Direct conversion of sunlight into useful energy: a whole new world

Adélio Mendes

Light, from the Earth to the Stars
Lisbon, July 2nd, 2015

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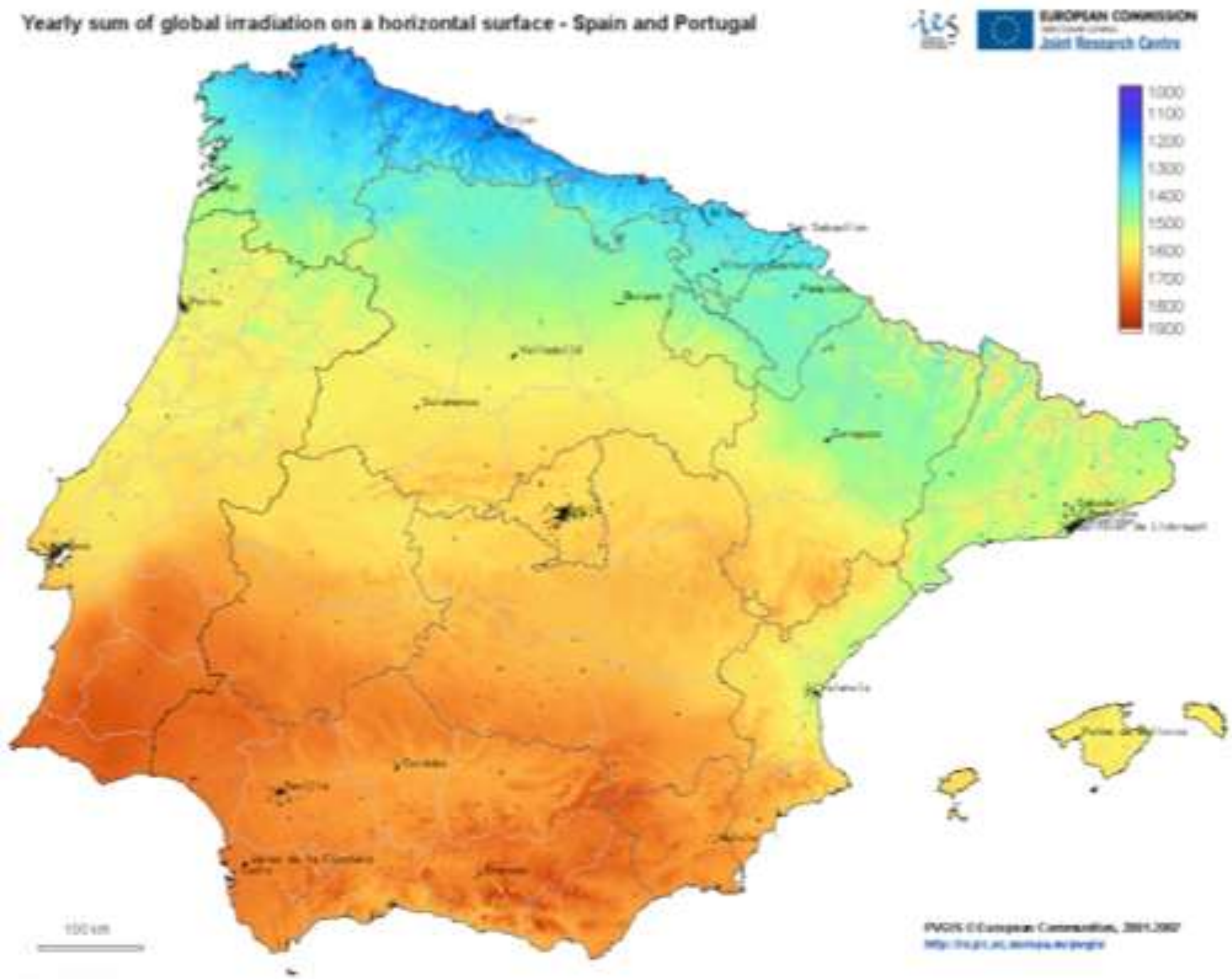
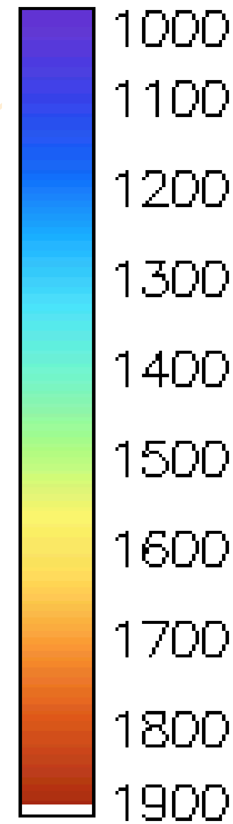
FEUP
Chemical Engineering Department

Lepabe
Laboratory for Process Engineering, Environment, Biotechnology and Energy

The sun





kWh·year^{-1}

Nearly zero-energy buildings

Nearly zero-energy buildings

Nearly zero-energy buildings – (Directive 2010/31/EU):

"Member States shall ensure that by 31 December 2020 all new buildings are nearly zero-energy buildings; and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings".

Nearly zero-energy buildings

A nearly zero-energy building is defined in Article 2 of the EPBD recast as:

> *"The nearly zero or very low amount of energy required should be covered to a* ***very significant extent by energy from renewable sources****, including energy from renewable sources* ***produced on-site or nearby****".*

Nearly zero-energy buildings

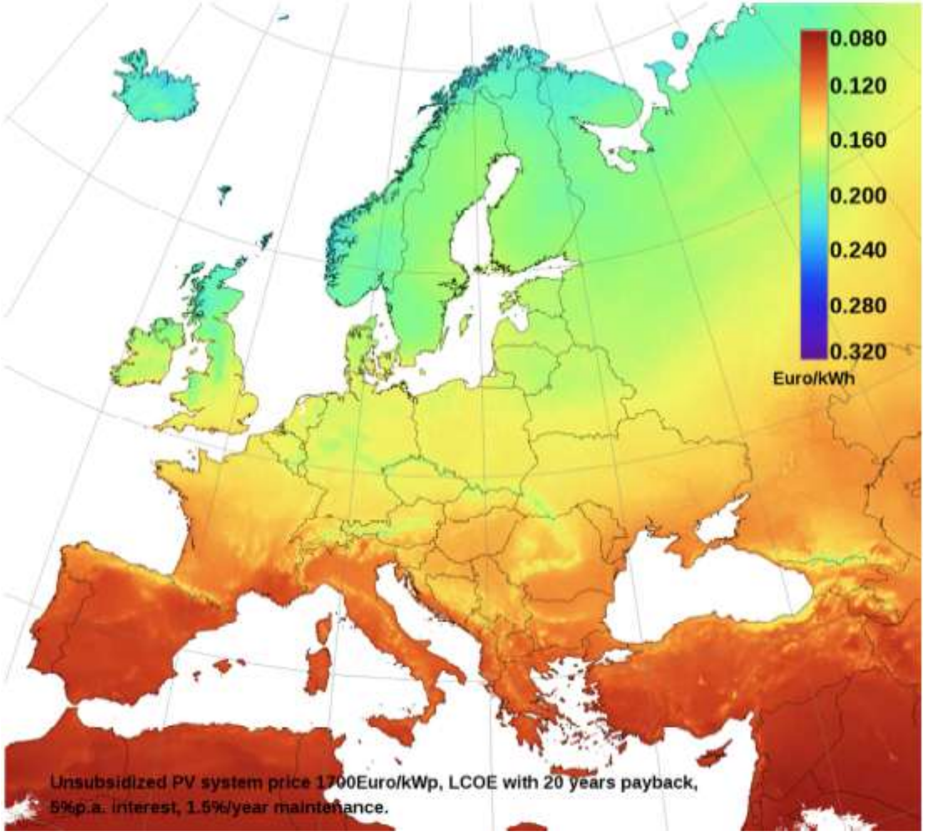
A great opportunity for my research? For my company?

http://www.neoclipart.com/12810-science-lab-safety-clipart.html

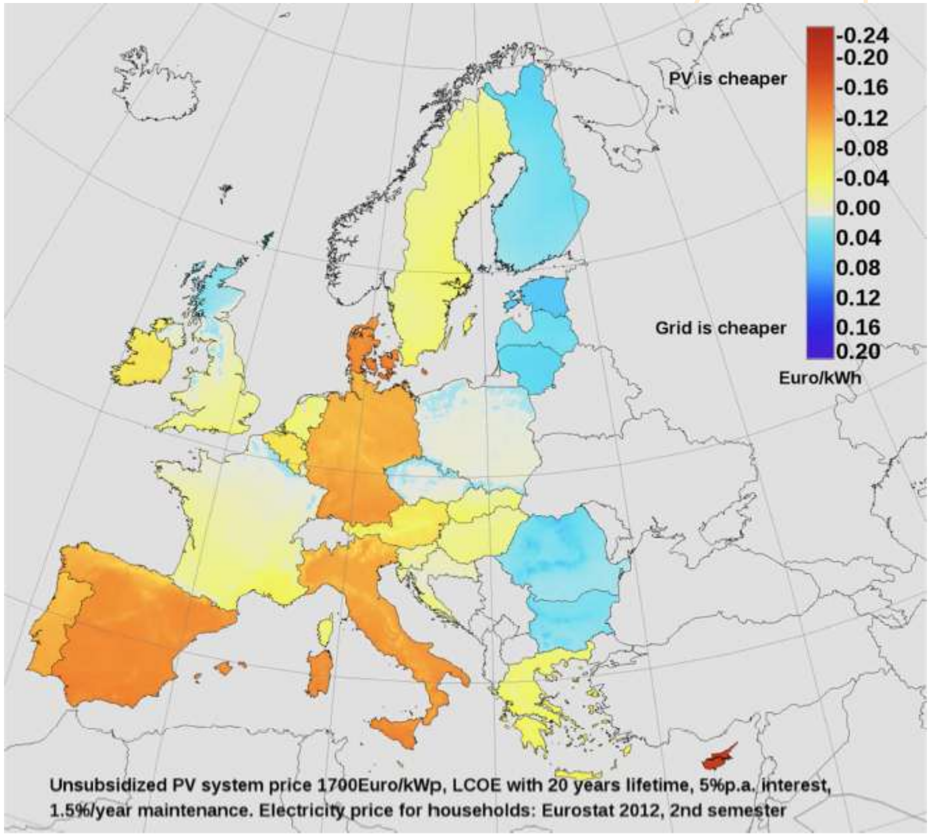
Nearly zero-energy buildings

Levelled cost of electricity from photovoltaics:

Photovoltaic electricity cost



Difference between the grid price and the PV electricity cost



Data from the EC of 2013

http://iet.jrc.ec.europa.eu/remea/sites/remea/files/reqno_jrc83366_jrc_83366_2013_pv_electricity_cost_maps.pdf

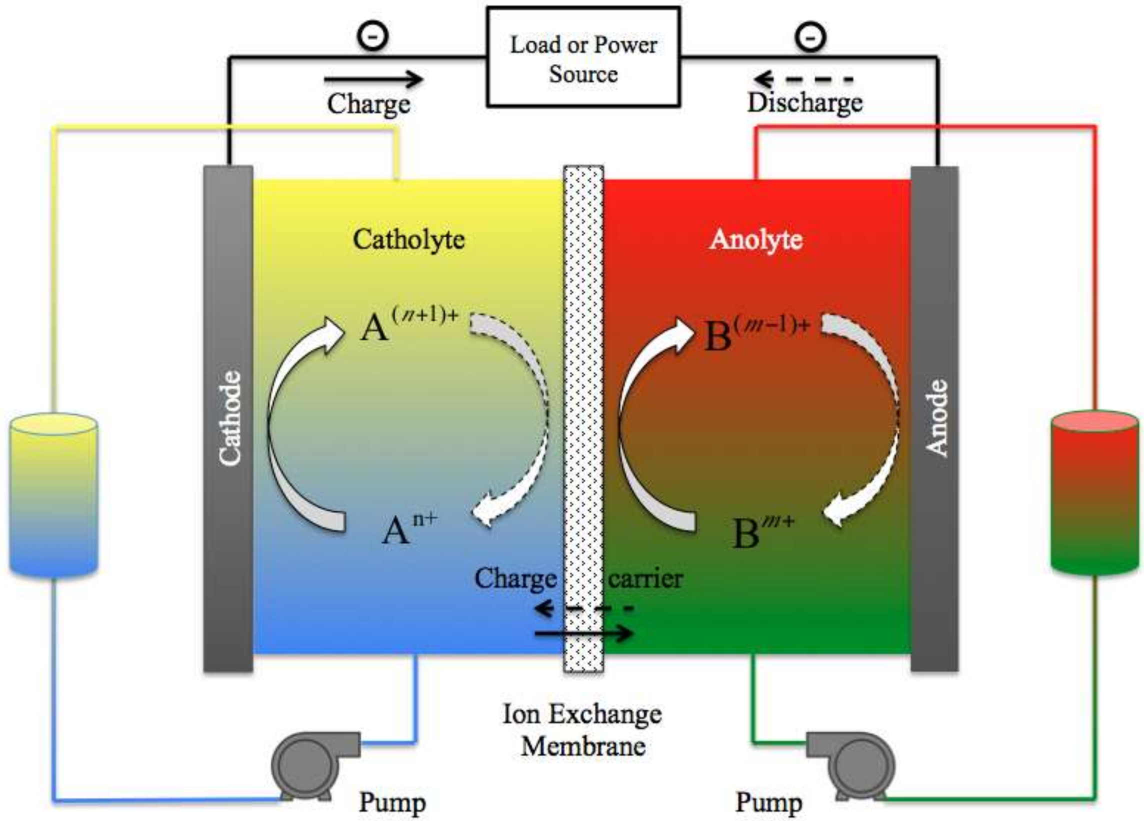
Nearly zero-energy buildings

Local electricity storage is required because:

- ✓ Stabilizing the local (low potential) grid;
- ✓ Make the renewable electricity dispatchable;
- ✓ Make the production of renewable electricity more profitable – no feed-in tariffs are assumed.

Redox flow battery

Redox flow battery



Charge

Positive (cathode): $A^{n+} \rightarrow A^{(n+1)+} + e^-$

Negative (anode): $B^{m+} + e^- \rightarrow B^{(m-1)}$

Redox flow battery

Available online at www.sciencedirect.com

ScienceDirect

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Journal of Power Sources 160 (2006) 716–732

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

Review

Redox flow cells for energy conversion

C. Ponce de León[a,*], A. Frías-Ferrer[b], J. González-García[b], D.A. Szánto[c], F.C. Walsh[a]

Charge

Positive (cathode): $VO^{2+} + H_2O \rightarrow VO_2^{+} + 2H^{+} + e^{-}$, $E^0 = -0.99\ V_{SHE}$

Negative (anode): $V^{3+} + e^{-} \rightarrow V^{2+}$, $E^0 = -0.26\ V_{SHE}$

$2VOSO_4 + 2H_2O + V_2(SO_4)_3 \rightarrow 2(VO_2)_2SO_4 + H_2SO_4 + 2VSO_4$, $\boldsymbol{E^0 = -1.25\ V}$

Redox flow battery

Concept and Efficiency

Vanadium RFB

Specific energy	~30 Wh·kg^{-1} (compared Li-ion, 150 Wh·kg^{-1}, gasoline ≈ 12 .5 kWh·kg^{-1})
Energy density	~30 Wh·L^{-1}
Charge/discharge efficiency	80 %
Time durability	20 years
Nominal cell voltage	1.25 V
Expected energy storage cost per cycle	3 ¢€·kWh^{-1}

Redox flow battery

200 kW all vanadium redox flow battery by Gildemeister

2015 Hannover Fair

Redox flow battery

Gildemeister – CellCube

Emerging redox flow battery

Emerging redox flow battery technologies

A metal-free organic–inorganic aqueous flow battery

Brian Huskinson, Michael P. Marshak, Changwon Suh, Süleyman Er, Michael R. Gerhardt, Cooper J. Galvin, Xudong Chen, Alán Aspuru-Guzik, Roy G. Gordon & Michael J. Aziz

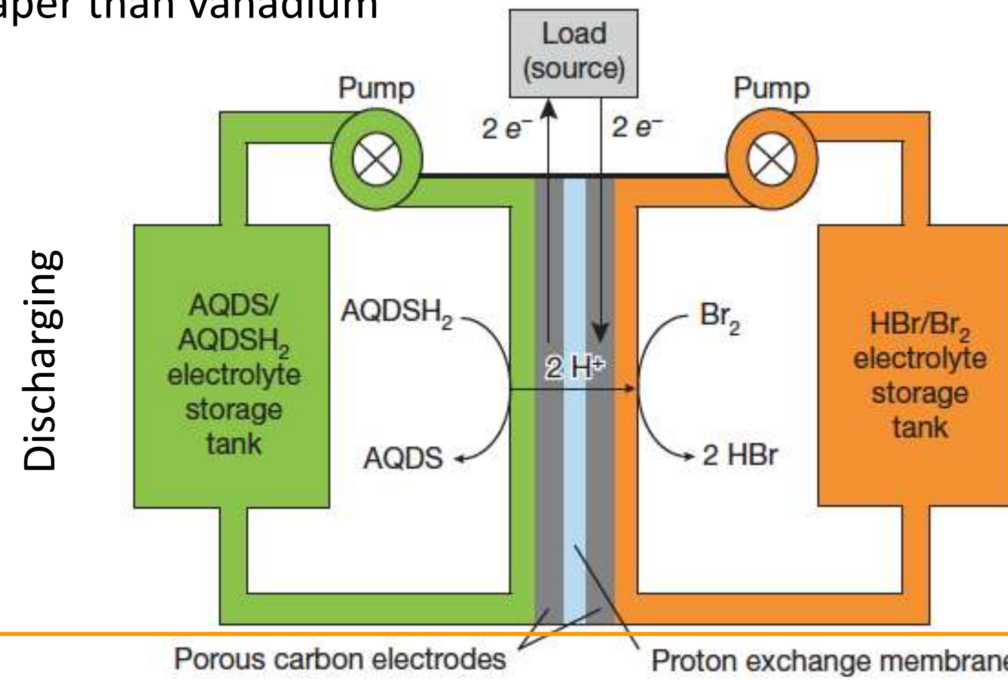
Affiliations | Contributions | Corresponding author

Nature **505**, 195–198 (09 January 2014) | doi:10.1038/nature12909

9,10-anthraquinone-2,7-disulphonic acid (AQDS) – bromide acid redox flow battery:

- ✓ 99 % cyclic efficiency!
- ✓ Maximum power density: 600 mW·cm^{-2};
- ✓ Current density: 1.3 A·cm^{-2};
- ✓ Nominal cell voltage: ca. 0.8 V;
- ✓ Energy density: 50 Wh·L^{-1};
- ✓ Cost: 70 % cheaper than vanadium

2014



Emerging redox flow battery technologies

A metal-free organic–inorganic aqueous flow battery

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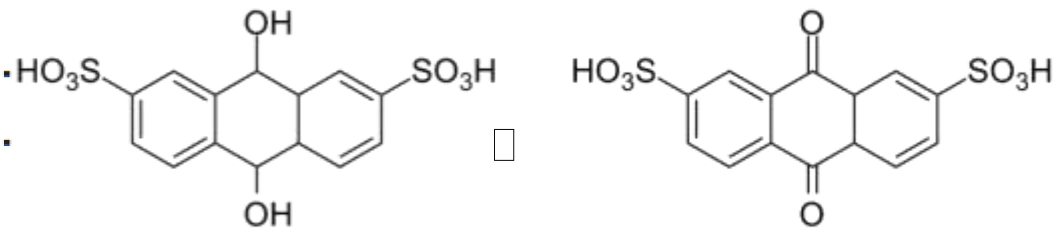
Anthraquinone (9,10-anthraquinone-2,7-disulphonic acid - AQDS)

Discharge



$+ 2e^- + 2H^+ \quad E^0 = -0.213$ V

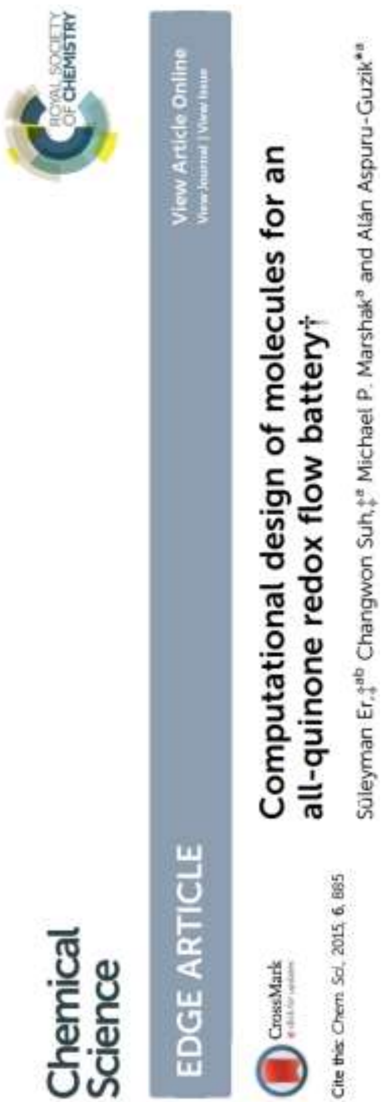
$AQDSH_2 \rightleftharpoons AQDS + 2e^- + 2H^+ \quad E^0 = -0.213\ V_{SHE}$

$Br_2 + 2e^- \rightleftharpoons 2Br^- \quad E^0 = 1.07\ V_{SHE}$

$\Delta V = 0.86$ V

2014

Emerging redox flow battery technologies


Chemical Science

EDGE ARTICLE

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Cite this: Chem. Sci., 2015, 6, 885

Computational design of molecules for an all-quinone redox flow battery†

Süleyman Er,‡[ab] Changwon Suh,‡[a] Michael P. Marshak[a] and Alán Aspuru-Guzik*[a]

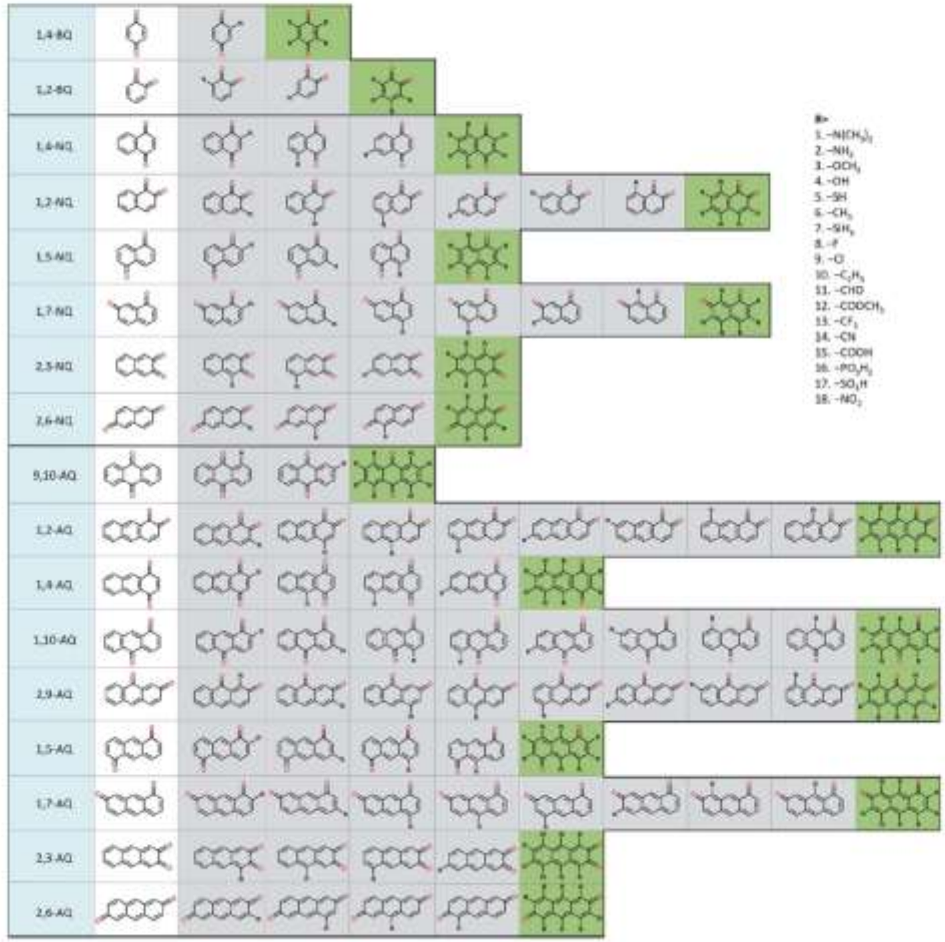
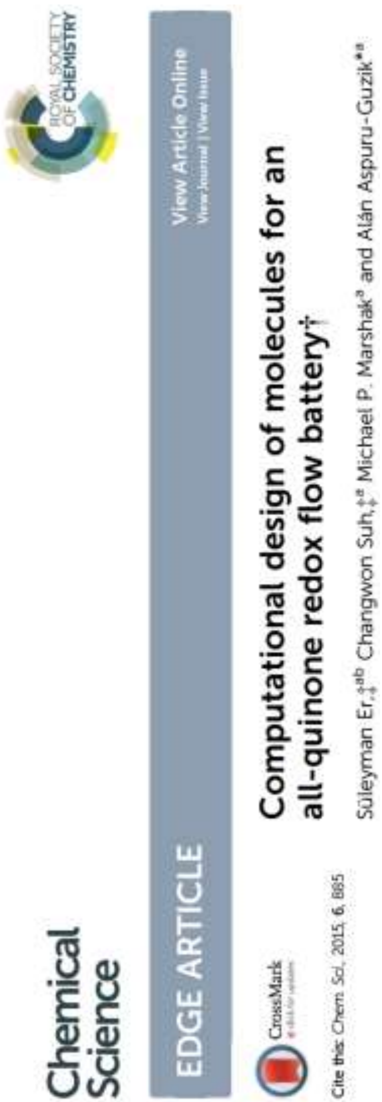


Fig. 1 A schematic representation of the molecular screening library. The parent BQ, NQ, and AQ isomers are shown on left (white). These quinone isomers are functionalized with 18 different R-groups singly (gray) and fully (green) to generate a total of 1710 quinone molecules.

2015

Emerging redox flow battery technologies



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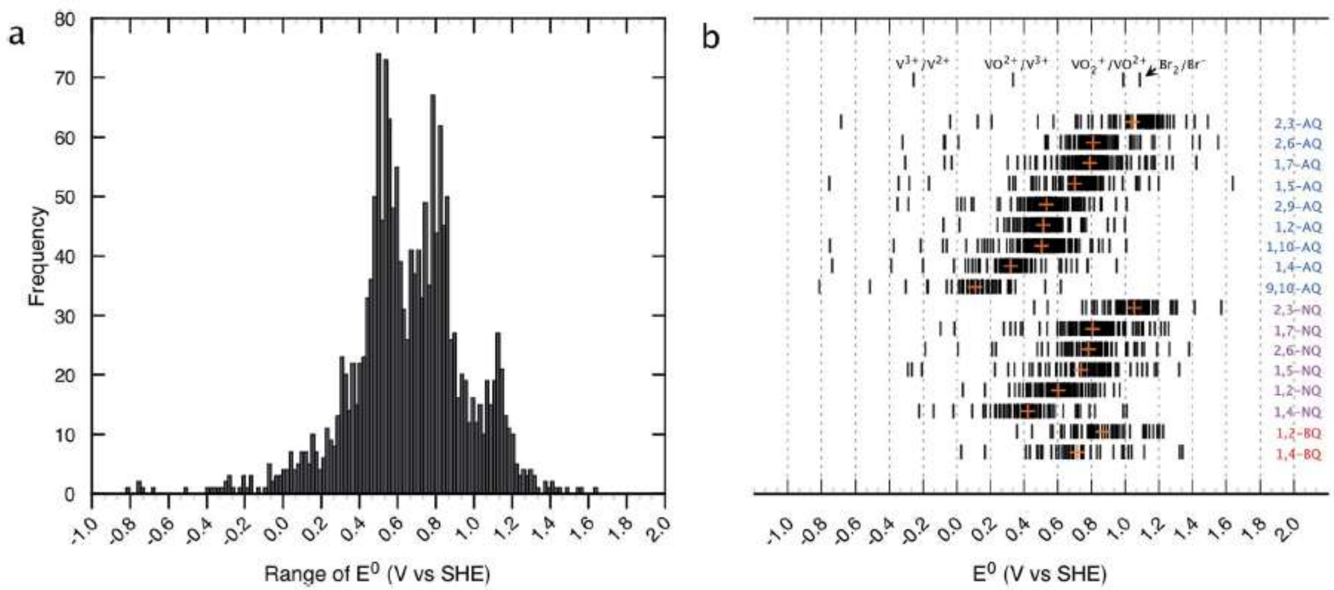


Fig. 2 Distribution of HT screened quinone/hydroquinone redox couples. (a) A histogram of theoretically predicted E^0 (V *vs.* SHE). Number of bins and width of the histogram are 130 and 0.1 V, respectively. (b) E^0 windows for the different classes of quinones. The orange crosses show the mean values of E^0 for each class. Redox potentials of the conventional inorganic AFB redox couples are noted for comparison.[43]

2015

Moving beyond the obvious

Moving beyond the obvious

Would be it possible to convert directly the sunlight into storable energy?

http://www.clipartpanda.com/categories/thinking-clip-art-pictures

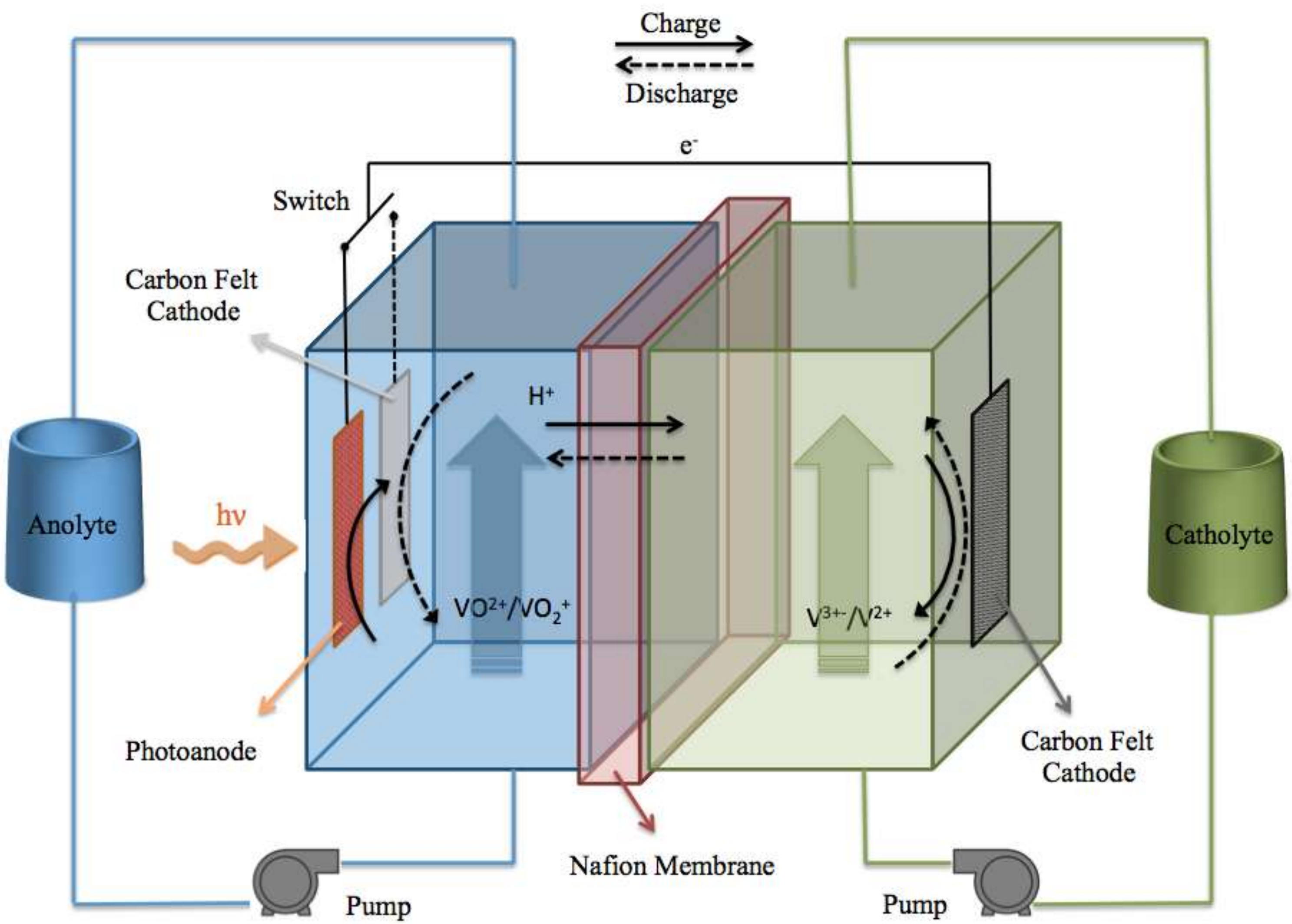
A completely new world:

Solar chargeable redox flow battery

Moving beyond the obvious

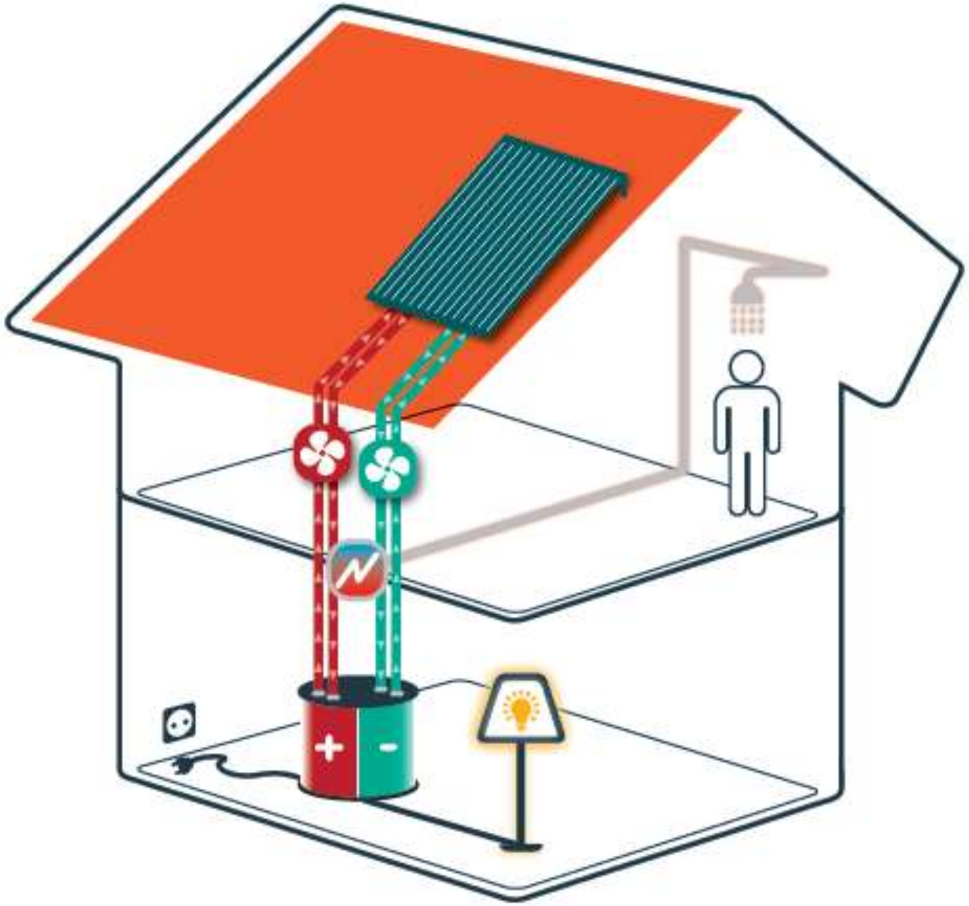
http://cliparts.co/clipart/177584

Solar chargeable redox flow battery - concept



Solar chargeable redox flow battery - concept

The concept - cogeneration



Sunlight -> storable electrochemical energy and heat

Solar chargeable redox flow battery - concept

Expected figures

Overall energy efficiency	~80 %
Electricity storage cost per cycle	3 ¢€/kWh
Time durability	20 years
Nominal cell voltage	1.3 V

Solar rechargeable redox flow battery

Specific power (assumed *η* = 10 %)	100 $Wp \cdot m^{-2}$
Specific energy (assumed 1.6 $MWh \cdot year^{-1} \cdot m^{-2}$)	4.4 $kWh \cdot day^{-1} \cdot m^{-2}$
Volume of electrolyte produced per day (assumed 30 $Wh \cdot kg^{-1}$)	29 $L \cdot day^{-1} \cdot m^{-2}$
Typical electricity house - consumption per day	9 kWh -> 300 L -> **20 m^2**
Heat production	61 $kWh \cdot day^{-1}$*

*Enough for heating 960 L of water from 5 °C to 60 °C assuming *η* = 70 %

Vanadium solar chargeable redox flow battery - experimentation

Redox flow battery

Chosen redox system

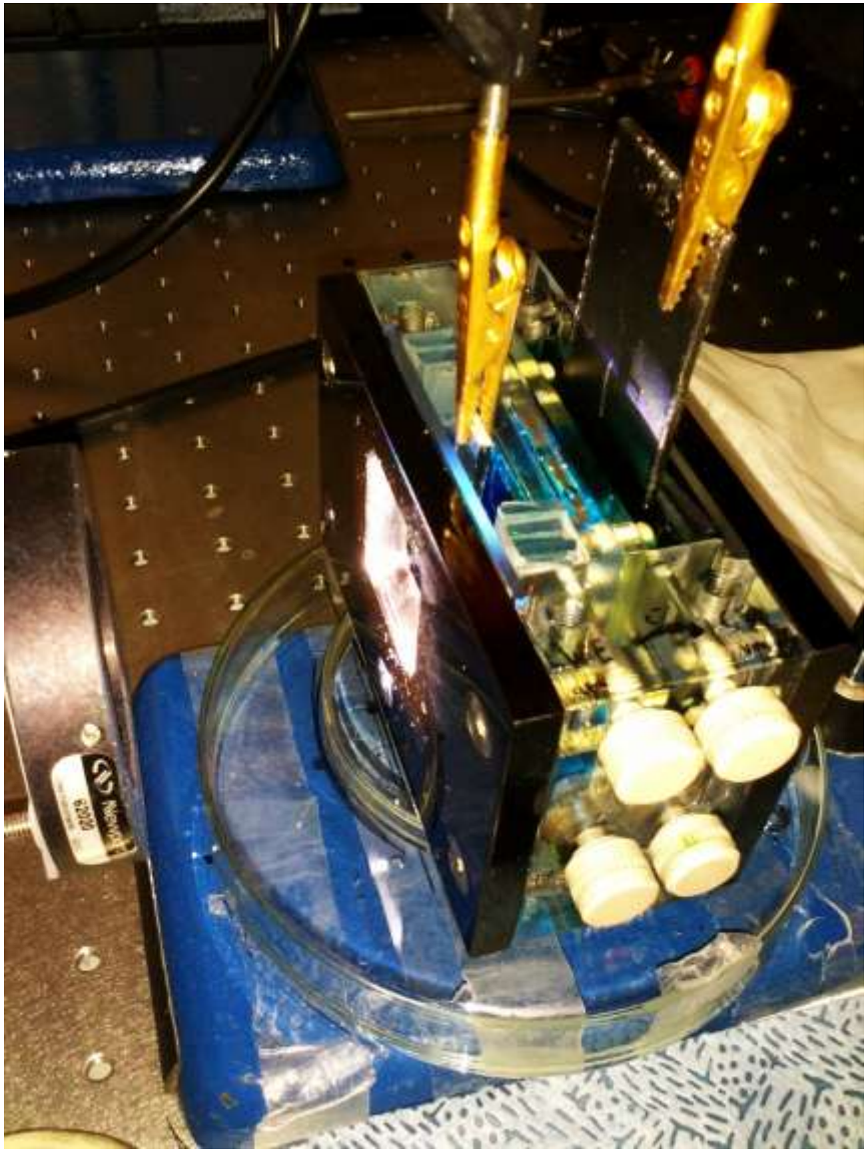
Charge

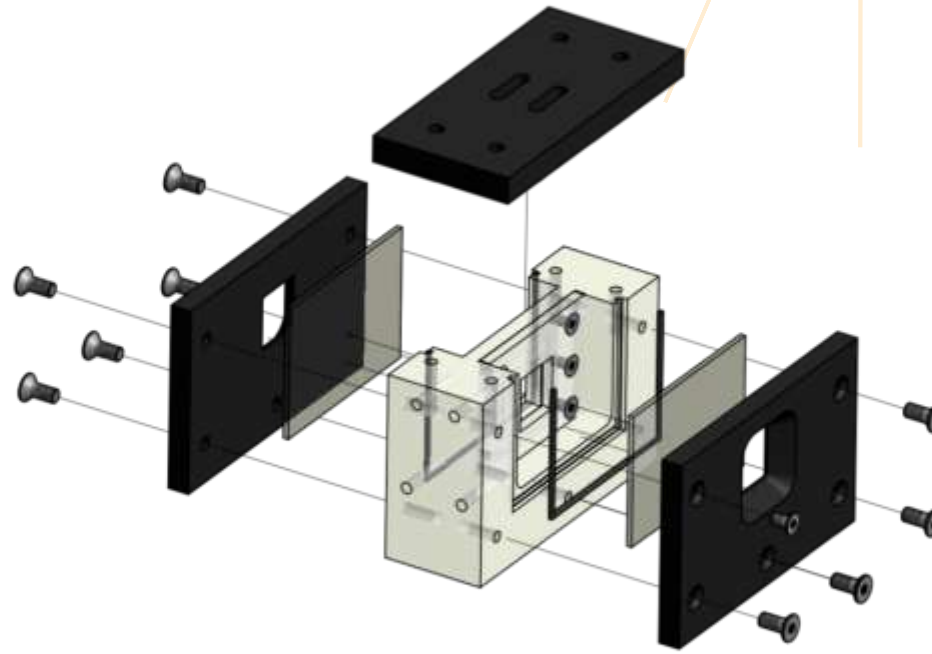
Positive (cathode): $V^{3+} + H_2O \rightarrow VO^{2+} + 2H^+ + e^-$, $E^0 = -0.34\ V_{SHE}$

Negative (anode): $V^{3+} + e^- \rightarrow V^{2+}$, $E^0 = -0.26\ V_{SHE}$

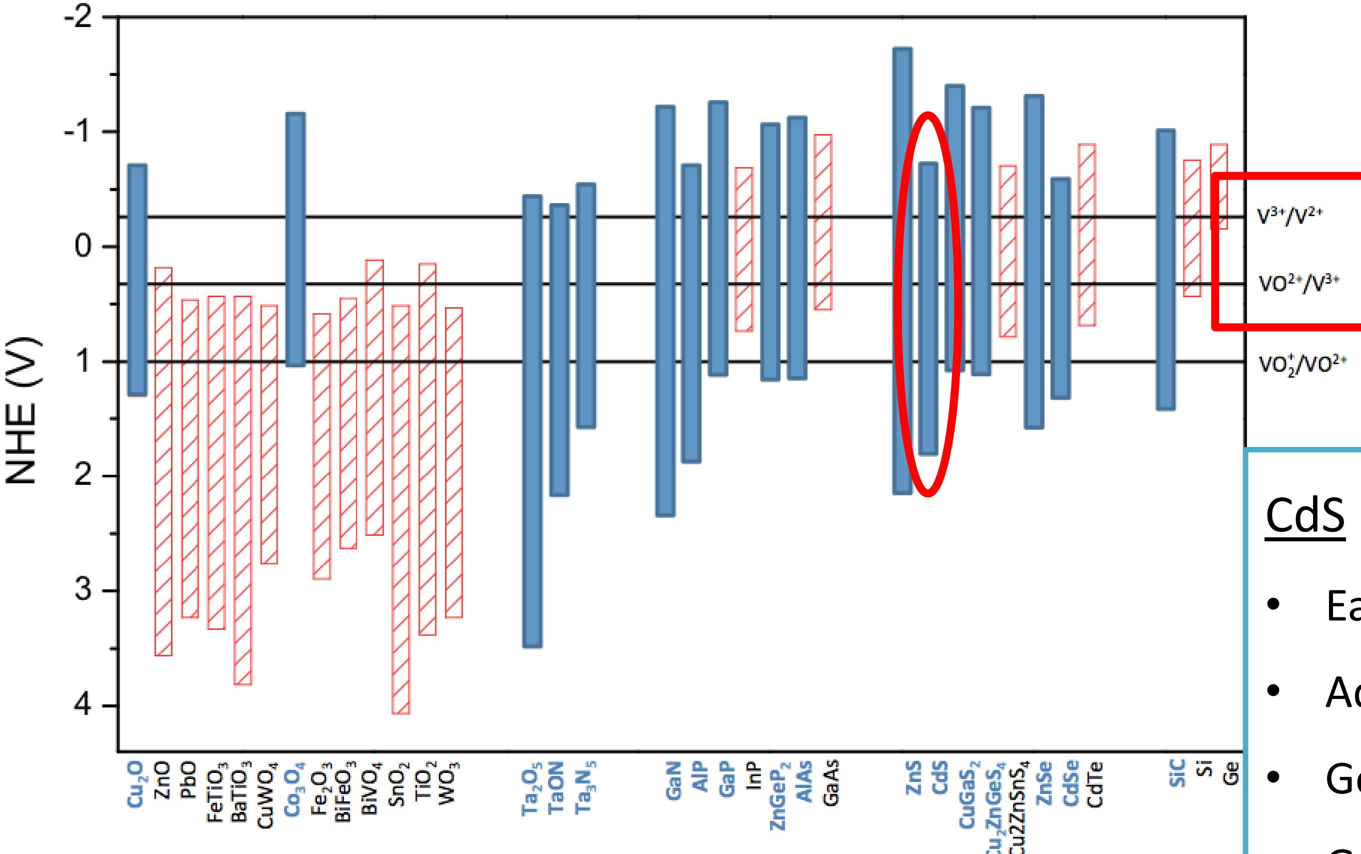
$V_2(SO_4)_3 + H_2O \rightarrow VOSO_4 + H_2SO_4 + VSO_4$, $\boldsymbol{E^0 = -0.60\ V}$

Solar chargeable redox flow battery





Solar chargeable redox flow battery



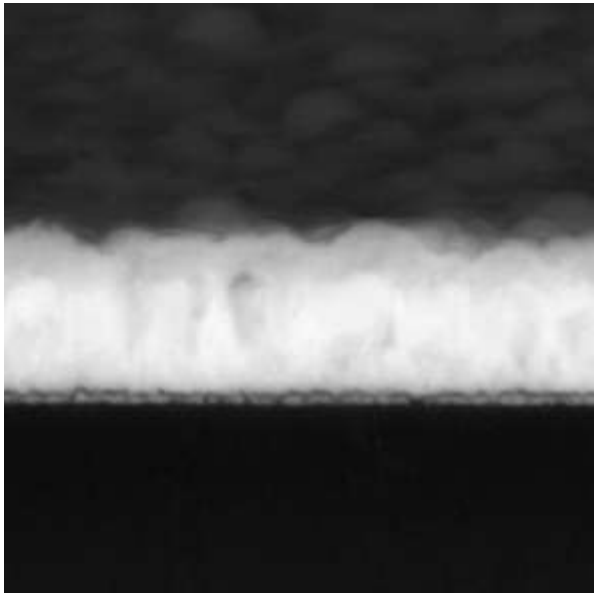
Band edge positions for selected semiconductors at pH 0, together with vanadium redox potentials.

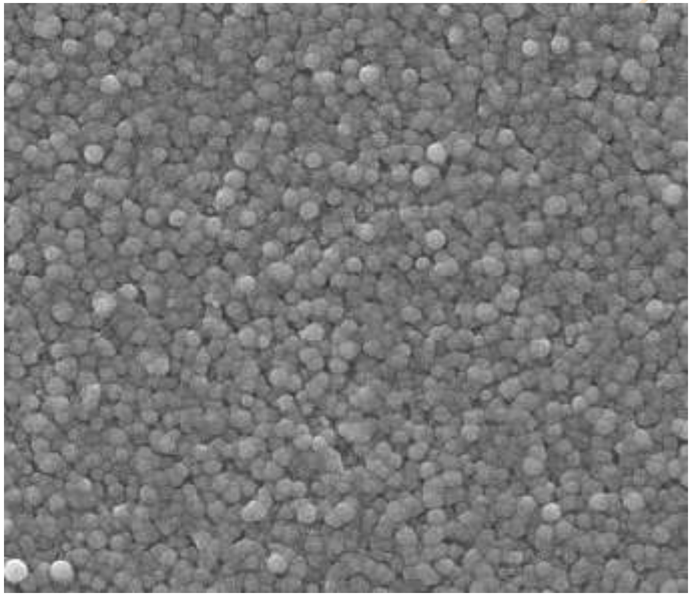
<u>CdS</u>

- Easy to prepare
- Adequate band gap
- Good light absorption
- Good electrical conductivity

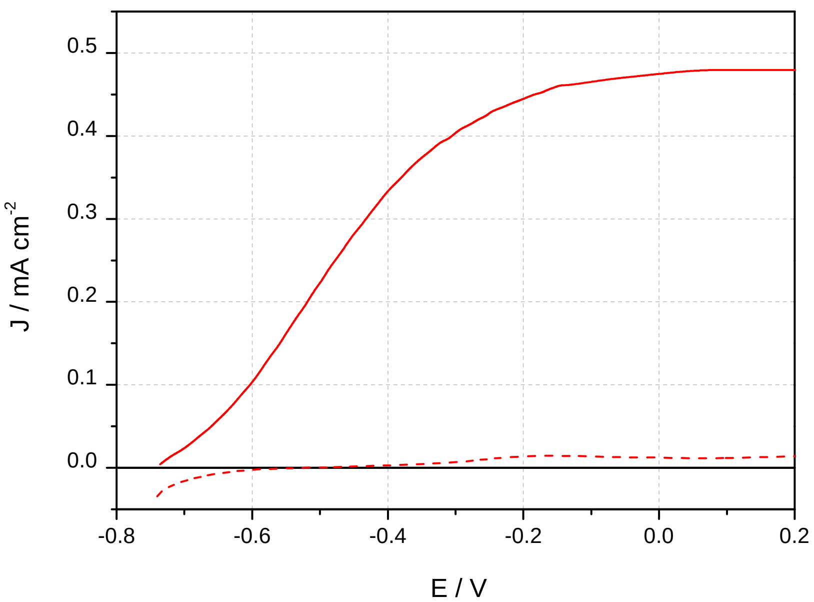
Solar chargeable redox flow battery

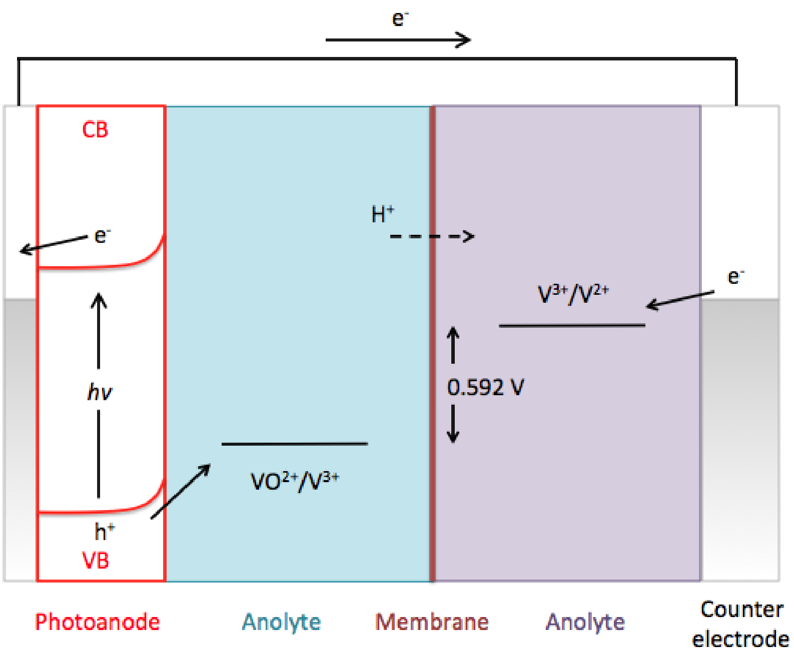
CdS photoelectrode





Solar chargeable redox flow battery





1.5 AM light and dark conditions (in 0.2 M V^{3+} / 2 M H_2SO_4 electrolyte) of a CdS photoanode

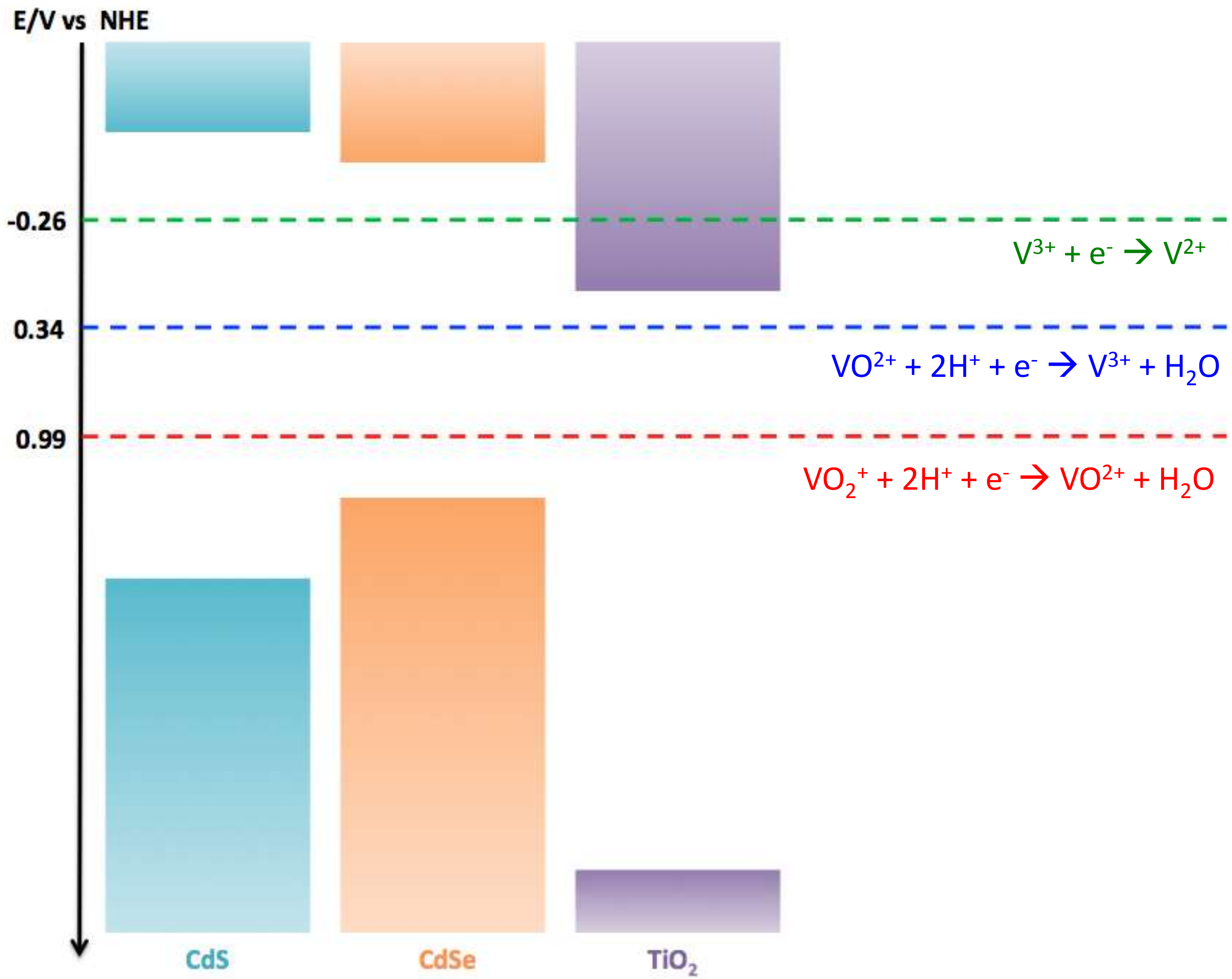
Solar chargeable redox flow battery

CdS photoelectrode with a CdSe protective layer

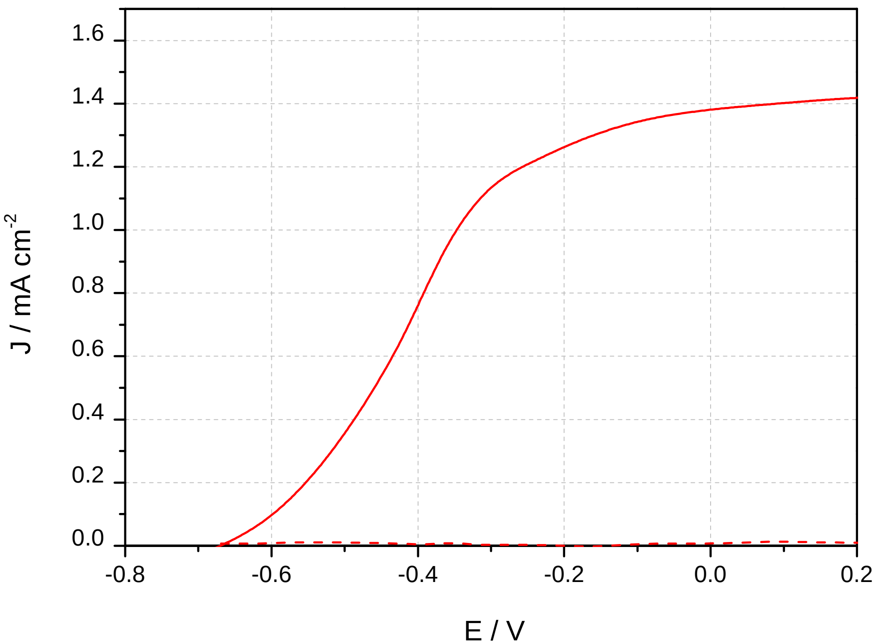
Sample ID	Anode/Cathode	Configuration	*J* at 0 V (mA/cm²)	J/J_0 after 5 min at 0 V (%)
1	Anode	Bare CdS	0.47	46
2	**Anode**	**CdS/200 nm CdSe**	**1.40**	**86**
3	Anode	CdS/200 nm CdSe (back illumination)	0.66	81
4	Anode	TiO_2 (paste)/CdS/200 nm CdSe	0.12	63
5	Cathode	CdS/200 nm CdSe/100 nm TiO_2 (ALD)	-1.90	47
6	Anode	CdS/200 nm CdSe/5 nm TiO_2 (ALD)	0.40	26

Solar chargeable redox flow battery

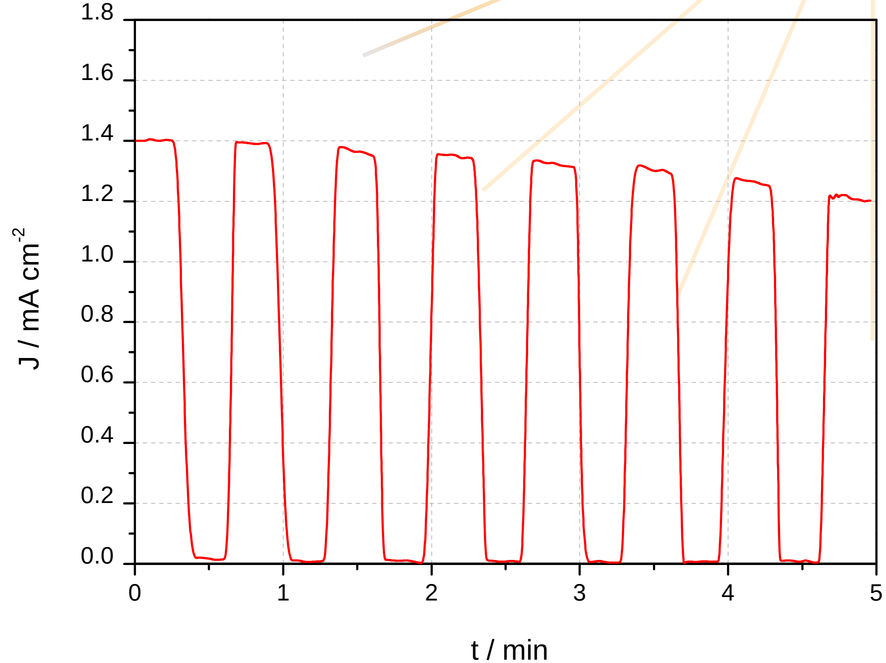
CdS photoelectrode with a CdSe protective layer



Solar chargeable redox flow battery



I-V curve of a Cd/CdSe photoelectrode sample



Stability of a Cd/CdSe sample

CdS / CdSe configuration

- ✓ Better light absorption in the visible range
- ✓ Higher photocurrents
- ✓ Improved stability

All vanadium solar chargeable redox flow battery – tandem arrangement

Redox flow battery

Charge

Positive (cathode): $VO^{2+} + H_2O \rightarrow VO_2^{+} + 2H^{+} + e^{-}$, $E^0 = -0.99\ V_{SHE}$

Negative (anode): $V^{3+} + e^{-} \rightarrow V^{2+}$, $E^0 = -0.26\ V_{SHE}$

$2VOSO_4 + 2H_2O + V_2(SO_4)_3 \rightarrow 2(VO_2)_2SO_4 + H_2SO_4 + 2VSO_4$, $\boldsymbol{E^0 = -1.25\ V}$

Solar chargeable redox flow battery

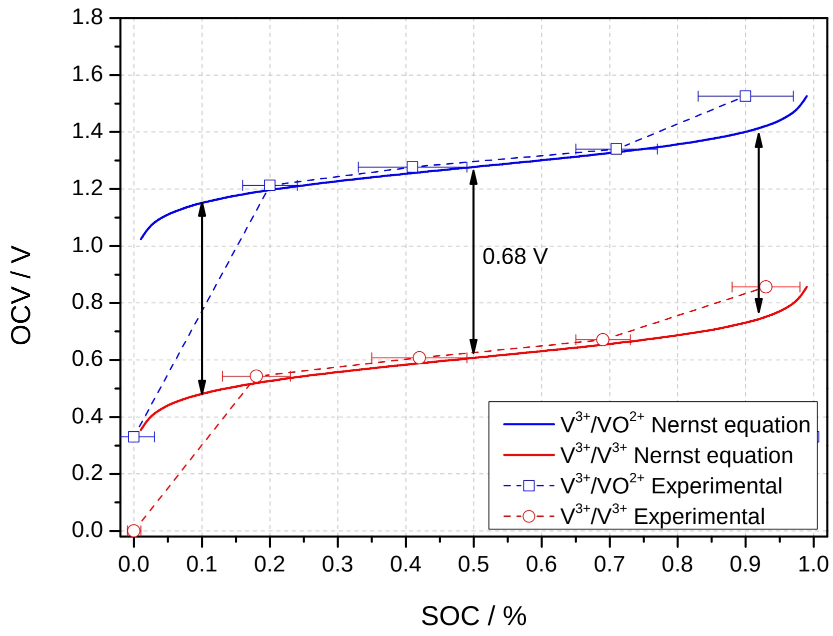
Dye sensitized solar cells (DSC) :

- ✓ Considered organic PV type.
- ✓ Maximum energy efficiency: 12 %.

- \+ Low cost and high efficiency harvesting diffuse light.
- \+ Very aesthetic for BIPV.
- \+ Uses abundant and non toxic materials.

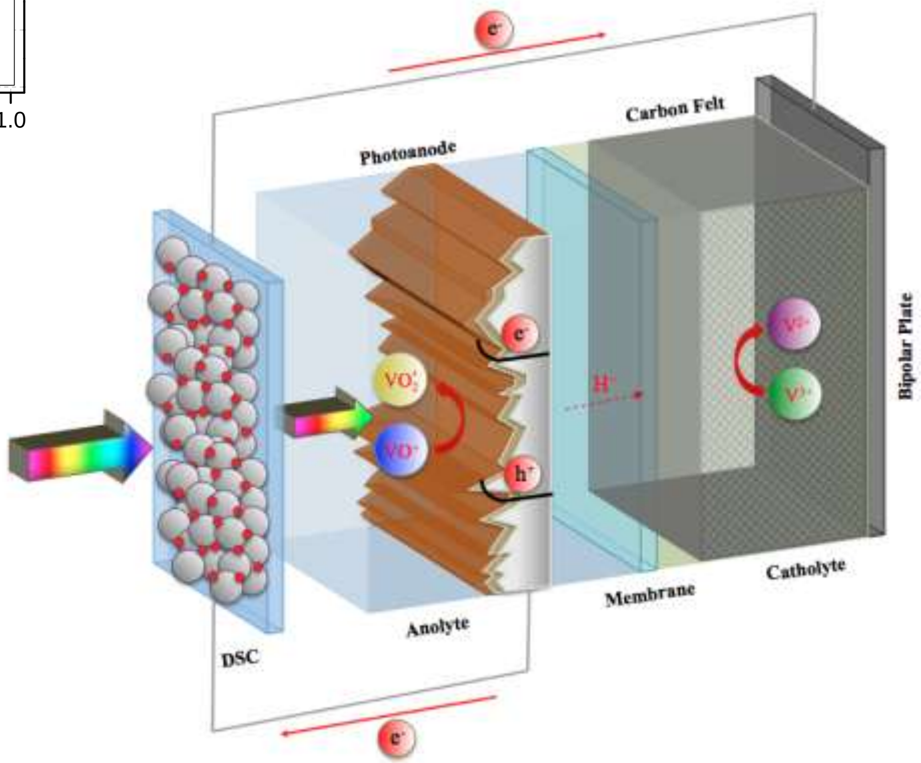
- \- Moderate efficiencies.
- \- Not yet commercial.

Solar chargeable redox flow battery



0.68 V extra to charge a standard all vanadium redox flow battery

Tandem Configuration



Conclusions

Conclusions & outlook

- ✓ Redox flow batteries will soon have a storage electricity cost of 3 ¢€/kWh/cycle – the lowest local storage cost technology;
- ✓ Photoelectrochemical cells are better used to store sunlight energy into RFB electrolytes!
- ✓ Tandem arrangements of PEC + DSC proved to charge completely a all vanadium battery;
- ✓ New are more exciting systems are around the corner and soon they will be reported.

A new world

My home is my castle:

I need sunlight but no grid!

Acknowledgements

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and the whole research team.

http://www.clipartpanda.com/clipart_images/teamwork-kids-5707313

Questions are welcome