A New Industrial Revolution for a Sustainable Energy Future

PERSPECTIVE

doi:10.1038/nature11475

Opportunities and challenges for a sustainable energy future

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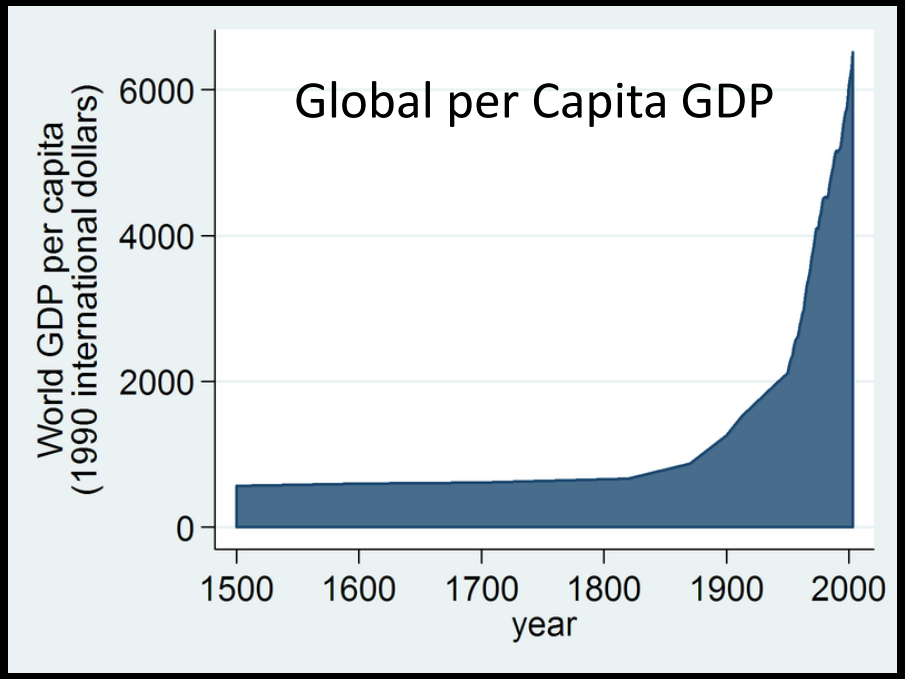
Nature, Vol. 488, pp. 294-303 (2012)

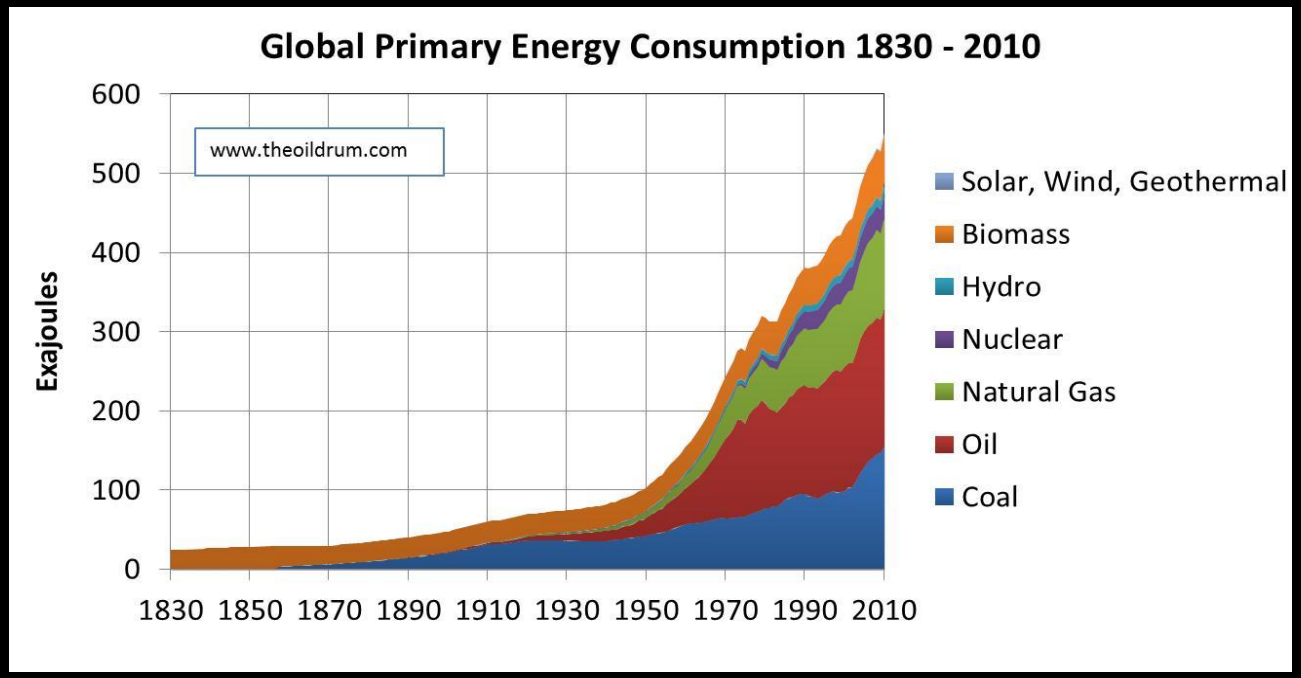
Industrial Revolution: Horse Power to Horsepower

304 Horsepower

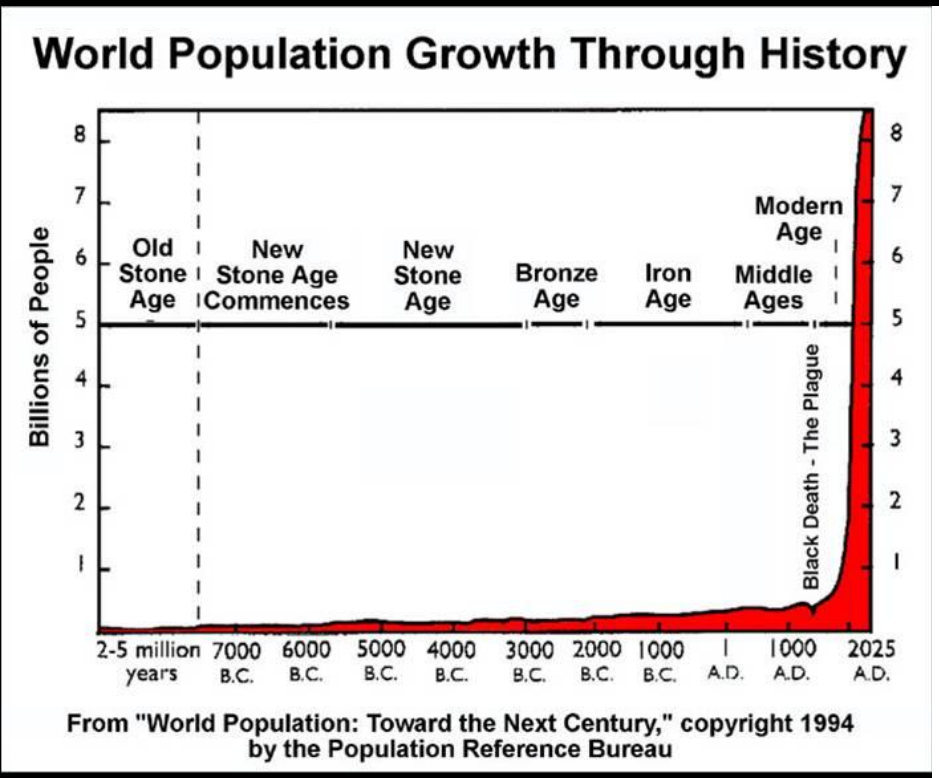
10,000 Horsepower

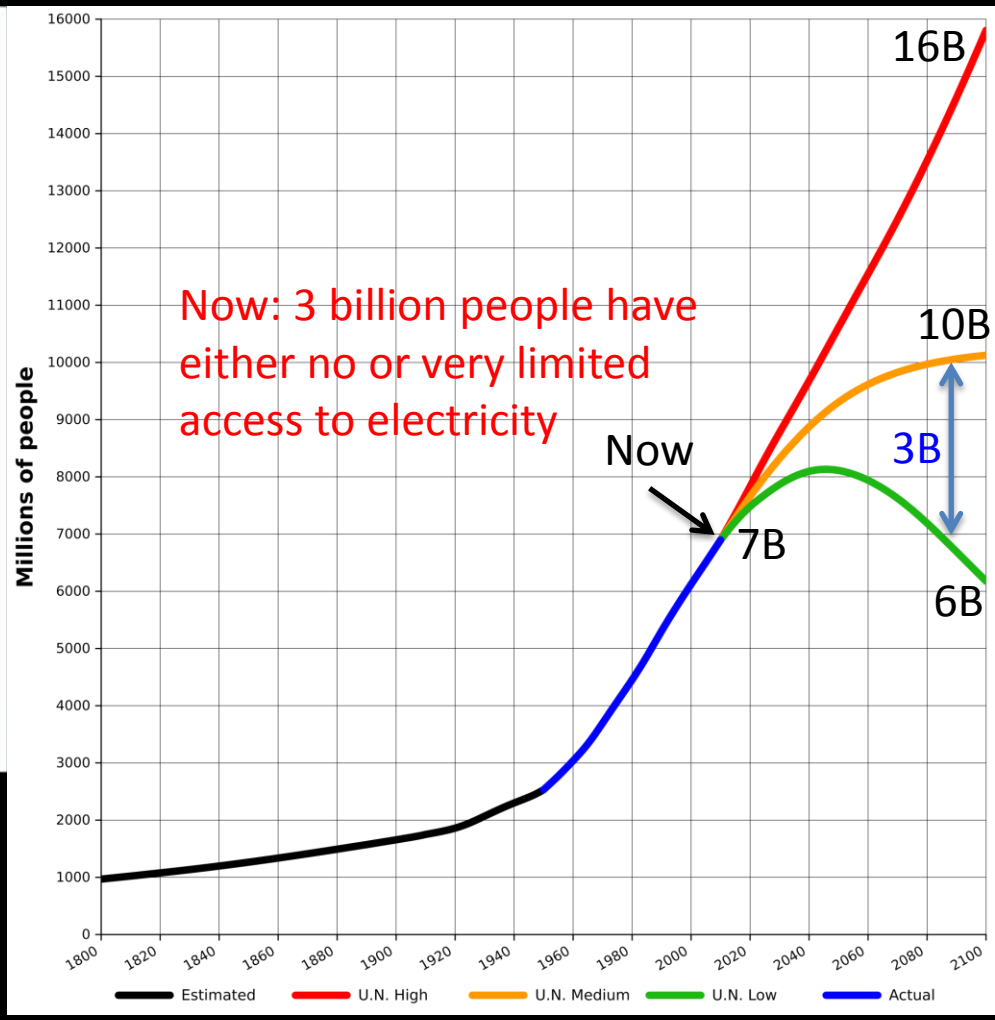
100,000 Horsepower


Global per Capita GDP
World GDP per capita
(1990 international dollars)
6000
4000
2000
0
1500
1600
1700
1800
1900
2000
year


Global Primary Energy Consumption 1830 - 2010
www.theoildrum.com
Exajoules
600
500
400
300
200
100
0
1830
1850
1870
1890
1910
1930
1950
1970
1990
2010
Solar, Wind, Geothermal
Biomass
Hydro
Nuclear
Natural Gas
Oil
Coal

World Population

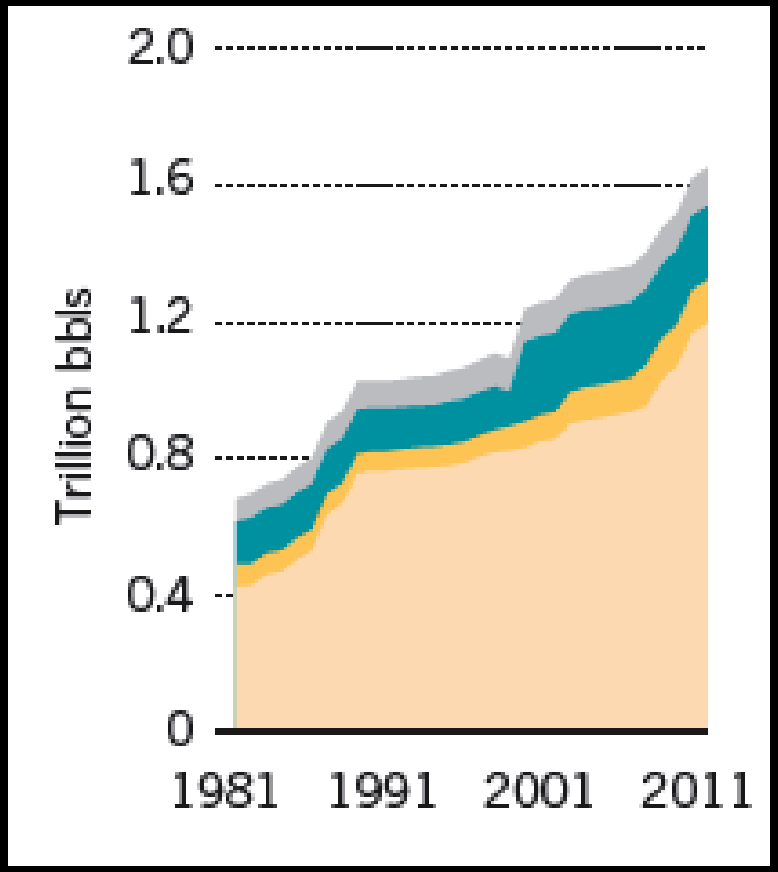




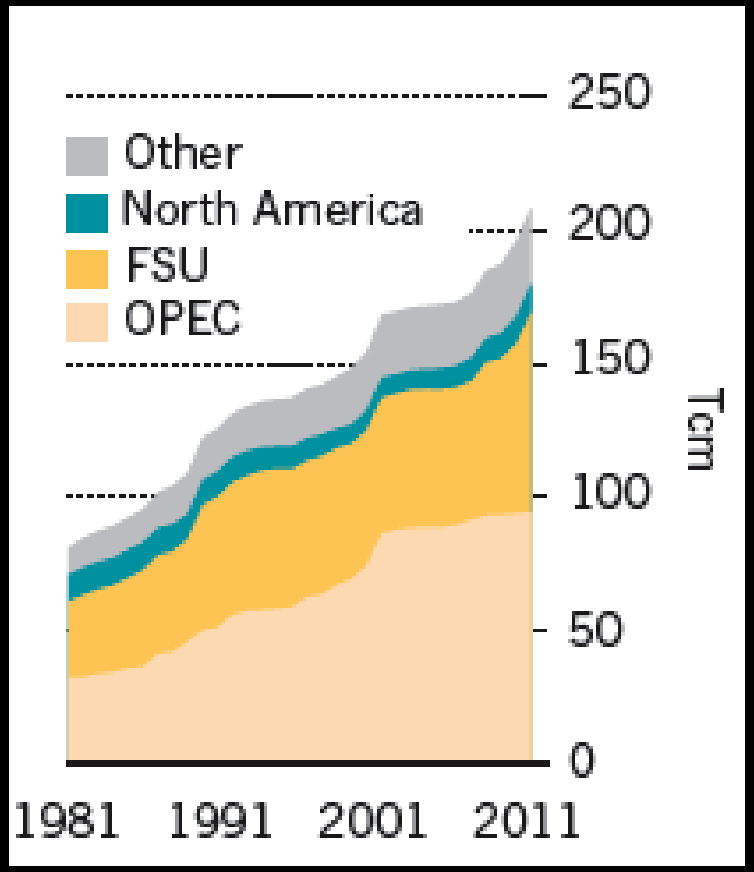
Source: United Nations

Oil & Gas Reserves

Global Oil Reserves

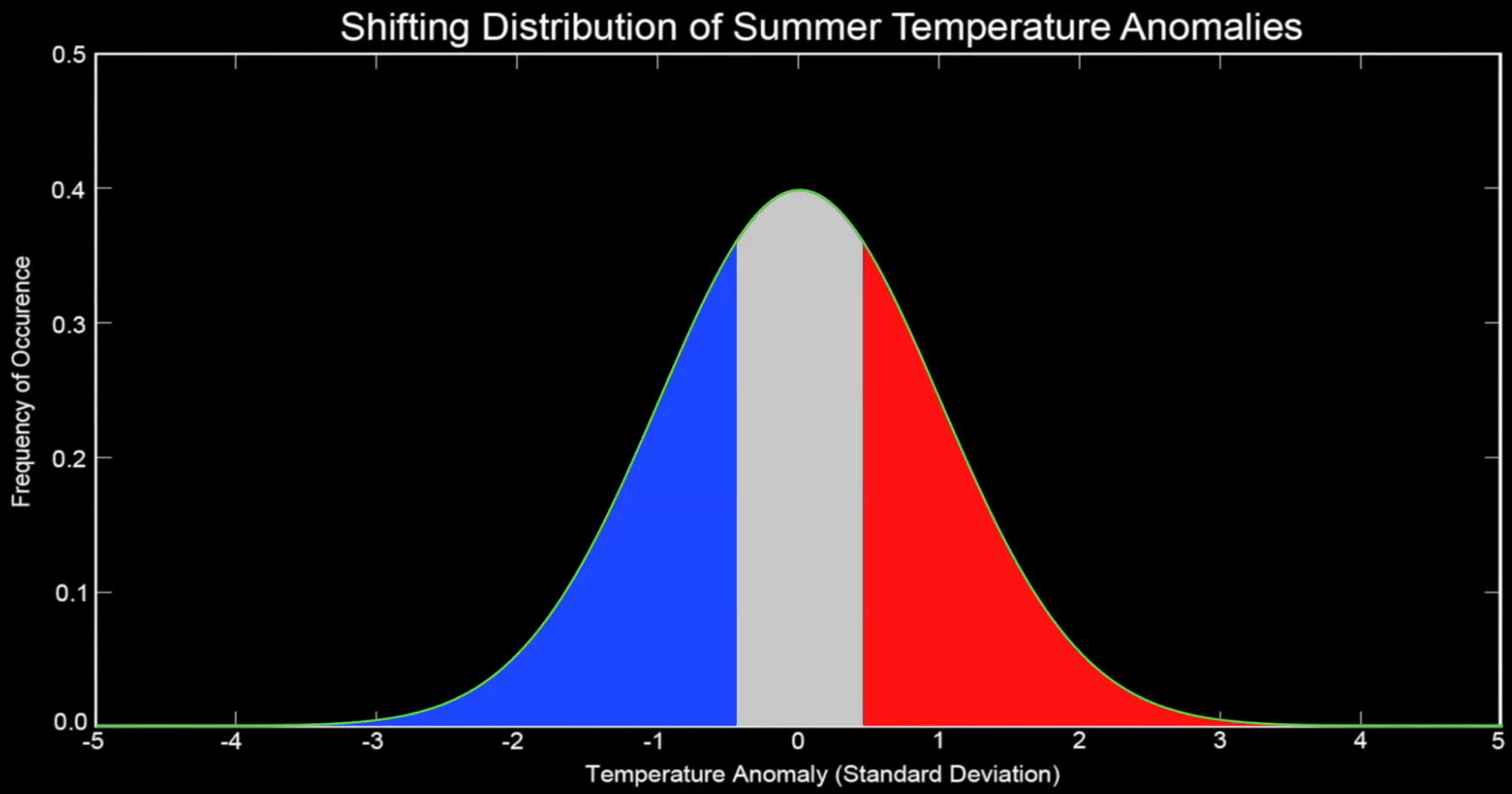


Global Gas Reserves w/o US Shale



BP Statistical Review of World Energy (2012)

Averages & Extremes



http://www.nasa.gov/multimedia/videogallery/index.html?media_id=149932291

Hansen, Sato, Ruedy, "Perception of climate change," *PNAS*, Aug. 6 (2012)

Cumulative CO_2 emissions since Industrial Revolution

1,100 Billion Tons

How much more CO_2 can we emit based on known fossil fuel reserves?

About 3,000 Billion Tons

75-100 years

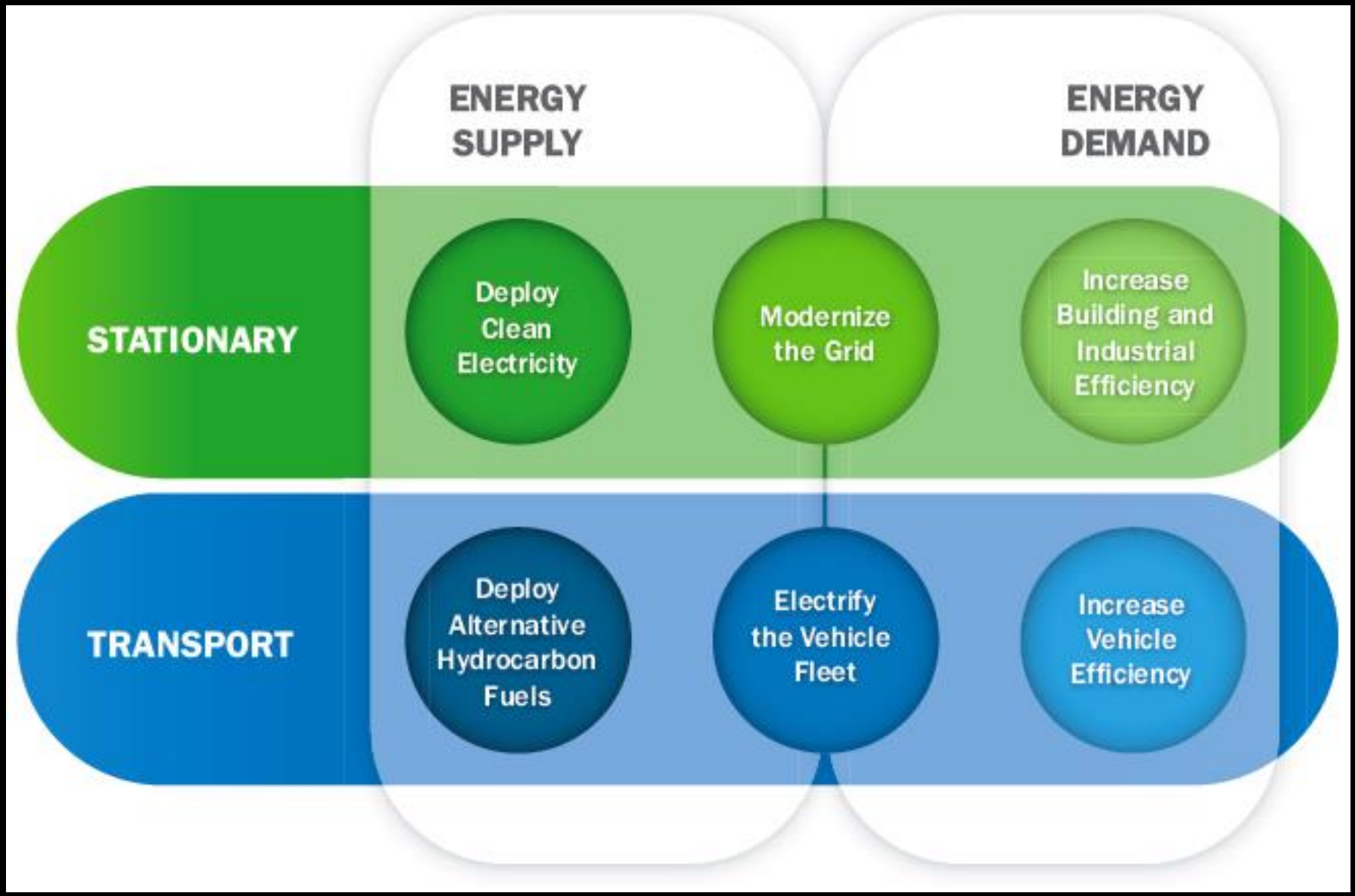
Worth $10s of Trillion!!

The Stone Age did not end because we ran out stones

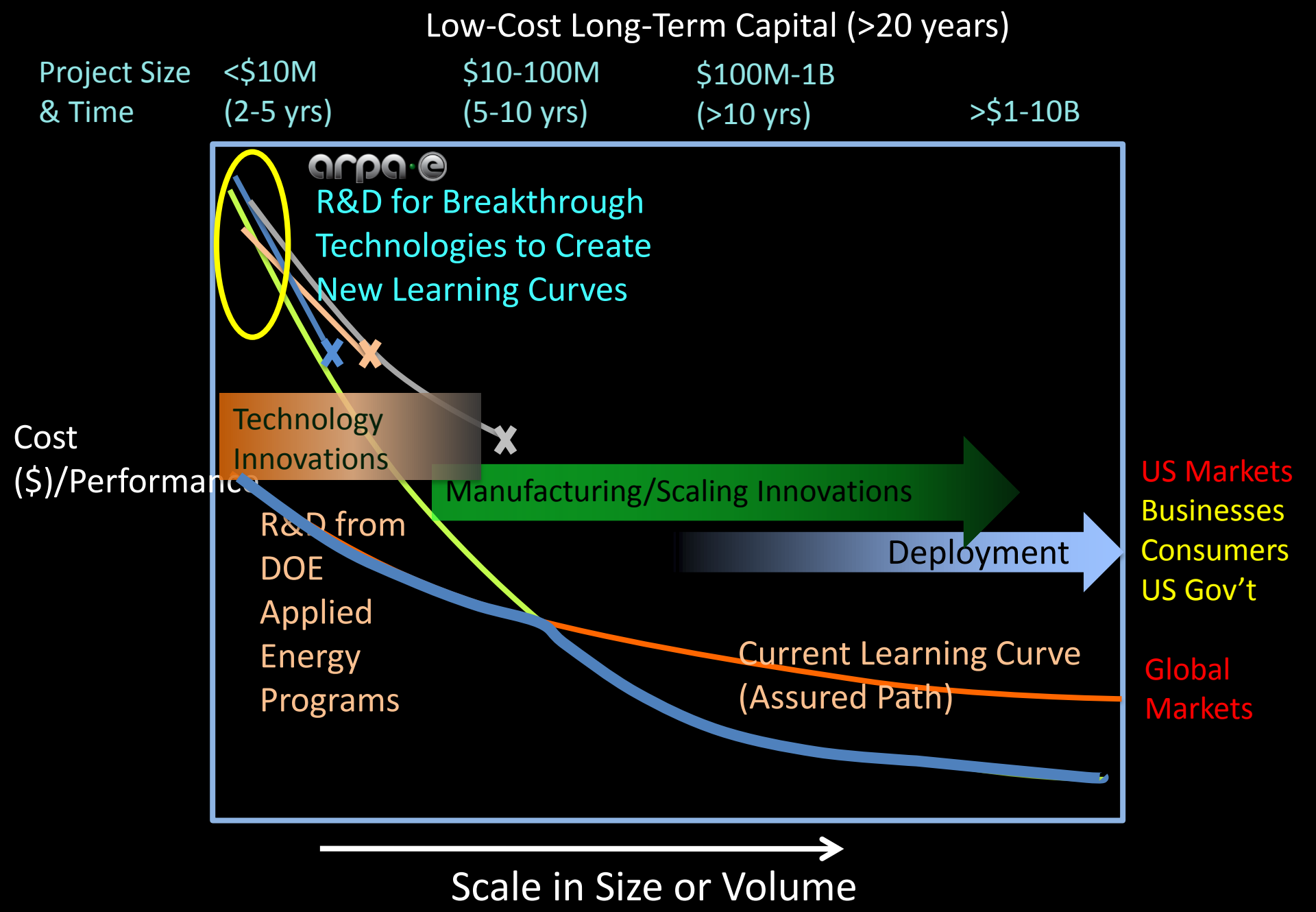
Sheikh Ahmed Yamani, former Oil Minister of Saudi Arabia

We transitioned to better solutions

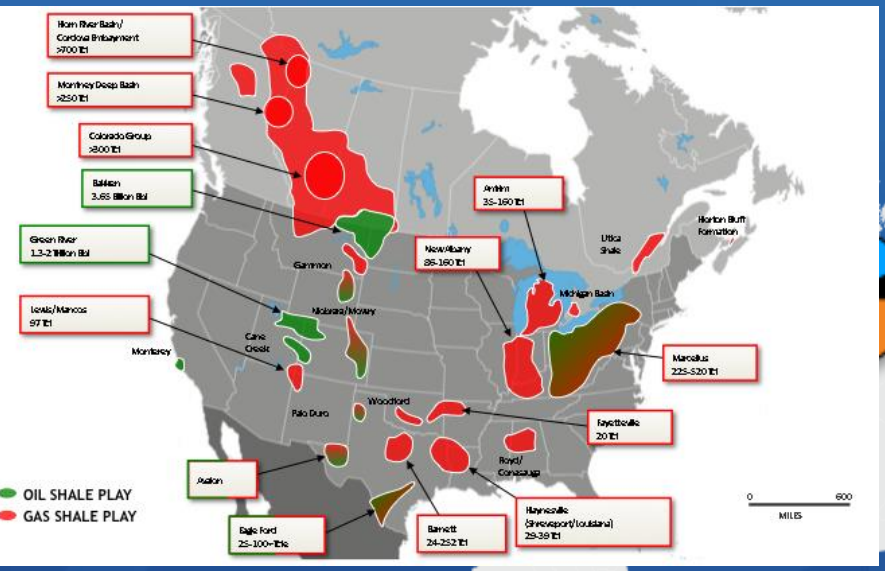
Energy Systems

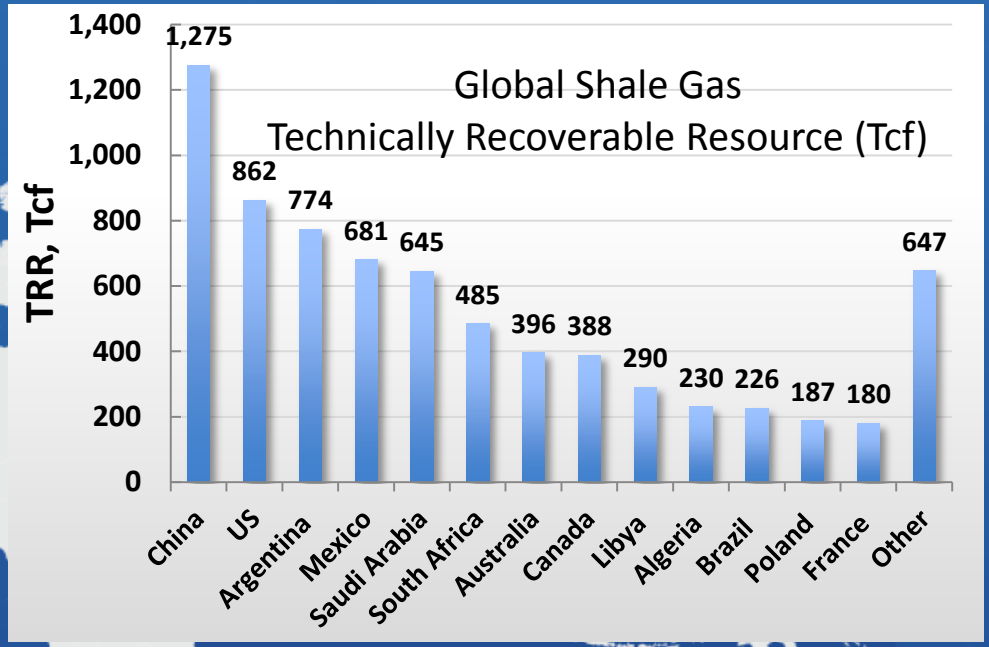


US Department of Energy. *Report on the First Quadrennial Technology Review. (US DOE, 2011).*


Low-Cost Long-Term Capital (>20 years)
Project Size & Time
<$10M (2-5 yrs)
$10-100M (5-10 yrs)
$100M-1B (>10 yrs)
>$1-10B
arpa·e
R&D for Breakthrough Technologies to Create New Learning Curves
Technology Innovations
Manufacturing/Scaling Innovations
Deployment
R&D from DOE Applied Energy Programs
Current Learning Curve (Assured Path)
US Markets
Businesses
Consumers
US Gov't
Global Markets
Cost ($)/Performance
Scale in Size or Volume

Shale Gas: Which Countries?





Tight Gas
Shale Gas
Coalbed Gas

Numbers represent TCF of unconventional gas

Over 44,300 TCF - Gas in Place

Over ~11,000 TCF – Technically Recoverable

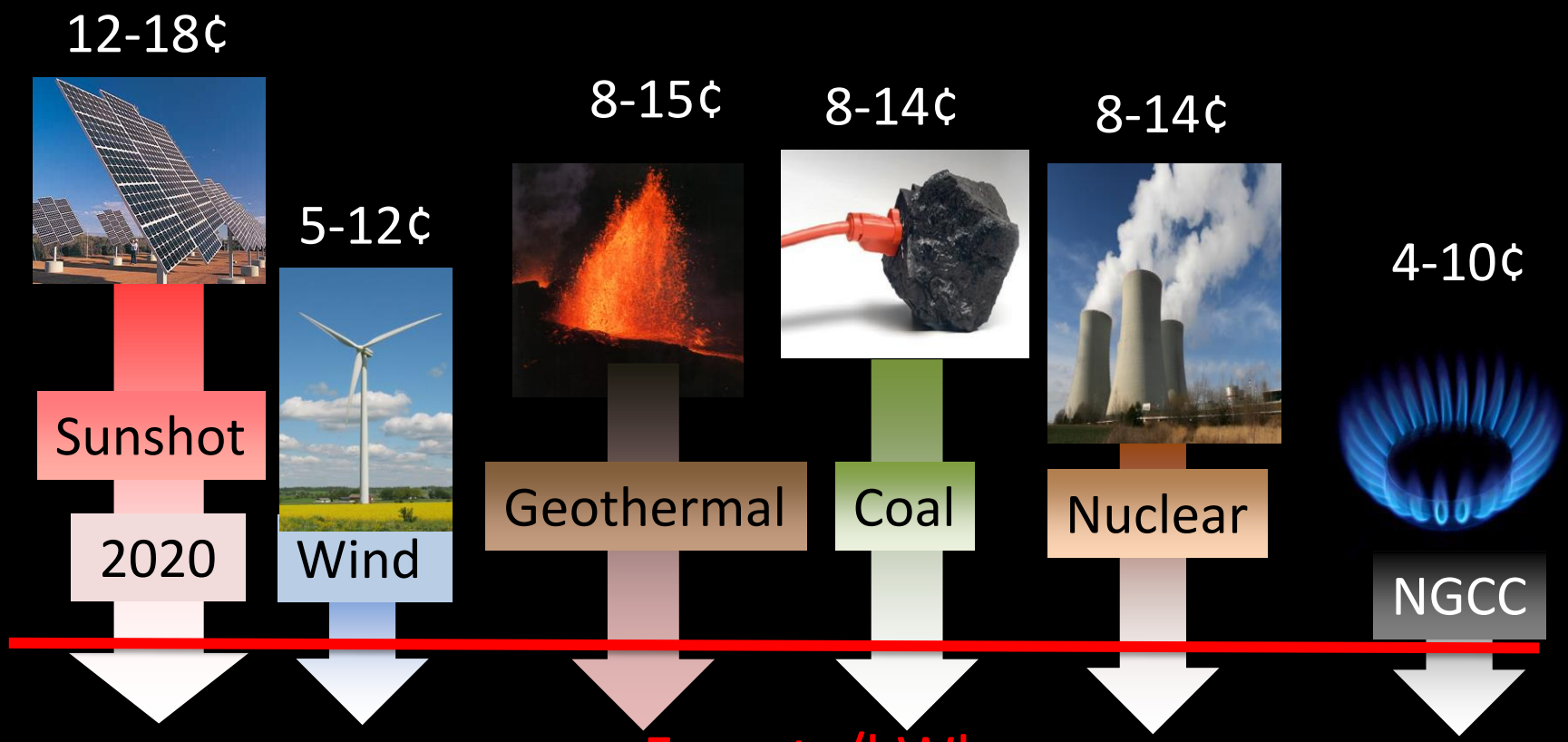
~ 70 Years at Current Consumption Levels

BAKER HUGHES

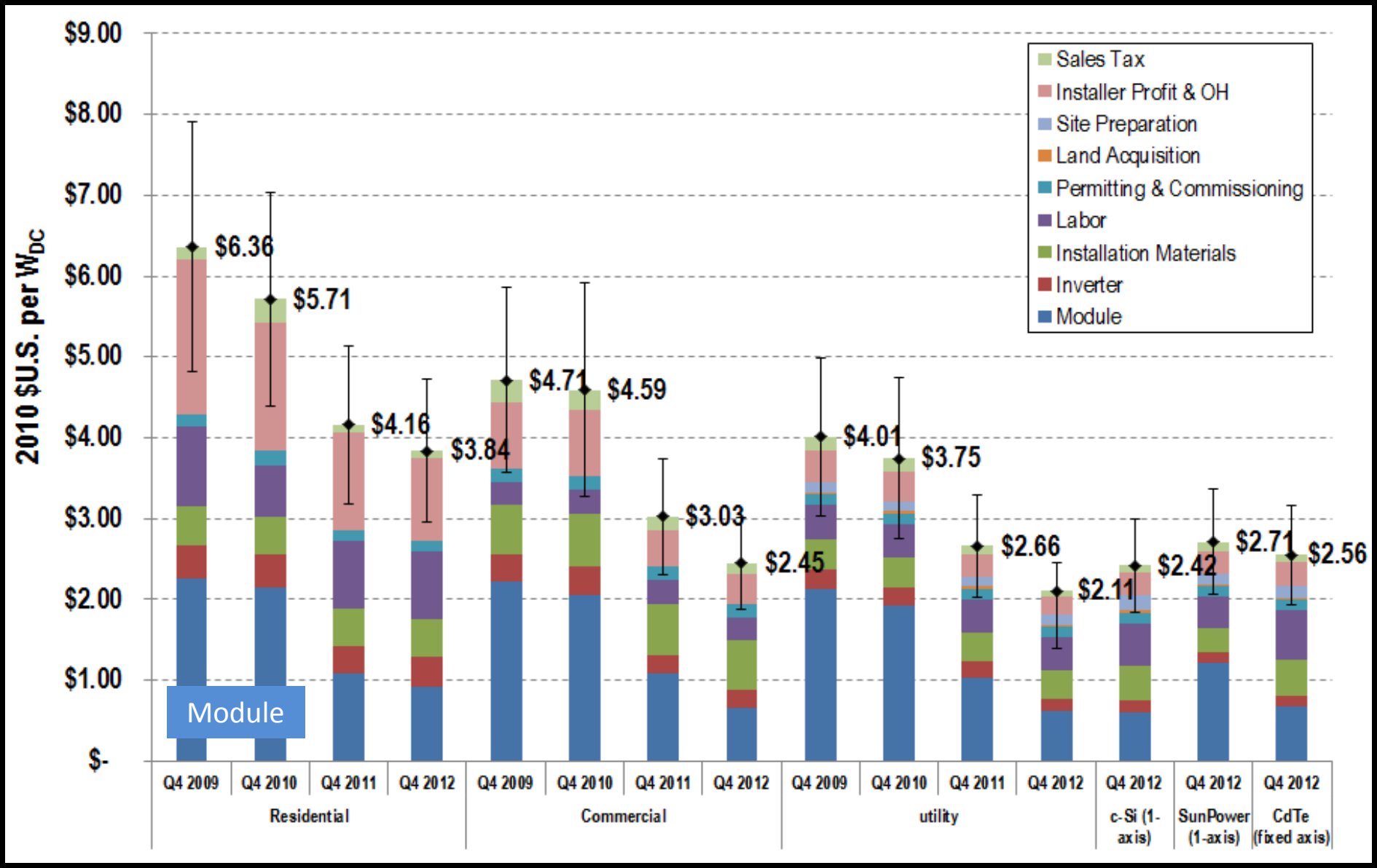
Courtesy: Mark Zoback, Stanford Univ.

Clean and Inexpensive Electricity

Subsidy Free



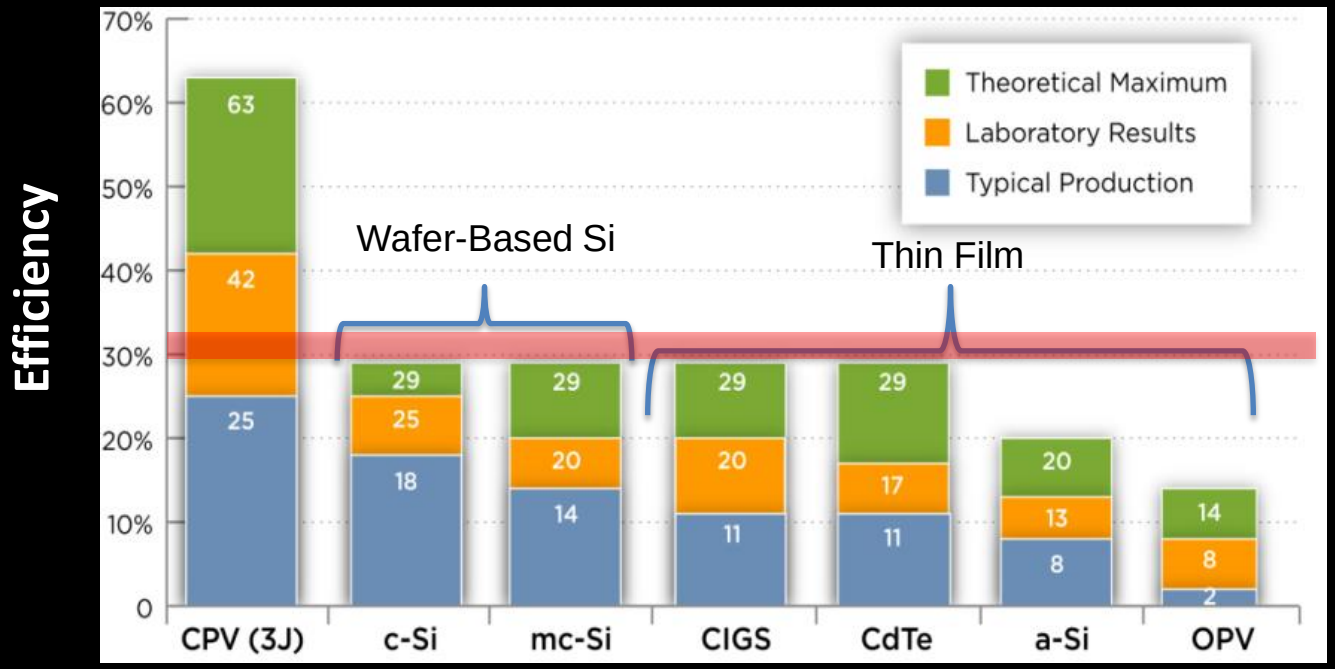
Solar PV System Cost



Courtesy: National Renewable Energy Laboratory

Solar Cell Efficiency

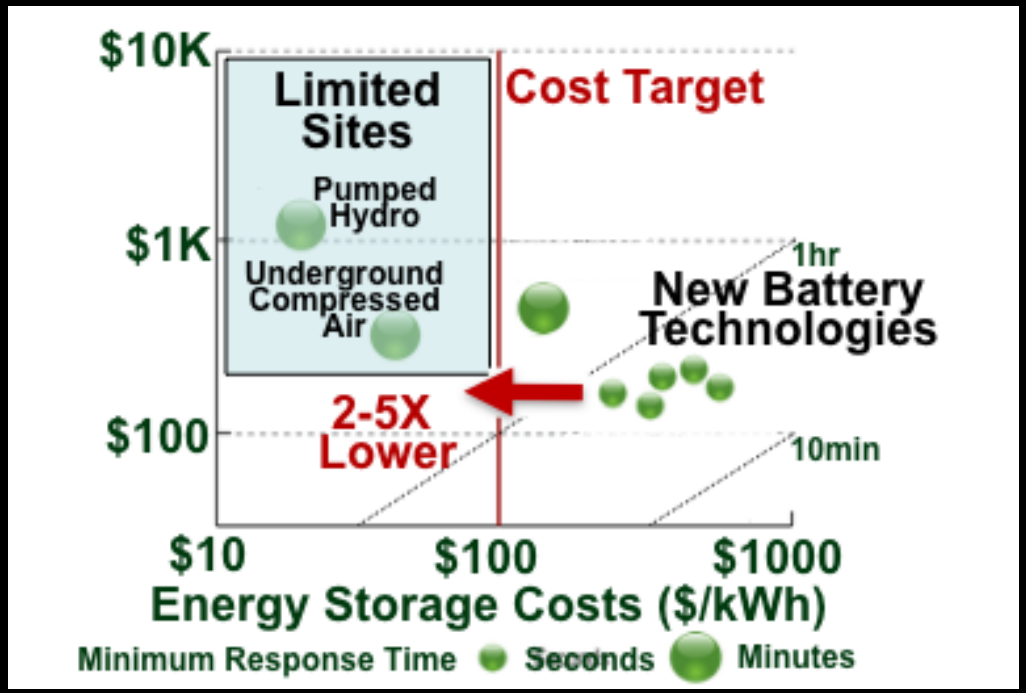
$$\frac{\$}{Watt} \mu \frac{Panel + Balanceof\ System\ Cost}{Efficiency}$$



III-V Based 28% efficient solar cells on plastic substrate

Alta Devces

Grid-Scale Storage (GWh Scale)

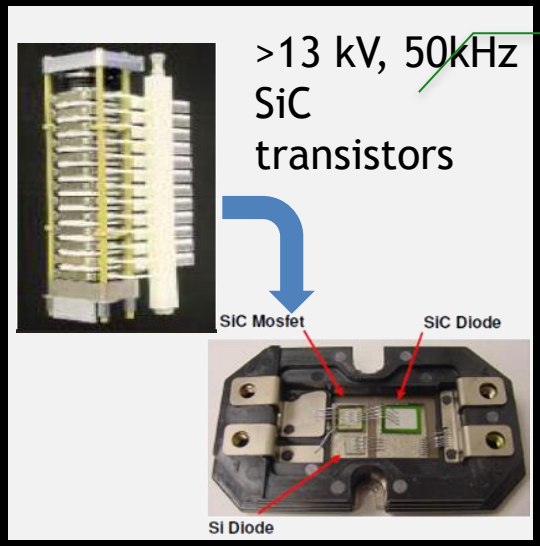


MIT-24M

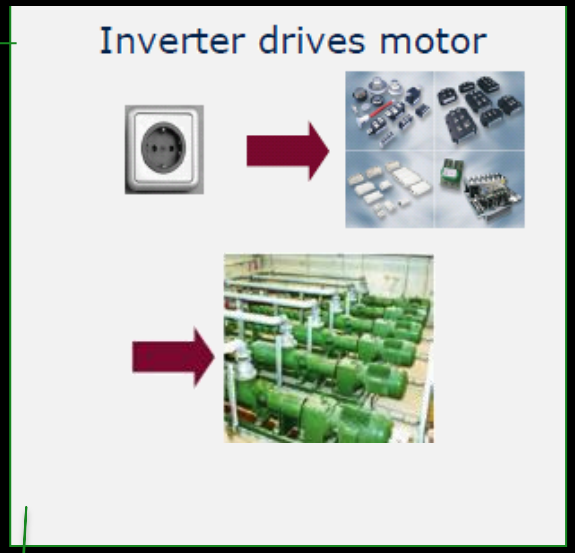
Target: $60/kWh

Power Electronics

GRID

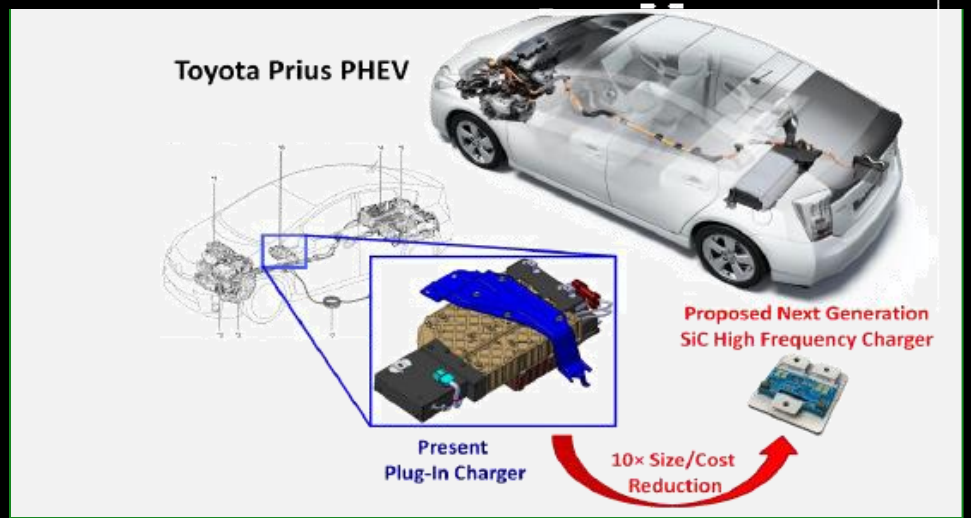


INDUSTRIAL MOTORS



- Power Electronic Switches (ω, Power)
- Inductors ($Z = j\omega L$)
- Capacitors ($Z = 1/j\omega C$)
- Circuits

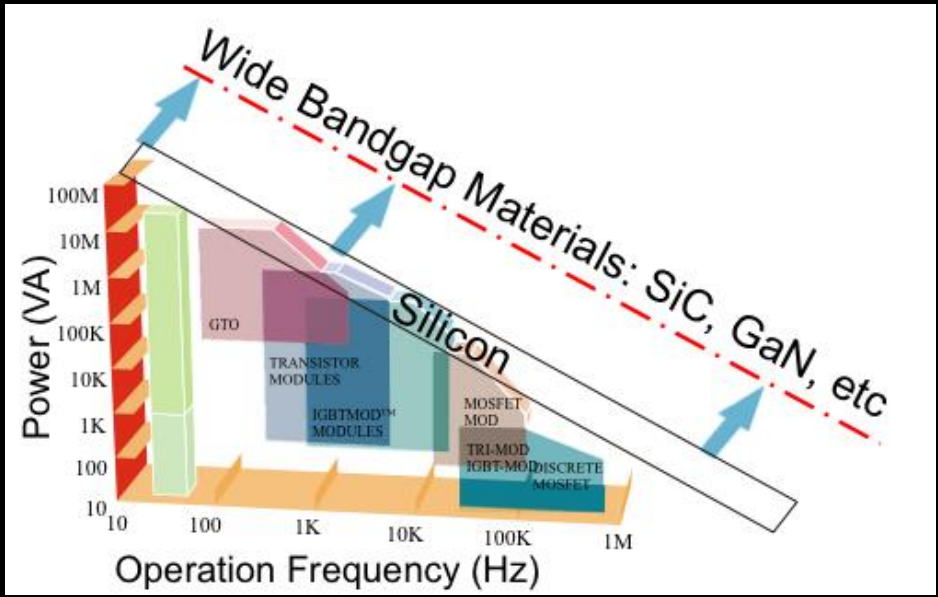
AUTOMOTIVE



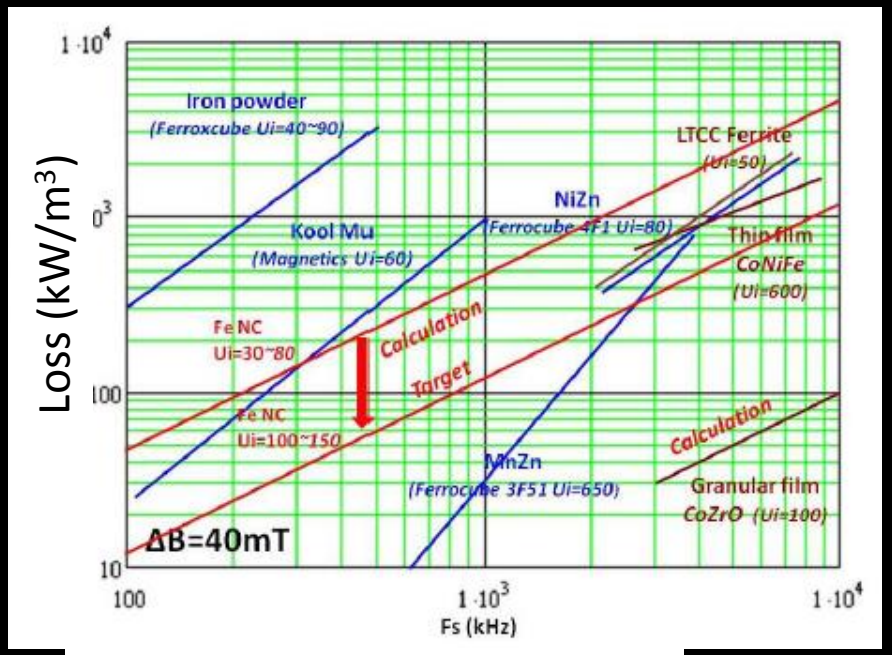
LIGHTING

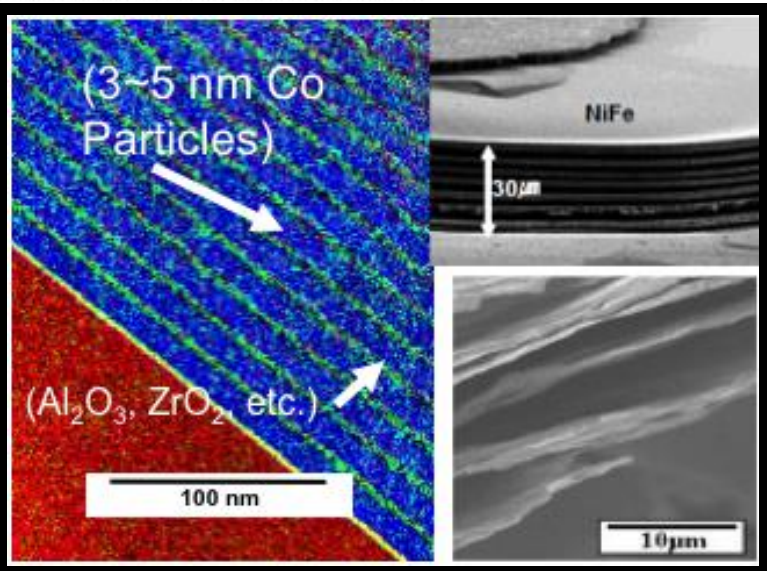
Power Electronics

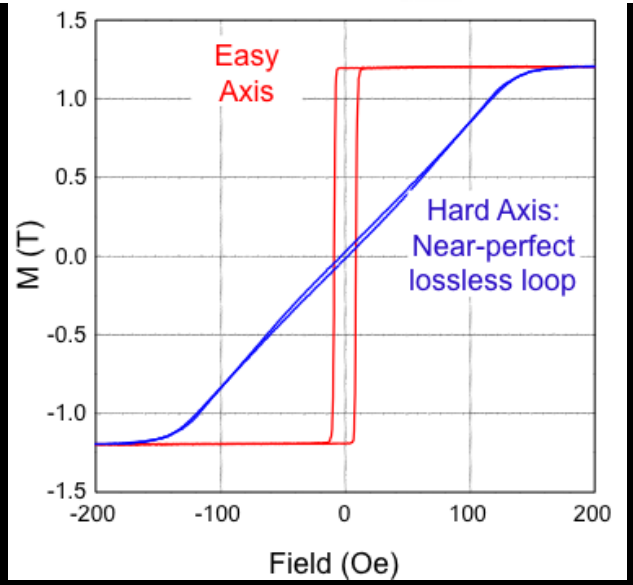
ELECTRONIC SWITCHES



SOFT MAGNETS



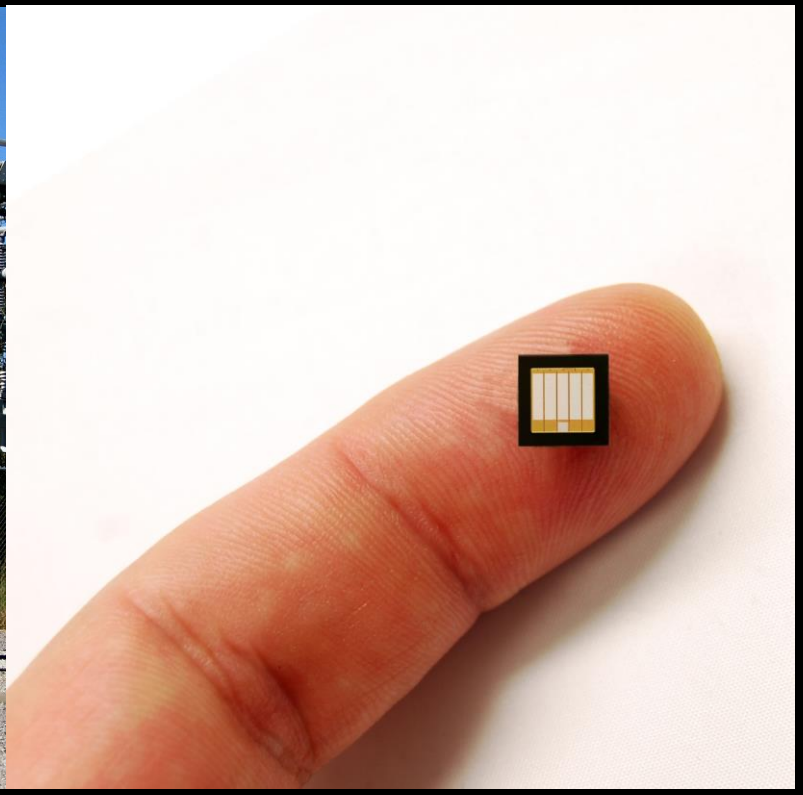




Power Electronics

8000 lbs, 60 Hz Distribution Transformer

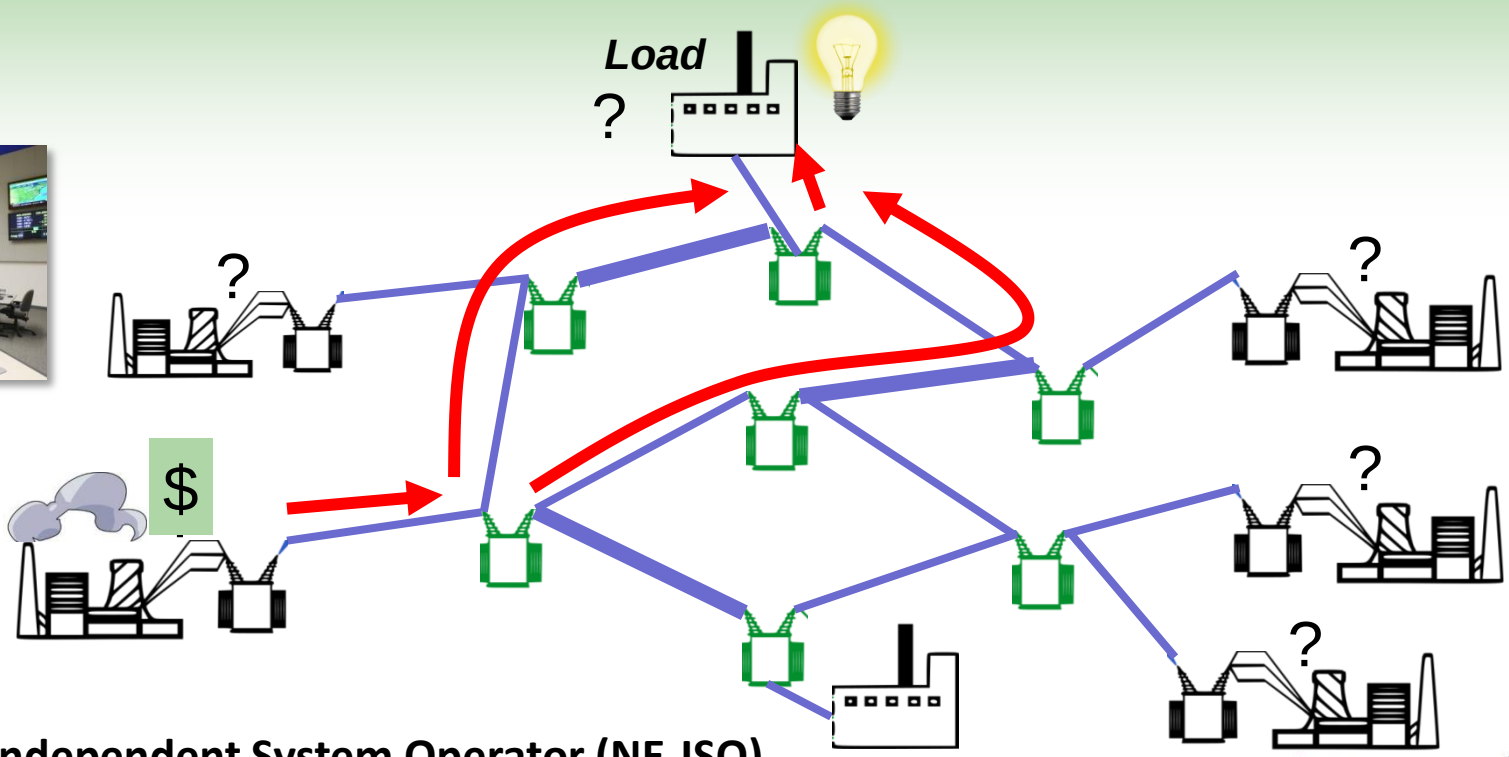
Average Age: 42 years, 2 years beyond projected lifespan



Silicon Carbide IGBT; 15 kV, 100 A; 50 kHz from Cree Inc.

Potentially 100 lbs transformer

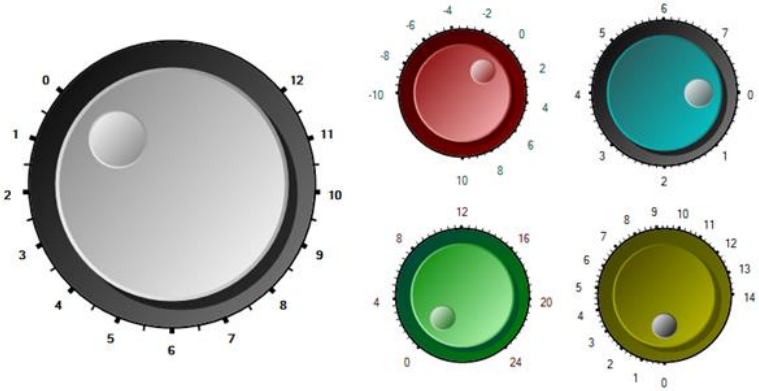
Delivering Electricity



New England Independent System Operator (NE-ISO)

Energy Dispatch (Day Ahead): 12,985 MW

Energy Dispatch (Real-Time [includes Day Ahead]): 14,937

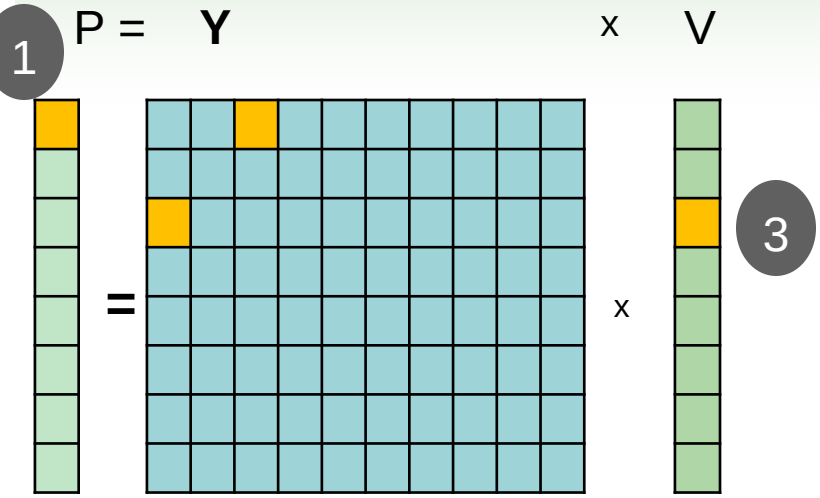


Thirty Minute Operating Reserve: 5785 MW

Ten Minute Spinning Reserve: 725 MW

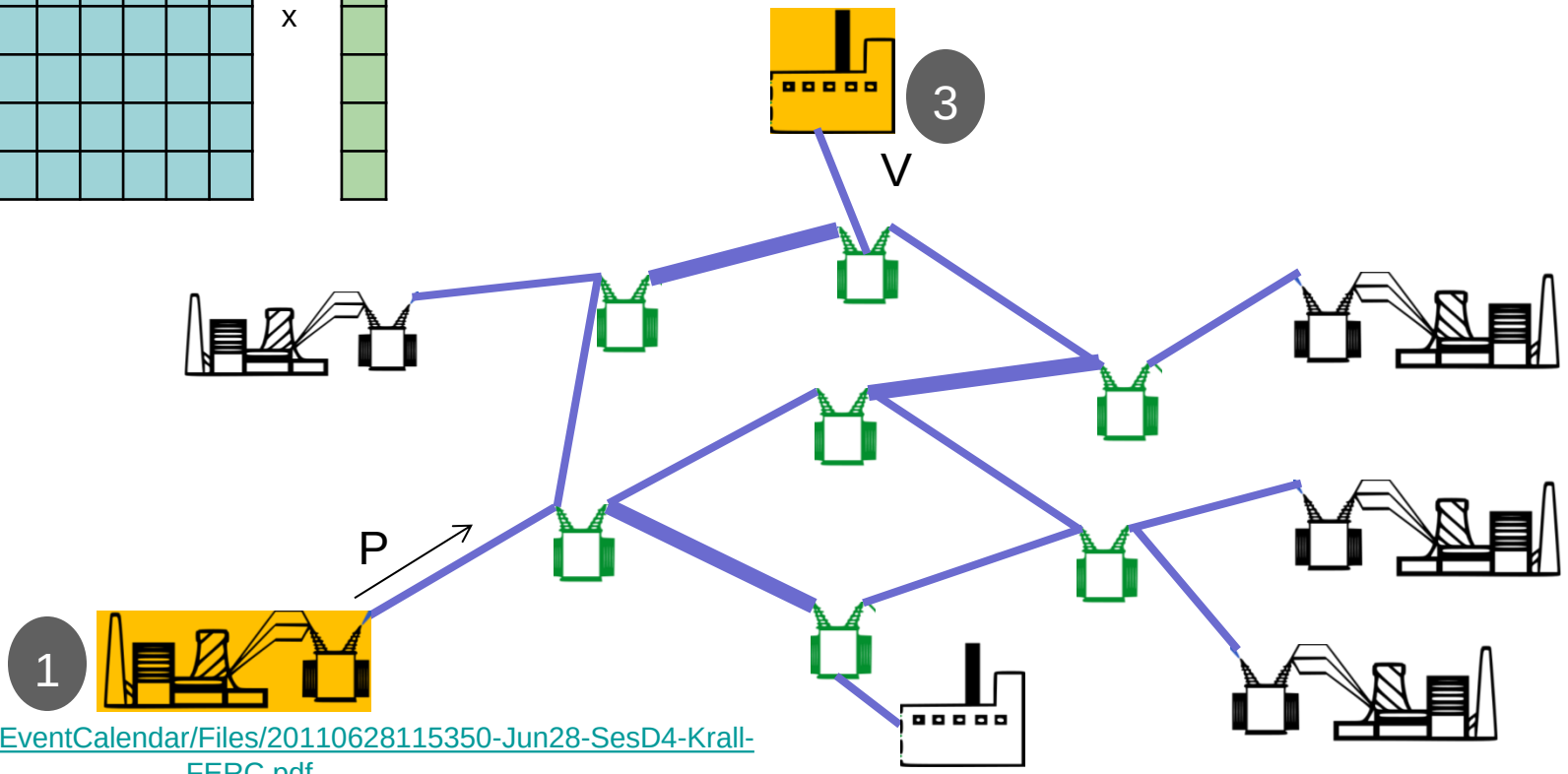
Ten Minute Non-Spinning Reserve: 1519 MW; Frequency Regulation: 100-200 MW

Designing Power Flow



Minimizing the cost of fuel to deliver power is Hard (NP)

- constrained by system balance, nodal balance, transmission constraints, generator constraints



http://www.ferc.gov/EventCalendar/Files/20110628115350-Jun28-SesD4-Krall-FERC.pdf

Controlling Power Flow

Example

ISO-NE: 689 generators, 2209 loads, 4500 bus, 6600 binary variables

Topology control (DC-OPF approx):

82 hrs [CPLEX on dual-core. 3.4GHz, 1GB RAM]

to optimize state **only 4** transmission lines

savings +5% for summer peak conditions($)/+7% for a medium load summer condition ($)

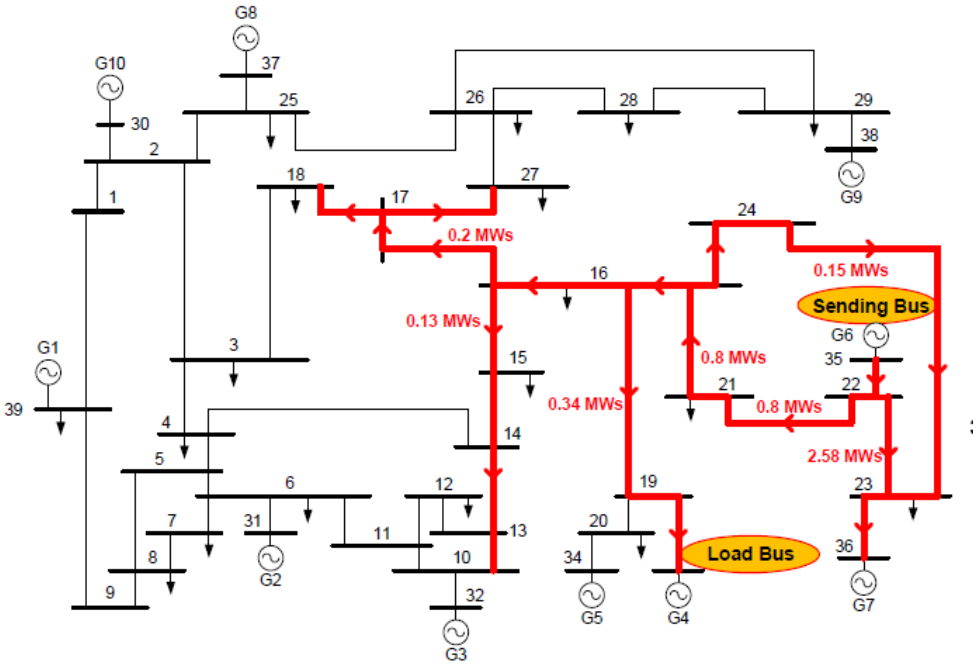
Hedman, K. W., O'Neill, R. P., Fisher, E. B., and Oren, S. S. (2011), "Smart flexible just-in-time transmission and flowgate bidding," IEEE Transactions on Power Systems,Feb 2011.

What kind of control?

- Linear vs. Non-linear [Generators deliver Power = I*V]
- Deterministic vs. Stochastic [Can't predict when a load comes on-line]
- Time-invariant vs. Time-varying [Impedances change]
- Continuous-time vs. Discrete-time

Green Electricity Network Integration (GENI)

Today: Uncontrolled Flows



Power Routing

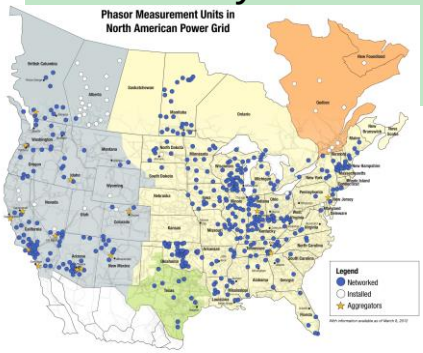
•Power flow control to route power along underutilized paths, 80% less transmission infrastructure required

GA Tech study of simplified IEEE 39 Bus system with 4 control areas, operation simulated for 20 years, 20% RPS phased in over 20 years, sufficient transmission capacity added each year to eliminate curtailment of renewable generation

Control Infrastructure

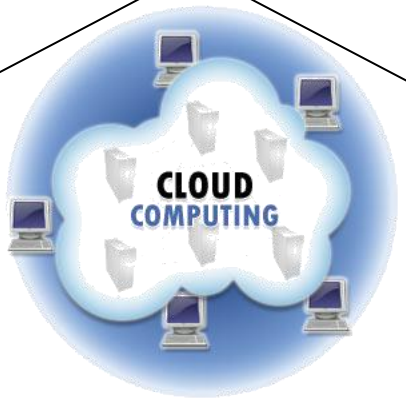
Improved Sensing

A PMU measures
- Current (Hall sensor)
- Frequency (LC Circuit)
- Time (GPS)
- Voltage
- Relative Phase
- **Sample 30 msec**
- Petabyte-scale data



Improved Communications

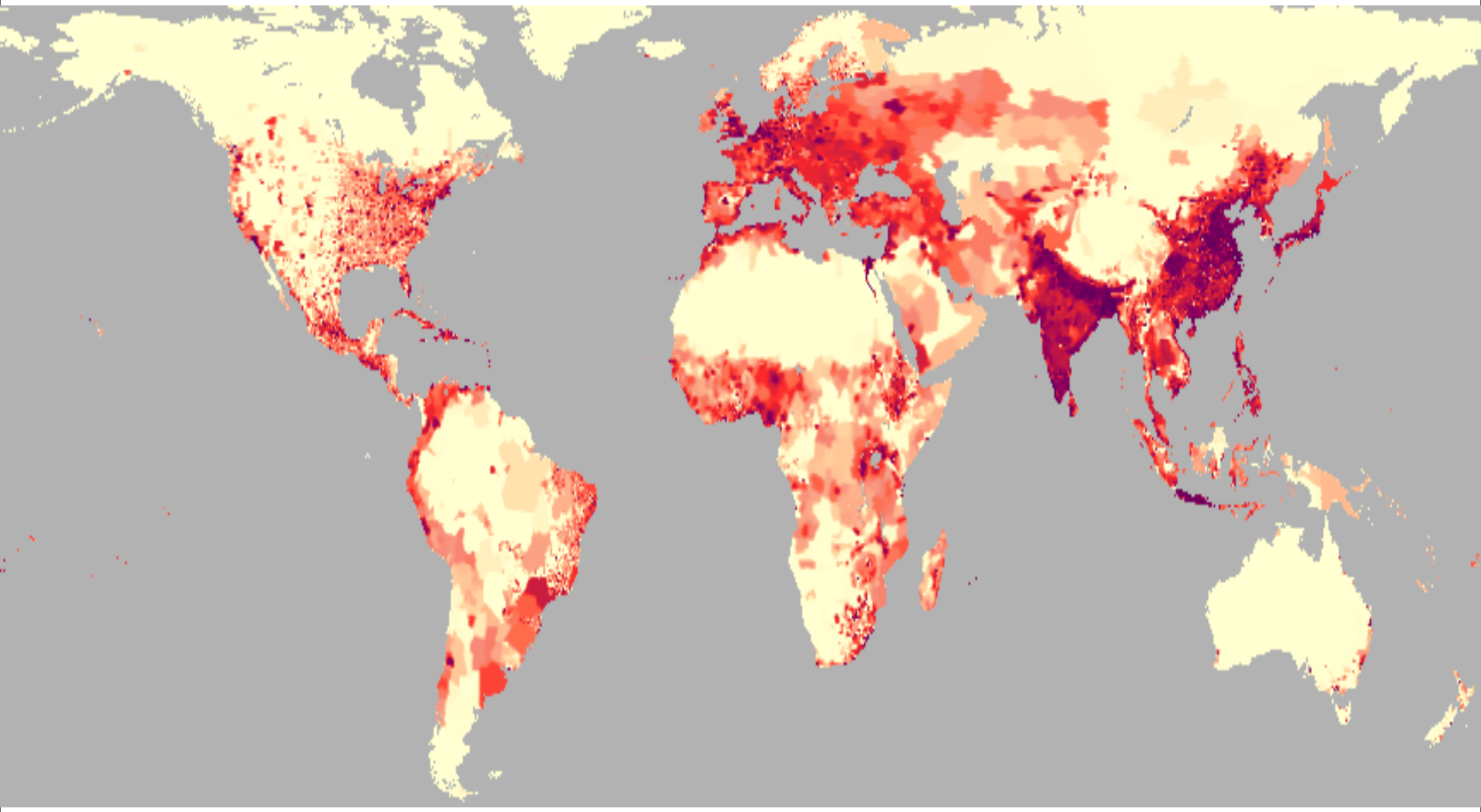
Grid Connected Router
- Low-latency
- MPLS
- Cyber security
- 100-600 μs for crypto

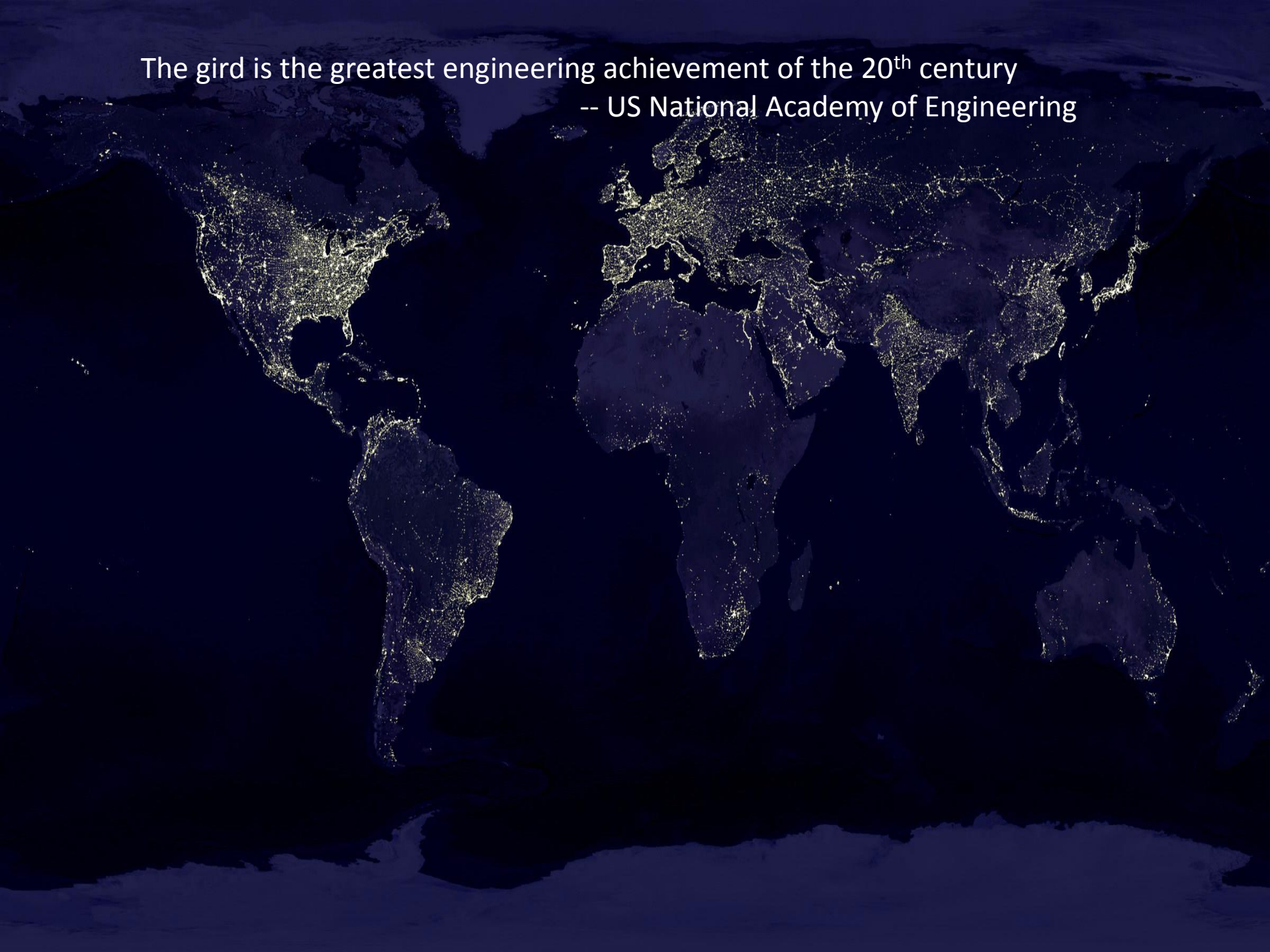


Distributed computing
- Fast
- Secure
- Resilient

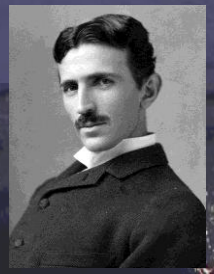
Improved Computation

Population Density

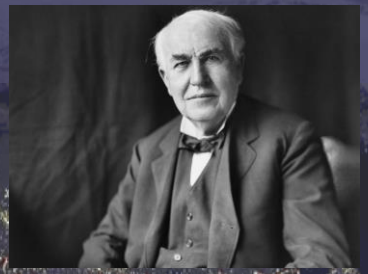



The gird is the greatest engineering achievement of the 20th century
-- US National Academy of Engineering

Tesla

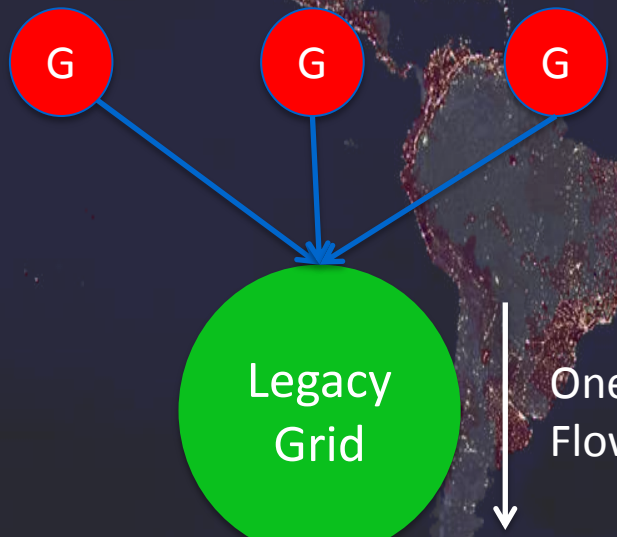


Edison



100 year old architecture!!

Centralized Generation

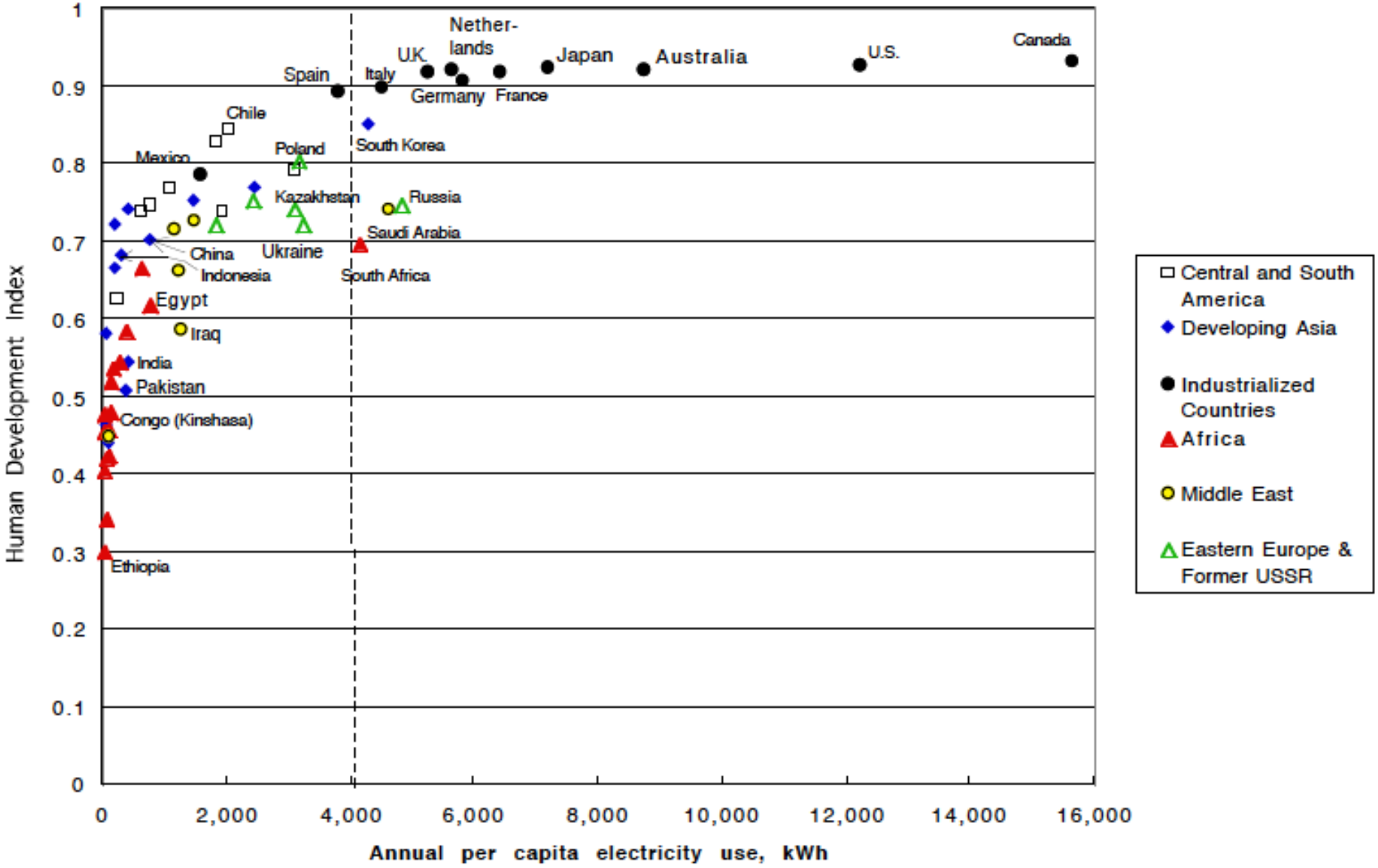


Distributed Load

3 billion people have either no or very limited access to electricity

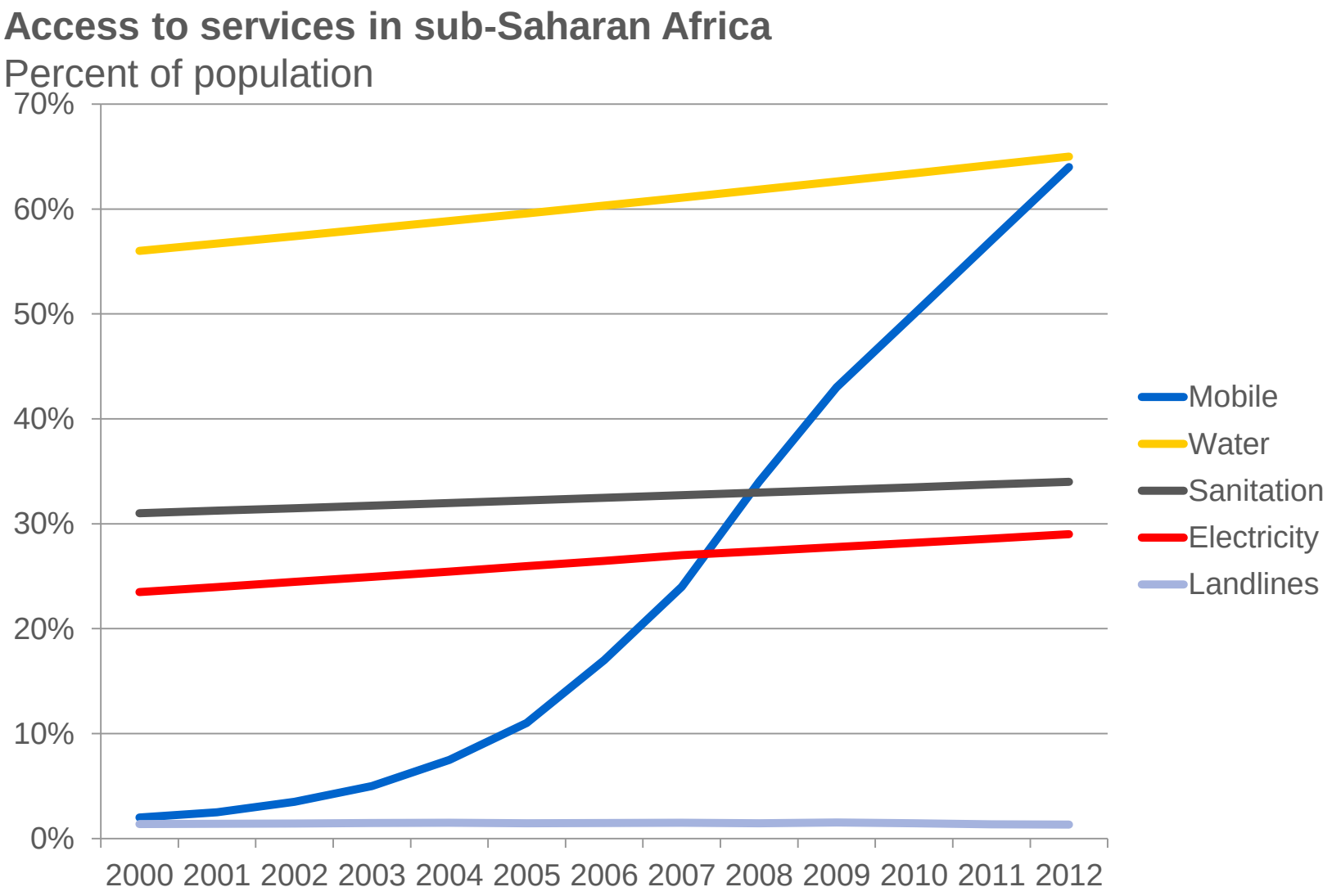
- Distributed and time-varying generation, storage, load
- Bi-directional power flows with flexible architecture

Human Development Index versus Annual Per Capita Electricity Use



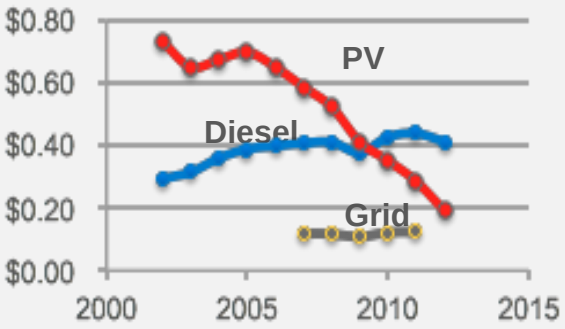
Alan Pasternak, "Global Energy Futures and Human Development: A Framework for Analysis," LLNL Report (UCRL-ID-140773), October 2000.

Scaling

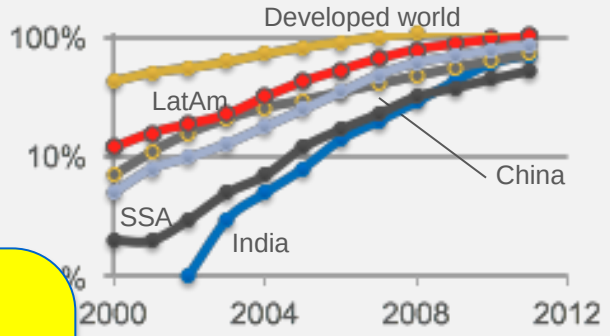

Access to services in sub-Saharan Africa
Percent of population
70%
60%
50%
40%
30%
20%
10%
0%
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
Mobile
Water
Sanitation
Electricity
Landlines

Perfect storm of technology and economics

Electricity cost $/kWh delivered, utility-scale, based on India



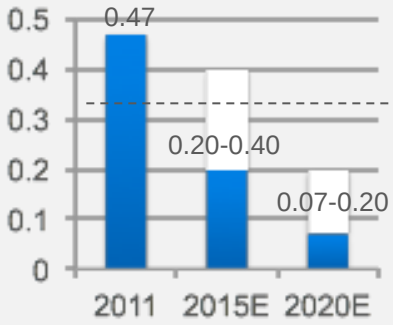
Mobile penetration Subscriptions per capita



Perfect Storm:

- Affordable electricity
- Local/distributed generation independent of utility
- Modern power electronics
- Access to communication
- Increasing demand

Li-ion storage cost ($/kWh delivered)
200-400 Wh/kg (cell); 100-200 Wh/kg (pack)



Lead acid (40Wh/kg)

WBG Power Electronics
300x size reduction in 25W AC-DC SSL Driver

Rethinking the grid for the 21st century