Theory and Practice of Solar Cells: A Cell to System

Solar Cells and Energy Storage

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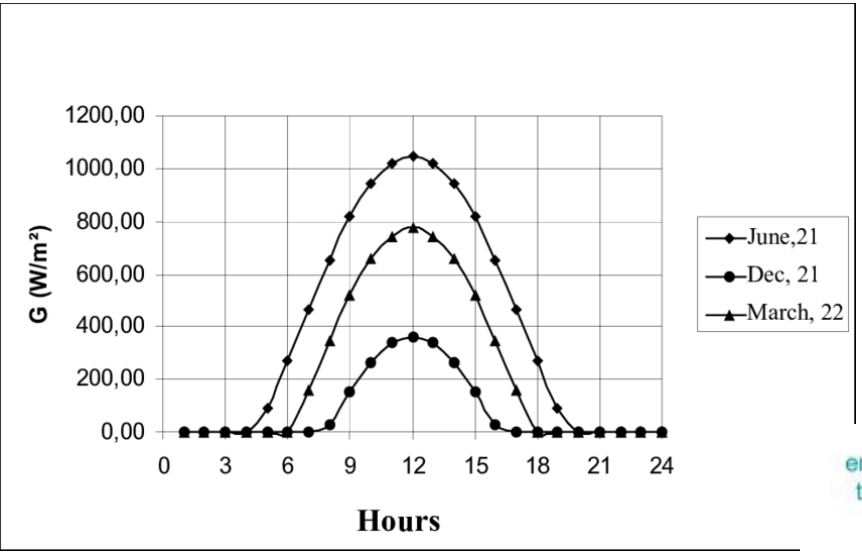
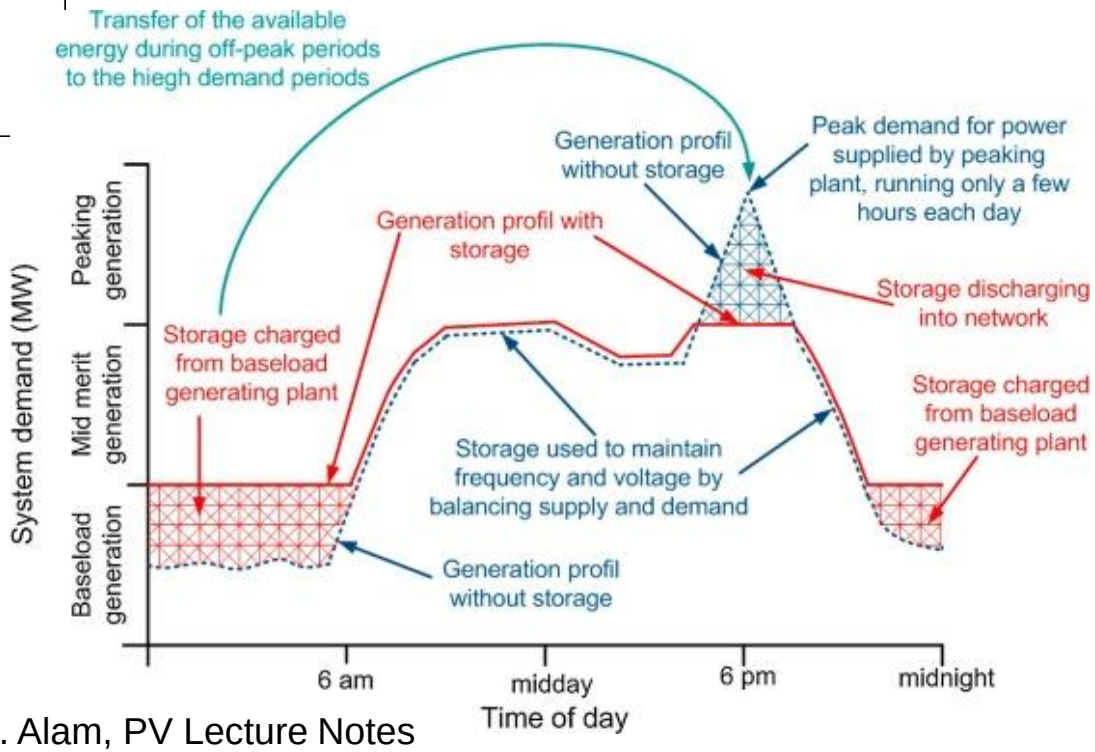
Outline

1) Background: Storage is a problem
2) Electro-mechanical storage of energy
3) Electro-chemical storage of energy
4) Direct integration of PV and EC systems
5) Conclusions

The trouble with solar





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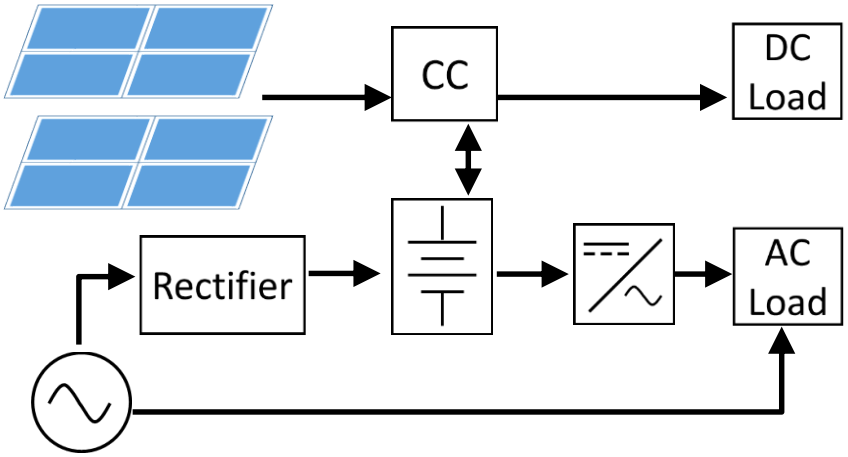
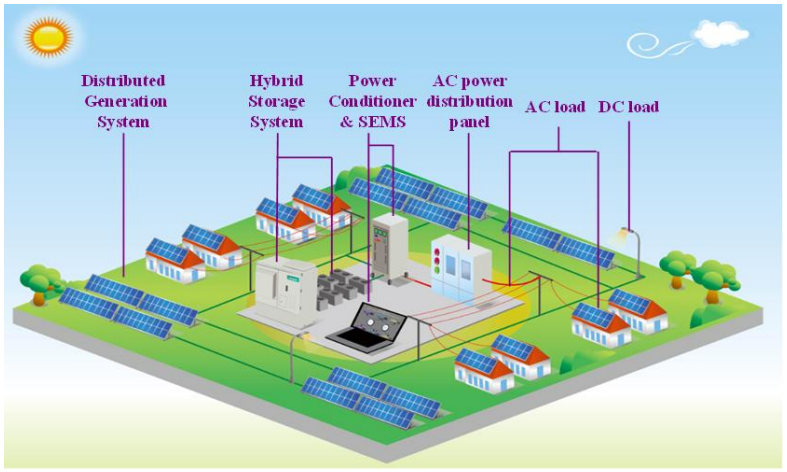
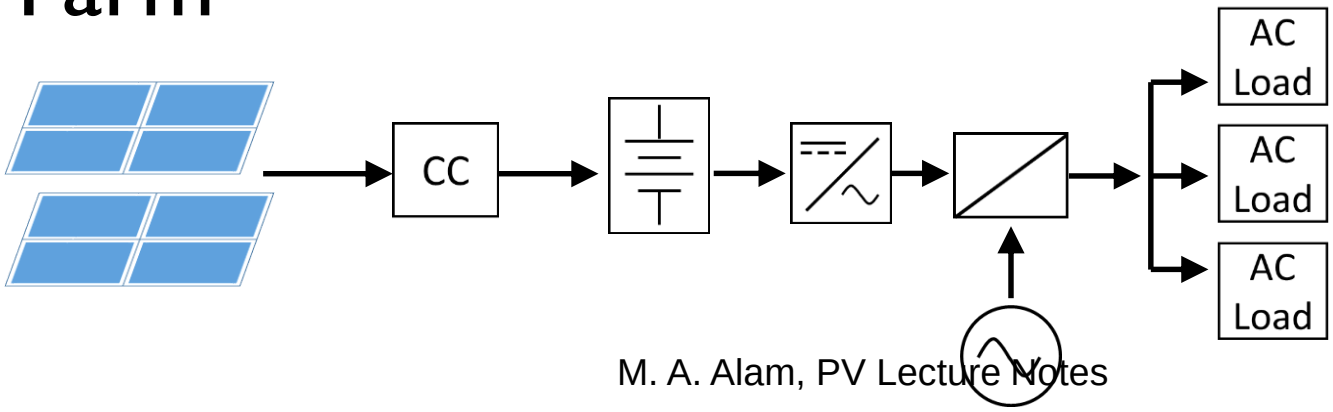
Need for storage

Home

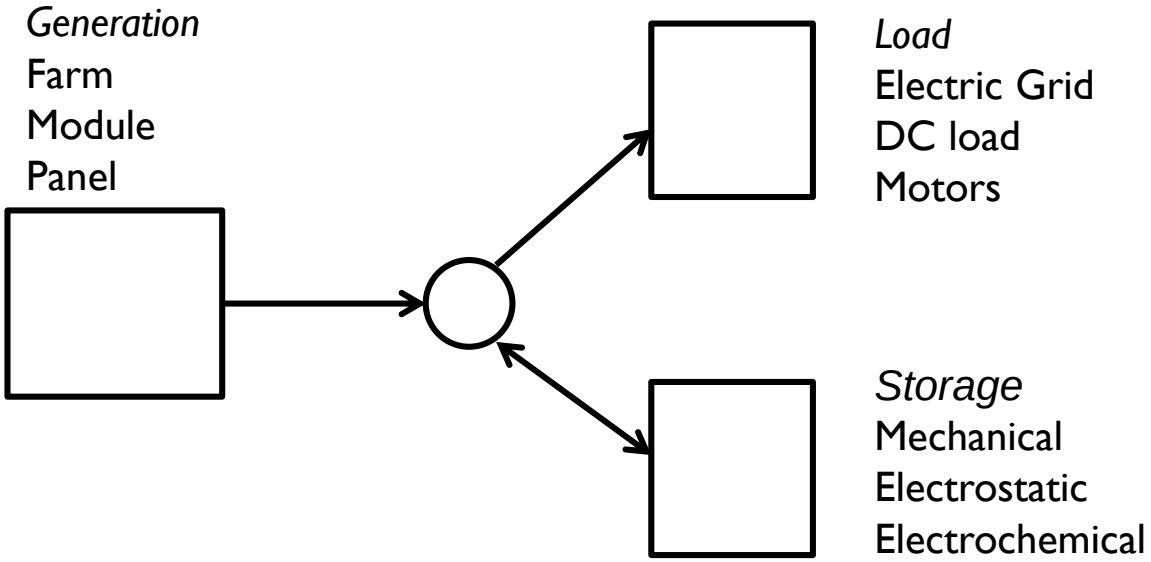


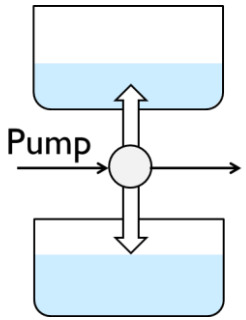


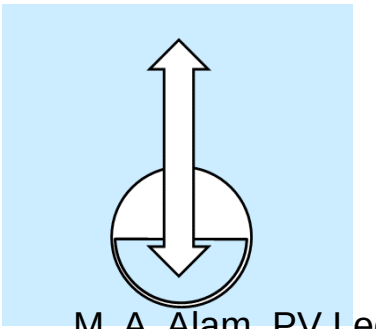
Farm

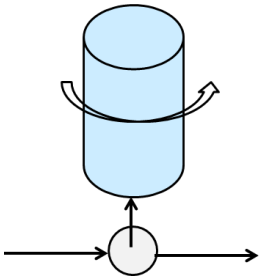


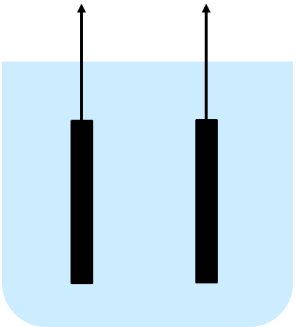
A Variety of Storage Concepts











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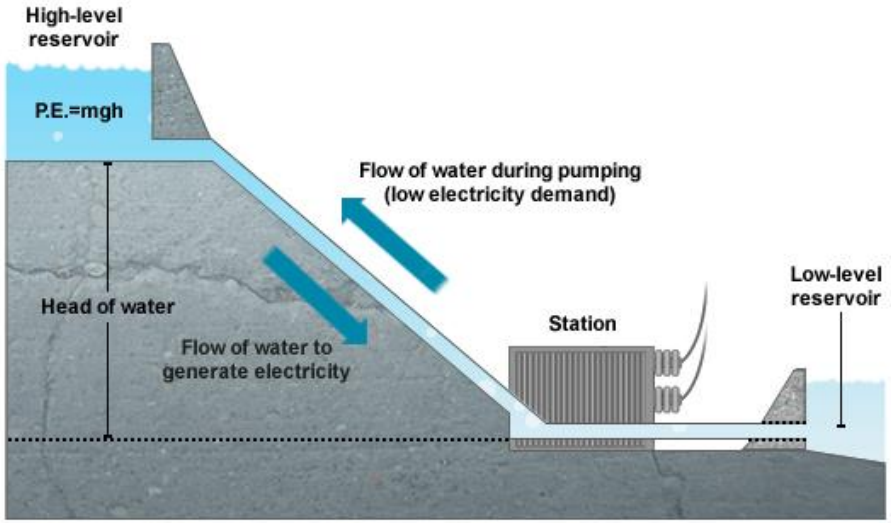
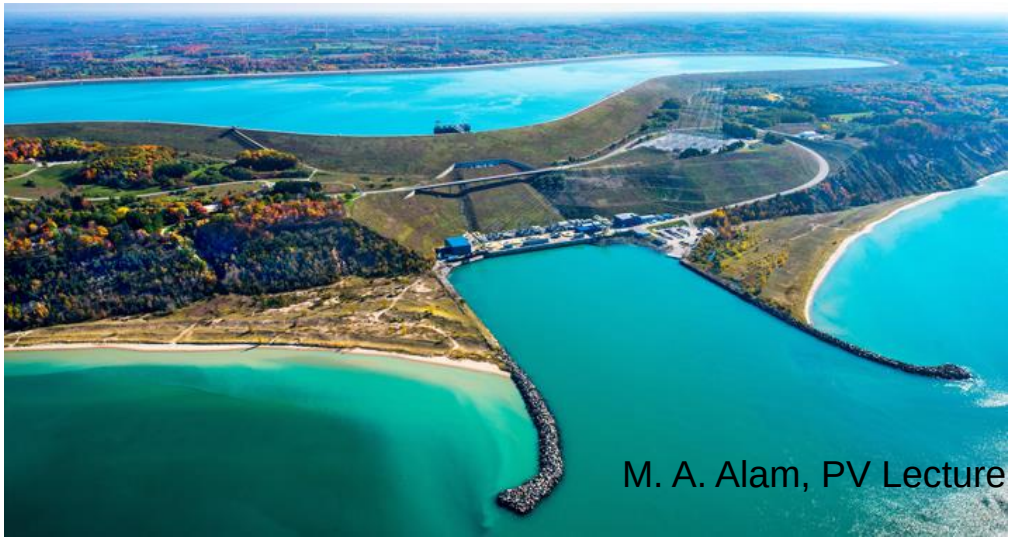
Mechanical: Pumped Hydro



$$W = mgh$$

$$\eta = 80 - 90\%$$



Ludington Pump Hydro
1000 acres, Lake Michigan
Since 1973

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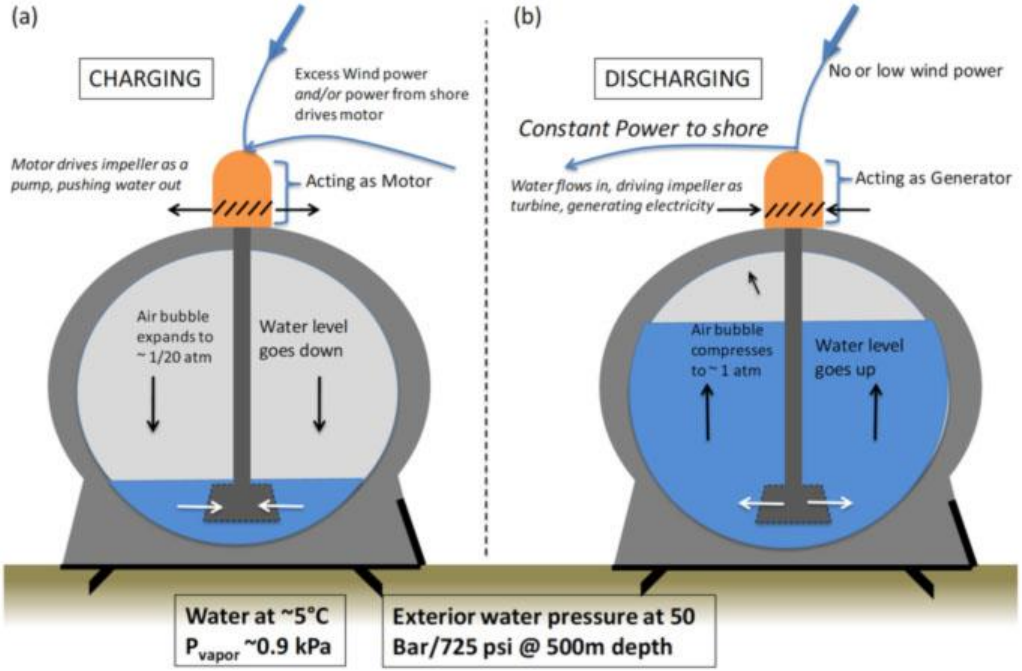
Mechanical: Pumped Air Storage

$$W \propto (P_2 - P_1)\, V$$



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Kinetic Energy Storage

$$W = \frac{1}{2} I \omega^2$$

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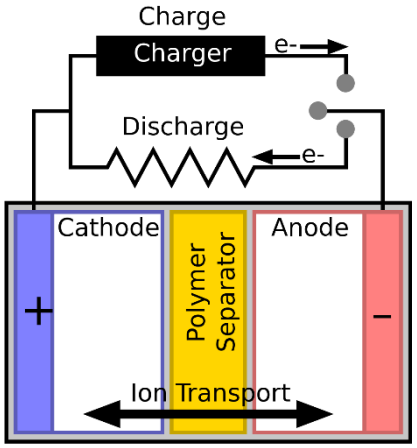
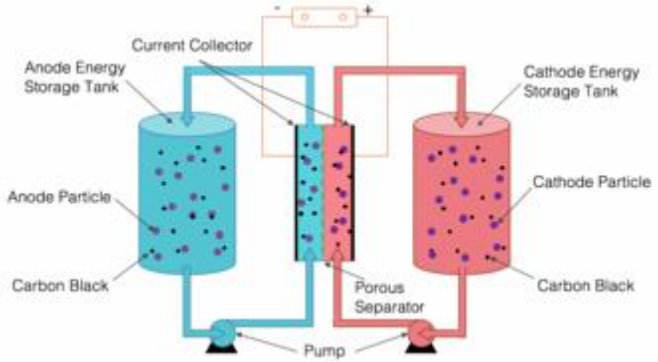
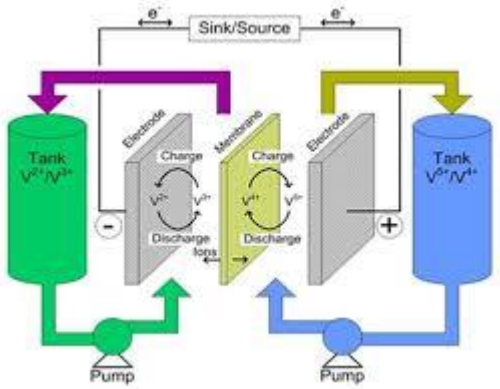
Electro-chemical Storage

EC Batteries



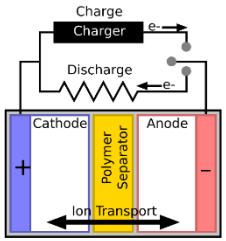
Flow batteries





Pb-acid, Li-ion, Ni-Cd
(cost, capacity, reliability)

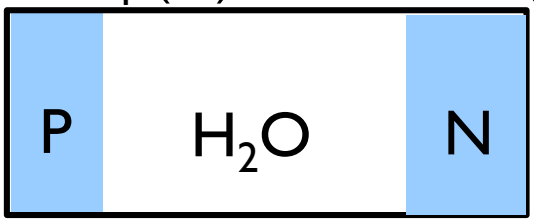
ZnBr, VRB, PSB
(Long life, rapid response)

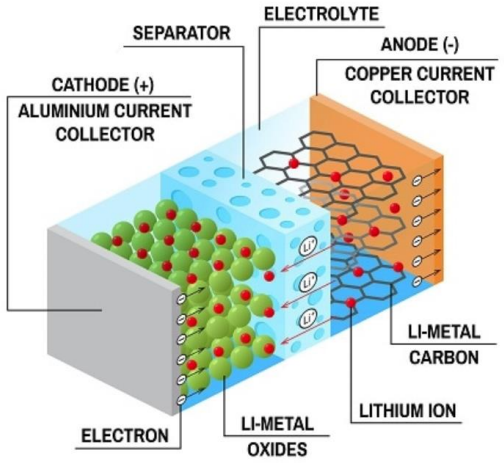


Electrochemical battery

Discharged state

$PbSO_4$ (C) PbSO4(A)

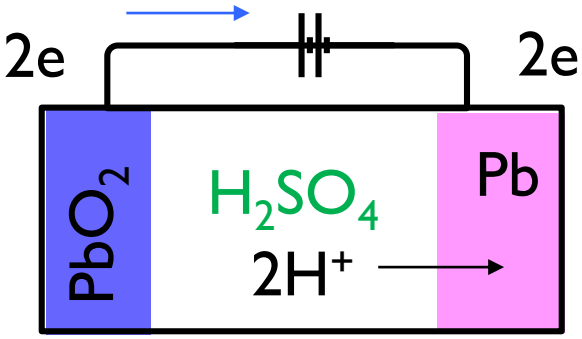


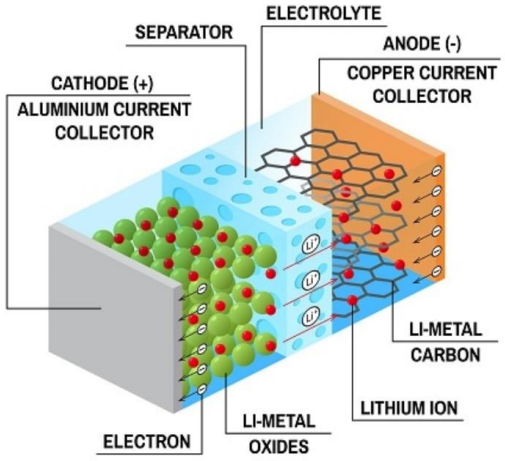


$PbSO_4 + 2H_2O \rightarrow PbO_2 + H_2SO_4 + 2H^+ + 2e^-$

CHARGE

Charged state





$PbSO_4 + 2H^+ + 2e^- \rightarrow Pb + H_2SO_4$

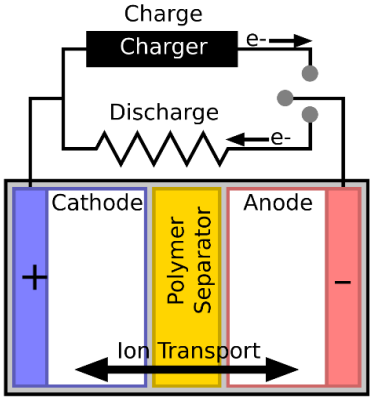
A Simple model for battery

$$I_{BV} = I_{0,BV}\left[e^{\alpha_F v} - e^{-\alpha_R v}\right] \qquad v \equiv \mathrm{m}\,(qV - E_0(t))/(k_B T)$$

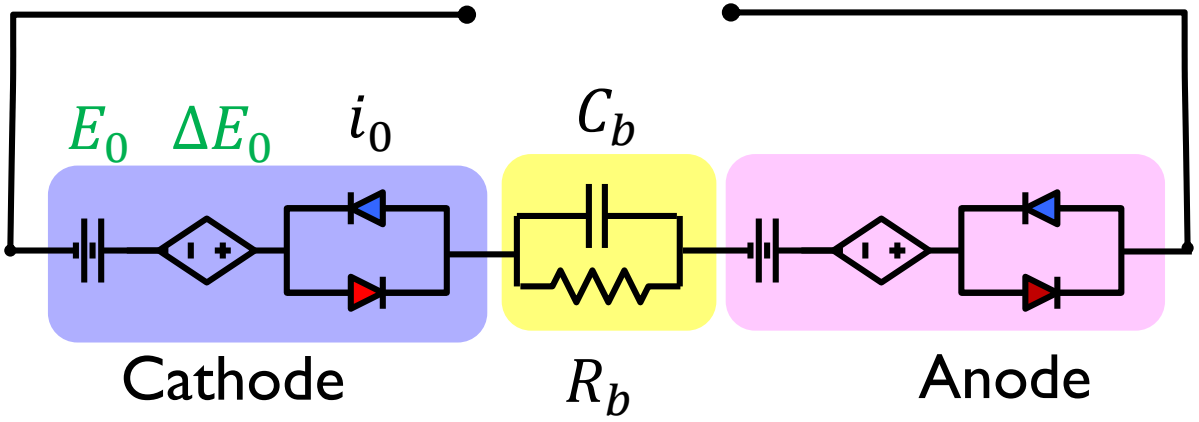
m … electrons reaction

E_0 …Reaction potential

$\alpha_F + \alpha_R = 1$



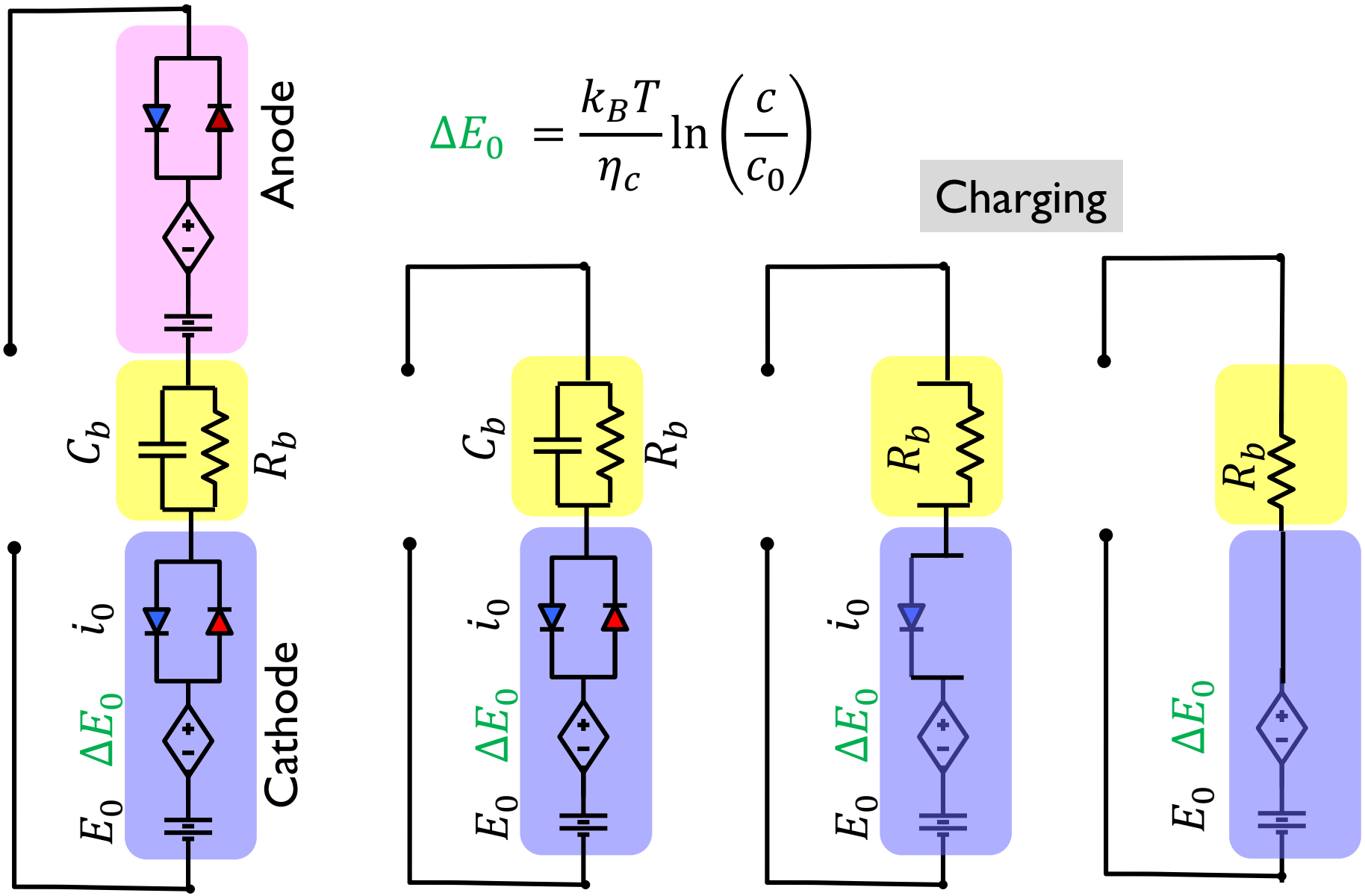
$$\Delta E_0 = \frac{k_B T}{\eta_c} \ln\left(\frac{c}{c_0}\right)$$



A Simple model for battery

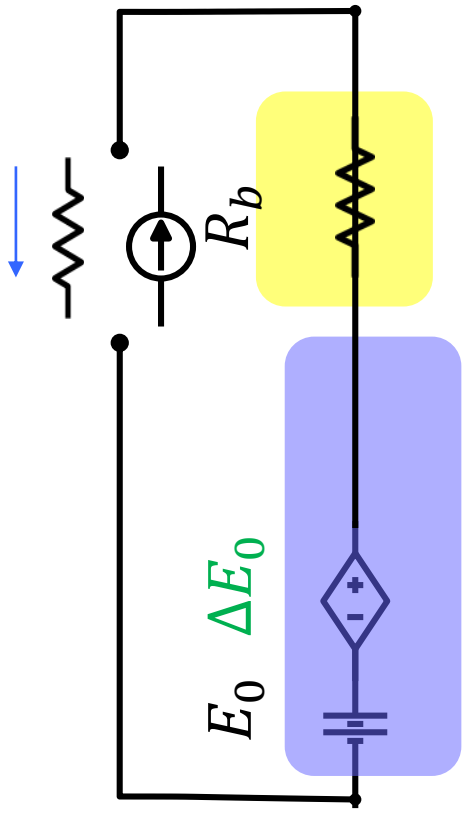
$$\Delta E_0 = \frac{k_B T}{\eta_c} \ln\left(\frac{c}{c_0}\right)$$

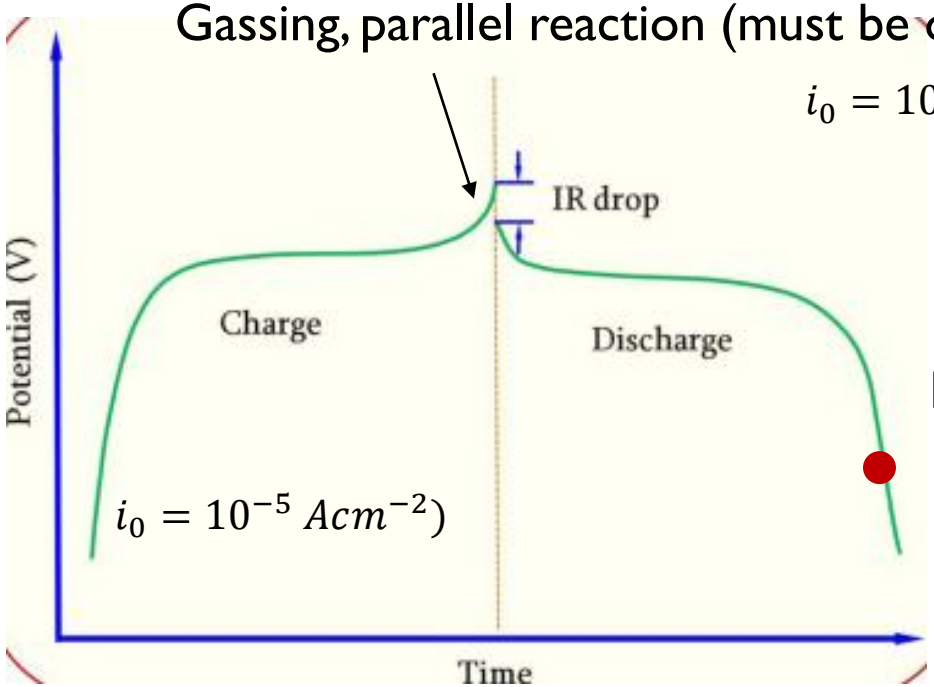
Charging



A Simple model for battery

$$\Delta E_0 = \frac{k_B T}{\eta_c} \ln\left(\frac{c}{c_0}\right) = \frac{k_B T}{\eta_c} \ln\left(\frac{I \times t}{c_0}\right)$$





Gassing, parallel reaction (must be optimized)

$i_0 = 10^{-13}\ A.cm^{-2}$

Depth of charge

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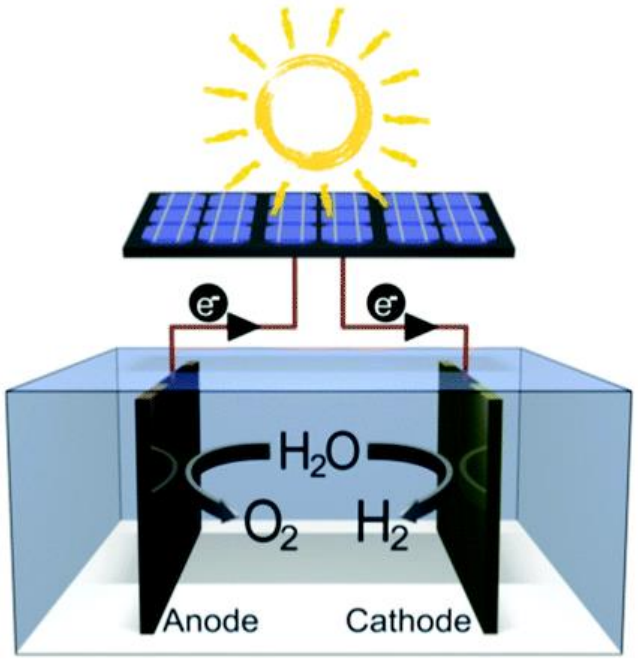
A power-plant!

Electrolyzing water and H2 storage



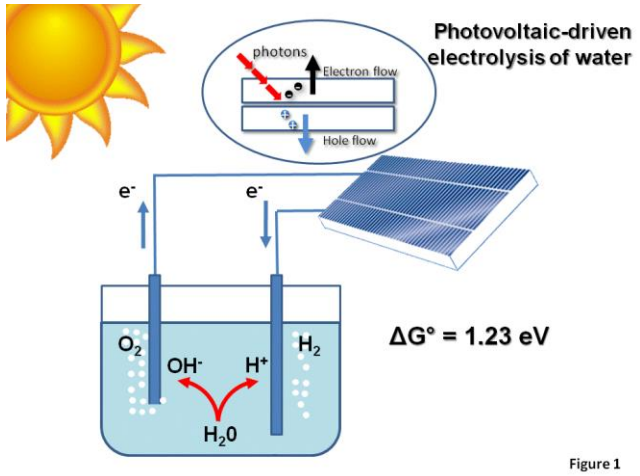
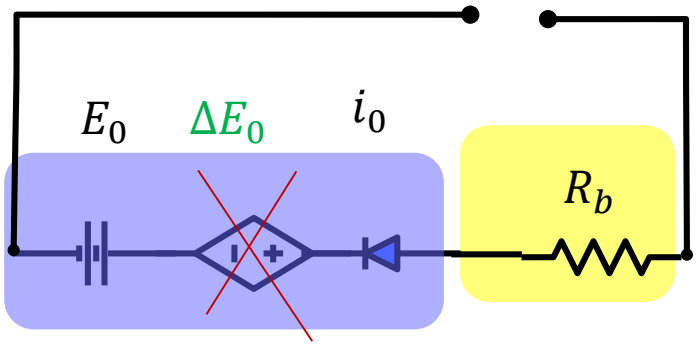
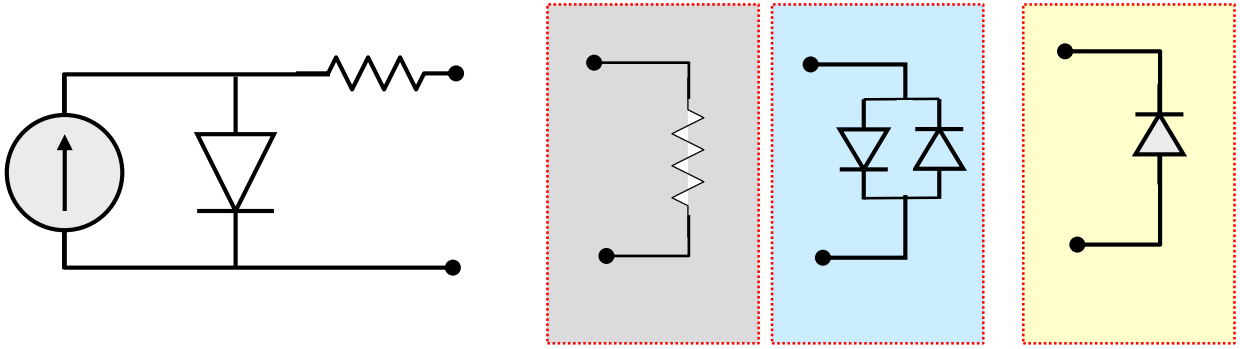


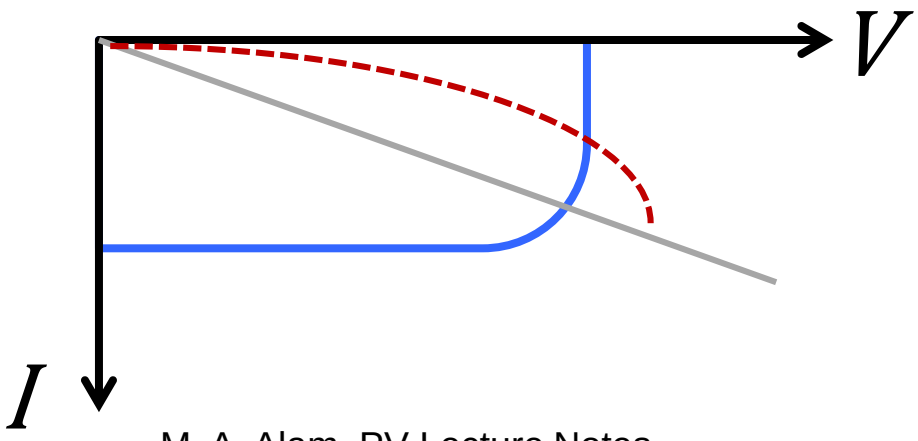
Figure 1

$$H_2O = H_2 + O_2$$



How to think about nonlinear loads





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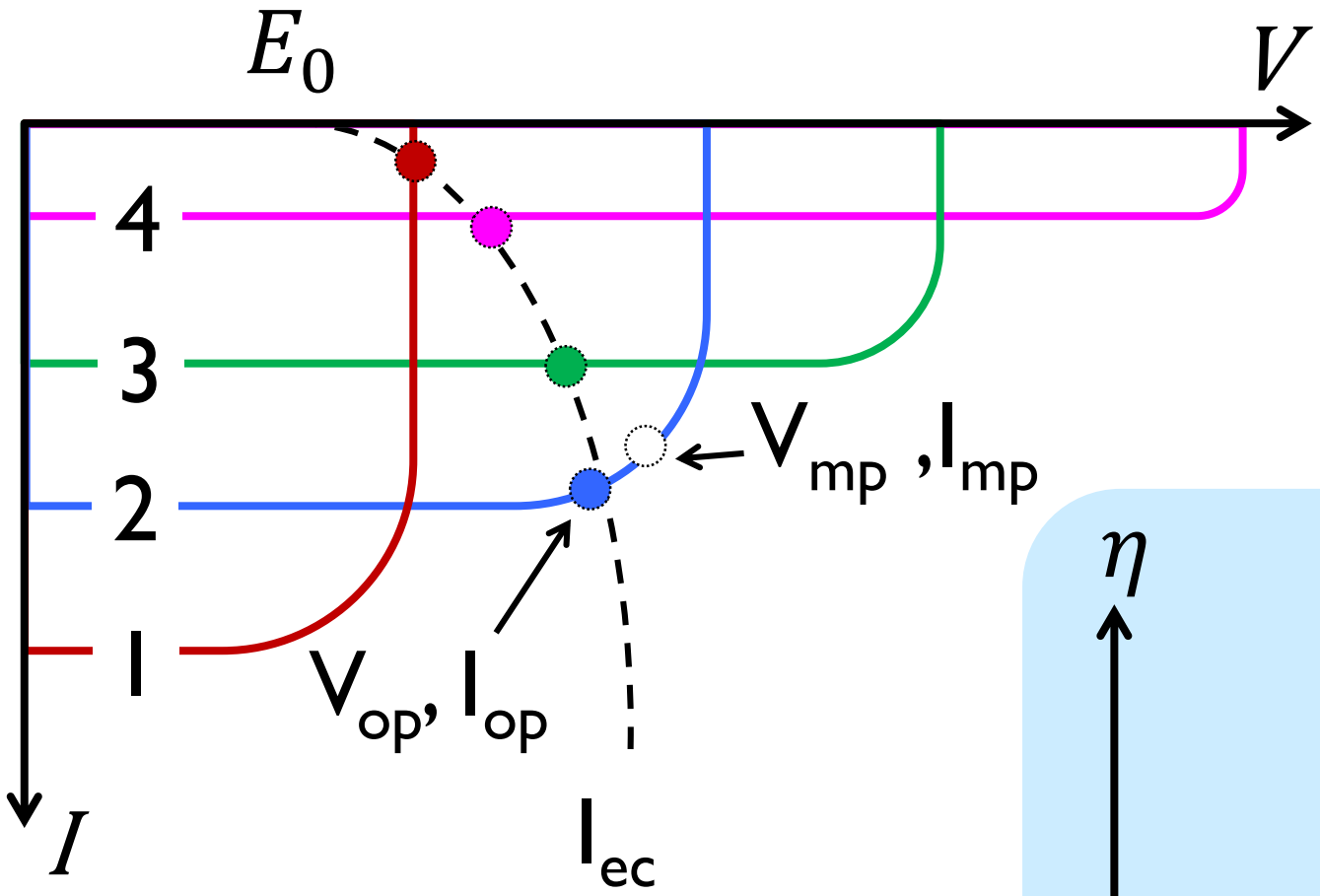
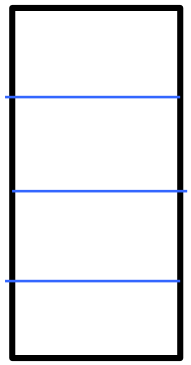
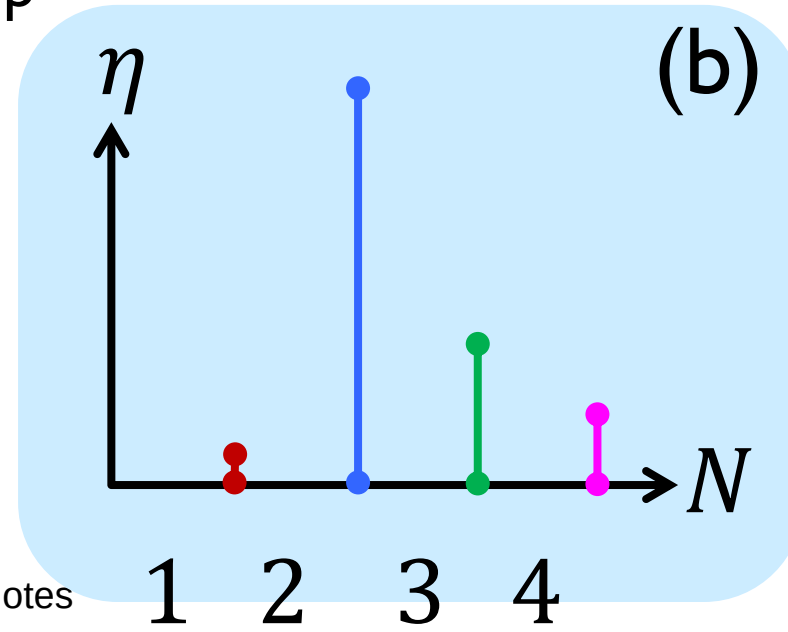
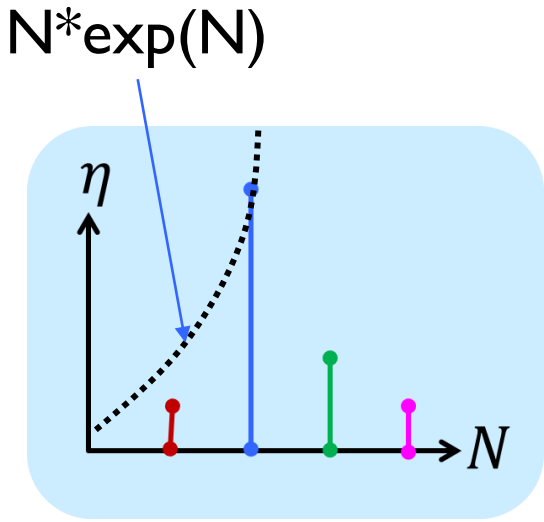
Efficiency vs. Number of Cells







HW: Analytical Results for N<2

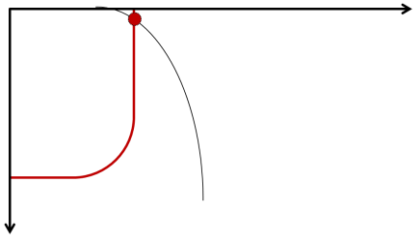


$$V_{op} = V_{mp}(N) \sim N\, V_{mp,1}$$

$$I_{BV} = I_{0,BV}\left[e^{\alpha_F v} - e^{-\alpha_R v}\right]$$

$$I_{BV} \cong I_{0,BV}\left[e^{\alpha_F v_{mp}}\right]$$

$$v_{mp} \equiv \mathrm{m}\,(NV_{mp,1} - E_0)/(k_B T) < 1$$



$$P_{out} = I_{ph}\, V_{op} = NV_{mp,1} I_{(0,BV)} e^{\alpha_F (NV_{mp,1} - E_0)\beta}$$

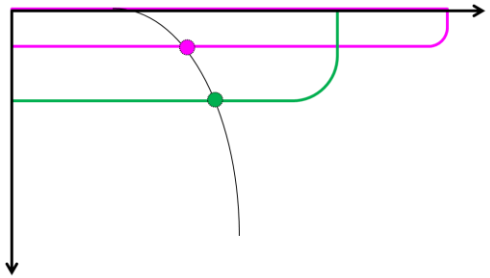
HW: Analytical results for N>2

$$I = I_{ph} - I_0(N,R)\left(e^{\beta V} - 1\right) = I_{BV}$$

$$I_{BV} = I_{0,BV}\left[e^{\alpha_F v} - e^{-\alpha_R v}\right]$$

$$I_{ph} = I_{mp,1}/(N+1) \sim I_{BV} = I_{0,BV} e^{\alpha_F v}$$

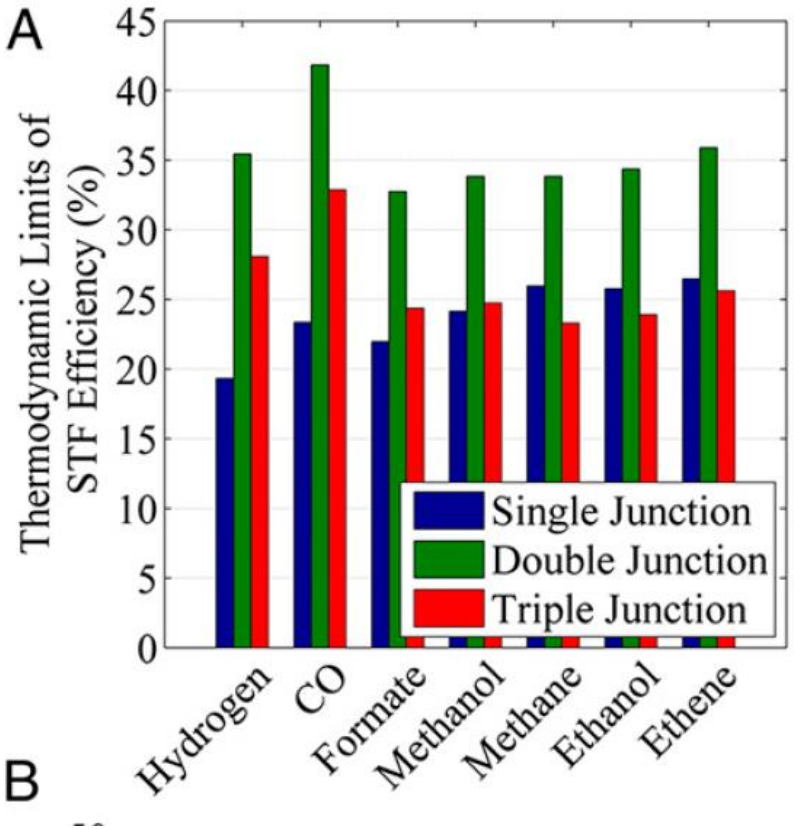
$$V_{op} = E_0 + \left(\frac{1}{m\beta}\right) ln \frac{I_{mp,1}/(N+1)}{I_{0,BV}}$$

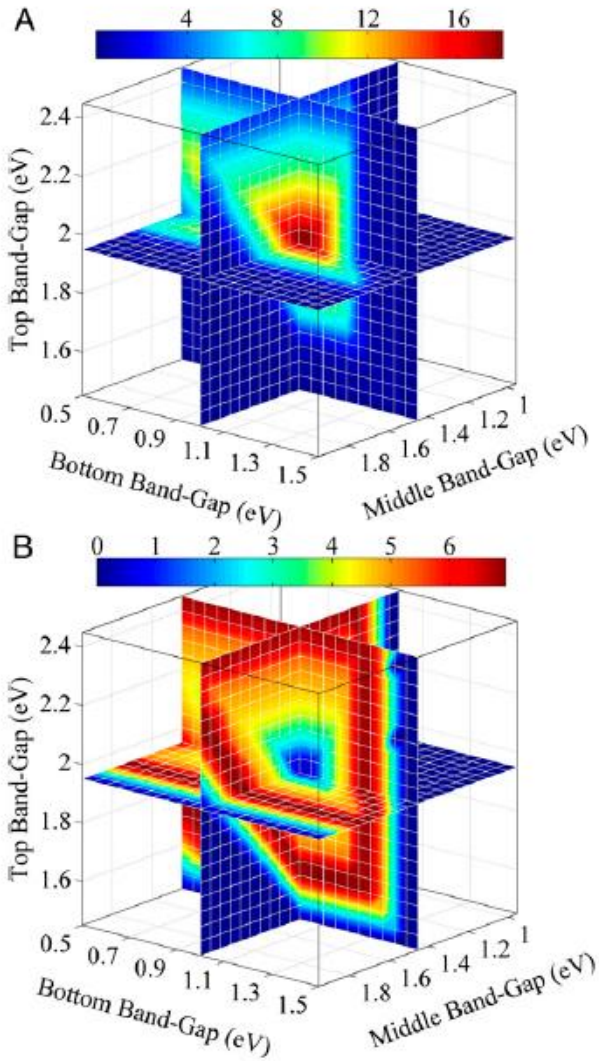


$$P_{out} = I_{ph}\, V_{op} = \frac{I_{mp,1}}{N+1} \times V_{op} \sim \frac{1}{N+1} \ln\left(\frac{1}{1+N}\right)$$

Numerical Analysis Confirms trends

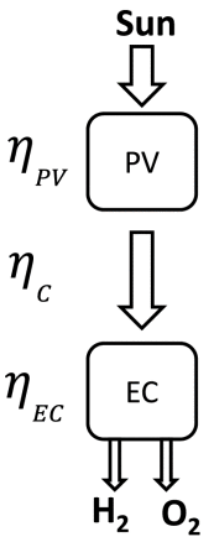
A. T. Bell, PNAS, 2016



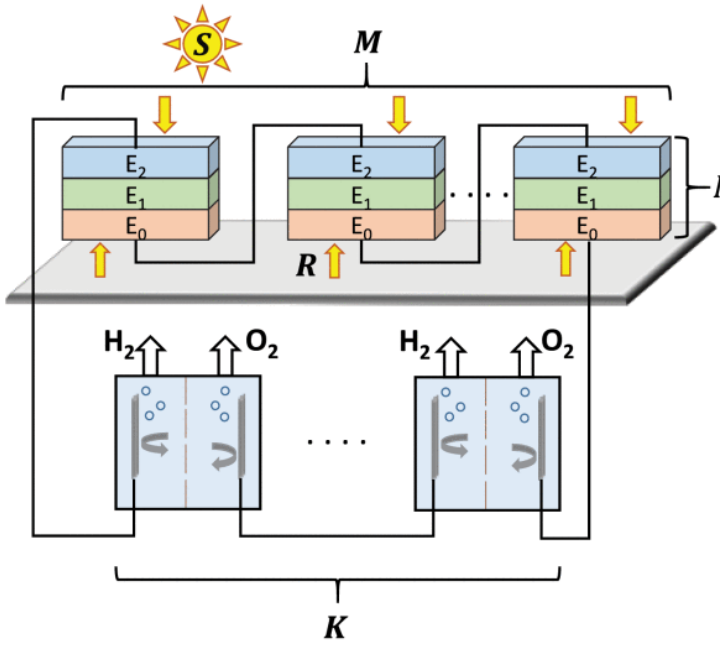


Tandem Farms and Tandem EC Cells

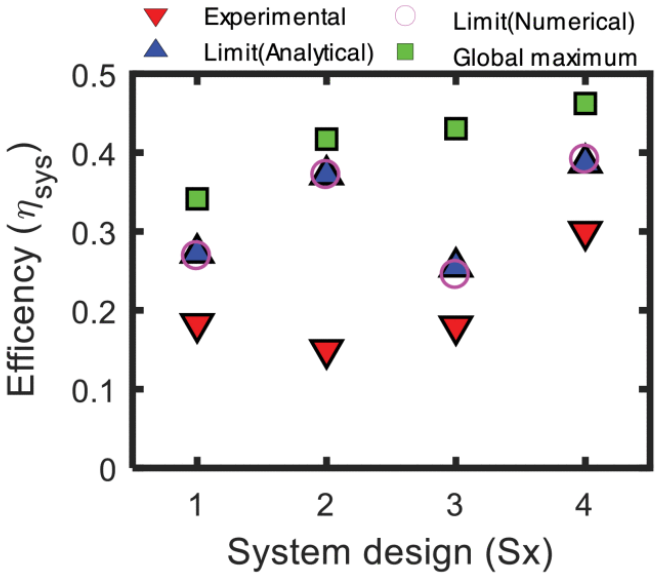
T. Patel, JPV, 8(4), 1082, 2018.



(a)



(b)

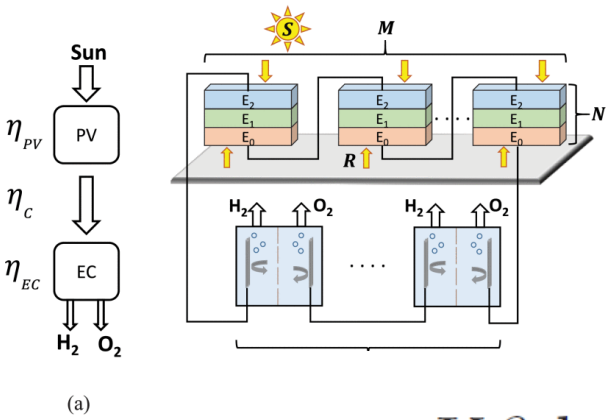


Format:
Sx: (S,R,M,N,K,AF)[Ref.]

S1: (1.35,0,1,2, 1,1)[9]
S2: (10,0,2,3,3,1/4)[10]
S3: (500,0,1,2,1, 0.19/30)[8]
S4: (42,0,1,3,2,0.316/6.25)[11]

$$M/K \sim 1.67 = 8/5,\ \eta_{\max} = 26.46\%$$

Tandem Farms and Tandem EC Cells



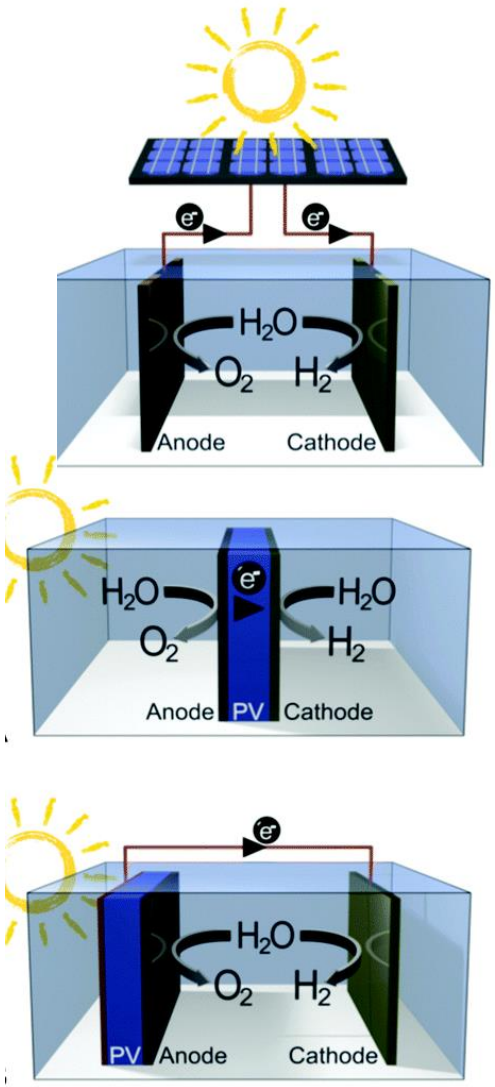
T. Patel, JPV, 8(4), 1082, 2018.

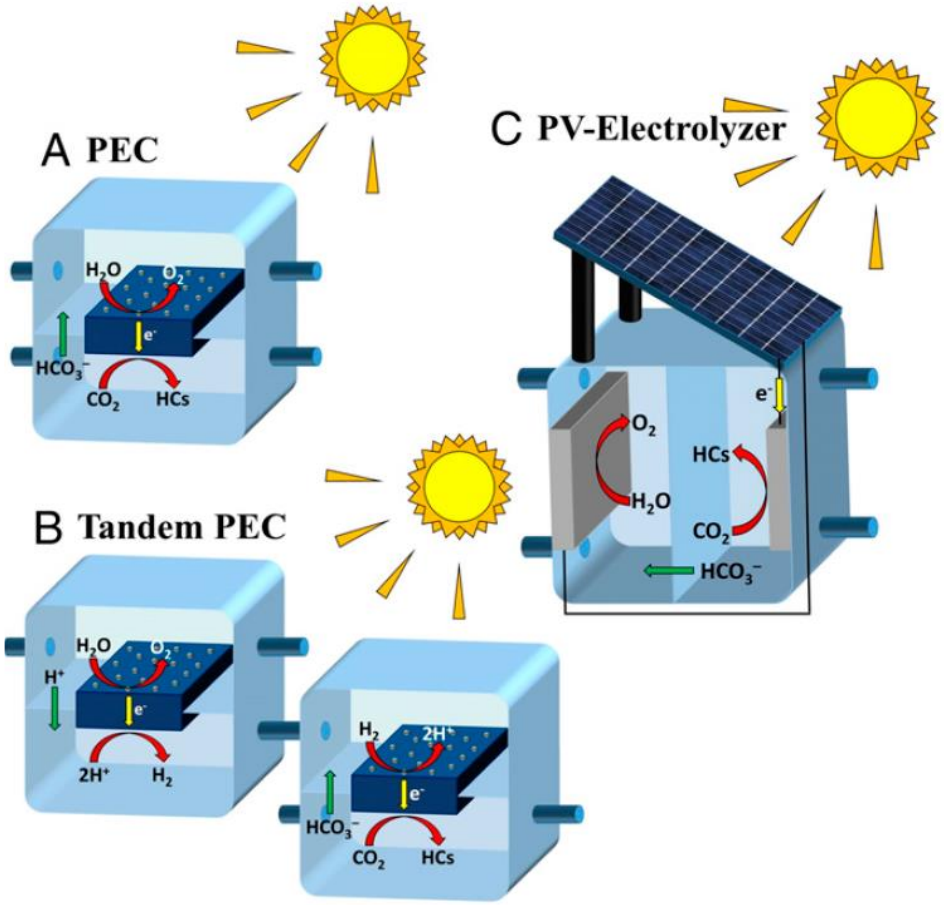
$$K\beta \ln\left[\left(\frac{SJ_{s0}\left(1-\alpha\, E_{g,\mathrm{top}}\right)}{J_{0,\mathrm{ec}}}\right) AF\right]$$

$$= \left(\frac{MN}{q}\right)\left[E_{g,\mathrm{av}}\left\{1-\left(\frac{T_D}{T_S}\right)\left(\frac{E_{g,\mathrm{top}}}{E_{g,\mathrm{av}}}\right)\right\}\right.$$

$$\left.-k_B T_D\left(\ln\left(\frac{\Omega_D}{S\Omega_S}\right)\right)\right].$$

Three ways to create hydrogen





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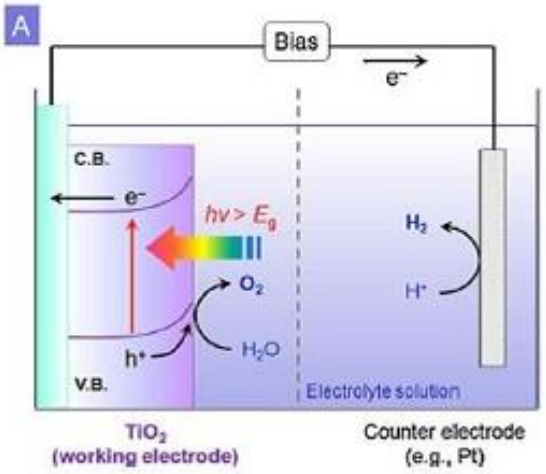
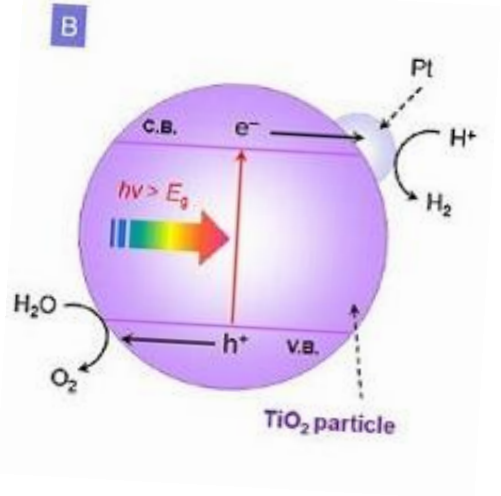
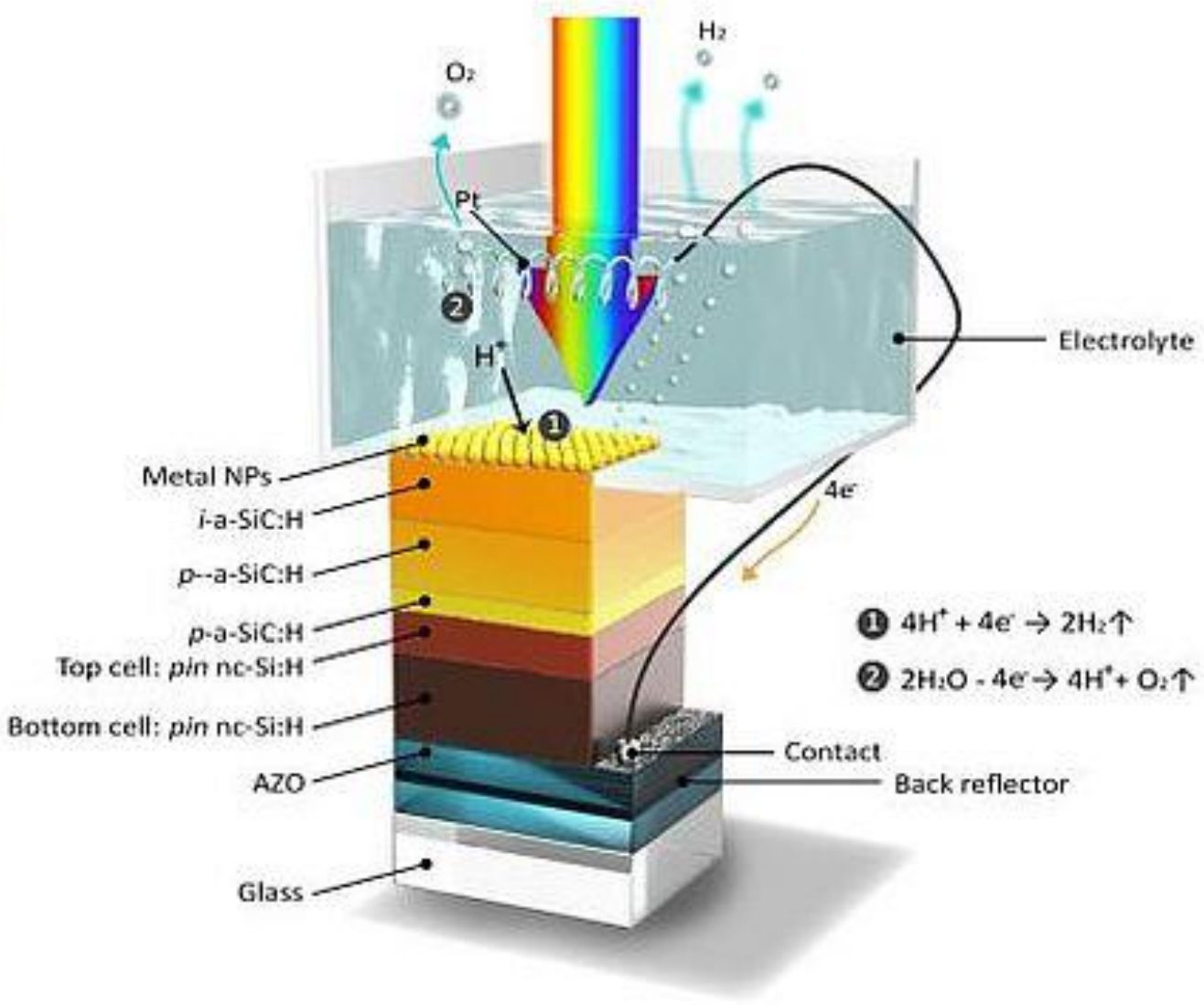
Multi-junction PV for water splitting







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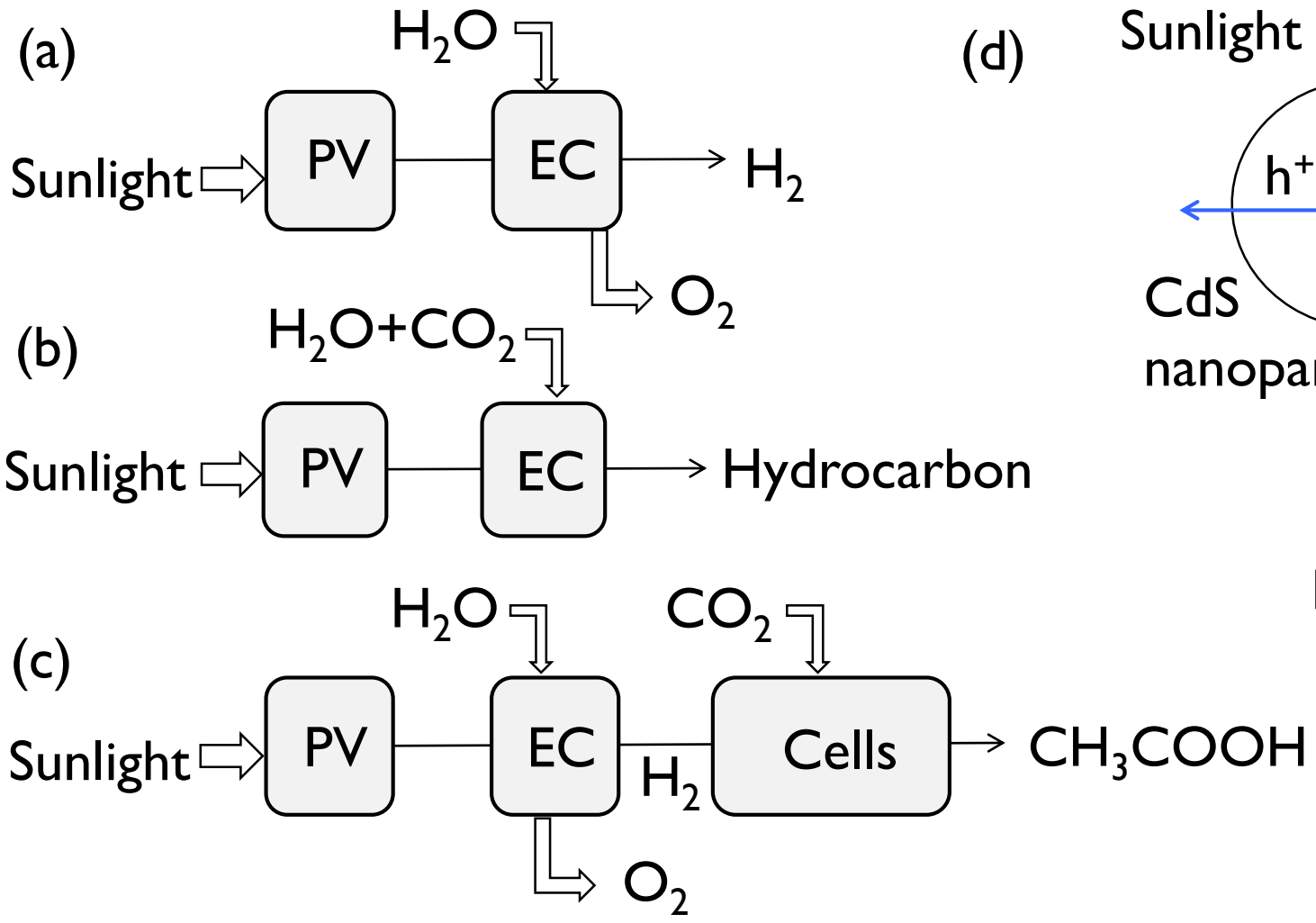
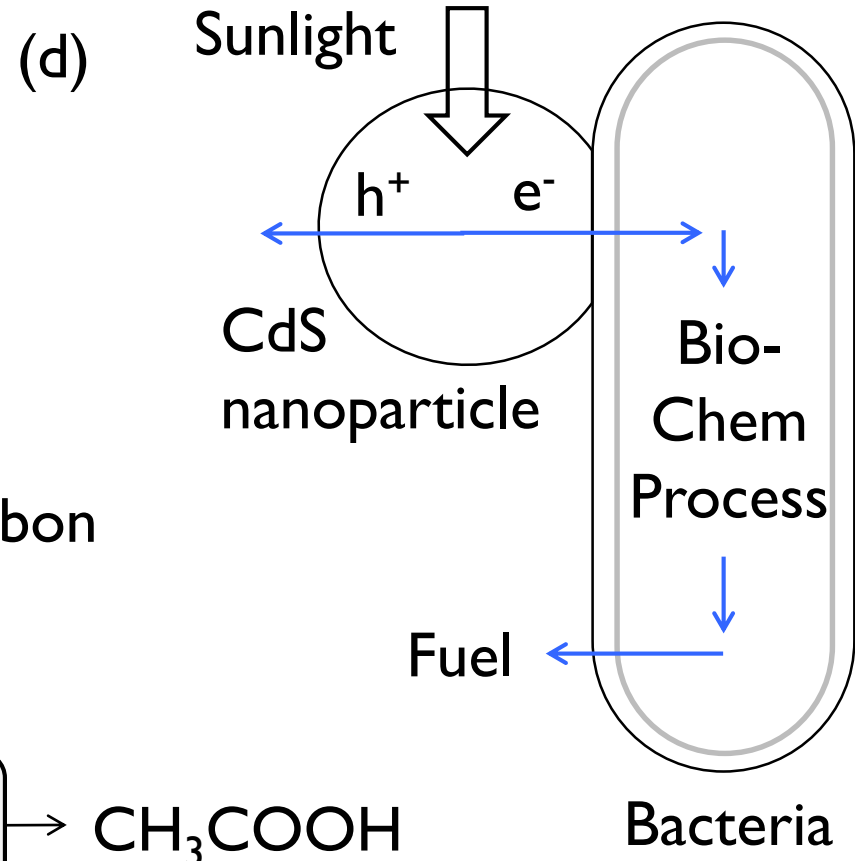
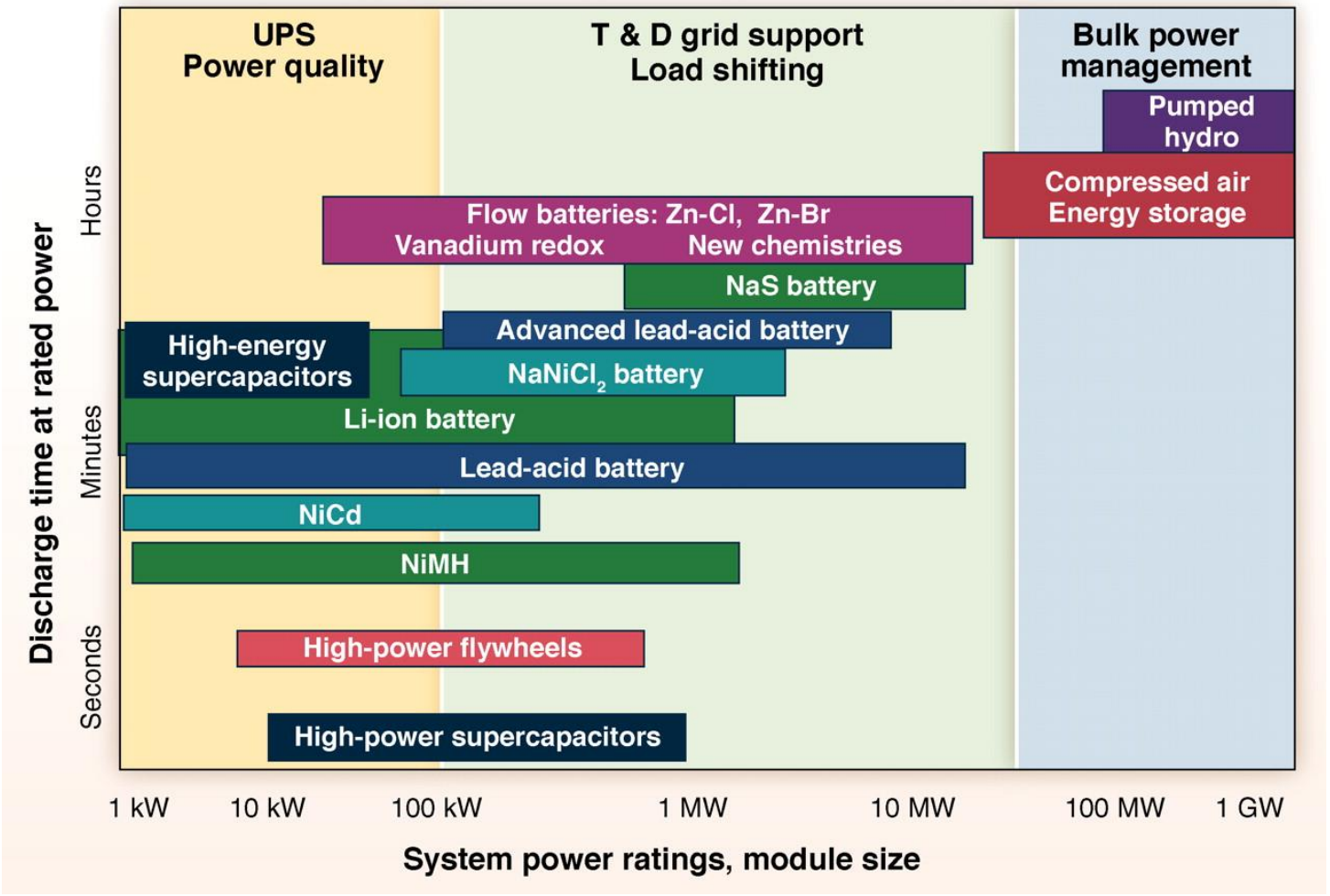
Direct storage into biofuels





Energy storage Options



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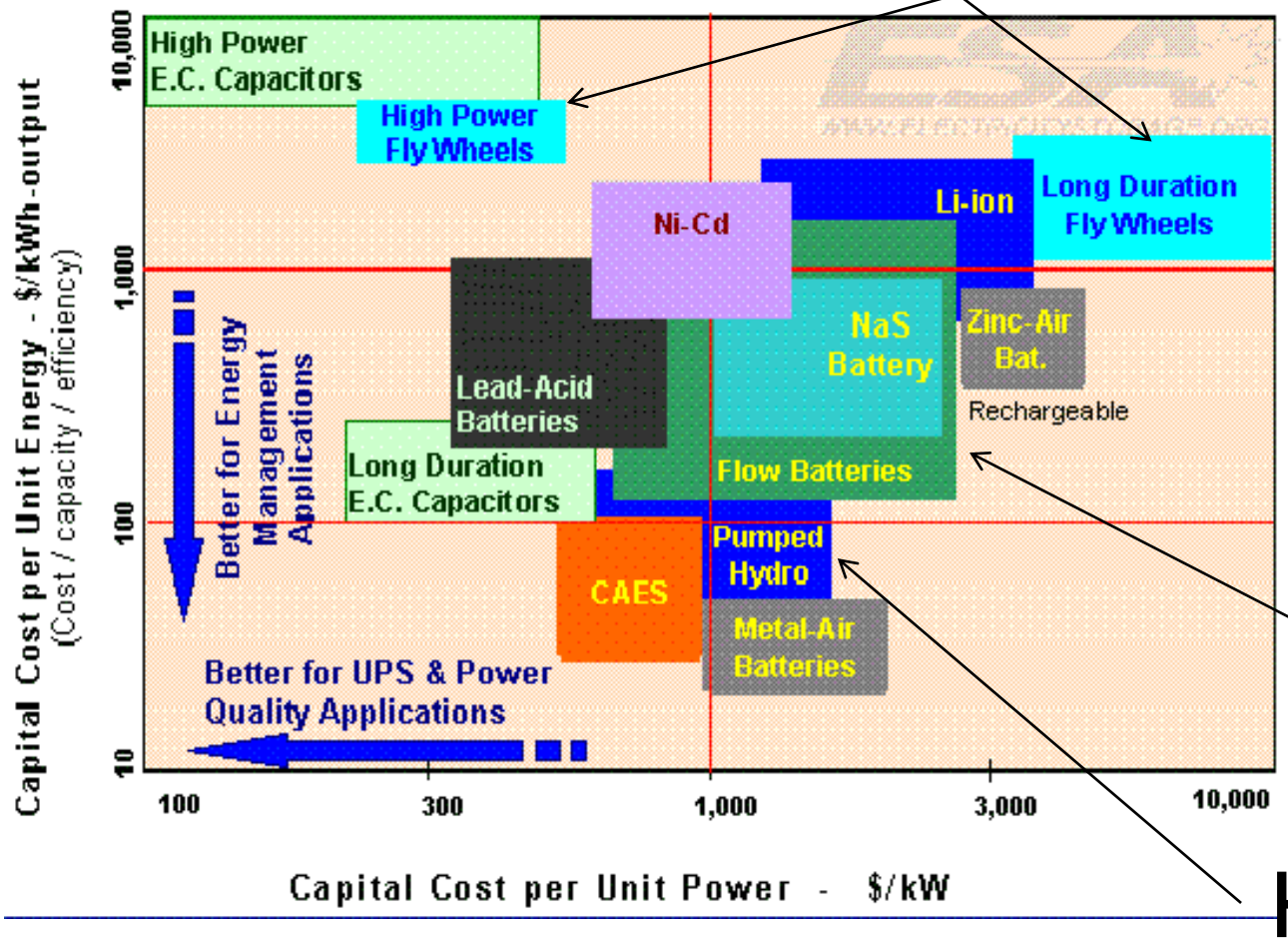
Cost of Energy storage



Flywheel

Batteries

Hydro

Conclusions

Energy storage is a fundamental challenge for solar cells. Both the price of PV and battery must drop to make PV economical.

There are a number of strategies for electro-mechanical storage.

It is easy to understand the essential features of battery charge storage and the principles of fuel cells as electro-chemical storage mechanisms.