arpa·e energy innovation summit

Doing More with Less: Opportunities for Increased Energy Efficiency

Moderator: Dr. Tim Heidel, ARPA-E

Dr. James Klausner, ARPA-E

Dr. Amul Tevar, ARPA-E

Dr. Bradley Zamft, ARPA-E

Overview of this session

Tim Heidel, ARPA-E Program Director

ADEPT & SWITCHES Programs

James Klausner, ARPA-E Program Director

Metals Production Consumes Significant Energy: ARPA-E Seeks Energy Efficiency

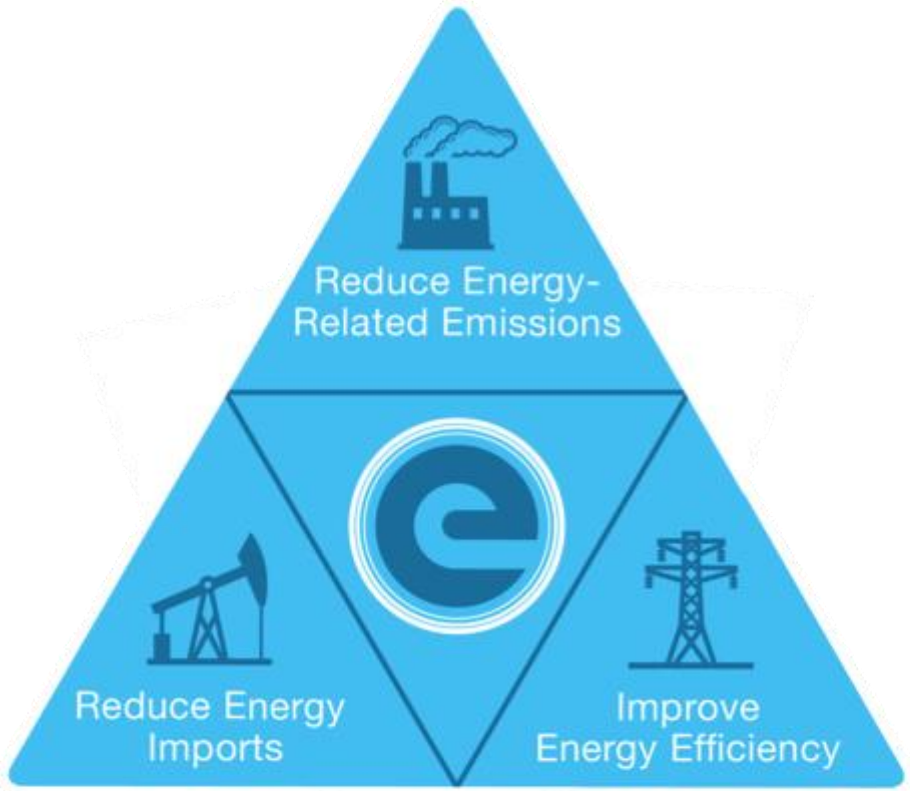
Bradley Zamft, ARPA-E Fellow

Microorganisms for Metals: Opportunities for Biology in the Mining Industry

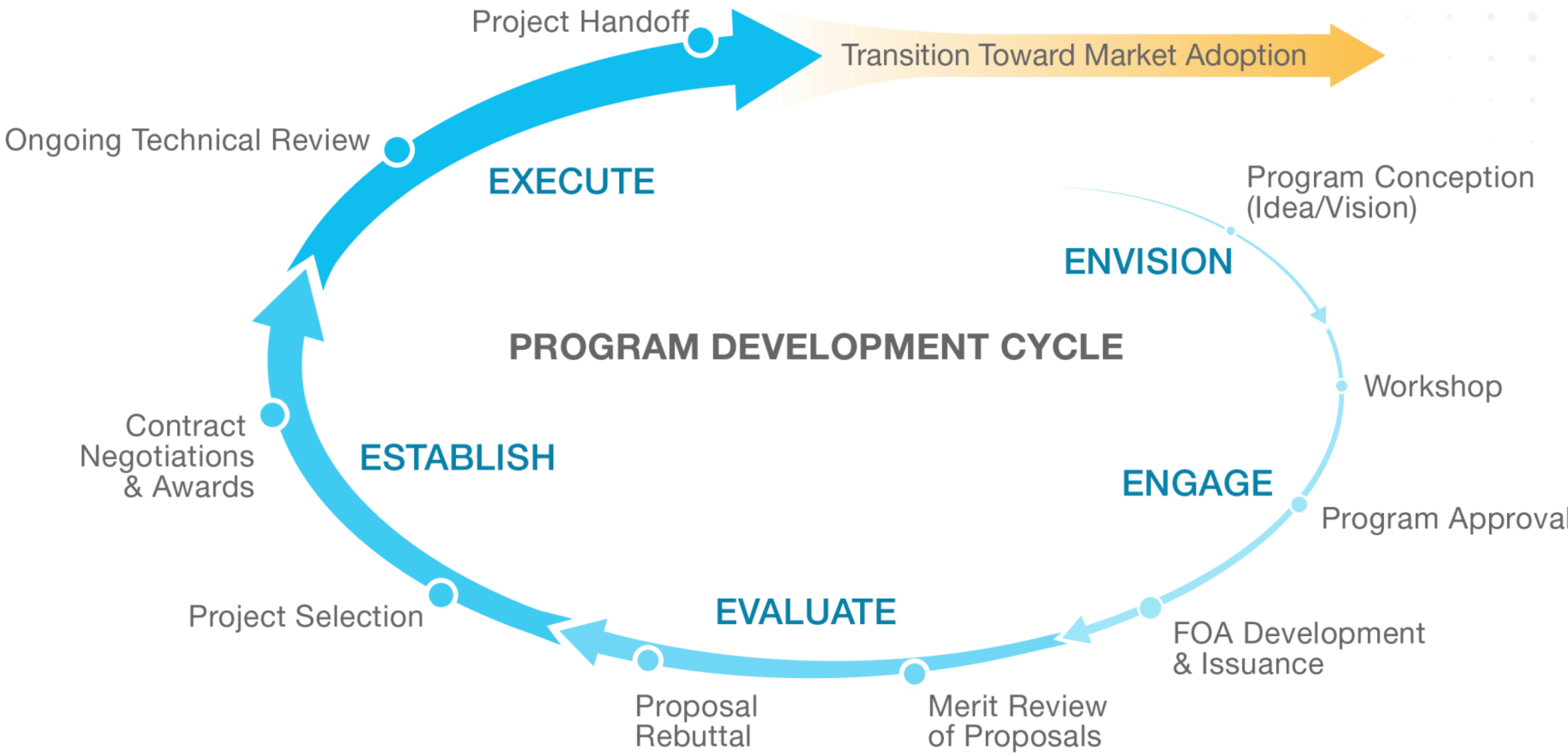
Amul Tevar, ARPA-E Fellow

The Far Future of the Energy & Water Nexus

ARPA-E Mission



Technology Acceleration Model



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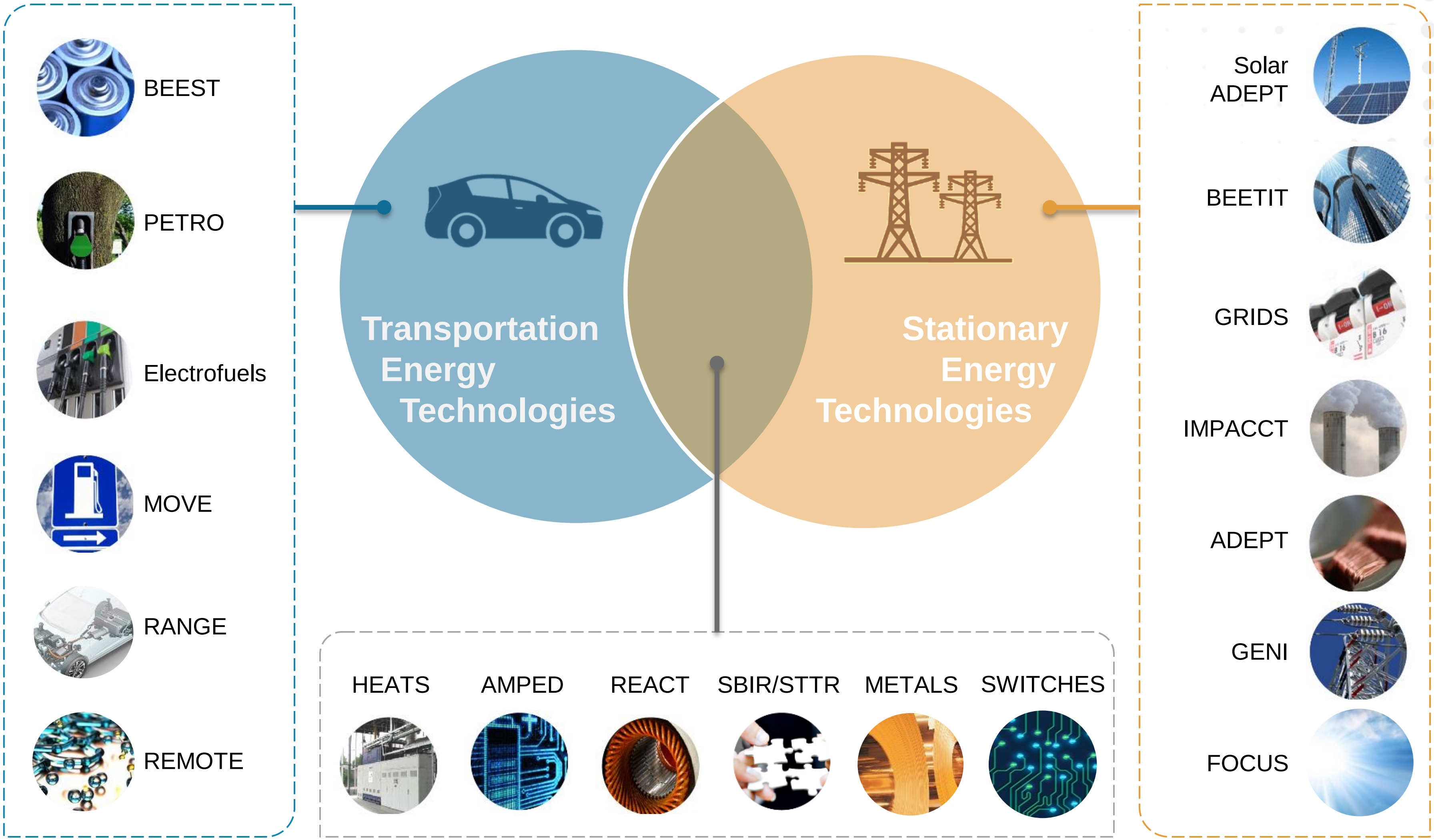
Focused Programs



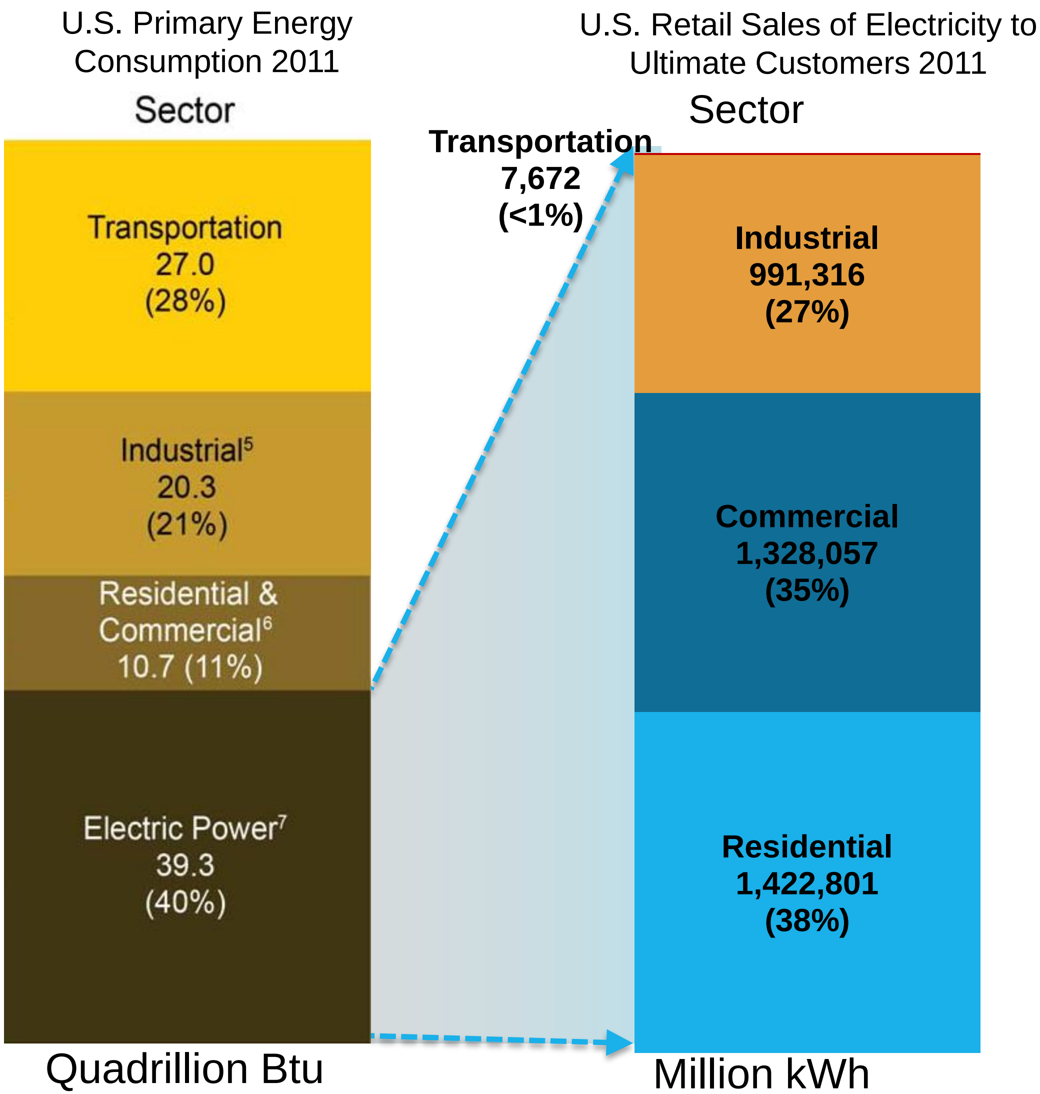
CHANGING WHAT'S POSSIBLE

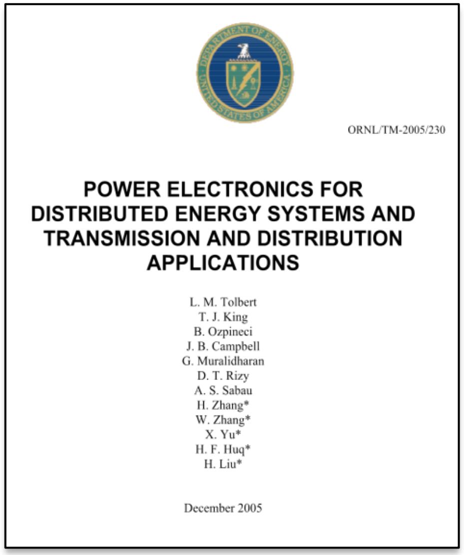
ARPA-E Investments in Power Electronics

ADEPT & SWITCHES Programs

Dr. Tim Heidel, Program Director

Electricity is ~40% of U.S. Energy Consumption




ORNL/TM-2005/230

POWER ELECTRONICS FOR DISTRIBUTED ENERGY SYSTEMS AND TRANSMISSION AND DISTRIBUTION APPLICATIONS

L. M. Tolbert
T. J. King
B. Ozpineci
J. B. Campbell
G. Muralidharan
D. T. Rizy
A. S. Sabau
H. Zhang*
W. Zhang*
X. Yu*
H. F. Huq*
H. Liu*

December 2005

- In 2005, **30%** of electricity in the U.S. flows through power converters.
- By 2030, **80%** of electricity could flow through power converters.

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U.S. Energy Information Administration (EIA), Retail sales of electricity to ultimate customers, January 30, 2013.
EIA, Annual Energy Review DOE/EIA-0384(2011), September 2012
L.M. Tolbert, et al., "Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications: Assessing the Technical Needs for Utility Applications." (Oak Ridge, TN: Oak Ridge National Laboratory, 2005)

ADEPT

EFFICIENT POWER CONVERSION

Goals

- Improve the energy efficiency of electronic devices and power systems
- Enable high efficiency, high power density power electronics
- Contribute to the development of a smart grid

Program Director	Dr. Tim Heidel (Dr. Rajeev Ram)
Kickoff Year	2010
Projects	13
Total Investment	$37.7 Million

Highlights

- Advanced charge storage devices
- Magnetic materials
- Advanced solid-state switch technologies
- Advanced circuit topologies and converter architectures

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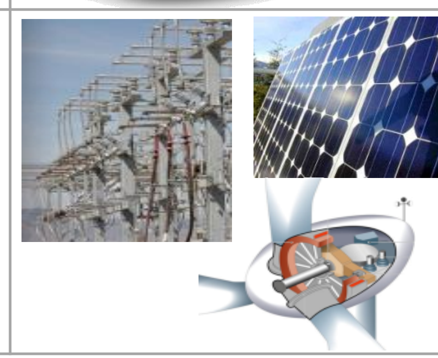
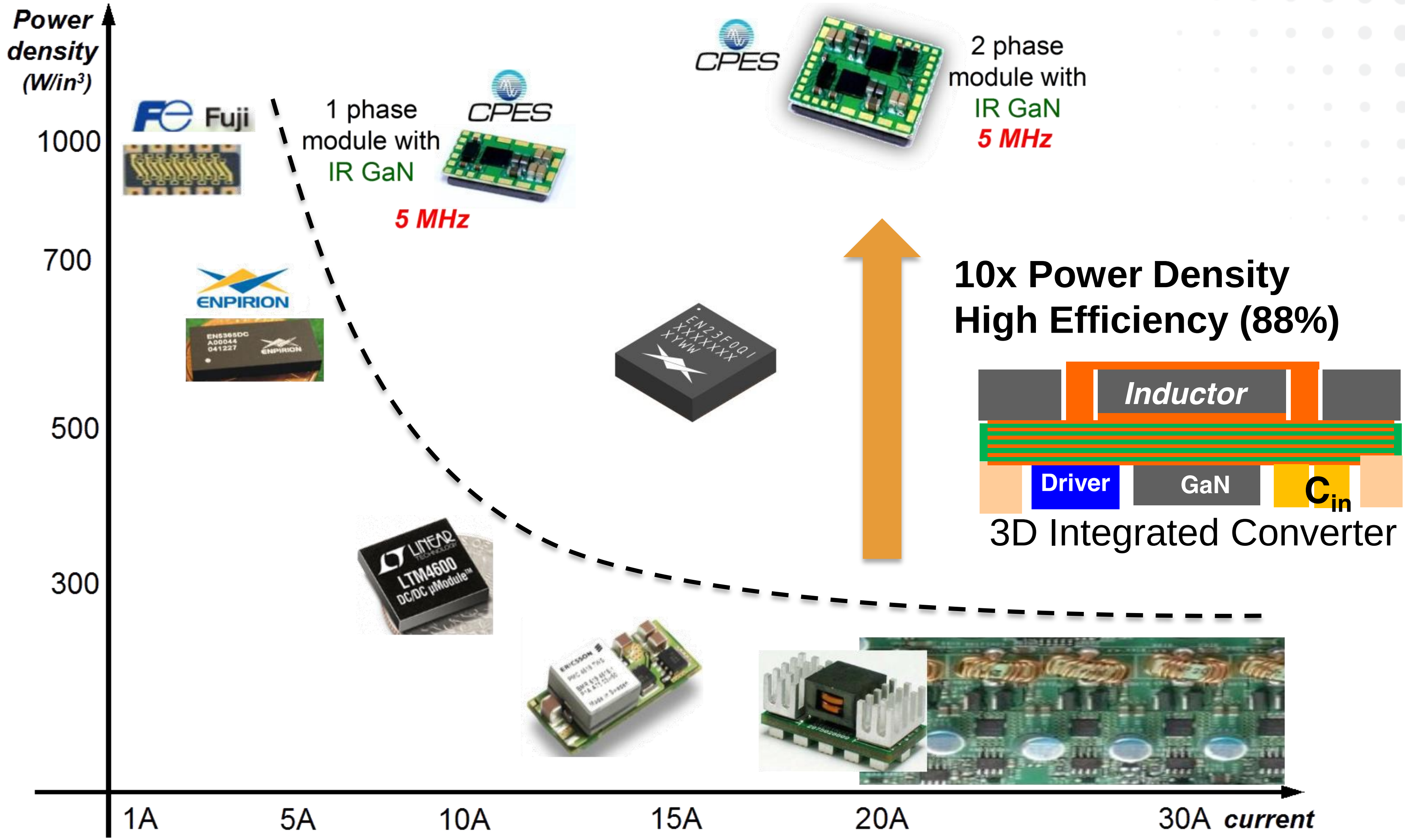
ADEPT Program Technical Targets

Category	Voltage & Power	Efficiency	Switching Frequency	Power Density	Applications
Fully Integrated, Chip-scale power converters	>100V 10-50W	>93%	>5 MHz	>300 W/in^3	
Package integrated power converters	>600V 3-10kW	>95%	>1 MHz	>150 W/in^3	
Lightweight, solid-state, medium voltage energy conversion	13kV 1MW	>98%	>50 kHz	N/A	

High Power Density Point of Load Converter



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VirginiaTech

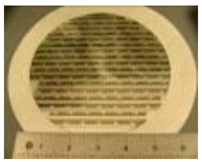
UNIVERSITY of DELAWARE

IOR International Rectifier

ALTERA MEASURABLE ADVANTAGE™

Automotive Applications

Vehicle Inverter (GaN)



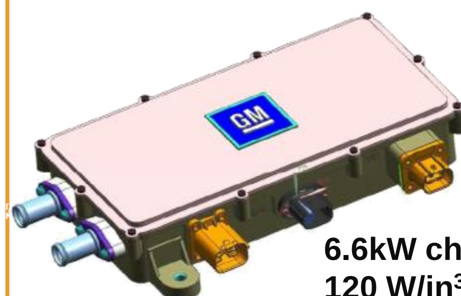
6" GaN/Si Wafer

Dual Side Sintered Packages

GaN Inverter

600V GaN-on-Si Dual Side Cooled Transistors, 50% Lower Cost, 50% Lower Losses

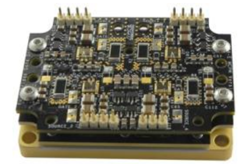
Bi-Directional Vehicle Battery Charger (GaN)



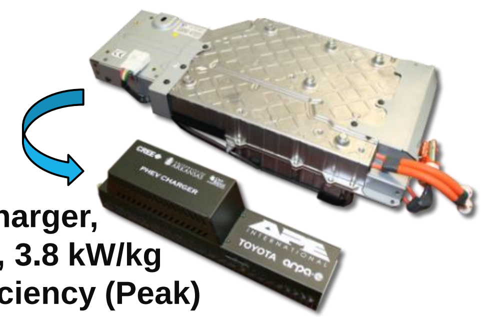
6.6kW charger, 120 W/in³

2x faster charging, 2x more efficient, 10x more compact

Bi-Directional Vehicle Battery Charger (SiC)



Multi-chip Power Module (MCPM) (1 MHz Operation)

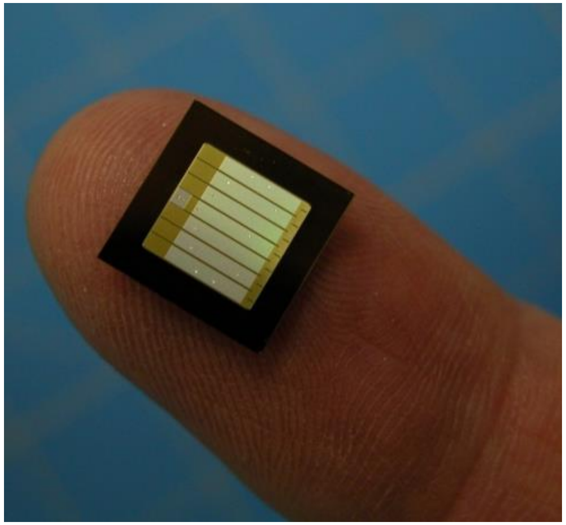


6.1kW charger, 83 W/in³, 3.8 kW/kg 95% Efficiency (Peak)

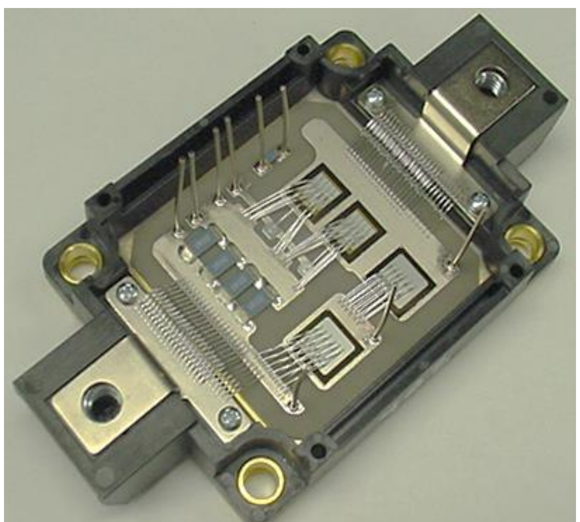
10x Increase in Power Density *and* Increased Efficiency

15kV+ SiC IGBTs, Solid State Transformers

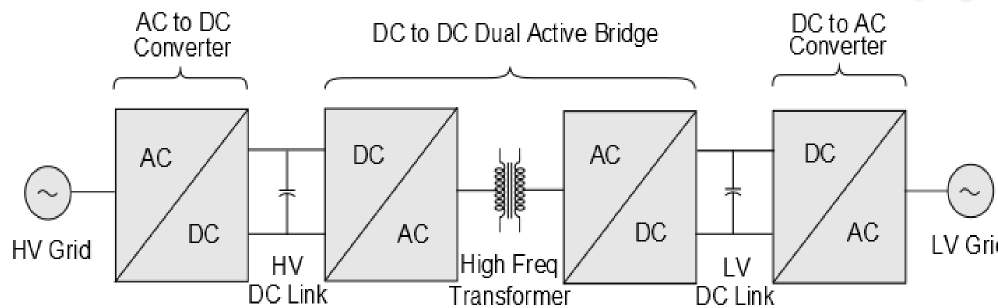
19 kV/20 A SiC n-IGBT

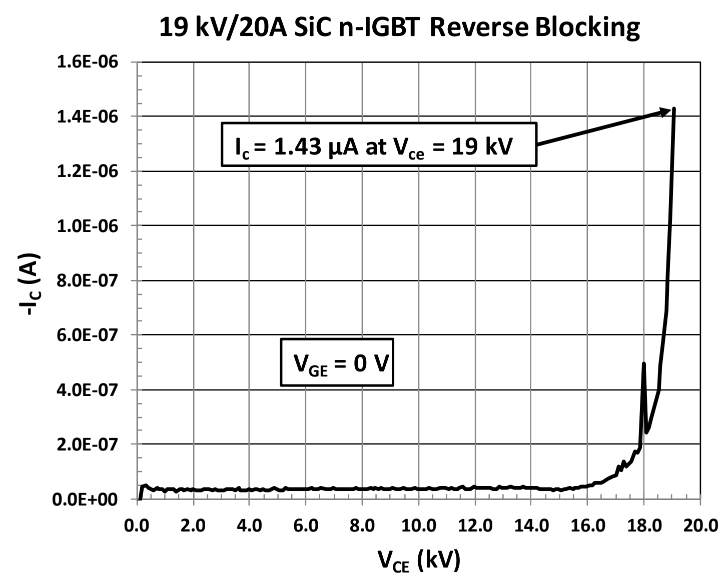


15kV/40A SiC IGBT Copack

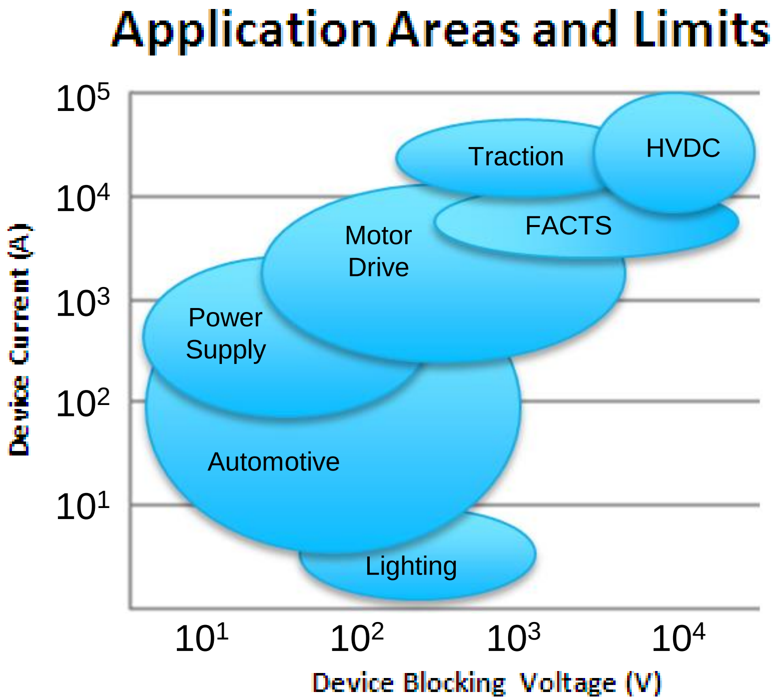


Transformerless Intelligent Power Substation (TIPS)





SWITCHES Program Builds on ADEPT Success



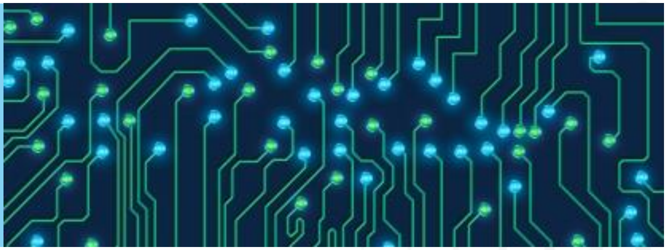
- Key Device Parameters:
  - Breakdown voltage
  - Junction temperature
  - Switching speed
  - Ease of driving
  - Current rating
  - $/Amp

ADEPT Program Focus Areas

SWITCHES Program Focus Areas

SWITCHES

Low Cost, High Current Wide Bandgap Switches



Goals

- High voltage (1200V+), high current (100A) single die power semiconductor devices at functional cost parity with silicon power transistors.
- Reduce the barriers to widespread deployment of low-loss WBG power semiconductor devices in stationary and transportation energy applications.

Program Director	Dr. Tim Heidel
Kickoff Year	2013
Projects	14
Investment	$27 Million

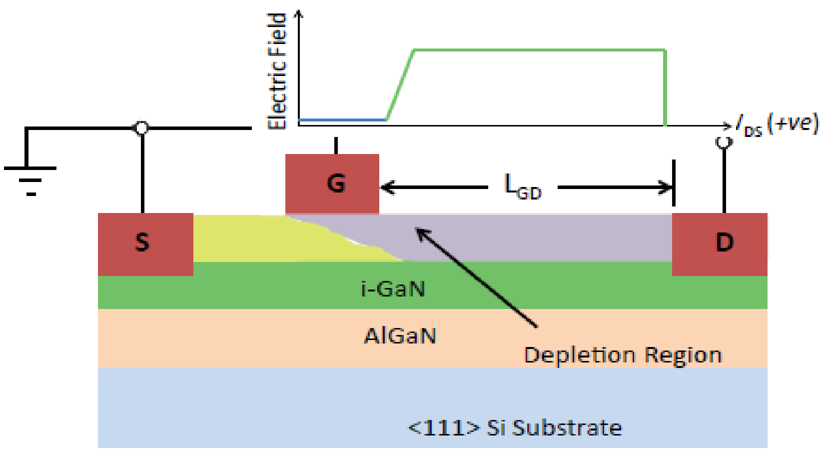
Highlights

- Low Cost (Foundry) SiC Device Fabrication
- Vertical GaN Transistors
- Diamond Semiconductor Devices

Pathways to Low Cost Gallium Nitride Devices

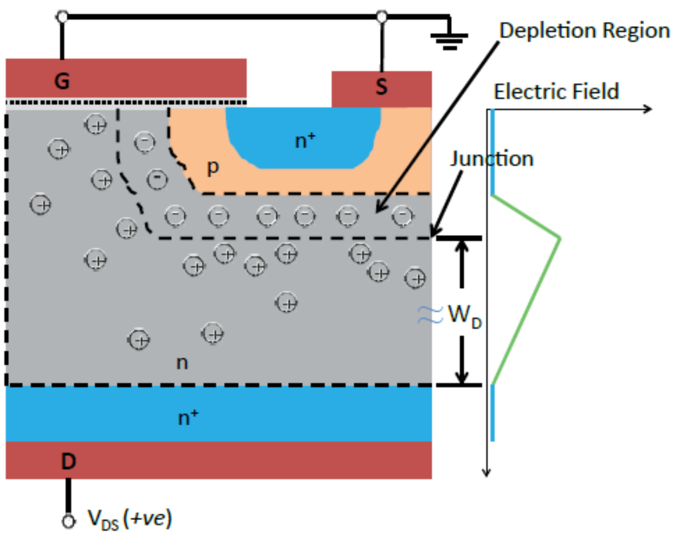
Lateral GaN High Electron Mobility Transistors (HEMTs)

- Lateral conduction: Low current density/die area, die size increases directly with breakdown voltage.
- Heteroepitaxy makes high current devices (>100A) extremely challenging.



Vertical GaN Transistors

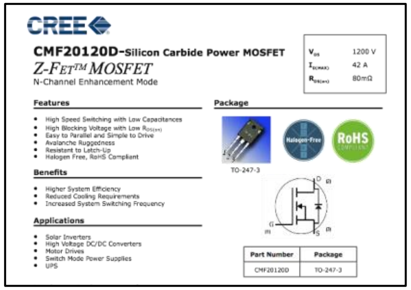
- Utilize more of the material for conduction, higher current densities.
- Breakdown voltage handled vertically.
- Challenge: Requires bulk GaN substrates.

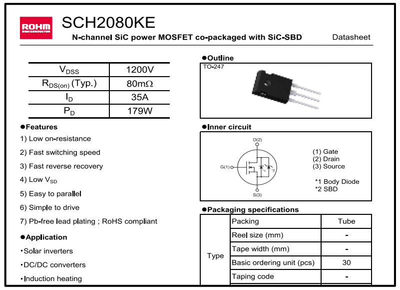


T. Uesugi and T. Kachi, Which are the Future GaN Power Devices for Automotive Applications, Lateral Structures or Vertical Structures?, CS MANTECH Technical Digest, Toyota, 2011.

Pathways to Low Cost SiC and Diamond Devices

Silicon Carbide



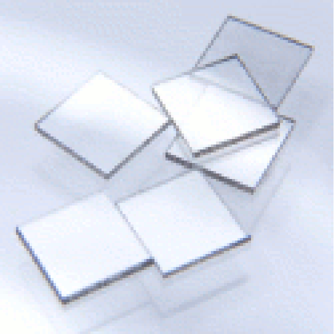


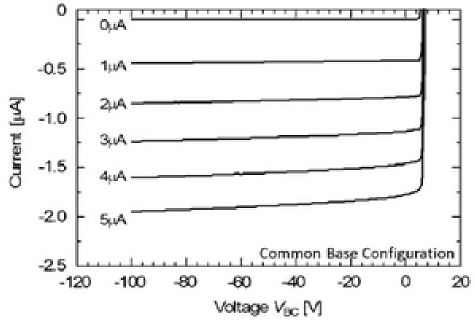
V_{DSS}	1200V
$R_{DS(on)}$ (Typ.)	80mΩ
I_D	35A
P_D	179W

Type	Packing	Tube
	Reel size (mm)	-
	Tape width (mm)	-
	Basic ordering unit (pcs)	30
	Taping code	-

- SiC MOSFETs currently 5-8X more expensive than Si devices ($/A).
- Challenges:
  - Carrier mobilities substantially below theoretical maximum
  - High temperature processing steps require use of dedicated, custom (low volume) SiC fabrication facilities.

Diamond





- Diamond material advantages:
  - Very high bandgap (5.45 eV)
  - Superior thermal conductivity
  - High electron mobility
- Why now?
  - Availability of single crystal substrates
  - p-type and n-type epi growth
  - Improved low resistance contacts
  - Demonstration of (low current) BJT

Images: Cree, Rohm, Element 6
Kato et al., *Diamond & Related Materials* 34 (2013), 41-44

GaN

Substrates

- FairfieldCrystal technology
- MicroLink Devices, Inc.
- kyma the new wave in nitrides
- SixPoint Materials
- iBeam Materials
- SORAA Simply Perfect Light™

Diodes & Transistors

- University of Notre Dame
- avogy advancing energy efficiency
- Columbia University
- HRL Laboratories
- University of California Santa Barbara

SiC

Diodes & Transistors

- Monolith Semiconductor Inc.

Diamond

Diodes & Transistors

- ASU
- Michigan State University

Metals Production Consumes Significant Energy: ARPA-E Seeks Energy Efficiency

METALS Program

Dr. James Klausner, Program Director

Program Objectives

- Enable **cost competitive** transformative light metal (Al, Mg, Ti) processing technologies

- Significant **energy reduction** in primary metal production from ore

- Significant **emissions reduction** in primary metal production

- Significantly **increase the supply** of high grade recycled light metal

4 QUADS Energy Savings

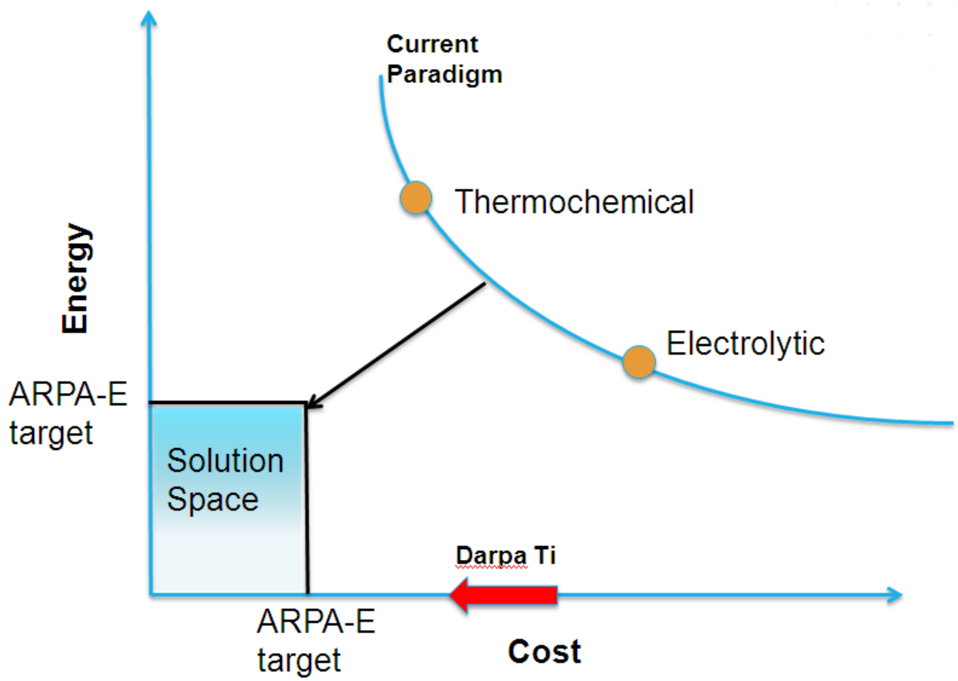
Light Metal to be Competitive with Steel

- Light metals (Al, Mg, Ti) enable **advanced alternative energy technologies**

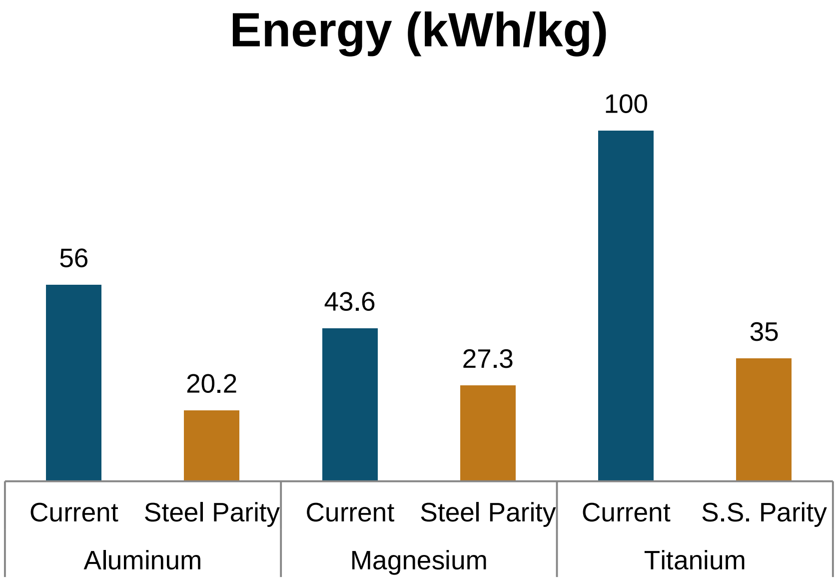
- Drive down:
  - **Energy**
  - **Emissions**
  - **Cost**

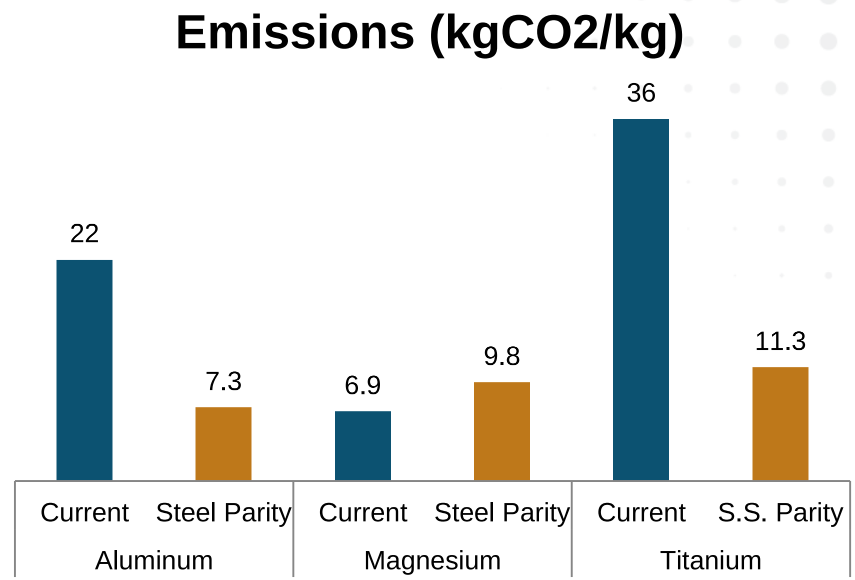
  ≡ **Steel**

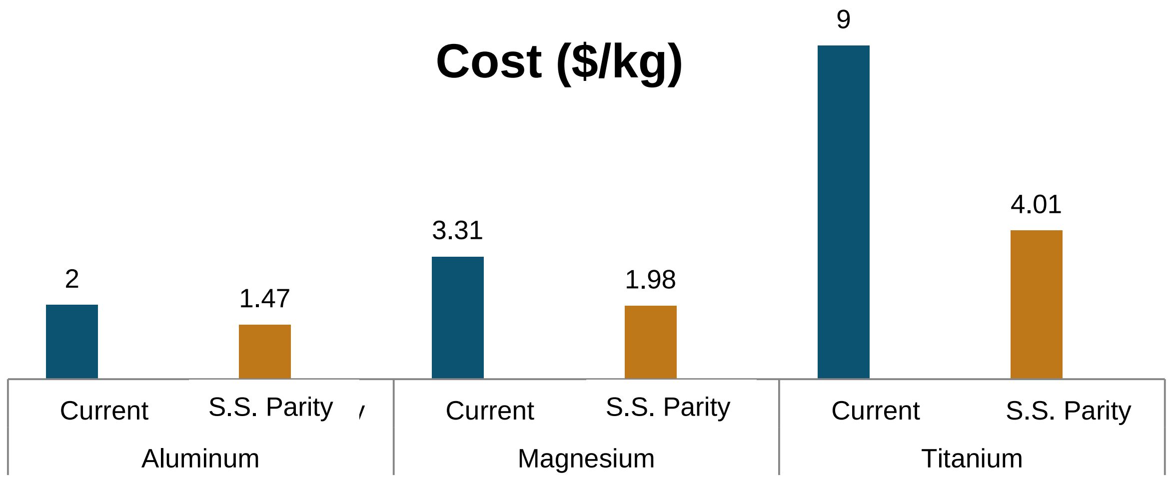
- Most **competitive light metal production** in the world; significantly reduce imports



Reach Parity with Steel and Stainless Steel







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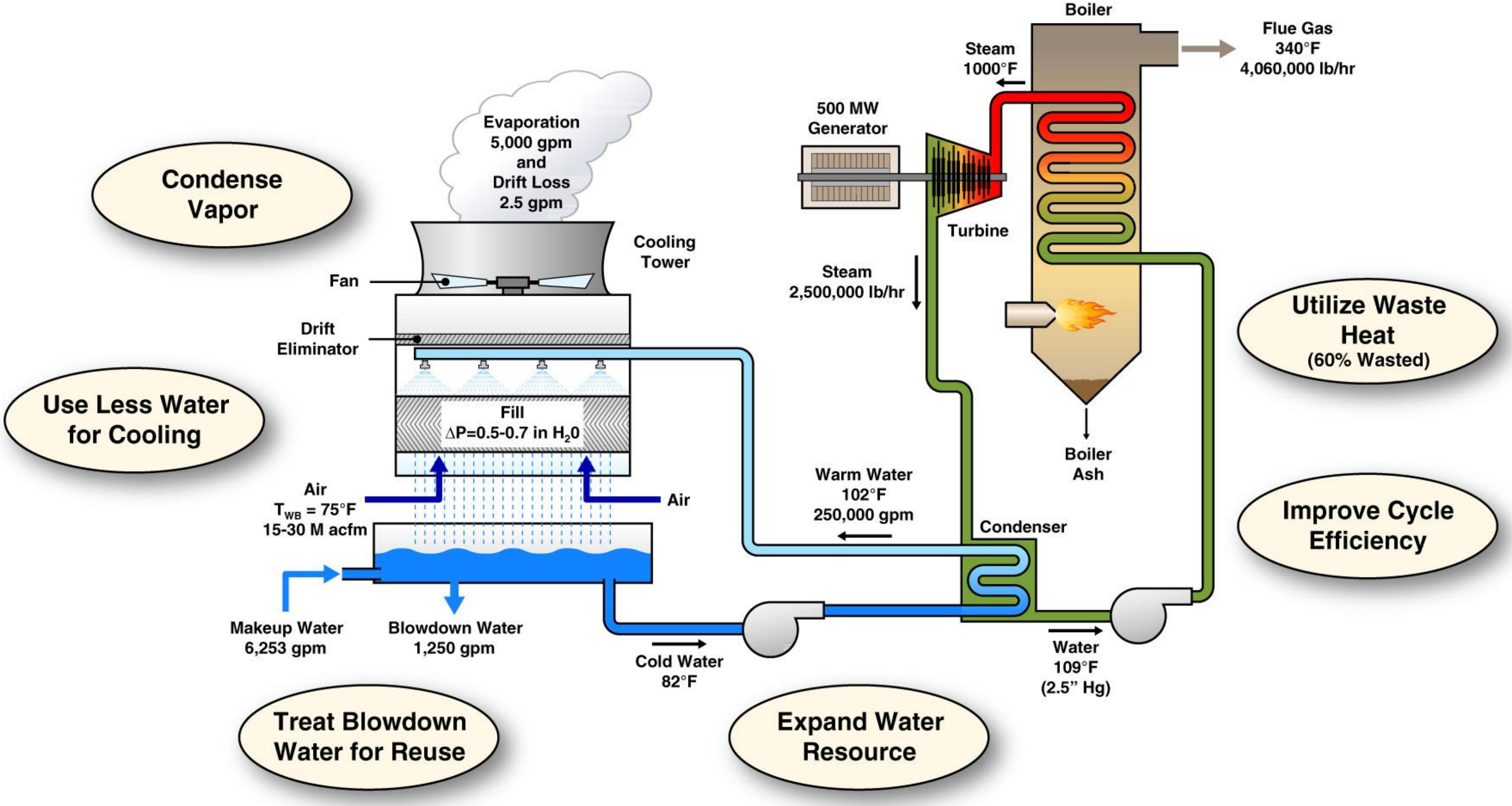
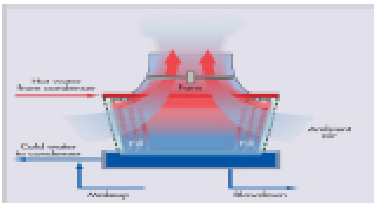
Energy/Water Interest



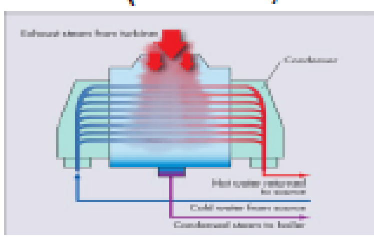
Conventional Power Plant Steam Condenser Technologies

Water Cooling

Cooling Tower[1] (42% in US)[2]



Once Through Cooling[1] (43% in US)[2]



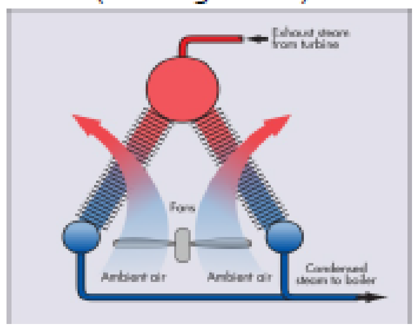
Cooling Pond

(14% in US)[2]

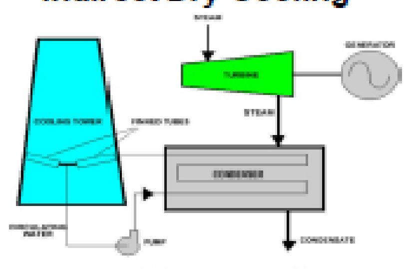
Dry Cooling

Direct Dry Cooling[1]:

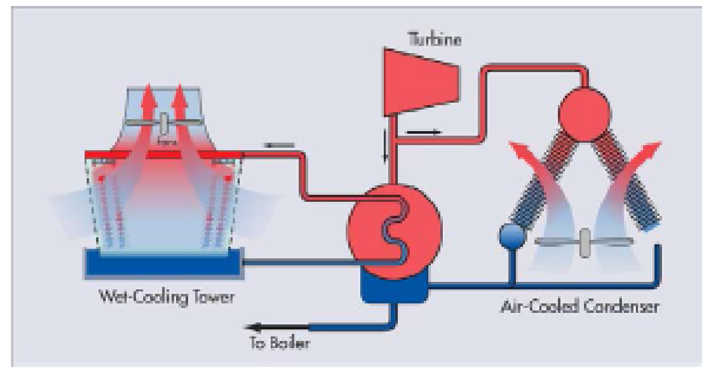
Air Cooled Condenser (1%Usage in US)[2]



Indirect Dry Cooling[3]



Hybrid Cooling[1]

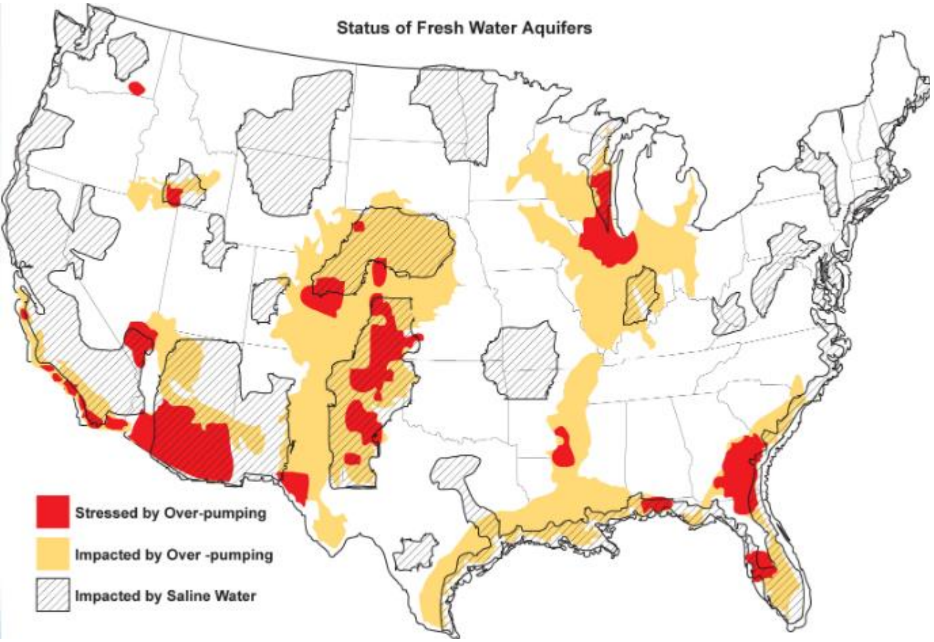


Increasing demand for dry cooling in water scarcity regions.

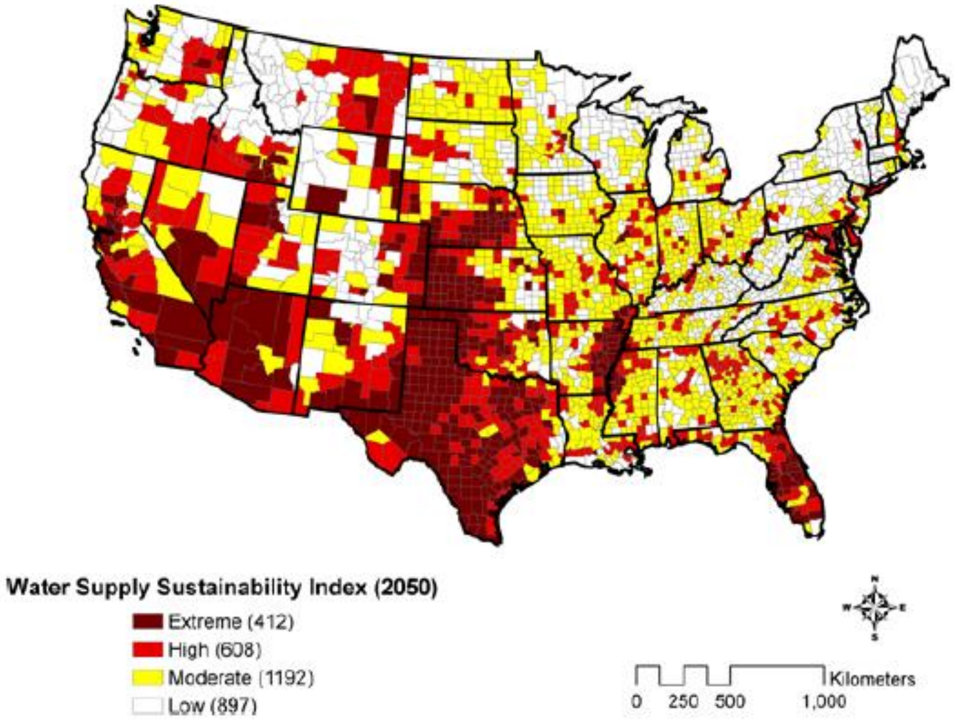
1. EPRI Report, "Water Use for Electric Power generation", No. 1014026, 2008.
2. Report of Department of Energy, National Energy Technology Laboratory, "Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements", DOE/NETL-400/2008/1339, 2008
3. http://www.globalccsinstitute.com/publications/evaluation-and-analysis-water-usage-power-plants-co2-capture/online/101181

Energy Conversion Efficiency at Risk due to Growth of Regional Water Supply Problems

Current scenario, more of a **regional problem** (high population centers)



With population growth and climate change, 2050 **water scarcity** is projected to be widespread



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ARPA-E Investigating Transformative Power Plant Cooling Technologies

- Advanced high performance **dry cooling technologies**, where heat is dumped to ambient air

- Use excess heat from stack gas to drive absorption cooling to create a **low temperature heat sink**

- **Radiant cooling** to sky

- Use **advanced manufacturing** -- i.e., 3D printing to develop complex and efficient heat exchange surfaces with low pressure drop

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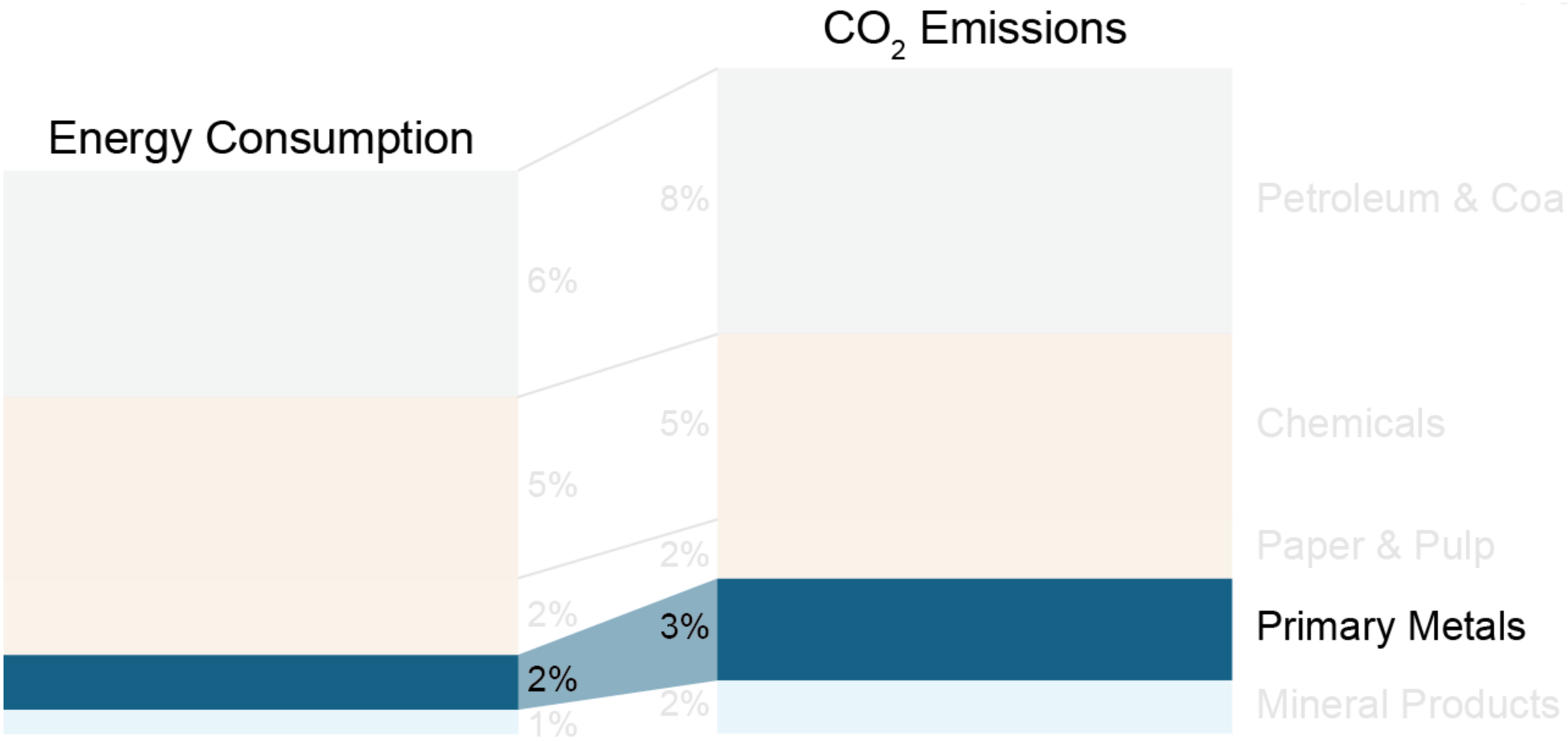
Microorganisms for Metals:

Opportunities for Biology in the Mining Industry

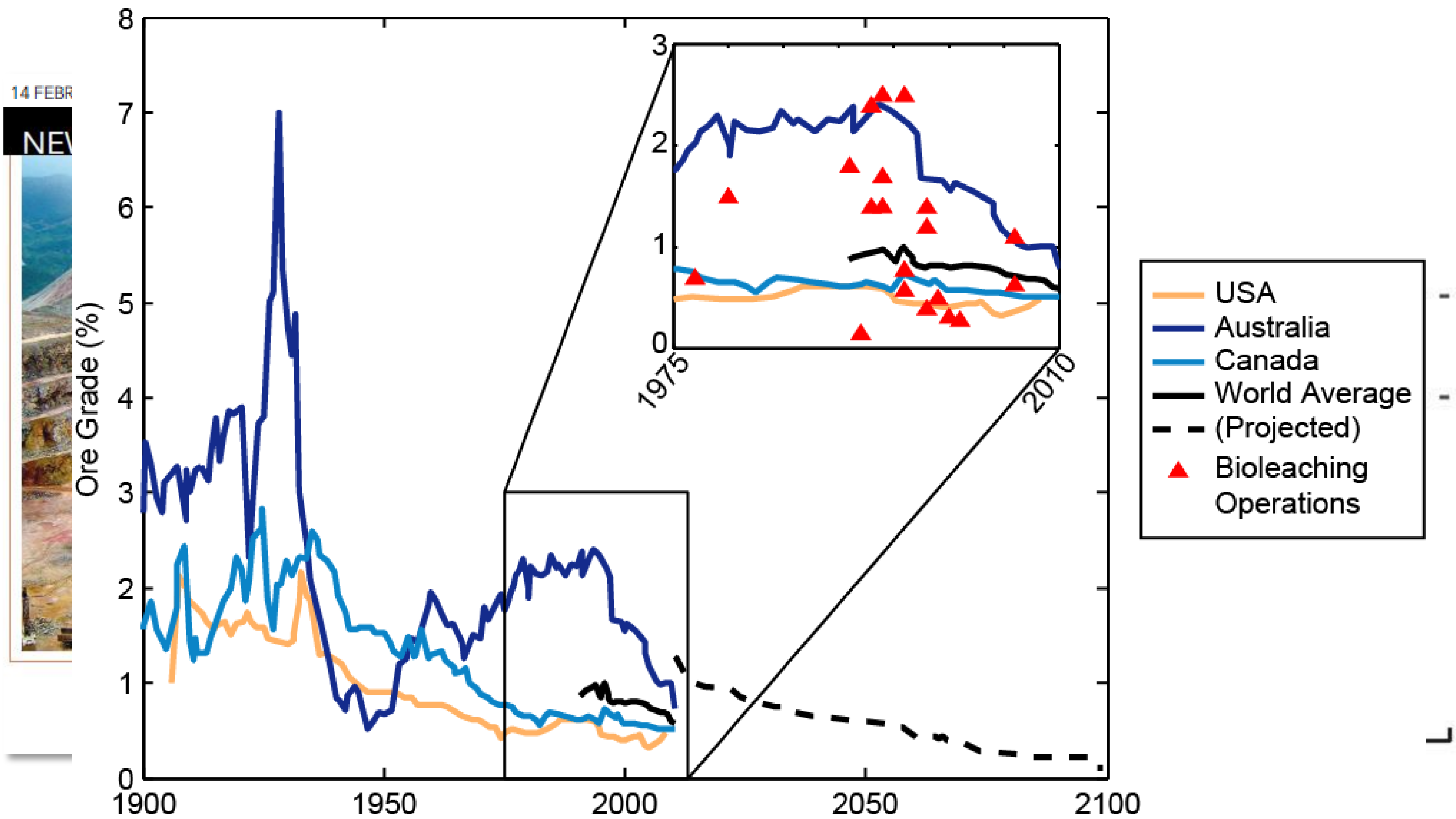
Brad Zamft, PhD, ARPA-E Fellow

Manufacturing Composes a Disproportionate Component of Emissions



EIA, "Manufacturing Energy Consumption Survey (2010)," http://www.eia.gov/consumption/manufacturing/data/2010/
EPA, "Quantifying Greenhouse Gas Emissions from Key Industrial Sectors in the United States," http://www.epa.gov/sectors/pdf/greenhouse-report.pdf

Copper: the Next Energy Critical Material?

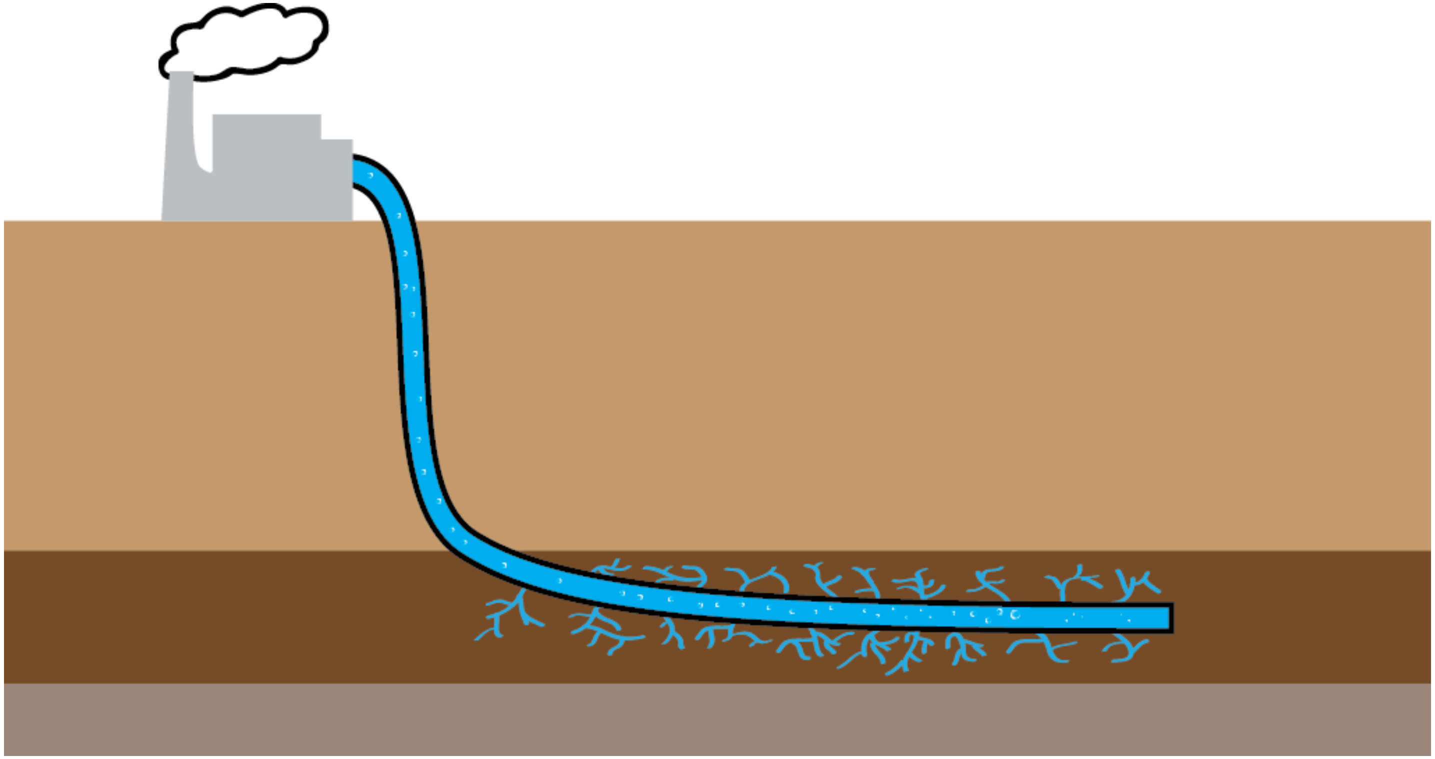


Adapted from The Resnick Institute, “Critical Materials for Sustainable Energy Applications,” http://resnick.caltech.edu/docs/R_Critical.pdf
Right graph from Northey et al. *Resour. Conserv. Recycling* 83 (2014) 190–201
Bioleaching Data from Watling *Hydrometallurgy* 84 (2006) 81–108

Current Mining Practices are Environmentally Intensive

Bingham Canyon Mine, http://www.ksl.com/index.php?page=1&sid=24748916&nid=460
Cerro Verde Heap Leach: http://peer.berkeley.edu/publications/peru_earthquake/Mines/mines2.html

Bringing Horizontal Drilling to Mining



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Open Pits to Directional Wells

vs.

Bingham Canyon Mine, http://www.ksl.com/index.php?page=1&sid=24748916&nid=460
http://en.wikipedia.org/wiki/File:Well_head_after_all_the_Fracking_equipment_has_been_taken_off_location.JPG

Downhole Leaching is Commercially Viable

- *In situ* leaching of uranium ore
  - 90% of the uranium mined in the US
  - 40% of the world's production in 2010
  - Sand beds – easy to leach
- Not currently feasible for other metals
- **Environmental concerns**: 1000 ft depth vs. miles
- *In situ* bioleaching considerations
  - Gas delivery
  - Biology of leaching

Metallofuels: Harnessing Mineral Energy

Per kg Butanol Produced

O_2

Ore	Cu (kg)	Fe (kg)	H_2O (L)	O_2 (kg) (consumed)	CO_2 (kg) (consumed)
$CuFeS_2$	0.6-0.8	0.5-0.7	1-2	4-5	2
FeS_2		1	1	5-13	2
10 H_2O					
Oxidation of pyrite to sulphate					1526 – 1202

Ore	Metal	2011 Global Production (M MT)[1]	ΔG (kJ/mol)[2]	% Primary Energy	Value (WTI)
$CuFeS_2$	Cu	16	-2200	0.1	$9 B
	Fe	1090		9	$800 B
FeS_2	Fe		-1200	5	$400 B

[1] USGS, "Mineral Commodity Summaries 2013," http://minerals.usgs.gov/minerals/pubs/mcs/2013/mcs2013.pdf
[2] Calculations include regeneration of H_2SO_4 for chalcopyrite, but does not include S^0 regeneration for pyrite, because H_2SO_4 is a commodity.

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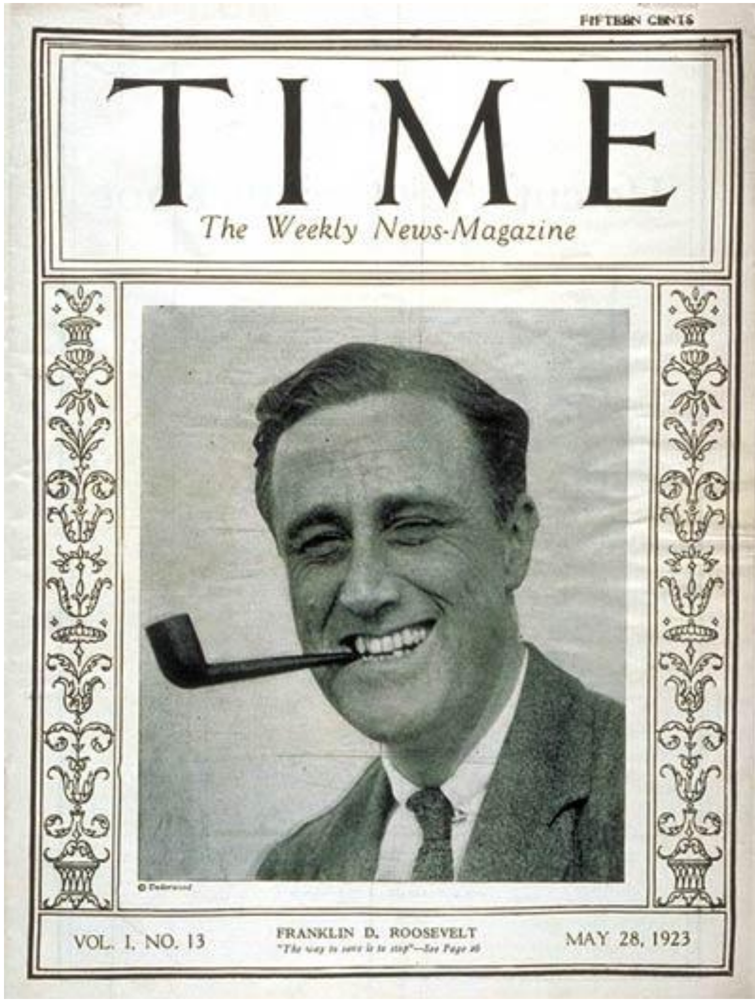
The Far Future of the Energy & Water Nexus

Dr. Amul D. Tevar, ARPA-E Fellow

February 24, 2014

Legacy Inefficiencies in Infrastructure



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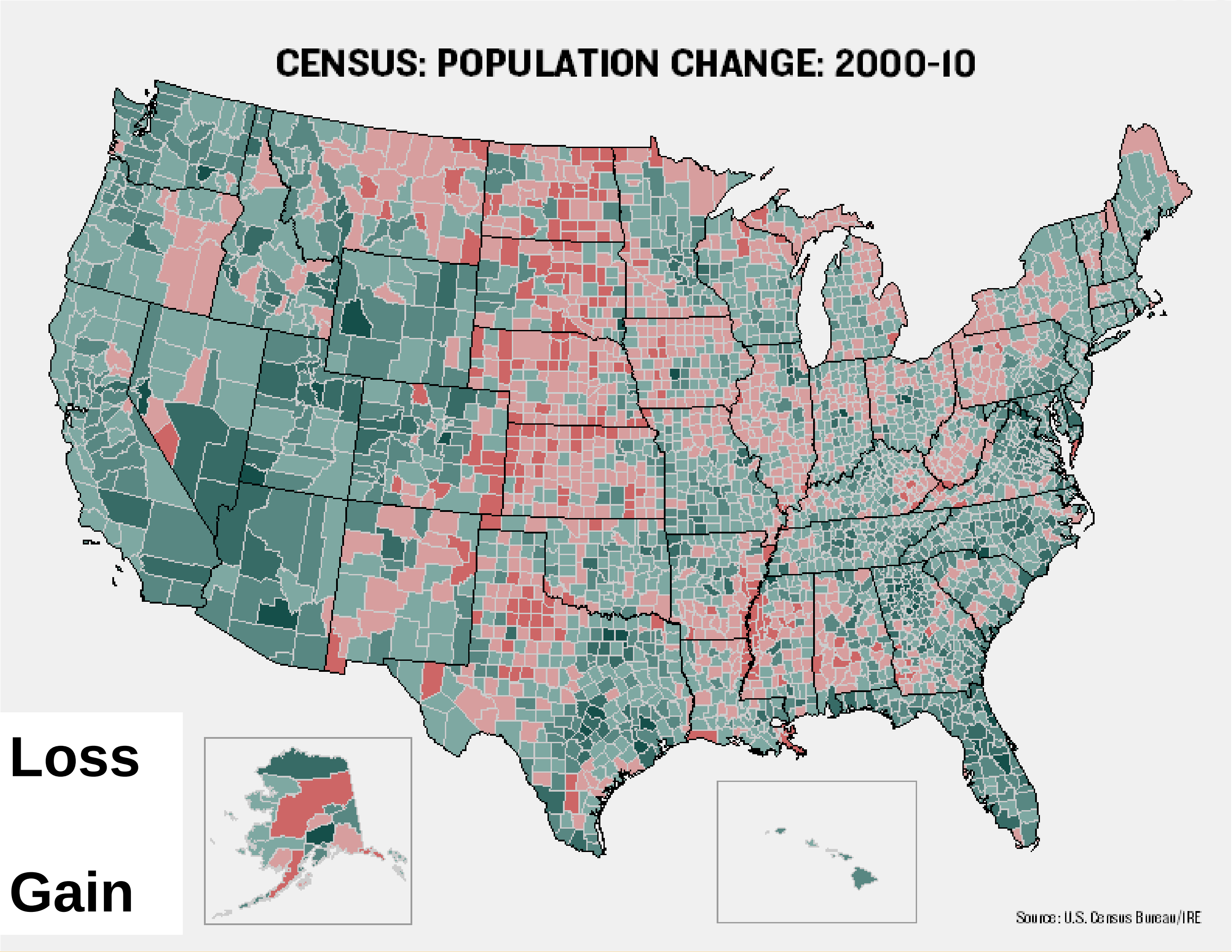
Time Magazine Cover, Governor FDR, 1929

New Deal Power line, http://skyways.lib.ks.us/towns/Brainerd/events.html

Shift from Rural to City-States

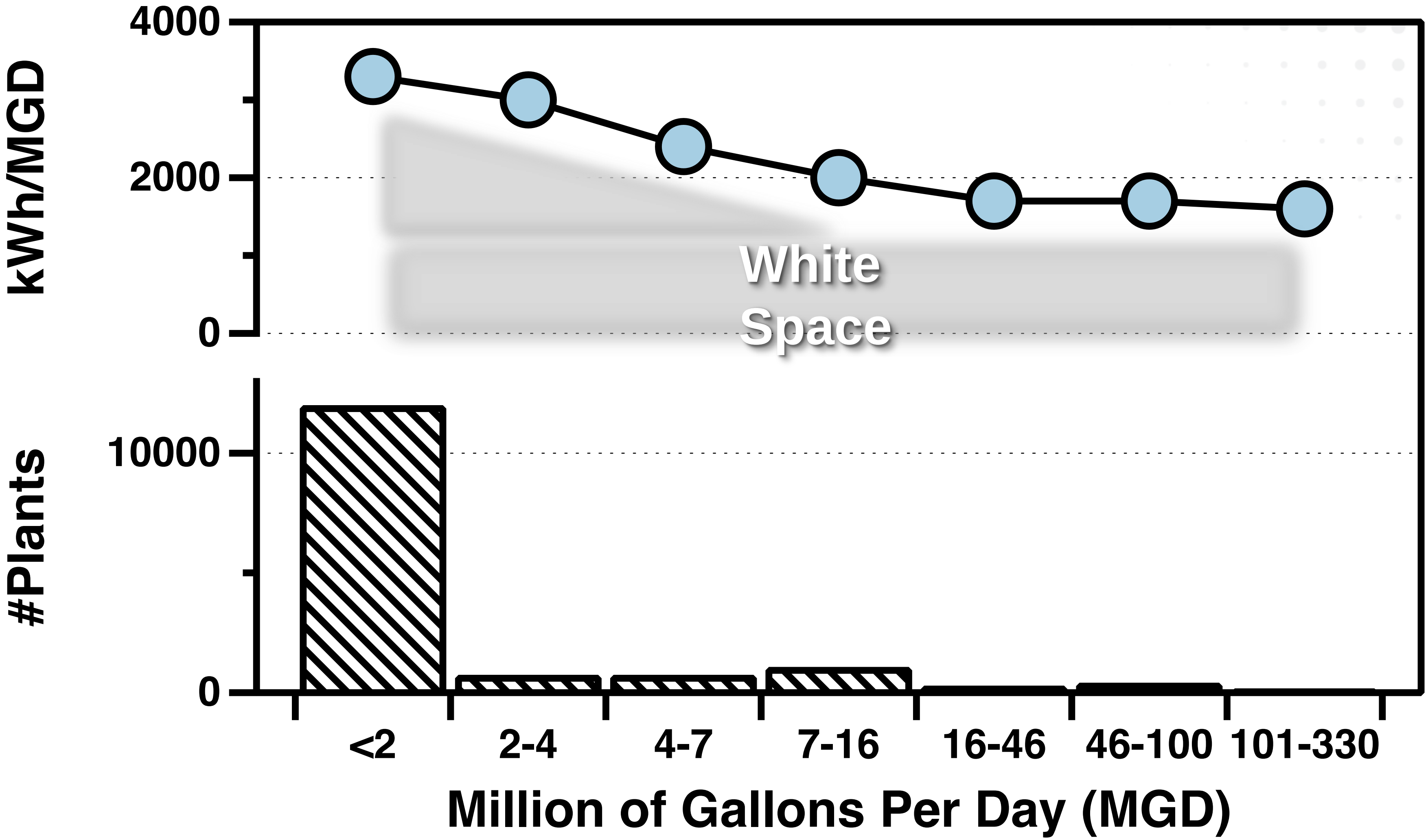


= Popl. Loss

= Popl. Gain

http://www.texastribune.org/2011/03/25/maps-visualize-us-population-growth-by-county/

~1 Quad for Wastewater



1. EPRI Report Wastewater Energy Report #3002001433, 2013

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Scoop on Poop: Energy Positive Treatment

Future: +100 kWh/MGD
Small Scale

?

Anaerobic Digestion

Automation

CHP

Advanced Bioreactors

Biogas Cleaning

Current: -1600 kWh/MGD
Large Scale

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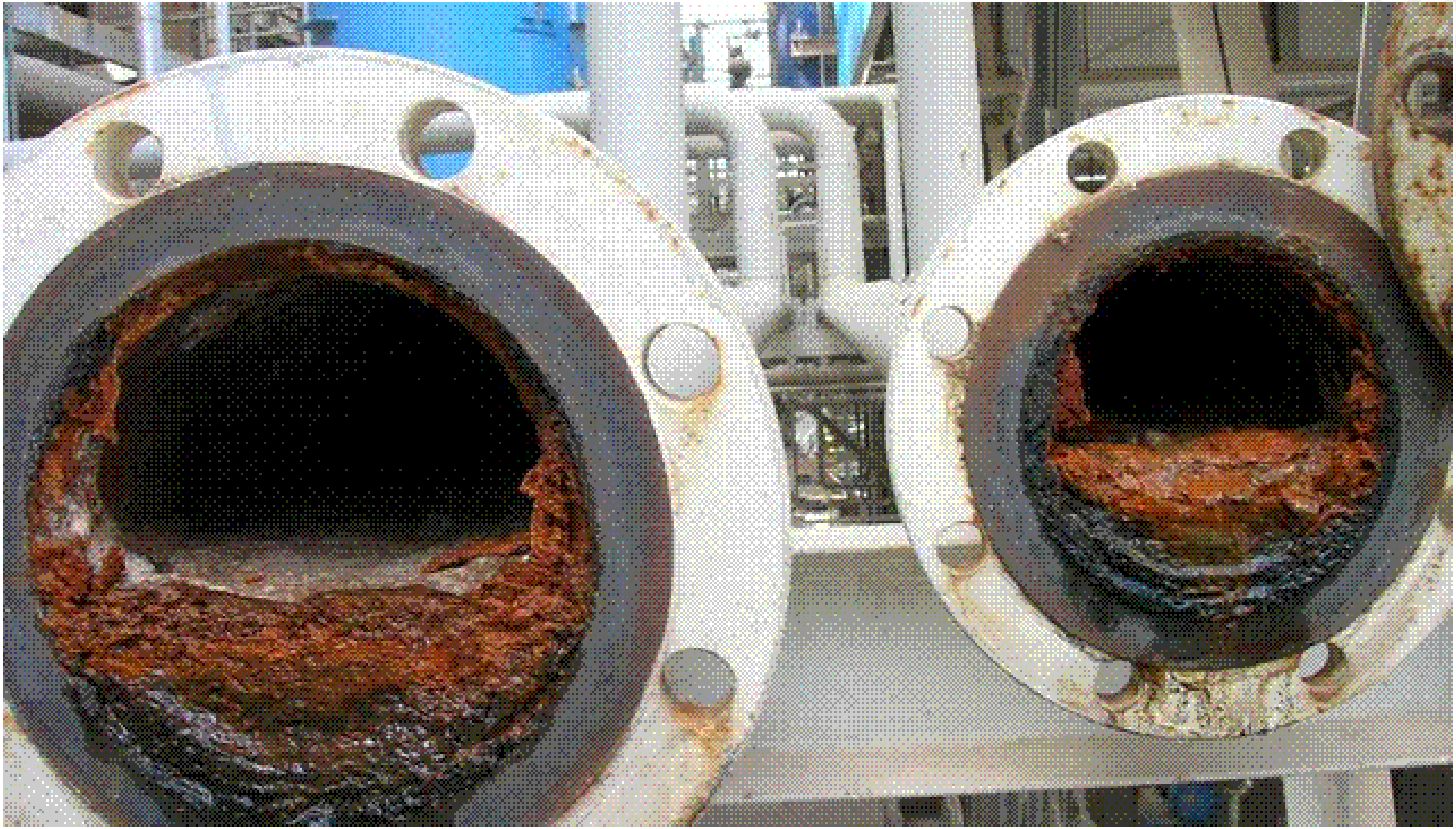
1. http://www.dreamstime.com/stock-photography-sewage-treatment-plant-modern-urban-wastewater-image34777622

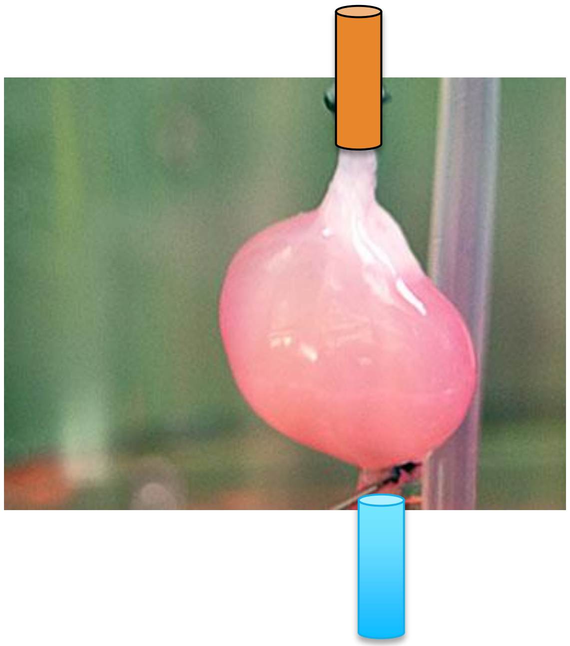
Biofouling Limits Membranes



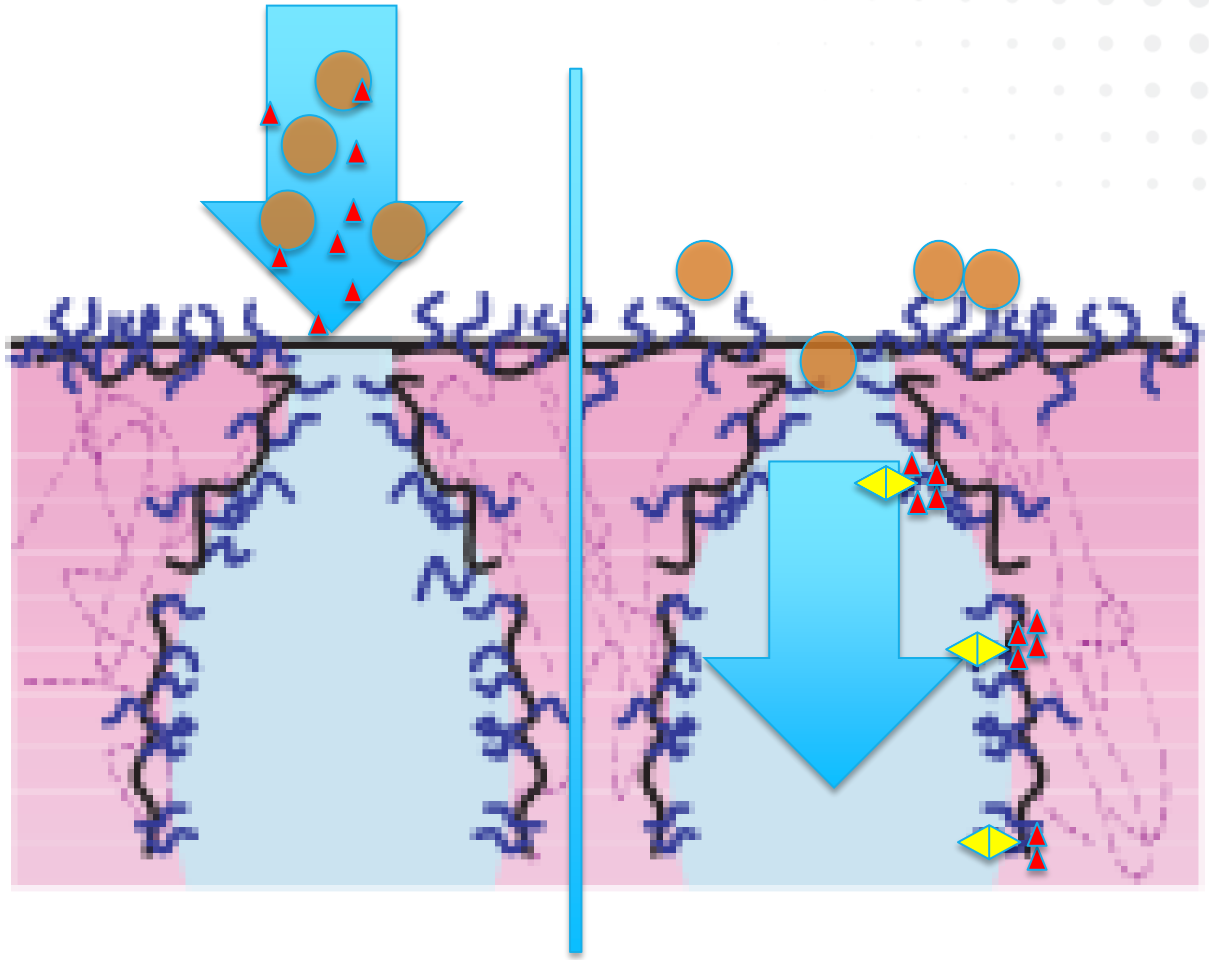
Biofouling Picture: http://seawaterfouling.wikispaces.com/What+is+Biofouling%3F

Biomimetic Membranes: Stealing a Kidney

Wastewater



Potable



Membrane Adapted from Image: Shannon, M. Nature vol. 452(20), 2008
http://www.theguardian.com/science/2013/apr/14/kidney-grown-lab-transplanted-animal

We All Share the Sources

Email: amul.tevar@hq.doe.gov

Cartoon: http://green-mom.com/wp-content/uploads/2014/01/waste-water-recycling.jpg

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