</td>
<td>1,789</td>
<td>516,822</td>
<td>517</td>
<td>86</td>
<td></td>
<td>172</td>
<td></td>
</tr>
<tr>
<td>Minnesota</td>
<td>1,679</td>
<td>489,271</td>
<td>489</td>
<td>82</td>
<td></td>
<td>163</td>
<td></td>
</tr>
<tr>
<td>New Mexico</td>
<td>1,645</td>
<td>492,083</td>
<td>492</td>
<td>82</td>
<td></td>
<td>164</td>
<td></td>
</tr>
<tr>
<td>Colorado</td>
<td>1,288</td>
<td>387,220</td>
<td>387</td>
<td>65</td>
<td></td>
<td>129</td>
<td></td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td><strong>33,711</strong></td>
<td><strong>9,376,694</strong></td>
<td><strong>9,377</strong></td>
<td><strong>1,563</strong></td>
<td><strong>$1,500</strong></td>
<td><strong>3,126</strong></td>
<td><strong>$2,000</strong></td>
</tr>
</tbody>
</table>

Wind energy source: Archer, Jacobson 2003
SEIA – AWEA Feb 09
“Green Power Superhighways: Building a Path to America’s Clean Energy Future”
AWEA 20% Wind by 2030

“Never be built ...”
AWEA: 20% Electricity from Wind by 2030
~ 7% US energy
## Electricity Capital Cost per GW-mile

<table>
<thead>
<tr>
<th>Capacity</th>
<th>KV</th>
<th>MW</th>
<th>$M / GW-mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEIA:</td>
<td>765</td>
<td>5,000</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>345</td>
<td>1,000</td>
<td>2.6</td>
</tr>
<tr>
<td>AEP-AWEA</td>
<td>765</td>
<td>5,000</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Consensus? 2.5
350 miles
5 GW
$ 5B

1,750 GW-miles @ $5,000M = $2.8M / GW-mile
Real time

WWSIS: April week: ~30% RE
Real time

CC gas

WIND

COAL

WWSIS: July week: ~10% RE
Total solar: $\sim 3 \times 10^{14} \text{ kg / yr}$

Total wind: $\sim 3 \times 10^{11} \text{ kg / yr}$

Rich, stranded Resources
Wind seasonality, Great Plains

- Winter = 1.20
- Spring = 1.17
- Summer = 0.69
- Autumn = 0.93

Source: D. Elliott, et al, NREL
Wind Seasonality, Northern Great Plains

Normalized to 1.0 per season

Seasonality Factor

<table>
<thead>
<tr>
<th>Season</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>1.2</td>
</tr>
<tr>
<td>Spring</td>
<td>1.4</td>
</tr>
<tr>
<td>Summer</td>
<td>0.8</td>
</tr>
<tr>
<td>Fall</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Wind Seasonality, Northern Great Plains

1,000 MW windplant: AEP = 3,500 GWh / yr
“Firm” goal = 875 GWh / season
Storage: 320 GWh per 1,000 MW wind

Source: NREL, D. Elliott
Annual – scale “Firming”
Great Plains Wind

• Potential, 12 states, ~50% land area:
  – 10,000 TWh = 100 quads = entire USA
  – 2,800,000 MW nameplate

• Seasonality:
  – “Firming” energy storage,
    per 1,000 MW wind = 320 GWh
“Firm” energy worth more

• Every hour, every year
• Strategically: indigenous, secure
• Market price
• Dispatchable
• Bankable large projects
• Risk avoidance: rapid climate change
Sunlight from local star

Solar Hydrogen Energy System
Hydrogen Transmission Scenario

- Low-pressure electrolyzers
- “Pack” pipeline: ~ 1-2 days’ storage = 120 GWh

Wind Generators

Electrolyzers

Compressors

Storage: 120 GWh

Wind Generators

1,000 miles Hydrogen Gas Pipeline 36" diameter ~ 1,000 psi

Generators ICE, CT, FC

AC grid Wholesale

End users Retail

Cars, Buses, Trucks, Trains

Liquefy

Aircraft Fuel
Norsk Hydro electrolyzer, KOH type
560 kW input, 130 Nm3 / hour at 450 psi (30 bar)
Compressorless system: No firming storage

Transmission

City gate

Distribution

Wind Generators

High-pressure Electrolyzers

Wind Generators

Pipeline Energy Storage

1,500 psi

500 miles

Hydrogen Gas Pipeline

20" diameter

1,500 -- 500 psi

Generators

ICE, CT, FC

End users

Retail

AC grid

Wholesale

Cars, Buses, Trucks, Trains

Liquefy

Aircraft Fuel

500 psi
“Firming” Cavern Storage

Hydrogen Energy Storage

- Wind Generators
- Electrolyzers
- Generators: ICE, CT, FC
- Cars, Buses, Trucks, Trains
- Liquefy
- Aircraft Fuel
- End users: Retail, Wholesale

1,000 miles Hydrogen Gas Pipeline 36" diameter, 1,500 - 500 psi
Pipeline Storage = 240 GWh

Geologic Storage?
- 860,000 m³ physical
- 150 bar = 2,250 psi
- 2,500 Mt net = 92,500 MWh
- $15M avg cap cost / cavern
- $160 / MWh = $0.16 / kWh
- Cavern top ~ 700m below ground

Domal Salt Storage Caverns
Texas
“Clemens Terminal”
Conoco Phillips
20 years
Praxair ‘07
PB ESS
Renewable-source GH2 geologic storage potential. Candidate formations for manmade, solution-mined, salt caverns.
**Optimistic: Total Installed Capital Cost**

1,000 mile Pipeline

“Firming” GH2 cavern storage

Windplant size  1,000 MW

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost [million]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind generators</td>
<td>$ 1,000</td>
</tr>
<tr>
<td>Electrolyzers</td>
<td>500</td>
</tr>
<tr>
<td>Pipeline, 20”</td>
<td>1,100</td>
</tr>
<tr>
<td># storage caverns</td>
<td>[4]</td>
</tr>
<tr>
<td>Caverns @ $10M ea</td>
<td>40</td>
</tr>
<tr>
<td>Cushion gas @ $5M ea</td>
<td>20</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$ 2,660</td>
</tr>
</tbody>
</table>

Cavern storage: ~ 3 % of total capital cost
(8 x 13) = 104 + (8 x 12) = 96  Total = 200 caverns per square mile
Each cavern is 200 ft diam, with minimum 200 ft web separation.
City-gate GH2 cost @ 15% CRF, 20” pipeline, from 2,000 MW Great Plains windplant

Competitive cost?

2005 $US / kg GH2

Pipeline length, miles

B1: Unsubsidized
B2: US fed PTC only
B3: PTC + Oxygen sales
B4: PTC + O2 sale + C-credit
Annual – scale “Firming”
Great Plains Wind

• Potential, 12 states, ~50% land area:
  – 10,000 TWh = 100 quads = entire USA energy
  – 2,800,000 MW nameplate

• Seasonality:
  – “Firming” energy storage, per 1,000 MW wind:
    • as electricity = 450 GWh
    • as GH2 = 15,712 tons, metric @ 2,500 tons / cavern = 6 caverns
  – “Firming” energy storage, all great Plains wind:
    • as GH2 = 17,000 caverns @ $15M each = $264 billion
AWEA 20% Wind by 2030

Wind Potential $\approx 3,000$ GW
Frontier Line + Transwest Express $\approx 115$ GW
AWEA 20% Wind by 2030

Wind Potential $\sim 3,000$ GW

Frontier Line + Transwest Express $\sim 115$ GW
Hydrogen “sector” of a benign, sustainable, equitable, global energy economy
ALL Denmark’s energy from windpower

• Prof Bent Sorensen, Roskilde Univ, DK

• WHEC, Montreal, June 02

• ALL Denmark’s energy from wind –
  ► Elec, oil, gas
  ► Transport, space heat-cool, industry

• IF convert ~ 15% to H2, store in extant salt caverns

• Can USA do same?

• Start with transport fuel?
Germany: window on the challenges of integrating high penetration of renewables
Falkenhagen Region in Northern Germany

- Increasing excess power
- Huge peak power
- Steep power gradients

Solution: Storage of excess wind power instead of curtailment.

Source: Presentation by Dr. Alexander Vogel, Head of Alternative Energy Systems, E.ON Ruhrgas at Gas to Power Conference, Cologne, Germany – November 2012
The NATURALHY approach: EC, R+D

NATURALHY:
- Breaks “chicken-egg” dilemma
- Bridge to sustainable future

Prepared by
O. Florisson
Gasunie
Free Storage + Free Transmission in E.on Natural Gas Pipeline System

Falkenhagen Region in Northern Germany

- Increasing excess power
- Huge peak power
- Steep power gradients

Solution: Storage of excess wind power instead of curtailment.

Source: Presentation by Dr. Alexander Vogel, Head of Alternative Energy Systems, E.ON Ruhrgas at Gas to Power Conference, Cologne, Germany – November 2012
E.ON first Power-to-Gas plant
Injecting hydrogen into natural gas grid

2MW Power-to-Gas Demonstration Plant in Falkenhagen, Germany
California’s surplus renewable generation

50% RPS
40% RPS
33% RPS

Curtailed?

Storage and DR

Do Not Cite
For Illustrative Purposes Only

Source: Adapted from + Valuing Storage, Eric Cutter, Energy + Environmental Economics – October 2013
Hydrogenics’ compact 1 MW PEM electrolyser
Increments up to 1,500 kg/day

*Future Hydrogenics’ PEM Electrolyser Configuration*
Estimated 2050 energy use
(H₂ fleet using wind electrolysis)
Hydrogen, Fuel Cell

Running on water?
Energy System of the Future

Hydro, Wind, Solar, Geothermal, Biomass, IGCC, Nuclear, Stationary Fuel Cell

H₂ Production/Use (Large / Small)

Potential Hydrogen Delivery System

Frank Novachek, Director Corporate Planning

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Utsira Island, Norway
Utsira Island
Norway

Wind – Hydrogen Autonomous System

Replaces aging electricity cable from mainland
The wind – hydrogen plant at Utsira

A vision becoming reality

- Wind turbine
- Control-system
- Transformer
- Electrolyser and compressor
- Fuel cell
- Hydrogen engine
- Hydrogen storage
Thermal Insulation
Vacuum
Electrical Insulation

~ 100 GW elec LVDC +
~ 100 GW LH2

* SC: MgB$_2$ magnesium diboride superconductor
** LH2: liquid hydrogen coolant, energy transmit

Continental Supergrid – EPRI concept “Energy Pipeline”
Airbus Industrie concept: liquid hydrogen fueled
Hydrogen’s principal value

• NOT fuel cell cars
• Gather, transmit, store:
  – Large-scale, diverse, stranded renewables
  – FIRM time-varying-output renewables
    • Pipeline transmission, storage
    • Geologic storage
    • “Renewables – nuclear Synergy . . .”, C. Forsberg
• Benign, if from renewables
• Global opportunity
• Hydrogen “sector”, not “economy”
  – Transportation fuel: ground, air
  – DG electricity, CHP, retail value
Pilot plant needed

- Every major new industrial process
- Diverse, large-scale, stranded
- Renewables-source systems
- IRHTDF
The Second Solar Civilization

Alaska should begin to build it
International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF) Pilot plant

Global opportunity: IPHE project
Pilot-scale Hydrogen Pipeline System: Renewables

- Diverse renewables
- Dispersed, diffuse
- Large-scale
- Stranded
  - Remote
  - No transmission
IRHTDF
International Renewable Hydrogen Transmission Demonstration Facility

* Ames
* Des Moines

Iowa Energy Center
This map was generated from data collected by the Iowa Wind Energy Institute under Iowa Energy Center Grant No. 93-04-02. The map was created using a model developed by Brower & Company, Andover, MA.

Copyright © 1997, Iowa Energy Center. All rights reserved. This map may not be republished without the written consent of the Iowa Energy Center.
IRHTDF: generation, conversion, collection, storage corridor

Biomass, Wind, Other Catchment Areas, with Delivery Points to GH2 pipeline

GH2 geologic storage

O2 pipeline

*
Anhydrous Ammonia \( \text{NH}_3 \)

N \hspace{0.5cm} \text{Nitrogen}

H \hspace{0.5cm} \text{Hydrogen}

Molecular weight = \( \sim 17 \)

18\% \text{H} \text{ by weight: “other hydrogen”}

\text{NH}_3 + \text{O}_2 = \text{N}_2 + \text{H}_2\text{O}
Why Ammonia? 
**Fertilizer and Fuel**

Only liquid fuel embracing:

- Carbon-free: clean burn or conversion; no CO₂
  - Excellent hydrogen carrier
  - Easily “cracked” to H₂
- Reasonably high energy density
- Energy cycle inherently pollution free
  - Potentially all RE-source: elec + water + Nitrogen
  - Cost competitive with hydrocarbon fuels?
- Decades of global use, infrastructure
  - Practical to handle, store, and transport
  - End-use in ICE, Combustion Turbine, fuel cell
  - Safety: self-odorizing; safety regs; hazard
Volumetric Energy Density of Fuels
(Fuels in their Liquid State)

Hydrogen Energy
Carbon Energy

kWh per Gallon (LHV)

Diesel (Cetane)
Gasoline (Octane)
Heptane
Hexane
Pentane
Butane
Ethane
Propane
Methane
Ethanol
Methanol
Ammonia
Hydrogen
C-free
Ammonia fueled - Norway

1933

Ammonia fuel tank
Ammonia Fueled Bus: Thousands of Problem-free Miles

Belgium

1943
X-15 rocket plane: NH₃ + LOX fuel

Mach 6.7 on 3 Oct 67

199 missions

1959 - 68
University of Michigan

Ammonia + Gasoline Powered

- Idle: gasoline
- Full power: 80% ammonia

Summer ’07 Detroit → San Francisco

2007
1,000 hours, ICE, 6 cyl, 100 hp
75% ammonia, 25% propane

Irrigation pump
Central Valley, CA
NH₃ Ag Fertilizer Tanks, Wind Generators, NW Iowa
Ammonia
( \( \text{NH}_3 \) )
Synthesis Plant
Natural Gas Feed
1 – 3,000 tpd

Haber-Bosch
“Synloop”
Haber-Bosch Process

1909 – 1913 BASF

- NH$_3$ synthesis
- Coal gasification $\rightarrow$ H2
- WW I explosives
- 40% humanity: N fertilizer

Haber-Bosch Reactor

1921

Ludwigshafen, Germany
Inside the Black Box: Steam Reforming + Haber-Bosch

\[ 3 \text{CH}_4 + 6 \text{H}_2\text{O} + 4 \text{N}_2 \rightarrow 3 \text{CO}_2 + 8 \text{NH}_3 \]

Energy consumption \( \sim 33 \text{ MBtu} \) (9500 kWh) per ton \( \text{NH}_3 \)
NH₃ Ag Fertilizer Tanks, Wind Generators, NW Iowa
Inside the Black Box: HB Plus Electrolysis

3 H₂O → 3 H₂ + 3/2 O₂
3 H₂ + N₂ → 2 NH₃

Energy consumption ~12,000 kWh per ton NH₃
Inside the Black Box: Solid State Ammonia Synthesis

\[ 6 \text{H}_2\text{O} + 2 \text{N}_2 \rightarrow 3 \text{O}_2 + 4 \text{NH}_3 \]

Energy consumption 7000 - 8000 kWh per ton NH\textsubscript{3}

Benchtop
Proof-of-concept
USA NH3 Infrastructure

- USA imports ~60% of 14 MMt / year
- ~ 3,000 miles pipelines
  - ~ 250 psi liquid
  - Smaller diameter than NG or hydrogen
- ~ 4.5 MMt large “atmospheric” tank storage
- Mild steel construction
  - Low cost
  - No corrosion or embrittlement
MONTHS: GH2, NH3
“Atmospheric” Liquid Ammonia Storage Tank

- 30,000 Tons
- 190 GWh
- $15M turnkey
- $77 / MWh
- -33 C
- 1 Atm
Ammonia
534 kg H2
$ 10,000

Hydrogen gas
350 kg H2
$ 400,000
320,000 MWh storage
Annual firming, 1,000 MW wind

- VRB
  - O&M: 80% efficiency round-trip
  - Capital: $500 / kWh = $160 Billion

- CAES
  - O&M: $46 / MWh typical
  - Iowa: Power = 268 MW
    Energy capacity = 5,360 MWh
    Capital: 268 MW @$800 / kW = $214 M
    @$40 / kWh = $13 Billion

- GH2 Capital $70 Million
- NH3 Capital $30 Million
MUST Run the World on Renewables – plus Nuclear?
MUST Run the World on Renewables – plus Nuclear?

- Emergencies:
  - Climate change
  - Ocean acidification
  - Sea level rise
  - Species extinction
- Conservation + efficiency
- GW scale renewables
- Beyond Electricity Grid
- Energy: beyond electricity
- Hydrogen, ammonia, ?
MUST Run the World on Renewables – plus Nuclear?

- Global system
- Indigenous
- Equitable
- Firm: available
- Benign: C-free
- Abundant
- Affordable
- Perpetual:
  - solar
  - geothermal
  - tidal
GAIA theory: Earth is a single living organism

James Lovelock
Garrett Hardin
1915 – 2003

1968, Science

“The Tragedy of the Commons”
Plan B 4.0: Mobilizing To Save Civilization

Lester Brown
Earth Policy Institute
New Myth

- Beyond “Gott mit Uns”
- Loyalty, allegiance, patriotism: Earth
- Stewardship
- Responsibility: united by threat
- Ethical, moral: fellow species in creation – evolution mystery
- Decide: Run world on renewables
Comparing the world’s energy resources*

Where should we invest for the long-haul??

SOLAR

World energy use

Annual Income

Capital

©Richard Perez, et al.

*yearly potential is shown for the renewable energies. Total reserves are shown for the fossil and nuclear “use-them, lose-them” resources. Word energy use is annual.
Integrity is wholeness, the greatest beauty is organic wholeness, the wholeness of life and things, the divine beauty of the universe.

Love that, not man
Apart from that, or else you will share man's pitiful confusions, or drown in despair when his days darken.
Running the World on Renewables:
Energy Sustainability with God on our side?

Handouts, DVD’s

Santa Clara University

22 October 22

Bill Leighty
The Leighty Foundation
wleighty@earthlink.net
Hydrogen Fuel Cell
Proton Exchange Membrane (PEM) type

Hydrogen (H2) combines with Oxygen (O2) to make electricity + heat + water (H2O)