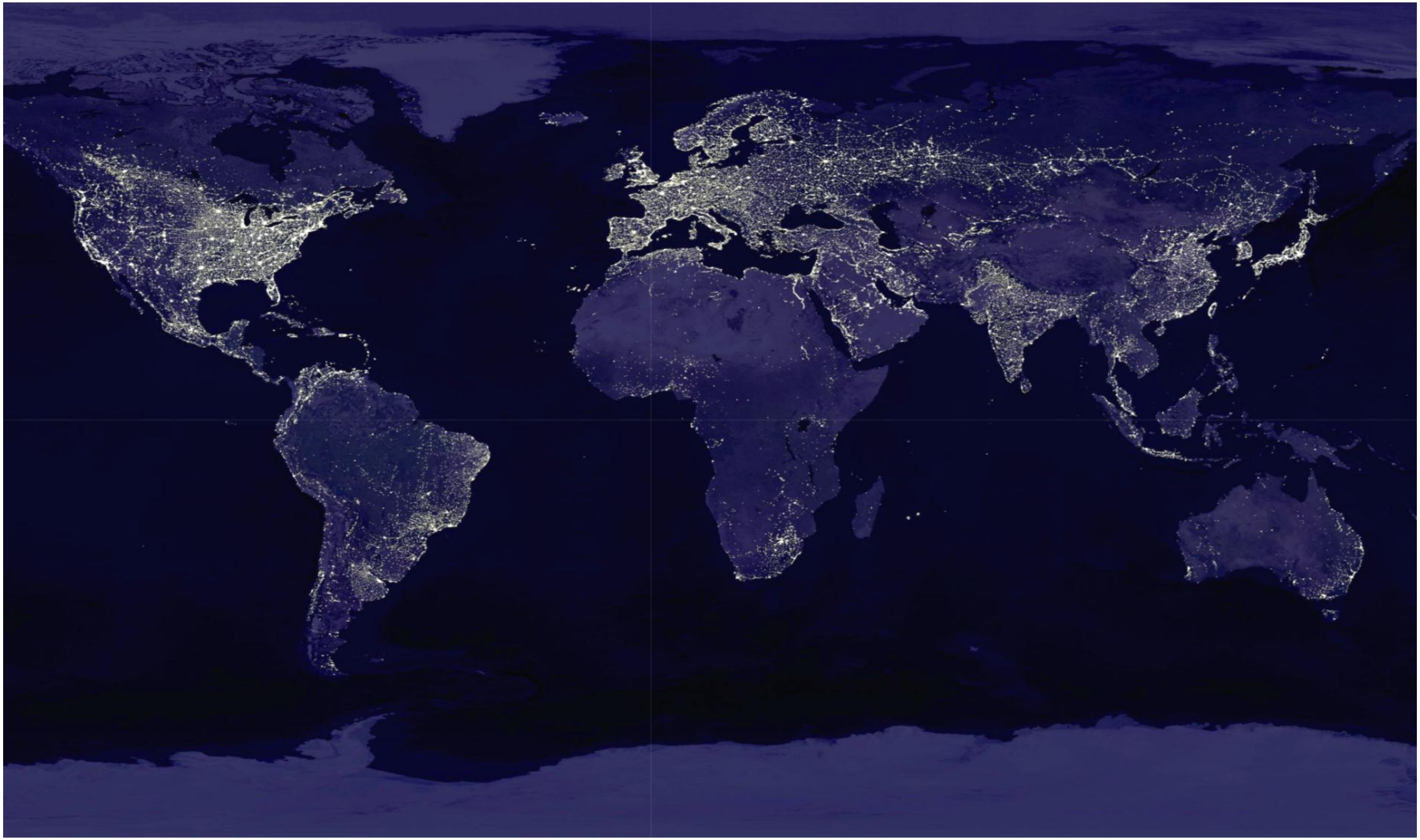
# Energy Technologies at Scale: Nanoscience by the Ton

**Eilat Eilot Green Energy Conference**

Peter Littlewood, Director
Argonne National Laboratory
pblittlewood@anl.gov

# Today, our mission is to solve the world's greatest challenges – with scalable solutions

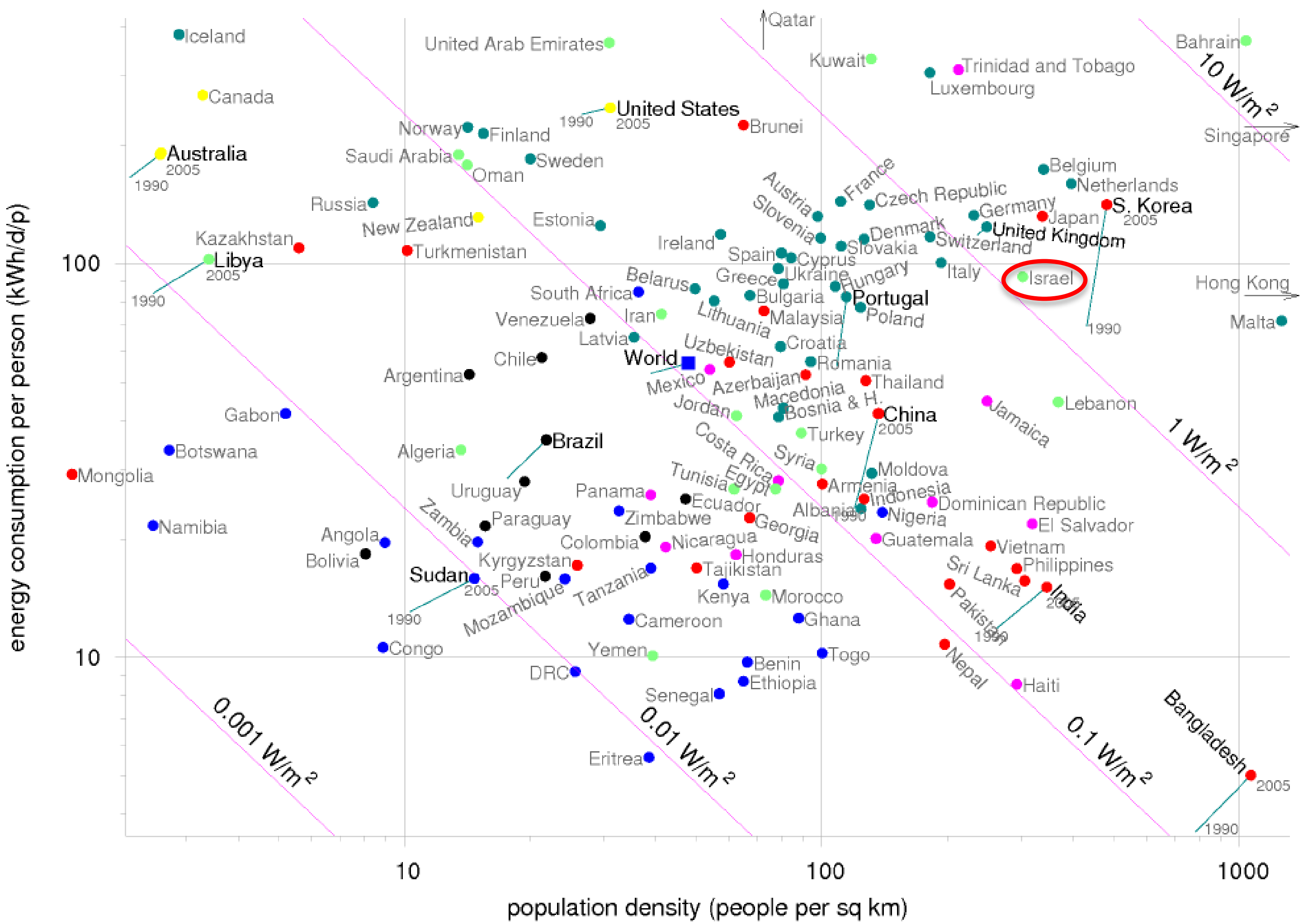


# Outline

- Scale : generation, storage and transmission of energy from renewable sources
- Cost : technology measured in $/kg
- Science
  - 20th century condensed matter physics has evolved along with its technologies --- transistor, laser, display --- to maximise information capacity in dense packages for consumption
  - how will our science evolve along with 21st century technology pulls?
- How much headroom, and how?

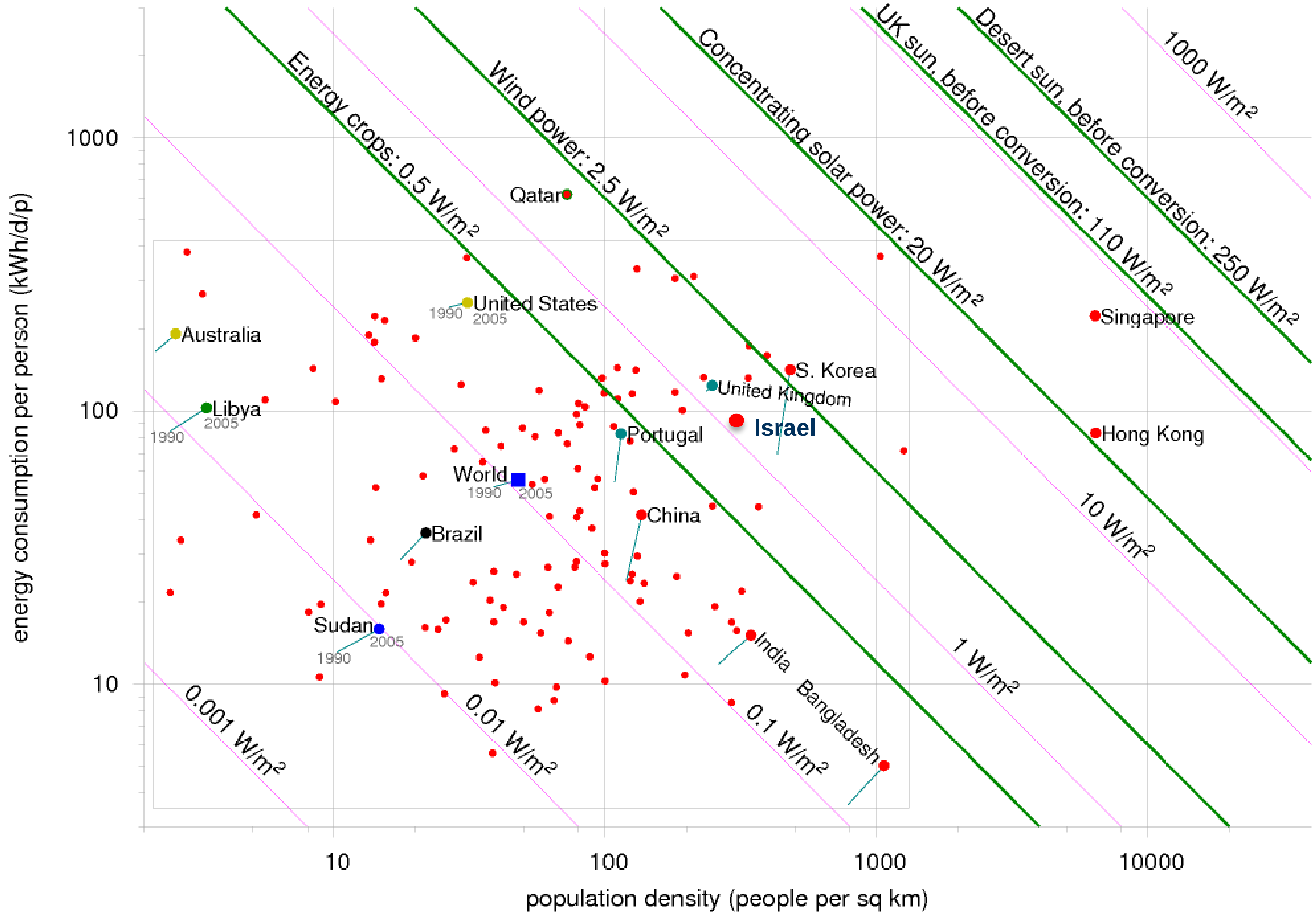
# Sources of renewable energy and the needs of the planet

# Energy usage per square meter




Courtesy D J Mackay, UK DECC

# Renewables must be deployed on country-sized scale




Courtesy D J Mackay, UK DECC

# Solar: the energy input

- Solar insolation is the major energy input to the planet
- Mean radiative solar flux =341.5 $W/m^2$
- This energy gets redistributed into other degrees of freedom
  - thermalised into infra-red --- “heat”
  - wind energy
  - wave energy
  - rainfall

**How much do we need ?**

USA average power consumption = 3 TeraWatt (Israel ~ 0.03TW)

10 kW per person (Israel ~ 4 kW)

5 billion microwave ovens

Solar flux on 10,000 $km^2$ = Delaware + Rhode Island (Israel 100 $km^2$)

# Solar photovoltaics in the USA

Photo courtesy SEPA

- The US uses 3 TeraWatts of power, averaged over the day
- In 2011 2 GigaWatts (peak) installed in US (about 20GW worldwide)
- Unfortunately the rating assumes 1kW/m$^2$ intensity of insolation (mid-day in Arizona)
- In practice, the average power is probably 20-30% of peak (at best) – so this is 0.02% of demand ....
- Can we scale this up ?

https://financere.nrel.gov/finance/content/calculating-total-us-solar-energy-production-behind-the-meter-utility-scale

# Technologies by volume

Global shipments of silicon wafers

1st quarter 2012

2033 million square inches[1]

[1] Source: semi.org

1.2 square kilometers

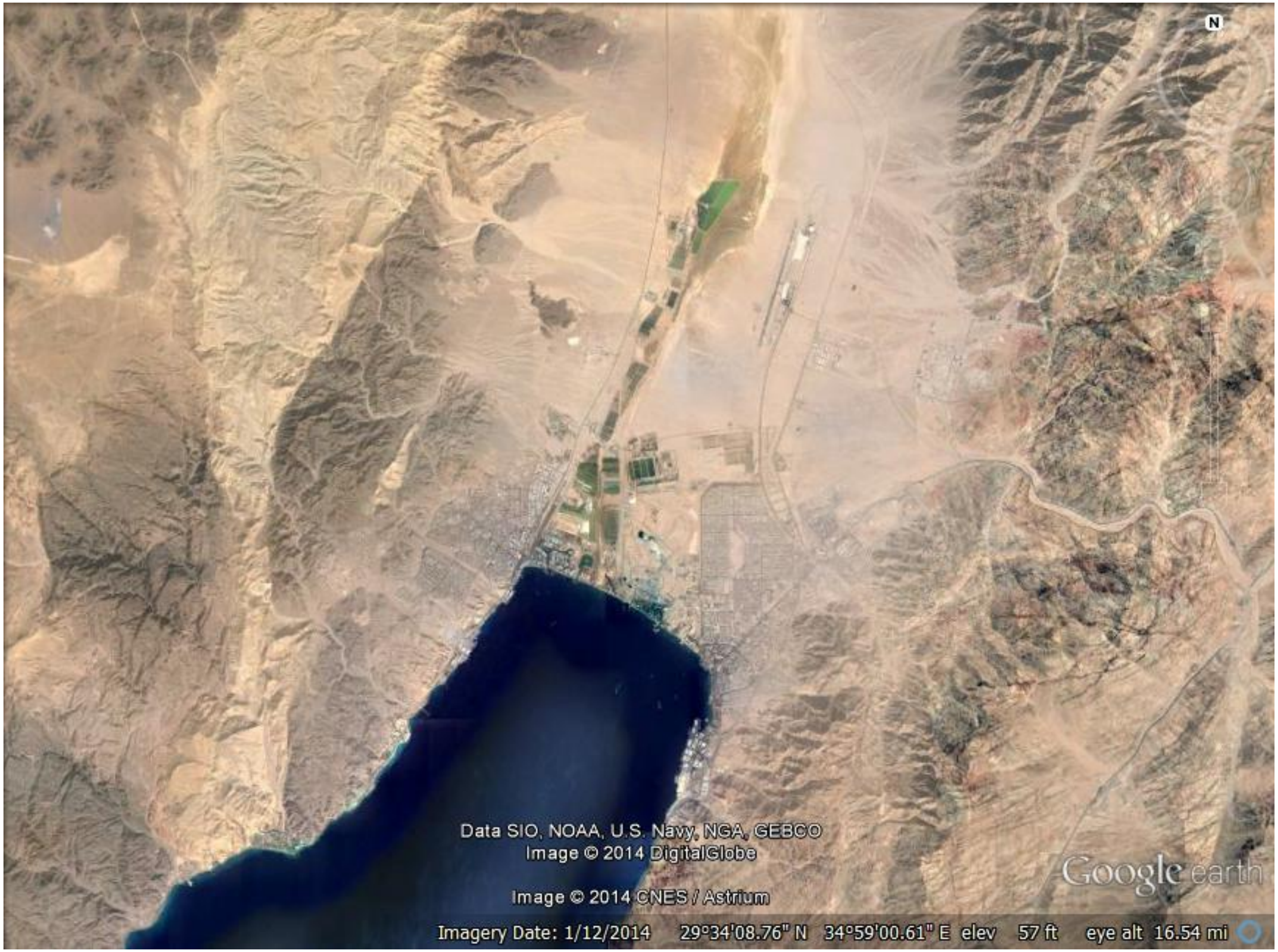
[Global Foundries Fab 8 in Malta NY]

# 2011 Solar PV Capacity in USA – 2 GW (peak)
## 10 square kilometers

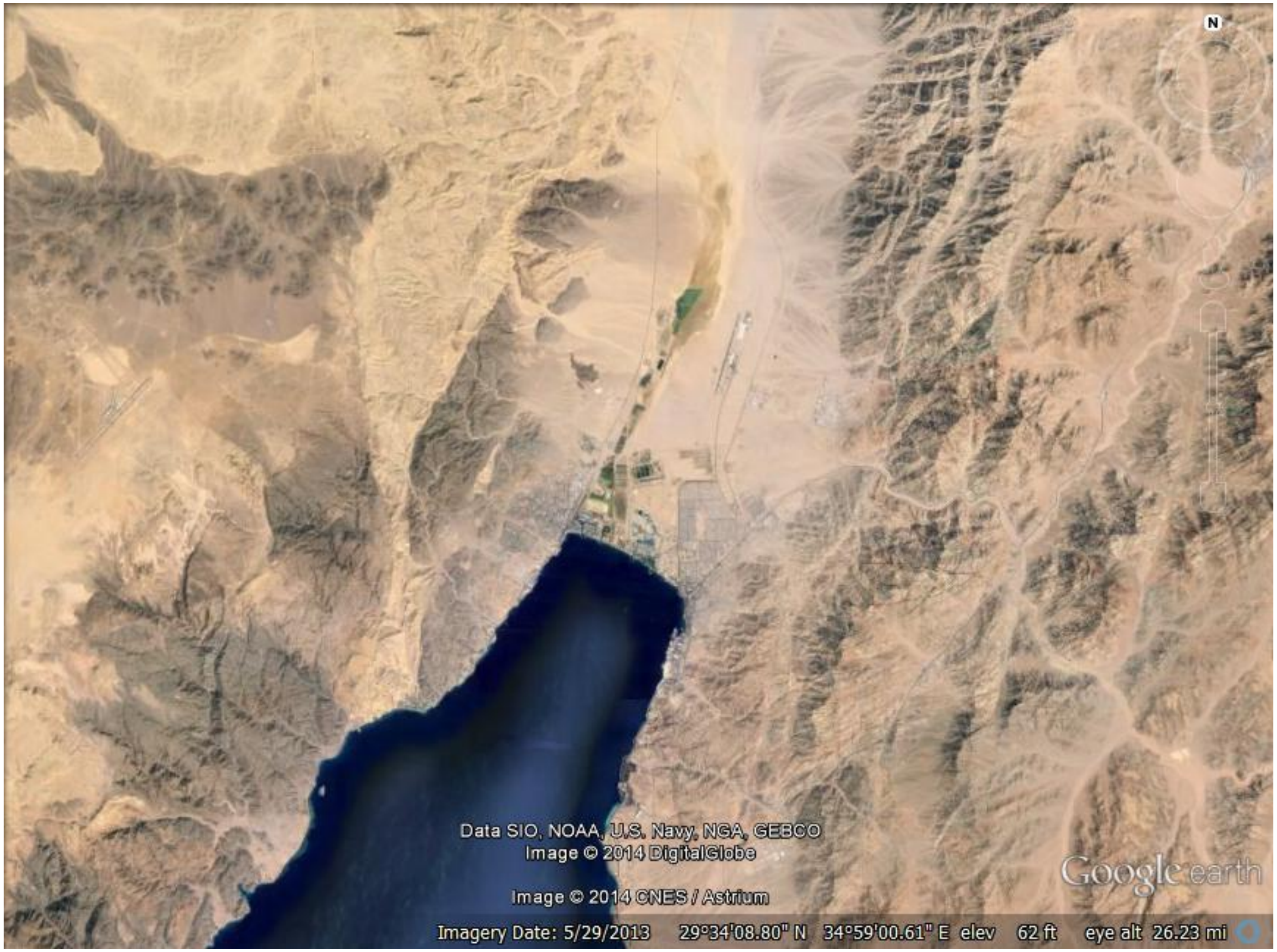
# 3 TW @ 300 W/m$^2$ (Full insolation in AZ) 10000 km$^2$

# 30 GW @ 300 W/m$^2$ (Full insolation in Eilat) 100 km$^2$

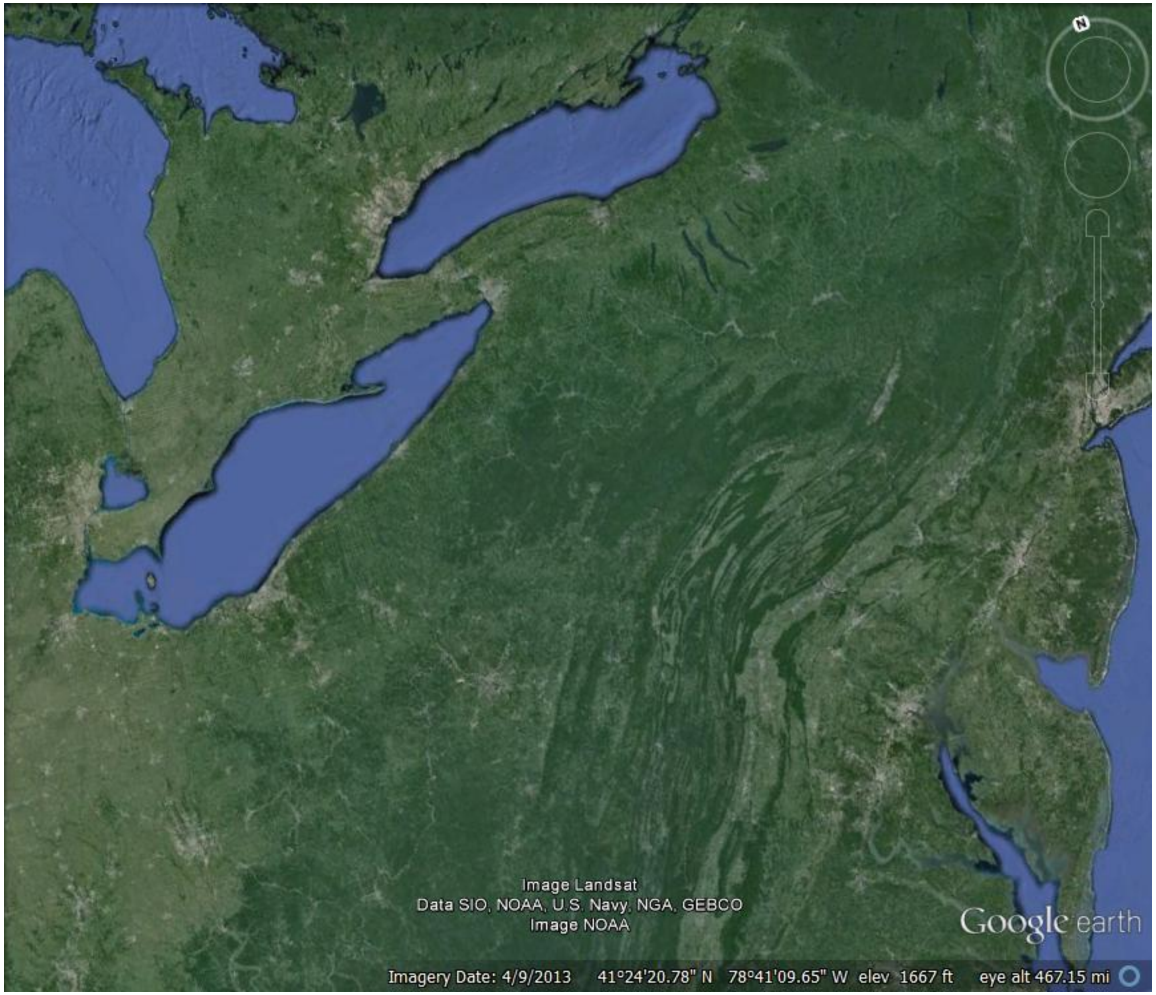
# 30 GW @ 80 W/m$^2$ 400 km$^2$
## State of the art PV - 30% efficient



# 30 GW @ 30W/m$^2$ 1000 km$^2$ (5% land area of Israel)
# Typical solar PV installation ~ 10% efficient



# 3 TW @ $5W/m^2$ 600000 $km^2$
# Typical installed PV under cloudy conditions

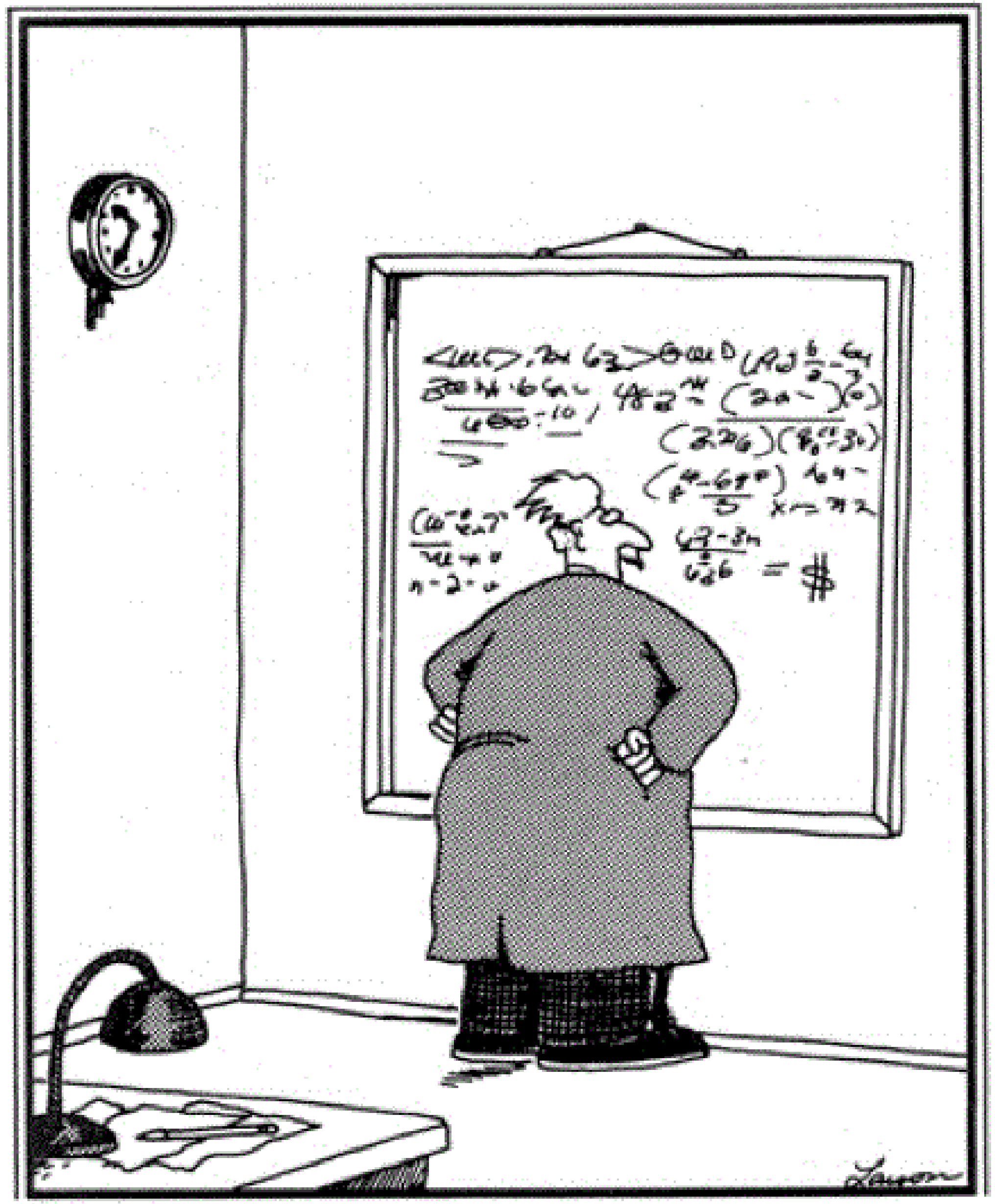


# Backing up grid renewables with storage


3 Terawatts x 12 hours equals:

9 times the **annual** energy generated by the Hoover Dam

$10^8$ tons of Li-ion batteries: ~ $10^3$ times current production



**Einstein discovers that time is actually money**

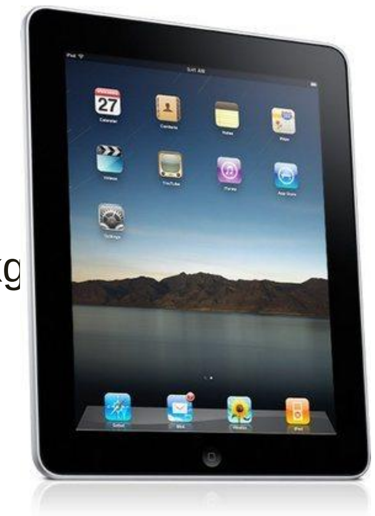
# The (energy) cost of making things

# Materials are energy, and energy is money

Energy input accounts for:

- 1/3 cost of steel ($1/kg)
- 1/2 cost of aluminum ($2.50/kg)

iPad
Cost: $500
Weight: 0.6 kg
**$1,000/kg**




Boeing 787-9
$243M
180,000kg
**$1,500/kg**

Honda Civic 1.8
$16,000
1,210 kg
**$13/kg**

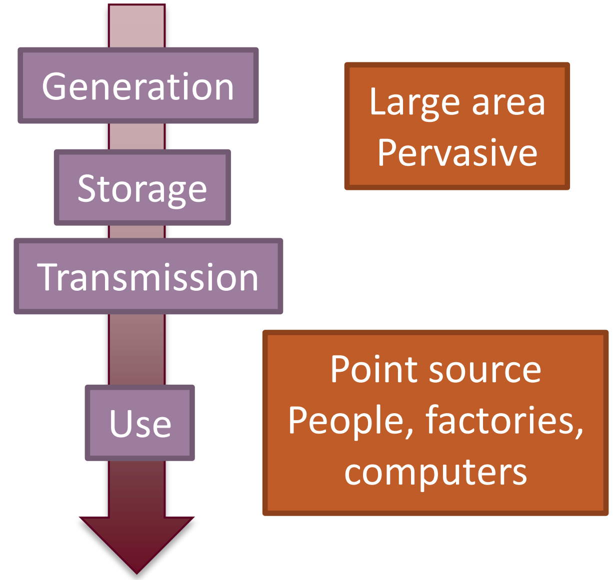

Ground beef
**$10/kg**

Enercon E-126
7.58 MW
$10M
6,000 tons
**$1.5/kg**
Payback
in 3-4 years
at 10¢/kWh

# How much headroom for new technologies ?

# Transformative materials technologies for the electrified economy

- Solar PV for electricity generation (or solar to fuel)
- Ultracapacitors/batteries for electrical storage
- Superconductors for electrical transmission/motors
- Thermoelectrics for refrigeration/scavenging
- Light emitting diodes for electrical lighting
- Membranes for water purification/desalination




Point use is easier: smaller scale for fabrication, straightforward path to introduction
Large scale disruptive technologies are very hard

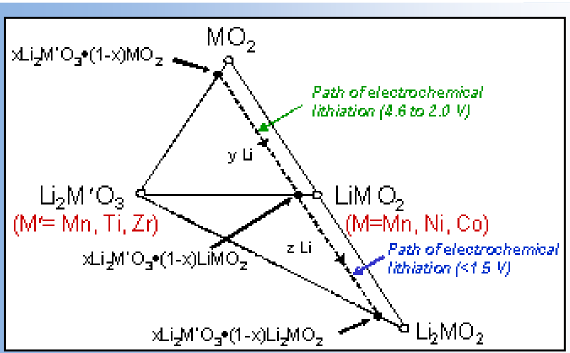
**Aside from the grid, we have no examples of implementing wide scale "by the ton" electrical materials technology**

# Why electrical storage?

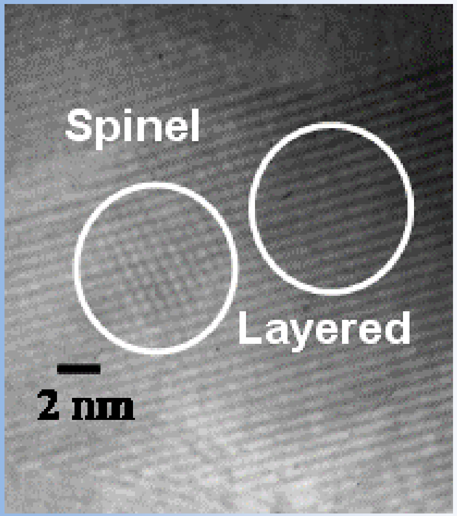

- Rechargeable lithium-ion batteries already a $40B business (2011)
  - Improving at few percent per annum
  - Can we do this faster?
- Laggard technology
  - Around 1% theoretical efficiency; (lighting ~80%, solar PV ~30%)
  - Can we do something much better?
- Scale – To back up U.S. power use (~3 TeraWatt) for 12 hours takes:
  - 9x annual energy production of the Hoover Dam
  - 1,000x the annual production of Li-ion batteries
  - Can we do something at scale?

# Argonne’s comprehensive energy storage portfolio

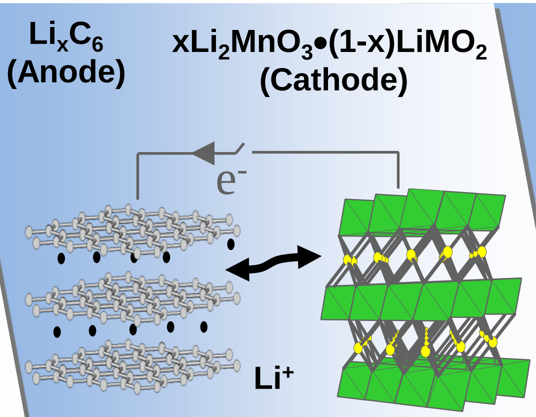
# Argonne's Li-ion battery research program: From fundamental research to cars on the road



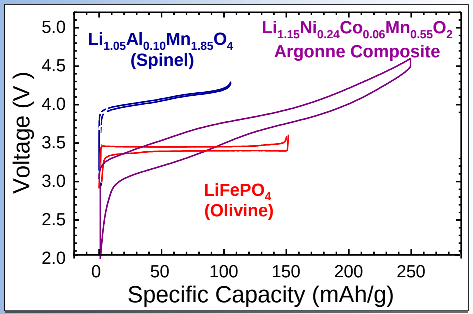

Discovered new composite structures for stable, high-capacity cathodes




Tailored electrode materials




Created high-energy Li-ion cells with double cathode capacity, enhanced stability




Licenses to materials cell manufacturers and automobile companies

# Argonne provides scale-up research in energy storage, offers testing facilities to users


# Joint Center for Energy Storage Research

TRANSPORTATION

**$100/**kWh

**400** Wh/kg **400** Wh/L

**800** W/kg **800** W/L

**1000** cycles

**80%** DoD C/5

**15 yr** calendar life

**EUCAR**

GRID

**$100/**kWh

**95%** round-trip efficiency at C/5 rate

**7000** cycles C/5

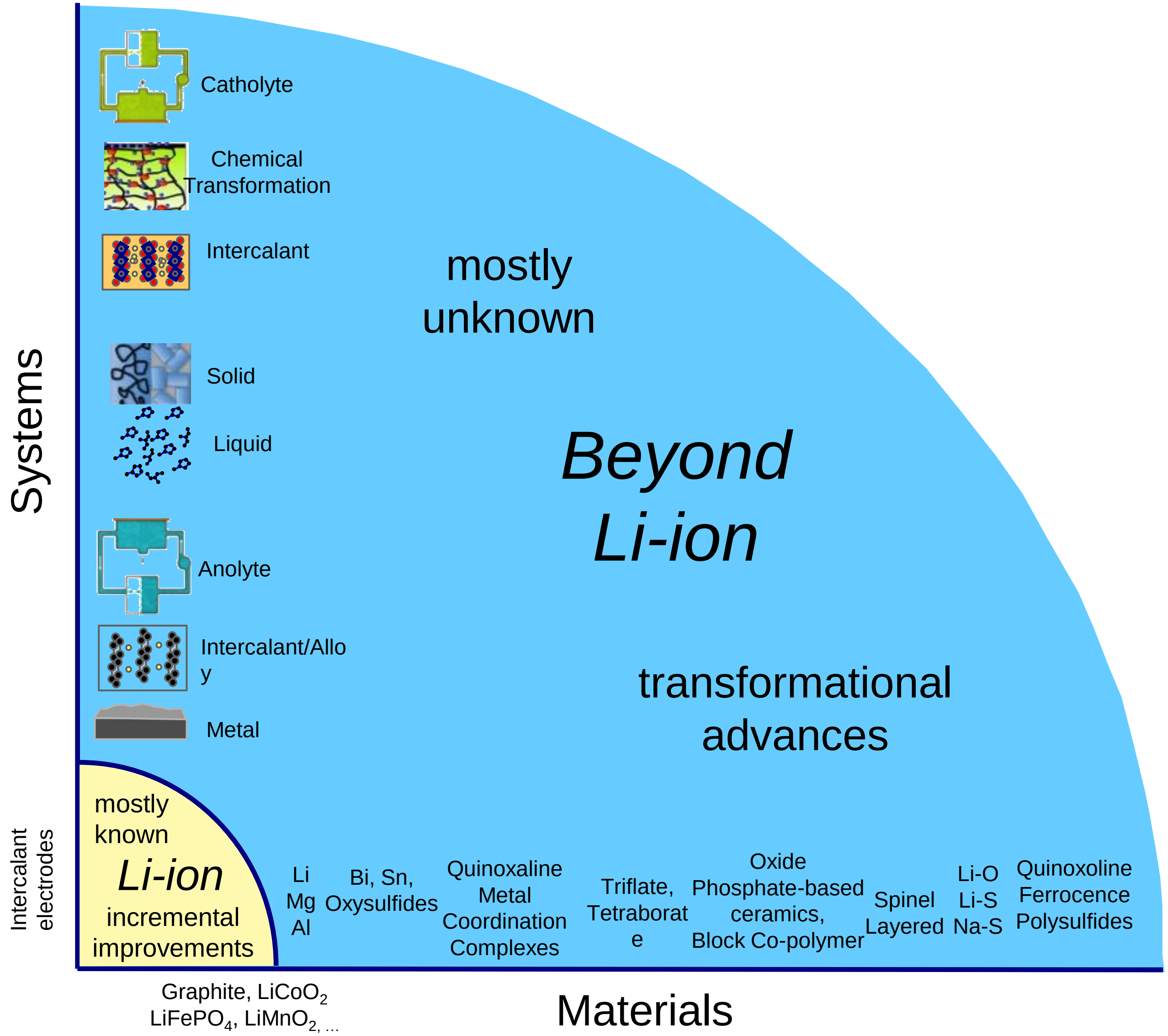
**20 yr** calendar life

**Safety** equivalent to a natural gas turbine

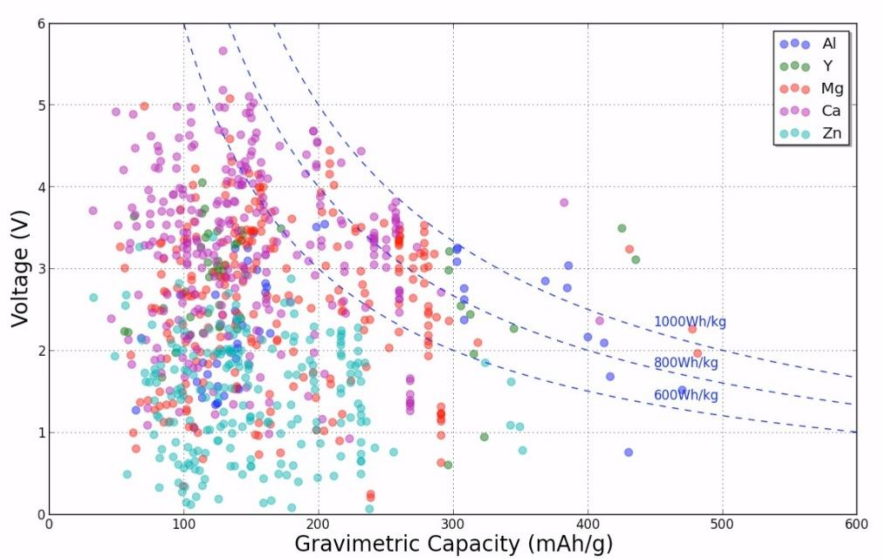
- Transformational goals: 5-5-5
  - 5 times greater energy density
  - 1/5 cost
  - within 5 years
- Legacies
  - Library of fundamental knowledge
    - *Atomic and molecular understanding of battery phenomena*
  - Pre-commercial prototypes for grid and transportation
  - New paradigm of battery development
    - *Build the battery from the bottom up*
    - *Systems-centric*
    - *End-to-end integration*

# Joint Center for Energy Storage Research: $25M per year – 15 core partners + affiliates

# Opportunity space beyond lithium-ion is large, unexplored and rich

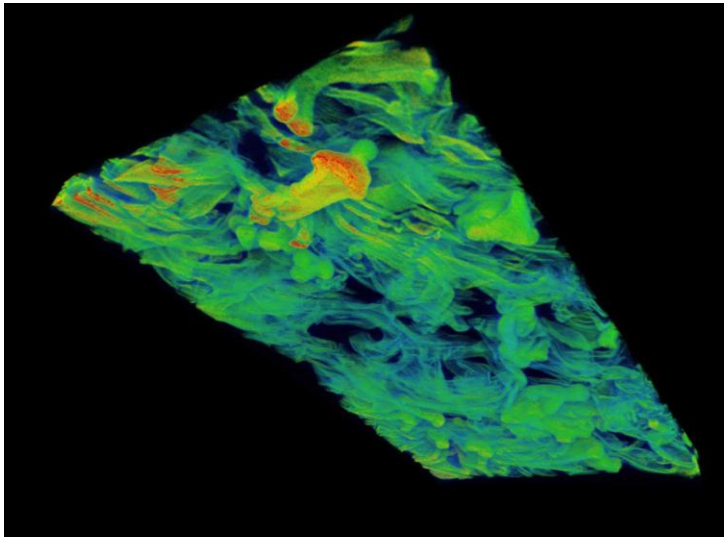


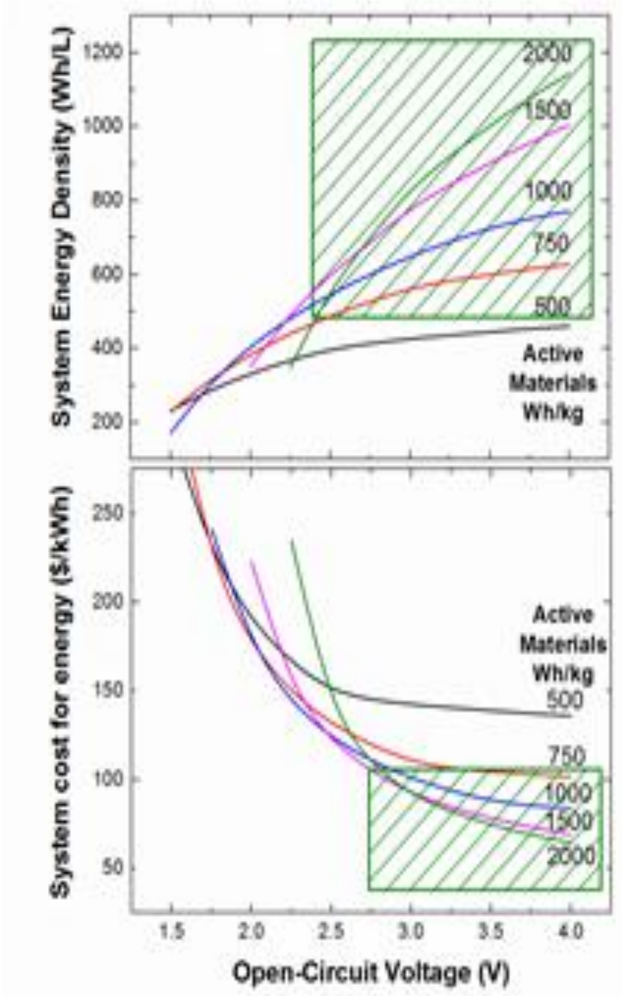
# Pruning the search tree




Screening of 1,800 intercalant hosts

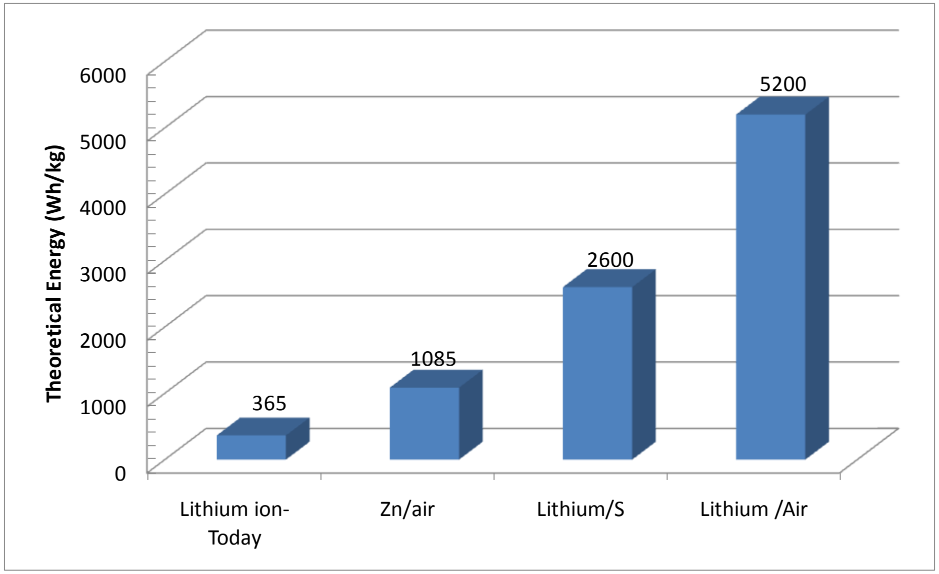
*In operando* X-ray

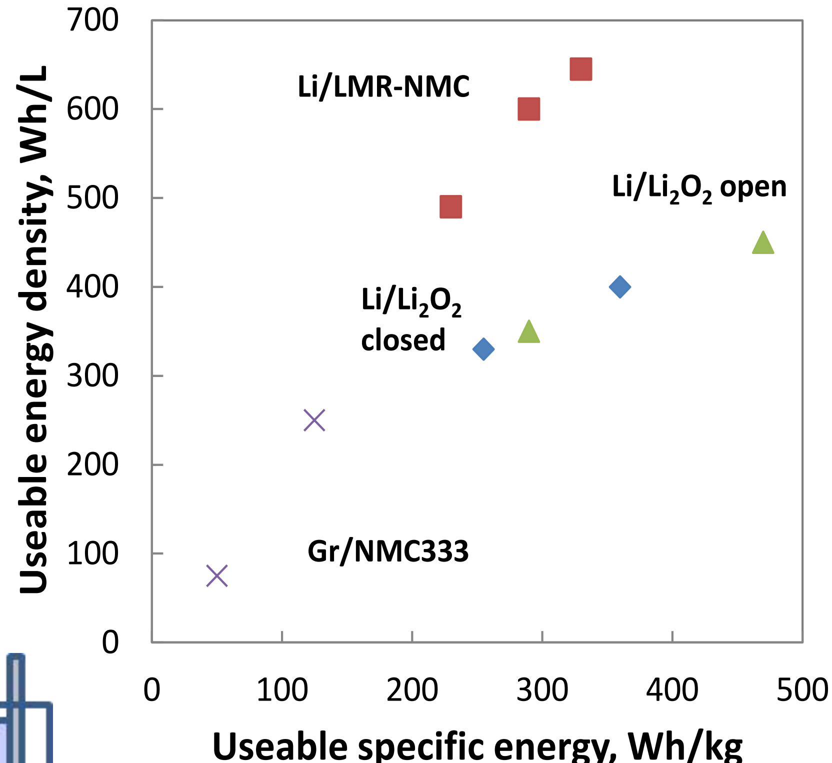





Systems analysis and techno-economic modeling

# Assessing the near-term challenges of lithium-air batteries



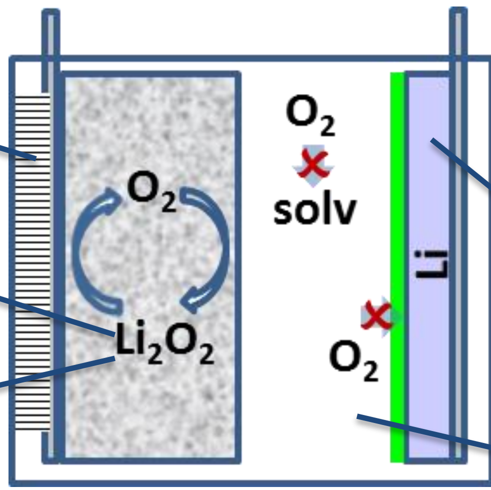




*100 kWh$_{use}$, 80 kW$_{net}$ 360 V battery*
*Systems-level calculation*
*– ANL, GM, Berkeley NL*

Oxygen ingress

Lithium peroxide is an insulator

Lithium peroxide growth/dissolution irreversible



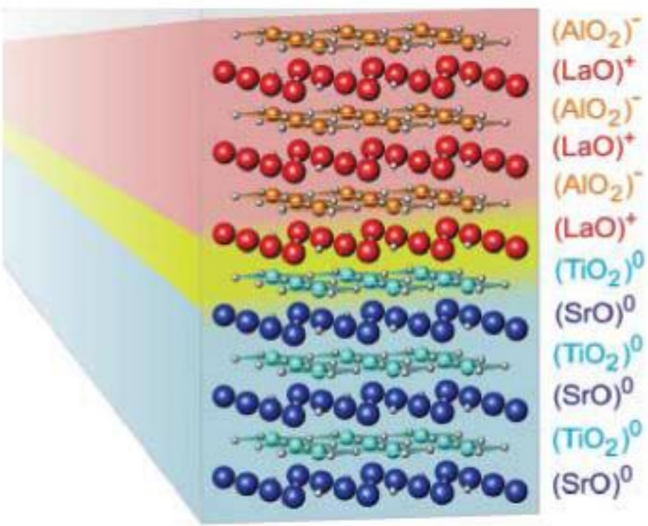

Li metal very reactive, forms dendrites

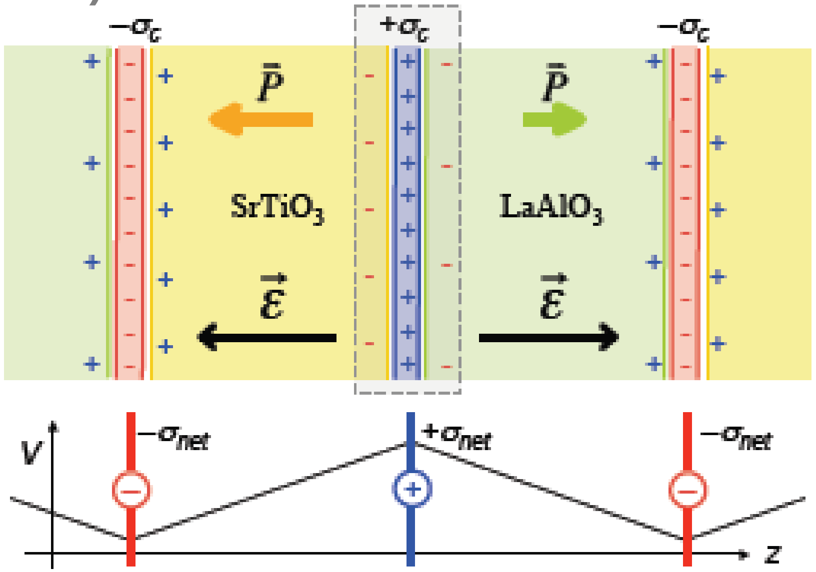
Electrolyte unstable on oxygen electrode

# What is actually possible?
# A thought experiment

# Polar heterostructures demonstrate there is a possible solution

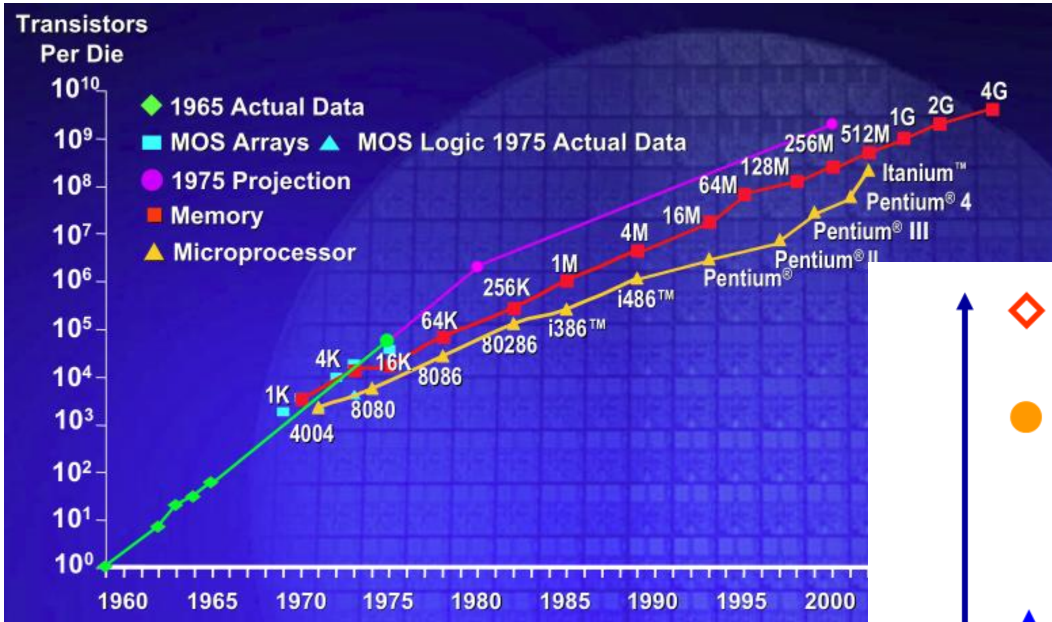
A Ohtomo & H Hwang, Nature **427, 423 (2004)**




- Once voltage offset = bandgap, chemical potential of carriers controlled by external circuit
- Carriers are lattice-constant sized, so in principle density high
- There are a few issues with materials growth, defects, reconstructed surfaces etc ... currently a fictional and extremely expensive device

# Can there be a Moore's law for batteries ?




Transformational technologies depend on reliable understanding and control of materials at scales ranging from the atomic to the mesoscale

◇ **Unk-HV-HC / Li metal**
Safe and reversible cycling of Li metal
Market entry >2021

● **Unk-HV-HC / Gr-Si**
Discovery of high voltage electrolyte >4.8 V
Discovery of reversible unknown high-voltage high-capacity cathode: 250 mAh/g @ 4.8 V
Market entry > 2019

△ **$Li_2MXO_4$ / Gr-Si**
Discovery of path to reversible multi-electron cathode material with 4V cell voltage
Market entry > 2017

■ **LMR-NMC / Gr-Si**
Stabilization of silicon
Market entry > 2015

◇ **LMR-NMC / Gr**
Stabilization of LMR-NMC
Market entry > 2013

● **LMO / Gr**

# Nanotechnology fabs of the future ...

# Thank you

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