UNL Renewable Energy Research Panel

Dr. Chris Cornelius, *College of Engineering*
Stonie Cooper, *School of Natural Resources*
Dr. Peter Dowben, *Nebraska Center for Materials & Nanoscience*

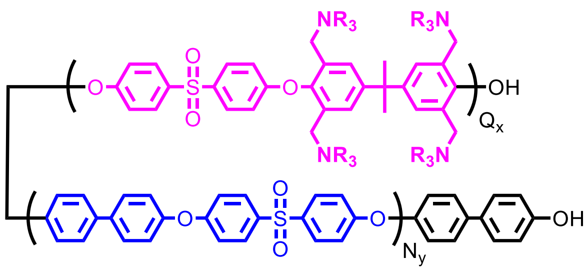
Moderator: Joe Francis, *Nebraska Department of Environment & Energy*

12TH ANNUAL
Nebraska Wind & Solar
CONFERENCE & EXHIBITION

Submit Questions at Slido.com - Code #M464

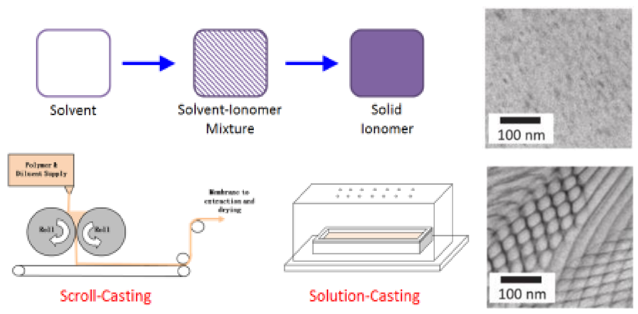
Storing Renewable Energy for Nebraska and Beyond using Vanadium Flow Batteries

Composition

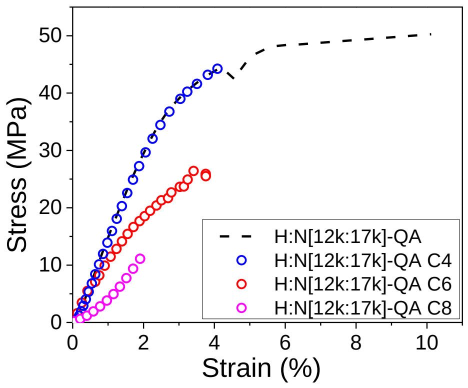


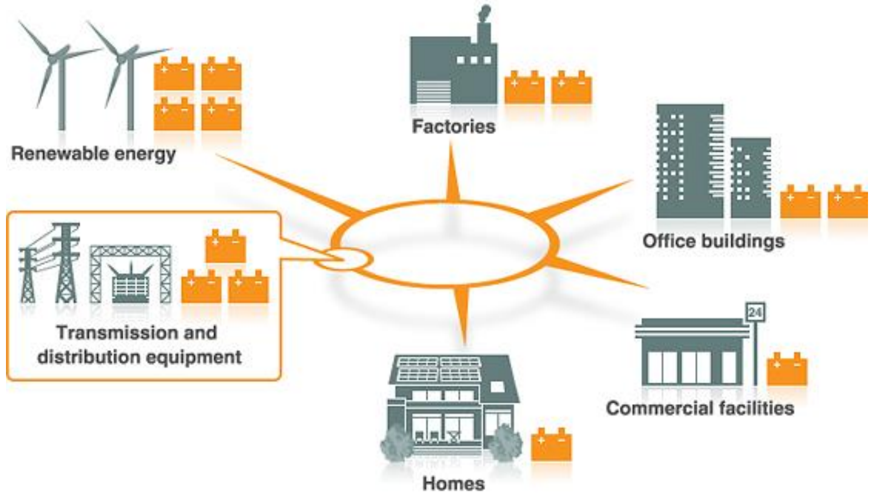
Q:N[X:Y] Multi-Block **AEM**

Processing



Properties





Chris J. Cornelius
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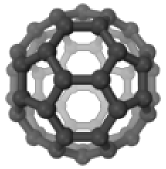
World's Top Ten Challenges
Sustainable Research

Richard Errett Smalley
1996 Nobel Prize
Fullerenes "Buckyball"

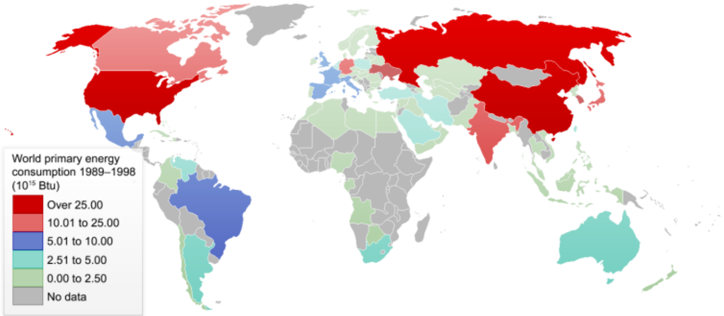


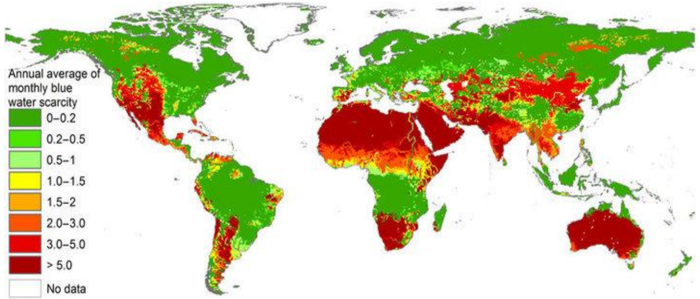
World:7.63 Billion (2018)
China: 1.38 (18.4%)
India: 1.30 (17.4%)
US: 328 Million (4.4%)

1. ENERGY
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. WAR (Terrorism)
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

1960: 3.0B

2020: 8.7B





Energy
- Supply & Demand
- Environment
- Sustainability

Water
- Supply & Demand
- Environment
- Sustainability

Motivation

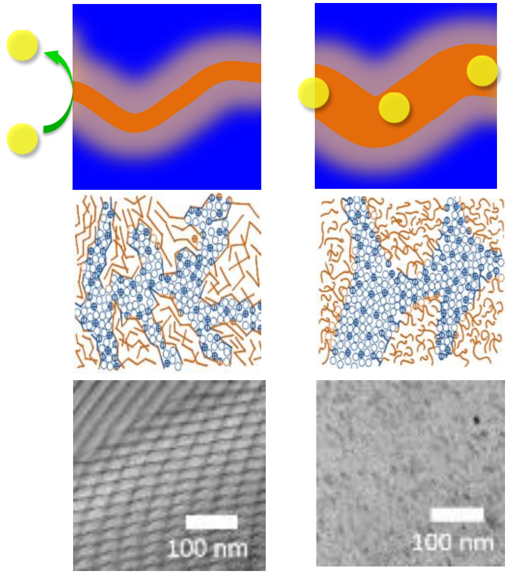
Materials and Sustainable Research

- Separations (gas, liquid, ions)
- Batteries (ions - redox)
- Fuel Cells (ion, gas, liquid)
- Coatings (barrier, biofouling)
- Drug Delivery (molecule)
- Biology (bioglass)

Composition
Physical Properties
Transport
Morphology

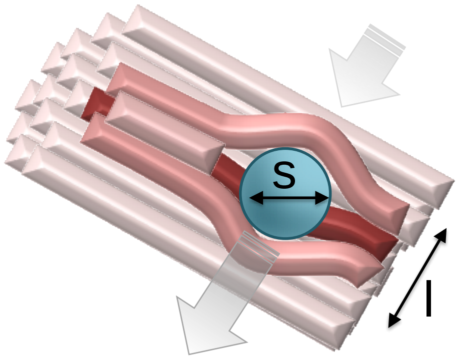
} ***Processing***

Small channel	Large channel



Solution Diffusion

P = DS

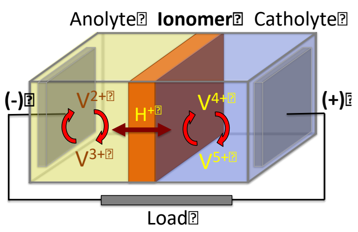


$$E_D = \frac{l\,ps^2}{4}\left(\frac{DH_v - RT}{V_m}\right)$$

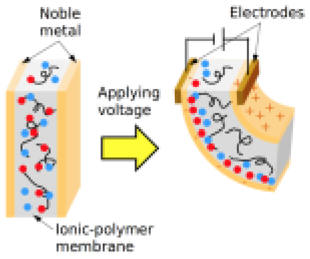
Sata, T. *J. Memb. Sci.* 2000, 167, 1–31.

Fan Y., Zhang M., Moore R.B., and Cornelius* C.J., *J. Memb.. Sci.*, 2014, *464*, 179-187.

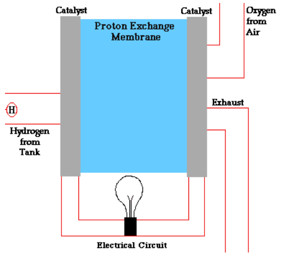
Flow-battery



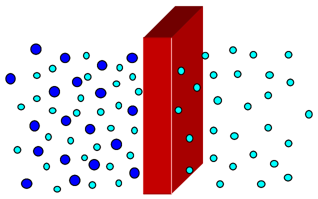
Actuator



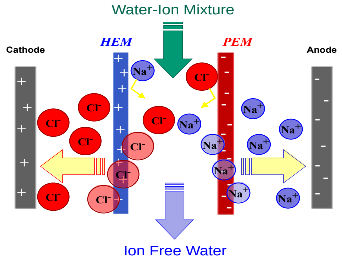
PEMFC



Gas Separation

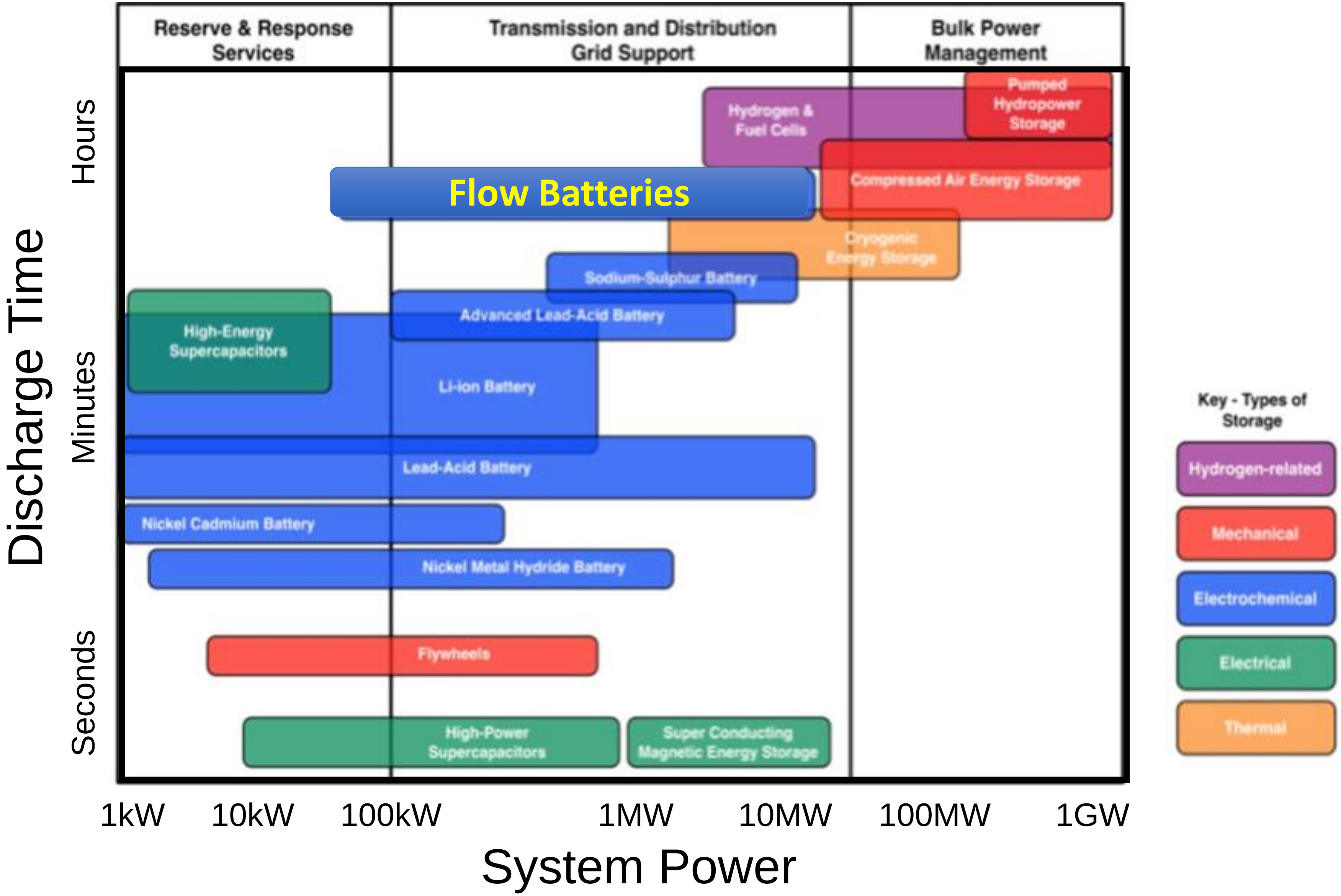


Desalination



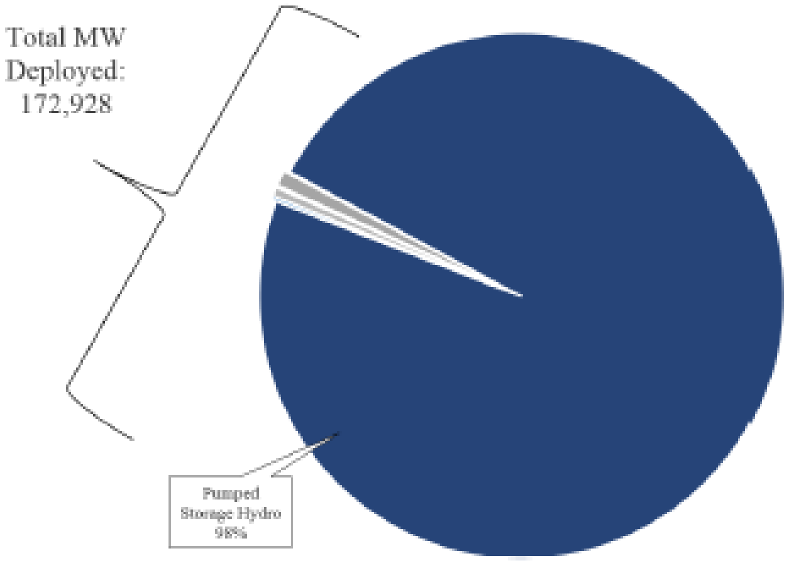
Energy Storage

Technology Summary



Energy Storage

Technology Summary and Pumped-Storage Hydropower (PSH)



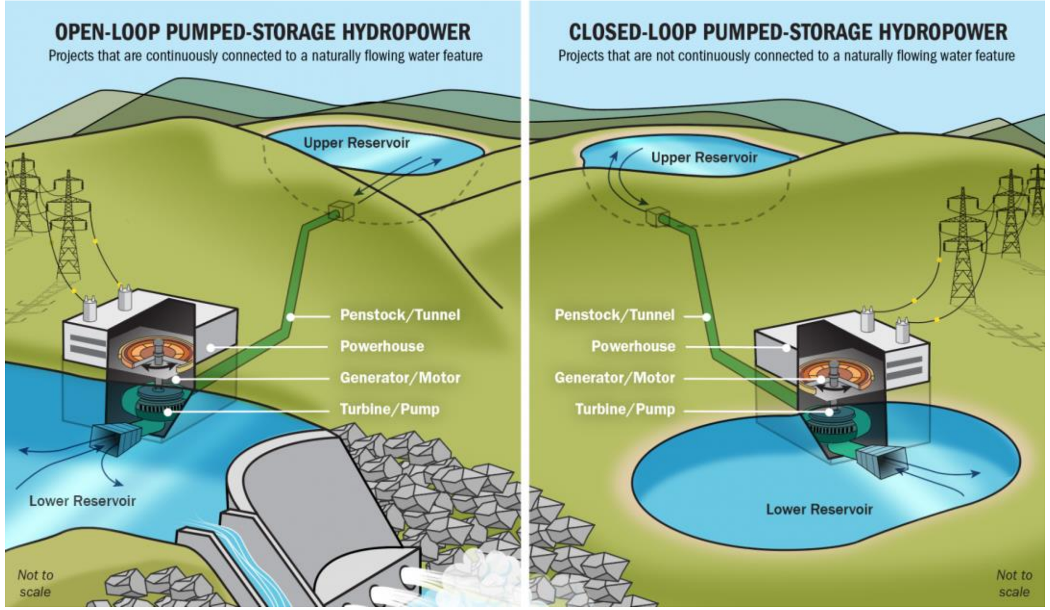
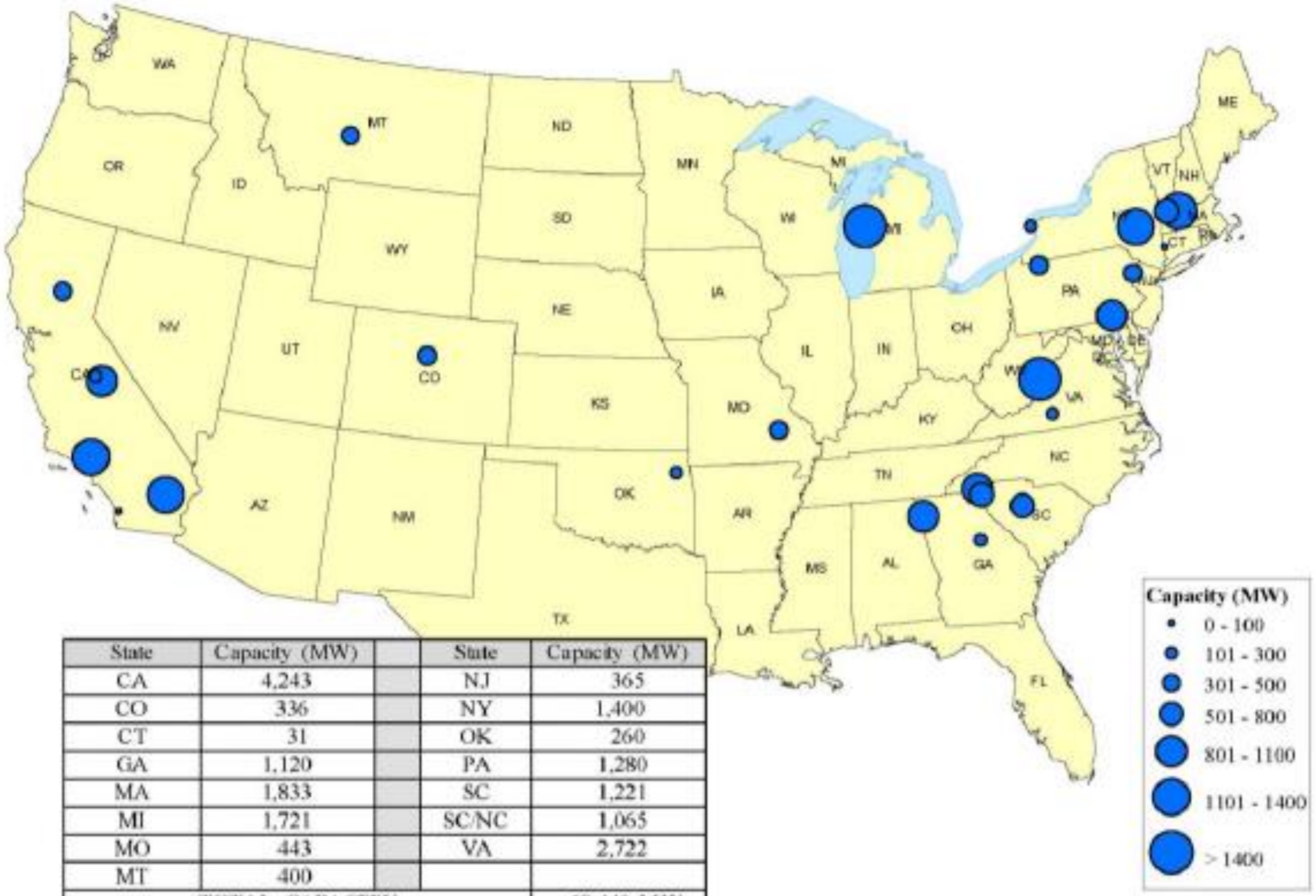


Table 2.1. Worldwide deployment by technology type, 2018.

Technology	MW Deployed
Sodium sulfur	189
Lithium-ion	1,629
Lead acid	75
Sodium metal halide	19
Flow battery	72
PSH	169,557
CAES	407
Flywheels	931
Electrochemical capacitor	49
Total	172,928

Energy Storage

Technology Summary and Pumped-Storage Hydropower (PSH)



State	Capacity (MW)		State	Capacity (MW)
CA	4,243		NJ	365
CO	336		NY	1,400
CT	31		OK	260
GA	1,120		PA	1,280
MA	1,833		SC	1,221
MI	1,721		SC/NC	1,065
MO	443		VA	2,722
MT	400			
TOTAL CAPACITY				18,440 MW

Source: FERC Staff, October 1, 2018

Federal energy regulatory commission map of PSH projects that have received licenses as of October 2018.

Energy Storage

Technology Summary

Type	Technology	Description	Typical Power Range	Typical Energy Range
Electrochemical Energy Storage	Sodium-sulfur battery	A molten-salt battery made up of sodium (Na) and sulfur (S) that operates at high temperature ranges and is primarily suitable for >4-hour duration applications.	Several kW to few MW	100 kWh or higher
	Li-ion battery	A battery based on charge and discharge reactions from a lithiated metal oxide cathode and a graphite anode. This battery technology is used in a wide variety of applications.	1 kW to 100 MW	<200 MWh
	Lead-acid battery	A battery made up of lead dioxide (PbO_2) for the positive electrode and a spongy lead (Pb) negative electrode. Vented and valve-regulated batteries make up two subtypes of this technology.	Up to a few MW	<10 MWh
	Sodium metal halide battery	A molten battery made up of nickel (Ni), sodium chloride (NaCl), and sodium (Na) which is kept at a temperature between 270°C and 350°C. Batteries using other materials are being developed to decrease cost and operation temperature.	Several MW	4 kWh – several MWh
	Zinc-hybrid cathode battery	A high-energy density battery storage technology that uses inexpensive and widely available materials. Zinc-hybrid cathode batteries use non-flammable, near-neutral pH aqueous electrolytes that are non-dendritic and do not absorb CO_2.	250 kW subsystem repeat unit up to 2 MW	1 MWh subsystem repeat unit up to 8 MWh
	Redox flow battery	A battery in which energy storage in the electrolyte tanks is separated from power generation in stacks. The stacks consist of positive and negative electrode compartments divided by a separator or an ion exchange membrane through which ions pass to complete the electrochemical reactions. Scalability due to modularity, ability to change energy and power independently, and long cycle and calendar life are attractive features of this technology.	Several kW – 30 MW	100 kW to 120 MWh

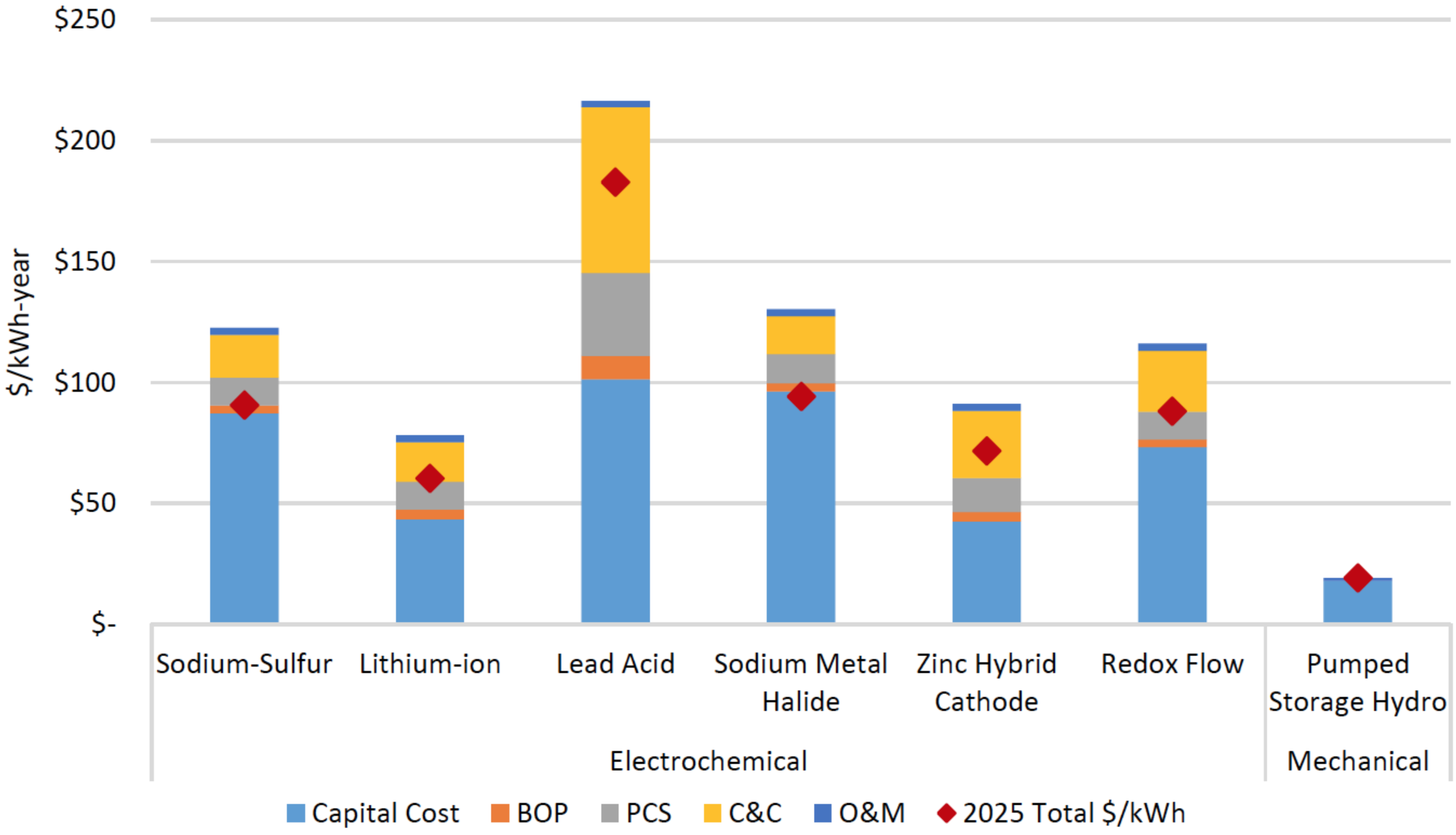
Energy Storage

Technology Summary

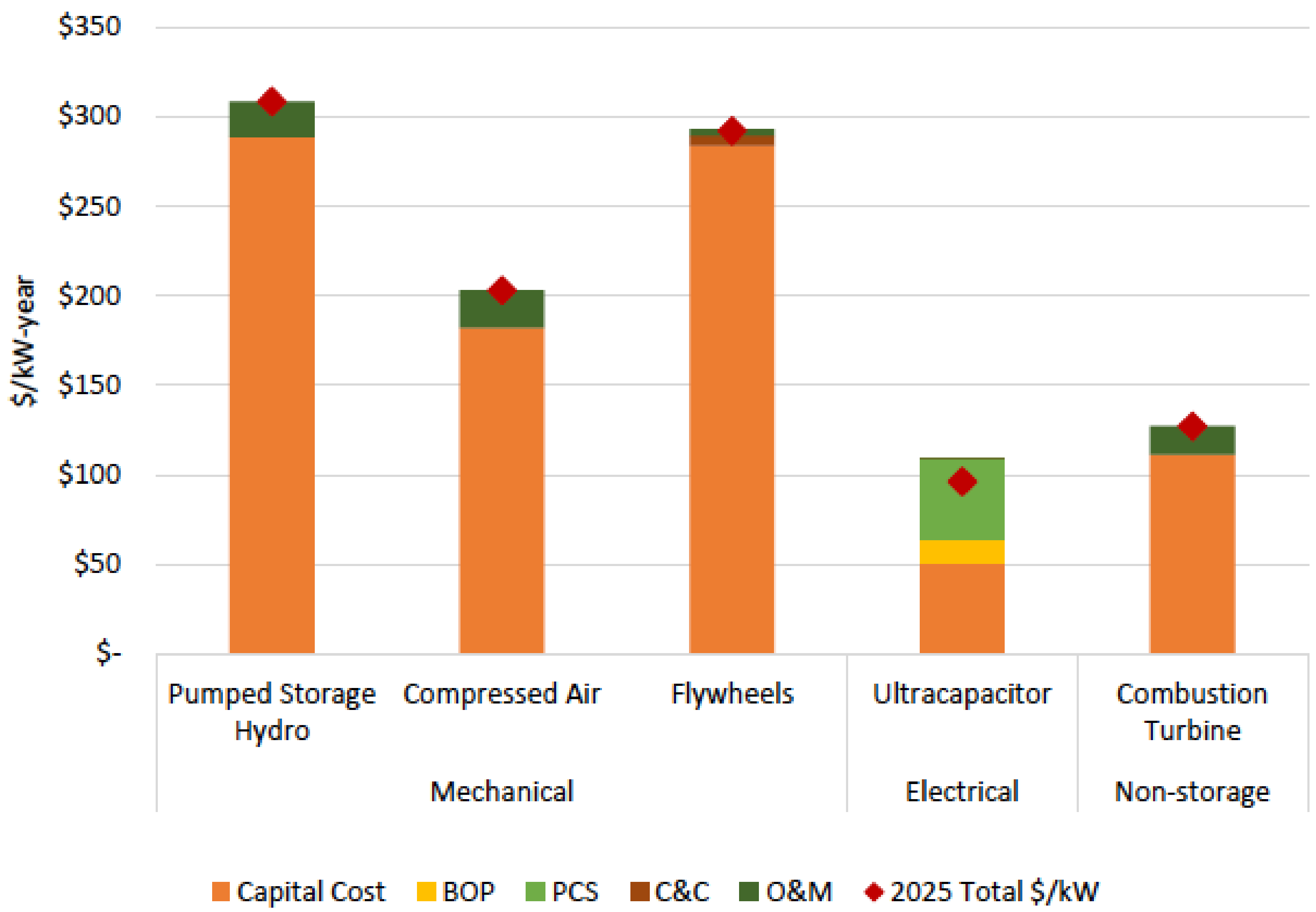
Type	Technology	Description	Typical Power Range	Typical Energy Range
Mechanical Energy Storage	Compressed air energy storage	This energy storage system is based on using electricity to compress air and store it in underground caverns. The air is released when needed and passed through a turbine to generate electricity.	Up to 500 MW	1 GWh to 20 GWh
	Flywheels	A storage system that relies on kinetic energy from rotor spinning through a "nearly frictionless enclosure" that can provide short-term power through inertia.	Up to 20 MW	Up to 5 MWh
	Pumped storage hydro	A technology that stores energy by pumping water from a lower to a higher reservoir and then releasing it back through the connection, passing through a turbine(s), which generates electricity. This technology is typically used for grid-scale storage.	Up to 3,600 MW	Up to 40 GWh
Electrical Energy Storage	Ultracapacitor	Ultracapacitors store energy at the double layer of each electrode separated by a dielectric and can discharge energy instantaneously. Due to lack of chemical reaction, the cycle life is orders of magnitude higher than battery cycle life.	250 kW to 2 MW	2.5 kWh to 20 kWh
Non-storage Generation	Combustion turbine	A gas turbine converts fuel such as natural gas to mechanical energy, which drives a generator to produce electricity.	10 kW – 100 MW	Not applicable

Energy Storage

Technology Summary

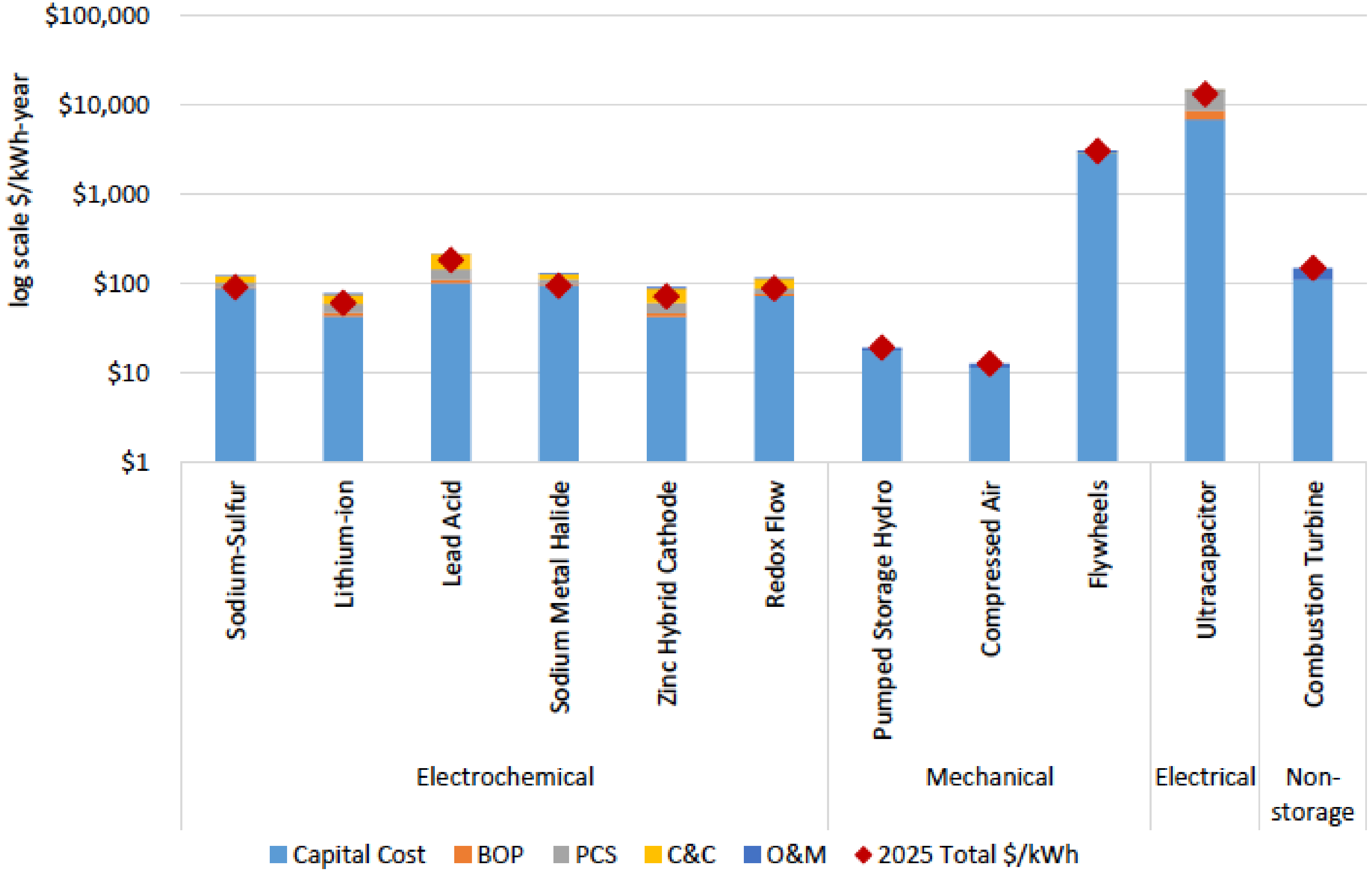


Energy Storage
Technology Summary



Energy Storage

Technology Summary



Energy Storage

Technology Summary

Table ES.1. Summary of compiled 2018 findings and 2025 predictions for cost and parameter ranges by technology type – BESS.[a]

Parameter	Sodium-Sulfur Battery		Li-Ion Battery		Lead Acid		Sodium Metal Halide		Zinc-Hybrid Cathode		Redox Flow Battery	
	2018	2025	2018	2025	2018	2025	2018	2025	2018	2025	2018	2025
Capital Cost – Energy Capacity ($/kWh)	400-1,000 **661**	(300-675) **(465)**	223-323 **271**	(156-203) **(189)**	120-291 **260**	(102-247) **(220)**	520-1,000 **700**	(364-630) **(482)**	265-265 **265**	(179-199) **(192)**	435-952 **555**	(326-643) **(393)**
Power Conversion System (PCS) ($/kW)	230-470 **350**	(184-329) **(211)**	230-470 **288**	(184-329) **(211)**	230-470 **350**	(184-329) **(211)**	230-470 **350**	(184-329) **(211)**	230-470 **350**	(184-329) **(211)**	230-470 **350**	(184-329) **(211)**
Balance of Plant (BOP) ($/kW)	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**
Construction and Commissioning ($/kWh)	121-145 **133**	(115-138) **(127)**	92-110 **101**	(87-105) **(96)**	160-192 **176**	(152-182) **(167)**	105-126 **115**	(100-119) **(110)**	157-188 **173**	(149-179) **(164)**	173-207 **190**	(164-197) **(180)**
Total Project Cost ($/kW)	2,394-5,170 **3,626**	(1,919-3,696) **(2,674)**	1,570-2,322 **1,876**	(1,231-1,676) **(1,446)**	1,430-2,522 **2,194**	(1,275-2,160) **(1,854)**	2,810-5,094 **3,710**	(2,115-3,440) **(2,674)**	1,998-2,402 **2,202**	(1,571-1,956) **(1,730)**	2,742-5,226 **3,430**	(2,219-3,804) **(2,598)**
Total Project Cost ($/kWh)	599-1,293 **907**	(480-924) **(669)**	393-581 **469**	(308-419) **(362)**	358-631 **549**	(319-540) **(464)**	703-1,274 **928**	(529-860) **(669)**	500-601 **551**	(393-489) **(433)**	686-1,307 **858**	(555-951) **(650)**
O&M Fixed ($/kW-yr)	10	(8)	10	(8)	10	(8)	10	(8)	10	(8)	10	(8)
O&M Variable (cents/kWh)	0.03		0.03		0.03		0.03		0.03		0.03	
System Round-Trip Efficiency (RTE)	0.75		0.86		0.72		0.83		0.72		0.675	(0.7)
Annual RTE Degradation Factor	0.34%		0.50%		5.40%		0.35%		1.50%		0.40%	
Response Time (limited by PCS)	1 sec		1 sec		1 sec		1 sec		1 sec		1 sec	
Cycles at 80% Depth of Discharge	4,000		3,500		900		3,500		3,500		10,000	
Life (Years)	13.5		10		2.6	(3)	12.5		10		15	
MRL	9	(10)	9	(10)	9	(10)	7	(9)	6	(8)	8	(9)
TRL	8	(9)	8	(9)	8	(9)	6	(8)	5	(7)	7	(8)

(a) An E/P ratio of 4 hours was used for battery technologies when calculating total costs.
MRL = manufacturing readiness level; O&M = operations and maintenance; TRL = technology readiness level.

Energy Storage
Technology Summary

Table ES.2. Summary of compiled 2018 findings and 2025 predictions for cost and parameter ranges by technology type – non-BESS.

Parameter	Pumped Storage Hydropower[(a)]				Combustion Turbine	CAES[(a)]	Flywheel[(b)]	Ultracapacitor[(c)]
Capital Cost – Energy Capacity ($/kW)	1,700-3,200 **2,638**				678-1,193 **940**	1,050-2,544 **1,669**	600-2,400 **2,400**	240-400 **400**
Power Conversion System (PCS) ($/kW)	Included in Capital Cost				N/A	N/A	Included in Capital Cost	350 (211)
Balance of Plant (BOP) ($/kW)								100 (95)
Construction and Commissioning ($/kW)							480 [(d)]	80 [(d)]
Total Project Cost ($/kW)	1,700-3,200 **2,638 [(f)]**				678-1,193 **940**	1,050-2,544 **1,669**	1,080-2,880 **2,880**	**930 (835)**
Total Project Cost ($/kWh)	106-200 **165**					94-229 **105**	4,320-11,520 **11,520**	**74,480 (66,640)**
O&M Fixed ($/kW-year)	15.9				13.0	16.7	5.6	1
O&M Variable (cents/kWh)	0.00025				1.05	0.21	0.03	0.03
System Round-Trip Efficiency (RTE)	0.80				0.328	0.52	0.86	0.92
Annual RTE Degradation Factor							0.14%	0.14%
Response Time		FS	AS	Ternary	From cold start: 10 min Spin ramp rate: 8.33%/min Quick start ramp rate: 22.2%/min	3-10 min	0.25 sec	0.016 sec
	Spinning-in-air to full-load generation	5-70 s	60 s	20-40 s				
	Shutdown to full generation	75-120 s	90 s	65-90 s				
	Spinning-in-air to full load	50-80 s	70 s	25-30 s				
	Shutdown to full load	160-360 s	230 s	80-85 s				
	Full load to full generation	90-220 s	280 s	25-60 s				
	Full generation to full load	240-500 s	470 s	25-45 s[(g)]				
Cycles at 80% Depth of Discharge	15,000				Not Relevant	10,000	200,000	1 million
Life (Years)	>25				20	25	>20	16
MRL	9 (10)				10	8 (9)	8 (9)	9
TRL	8 (9)				9	7 (8)	7(8)	8

(a) E/P = 16 h
(b) E/P = 0.25 h
(c) E/P = 0.0125 h
(d) 20 percent of capital cost
AS = adjustable speed; FS = fixed speed.

Vanadium Redox Flow Battery

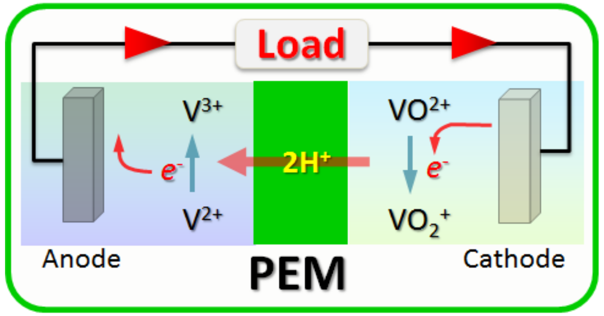
Ionomer Design and Processing

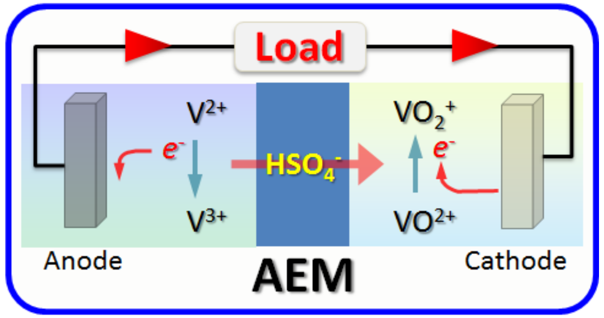
Redox Flow Battery

- Rechargeable
- Modular Power and Capacity
- Unlimited Longevity

Challenges

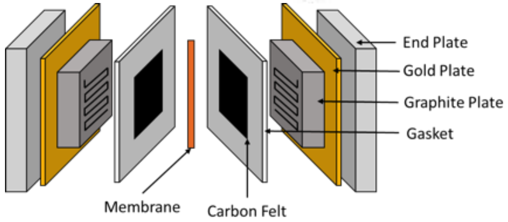
- Membrane Stability
- Ion Cross-over
- Electrolyte Cost

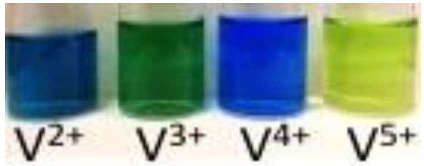




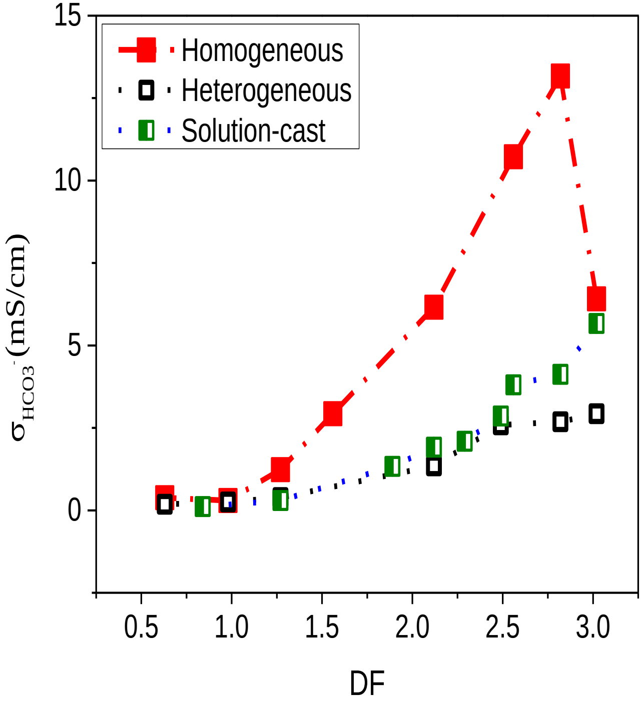
$$J_{tot} = \sum_i J_i = J_{D_i} + J_{E_i} + J_{C_i} = \left(-D_i \frac{dC_i}{dx}\right)_D + \left(-D_i C_i \frac{z_i F}{RT}\frac{d\Psi}{dx}\right)_E + (C_i v)_C \sigma$$

$$V^{2+} + VO_2^+ + 2H^+ \rightleftharpoons VO^{2+} + V^{3+} + H_2O$$





$$E = E^o + \frac{RT}{F}\left\{\ln\left(\frac{[VO_2^+][H^+]}{[VO^{2+}]}\right)\left(\frac{[V^{2+}]}{[V^{3+}]}\right)\right\}$$



Redox Flow Battery

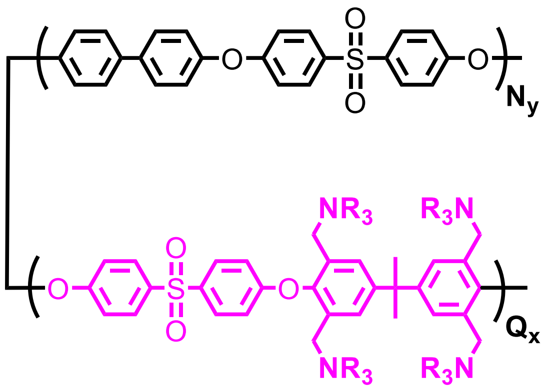
Technology Capital Costs

Table 4.16. Capital costs for redox flow batteries.

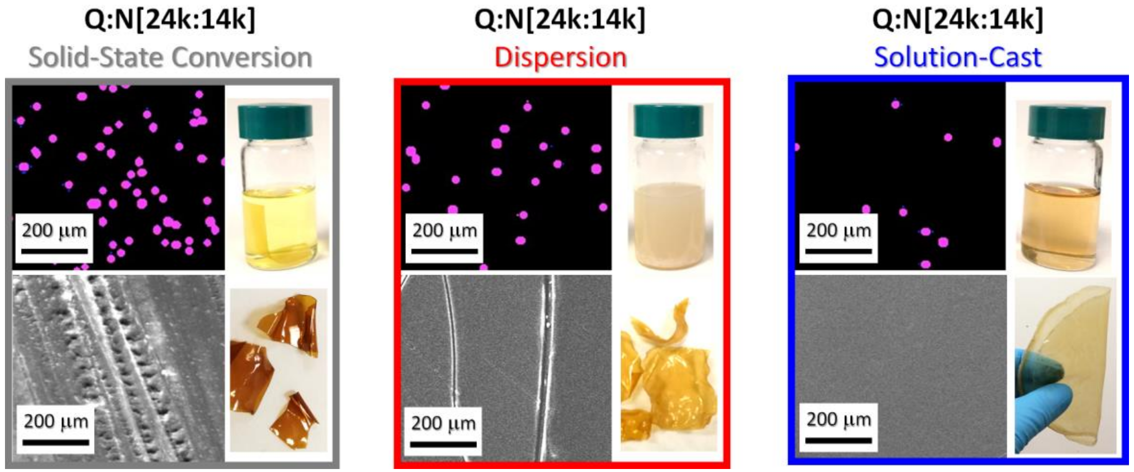
Battery Capital Cost ($/kWh)	Notes	Source
$490	5 kW, 20 kWh	RedT Energy Storage (2018)
$444	400 Euros	Uhrig et al. (2016)
$463		Noack et al. (2016)
$730-$1,200	Includes PCS cost and $131/kWh performance guarantee	Aquino et al. (2017a)
$542-952	After removing PCS and performance guarantee costs	Aquino et al. (2017b)
$500-$700		DNV GL (2016)
$468		Selmon & Wynne (2017)
$435-584	PNNL calculations – increased energy cost by 10% to account for lower DoD than the 80% DoD used for the calculations. Increased cost by 15% to account for container, DC controls, BMS.	Viswanathan et al. (2014), Crawford et al. (2015)
$357-552	$570-$910 for installed cost. Removed PCS, grid integration and equipment tax, fees, and G&A costs.	Damato (2017)
$676	Volterion stack costs including control units was 800 Euros/kW. Conversion to US dollars and using stack costs as 35% of DC system cost.	Seipp (2018)
$488	Volterion mid-term stack costs – mid-term was not specified, it may be assumed to be 2021.	Seipp (2018)
$293	Based on stack cost of $250/kW, a 69% reduction due to R&D.	Seipp (2018)

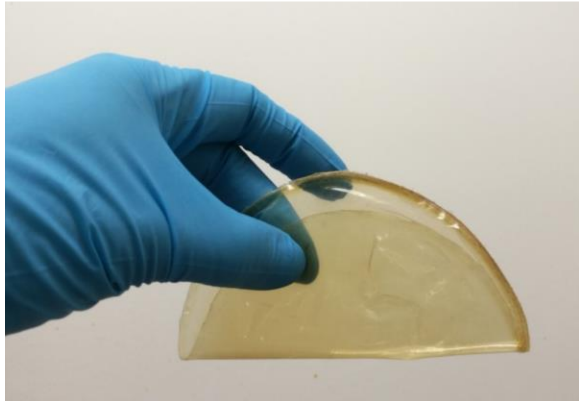
Ionomers

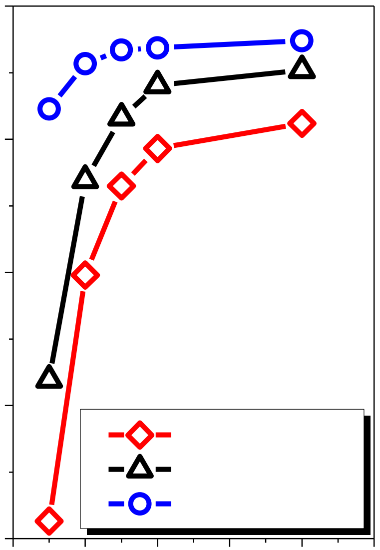
Composition and Functionalization (Processing)

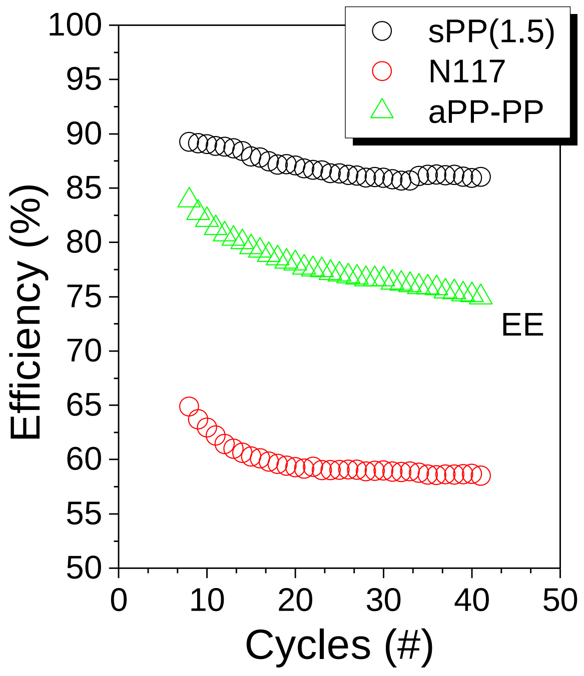


Q:N[X:Y] Multi-Block **AEM**



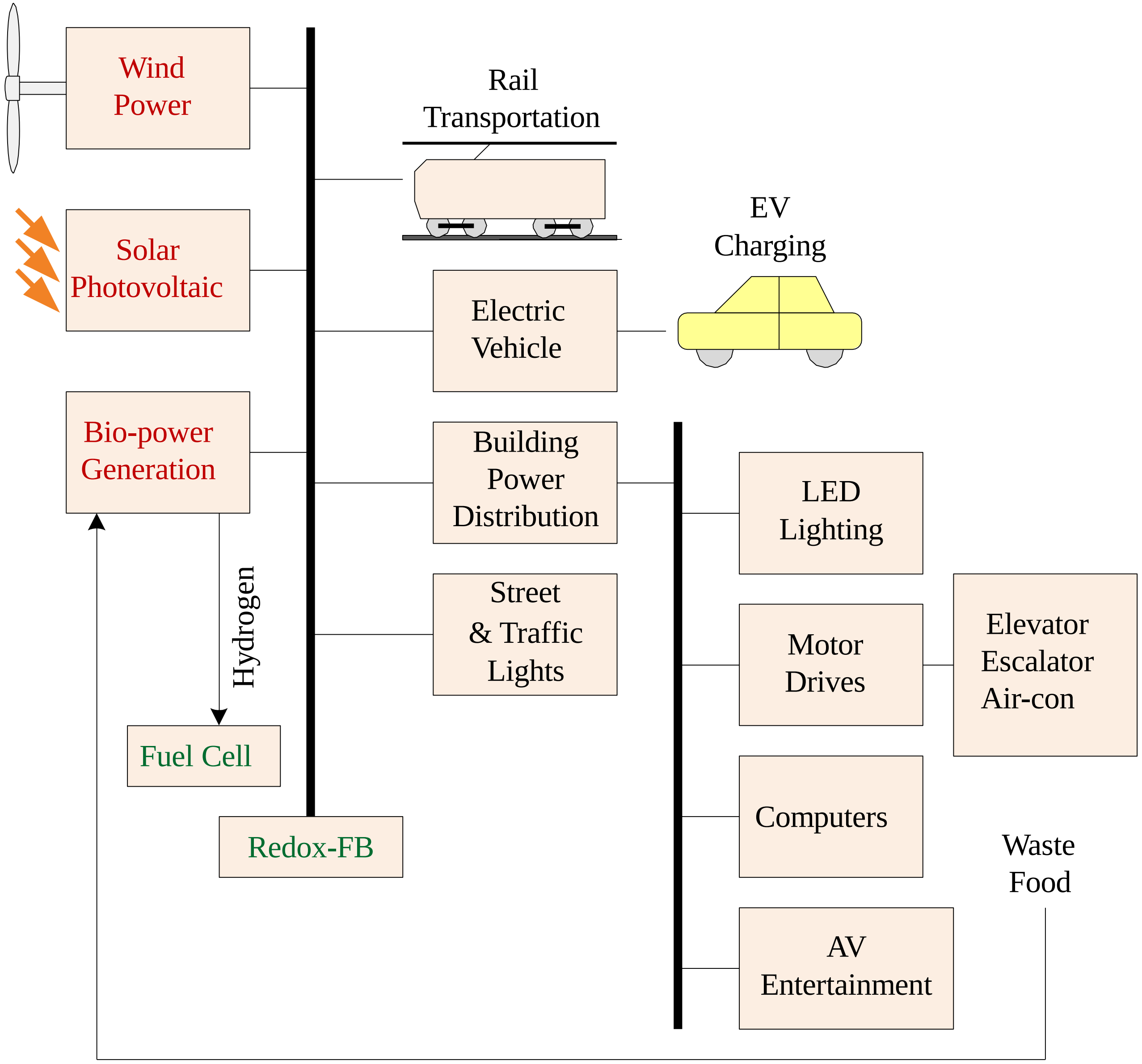






Energy Storage

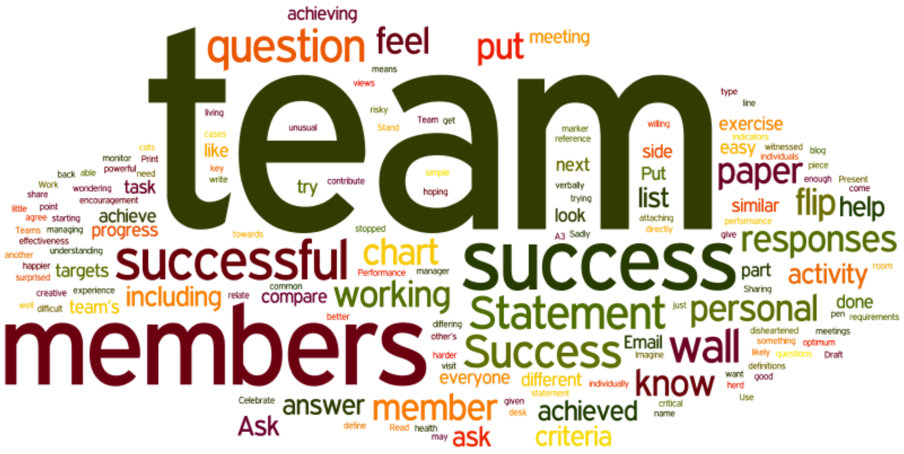
Redox Flow Battery



Thank You

Questions & Discussion

> Before everything else, "**Getting Ready**" is the secret of success.
>
> *Henry Ford*

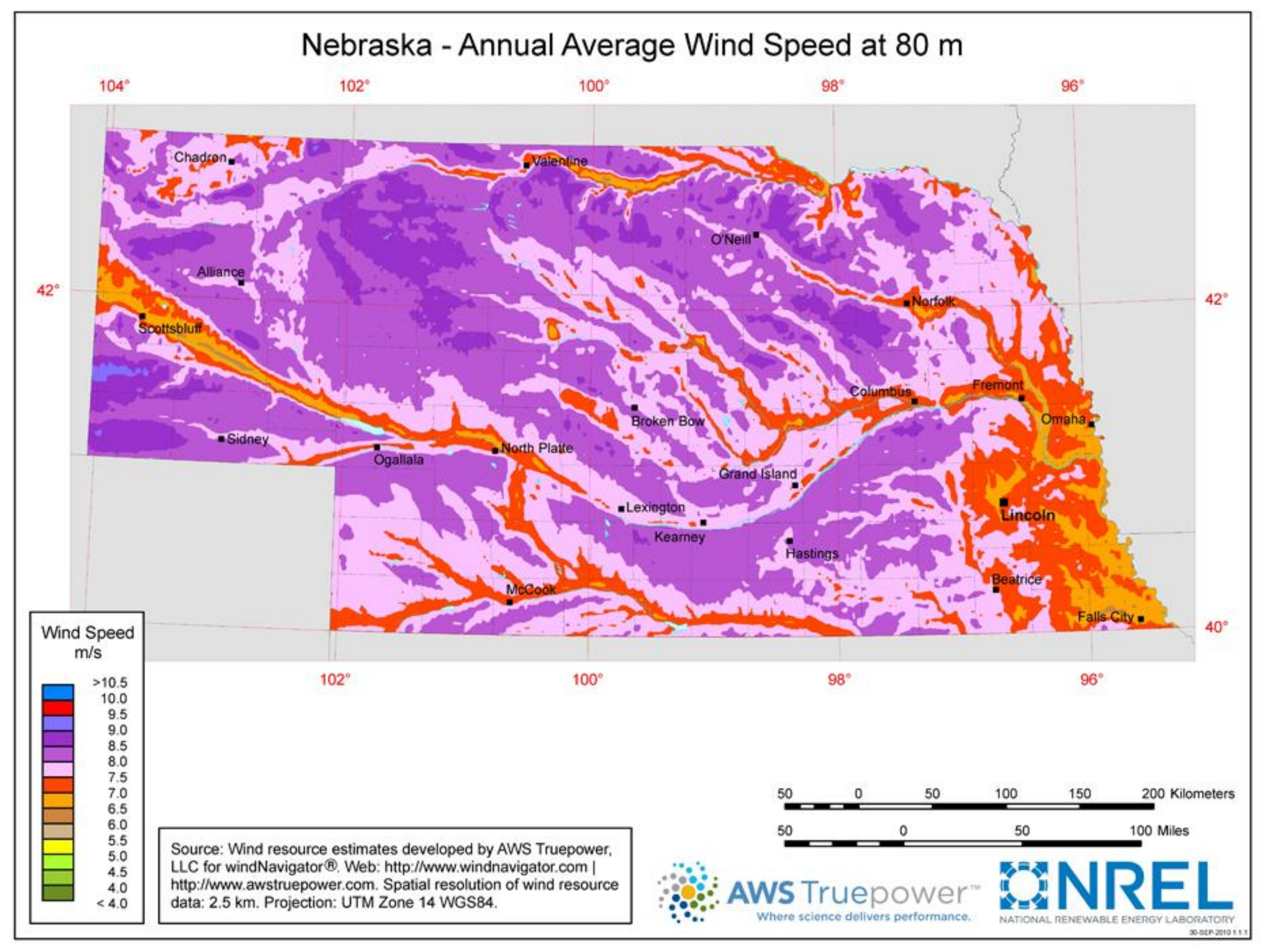


An Integrated Approach to Improved Wind Forecasting in Nebraska

Stonie Cooper, Mesonet Manager
Nebraska State Climate Office
School of Natural Resources
University of Nebraska - Lincoln

Wind Potential

- Nebraska lies in area of high wind energy potential.
- Wind can vary significantly over space and time.
- Accurate wind forecasts at turbine height are underutilized.



Goal and Objectives

GOAL

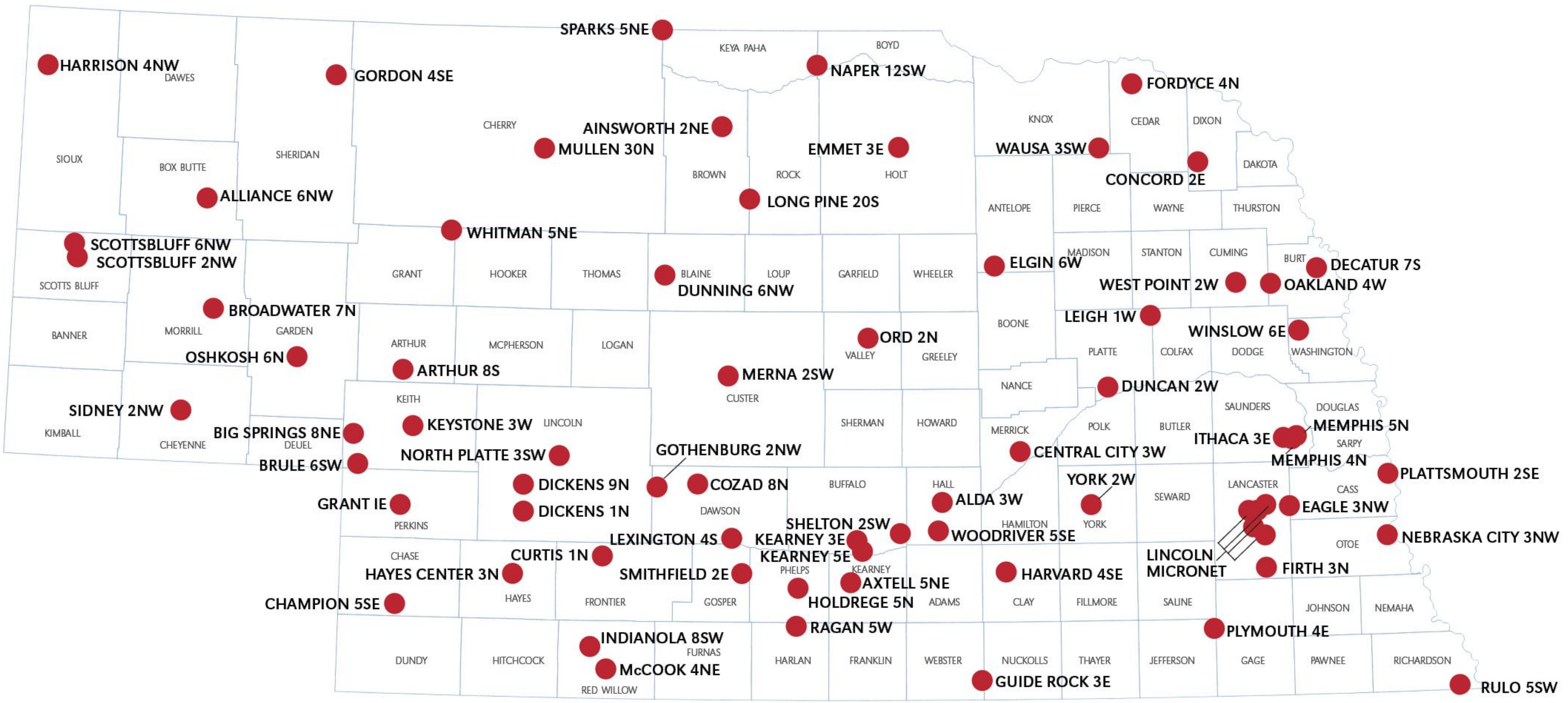
Provide a reliable and timely wind forecasting tool for use in energy production applications.

OBJECTIVES

- Incorporate Nebraska Mesonet data into weather forecasting model and document change in skill.
- Develop specialized wind forecast product for NPPD.

The Nebraska Mesonet

mesonet.unl.edu

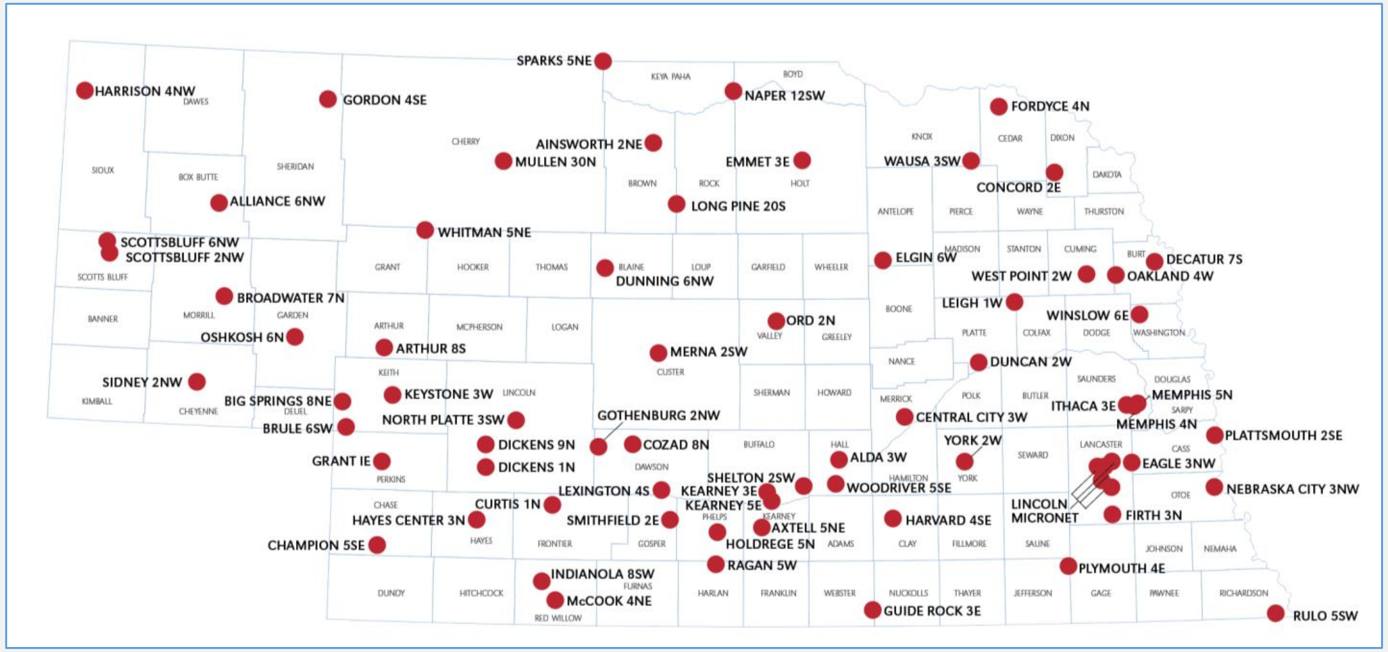


NEBRASKA STATE CLIMATE OFFICE

Observations:

- Air temperature
- Humidity
- Wind speed, direction
  9’ (3m) and 30’ (10m)
- Liquid precipitation
- Solar radiation
- Soil temperature
  4” (10cm)
- Soil moisture
  and temperature at 2”, 4”, 8”, 20” and 40” (5, 10, 20, 50, 100cm)
- Barometric pressure

Methods



WRF Model

All Mesonet stations assimilated into WRF model.

- ✓ WRF run every 3 hours out to 72 hours.
- ✓ 22.4mile x 22.4mile (22.4miles = 36km) grid resolution (horizontal).
- ✓ 49 terrain-following levels (vertical) up to 12.4miles (20km).
- ✓ 3DVAR used to assimilate air temperature, wind, humidity, air pressure.
- ✓ 197feet (60m) altitude closest to wind turbine height.

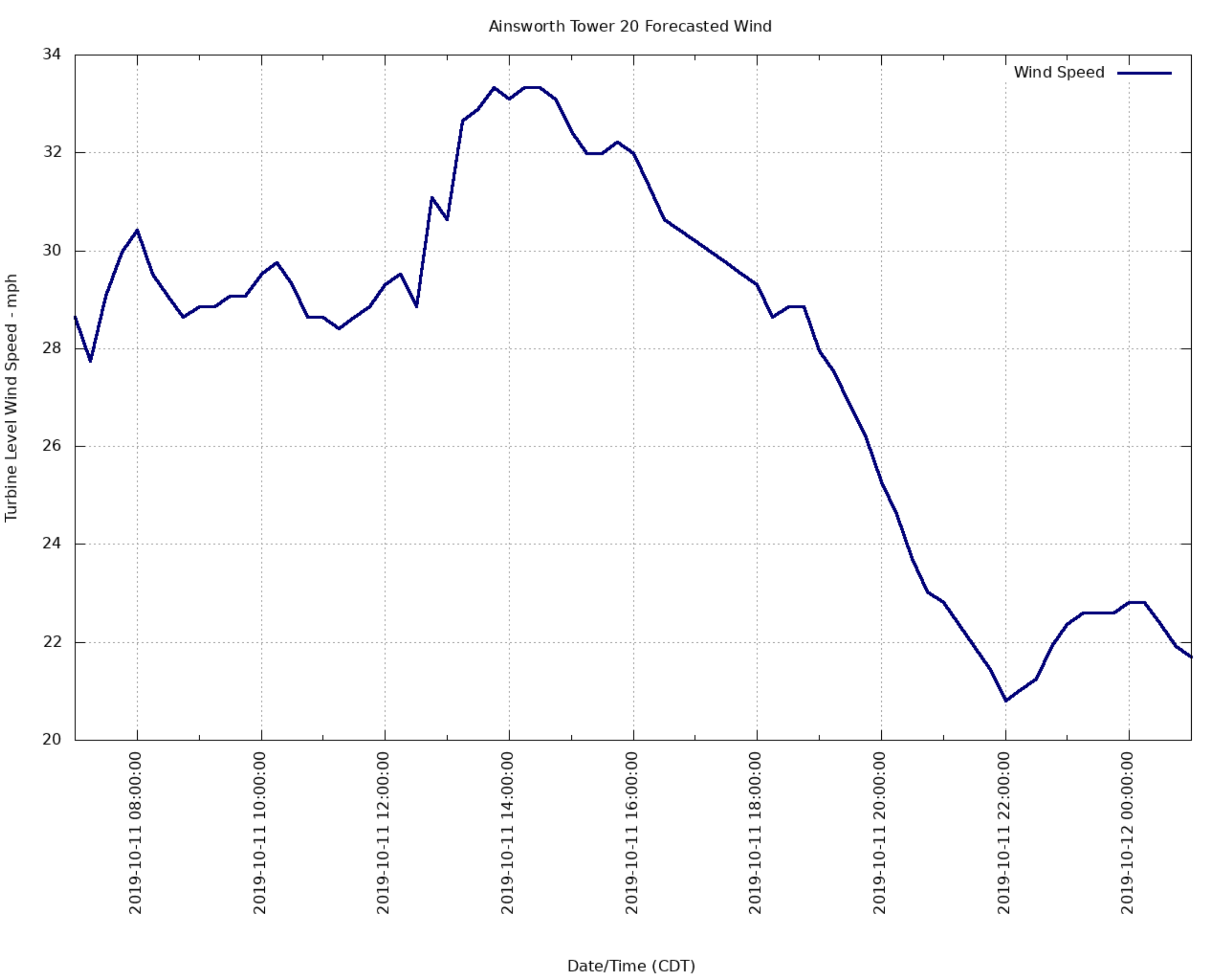
Results: Wind speed comparison

- ✓ Regional model **overestimates** wind speed by **3.4 mph** (1.5m/s).
- ✓ **Bias improves** with Mesonet assimilation to **1.3 mph** (0.6m/s) overestimate.
- ✓ Best improvement with Mesonet assimilation seen in central, eastern Nebraska.

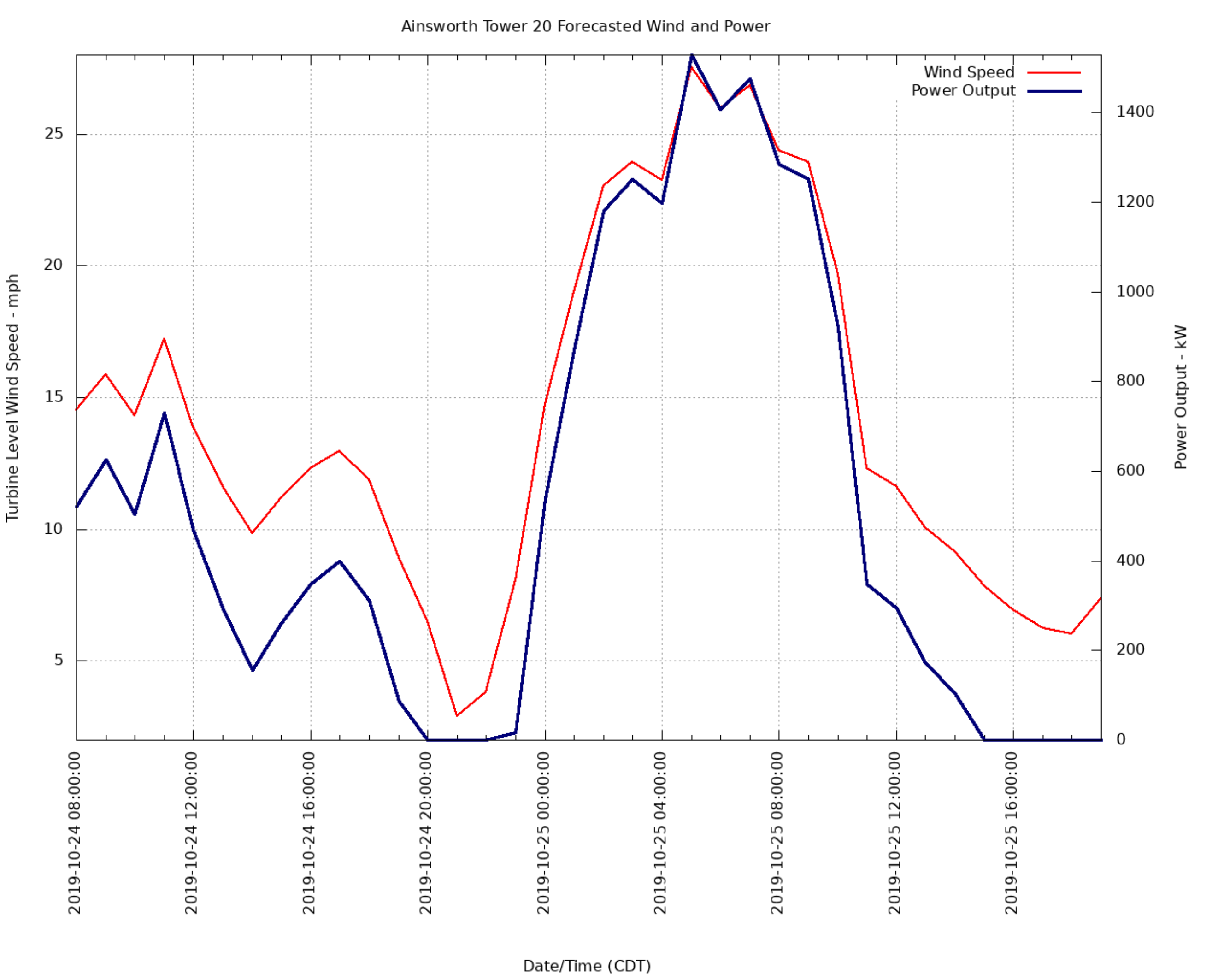
Results: Wind speed comparison

- ✓ The greatest benefit to locally generated numerical wind speed forecast with inclusion of Nebraska Mesonet data is at lower wind speeds, well below name-plated generation potential.
- ✓ Focus on local "MOS" – model output statistics – to take current NOAA generated numerical forecast and use near-historical generation profiles on a per-tower basis to enhance forecasts

Wind speed forecast at turbine level



Wind power forecast at turbine level



Questions?
An Integrated Approach to Improved Wind Forecasting in Nebraska

Stonie Cooper
scooper6@unl.edu

Printable Solar Cells

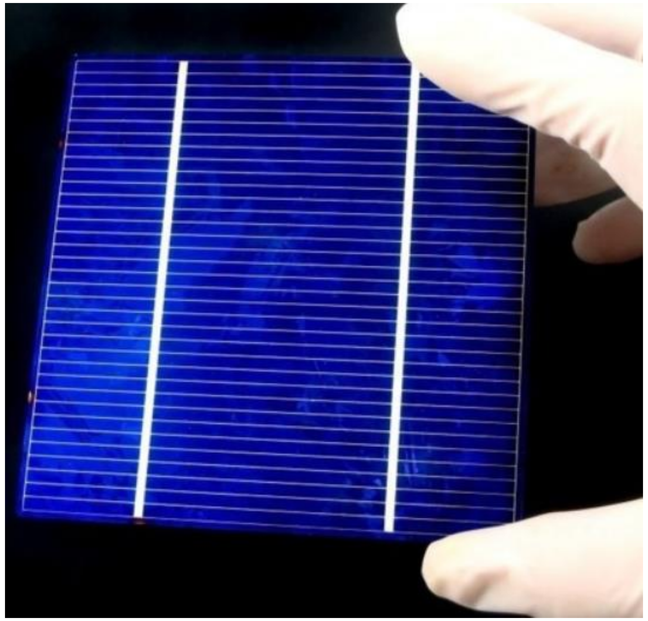
Peter Dowben
Department of Physics and Astronomy

Prof. Andrew Yost	Prof. Wai-Ning Mei
Prof. Ned Ianno	Ms. Thilini Ekanayaka
Prof. Takashi Komesu	Mr. Archit Dhingra
Prof. Alex Sinitskii	Prof. Alexei Gruverman
Prof. Xiao Zeng	Prof. Tula Paudel

University of Nebraska Lincoln

Silicon Solar Cell

It is cheap, it is reliable and it is the standard

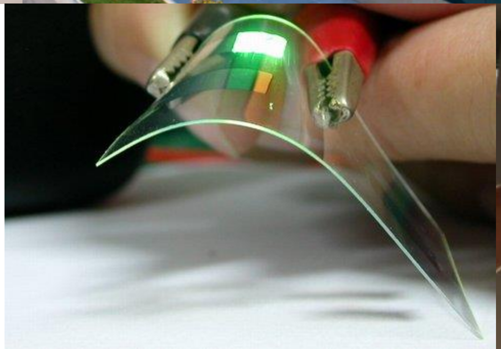


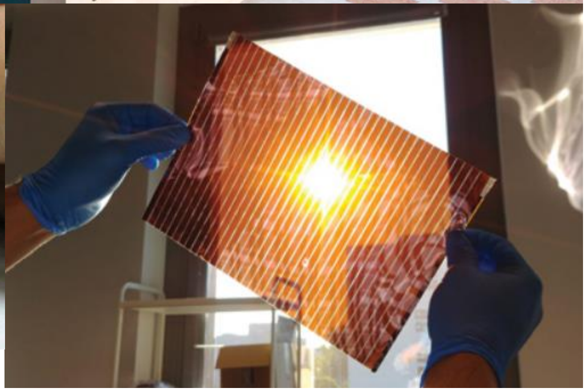
Why look any farther ???

Low cost High Efficiency: Inkjet printing for Photovoltaic Windows

Howard L. Hawks Hall

Low weight
500 g/m^2



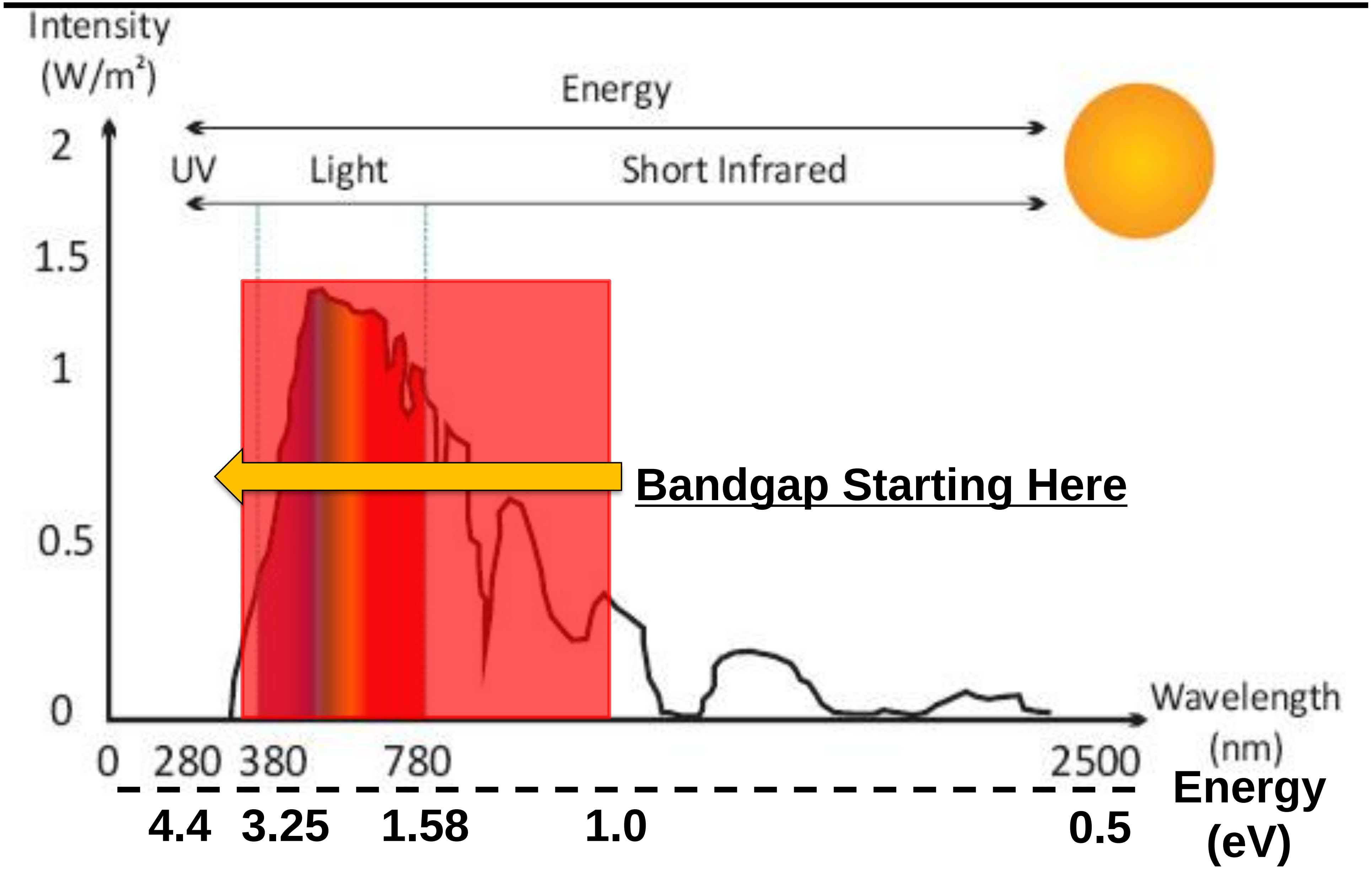


Semi Transparent

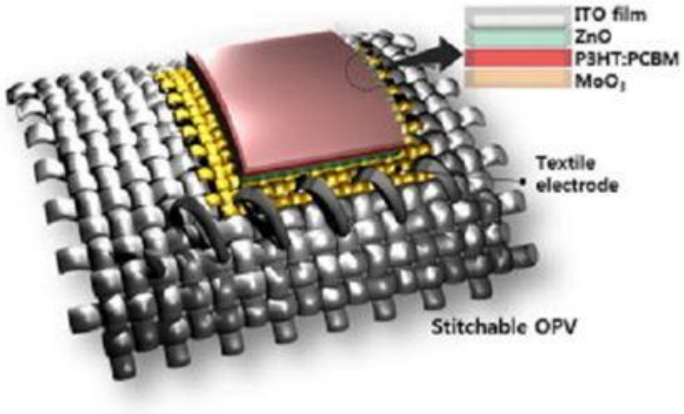
Shadow Absorption

Flexible Substrates

Covering the Solar Spectrum



Photovoltaics from Organics

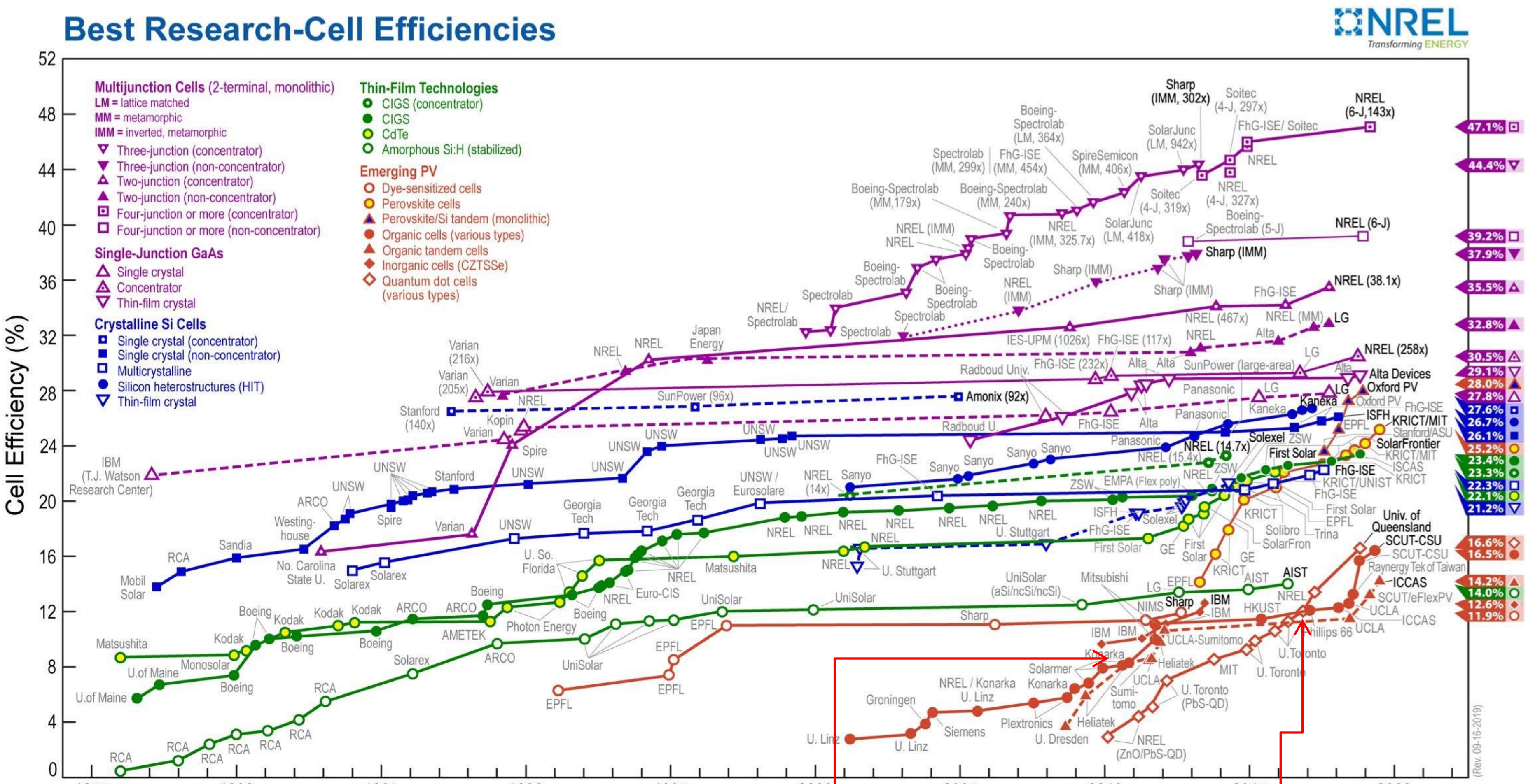


Organics are in principle cheap, flexible, bendable, and amenable to a variety of high throughput production methods

Not just solar cells, but displays too

Motion Articles on Paper

Organic Photovoltaics are emerging and promising, with some problems…



Red are the organic solar cells

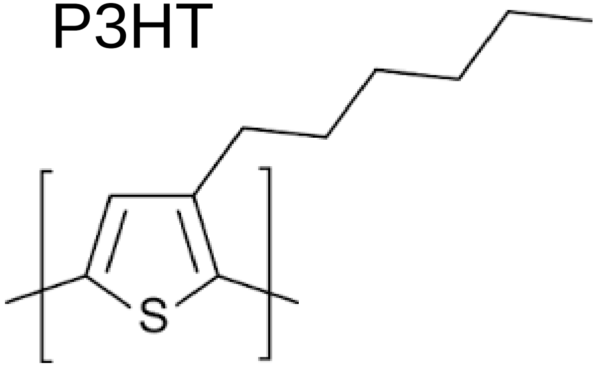
And these are not very stable

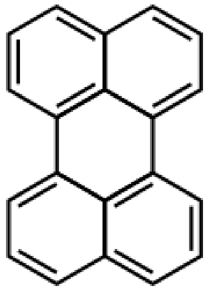
Problems with Organic Photovoltaics

- Organic solar cells need to stable! They have to work for a long, long time and survive in harsh conditions.
  - solution: need additives to stabilize the organics
- They need to be made more efficient! Now efficiency is low (about 5%) or high (23%) but in materials not very stable. (high efficiency materials are the ones that degrade in sunlight)
  - solution: need additives to stabilize the organics – these will be dipolar molecules, and graded multilayers could improve efficiency a lot
- The organic solar cells need to be scalable! Can the materials be manufactured cheaply on a large scale?
  - Solution: Deposition from solution

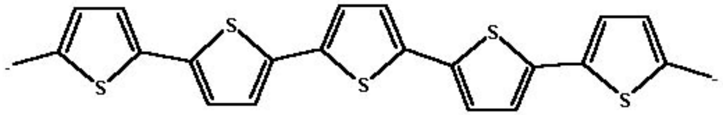
Organic Semiconductors and Conductors

Poly(3-hexylthiophene-2,5-diyl)
P3HT

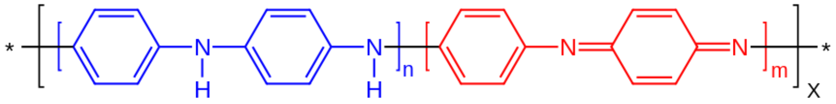




Perylene

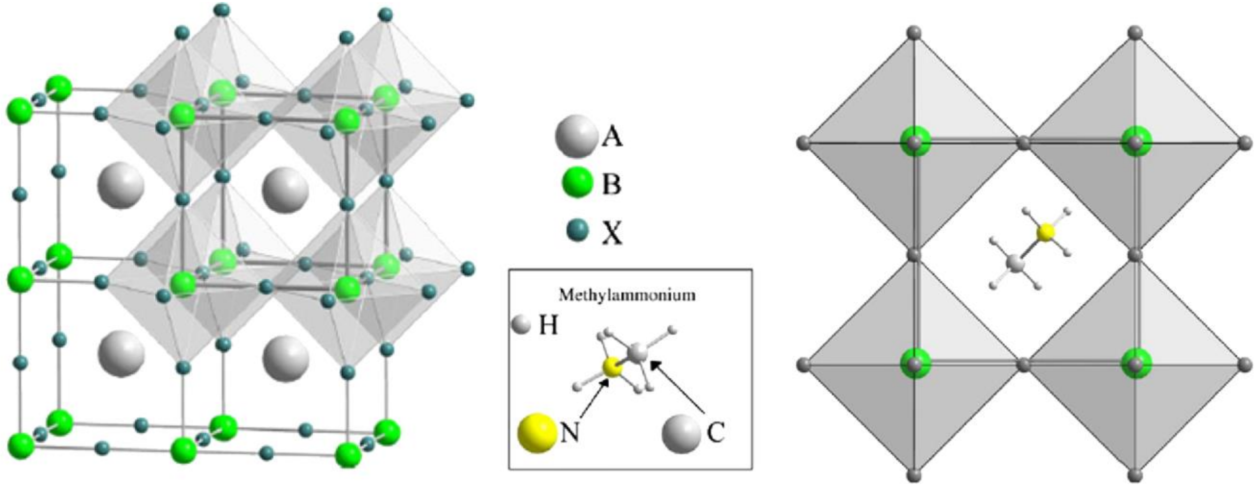


Polythiophene



Polyaniline

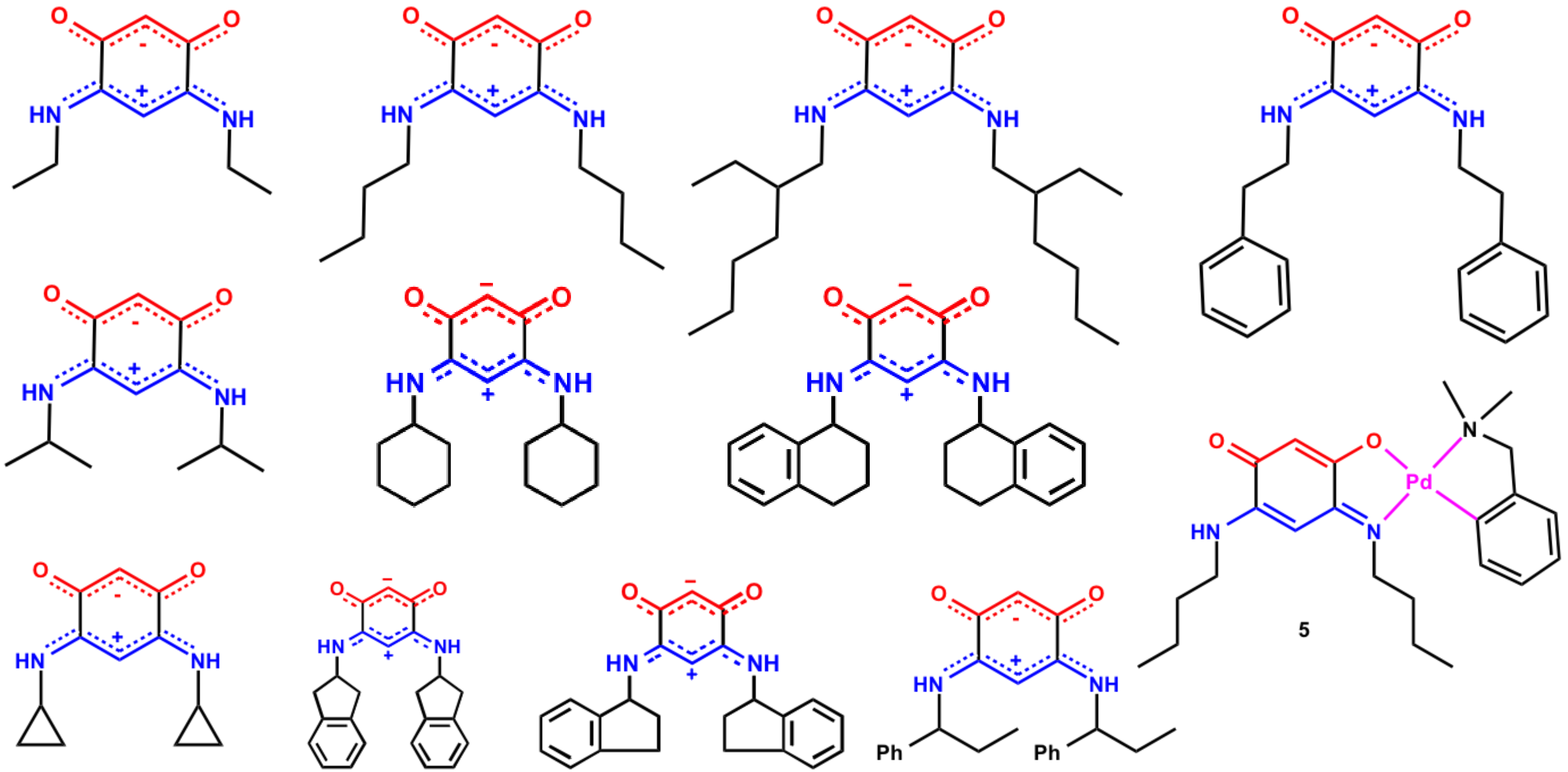
organolead
trihalide
$CH_3NH_3PbX_3$
(organic perovskite)

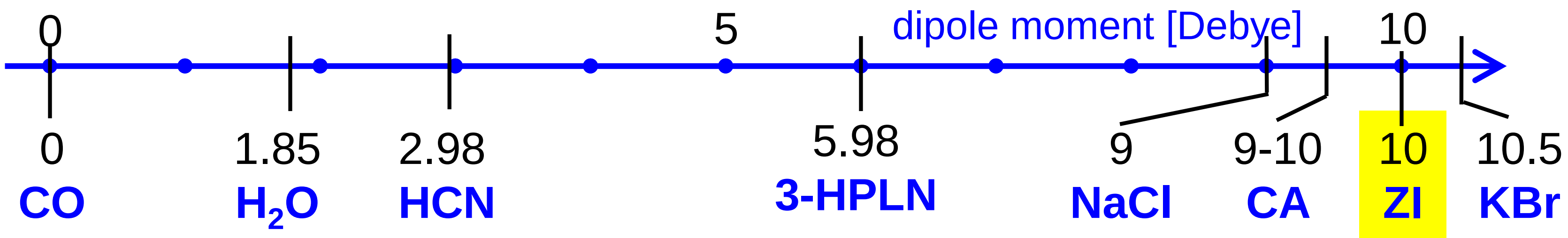


D. Shi, Peter A. Dowben, O. M. Bakr, et al, “Exceptionally low trap-state density and long carrier diffusion in room-temperature grown $MAPbBr_3$ perovskite single-crystal wafers”, *Science* **347** (2015) 519-522

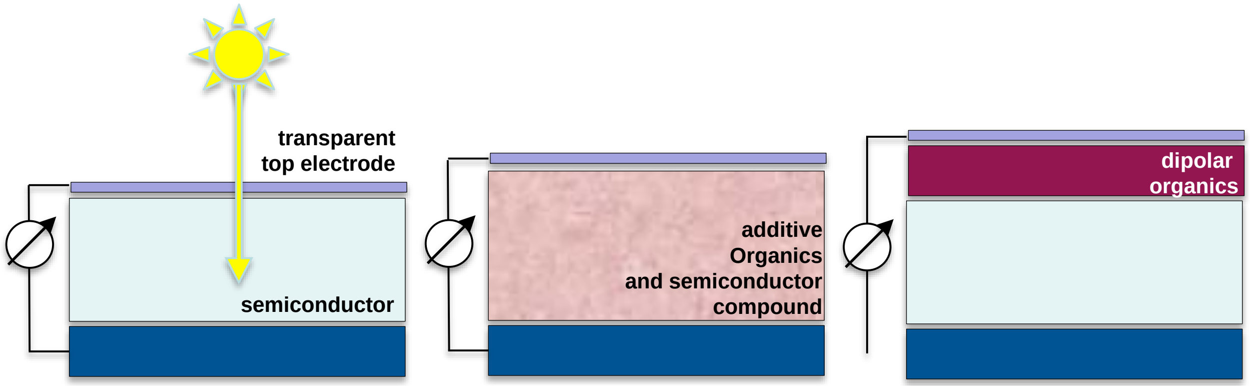
"Modifiers"

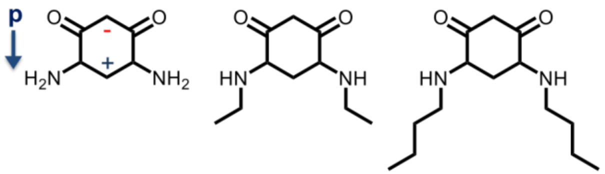
We have over 50 different kinds of p-benzoquinone monoimine zwitterions





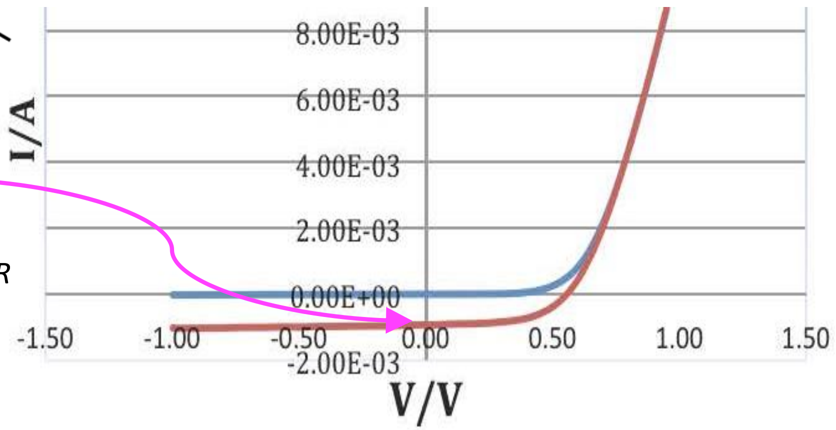
Demonstration of Additives on PV Performance





The signature of a successful organic solar cell combination: current at zero applied volts.

Enders, Dowben, and Doudin; unpublished data for dipolar zwitterion molecule (where R = C_4H_9) in combination with the organic semiconductor PEDOT (Poly(3,4-ethylenedioxythiophene).



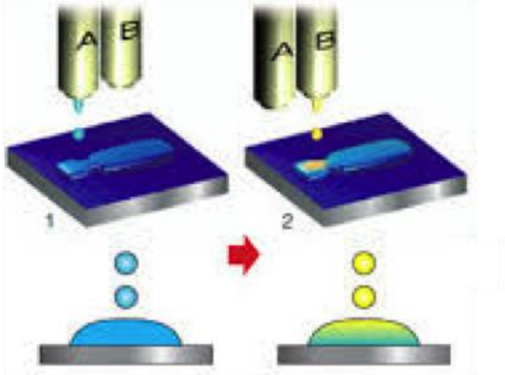
The additives enhance photo current generation!
But:
We still need to increase this current generation!

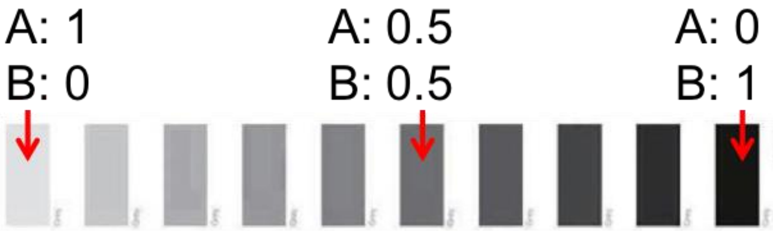
Dipolar molecules produce an intrinsic electric field that enhances the electron-hole separation in the semiconductor. This is new science!

University of Nebraska Lincoln

Rapid Prototyping of Materials Combinations

Rapid prototyping with inkjet printer technology sing a modified inkjet printer





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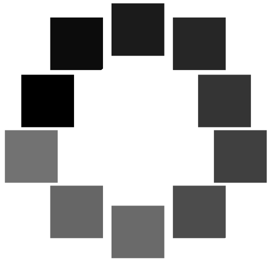
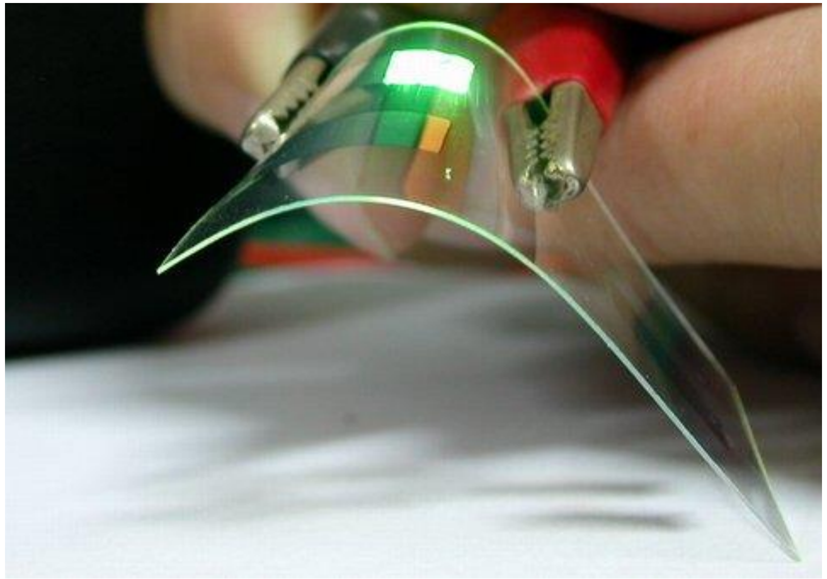
Ink



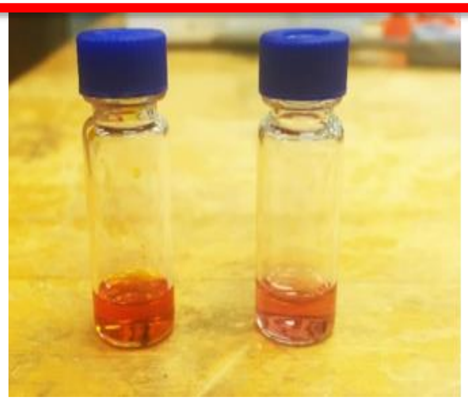
Template design for CD/DVD tray of printer

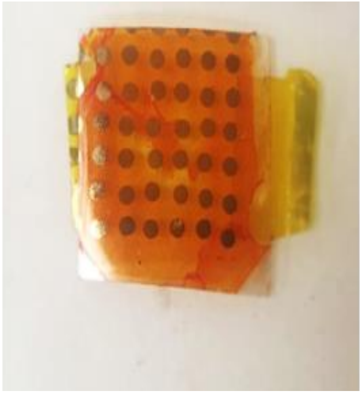
Grayscale ink printing (10 samples)

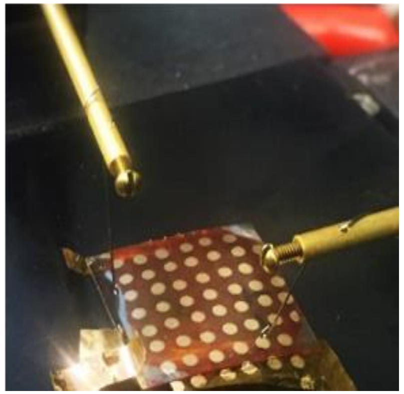
Cheap and Flexible

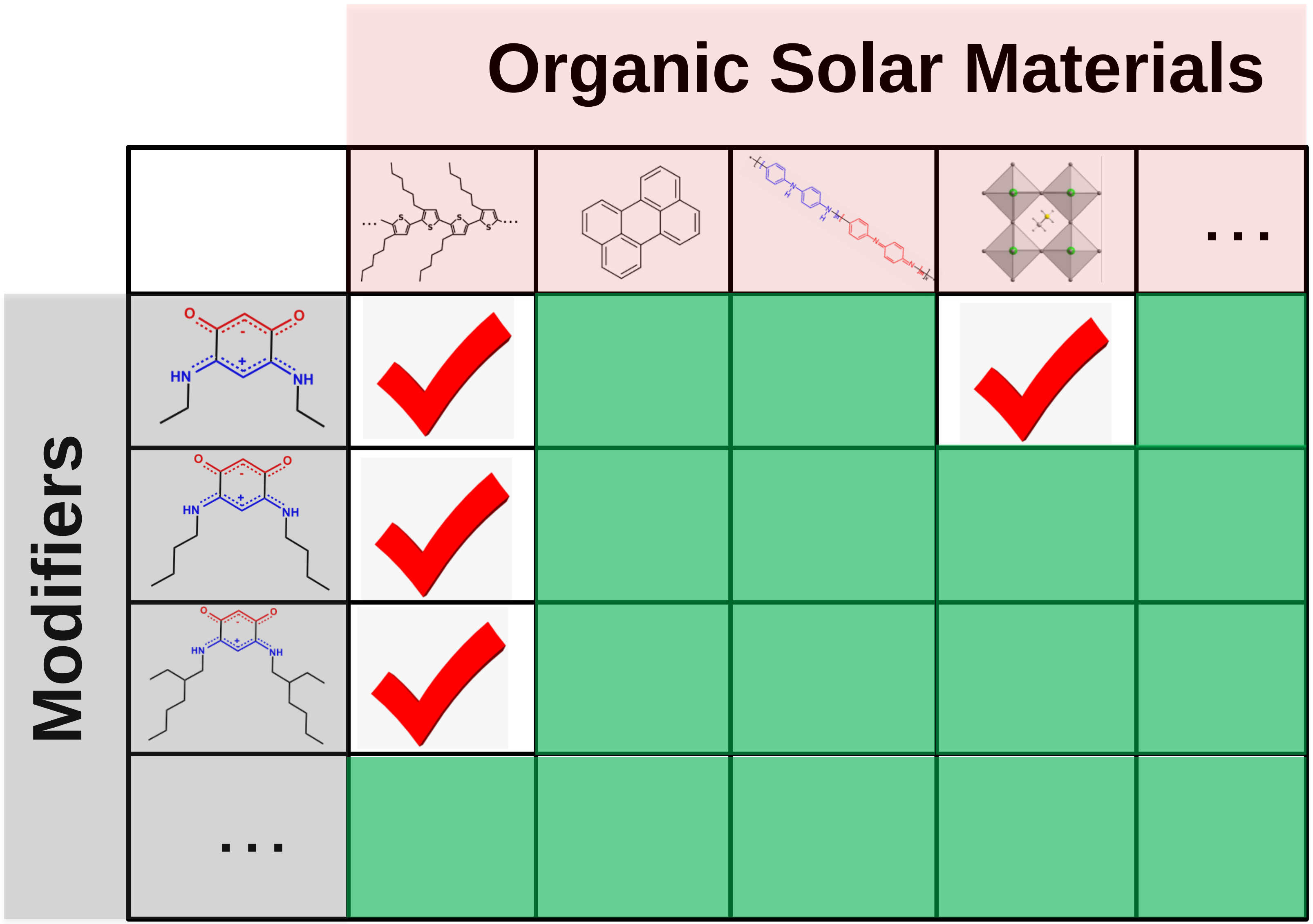


Simple Mass Production



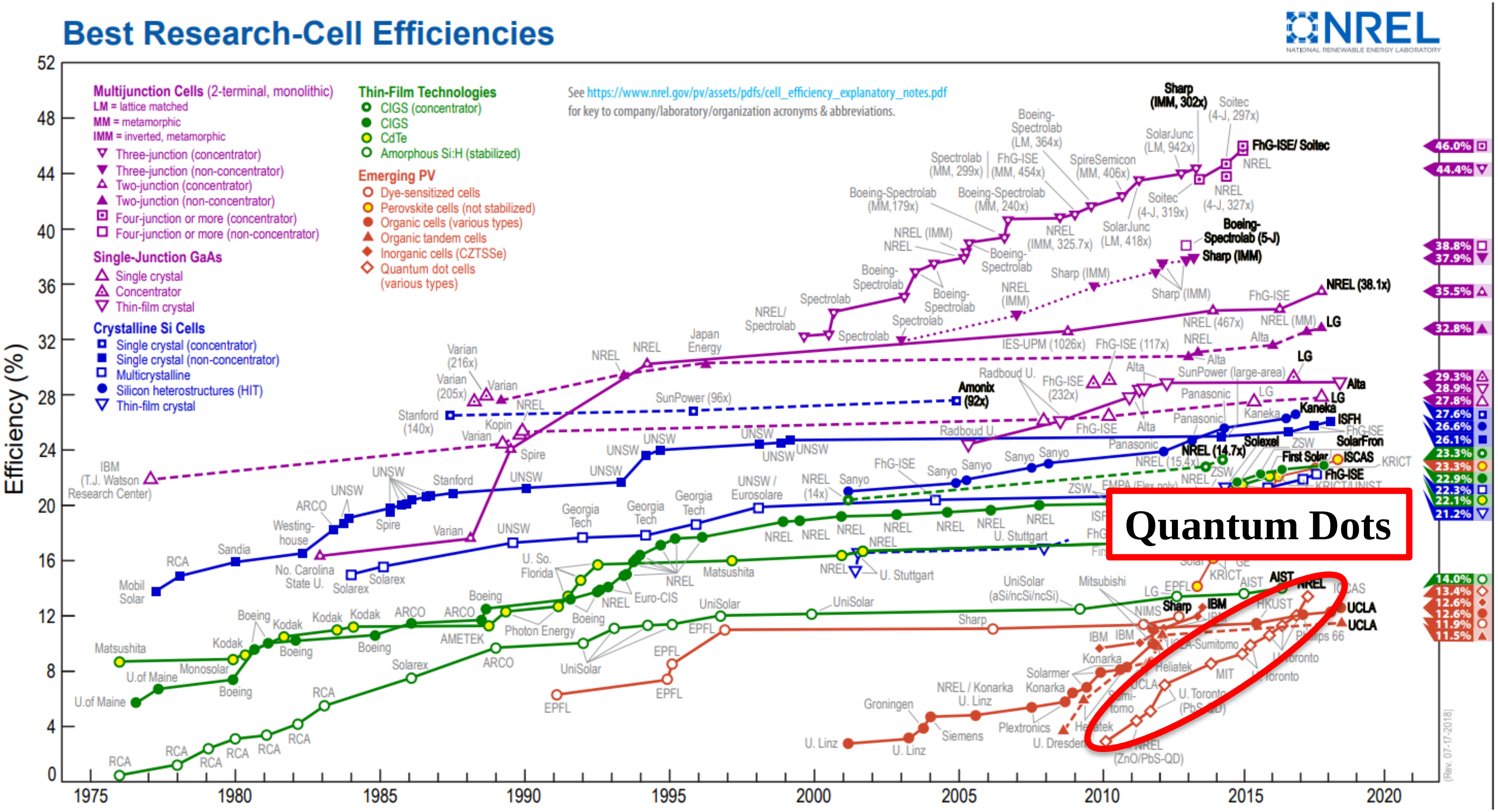




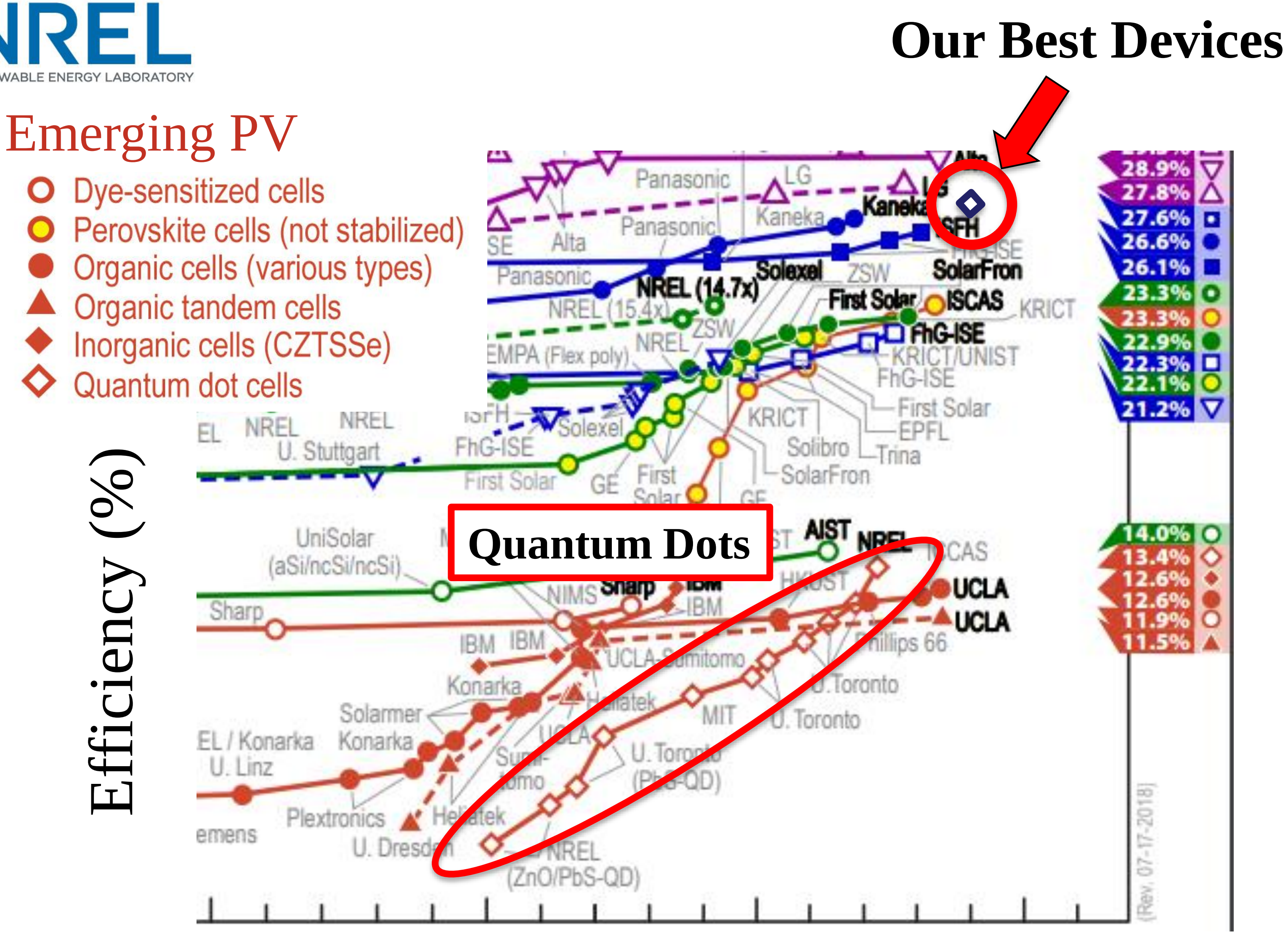

Organic Solar Materials
Modifiers
HN
NH
. . .

UNIVERSITY OF Nebraska Lincoln

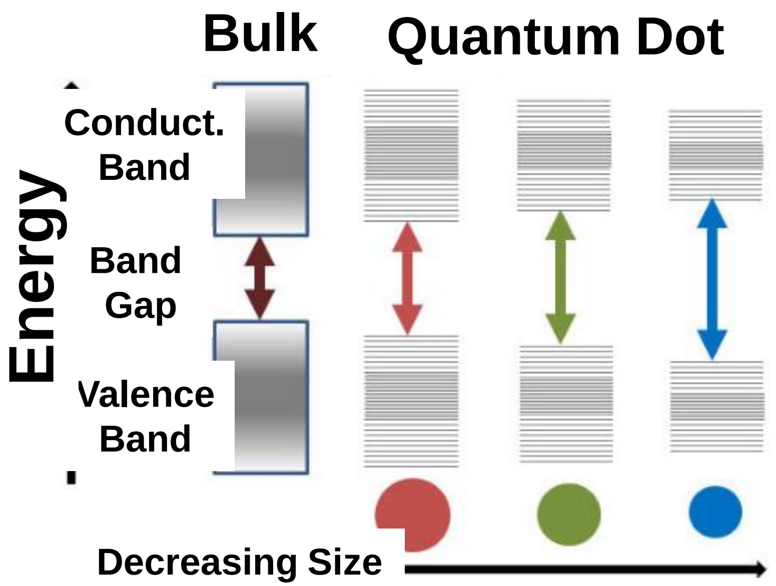
Where do Quantum Dot Solar Cells Rank?

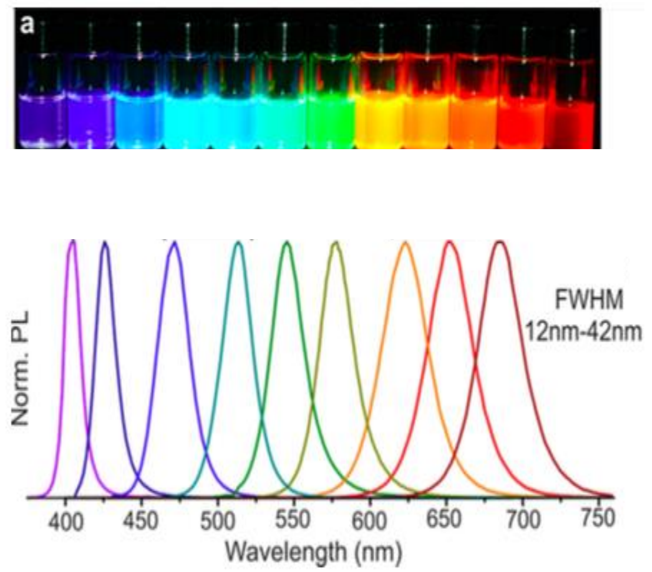


We are leaders

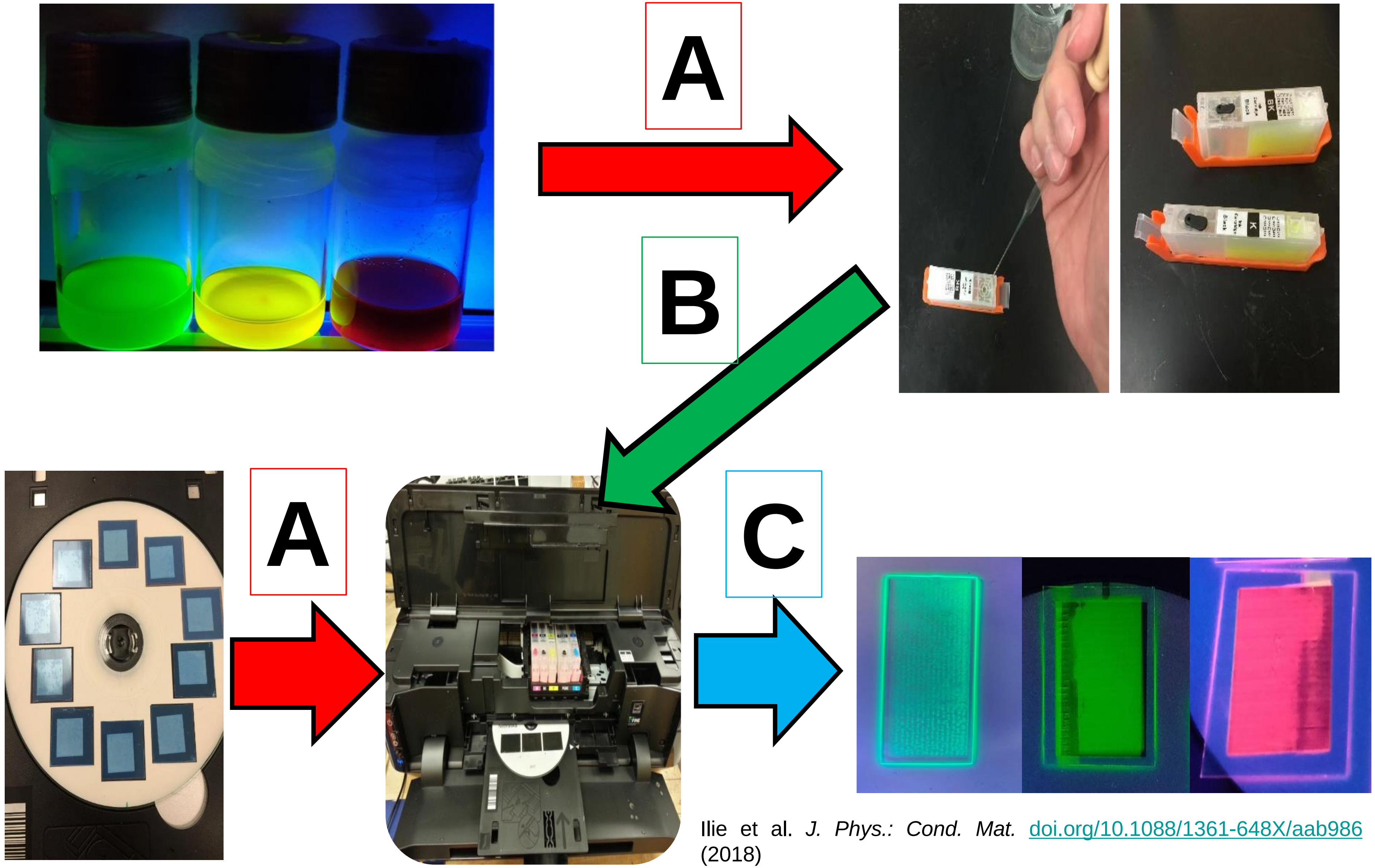


WE can tune the color by size or chemistry





Inkjet Printing of Solar Cell Inks

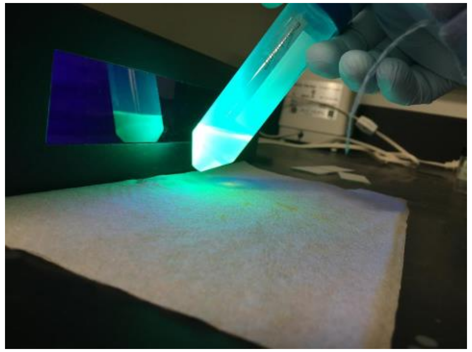


Ilie et al. *J. Phys.: Cond. Mat.* doi.org/10.1088/1361-648X/aab986 (2018)

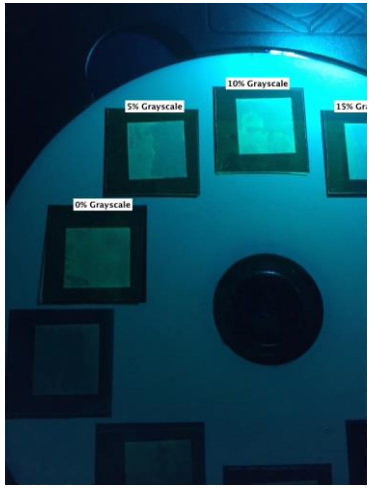
Applicability: “Printable” Solar Cells

Rapid prototyping with inkjet printer technology

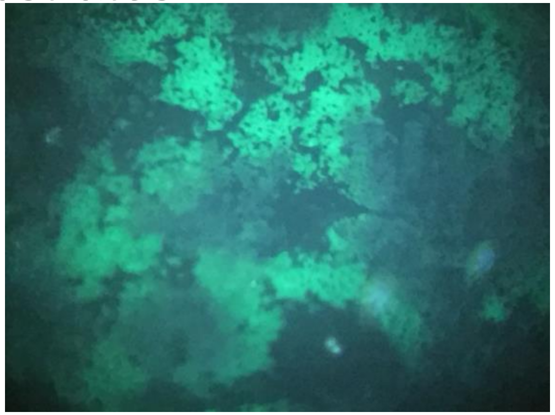
Again, how to test all the possible combinations to find the best combinations for the most successful photovoltaic ?



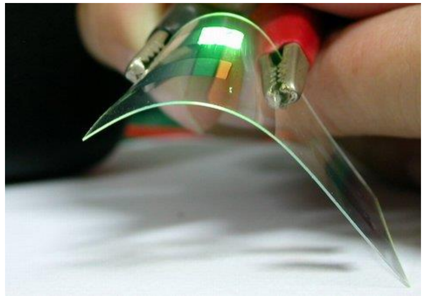
Perovskite Synthesis
Inexpensive wet lab solution-phase synthesis of $CsPbX_3$ NCs



Inkjet Printing of NCs in solvent on substrates



Constructing Shapes using printed NCs



Developing Thin-Film Solar Cells from printed NCs

Efficiency is not every thing:

If you cover more surface area and generate more current at much lower cost, you win.

So a window you look through but is also a solar cell could be a BIG winner, even if not very efficient.

SAULE TECHNOLOGIES

DYESOL

nanograde®

OMEGA OPTICAL

Borun New Material

CORNING

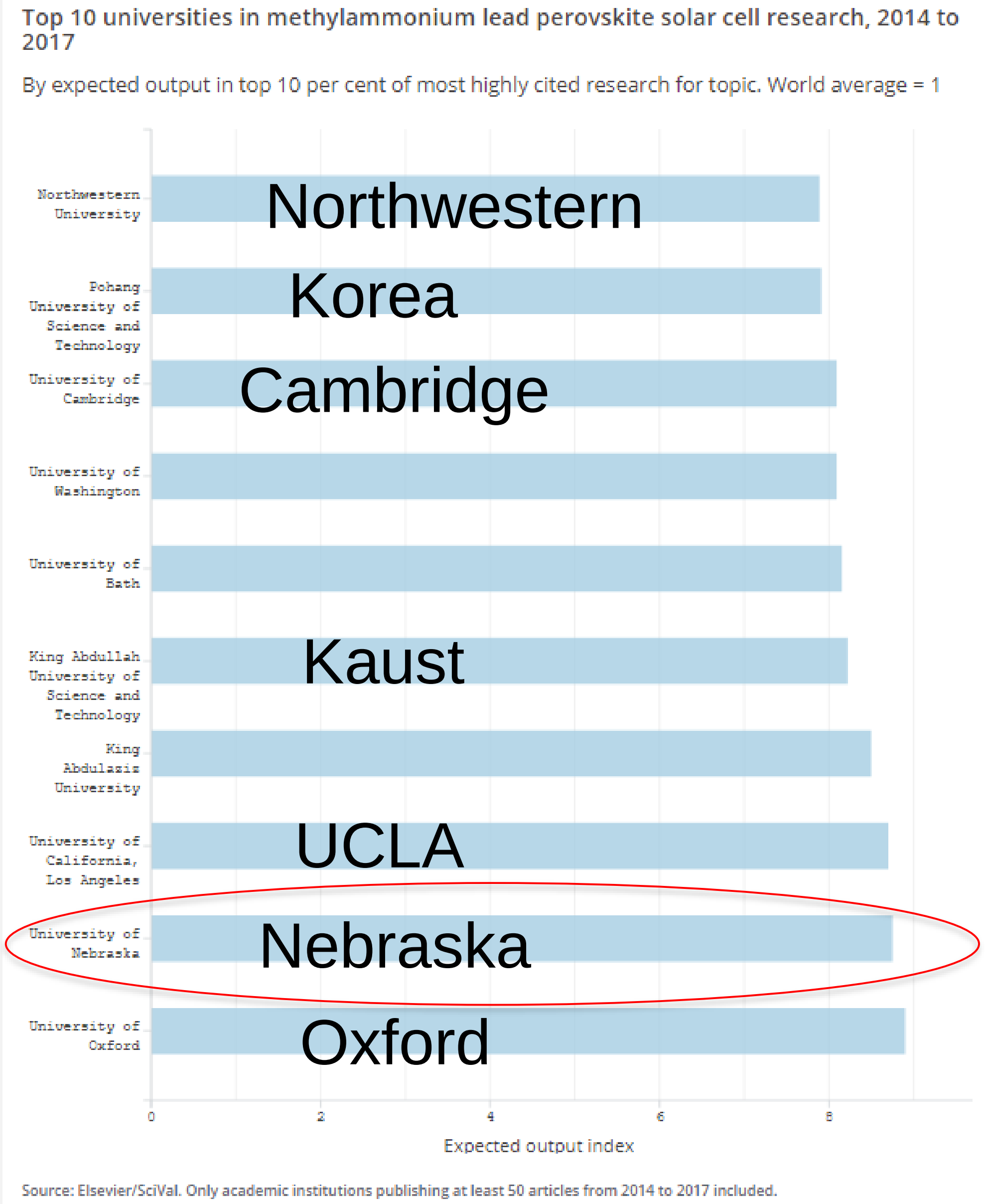
AST

Heliatek® The future is light

In The News!

Top universities and researchers in perovskite solar cell research

We are No. 2 in the world for novel materials in photovoltaic research



Nebraska Public Power District

NASA EPSCoR Nebraska

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NSF

Nebraska MRSEC