"Challenges/Opportunities at the Energy/Water(Food) Nexus"

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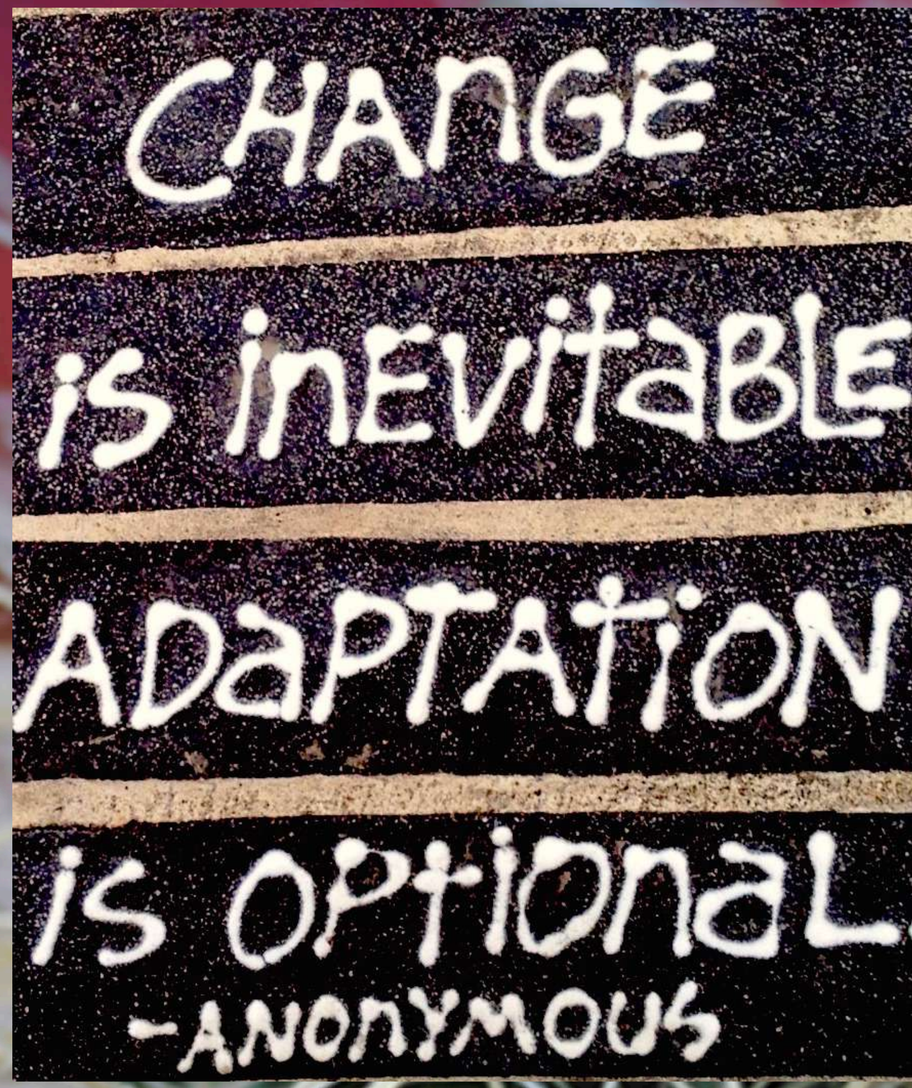
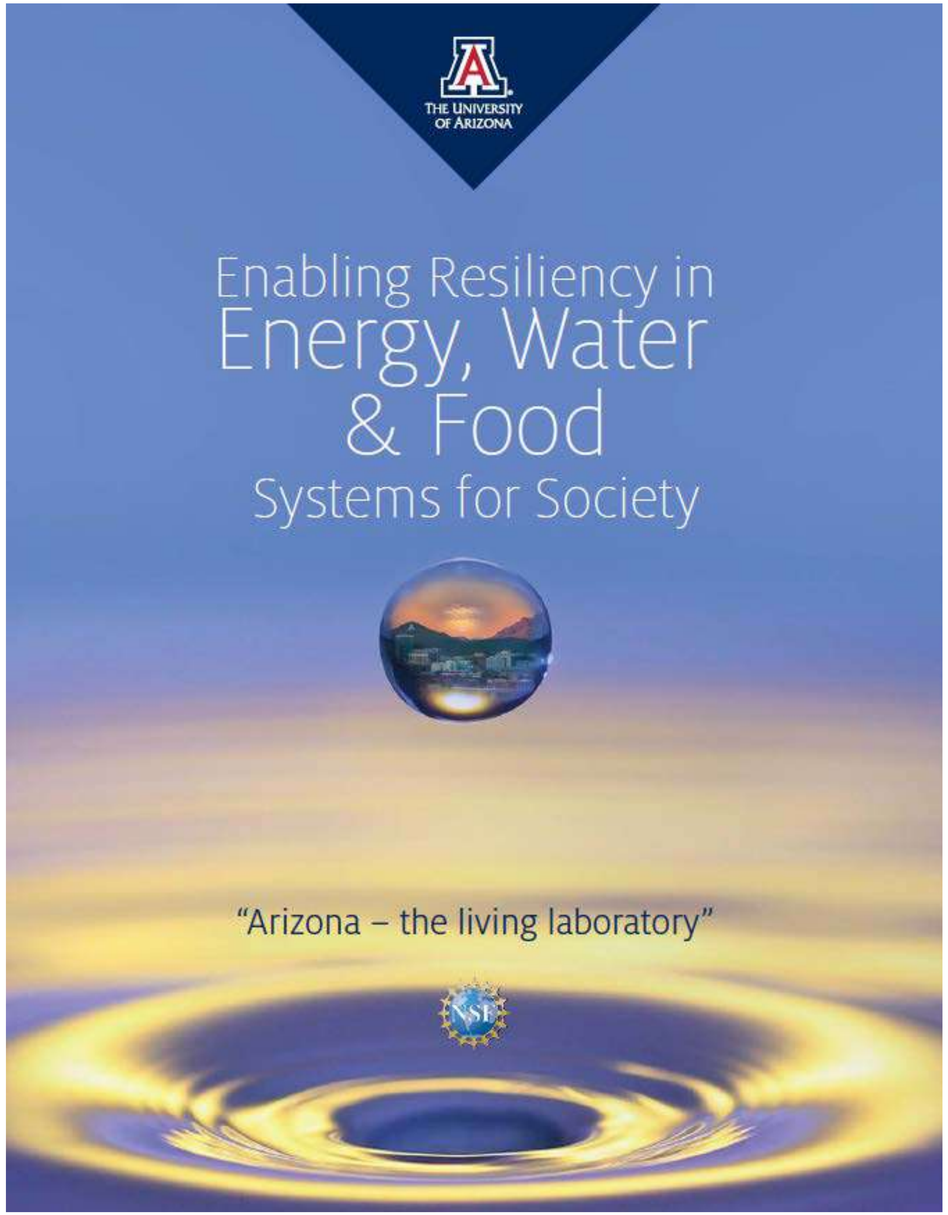
Research, Discovery & Innovation

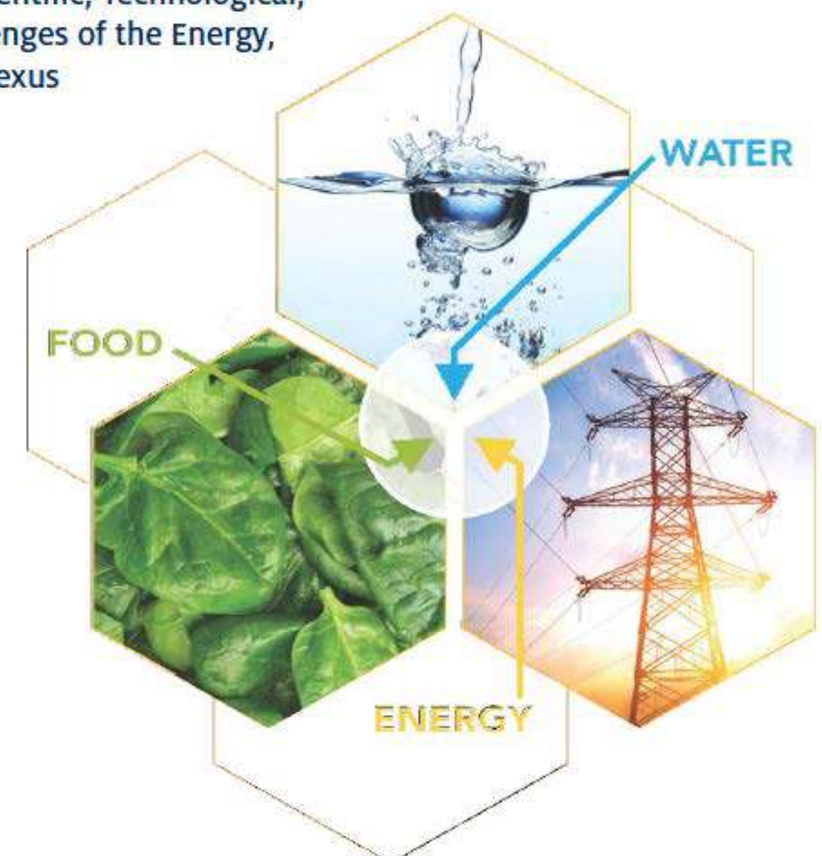




Enabling Resiliency in Energy, Water & Food Systems for Society

Addressing the Scientific, Technological, and Societal Challenges of the Energy, Water, and Food Nexus

April 15–17, 2015
held at Biosphere 2
University of Arizona
Tucson, Arizona



The presentations and images from this workshop are available on the dedicated web site
http://energywaterfoodnexus.wordpress.com

NSF workshop reports and outcomes for the entire INFEWS Program:
https://foodenergywaternexus.org/nsf-infews-workshops/

Research
Office for Research & Discovery

The Basic Science Problems:

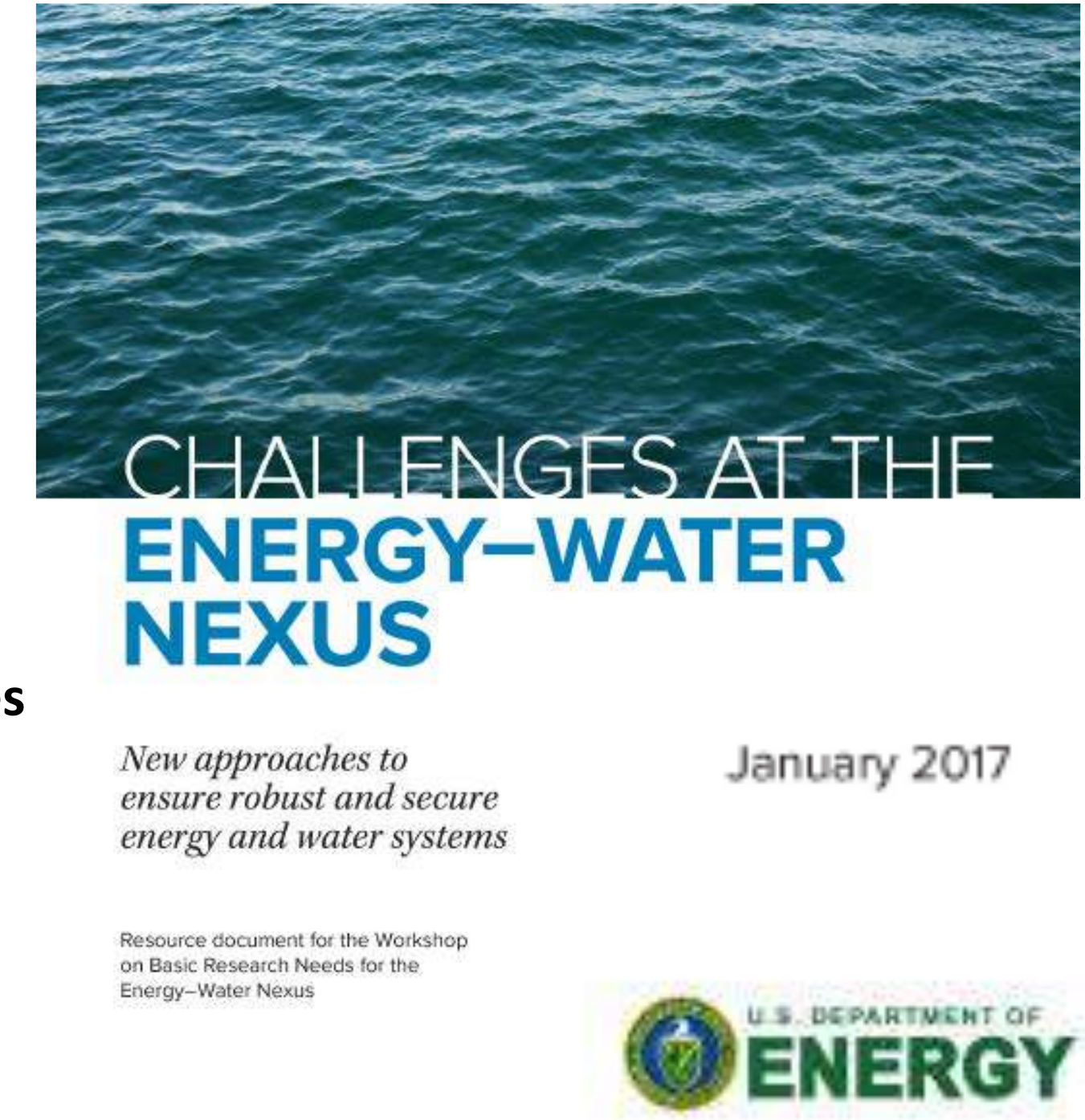
- Water and geologic systems
- Water use for fuel and energy
- Extraction
- Materials chemistry in aqueous environments
- Cooling in thermopower plants
- Waste heat recovery

Separations – Removing Impurities

- Membranes
- Sorbents
- Electro/capacitive technologies

Catalysis – Destroying Impurities

- Bio-based catalysis
- Electrocatalysis
- Photocatalysis



Coming soon!

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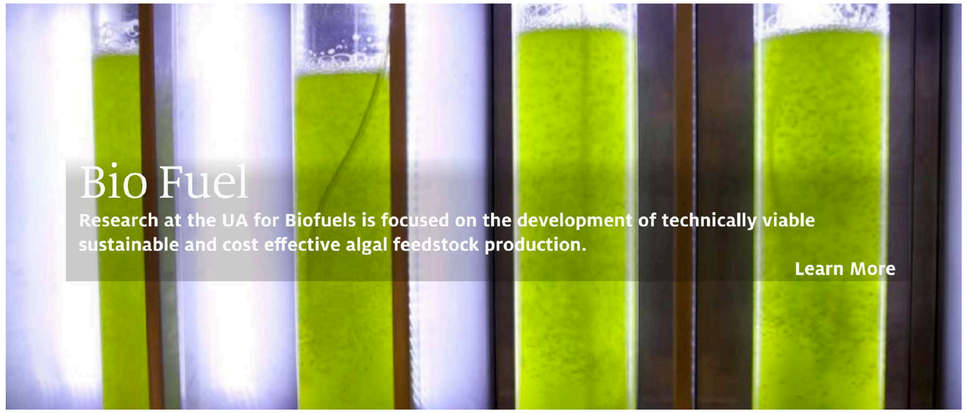
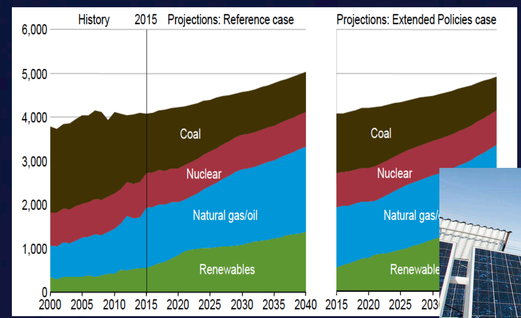
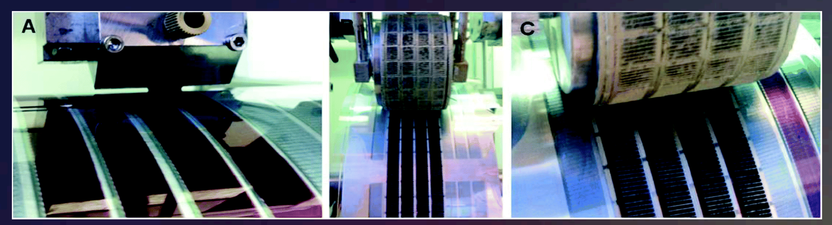
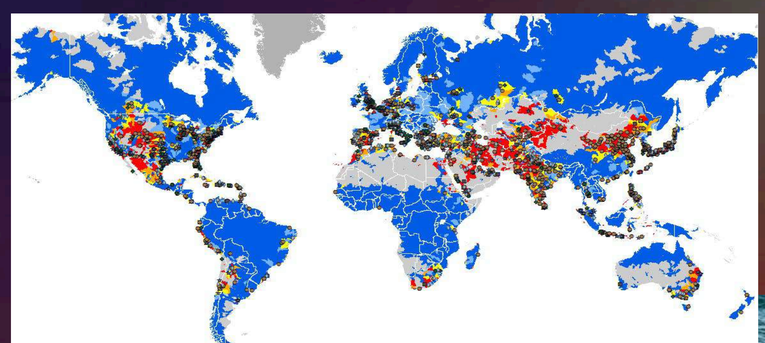
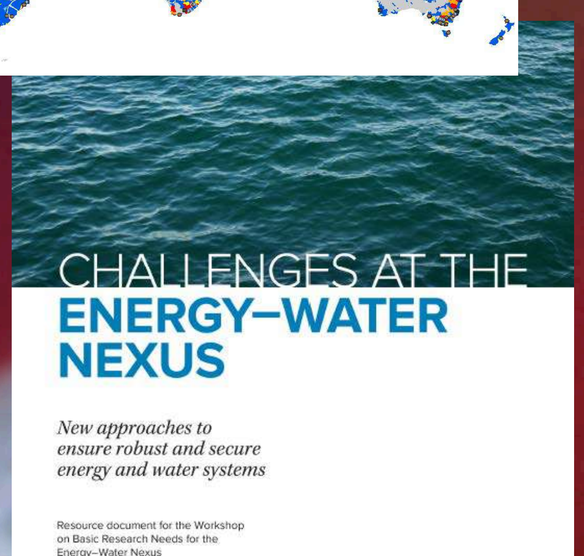










Materials Research Society
MRS ENERGY & SUSTAINABILITY
A Review Journal

The takeway messages:

- *Outlook for energy utilization in the U.S. and the world – costs are down, carbon is up, we'll need more water!!*
- *Solutions to the Energy/Water/Food Nexus problems need to be modular, distributed, and cheap!*
- *Solutions in developed countries may not apply in less-developed regions of the world? Or maybe they will?*

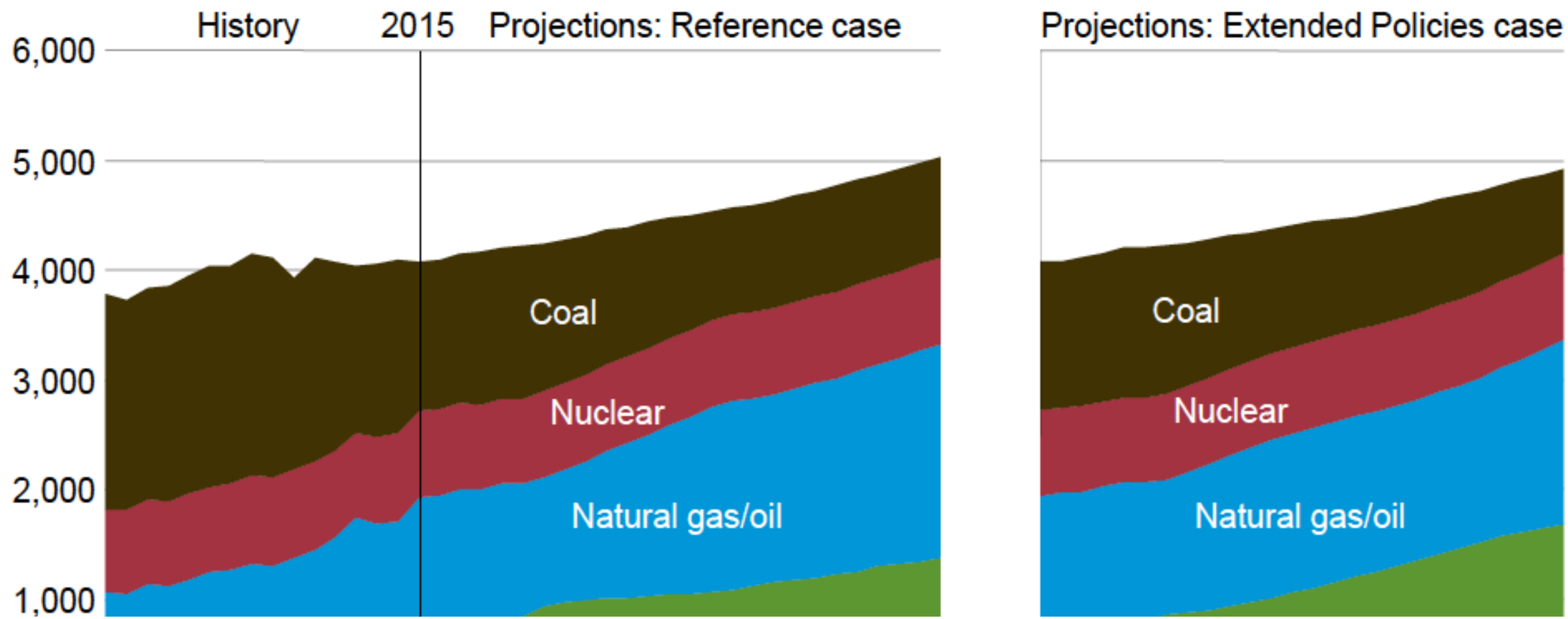
What is the Problem? – Energy/Water/(Food) Nexus: – Connections between Energy, Water (and Food) – in the U.S. – a pretty sobering assessment

Annual Energy Outlook 2016

with projections to 2040

Independent Statistics & Analysis
U.S. Energy Information Administration

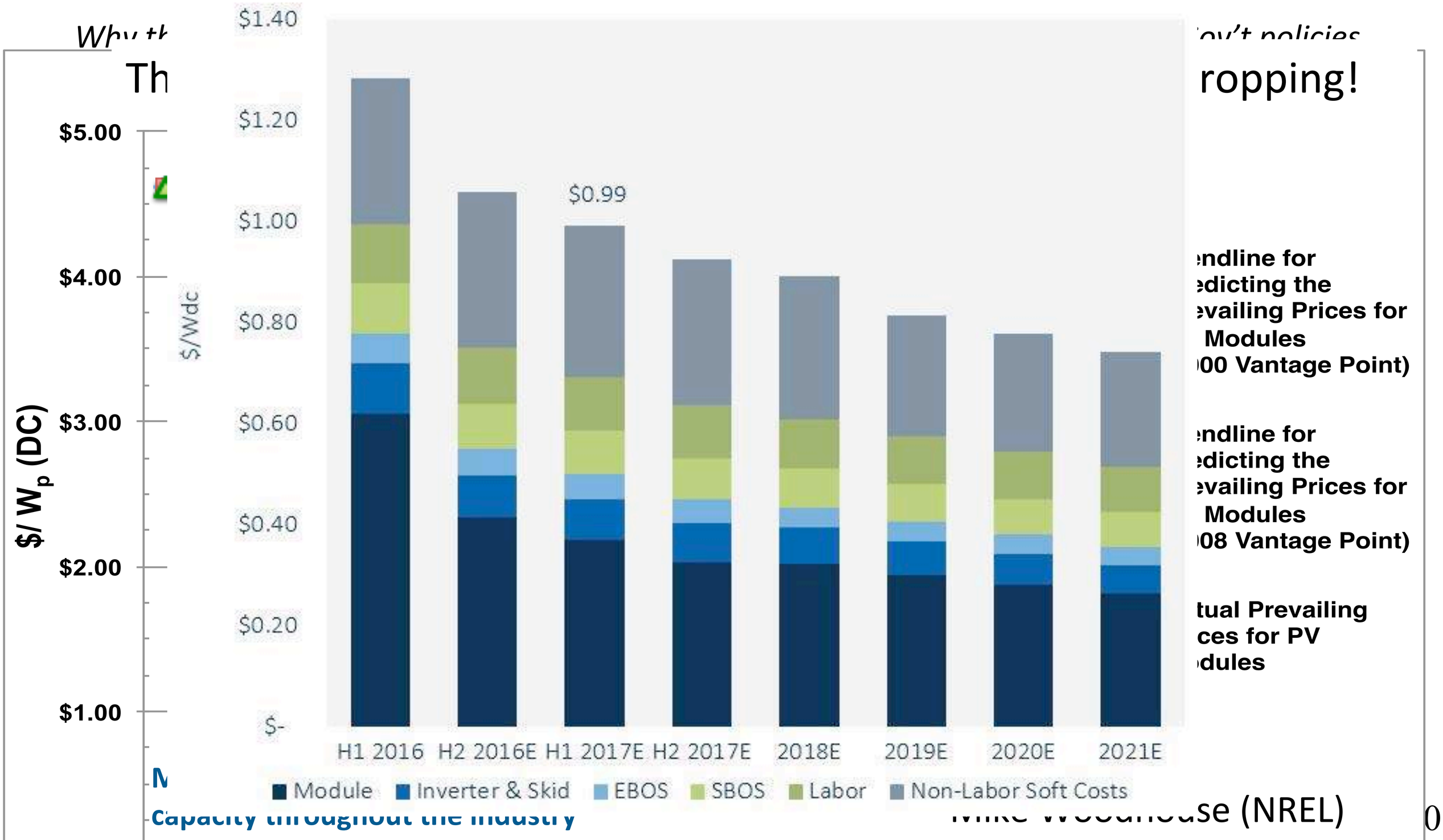
What is the Problem? – Energy/Water/(Food) Nexus: – Connections between Energy, Water (and Food) – in the U.S. – a pretty sobering assessment



- We are using more energy all the time – lots of it from fossil fuels
- Whether you believe this is associated with climate variability or not – it's likely to get hotter, drier (in places like SW U.S. and Mexico) – and these energy estimates may be low, since we haven't really factored in situational scarcities in water (food)

Why th ... ov't policies

Th ... ropping!



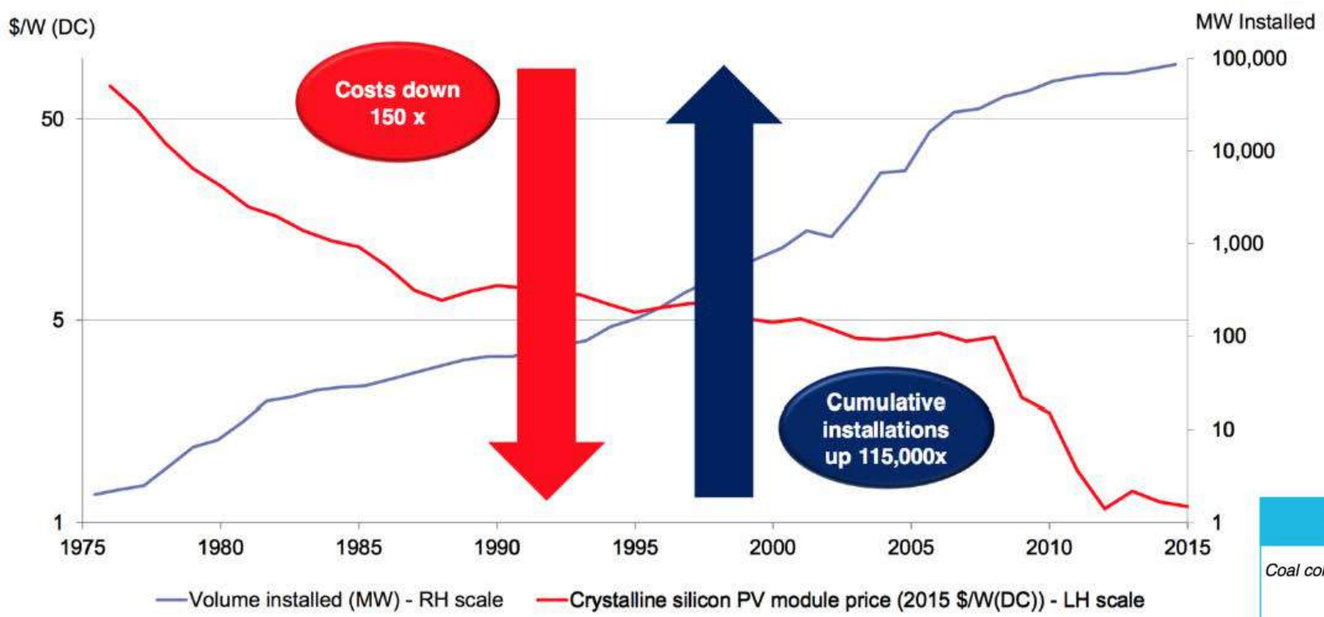
U.S. Utility PV Fixed-Tilt Turnkey EPC System Pricing, H1 2016-2021E ($/Wdc)

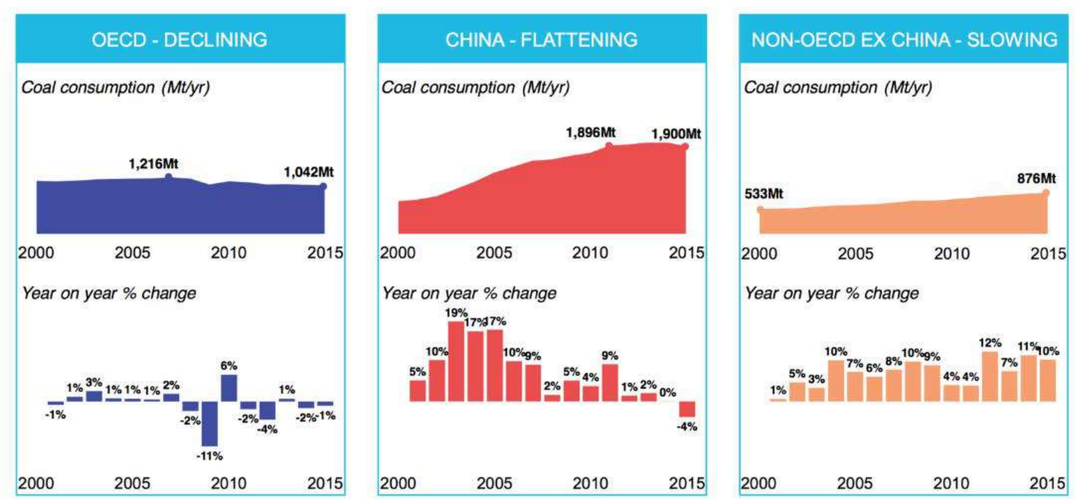
https://www.greentechmedia.com/articles/read/10-Solar-Trends-to-Watch-in-2017

Wind and Solar Are Crushing Fossil Fuels

https://www.bloomberg.com/news/articles/2016-04-06/wind-and-sol...

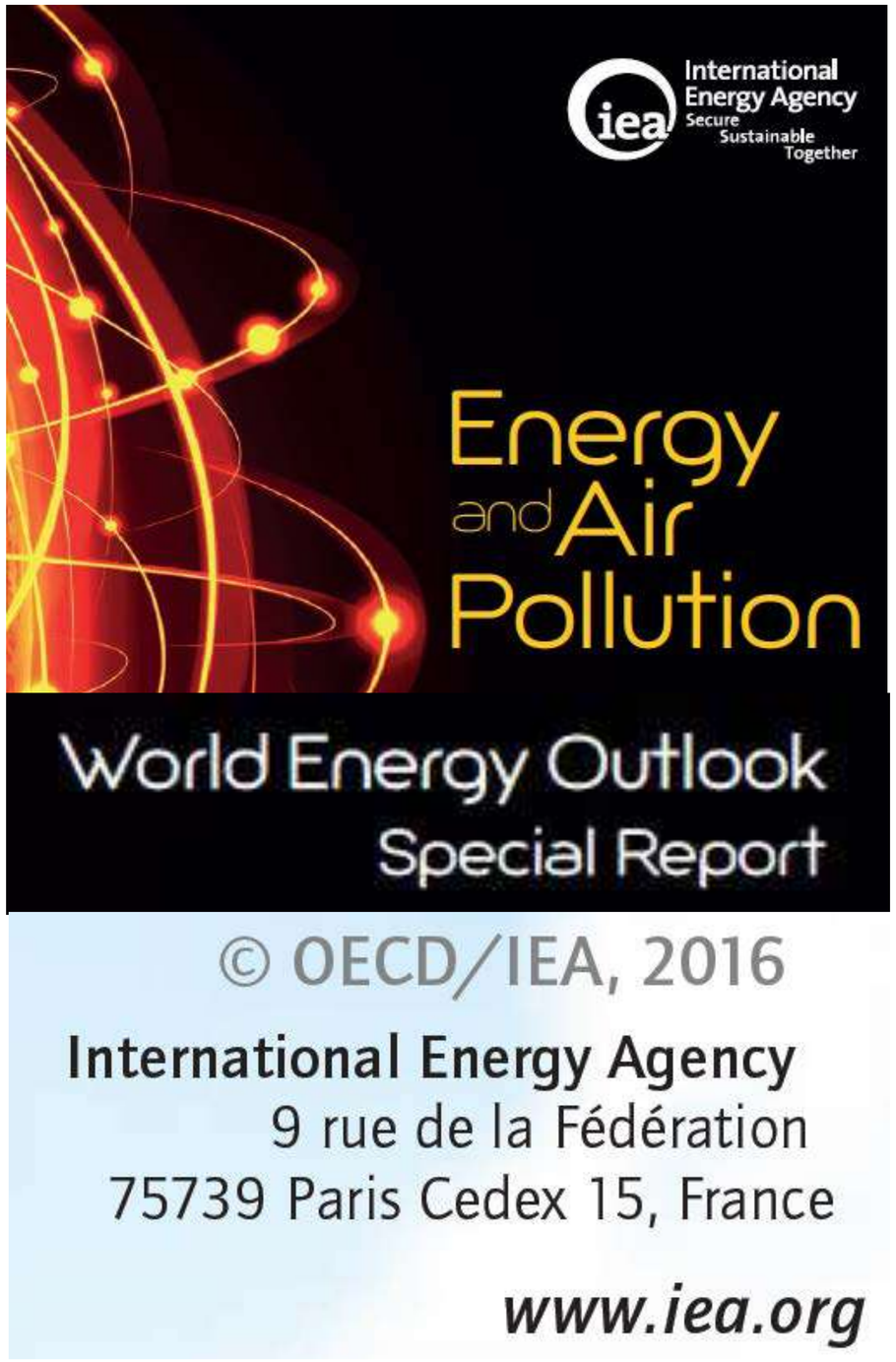
Record clean energy investment outpaces gas and coal 2 to 1.





Coal phases out in wealthier countries first

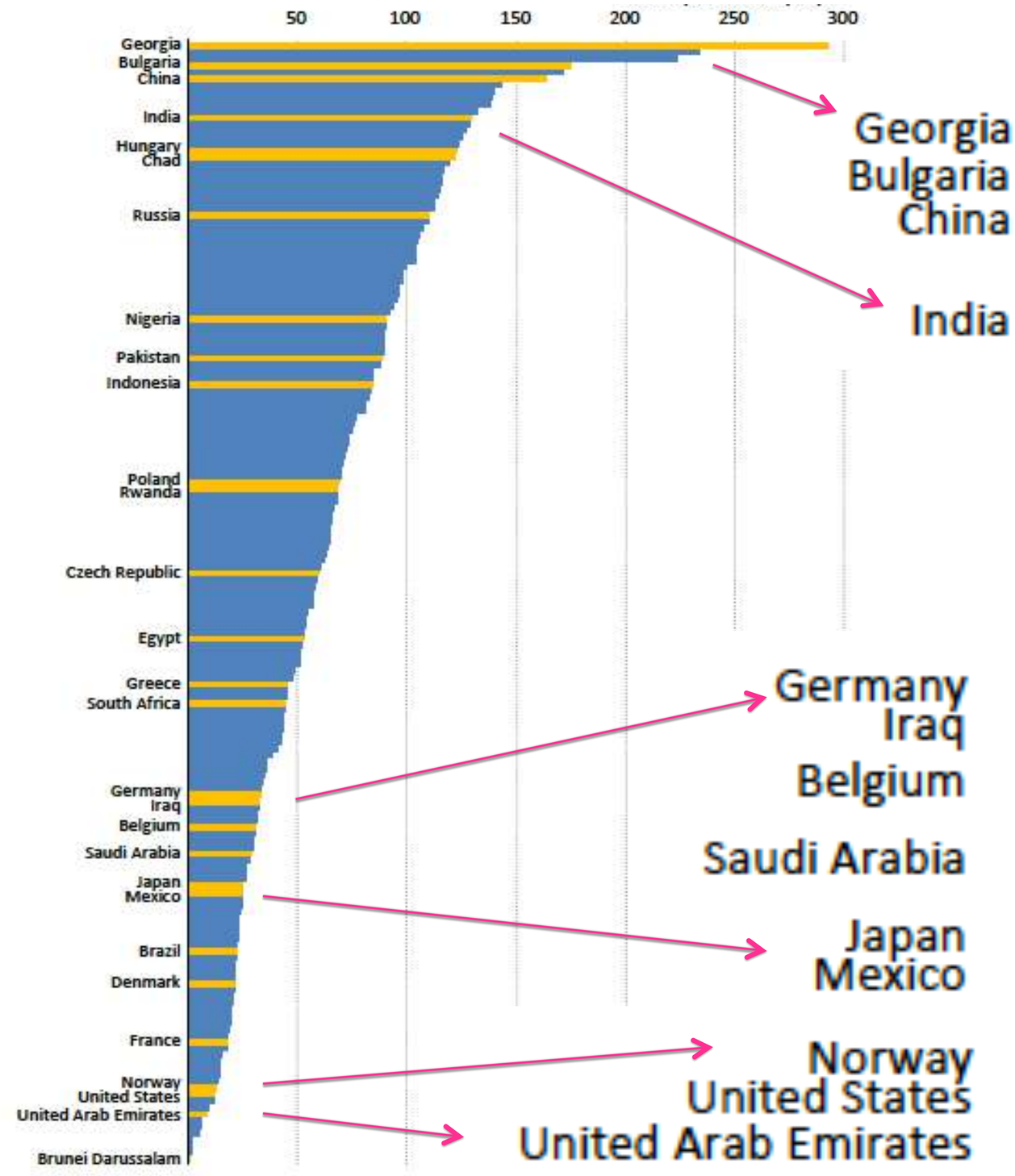
Mortality rate attributed to air pollution (household ar
outdoor) by country, 2012



https://www.iea.org/publications/freepublications/publication/
WorldEnergyOutlookSpecialReport2016EnergyandAirPollution.pdf

"Social Justice" and Health are linked to these problems

Deaths per 100,000 people



Renewable energy – cheap, clean?

Silicon solar cells – they work well, live long – cost less all the time, but…….

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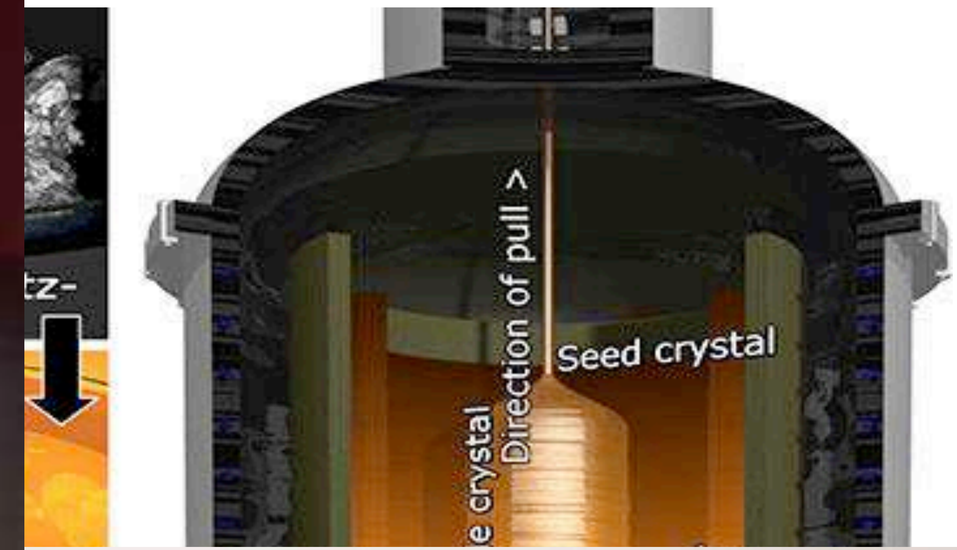
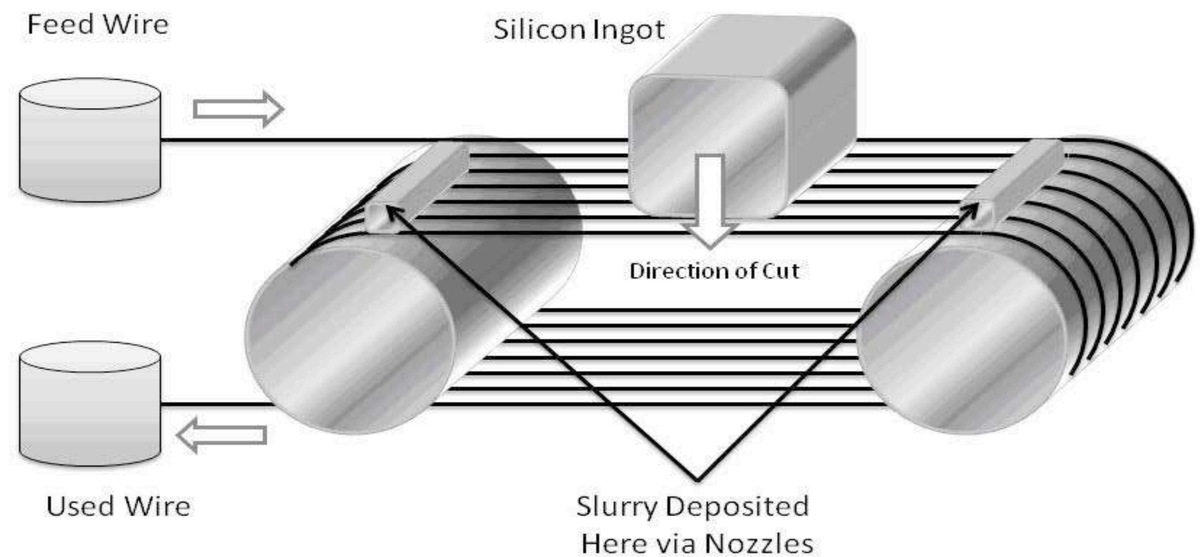


And get more expensive

“poly-silicon” somewhat cheaper, works well, but we still need to “slice” into wafers



Best Research-Cell Efficiencies

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Multijunction Cells (2-terminal, monolithic)
- **LM =** lattice matched
- **MM =** metamorphic
- **IMM =** inverted, metamorphic
- Three-junction (concentrator)
- Three-junction (non-concentrator)
- Two-junction (concentrator)
- Two-junction (non-concentrator)
- Four-junction or more (concentrator)
- Four-junction or more (non-concentrator)

Single-Junction GaAs
- Single crystal
- Concentrator
- Thin-film crystal

Crystalline Si Cells
- Single crystal (concentrator)
- Single crystal (non-concentrator)
- Multicrystalline
- Silicon heterostructures (HIT)
- Thin-film crystal

Thin-Film Technologies
- CIGS (concentrator)
- CIGS
- CdTe
- Amorphous Si:H (stabilized)

Emerging PV
- Dye-sensitized cells
- Perovskite cells (not stabilized)
- Organic cells (various types)
- Organic tandem cells
- Inorganic cells (CZTSSe)
- Quantum dot cells

Higher efficiencies = lower energy costs!

Efficiency (%)

0, 4, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48, 50

1975, 2005, 2010, 2015

Sharp (IMM, 302x)
Soitec (4-J, 297x)
Fraunhofer ISE/ Soitec 46.0%
NREL 44.4%
Boeing-Spectrolab (LM, 364x)
Solar Junction (LM, 942x)
Spectrolab (MM, 299x)
Fraunhofer ISE (MM, 454x)
Spire Semiconductor (MM, 406x)
Boeing-Spectrolab (MM,179x)
Boeing-Spectrolab (MM, 240x)
Soitec (4-J, 319x)
NREL (4-J, 327x)
NREL (IMM)
NREL
NREL (IMM, 325.7x)
Solar Junction (LM, 418x)
Boeing-Spectrolab (5-J) 38.8%
Sharp (IMM) 37.9%
Boeing-Spectrolab
Boeing-Spectrolab
Sharp (IMM)
Sharp (IMM)
Spectrolab
Boeing-Spectrolab
NREL (IMM)
NREL/ Spectrolab
Spectrolab
Spectrolab
FhG-ISE
NREL (467x) 34.1%
NREL
NREL
Japan Energy
IES-UPM (1026x)
FhG-ISE (117x)
NREL 31.1%
Alta Devices
Alta Devices
Radboud U.
FhG-ISE (232x)
Amonix (92x)
Panasonic
LG Electronics 29.1% 28.8%
(205x)
SunPower (96x)
Stanford (140x)
Kopin
Varian
Spire
Radboud U.
FhG-ISE
Alta Devices
Panasonic
SunPower (large-area) 27.6% 27.5%
UNSW
UNSW
UNSW
Panasonic
NREL (14.7x) 25.6% 25.0%
IBM (T.J. Watson Research Center)
UNSW
Stanford
UNSW
UNSW
FhG-ISE
Sanyo
Sanyo
Sanyo
Sanyo
NREL (15.4x)
Solexel 23.3%
ZSW 21.7%
First Solar 21.5%
ARCO
Westing-house
Spire
Varian
UNSW
Georgia Tech
Georgia Tech
Georgia Tech
Sanyo
ZSW
EMPA (Flex poly)
NREL
Trina Solar 21.2%
Solibro 20.8%
KRICT 20.1%
Sandia
RCA
Mobil Solar
No. Carolina State U.
Solarex
Solarex
U. So. Florida
NREL
NREL
NREL
NREL
ISFH
Solexel
U. Stuttgart
Fraunhofer ISE
Solar Frontier
GE Global Research
First Solar
Matsushita
NREL
U. Stuttgart
First Solar
GE Global Research
KRICT
Euro-CIS
Boeing
Boeing
Kodak
Kodak
Kodak
ARCO
ARCO
Photon Energy
Boeing
United Solar
United Solar
Electronics
EPFL
AIST 13.6%
Hong Kong UST 12.6%
Sharp
IBM 11.9%
NIMS
Sharp
IBM
IBM
IBM
UCLA-Sumitomo Chem. 11.5%
Matsushita
Kodak
Boeing
Boeing
AMETEK
EPFL
Heliatek
Konarka
UCLA
U. Toronto 10.6%
U. Toronto
U.of Maine
Monosolar
Solarex
ARCO
United Solar
EPFL
Solarmer
Konarka
Sumi-tomo
MIT
U.of Maine
Boeing
RCA
EPFL
EPFL
NREL / Konarka
U. Linz
Groningen
Siemens
Plextronics
Heliatek
U. Toronto (PbS-QD) 9.9%
U. Linz
U. Linz
U. Dresden
NREL (ZnO/PbS-QD)
RCA
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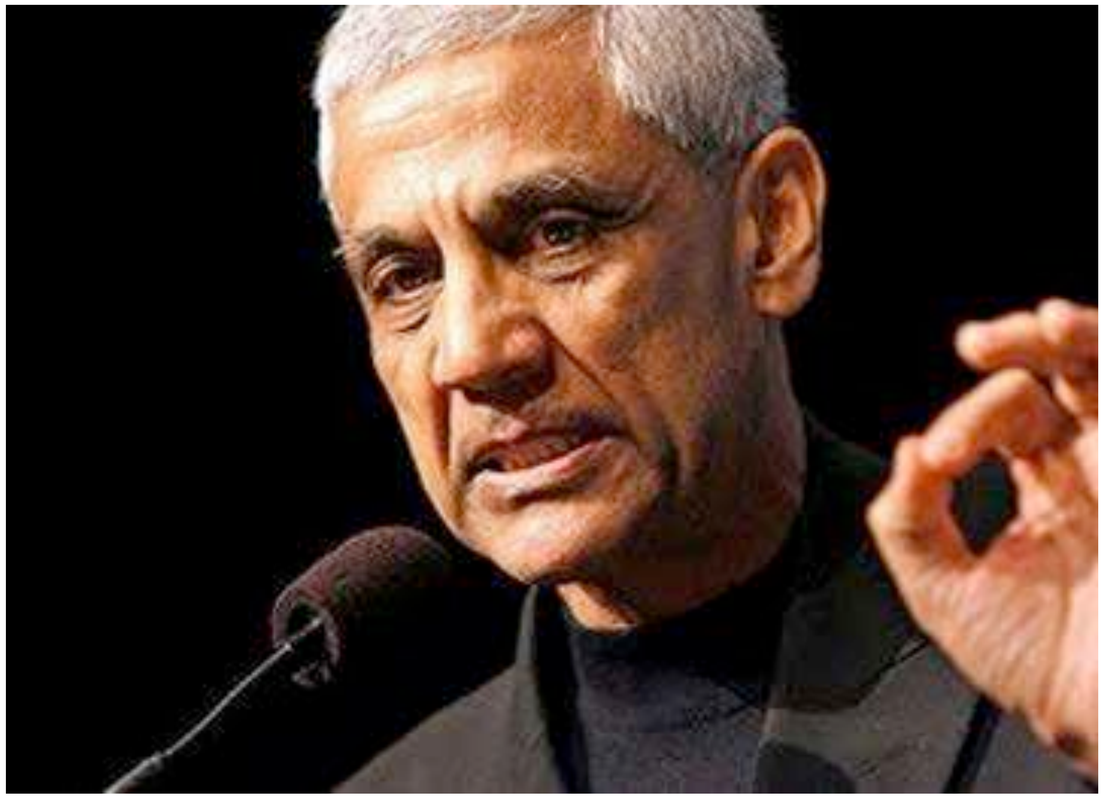
(Rev. 08-06-2015)

"Power Conversion Efficiencies"

Vinod Khosla Slaps Green Energy Technologies With Some Tough Love:



"The world cannot simply conserve its way out of the current environmental and energy crises >> We must create technology alternatives that are Both affordable and widely accepted

5 billion people are coveting the energy-rich lifestyles currently enjoyed by 500 million people in the developed world

Incremental technology progress will not satisfy this craving >> nonlinear jumps in technologies -- **"Technological Black Swans! "**

"Black Swans" are technologies that are market competitive without subsidies, once scaled, and hit the Chindia price point (the price at which people in India and China will willingly purchase without subsidy) while providing sufficient scale to have measureable impact."

Cheaper solar electric energy

First Solar.

“Thin Film PV” CdTe

GLOBAL SOLAR
A COMPANY OF
Hanergy

“Thin Film PV” -- (CIGS – Copper-Indium-Gallium-Selenide

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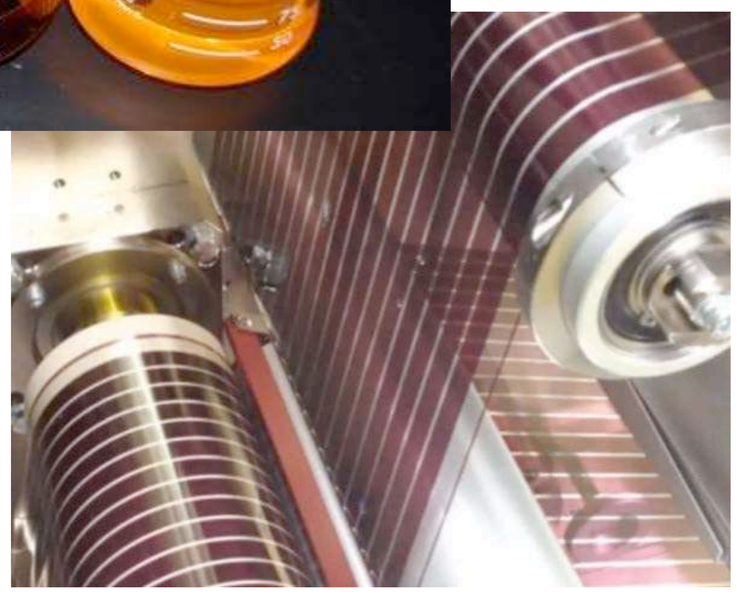
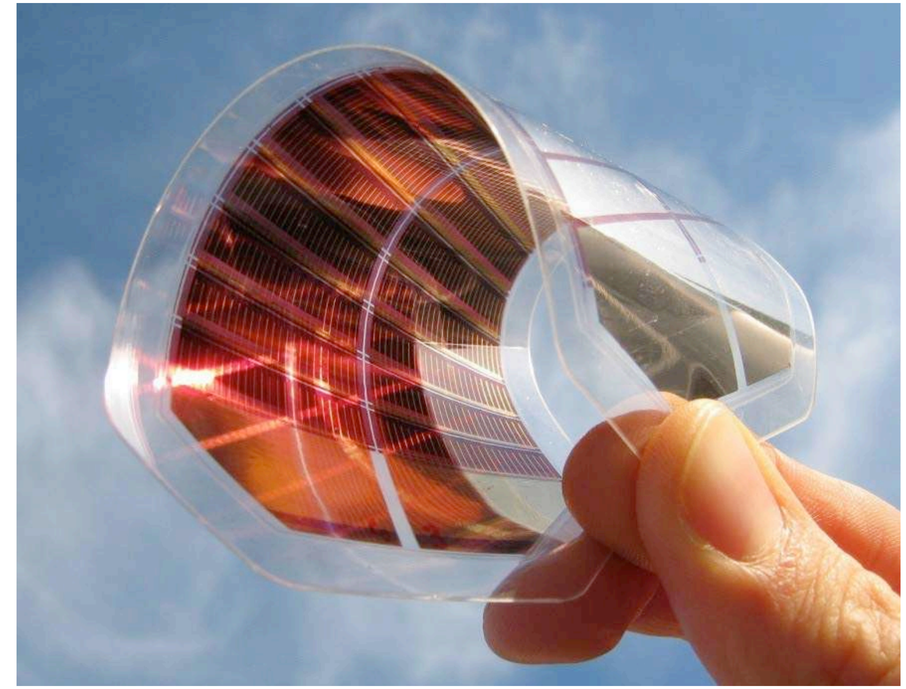
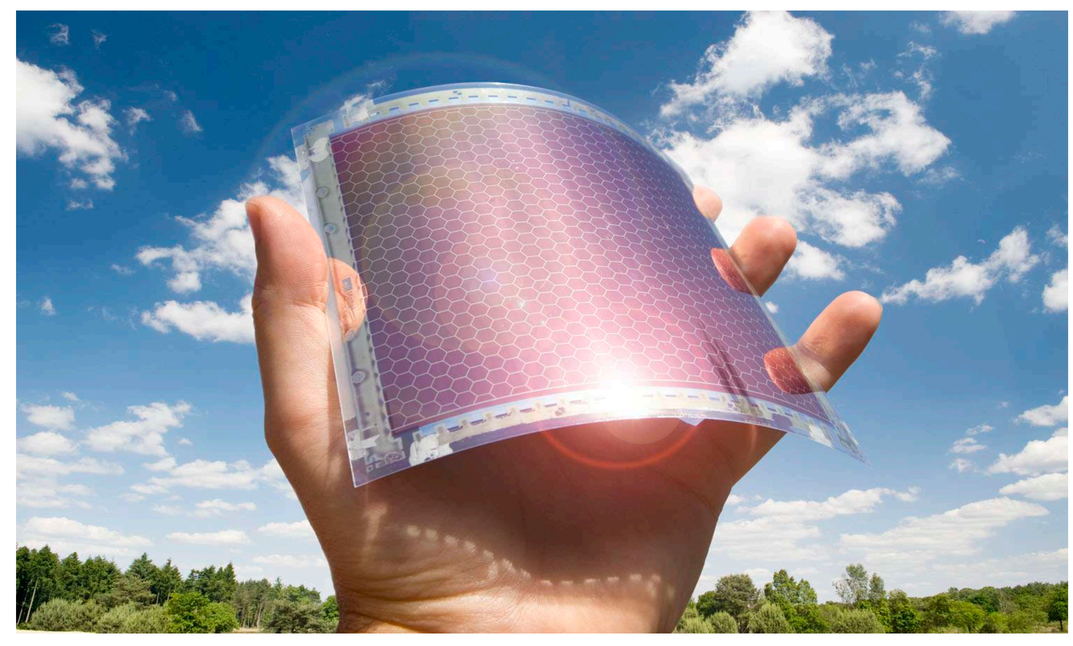
Black ish, but NOT swans!

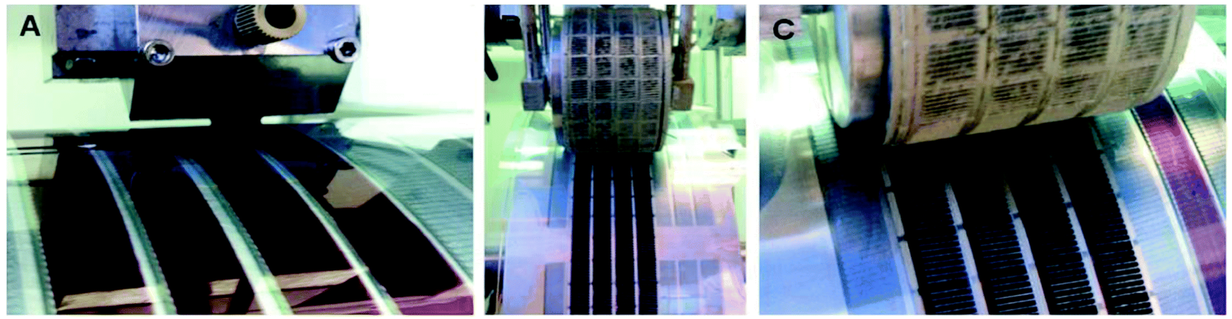
Paper-thin printed solar cells could provide power for 1.3 billion people -- http://inhabitat.com/paper-thin-printed-solar-cells-could-provide-power-for-1-3-billion/



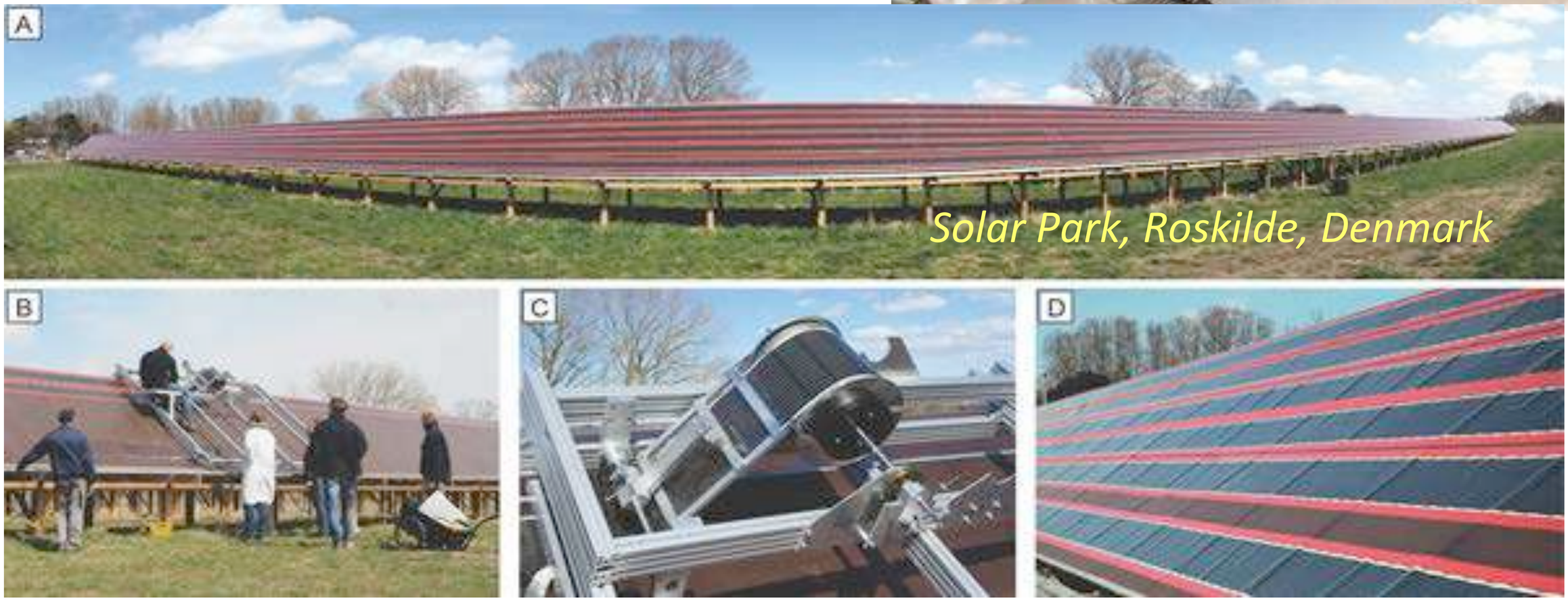


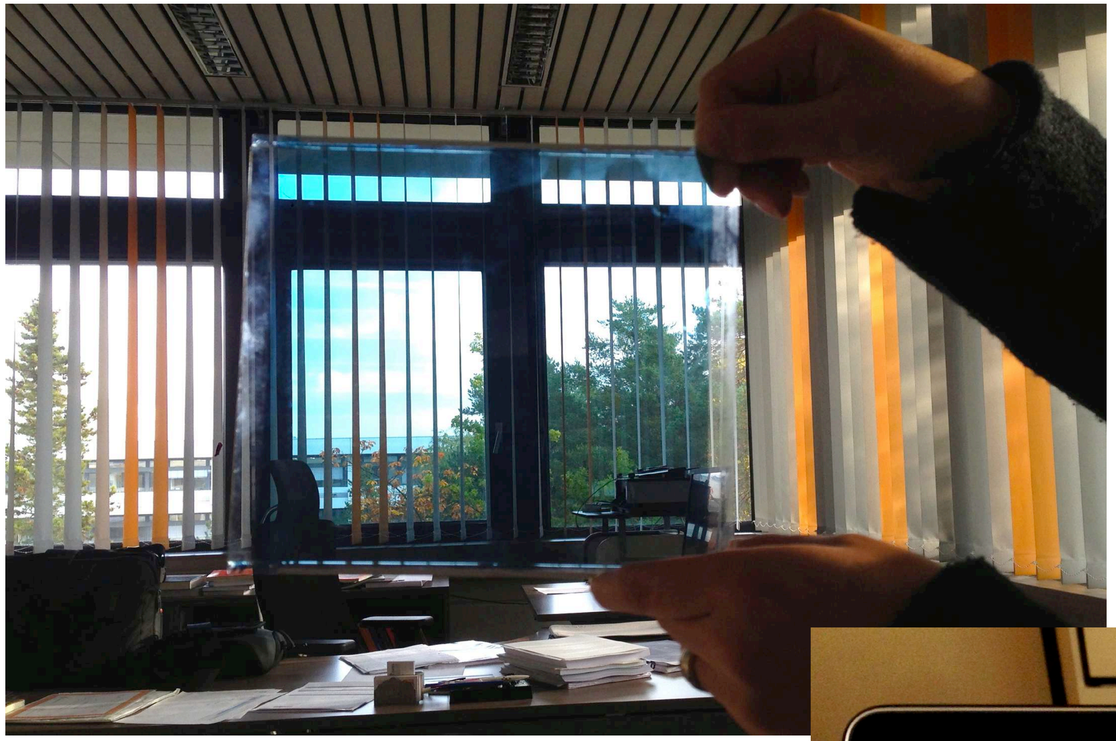


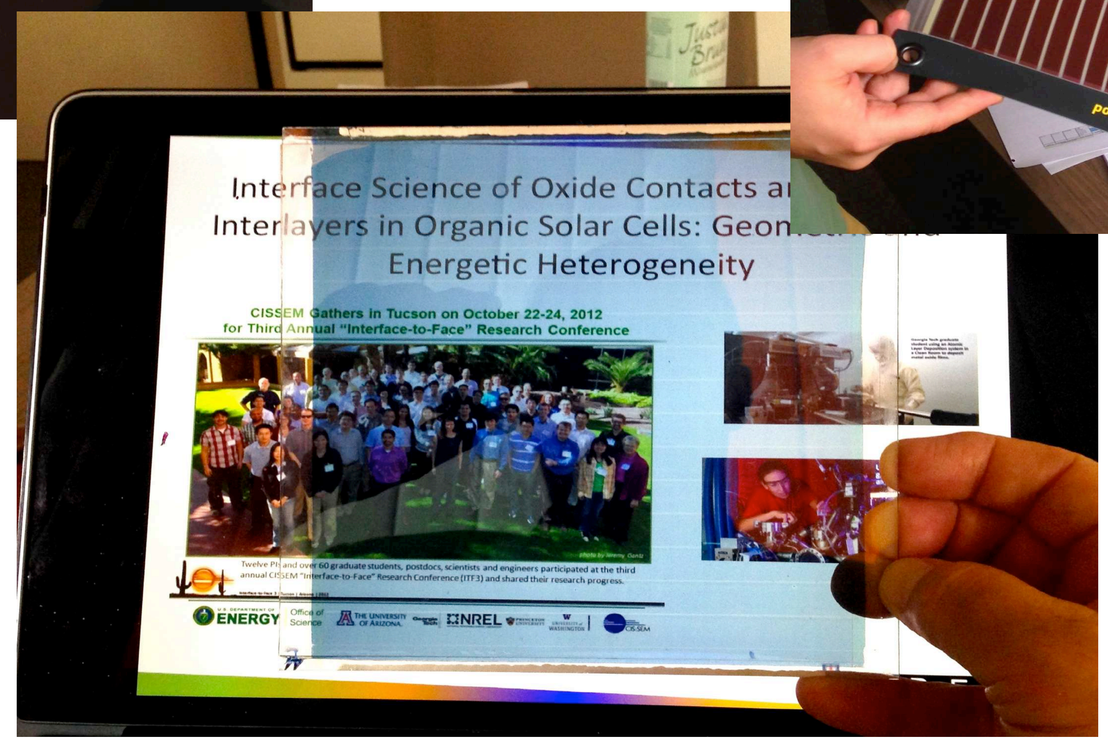
New classes of PV materials – "printable"



The potential payoff
Denmark, Germany, France, ...





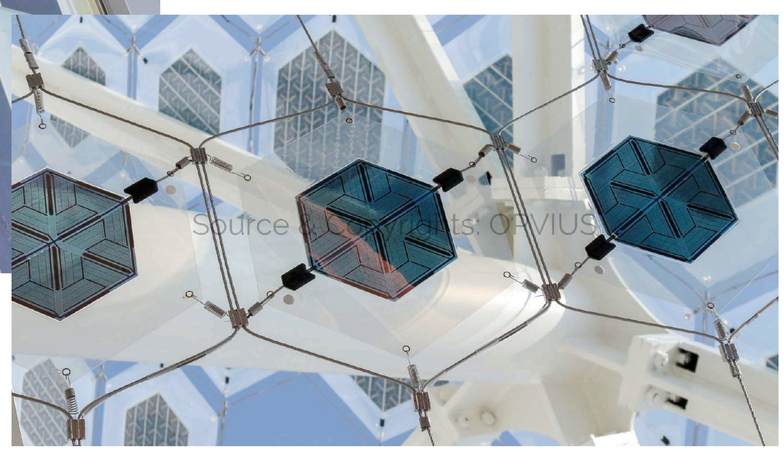


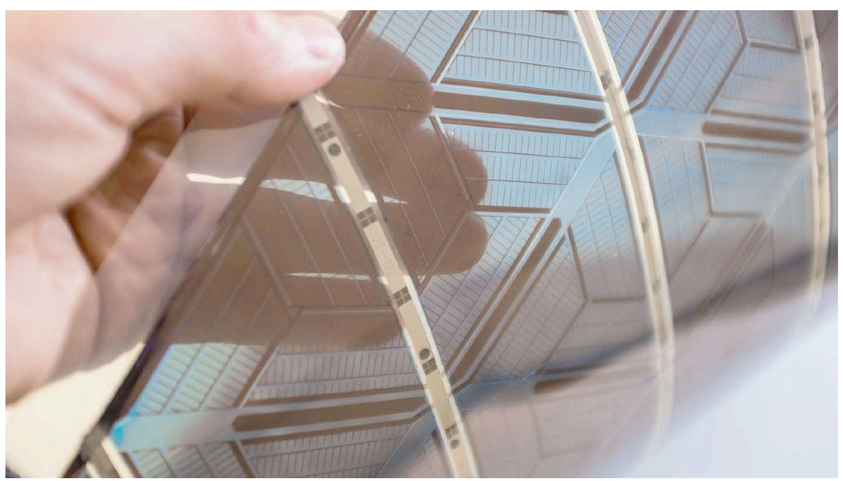
Christoph Brabec et al.
Erlangen, Germany –
semitransparent solar
cells – in glass

Institute Materials for Electronics and Energy Technology

https://www.i-meet.ww.uni-erlangen.de/

First installations, Building Integrated PV from OPVIUS



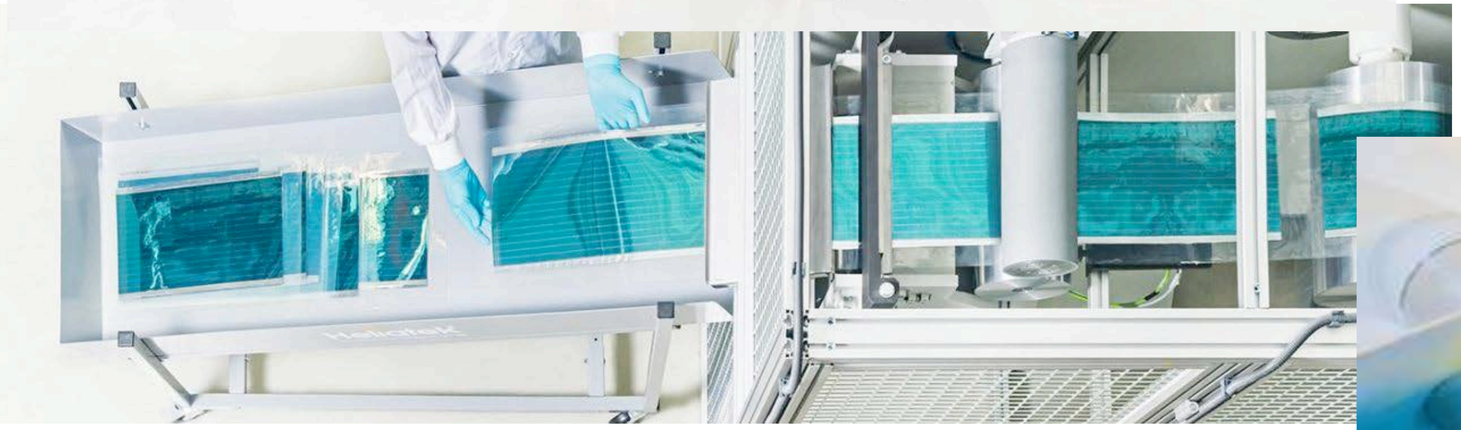


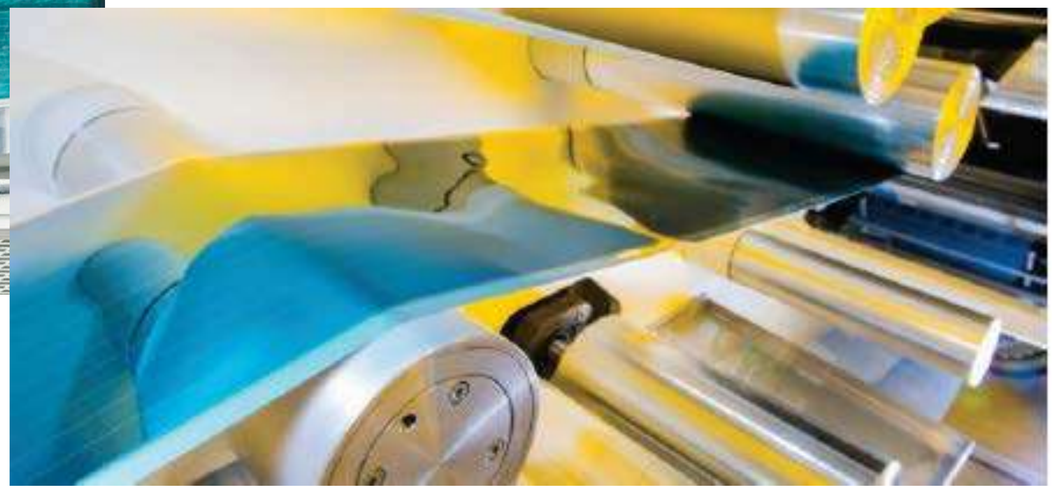
http://www.opvius.com/

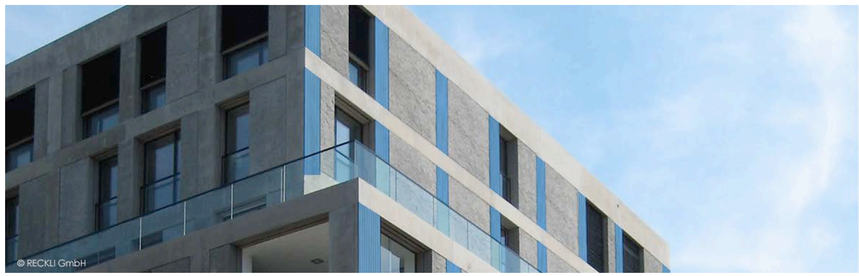
Heliatek®

The future is light

Dresden, Germany

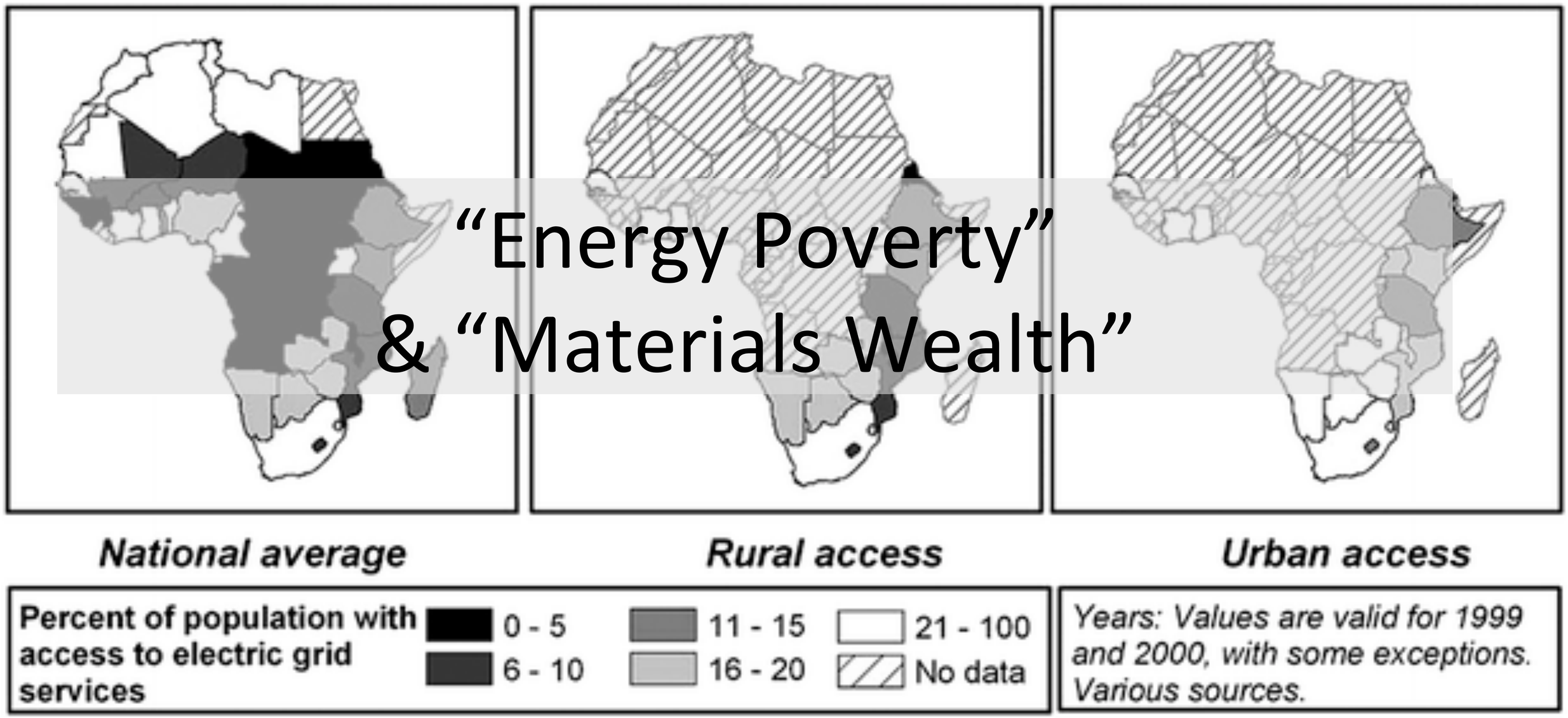




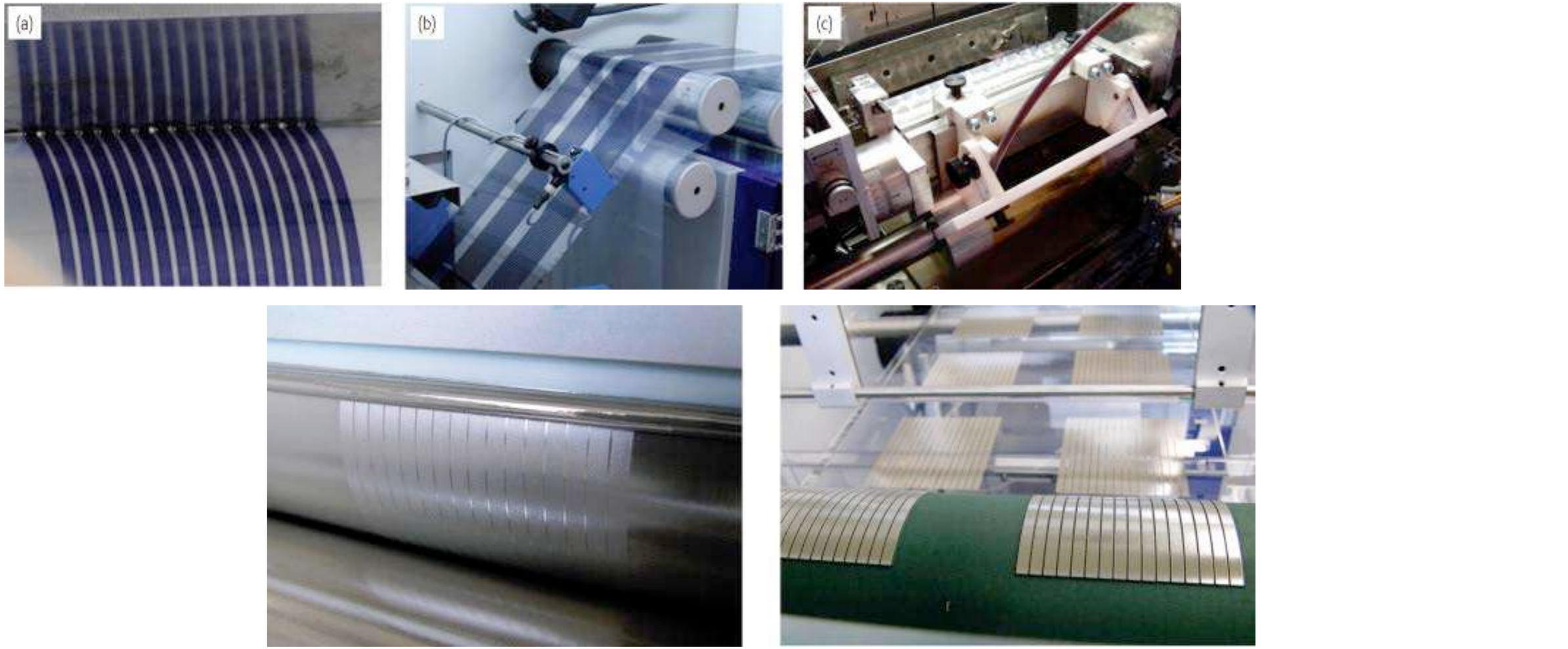


http://www.heliatek.com/en/

Manufacture, integration and demonstration of polymer solar cells in a lamp for the “Lighting Africa” initiative -- Energy Environ. Sci., 2010, **3**, 512-525
Frederik C. Krebs et al.

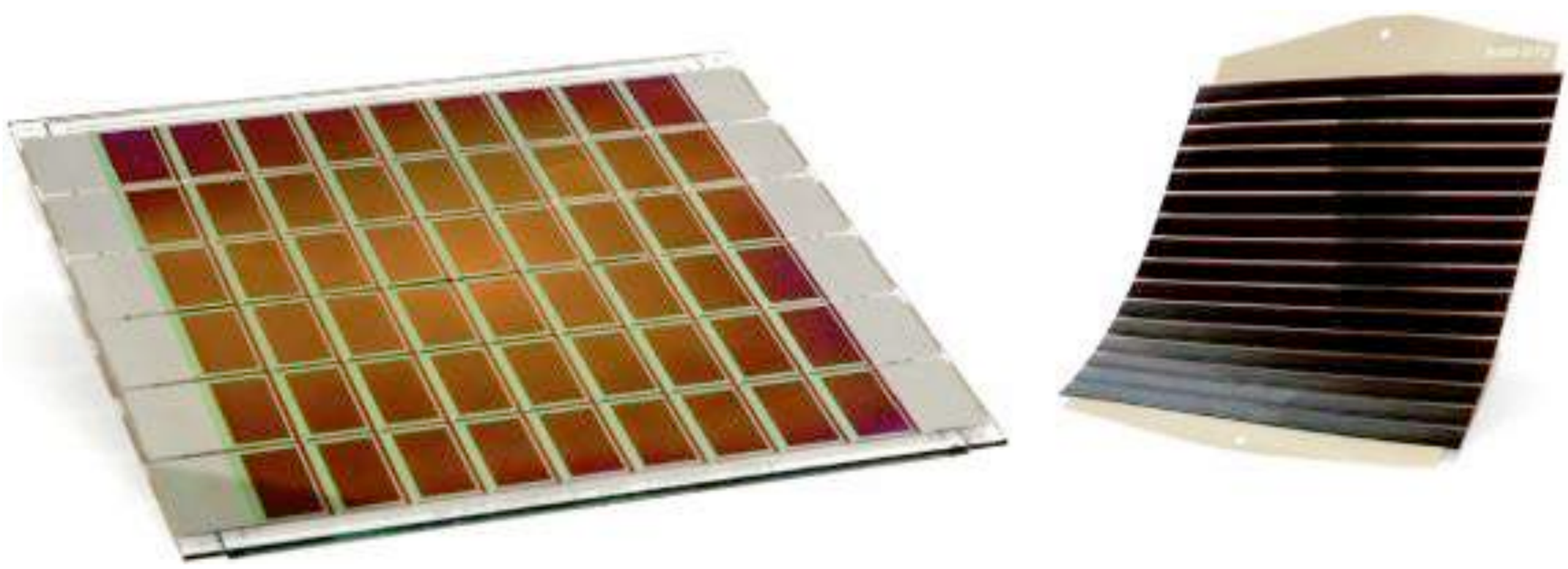


“Energy Poverty”
& “Materials Wealth”



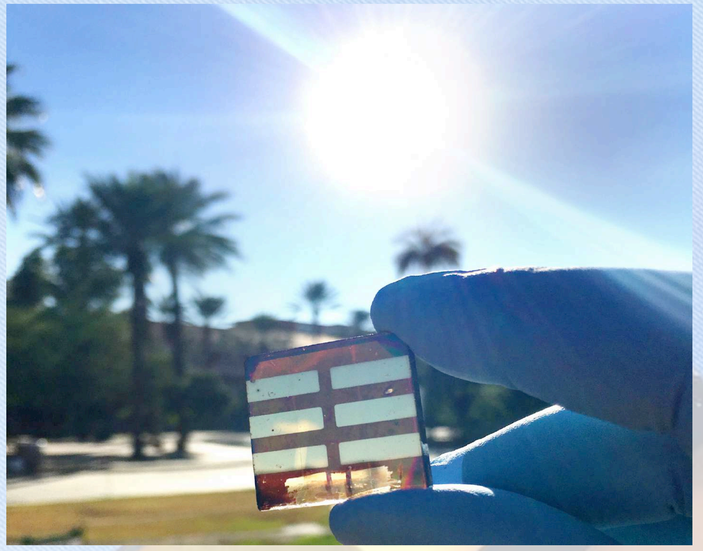
Krebs and coworkers:

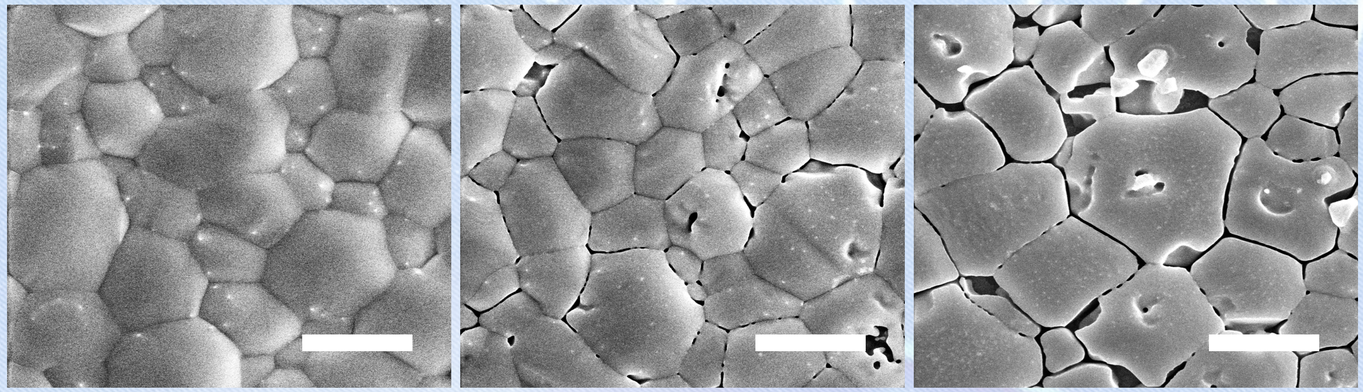
Materials Today
Volume 15, Issues 1–2,
January–February
2012, Pages 36–49



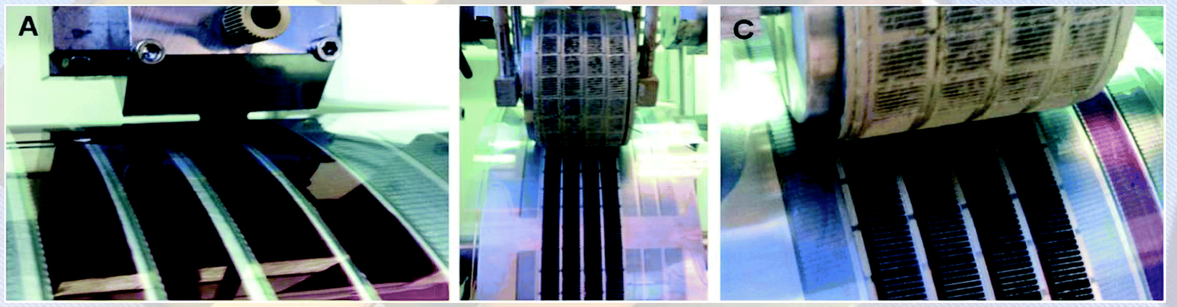
Emerging “Printed” Solar Cell Technologies: Perovskite Solar Cells

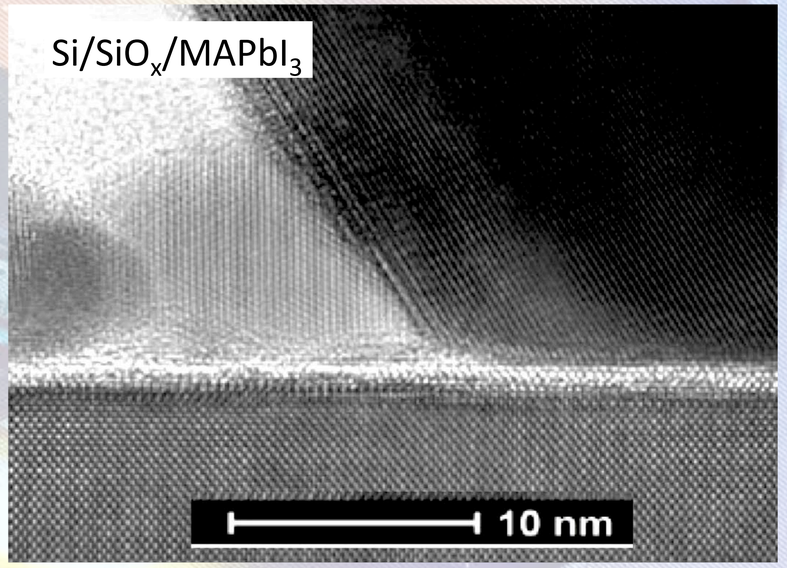
Clayton Shallcross, S. Scott Saavedra, N.R. Armstrong et al?





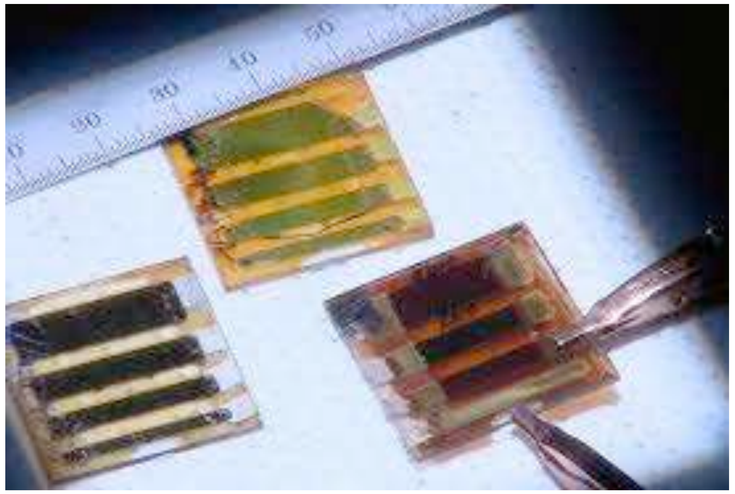
Clayton Shallcross et al.:
J. Amer.Chem. Soc. 2017





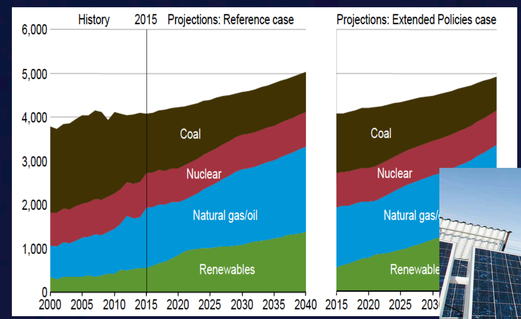
Arizona Board of Regents – Research Innovation Fund

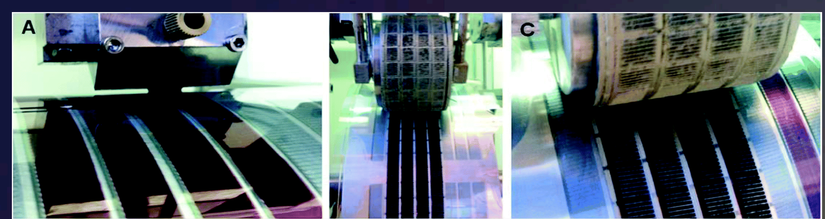
Low-cost solar cells poised for commercial breakthrough - Science -- Dec. 7, 2016

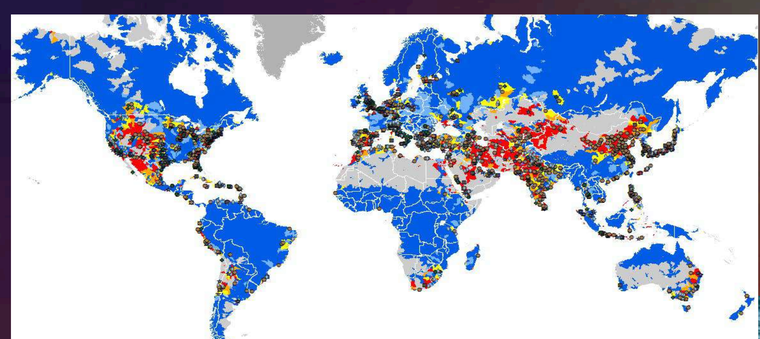


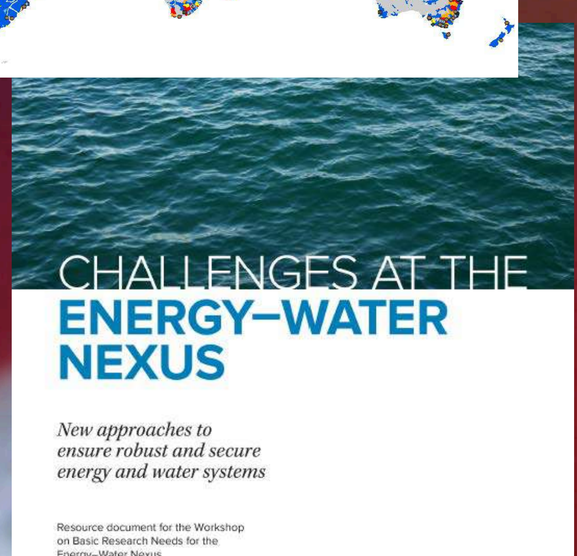
SOLAR CELL TYPE	RECORD EFFICIENCY (%)
Silicon (single crystal)	25.3
Perovskite-perovskite (2T)	17
Perovskite-perovskite (4T)	20.3
Silicon-perovskite (2T)	23.6
Silicon-perovskite (4T)	25.2

Michael McGehee
Stanford









The takeway messages:

- *Outlook for energy utilization in the U.S. and the world – costs are down, carbon is up, we'll need more water!!*
- *Solutions to the Energy/Water/Food Nexus problems need to be modular, distributed, and cheap!*
- *Solutions in developed countries may not apply in less-developed regions of the world? Or maybe they will?*

Global Interest in the Water-Energy Nexus (from the DOE quadrennial review – courtesy Mike Knotek)

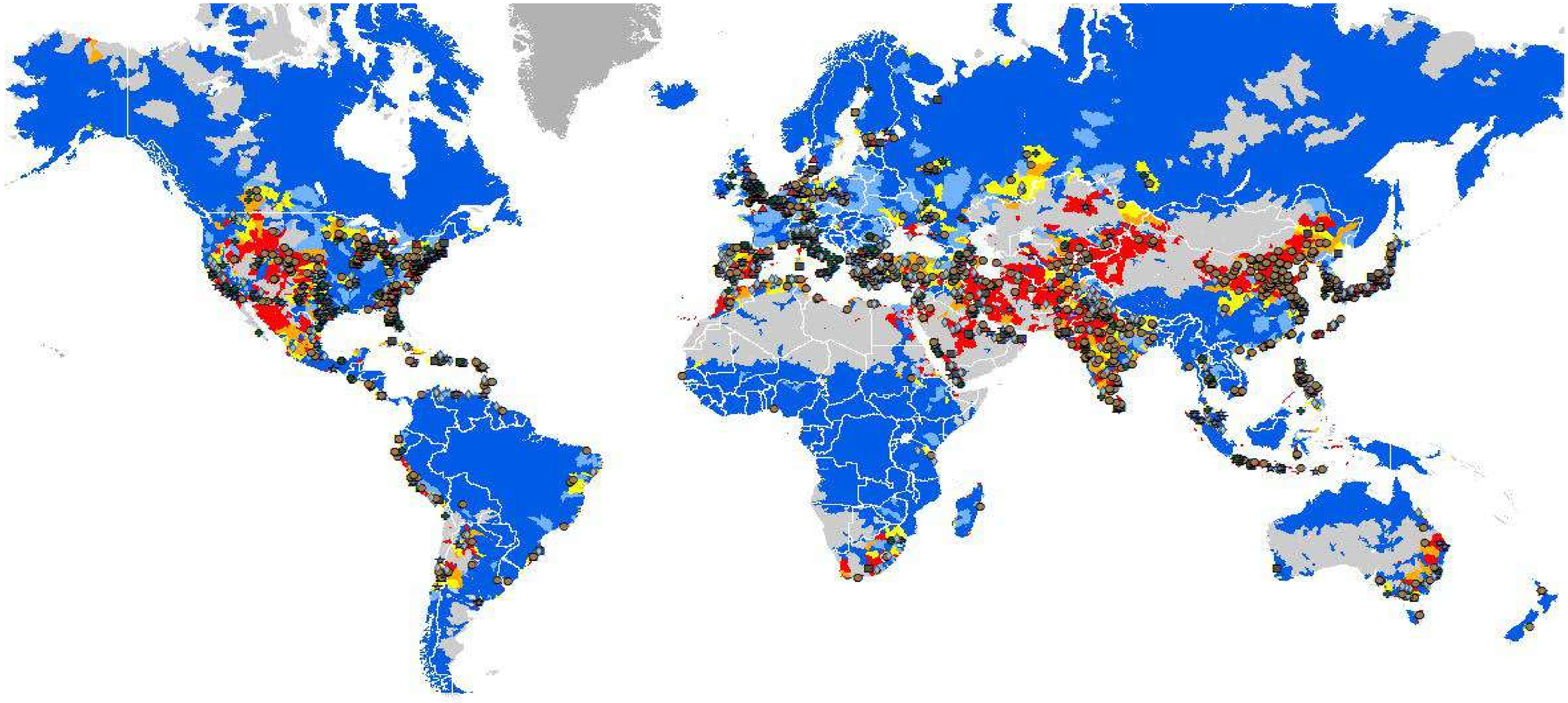


Figure 2 -- Global Generation Units with Water Stress -- yellow, orange, and red correspond with medium, high, to extremely high stress levels (from: "Resilience: Global Imperatives for 2013 and Beyond" -- Peter C. Evans, PhD, Vice President at Center for Global Enterprise, General Electric);
see also: http://www.ncac-usaee.org/pdfs/2013_04Aponte.pdf Notes: Includes thermal and hydro plants. For visualization purposes, plants with design capacity less than 100 MW are not shown. Source: Platts UDI Database 2012 and WRI Aqueduct data. Over 26,000 units are in areas of medium to extremely-high water stress

What is the Problem? – Energy/Water/(Food) Nexus: – It takes lots of water to make (conventional) energy

Water and Energy Interactions

Annu. Rev. Environ. Resour. 2011. 36:163–91

James E. McMahon and Sarah K. Price

Table 4 Water consumption per megawatt-hour for electricity generation[a]

Generation source	Liters/megawatt-hour		Gallons/megawatt-hour	
	Raw materials[b]	Transformation	Raw materials	Transformation
Wind		Minimal		Minimal
Photovoltaic		Minimal		Minimal
Thermoelectric fuels		Closed loop: 720–2,700		Closed loop: 190–720
Coal	20–270		5–70	
Oil, natural gas	Variable		Variable	
Uranium	170–570		45–150	
Concentrating solar		2,800–3,500		750–920
Geothermal		5,300		1,400
Hydroelectric		Evaporative losses: 17,000 (average)		Evaporative losses: 4,500 (average)

The higher up the food chain you eat, the more water it takes to produce your food

The Nexus of Food, Energy, and Water

John W. Finley*,† and James N. Seiber§

Table 5. Water Requirements for Food Commodities[27]

product	unit	equivalent water (m^3/unit)
cattle	head	4000
sheep and goats	head	500
fresh beef	kg	15
fresh lamb	kg	10
fresh poultry	kg	6
cereals	kg	1.5
citrus fruits	kg	1
palm oil	kg	2
pulses, roots, and tubers	kg	1

Table 6. Water Requirements for Processed Foods[27]

product	quantity	equivalent water (L)
glass of beer	250 mL	75
glass of wine	125 mL	120
glass of milk	200 mL	200
glass of apple juice	200 mL	190
cup of coffee	125 mL	140
glass of orange juice	200 mL	170
cup of tea	250 mL	35
bag of chips	200 g	185
slice of bread	30 g	40
egg	40 g	135
slice of bread with cheese	30 g + 10 g	90
hamburger	150 g	2400
potato	100 g	25
tomato	70 g	13
apple	100 g	70
orange	100 g	50

Table 9. Energy Required To Produce 1 lb of Various Foods[30]

food	energy (kWh) to produce 1 lb
corn	0.43
milk	0.75
apples	1.67
eggs	4
chicken	4.4
cheese	6.75
pork	12.6
beef	31.5

JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

J. Agric. Food Chem. 2014, 62, 6255−6262

Our unique "local" situational scarcity

Situational scarcity

Situational

Co-location of systems

Integrated planning

Right Sourcing Resources

"The (California) State Water Project pumps water 2,000 feet OVER the Tehachapi Mountains —
the highest lift of any water system in the world."

"Energy used to deliver that water to Southern California is equivalent to approximately one-third of the total average household electric use in the region." – "Energy Down the Drain," NRDC Report 2004

Similar claims can be made for the CAP project in Arizona, to bring water to Phoenix and Tucson.

NRDC
THE EARTH'S BEST DEFENSE

ENERGY DOWN THE DRAIN

The Hidden Costs of California's Water Supply

https://www.nrdc.org/sites/default/files/edrain.pdf

TRANSPORTING WATER IS MORE COSTLY (IN ENERGY AND CARBON FOOTPRINT), THAN PURIFICATION

And yet, we maintain a vibrant agricultural industry in the same states:
Yuma, Arizona (region) & Imperial Valley, CA:

Home to 70-90% of winter vegetables in the U.S., and LOTS of millionaires!!

Navajo Generating plant 3x 750 MW generators:

- Provides more than 90% of the power CAP needs to deliver water to Phoenix/ Tucson
- Consuming half gallon of (pumped) water per kilowatt hour of generated electricity
- 8M tons of coal, and 28M gallons of water producing 2,250 mWh of electricity
- Thirteenth largest producer of greenhouse gases in the U.S.: greater than 19M tons of CO_2 per year
- Replaced by gas-fired power plants in Central AZ – using what source of water?
- Economic impact to Native communities in AZ with loss of revenue from coal production

New materials & technologies

Water Purification

Bio-inspired

Sensor Platforms

Energy Production & Storage

Separations | Charge Transfer | Catalysis

Water re-use and purification (fit-for-purpose) is going to be imperative:
New materials platforms and systems-level technologies – flexibly targeted:

- energy-efficient water reuse and purification – municipal, agricultural, mining, and energy production
- economical, distributed energy sources and energy storage platforms
- multi-analyte sensor platforms
- Atomic- and molecular-scale understanding of separations, molecular recognition, and charge transfer and catalysis.

Research
Office for Research & Discovery

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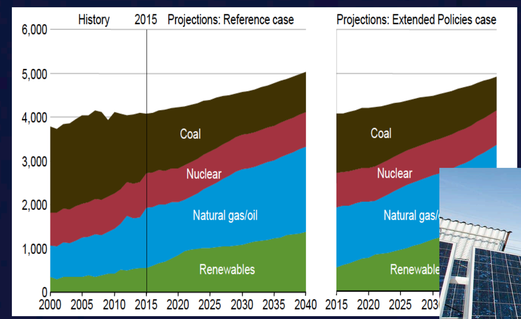
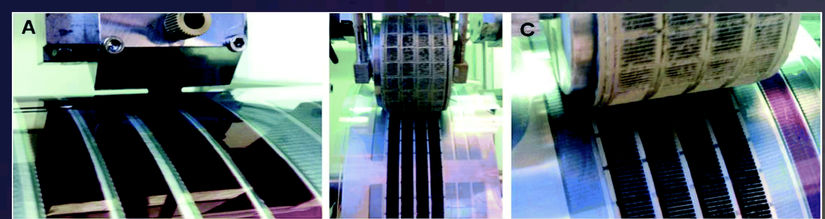
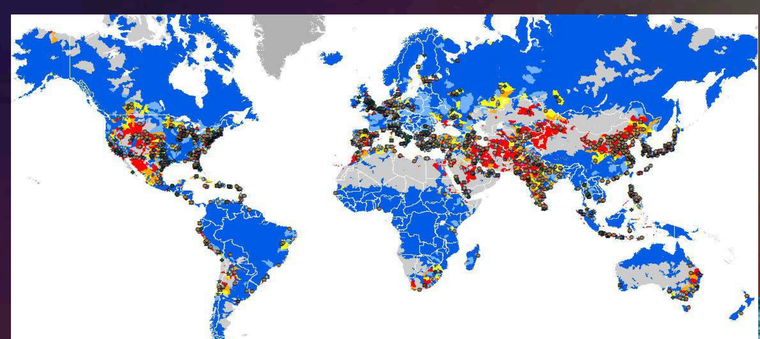
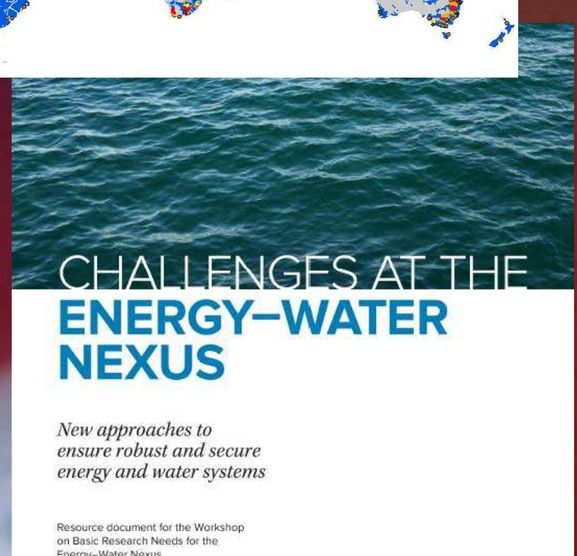
OFFICE FOR RESEARCH & DISCOVERY
Institute for Energy Solutions









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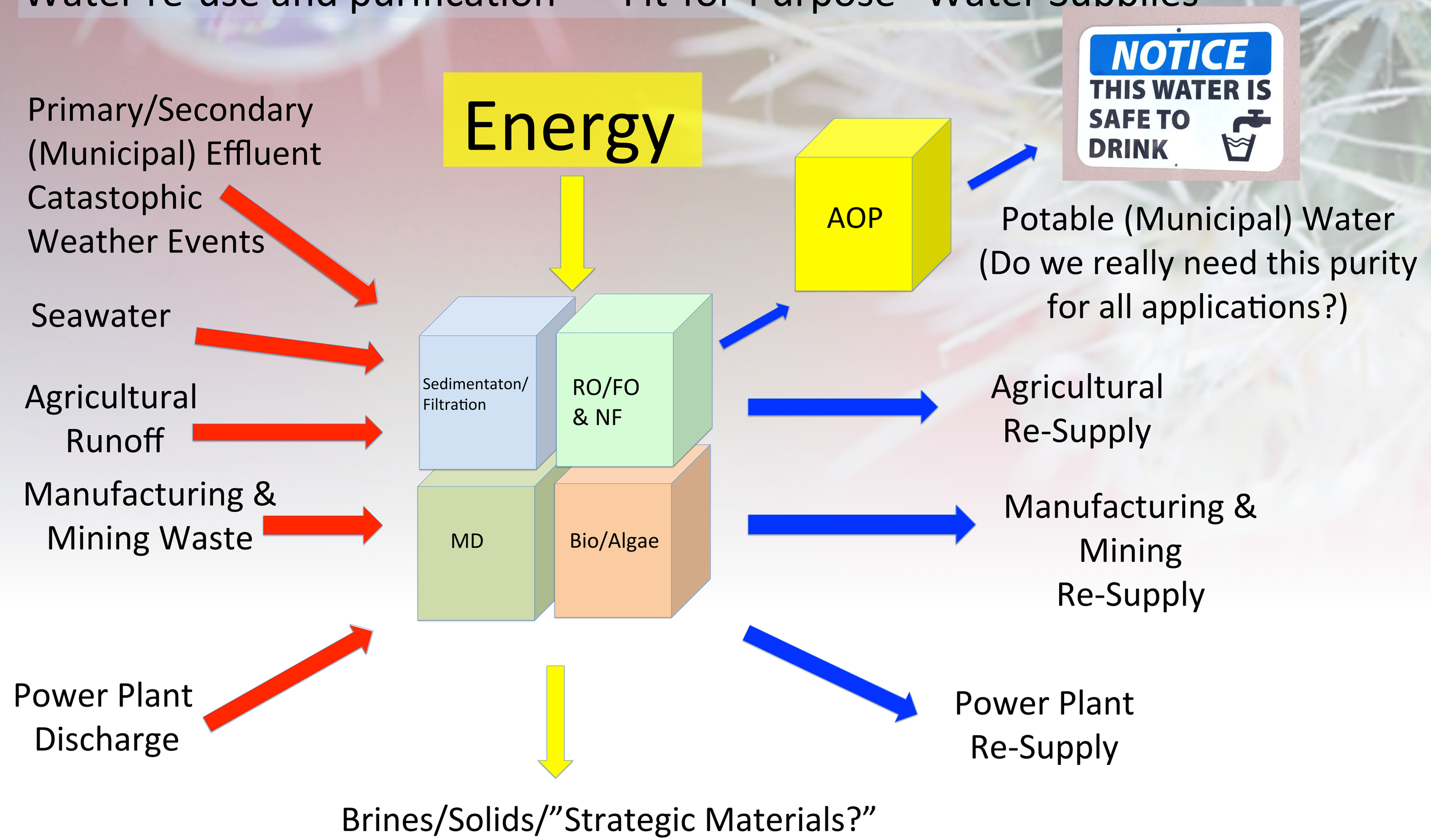
The future of water: modular, distributed, energy efficient
Water re-use and purification -- “Fit-for-Purpose” Water Supplies



DOE is (finally) interested

Schematic view of water purification from varied sources using membrane filtration and osmosis.

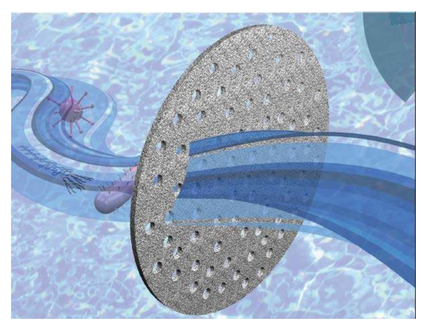
Filtration processes -- membranes whose average pore diameters, and pore size distribution, control the size selectivity for rejection of contaminants.

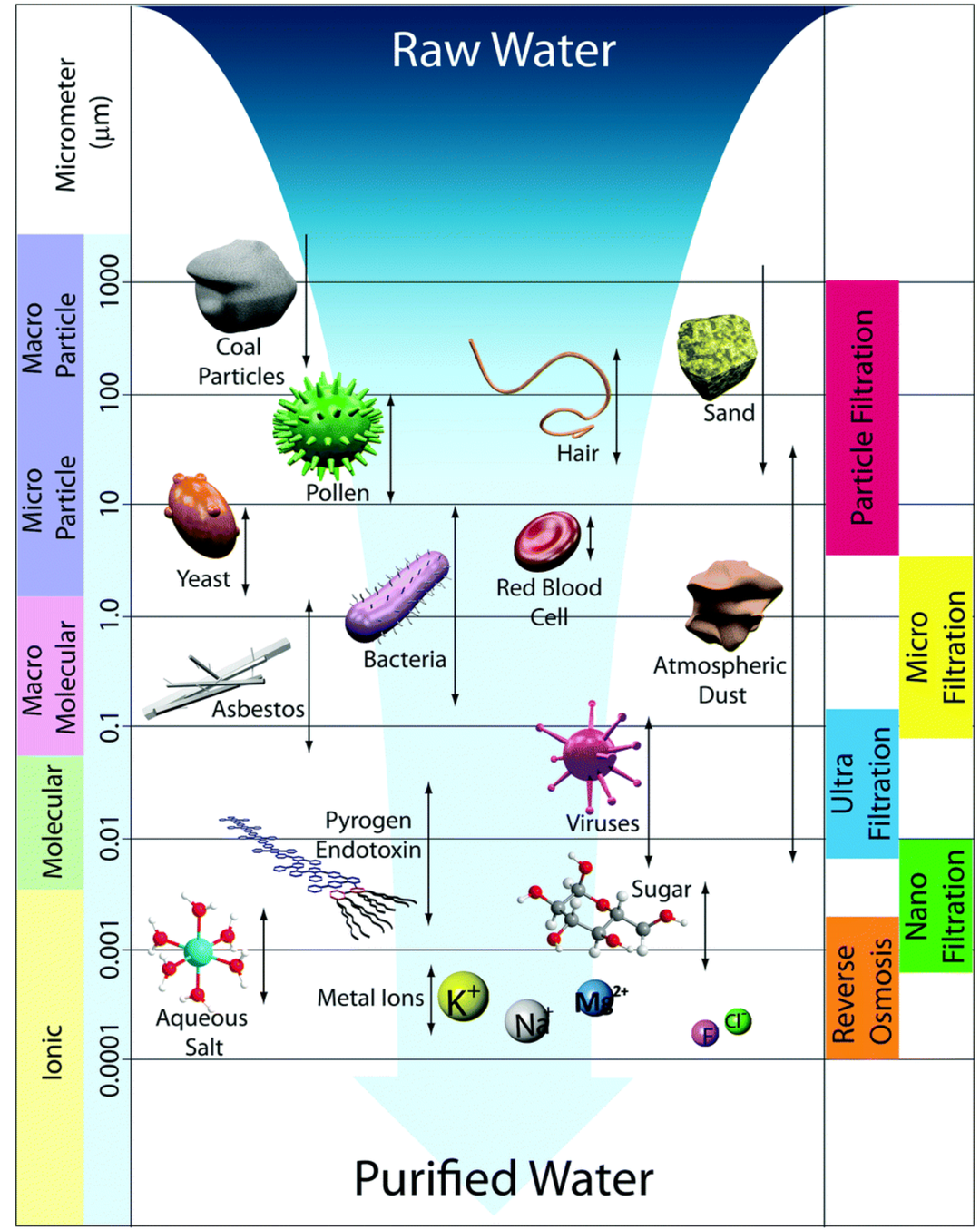
Reverse osmosis -- membranes are much denser, concentration of the impurity on one side of the membrane occurs via application of external pressure gradients (ΔP) which exceed the "osmotic pressure" differential on both sides of the membrane ($\Delta\pi$)

Membrane materials for water purification: design, development, and application

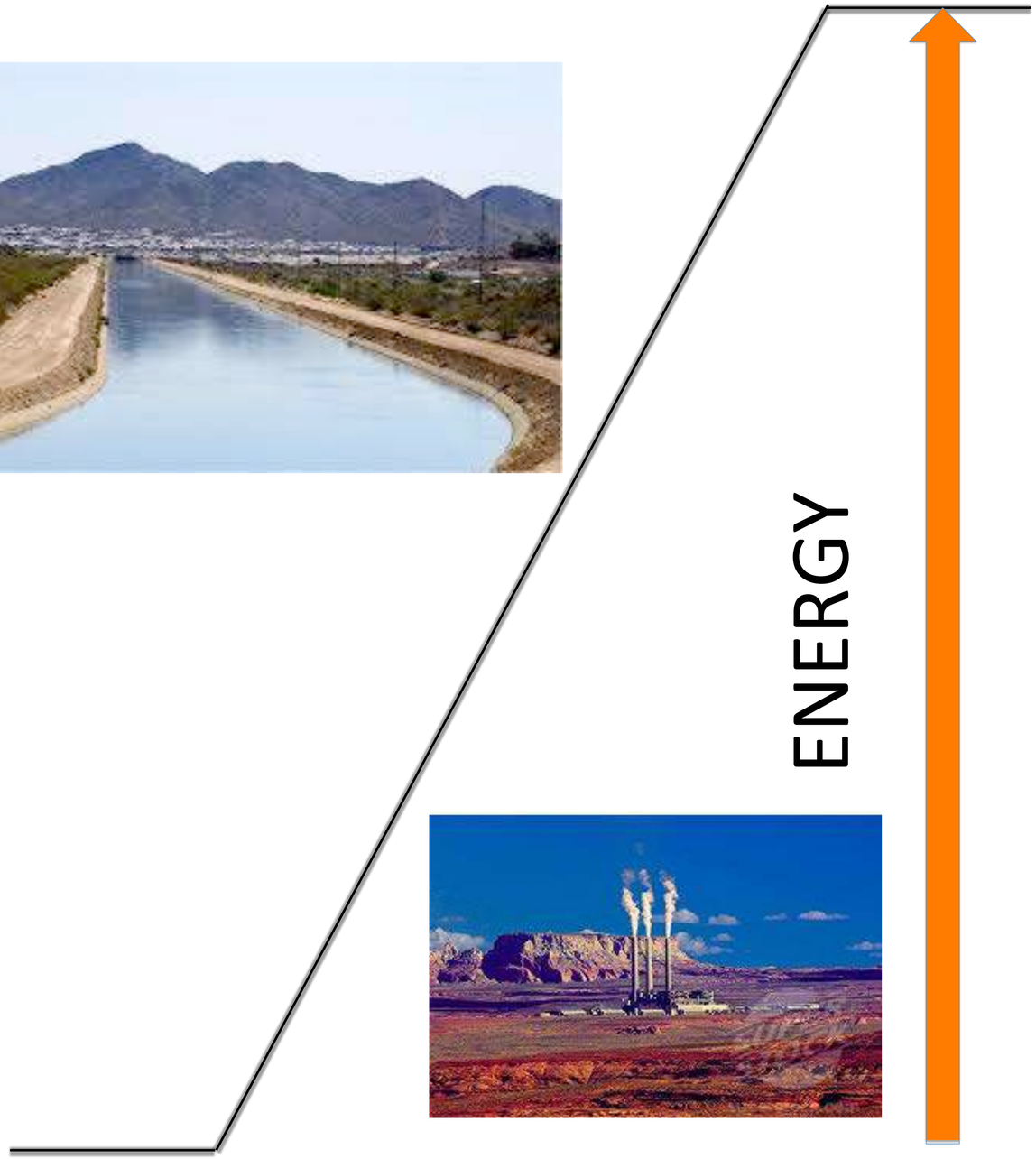
Anna Lee, Jeffrey W. Elam and Seth B. Darling - 2016

Environmental Science
Water Research & Technology



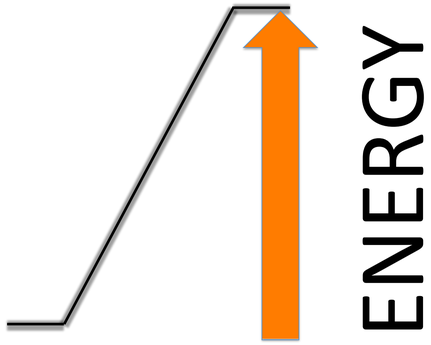


"Transporting water long distances, or from great depths, costs more energy that in-place recovery, purification and re-use" – MAYBE!!!



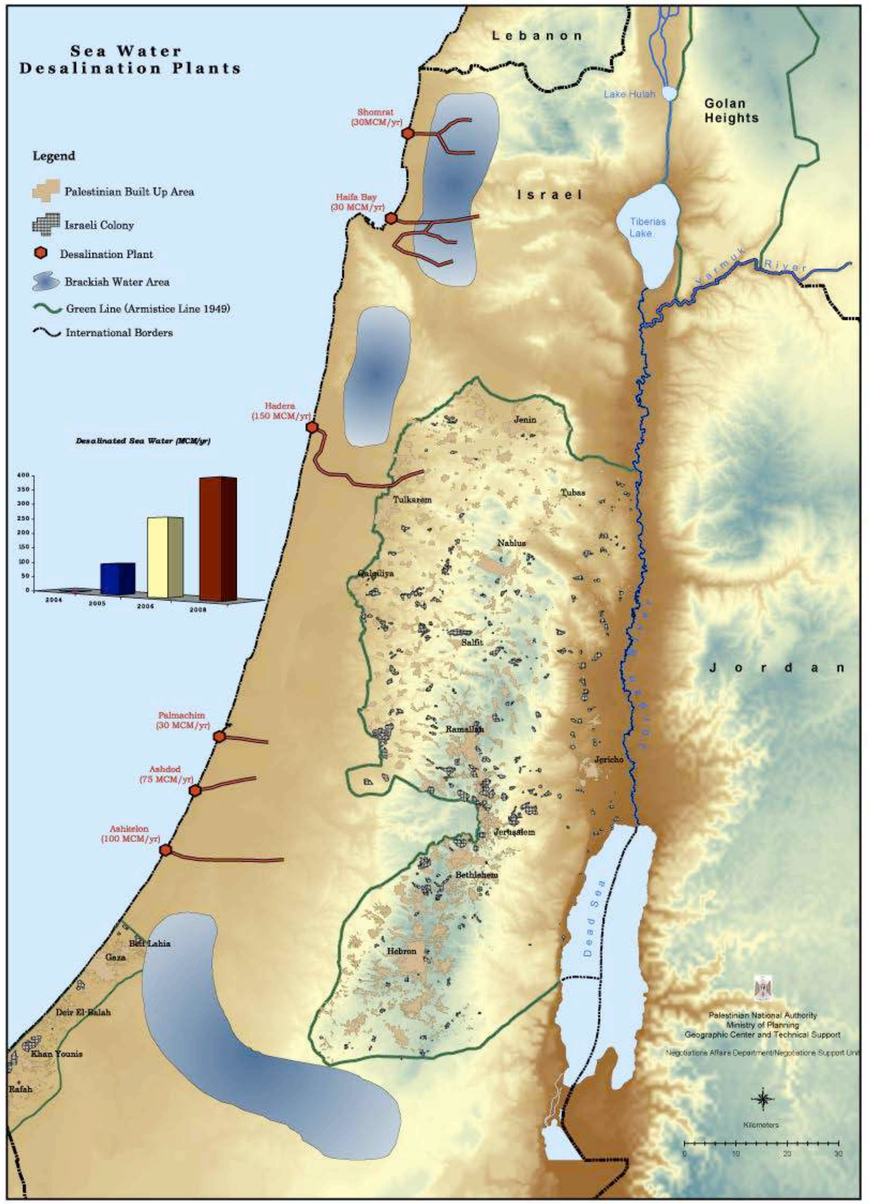
The theoretical absolute minimum amount of energy required by natural **osmosis** to desalinate average seawater is ca. **1 kwh/m³ of water produced**, or 3.8 kwh/1000 gal.

How close can one come to this, depending upon other water sources – as of 2017 -- **2 kwh/m³ of water produced**?



https://www.nickelinstitute.org/NickelUseInSociety/MaterialsSelectionAndUse/Water/DesalinationandPurification.aspx

Help is on the way? -- Megascale Desalination: The world's largest and cheapest reverse-osmosis desalination plant is up and running in Israel
https://www.technologyreview.com/s/534996/megascale-desalination/



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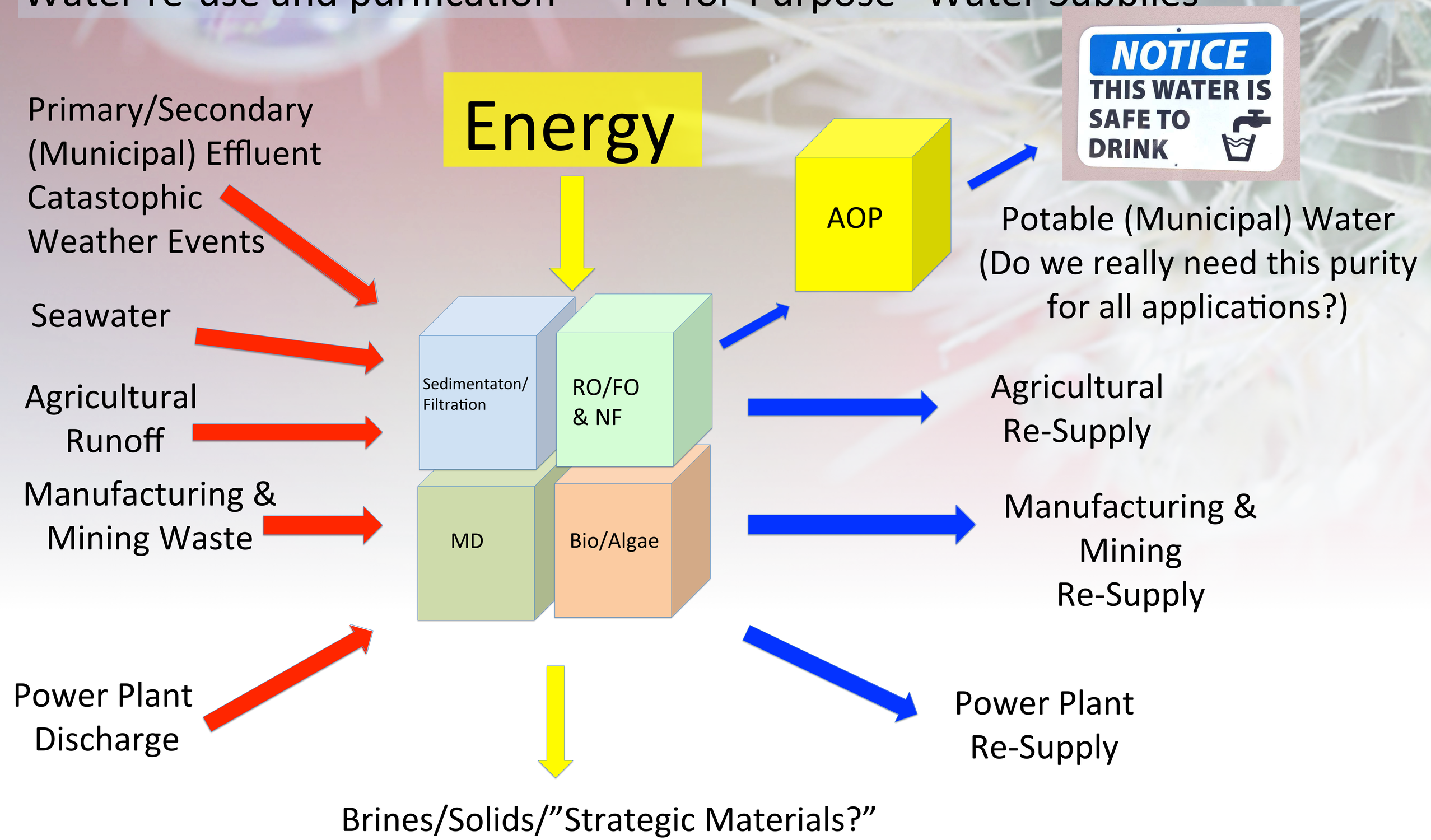
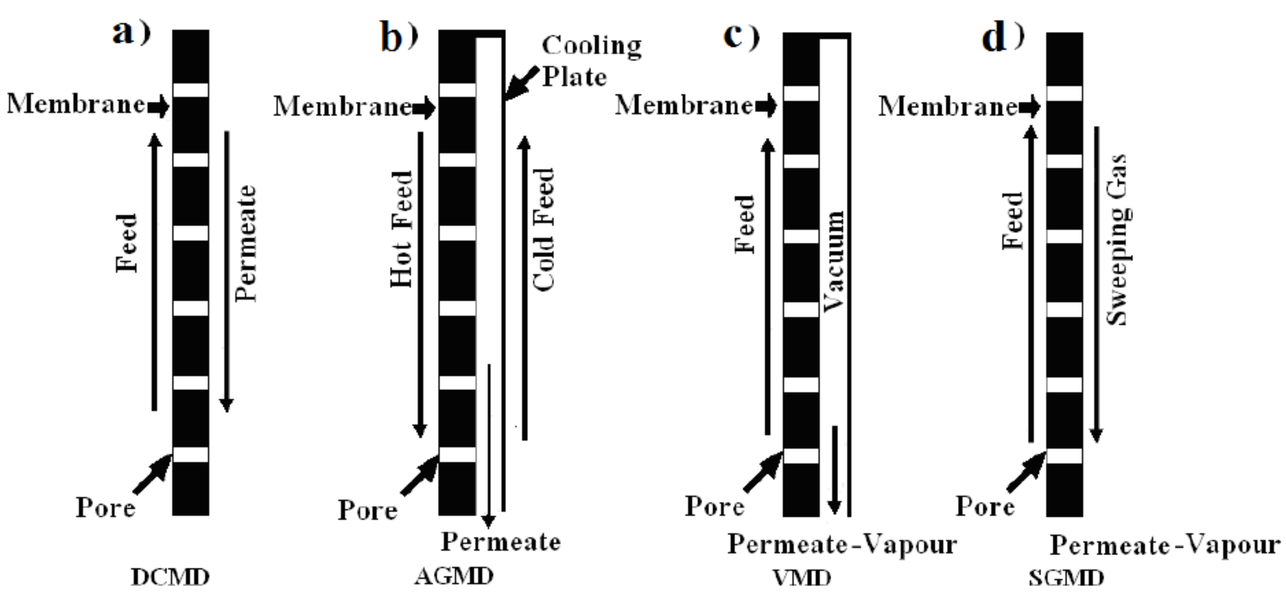


An Attractive Alternative: Membrane Distillation – Finding a Use for "Waste Heat" – Sources of waste heat = power plants, solar PV, computer servers!!.....

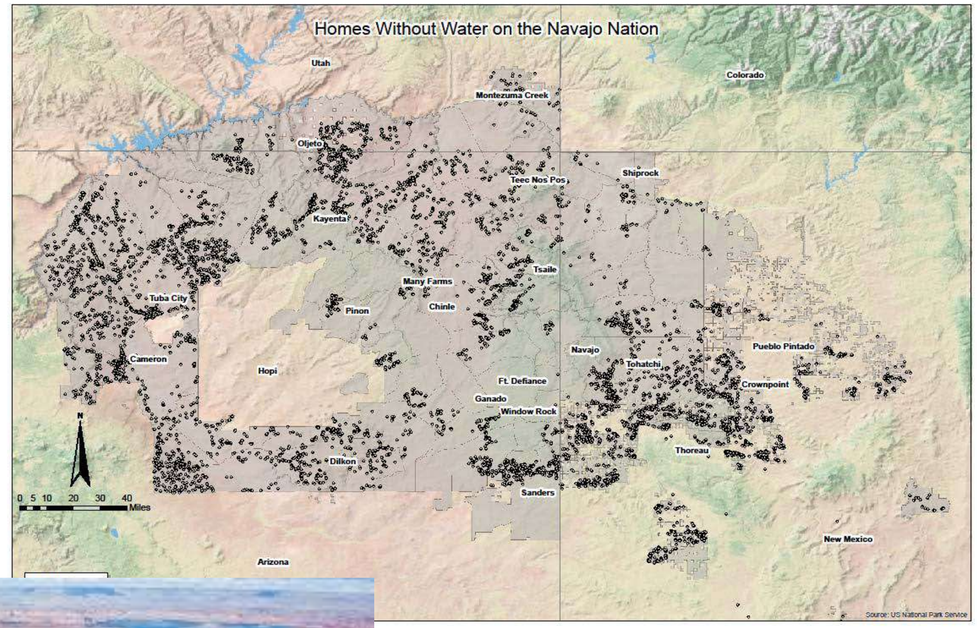
Advances in Membrane Distillation for Water Desalination and Purification Applications

Lucy Mar Camacho [1,*], Ludovic Dumée [2,3], Jianhua Zhang [3], Jun-de Li [4], Mikel Duke [3], Juan Gomez [5] and Stephen Gray [3,*]

Water **2013**, *5*, 94-196; doi:10.3390/w5010094



A Modern, Critical Application: Navajo Nation Solar Desalination Demonstration Pilot Project



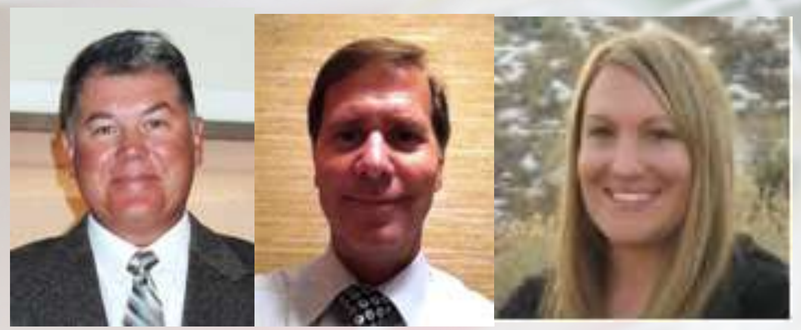
- Diminishing water supply , impaired brackish water supply, need to incorporate renewable energy
  - 40% population off-grid in Southwestern area
  - $10 - $35/1000 gallons
  - 1500 – 15000 TDS
  - Well depth 400 to 1,600 feet
  - Hauling water averages 40 miles round-trip
  - Residential gas generators used for temporary power

- Can a new water supply be developed incorporating an economically and culturally appropriate desalination technology that utilizes renewable energy to service areas lacking basic infrastructure for water and electricity?

“Seeking Water From the Sun”

http://indiancountrytodaymedianetwork.com/2012/07/08/seeking-water-sun-documentary-profiles-solar-water-purification-program-navajo-nation

University of Arizona



Bureau of Reclamation

https://youtu.be/SgWuTU10bfE

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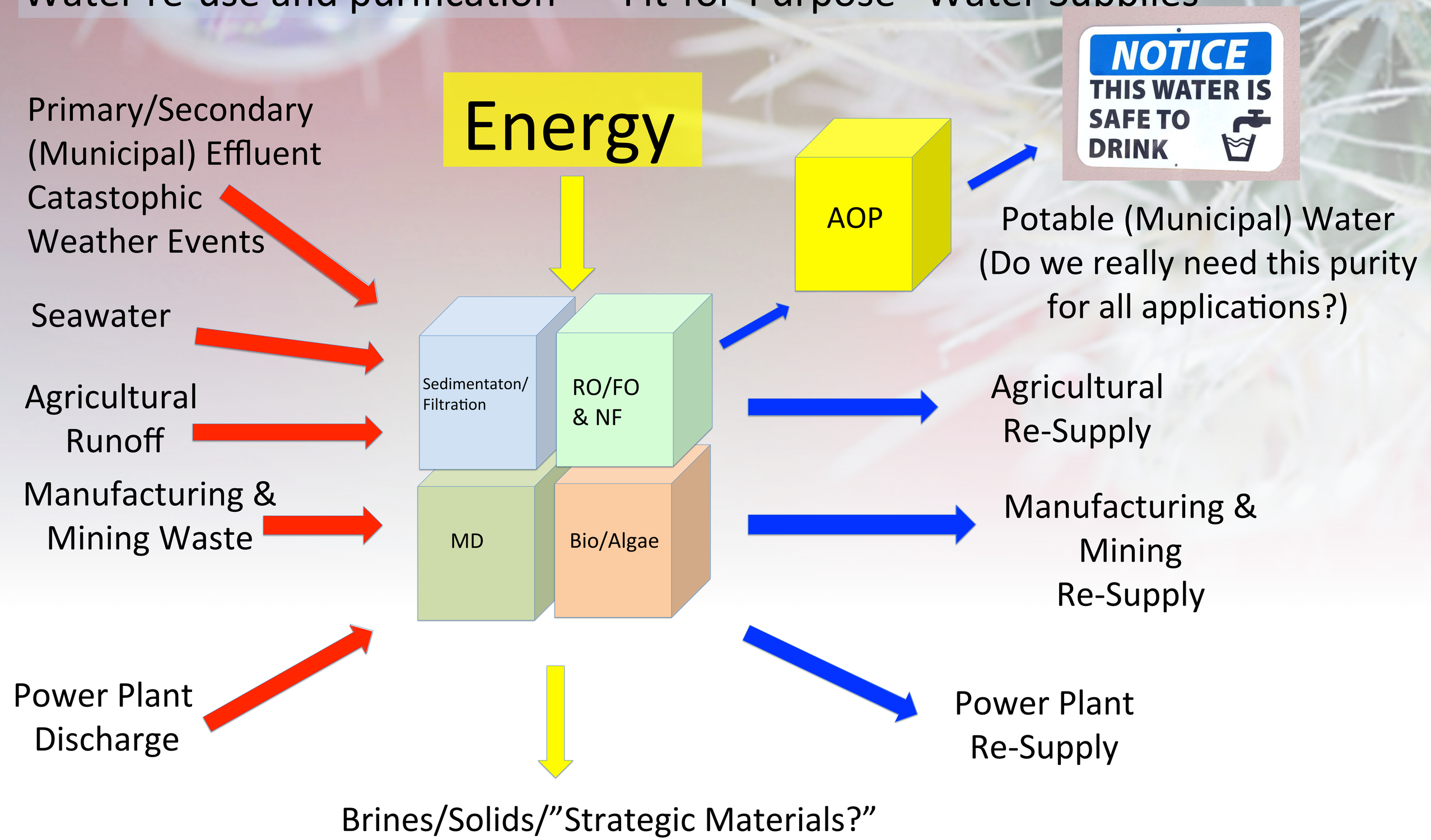
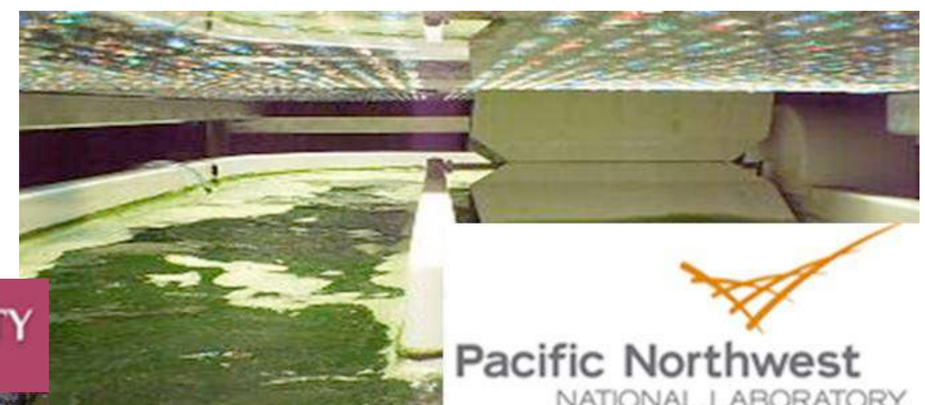


Regional Algal Feedstock Testbed (RAFT)
http://raft.arizona.edu/
University of Arizona
Pacific Northwest Laboratories (PNNL)
Texas A&M
New Mexico State Univ.

Algae for food, fuel & water purification!!



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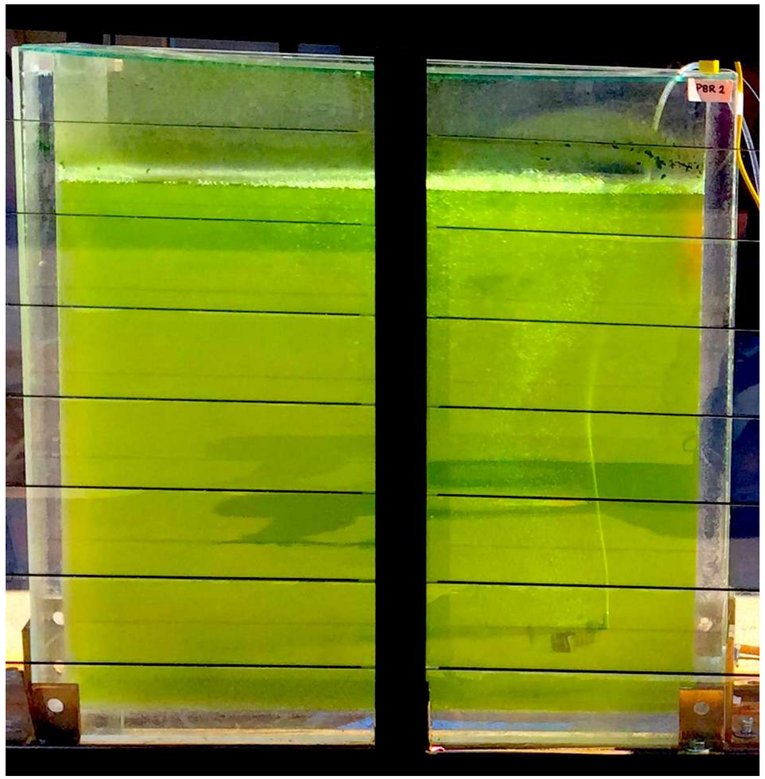
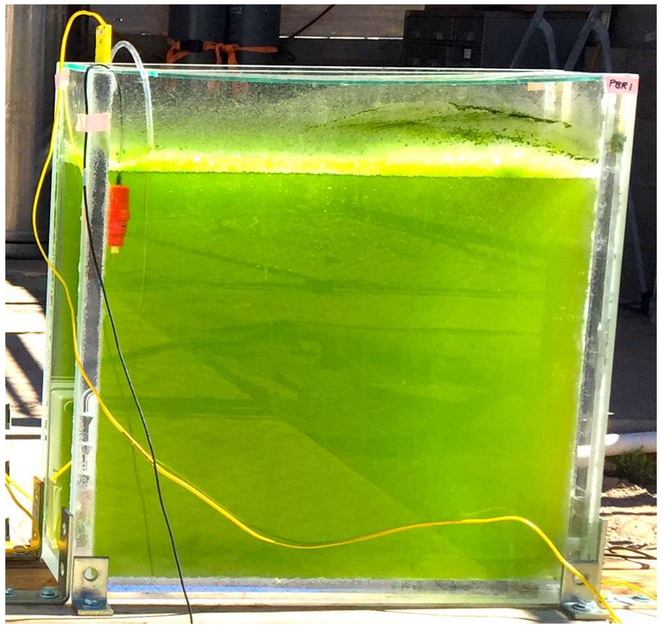
U.S. DEPARTMENT OF ENERGY

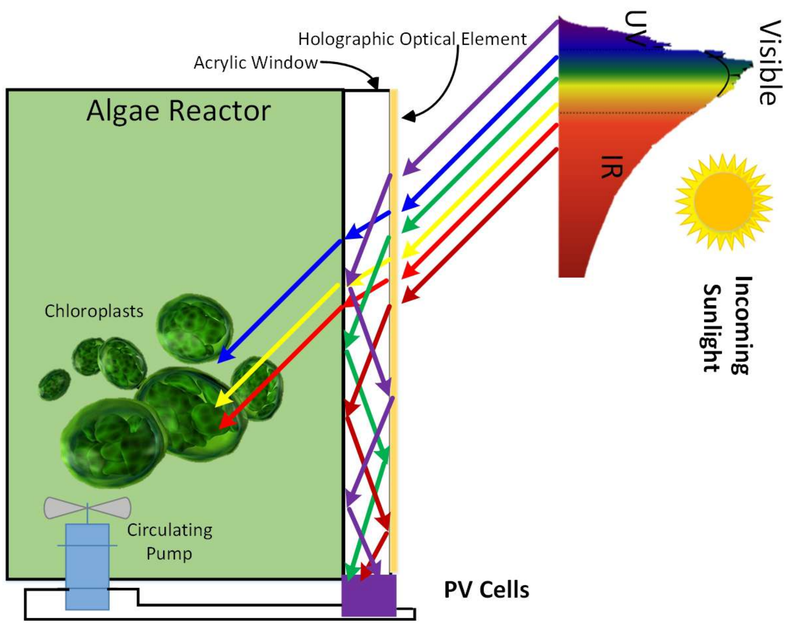
Algae Bioreactors + Holographic optical elements – “Solar Glass” – optimized light for photosynthesis AND electricity production

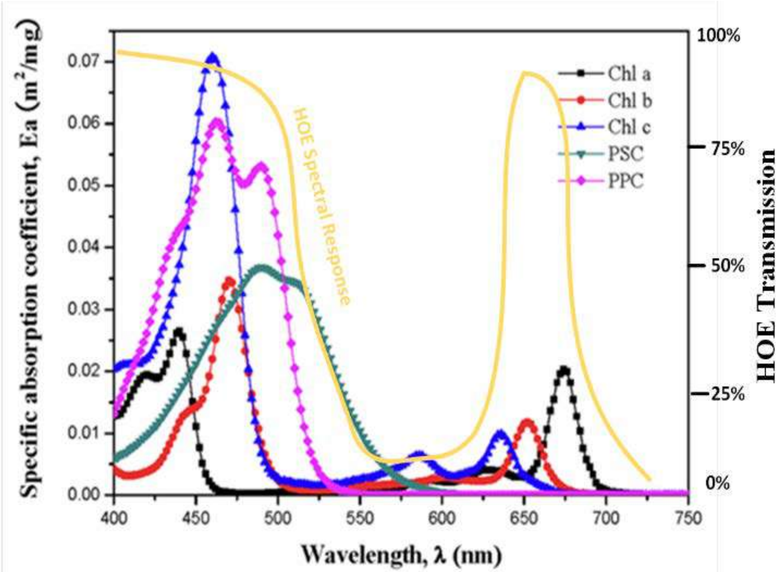
– Lloyd Lacomb, Nasser Peyghambarian et al.





Kim Ogden et al.





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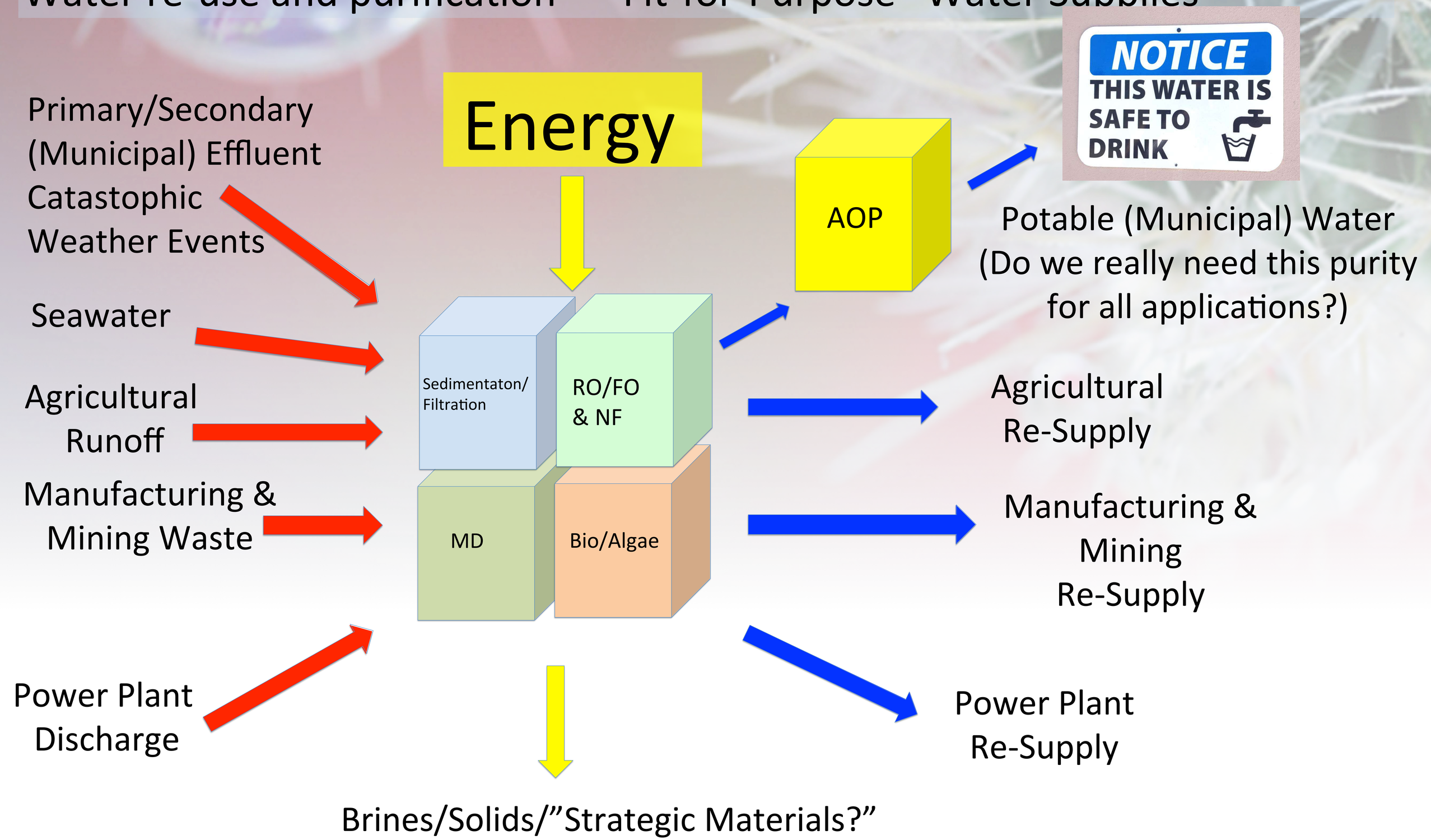


Other possible solutions: Controlled Environment Agriculture – May solve many of the problems of the Energy/Water/Food Nexus – but are they scalable?

Controlled Environment Agriculture Center

http://ceac.arizona.edu/

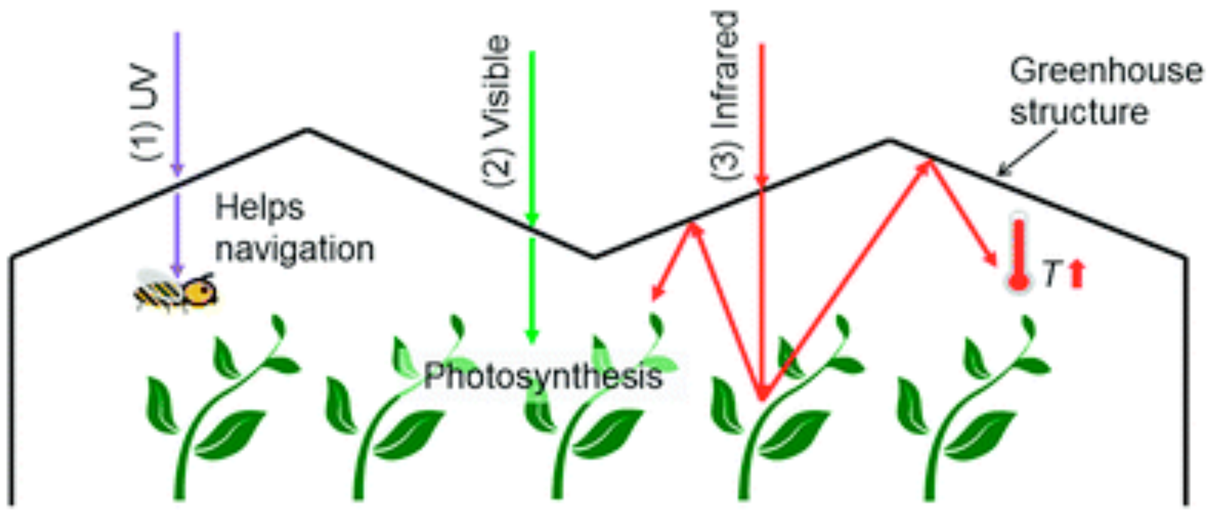
Reality >>>

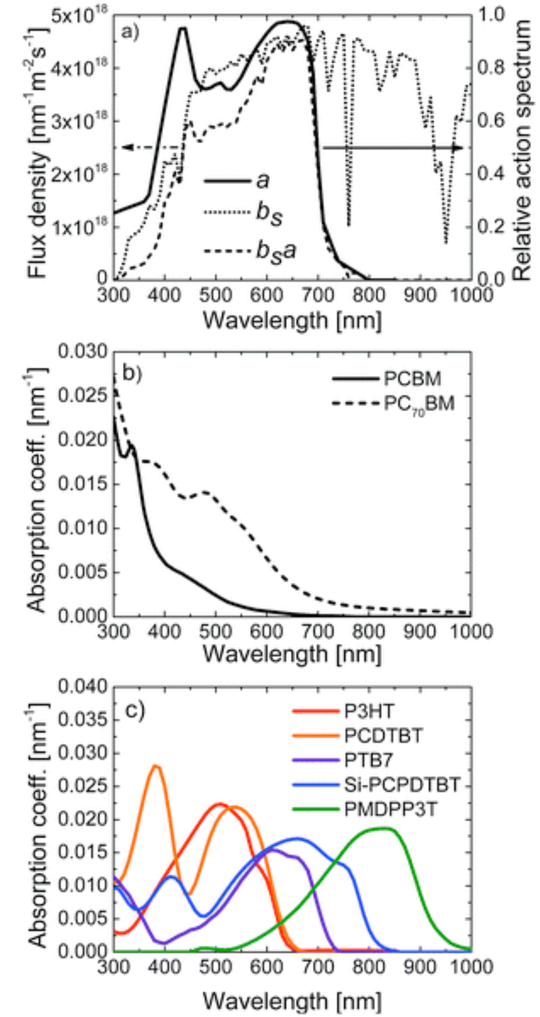
Vision >>>

Opportunities for integration of “light-management” technologies:

Organic photovoltaic greenhouses: a unique application for semi-transparent PV?

Energy Environ. Sci., 2015, 8, 1317-1328



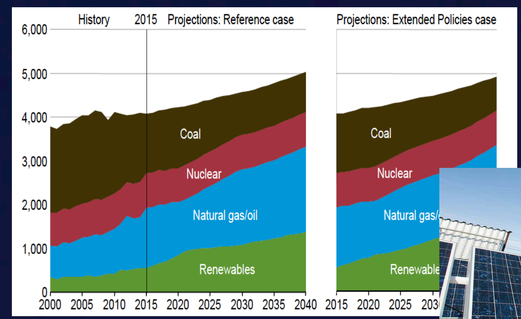


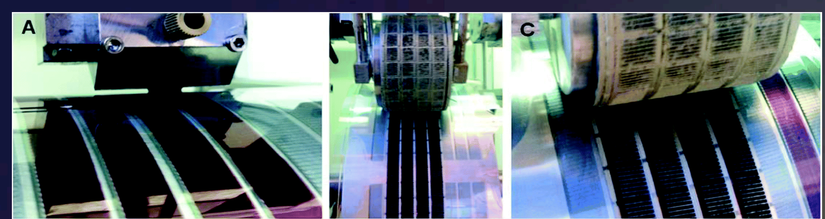
(1) UV light allows pollinating insects to navigate; (2) visible light for photosynthesis and heats the greenhouse; (3) infrared light heats the greenhouse.

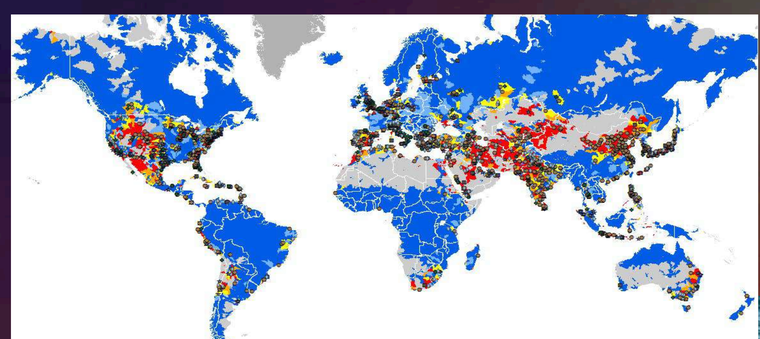
Transparency >>>>

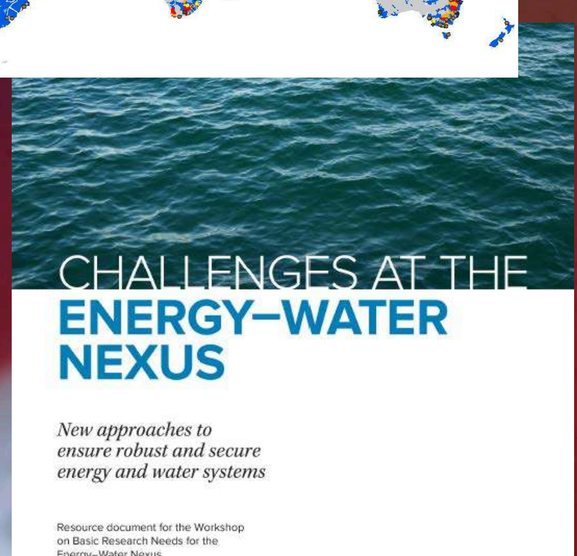
Color >>>>

Heliatek®
The future is light





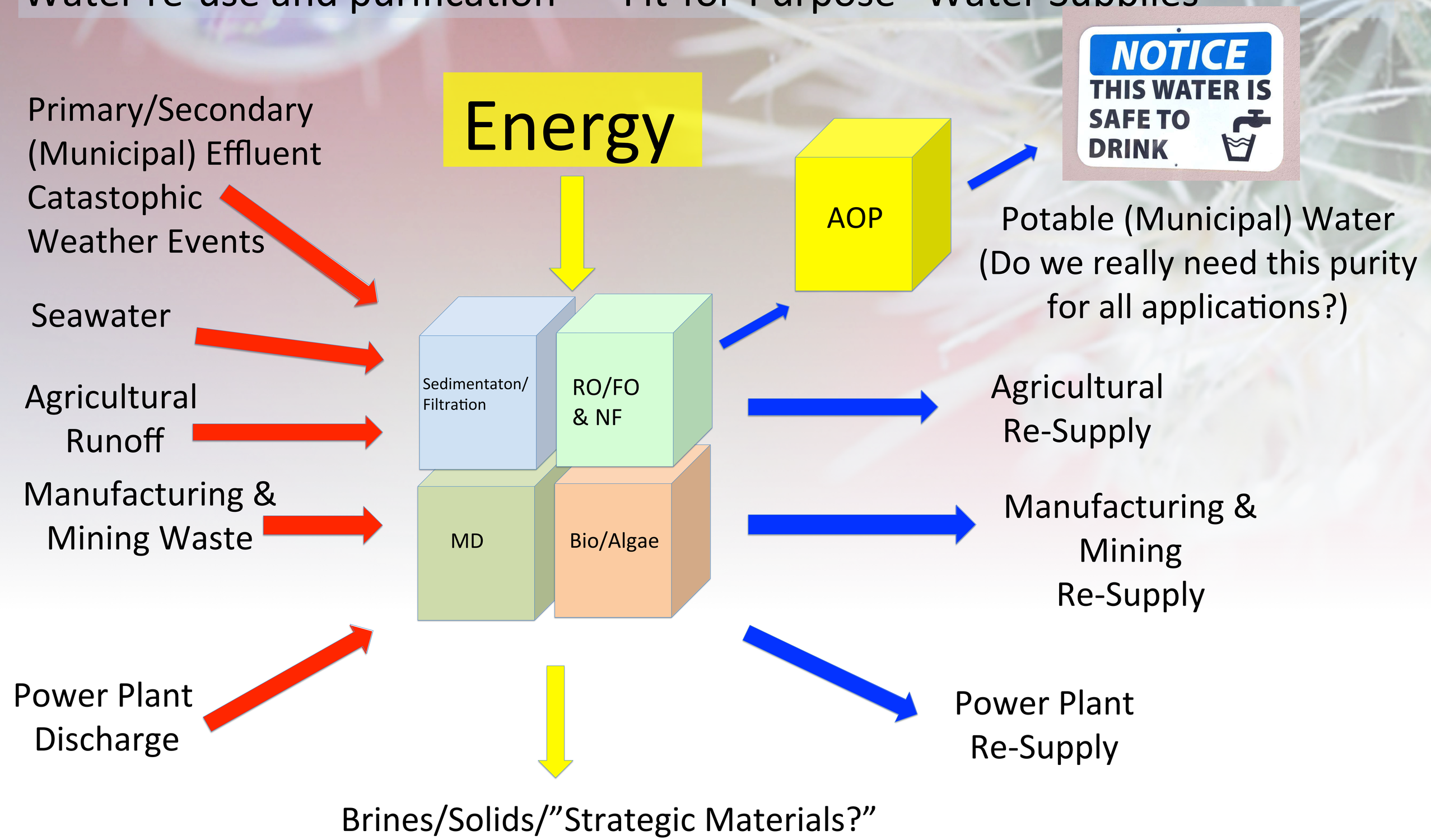




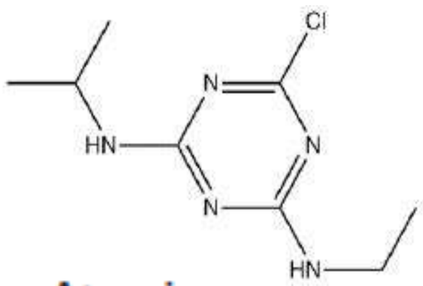
The takeway messages:

- *Outlook for energy utilization in the U.S. and the world – costs are down, carbon is up, we'll need more water!!*
- *Solutions to the Energy/Water/Food Nexus problems need to be modular, distributed, and cheap!*
- *Solutions in developed countries may not apply in less-developed regions of the world? Or maybe they will?*

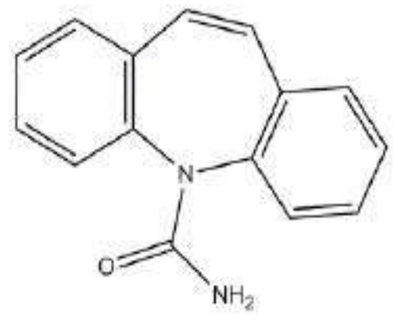
The future of water: modular, distributed, energy efficient
Water re-use and purification -- “Fit-for-Purpose” Water Supplies



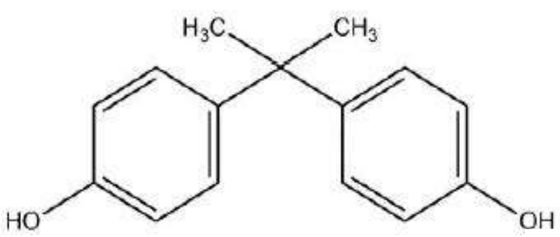
Examples (surrogates) for what is in your water, that passes most RO/FO purification systems: (Snyder etl al. Envr. Sci. Technol. 2016



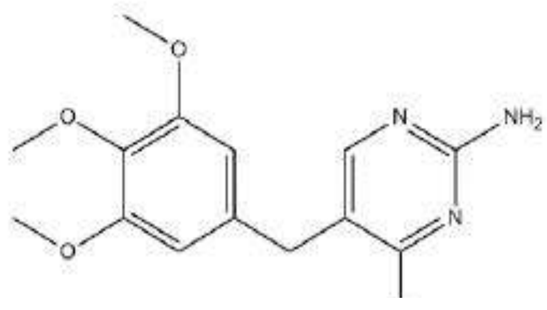
Atrazine



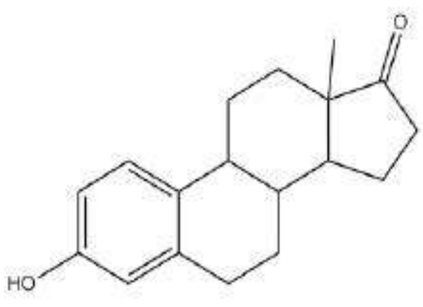
Carbamazepine[a]



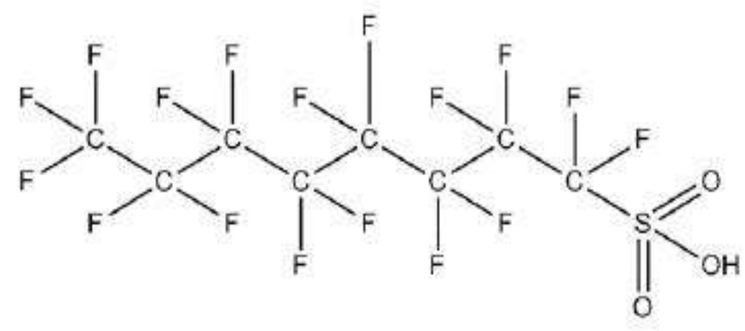
Bisphenol A[a]



Trimethoprim[a]



Estrone[a]



Fluorosurfactant

WEST CENTER
WATER & ENERGY SUSTAINABLE TECHNOLOGY

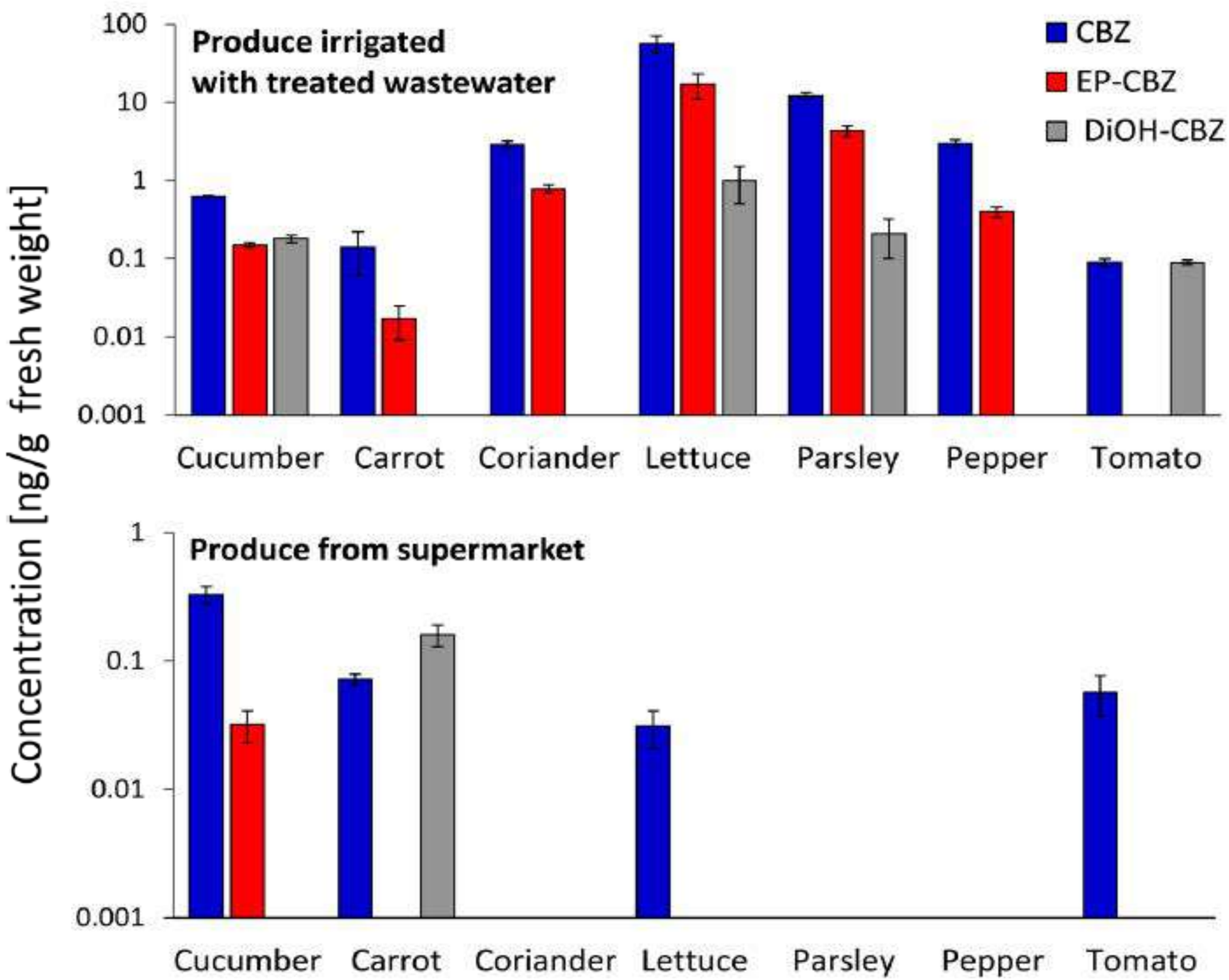
THE UNIVERSITY OF ARIZONA

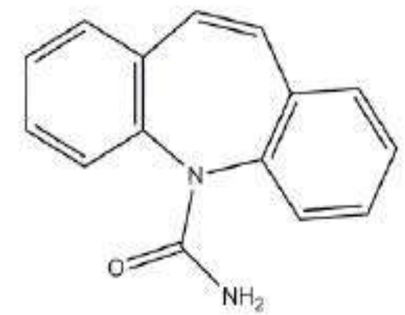
And is this important? Most likely yes!!

Environ. Sci. Technol. 2016, 50, 4476–4482

Human Exposure to Wastewater-Derived Pharmaceuticals in Fresh Produce: A Randomized Controlled Trial Focusing on Carbamazepine

Ora Paltiel,[*,†,‡,§] Ganna Fedorova,[§,∥] Galit Tadmor,[†,§,∥] Geffen Kleinstern,[†,§] Yehoshua Maor,[§] and Benny Chefetz[§,∥]





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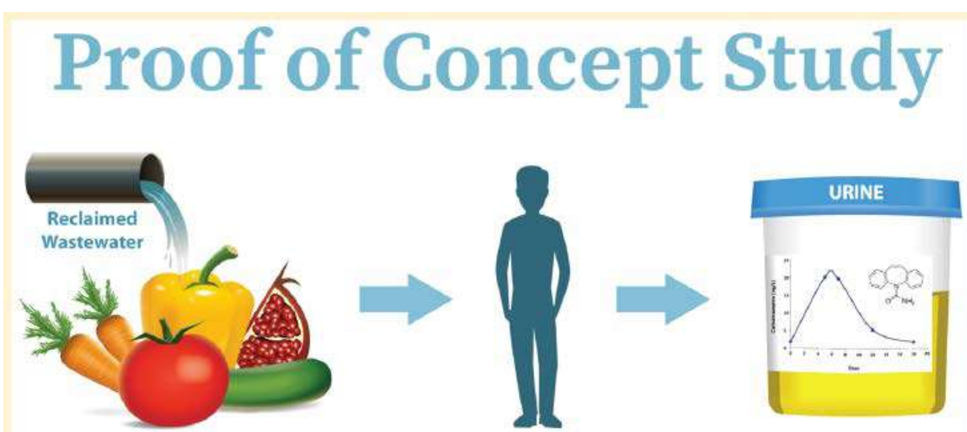
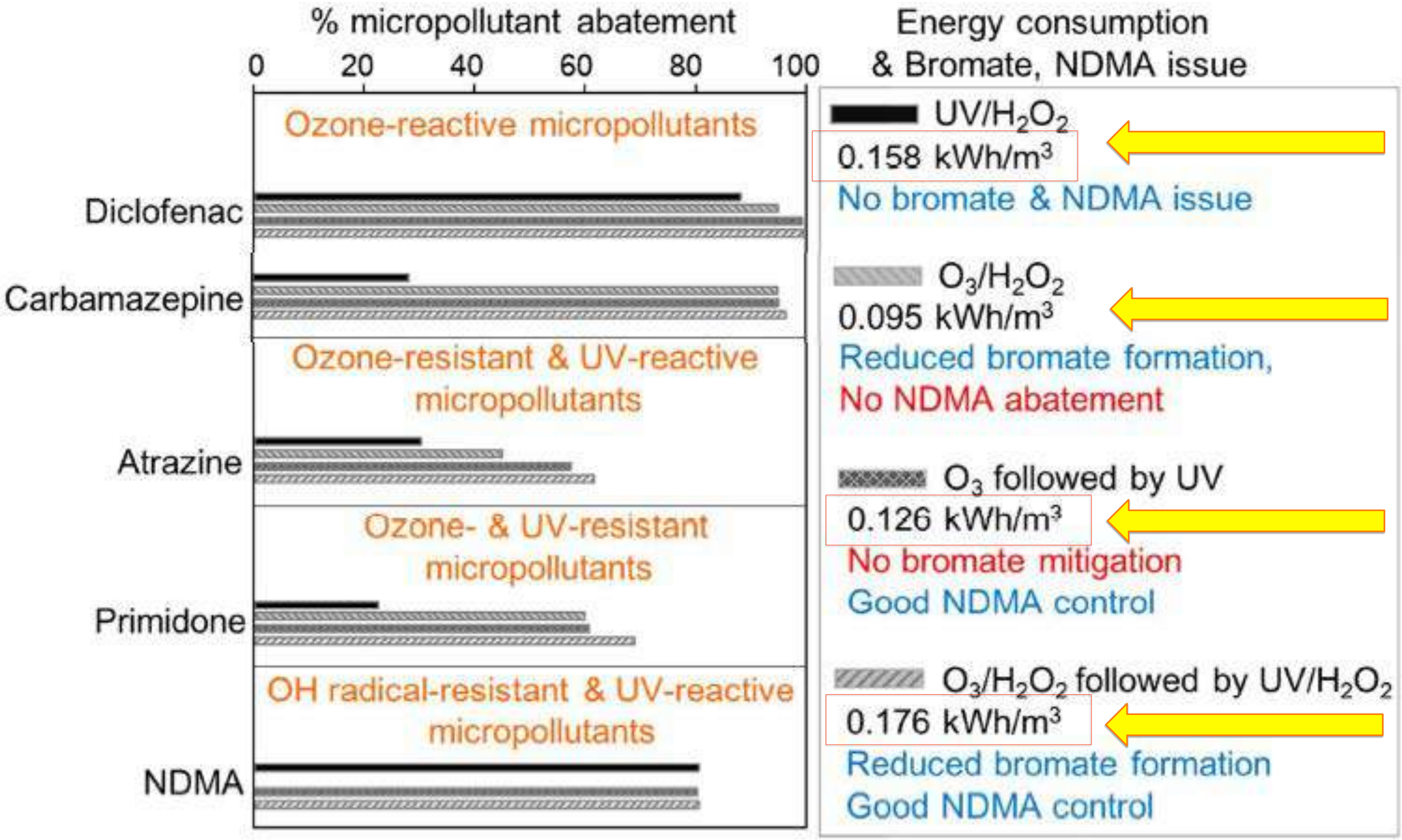


Organic Contaminant Abatement in Reclaimed Water by UV/HO and a Combined Process consisting of O/HO followed by UV/HO: Prediction of abatement efficiency, energy consumption, and by-product formation

Yunho Lee, Daniel Gerrity, Minju Lee, Sujanie Gamage, Aleksey Pisarenko, Rebecca A. Trenholm, Silvio Canonica, Shane A. Snyder, and Urs von Gunten

Environmental Science & Technology



WEST CENTER
WATER & ENERGY SUSTAINABLE TECHNOLOGY

Something new will be brewing in Arizona next summer. The Southwest Water Campus has won a $250,000 grant to ease Arizonans into drinking reclaimed wastewater by first turning it into beer.

CYVERSE

Smart data

Real-time Response

Sensor Networks

Regionally Specific

Precision Agriculture

Water and Energy Grid

Smart Villages are going to need Smart Data and Decision-Making –

Measurement, analysis, and optimization (control) of chemical and physical parameters on previously unrealized scales.

Generation of massive data sets requiring new modes of transmission, storage, access, and robust links to policy and decision-making processes.

http://www.cyverse.org/

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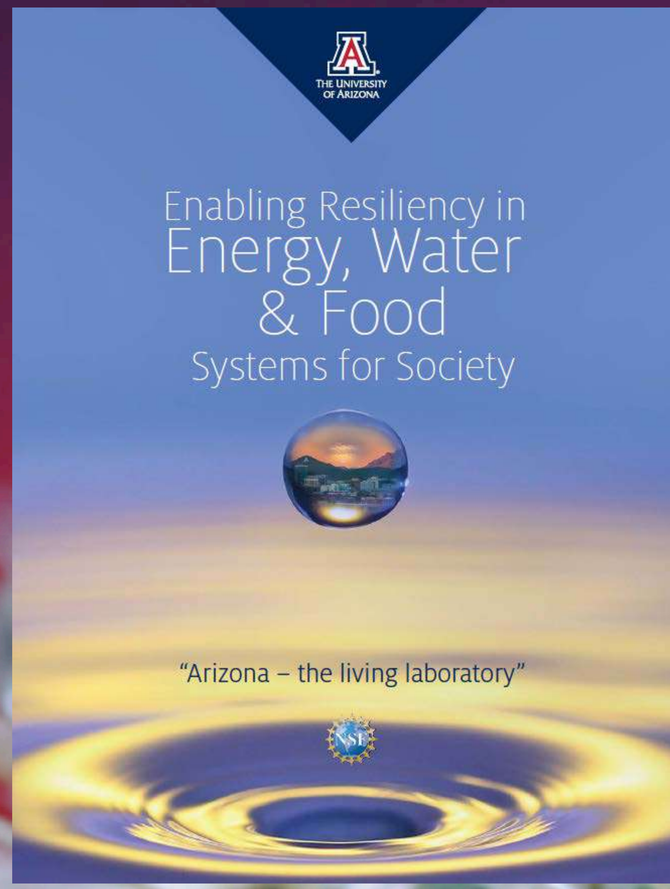
OFFICE FOR RESEARCH & DISCOVERY
Institute for Energy Solutions

Find us here:

http://energywaterfoodnexus.wordpress.com
http://www.energy.arizona.edu/



Situational scarcity

Situational

Co-location of systems

Integrated planning

Right Sourcing Resources

Smart data

Real-time Response

Sensor Networks

Regionally Specific

Precision Agriculture

Water and Energy Grid

New materials & technologies

Water Purification

Bio-inspired

Sensor Platforms

Energy Production & Storage

Separations | Charge Transfer | Catalysis

Regional test beds

Model Systems

Efficient resource use

Regional Evaluation

Optimized decision-making

Speed to market

Policy response

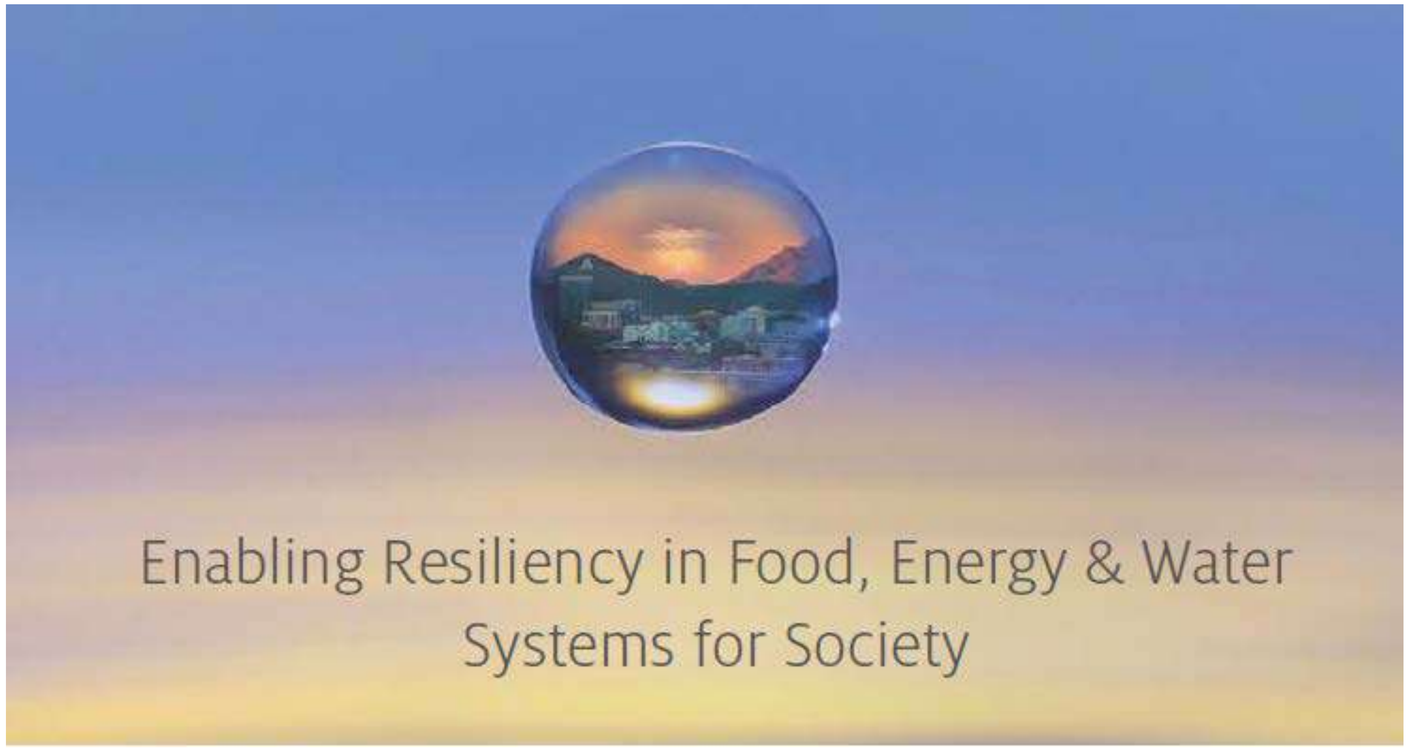
Key Costs & Benefits

Scenario Planning

Integrated Resource Planning

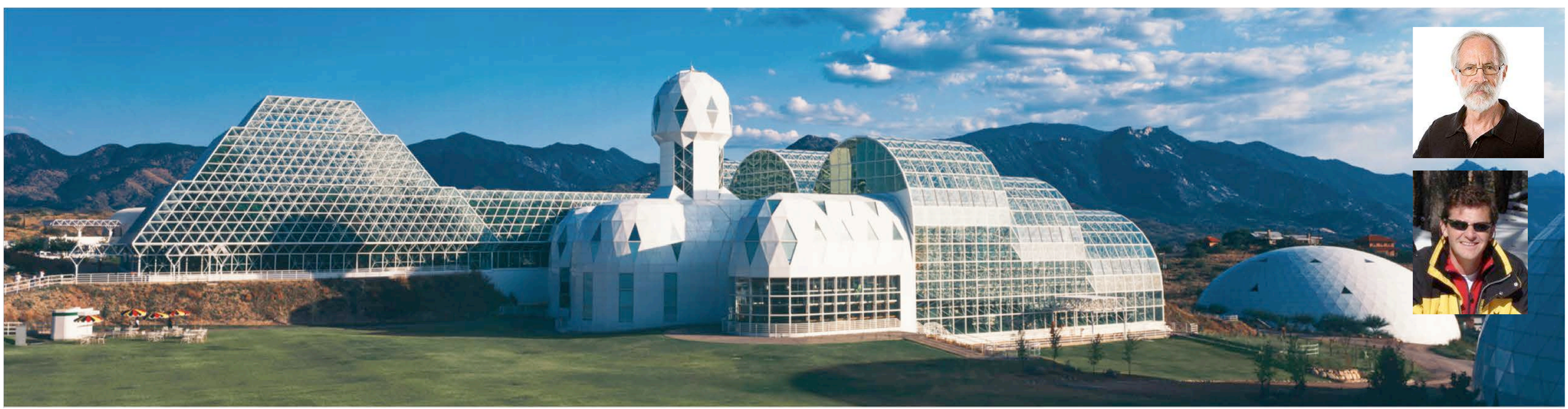
Social Acceptance

Test beds will be essential!!!



Regional test beds

- Model Systems
- Efficient resource use
- Regional Evaluation
- Optimized decision-making
- Speed to market



Policy response

Key Costs & Benefits

Scenario Planning

Integrated Resource Planning

Social Acceptance

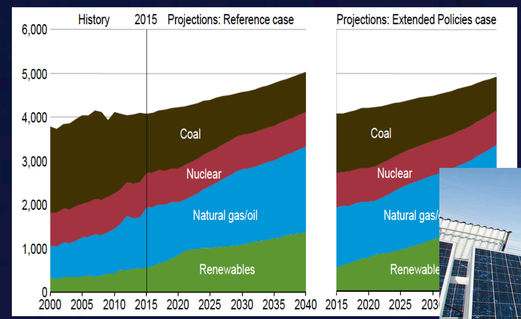
Technology solutions without policy solutions won't work:

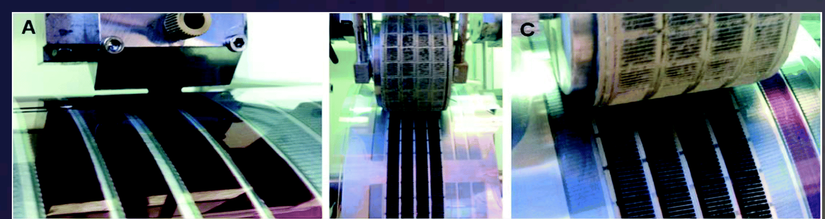
a) Bottom-up integration of new science and new technology with policy development, decision-making and support, and education and awareness;

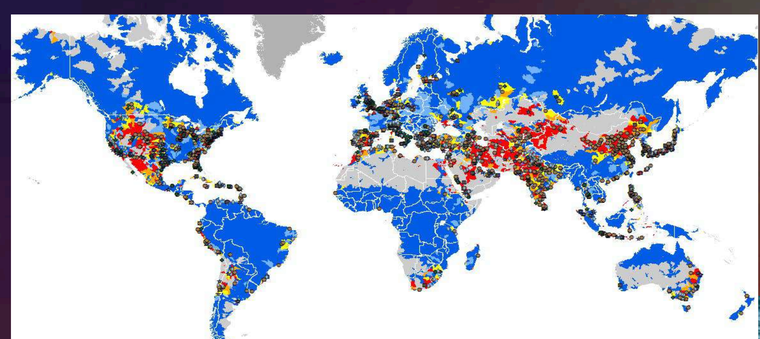
b) Revitalization of local communities, human resources, and development of new workforces;

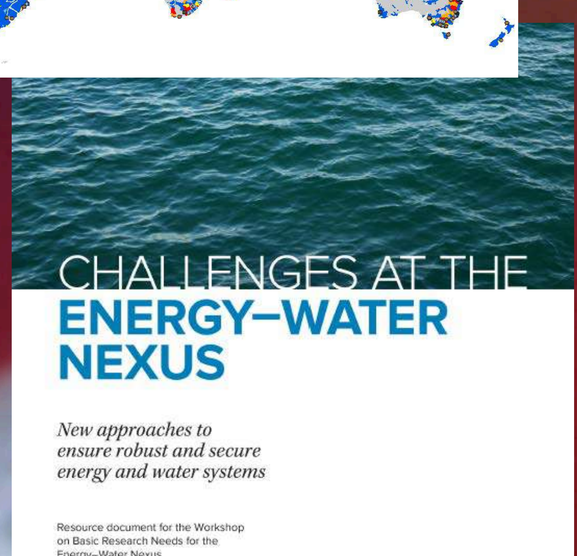
c) Development of policies that transform the regulatory and market environment;

d) Integrated and coordinated planning across sectors and public and private organizations









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THANK YOU!!

Advancing Solar Technology

Tucson Electric Power has an extensive partnership with the University of Arizona to study and identify the optimal integration of renewable energy technology. Researchers and scientists in the UA Renewable Energy Network work closely with TEP personnel to test solar panels, forecast weather, experiment with different solar technologies and develop batteries for storing energy.

Situational scarcity

Situational

Co-location of systems

Integrated planning

Right Sourcing Resources

Energy, water, food, and materials (e.g. strategic minerals and fuels) -- extremely scarce in localized regions and at different periods of time.

Situational scarcity amplified by:

- Increasing climate variability
- Inadequate management of local and regional water, energy and food supplies, expanding populations
- Lack of coherent integrated technology and policy solutions

New materials & technologies

Water Purification

Bio-inspired

Sensor Platforms

Energy Production & Storage

Separations | Charge Transfer | Catalysis

New materials platforms and systems-level technologies – flexibly targeted:

- Energy-efficient water reuse and purification – municipal, agricultural, mining, and energy production
- Economical, distributed energy sources and energy storage platforms
- Multi-analyte sensor platforms
- Atomic- and molecular-scale understanding of separations, molecular recognition, and charge

Regional test beds

Model Systems

Efficient resource use

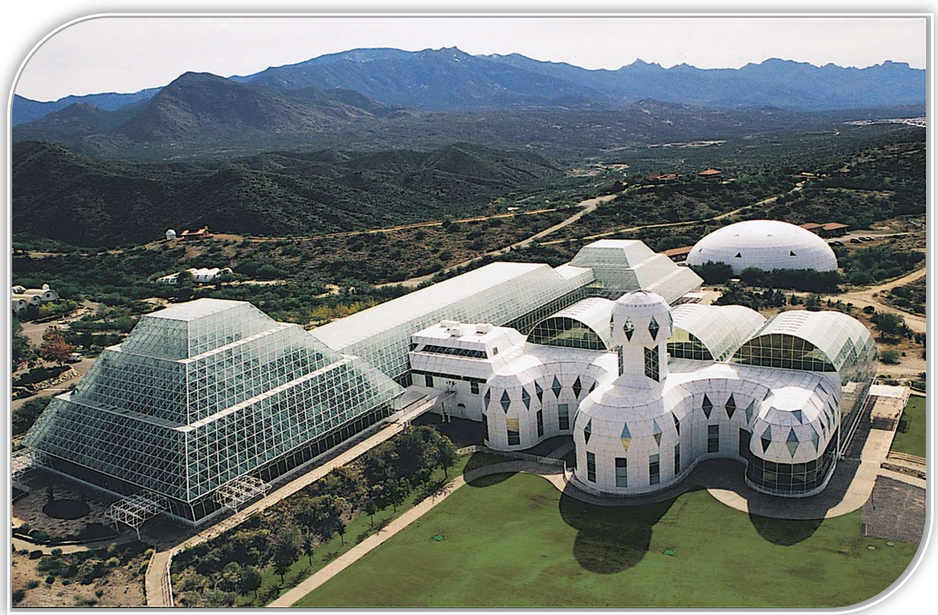
Regional Evaluation

Optimized decision-making

Speed to market

Need for regionally specific test beds that integrate public and private interests and investment.

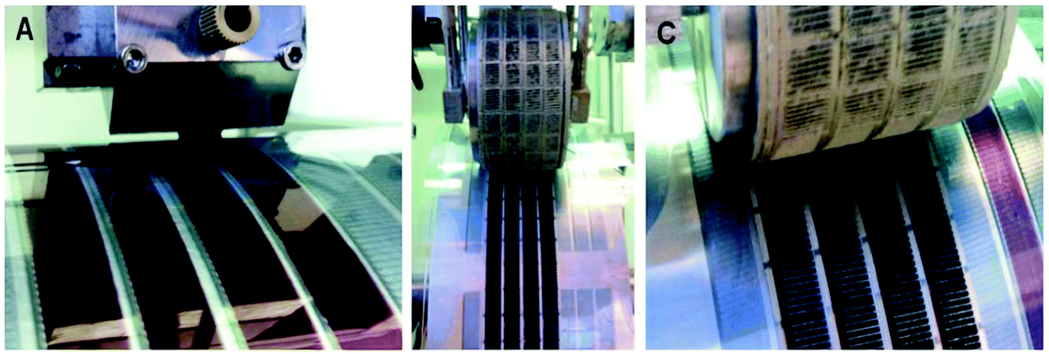
a) Large and complex enough to challenge the integration of new energy conversion, storage and energy management systems, new water purification and re-use platforms, and new precision agricultural systems
b) Small enough to be easily isolated so that sufficient control can be achieved



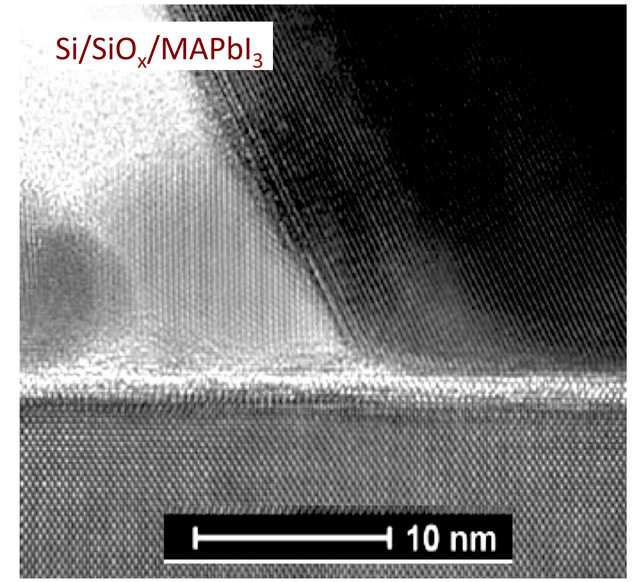
Emerging Materials and Materials Characterization for Solar Energy Conversion, Energy Storage and Optoelectronics

THE UNIVERSITY OF ARIZONA
Research, Discovery & Innovation

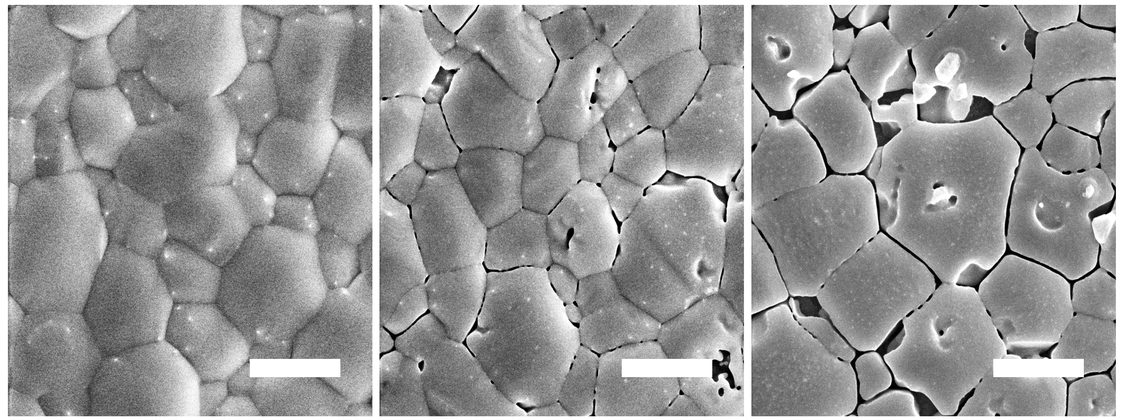
Interface Science of "Printed" Solar Cell Technologies
– Neal Armstrong, Scott Saavedra – CBC/Op. Sci.

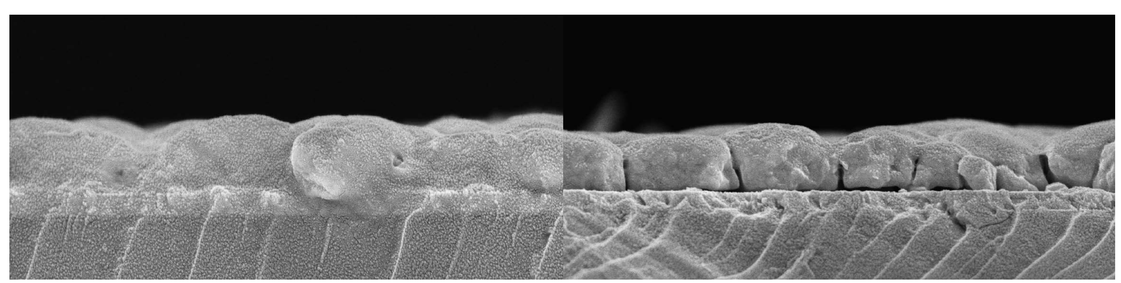


Photoemission spectroscopies, scanning probe and electron microscopies, waveguide spectroscopies, spectroelectrochemistry



Hybrid Organic/Inorganic Perovskite Active Layers

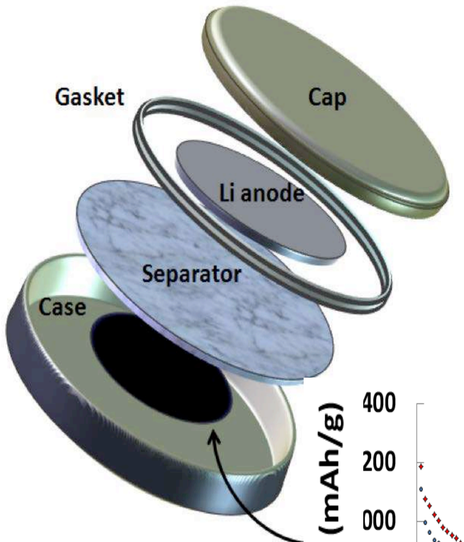


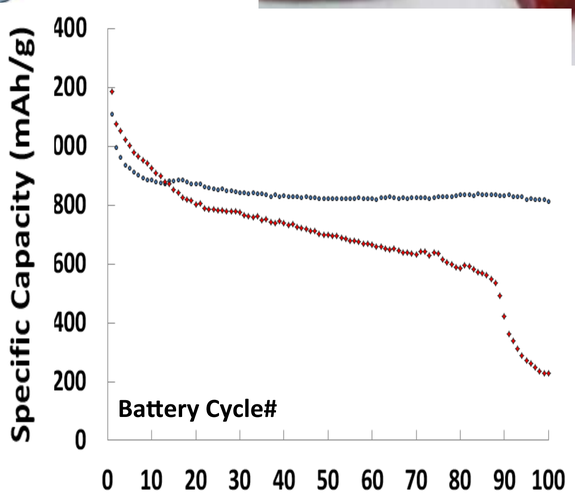


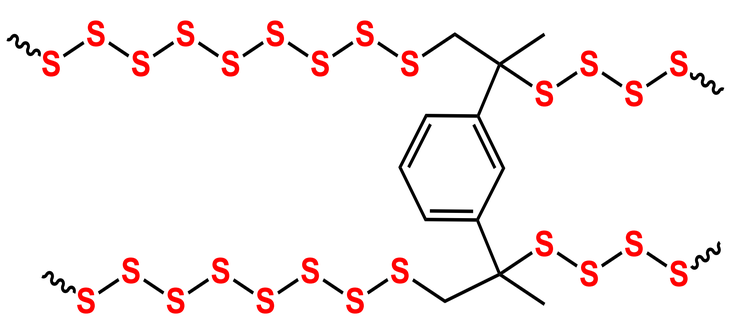
Materials for Solar Energy Conversion, Energy Storage and Optoelectronics

THE UNIVERSITY OF ARIZONA
Research, Discovery & Innovation

Turning Waste Sulfur into Processable Polymers for Low-Cost Li-Batteries with High Energy Storage Densities – Jeff Pyun, Dick Glass - CBC



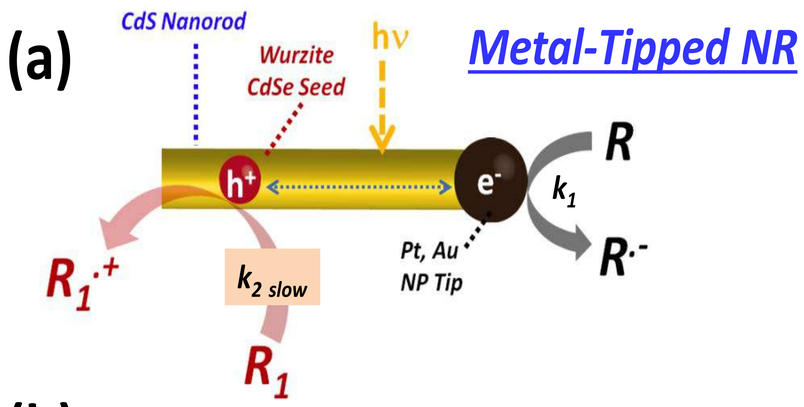


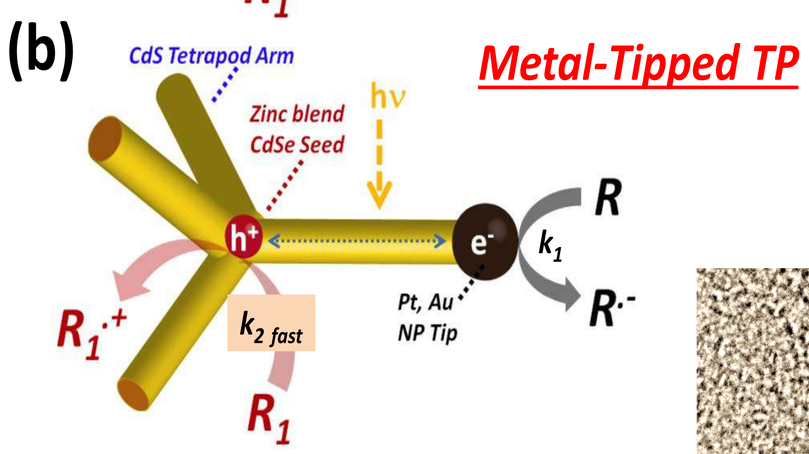


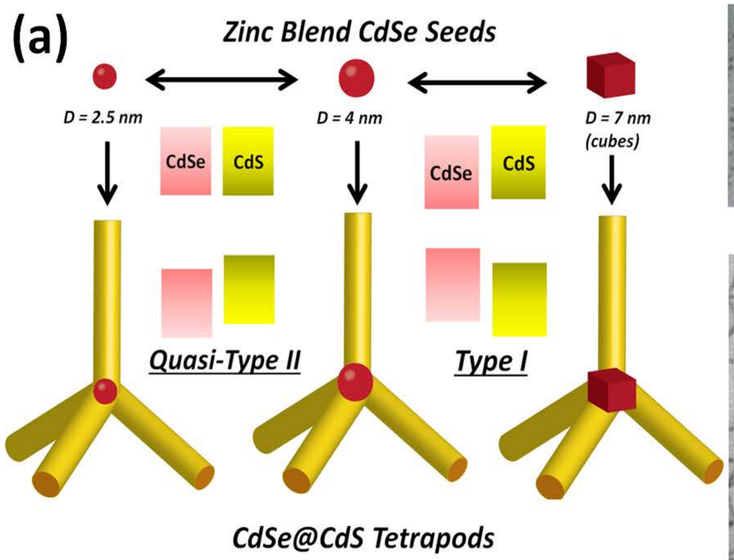
Materials for Solar Energy Conversion, Energy Storage and Optoelectronics

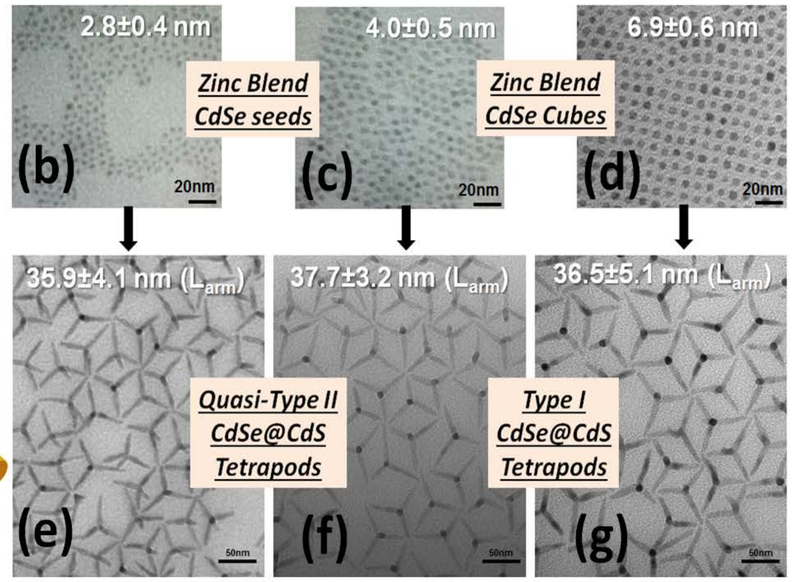
THE UNIVERSITY OF ARIZONA
Research, Discovery & Innovation

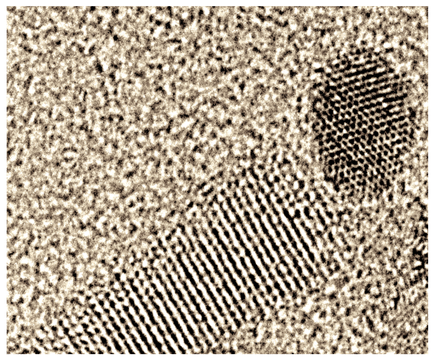
New Semiconductor Nanorods and Tetrapods for Formation of Solar Fuels
– Jeff Pyun, Scott Saavedra, Neal Armstrong - CBC











Department of Energy
= Office of Science

Materials for Solar Energy Conversion, Energy Storage and Optoelectronics

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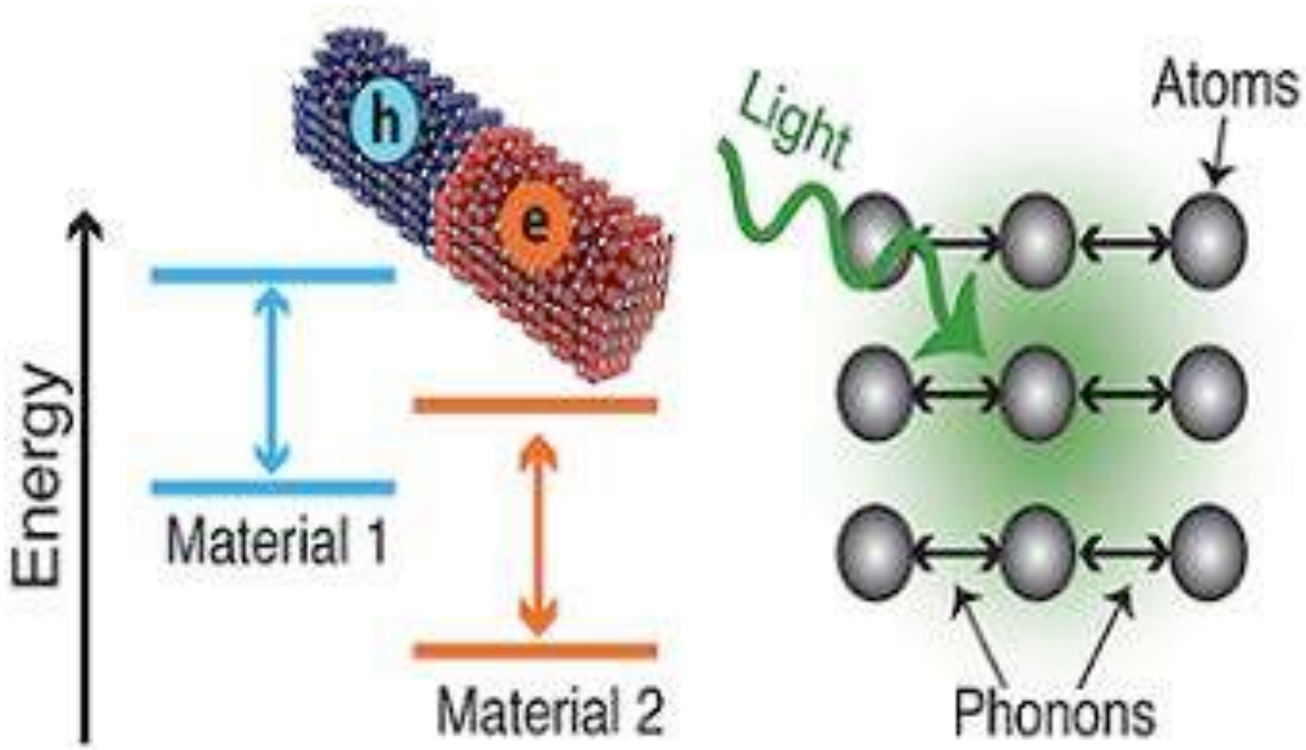
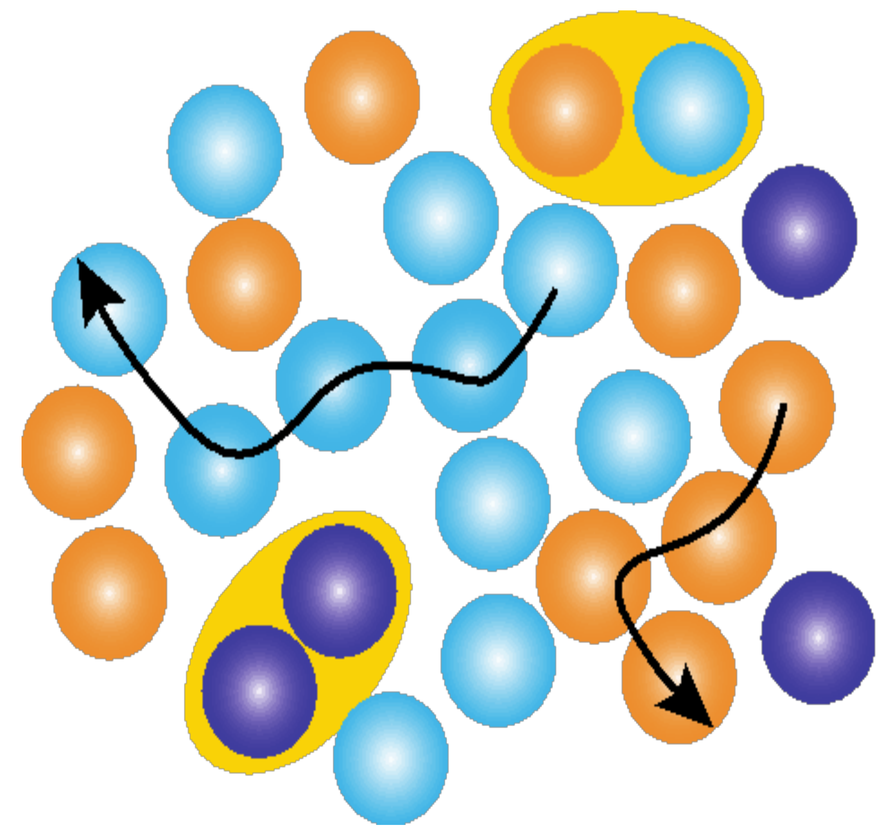
Research, Discovery & Innovation

Photoactive Nano-crystalline Semiconductors and Photosynthetic Aggregates – Vanessa Huxter - CBC

Ultrafast Optical Switching in Strained Nanocrystal Heterostructures



Hidden Interactions in Photosynthetic Aggregates



Materials for Solar Energy Conversion, Energy Storage and Optoelectronics

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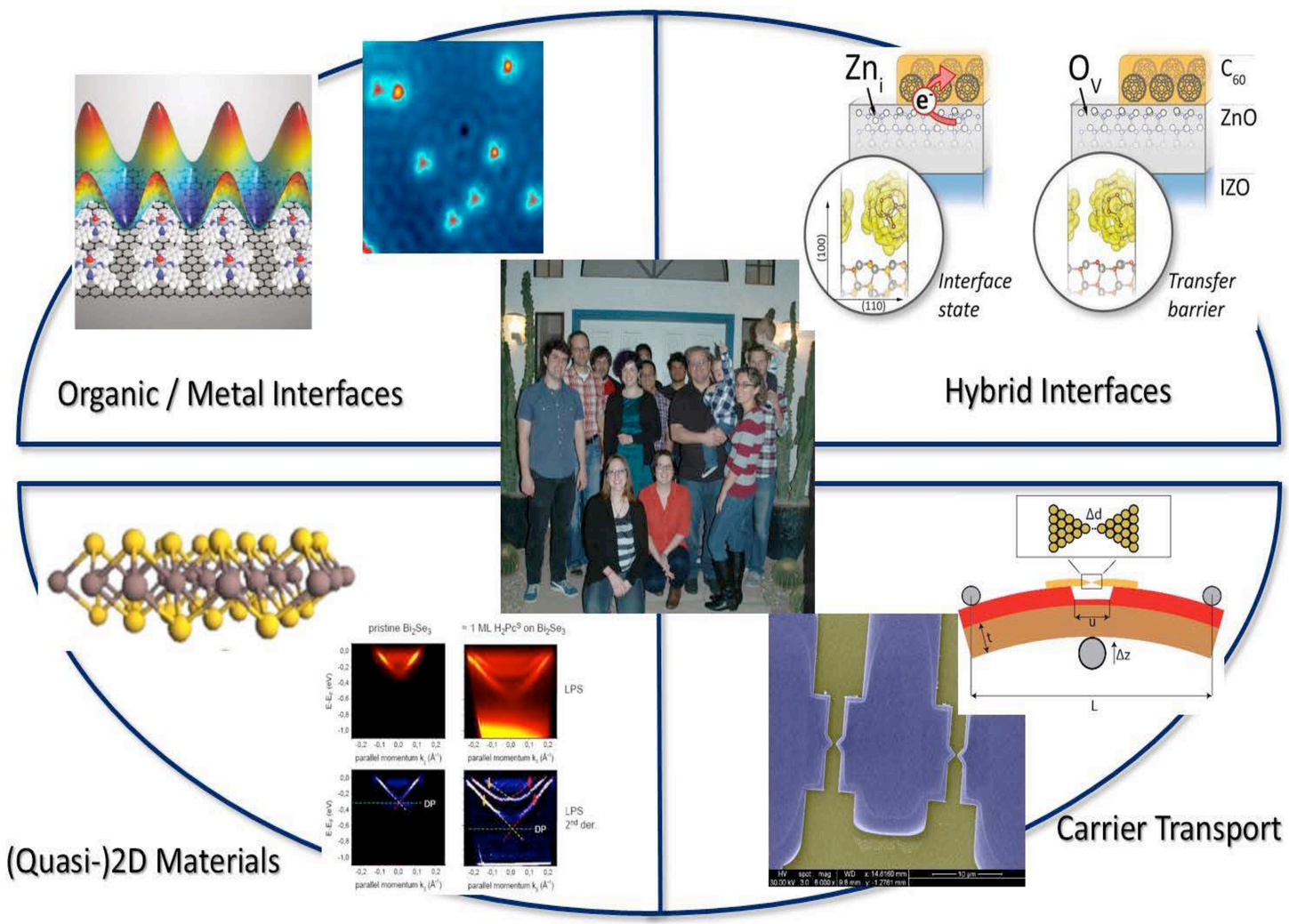
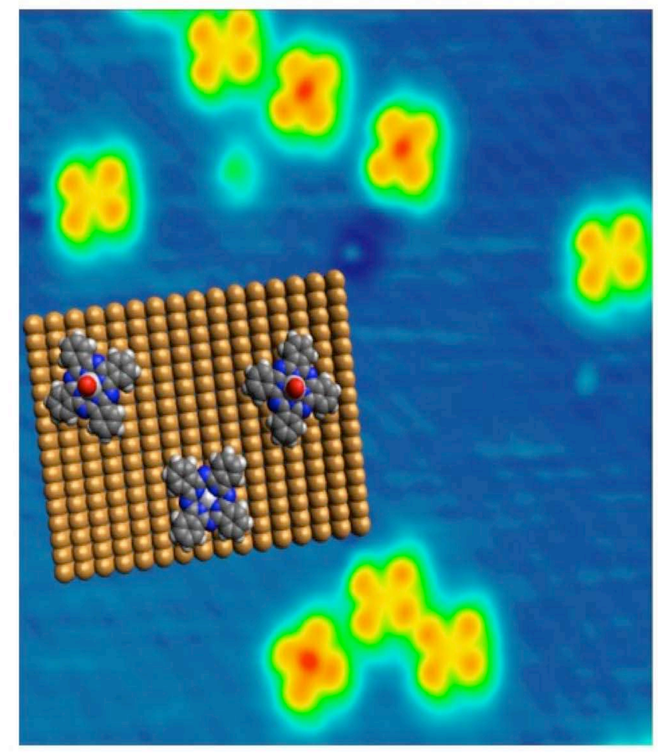
interfacial processes in organic electronic devices: organic photovoltaic cells, organic thermoelectrics, organic spin valves – Oliver Monti - CBC

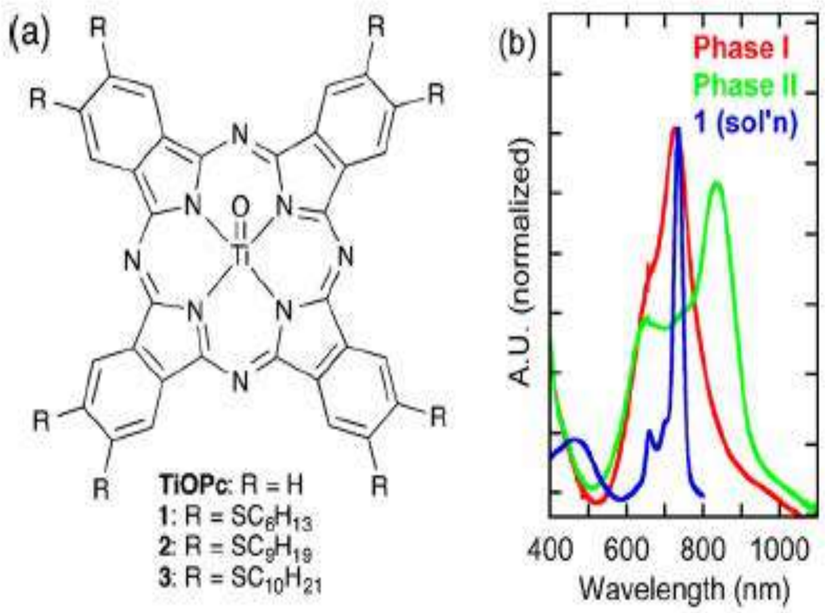


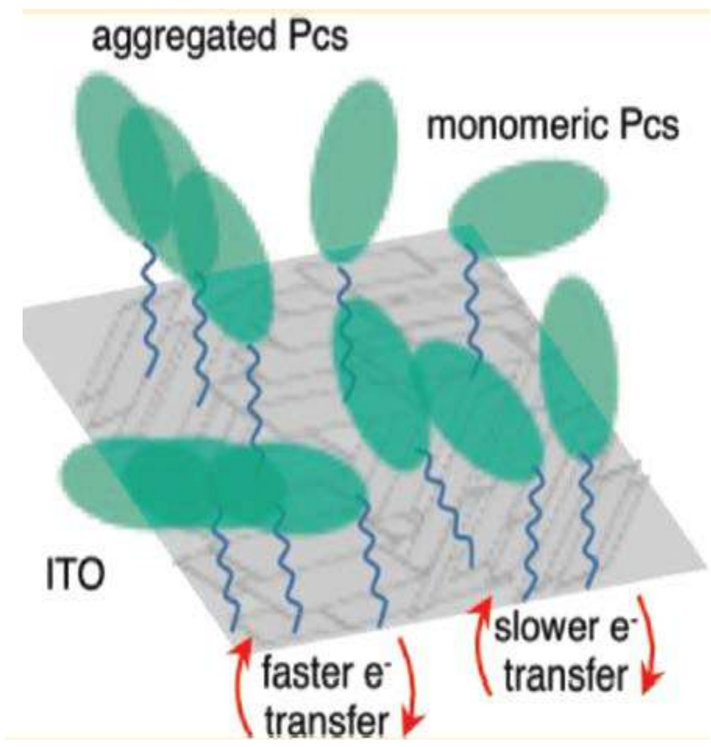


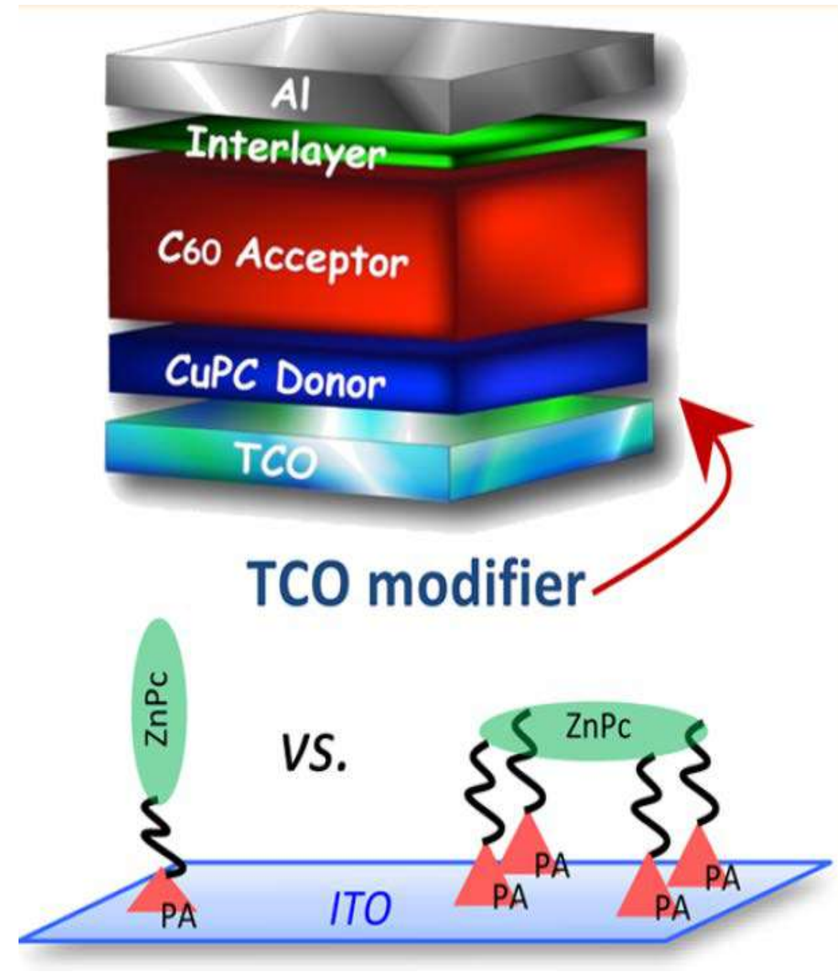
Materials for Solar Energy Conversion, Energy Storage and Optoelectronics

THE UNIVERSITY OF ARIZONA
Research, Discovery & Innovation

New solution processed active layers and interfacial modifiers for organic solar cells – McGrath, Saavedra - CBC







Materials for Solar Energy Conversion, Energy Storage and Optoelectronics

THE UNIVERSITY OF ARIZONA
Research, Discovery & Innovation

Light Management Materials: PV and Photothermal Energy Conversion – Bob Norwood – Op. Sci.

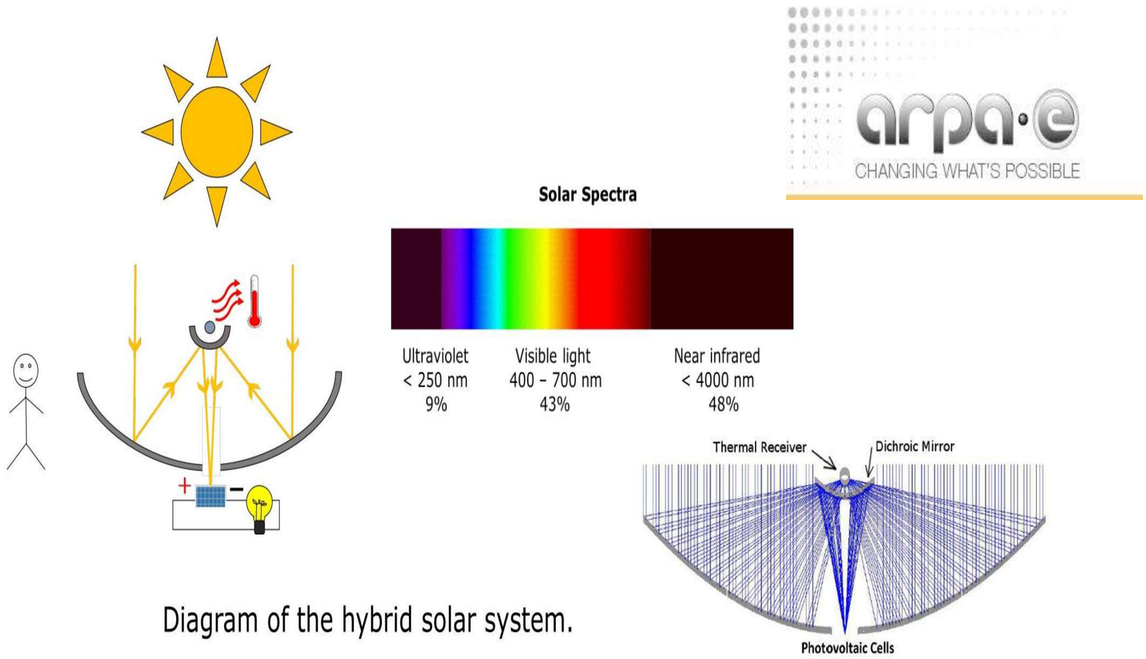
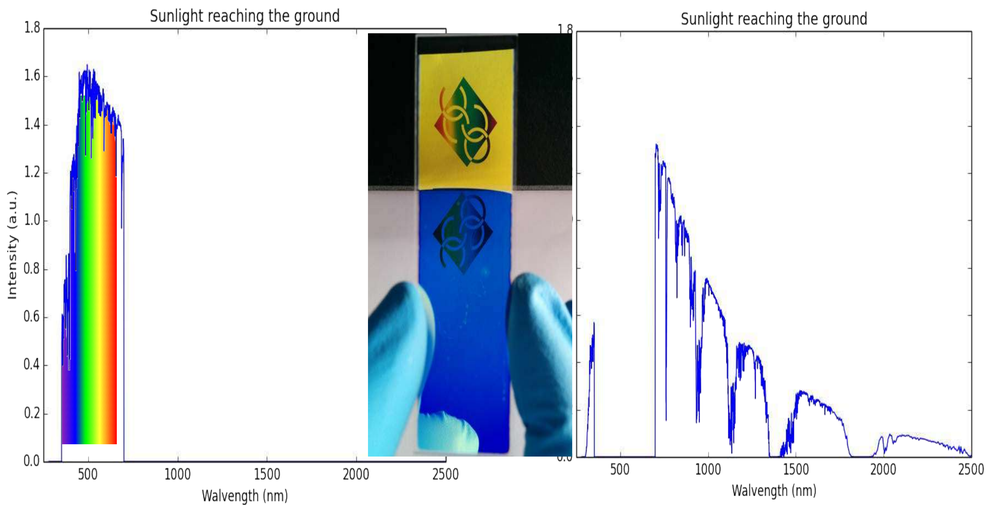
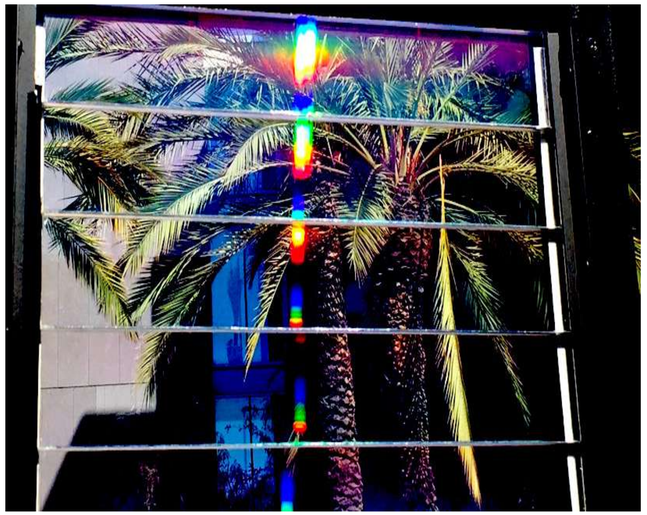
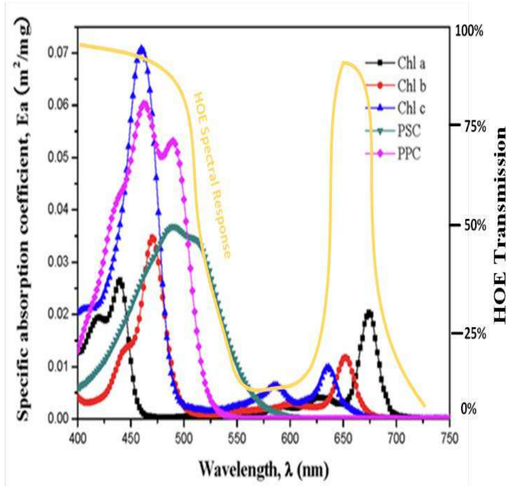


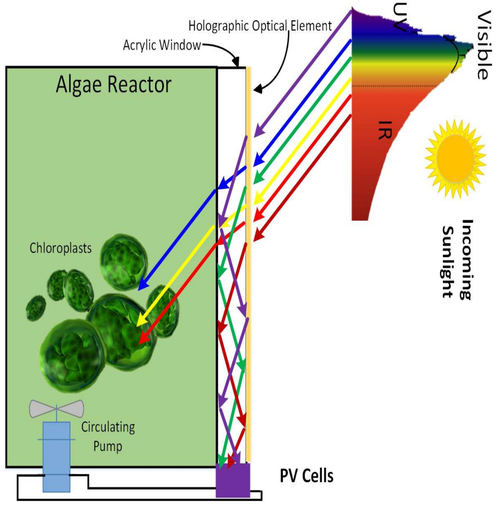
Diagram of the hybrid solar system.



Light Management Materials: Holographic Optical Elements for Solar Glass – Lloyd Lacomb/Nasser Peyghambarian – Op. Sci.







Materials for Solar Energy Conversion, Energy Storage and Optoelectronics

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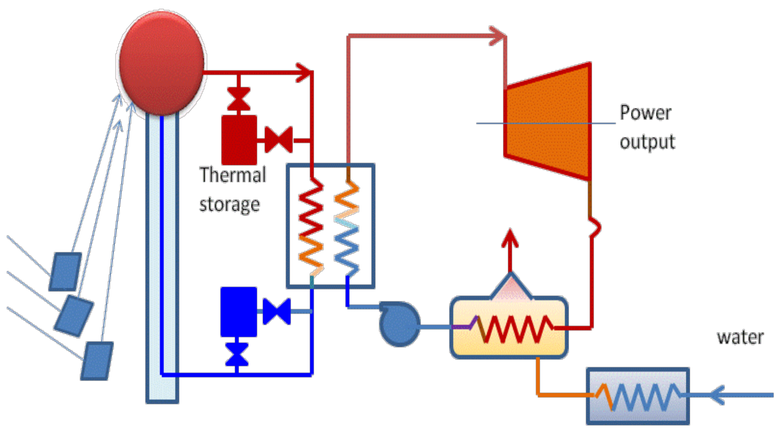
Research, Discovery & Innovation



Concentrated solar thermal power (CSP)
MURI Project funded by DOE (Perry Li *et al.*)

- "Our research is focused on finding a high-temperature heat transfer fluid to advance the efficiency of concentrated solar thermal power and develop the next generation of CSP Technology."
  - Peiwen "Perry" Li, Director of the UA Energy and Fuel Cell Laboratory

xtresol solar plant. Photograph: GE Energy Financial Services

Advantage:

- **Thermal storage & power dispatch**

Challenges:

- **>High temperature stability in heat transfer fluid (UA)**
- **>Thermal storage (UA) –** below 250°C that are stable at temperatures well above 800°C.
- **>Cost reduction (UA)**

Materials for Solar Energy Conversion, Energy Storage and Optoelectronics

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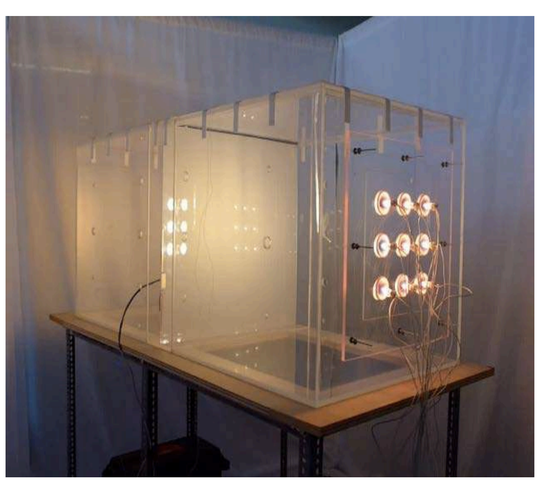
SWAMP Intelligent Building Envelope Technology Framework

Shane Smith, CAPLA; Clayton Morrison, SISTA; Pierre Lucas, MSE; Kuo-Shiuan Peng, ECE.

Materials: PCMs and Hydrogel integrated with ceramics for optic, heat transfer and moisture transport properties. The hydrogel-based façade modules for heat capacitance, daylight diffusion and evaporative cooling effects and self-Actuation of hydrogel polymers through sorption phases.

Learning-based intelligent controllers; In the specific controlled Environment Weather (EW) condition, an Artificial Intelligent Controller (AIC) to keep the Building Weather (BW) in Consistent and Optimize the Power Consumption – Called the REN simulator.



Building Weather Model

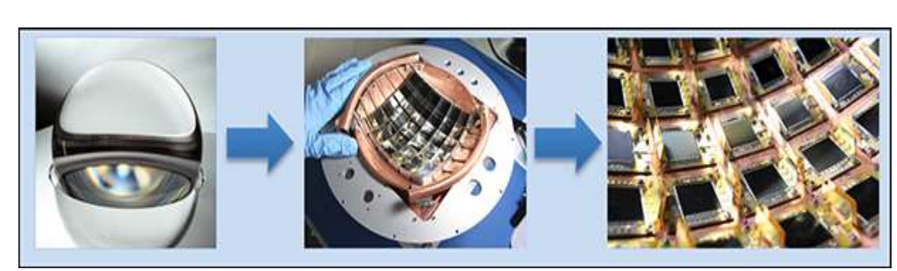
Large-scale CPV

– Roger Angel – Opt Sci.

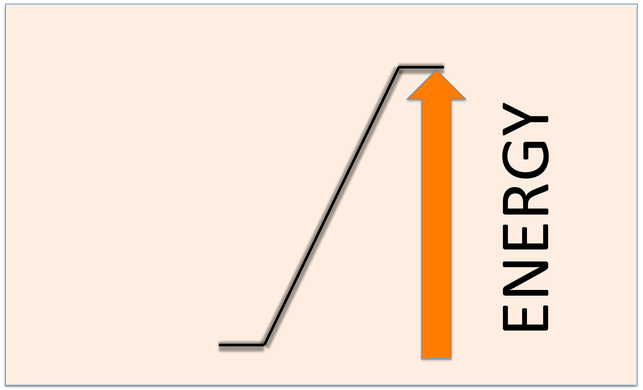
$1M, DOE Incubator
Private Funding
Patents and 1 start-up

- A tandem solar collector employing a "PVMirror" that has the potential to both increase energy conversion efficiency and provide thermal storage. A concentrating mirror, spectrum splitter, and light-to-electricity converter all in one: It consists of a curved arrangement of PV cells that absorb part of the solar spectrum and reflect the remainder to their shared focus, at which a second solar converter is placed.
- PV-PV tandems that are under concentration can also generate nearly as much energy as silicon flat-plate PV while simultaneously providing the full energy storage benefit of CSP."
  - IEEE Journal of Photovoltaics (Volume: 5, Issue: 6, Nov. 2015)

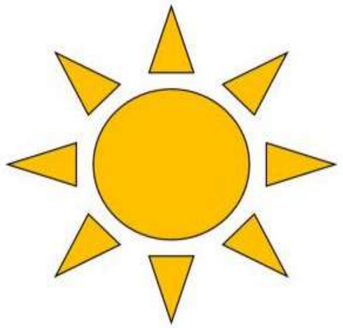
REhnu
gigawatt scale solar

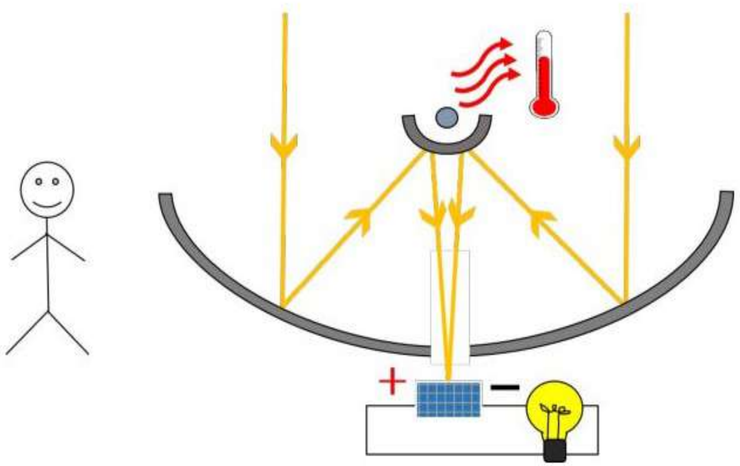


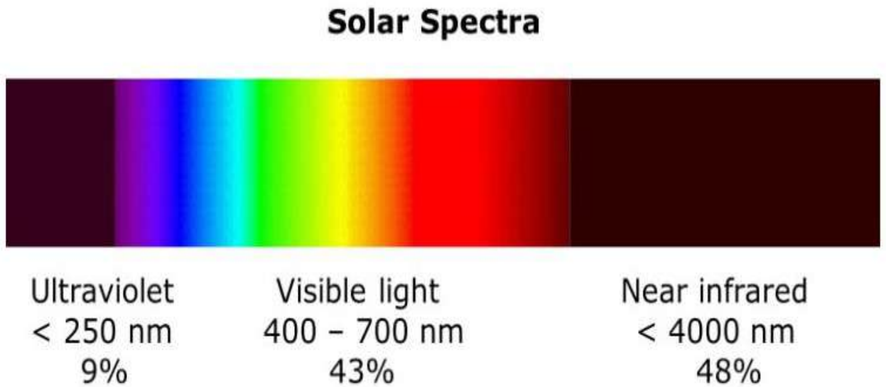
We need BOTH waste heat and electrical power:
Integrating Energy Converson and Energy Storage Systems into Water Purification/Re-Use??:



One possible route: FOCUS – Full Spectrum Optimized Conversion and Utilization of Sunlight – High Efficiency Production of Electric and Heat







College of Optical Sciences
THE UNIVERSITY OF ARIZONA®

Bob Norwood et al. (UA), Sharp Laboratories of America (lead), Solargenix, University of Arizona, University of Missouri

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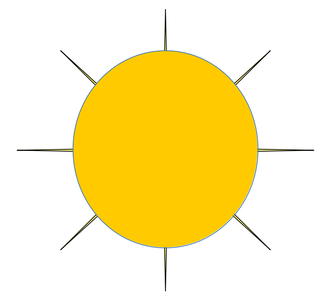
FOCUS – Solar spectrum use

Applied Optics 55, 1849 (2016)

High efficiency (>40%) III-V multijunction cells under high concentration



Classic parabolic trough with heat tube – energy can be stored for ~ 14 hrs

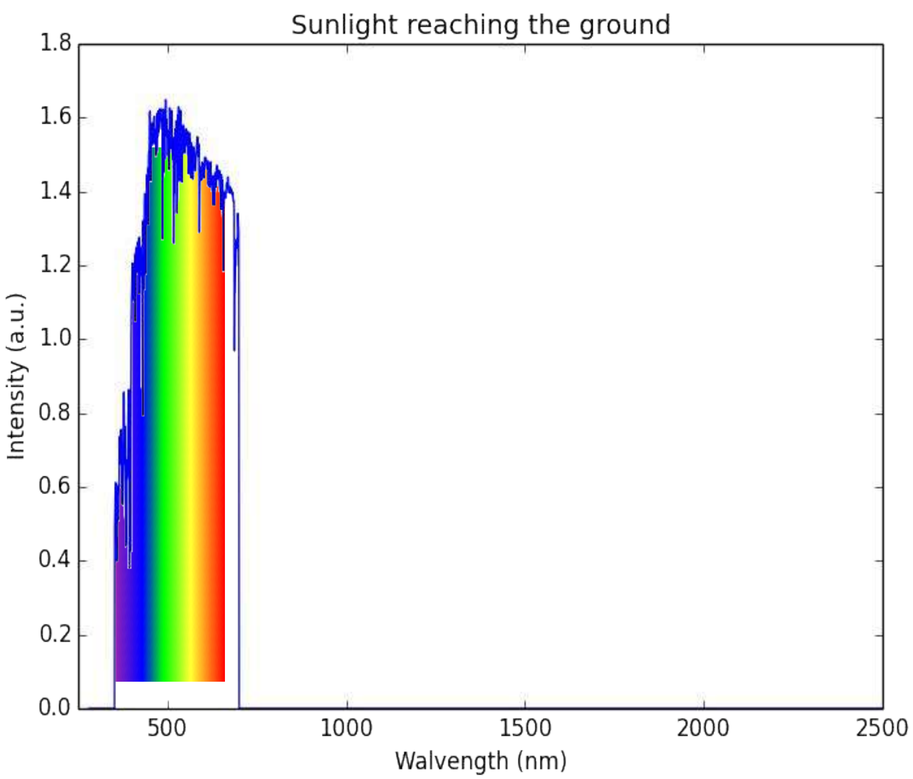
Direct electricity

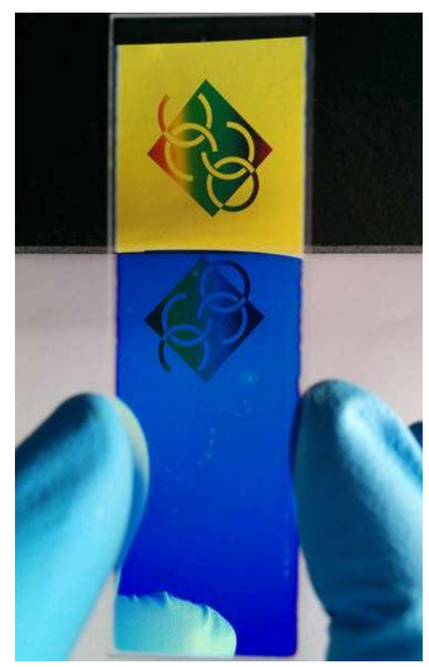
Photovoltaic

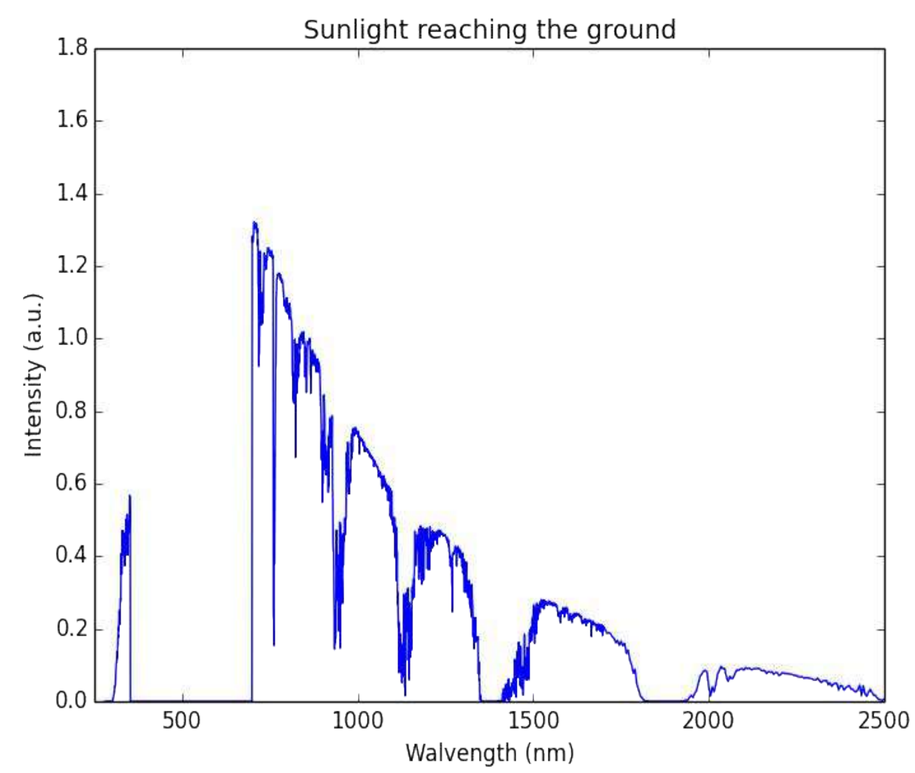
Dichroic Mirror

Dispatchable

Thermal

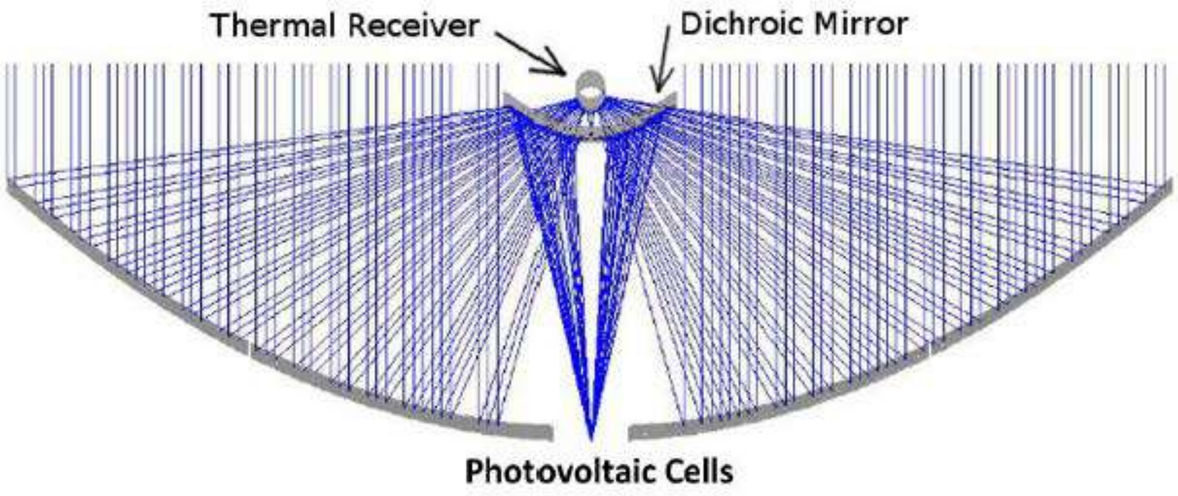






Integration of technologies is key!!

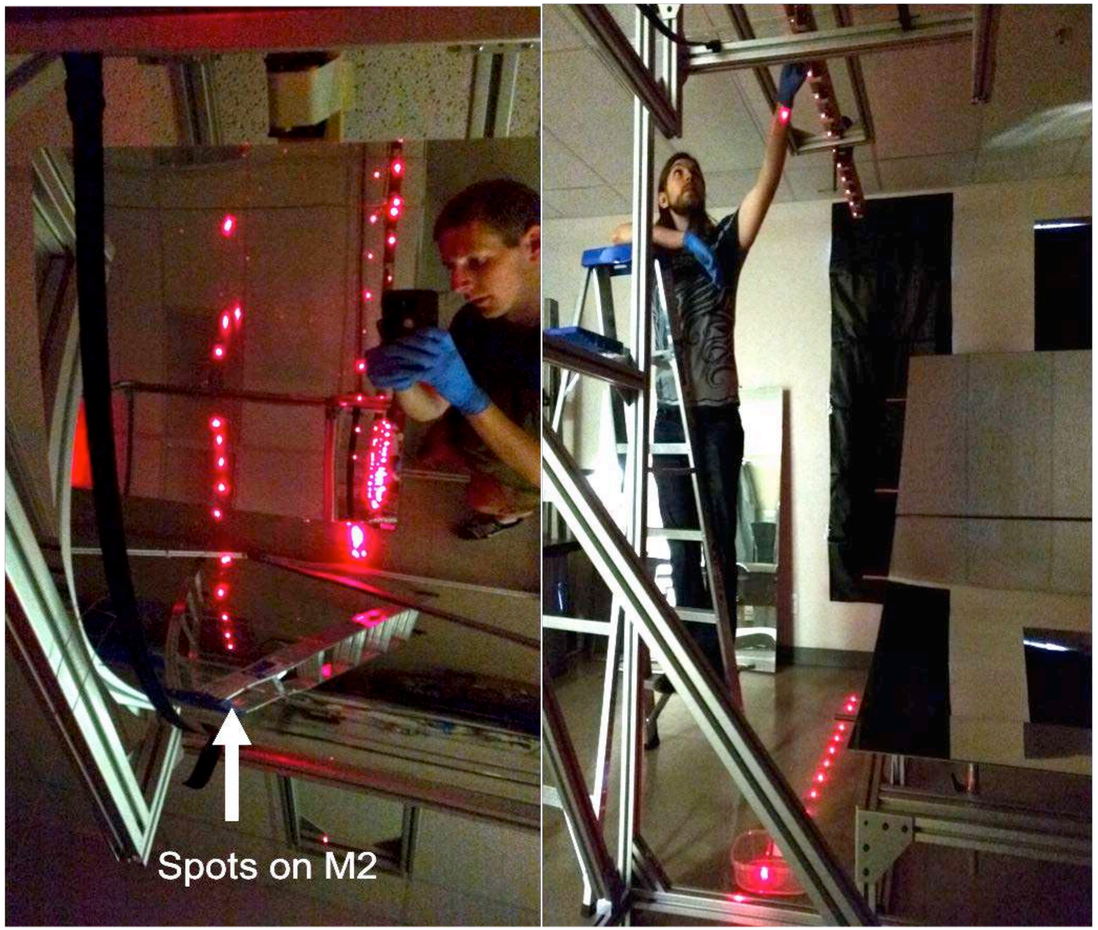
- Based on a commercial solar thermal parabolic trough with N-S tracking (Solargenix)
- A hyperbolic secondary with dichroic coating (UA)
- Custom multi-junction PV cells designed to operate under concentration (Sharp and UA)
- Goal: >40% Efficiency

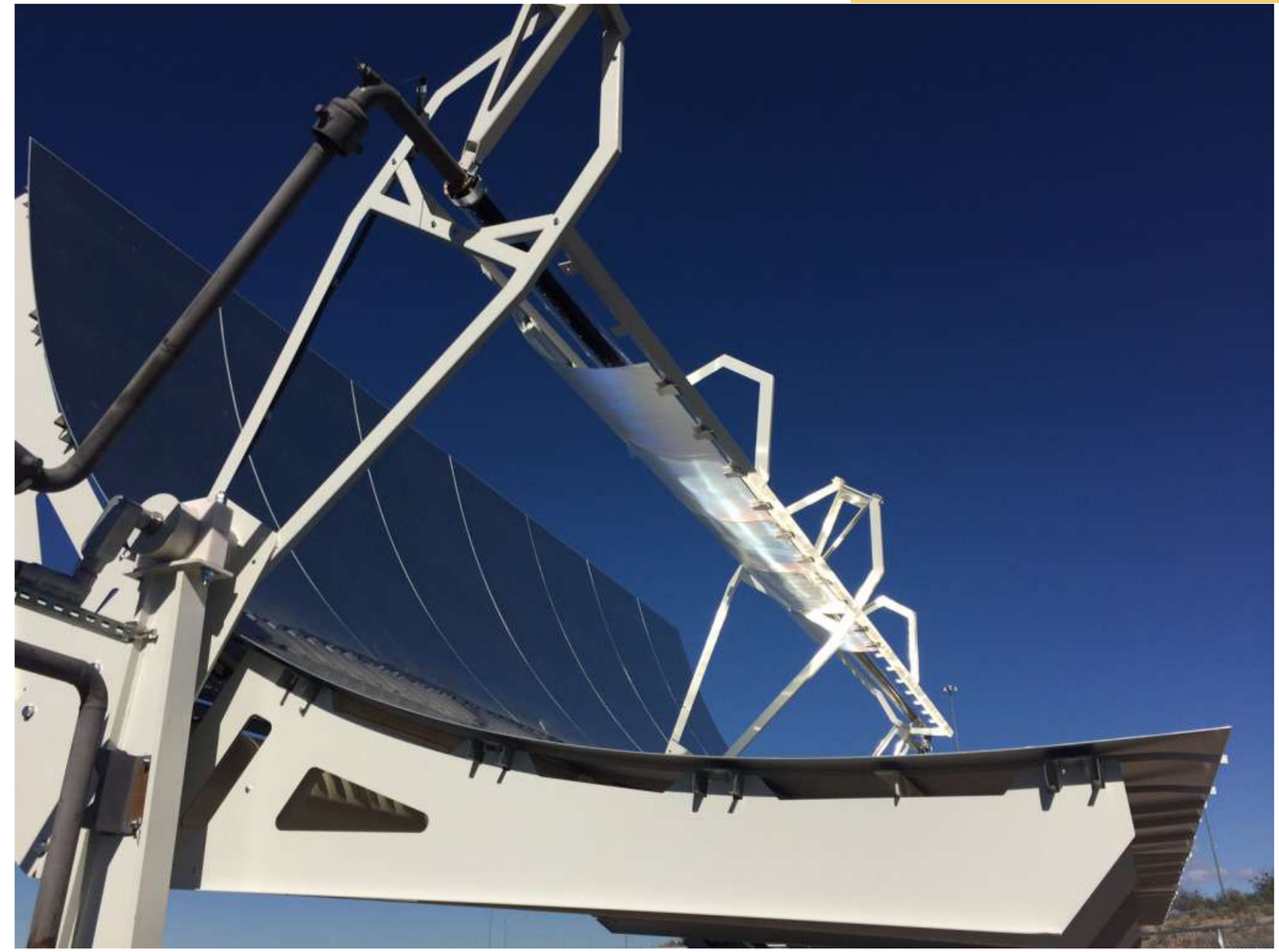


***Applied Optics* 55, 1849 (2016)**

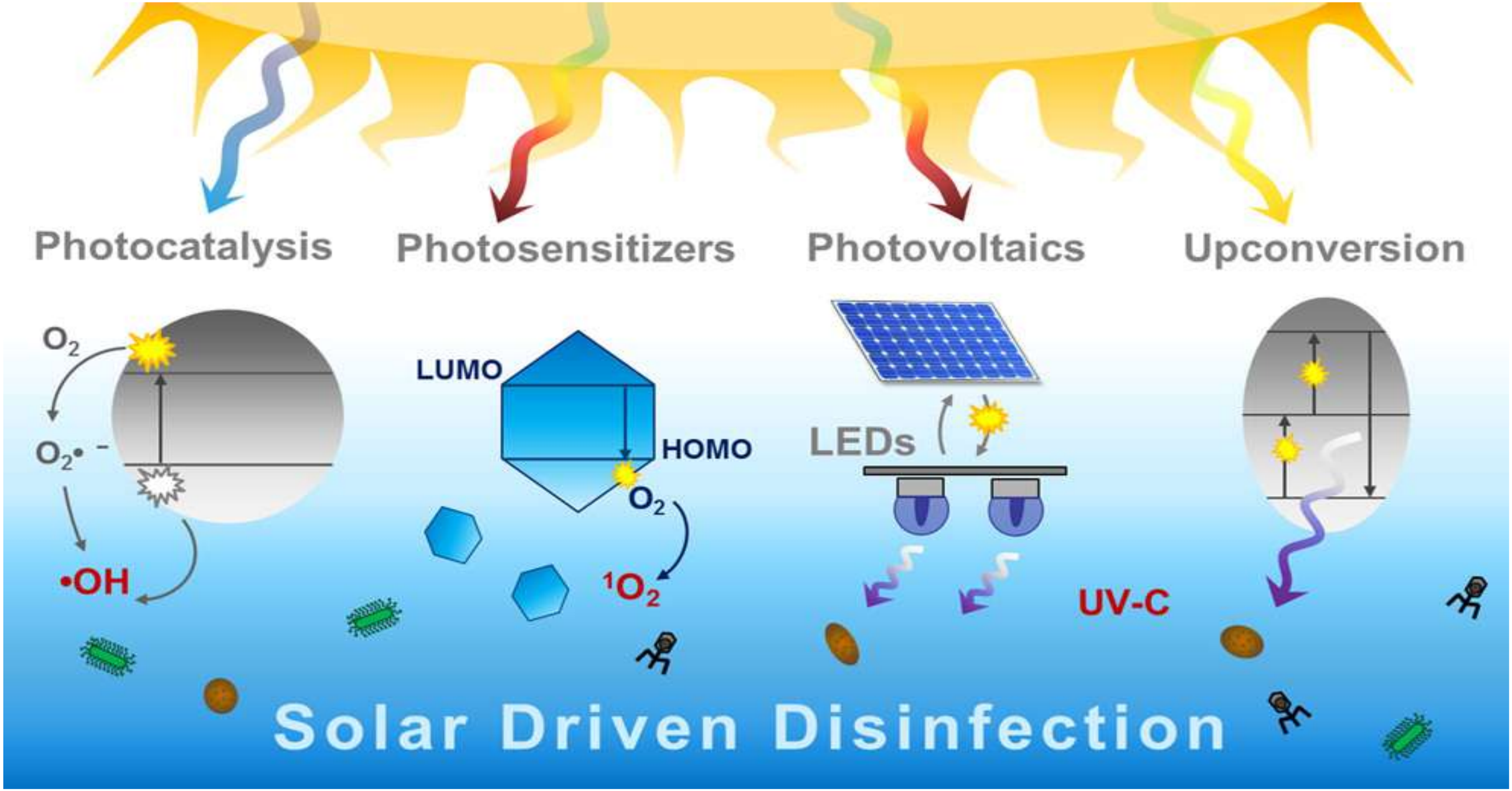
Designing spectrum-splitting dichroic filters to op
current-matched photovoltaics Alexander Miles,
Cocilovo, Brian Wheelwright, Wei Pan, Doug Tweet, and
Robert A. Norwood

Integration of technologies is key!!





- Located on the CALS West Campus near I-10 and Miracle Mile
- M2 installation is 60% complete – targeted for completion by March 15
- This is a single 8m x 5m trough, which, when optimized will put out about 4kW
- Trough tracks east-west, while concentrated PV optics track north-south



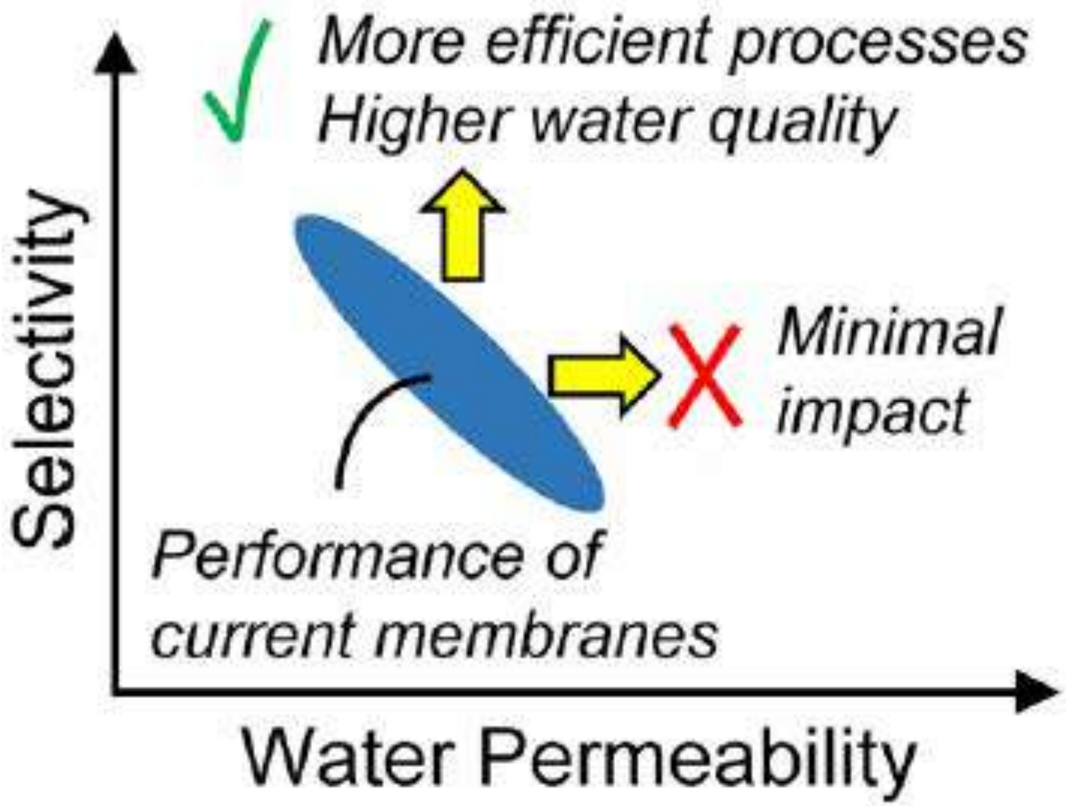
Stephanie Loeb, Ron Hofmann, and Jae-Hong Kim, Beyond the Pipeline: Assessing the Efficiency Limits of Advanced Technologies for Solar Water Disinfection Environ. Sci. Technol. Lett. 2016

The Critical Need for Increased Selectivity, Not Increased Water Permeability, for Desalination Membranes

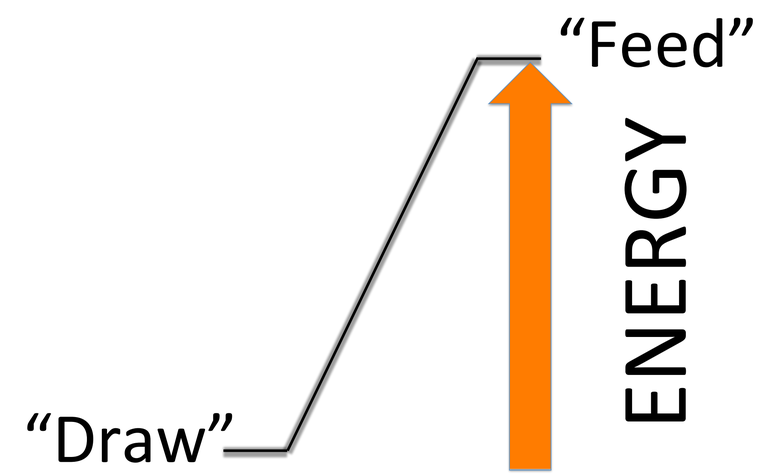
Jay R. Werber,[†] Akshay Deshmukh,[†] and Menachem Elimelech[*,†,‡]

2015

Environmental Science & Technology Letters



$$J_w = A\left(\Delta\pi_{eff} - \Delta P\right)$$



Energy required to produce a unit volume of permeate water in desalination has **decreased over the last 4 decades from ~ 16 to 2 kWh m^{-3}** (or less) for SWRO

Further reductions in energy consumption >> development of composite membranes

New materials & technologies

Water Purification

Bio-inspired

Sensor Platforms

Energy Production & Storage

Separations | Charge Transfer | Catalysis

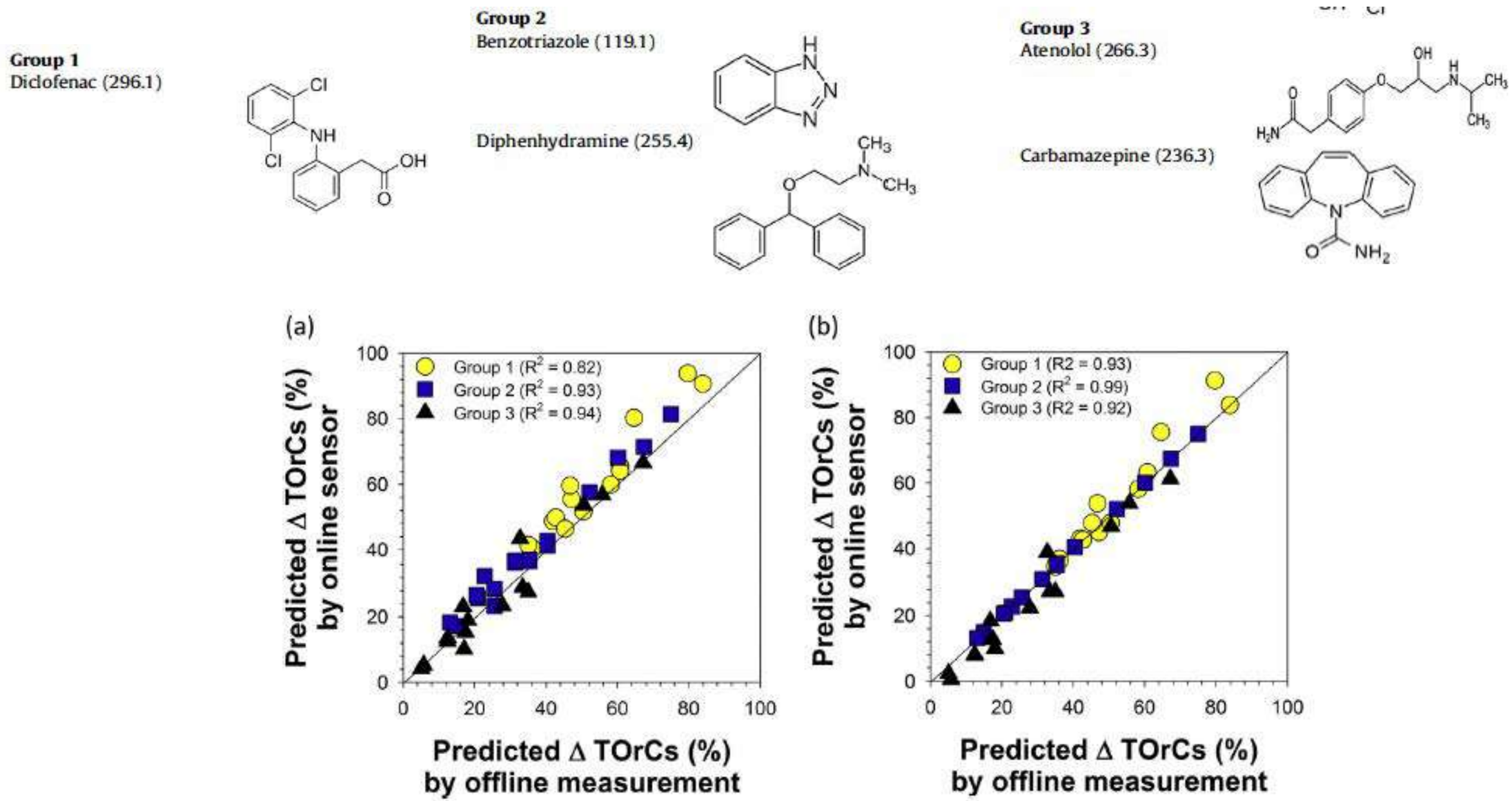
New materials platforms and systems-level technologies – flexibly targeted:

- Energy-efficient water reuse and purification – municipal, agricultural, mining, and energy production
- Economical, distributed energy sources and energy storage platforms
- Multi-analyte sensor platforms
- Atomic- and molecular-scale understanding of separations, molecular recognition, and charge transfer and catalysis.

On-line sensor monitoring for chemical contaminant attenuation during UV/H_2O_2 advanced oxidation process

Water Research 81 (2015) 250–260

Hye-Weon Yu [a, b], Tarun Anumol [a, c], Minkyu Park [a], Ian Pepper [b], Jens Scheideler [d], Shane A. Snyder [a, e, *]



CYVERSE

http://www.cyverse.org/

Smart data

Real-time Response

Sensor Networks

Regionally Specific

Precision Agriculture

Water and Energy Grid

Smart data and decision-making for “precision communities”

Measurement, analysis, and optimization (control) of chemical and physical parameters on previously unrealized scales.

Generation of massive data sets requiring new modes of transmission, storage, access, and robust links to policy and decision-making processes.

Research
Office for Research & Discovery