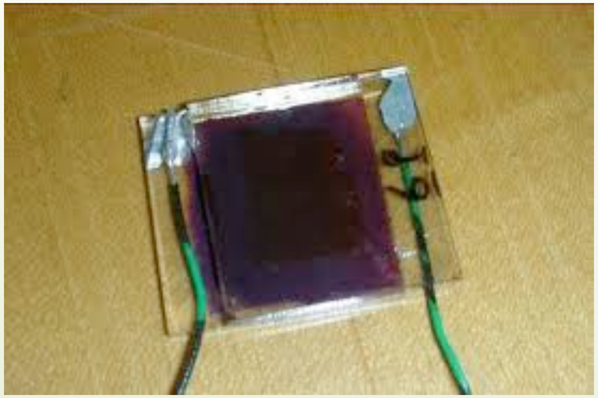

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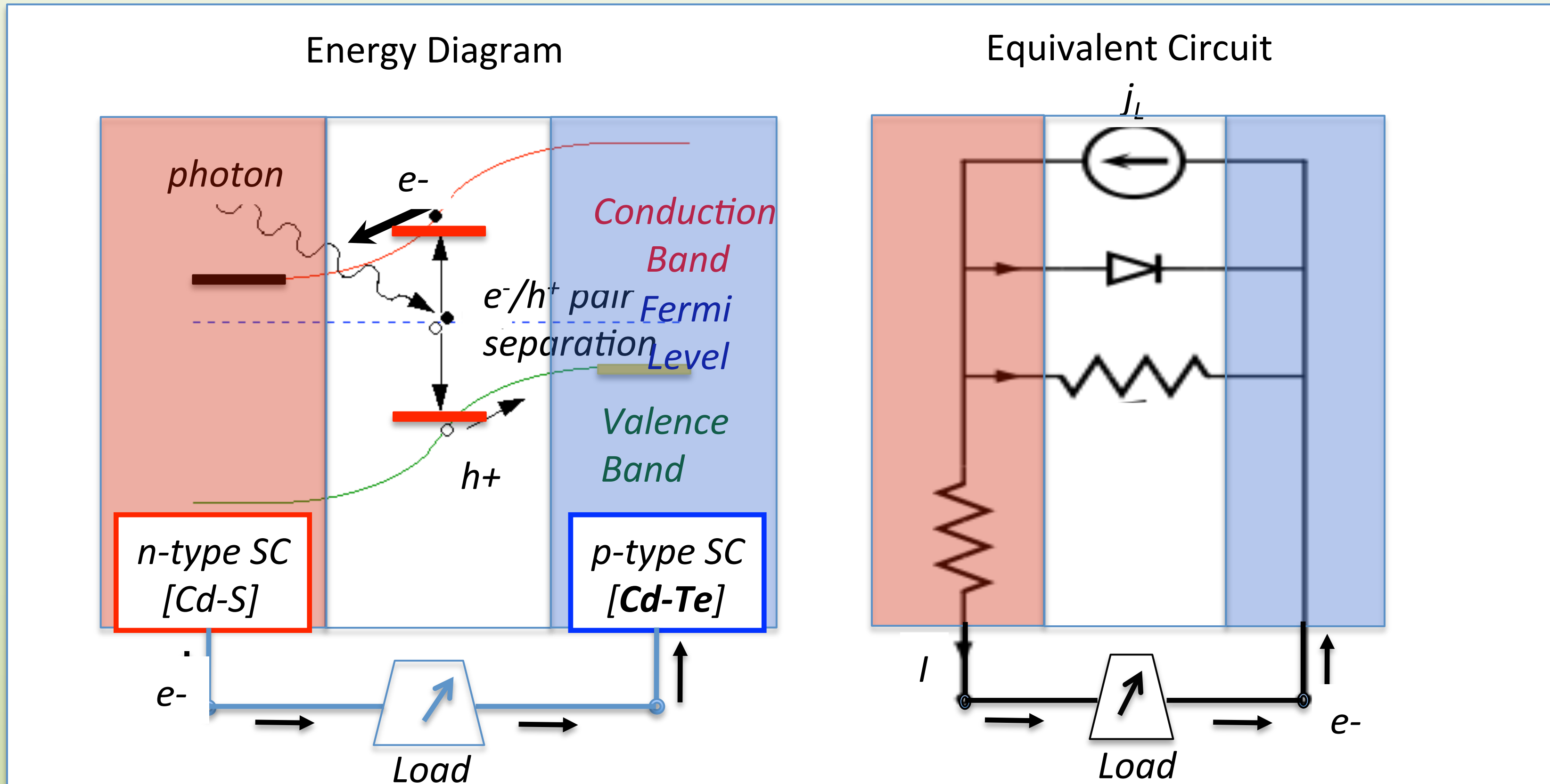
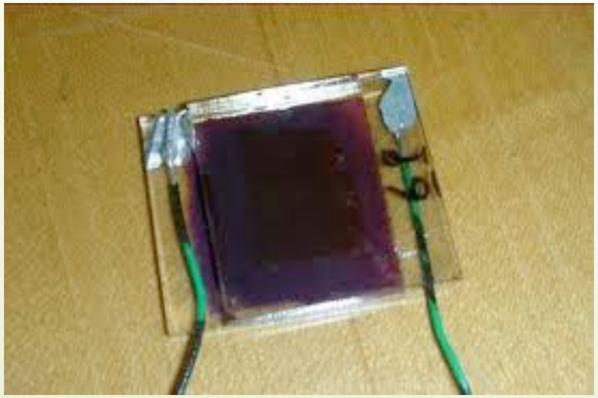
Modeling Photovoltaic Solar Cells

Traditional Photovoltaic Solar Cells

First and Second Generation: p-n junctions



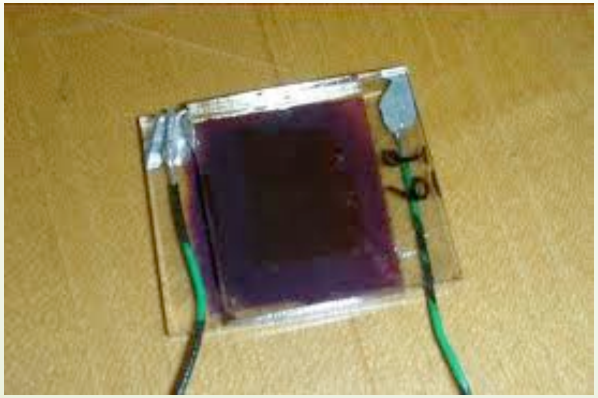
The Power of the Sun: Walter Kohn's Description of Photovoltaic Solar Cells



Section II
Prof. Victor S. Batista

Computational Modeling and Physical Principles

- Computational design and characterization
- Solar cells for electricity
- Photocatalysis, biomimetic water oxidation
- Hydrogen economy



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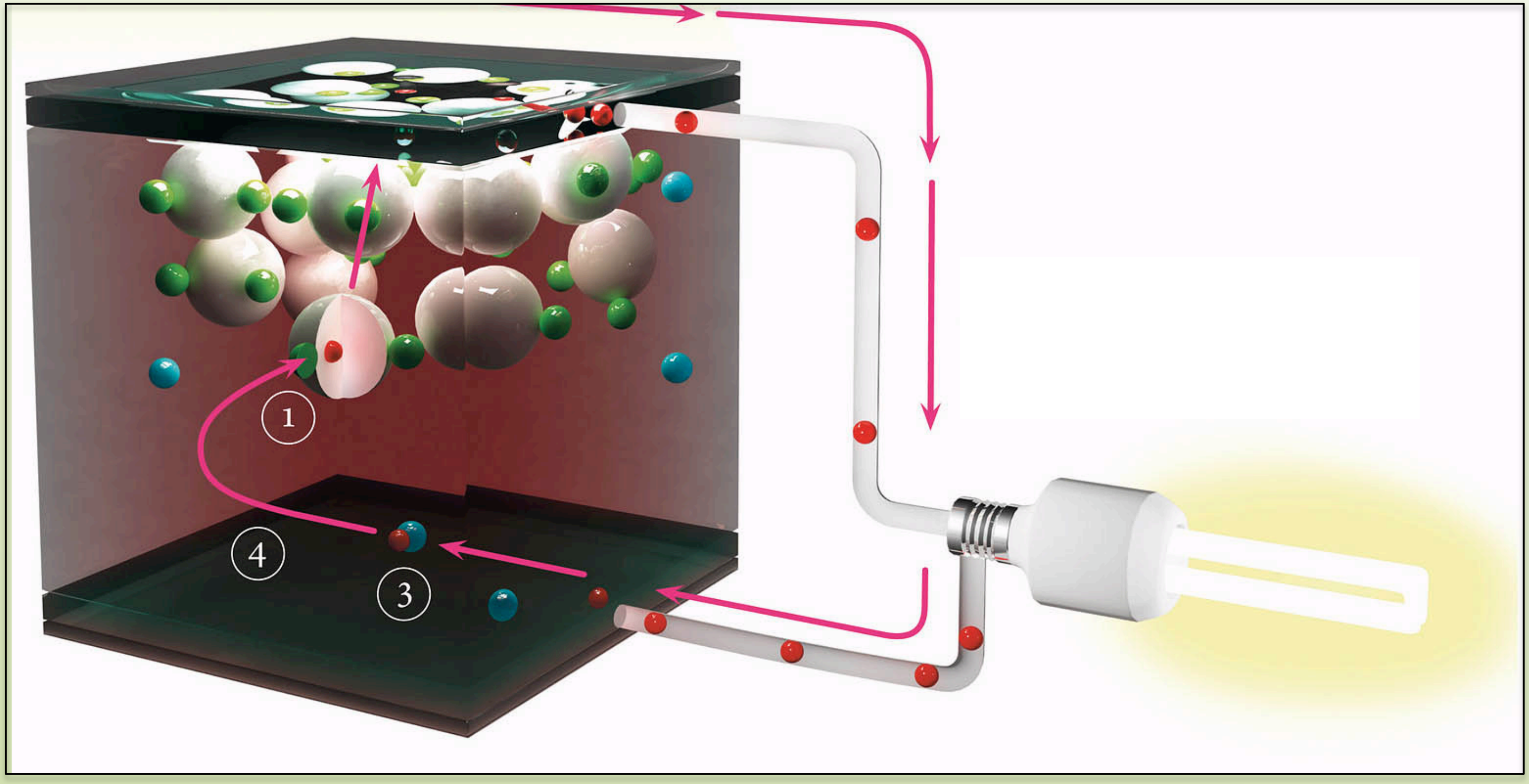
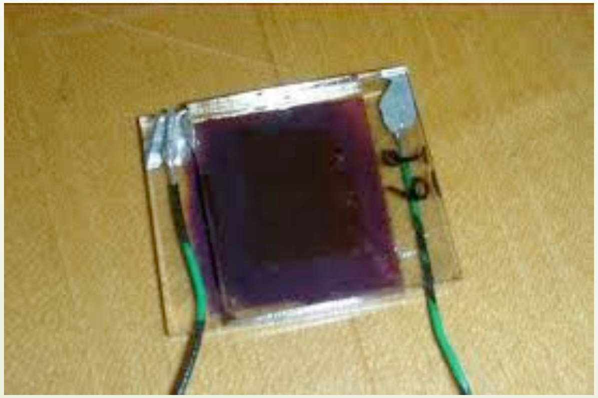
Dye-Sensitized Solar Cells

Third Generation Photovoltaic Solar Cells





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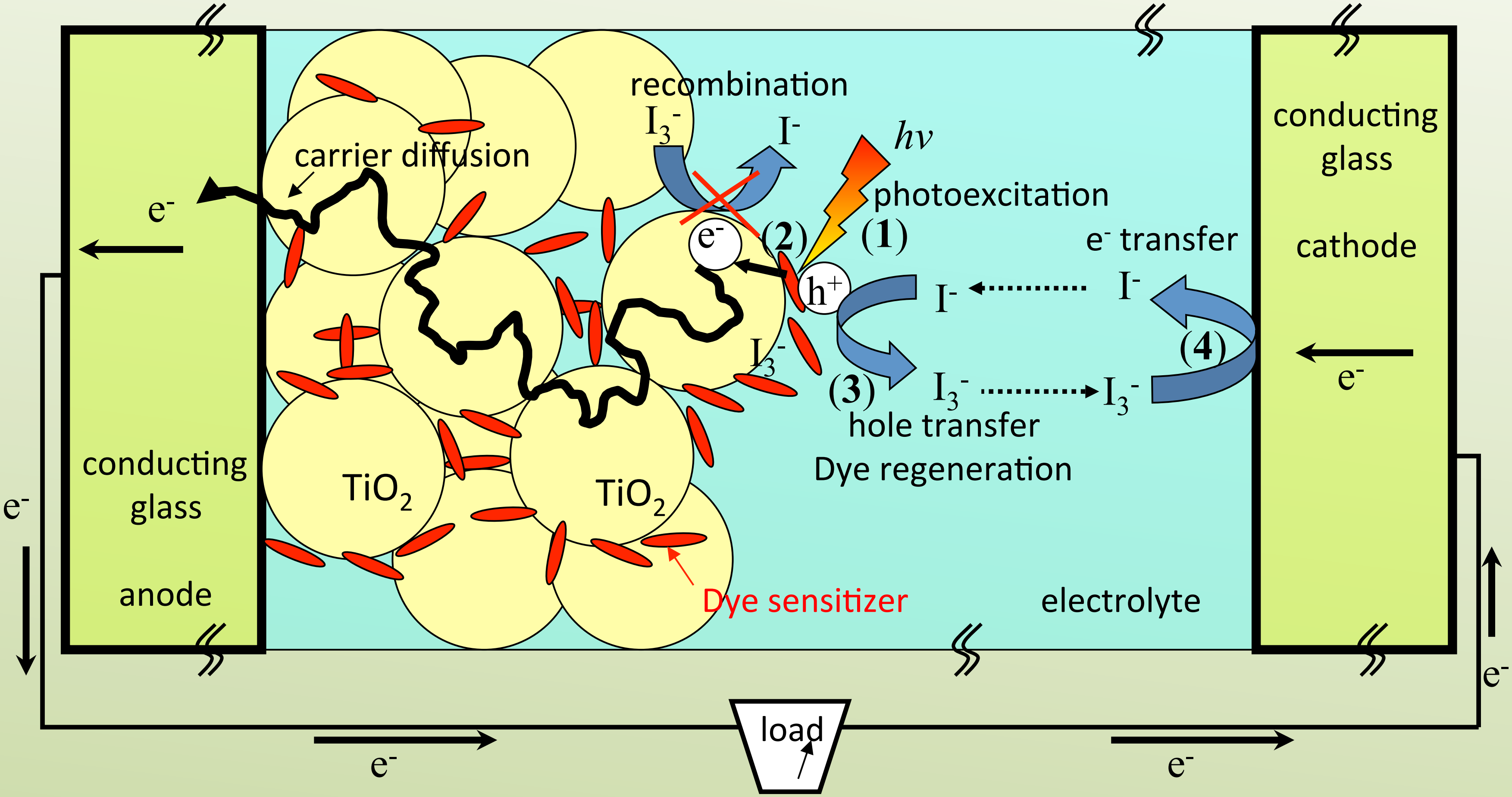
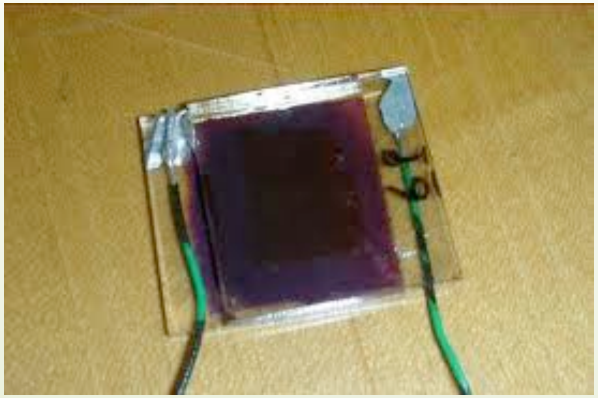
Modeling Dye-Sensitized Solar Cells

Photoconversion in 4 steps: (1)-(4)





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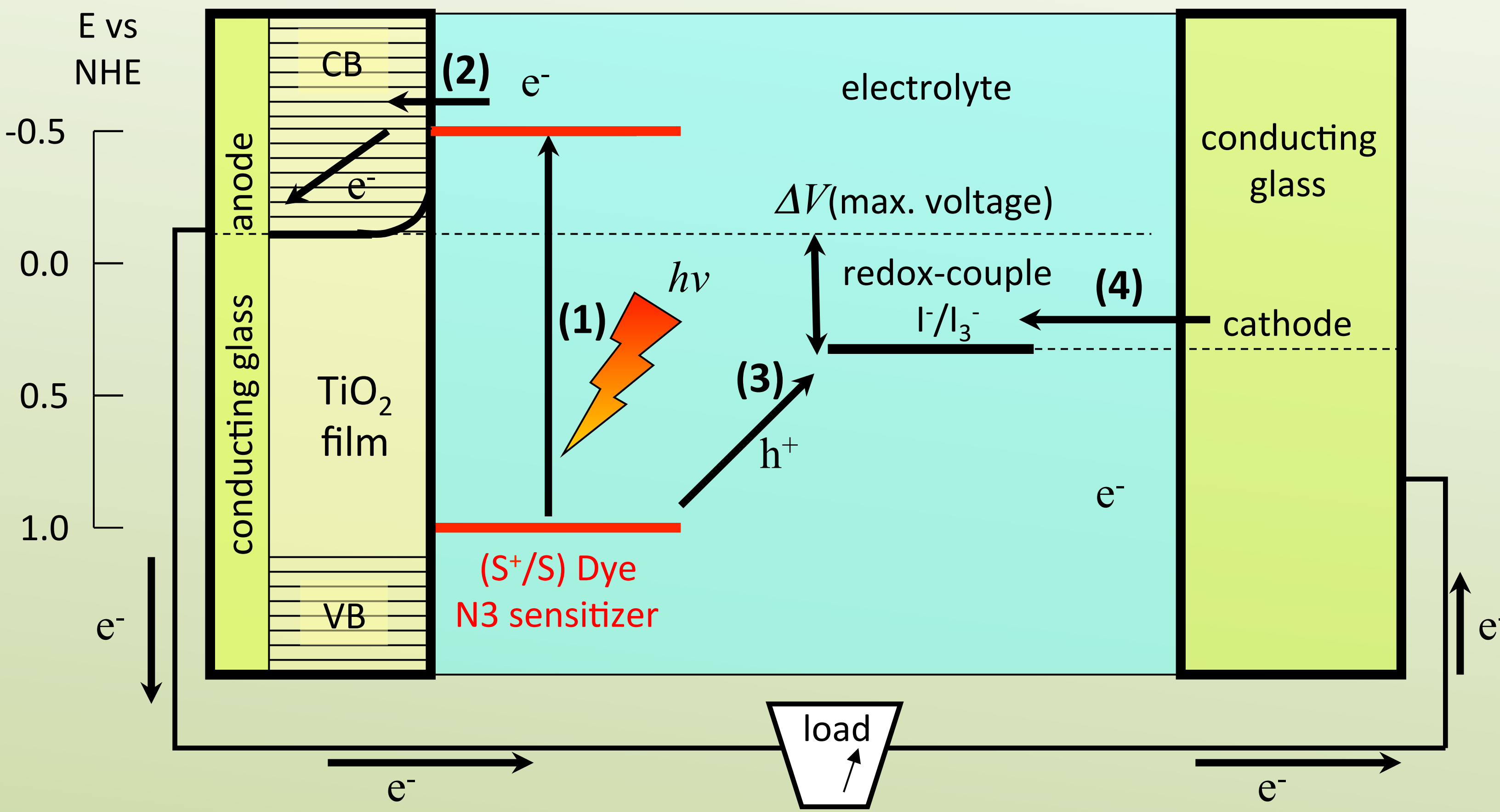
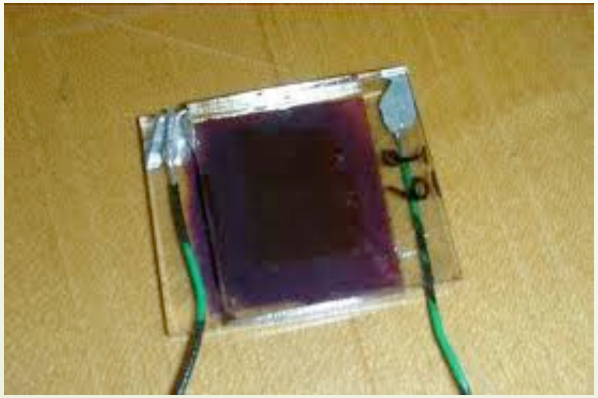
Modeling Dye-Sensitized Solar Cells

Photoconversion: Energy Diagram





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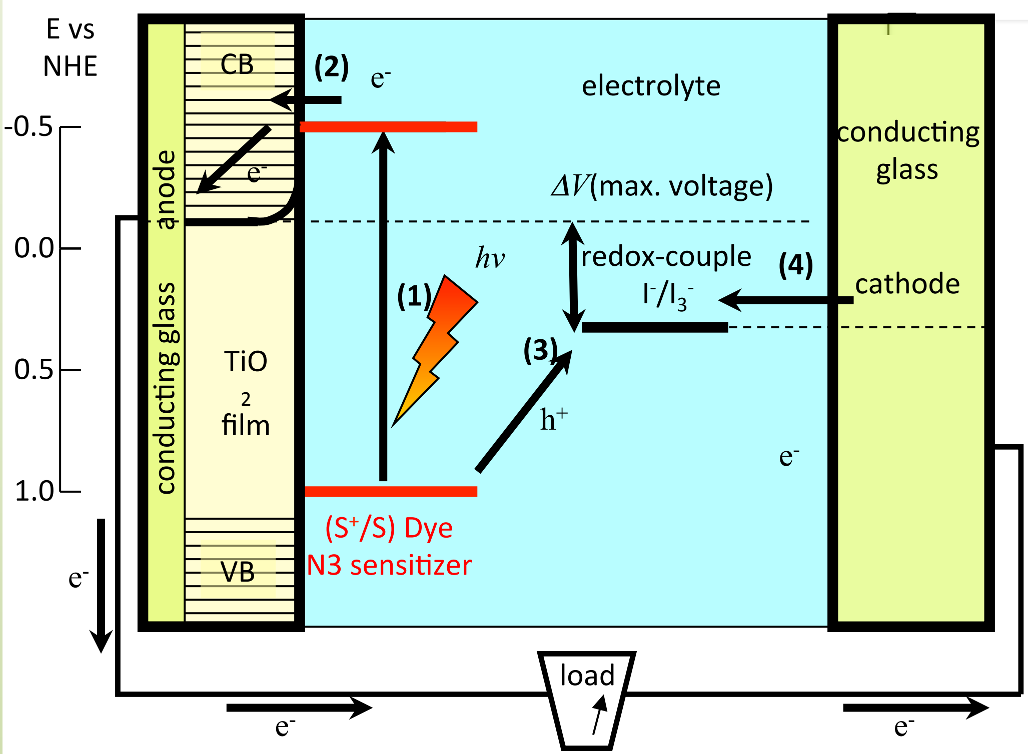
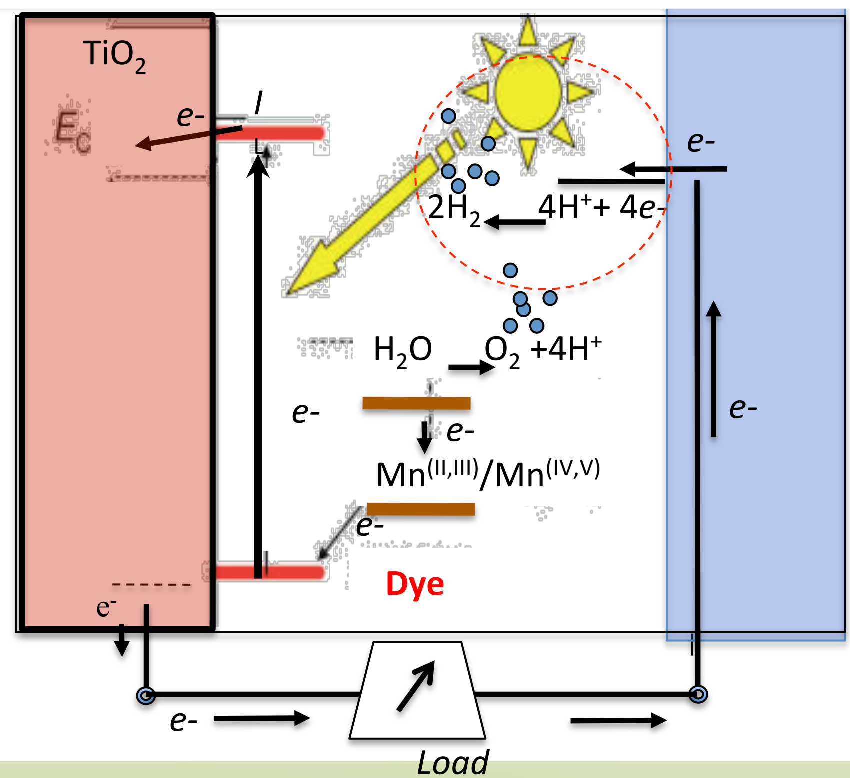
Modeling Dye-Sensitized Solar Cells

Photoconversion into Chemical Bonds: Fuel

Solar-to-Electricity Conversion



Solar-to-Fuel (H_2) Conversion

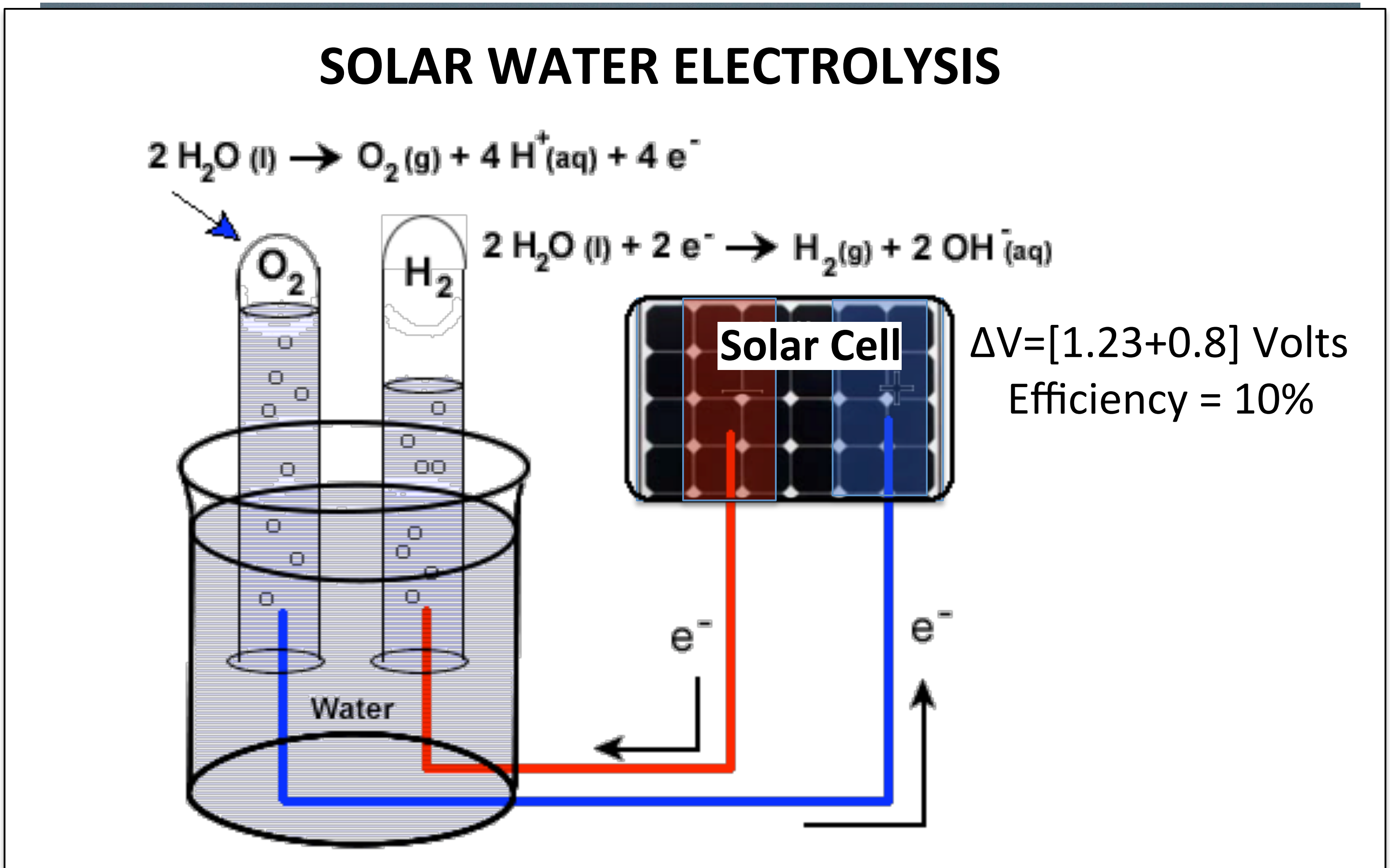


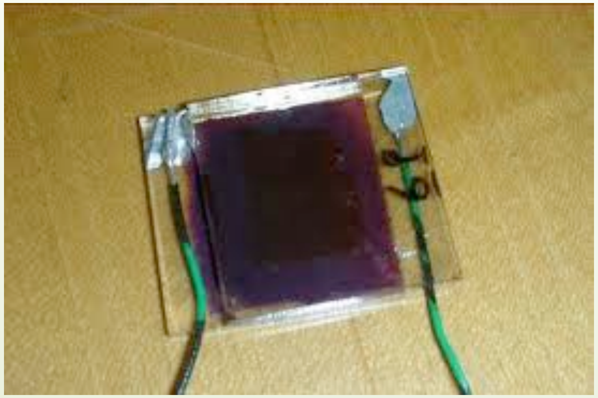
A viable solution to alternative and renewable energy

Hydrogen Production by Solar Water-Splitting

$$2H_2O(l) \xrightarrow{\text{sun}} O_2\ (g) + 4H^+\ (aq) + 4e^-$$

$$4H^+(aq) + 4e^- \longrightarrow 2H_2(g) \longrightarrow H_2\text{-Storage}$$





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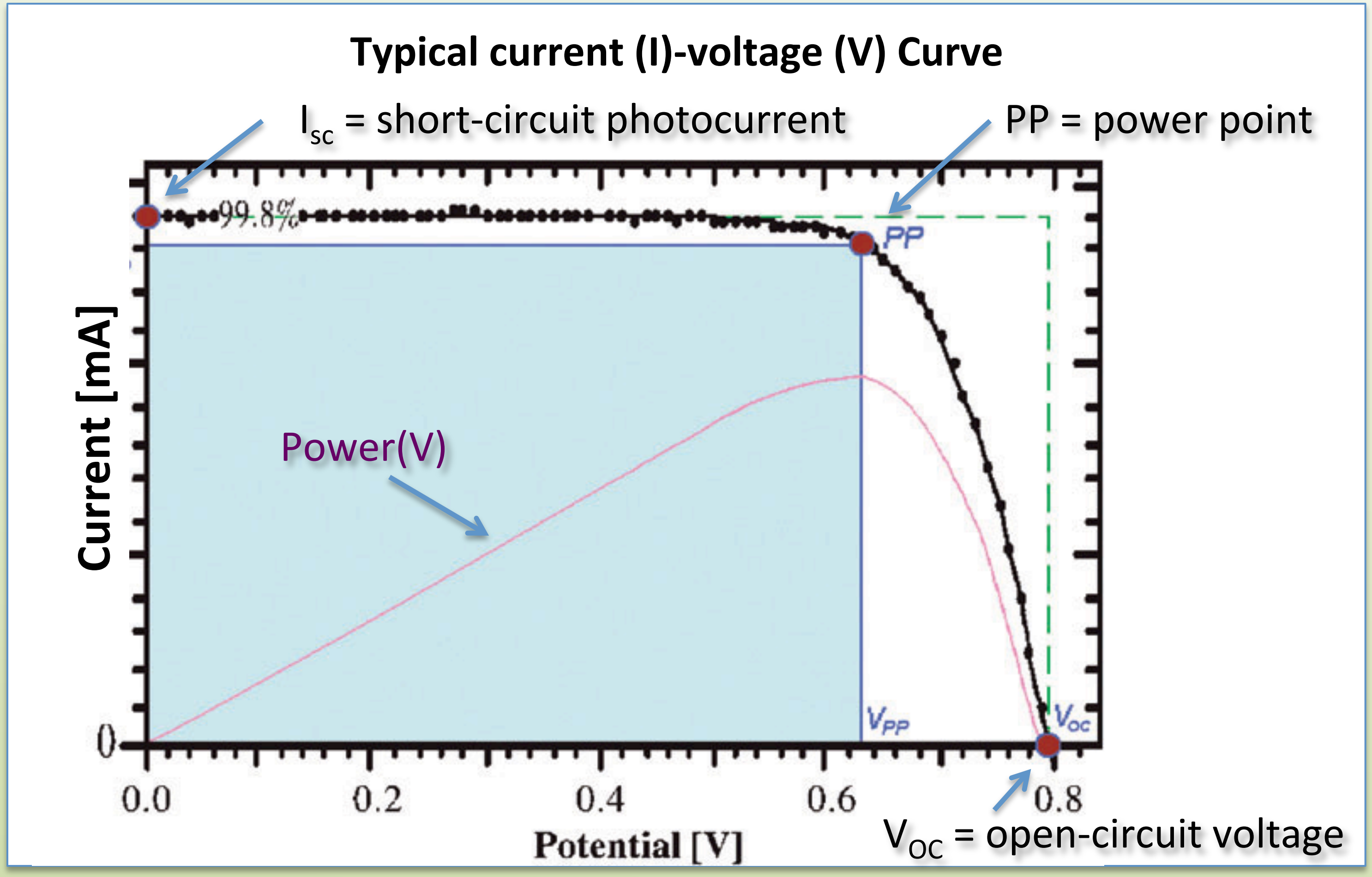
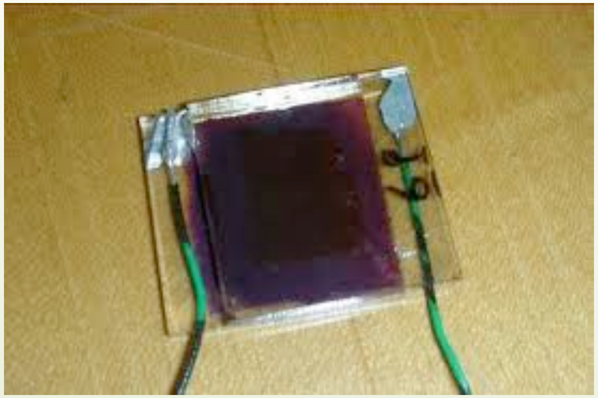
Modeling Dye-Sensitized Solar Cells

Characteristic I-V Curve of Photoconversion





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Modeling Dye-Sensitized Solar Cells

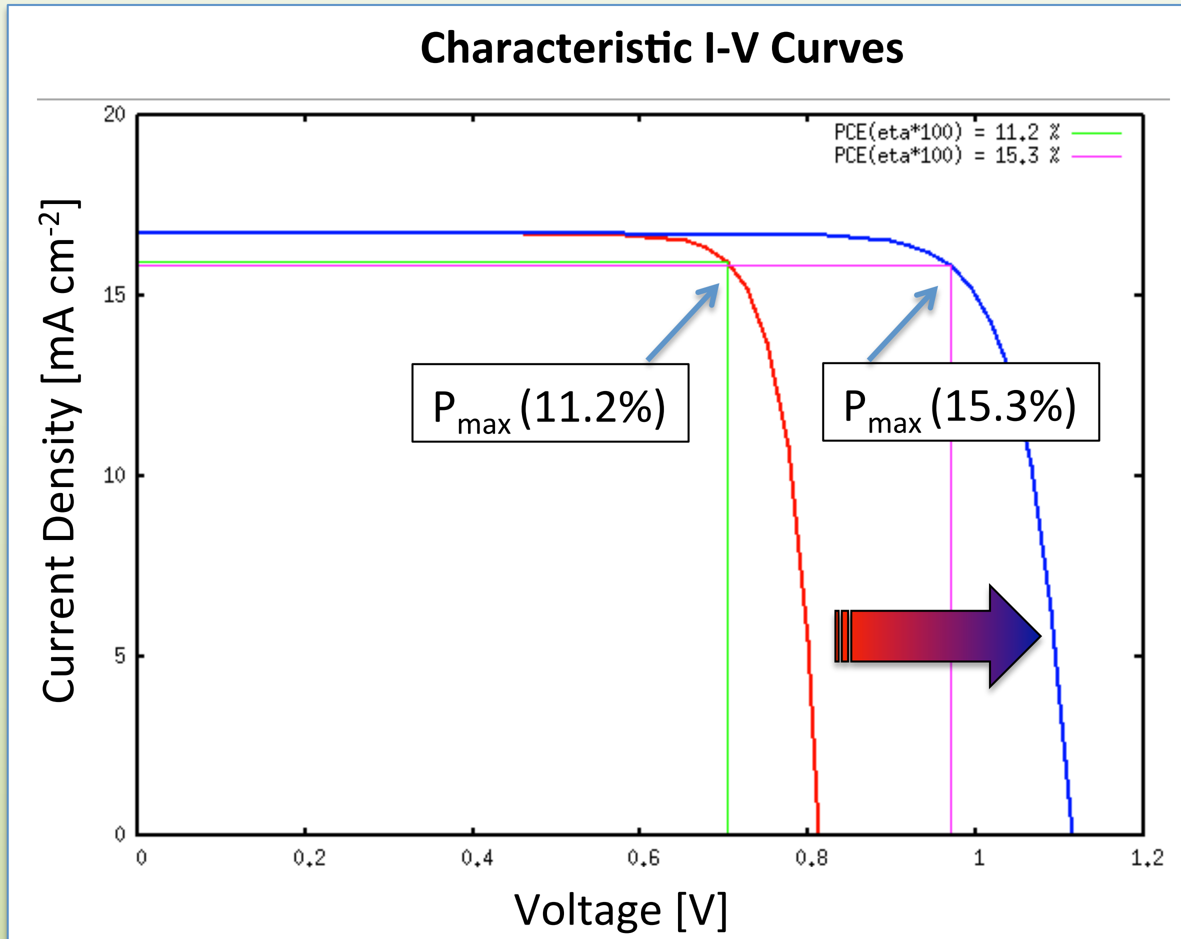
Photoconversion: Efficiency

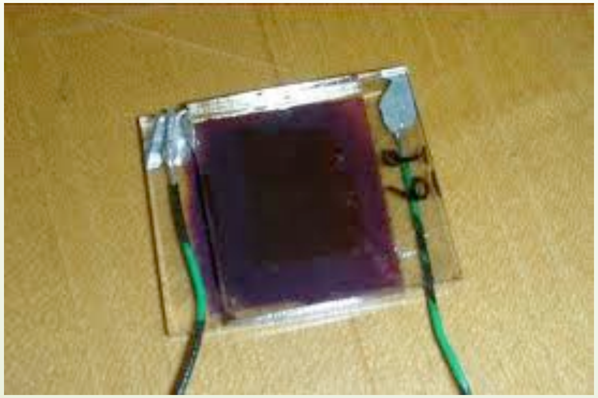
Power output

$P_o = I \times V$

Light-to-electrical power conversion % efficiency

$\eta = 100 \times P_o/P_i$





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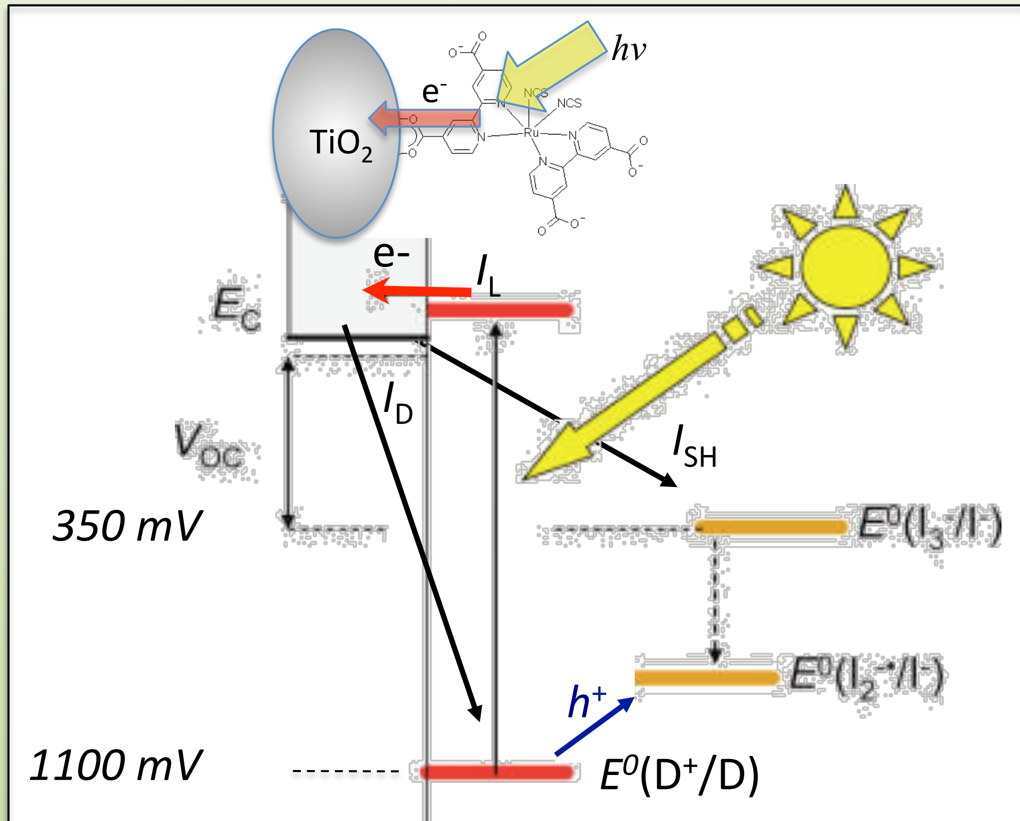
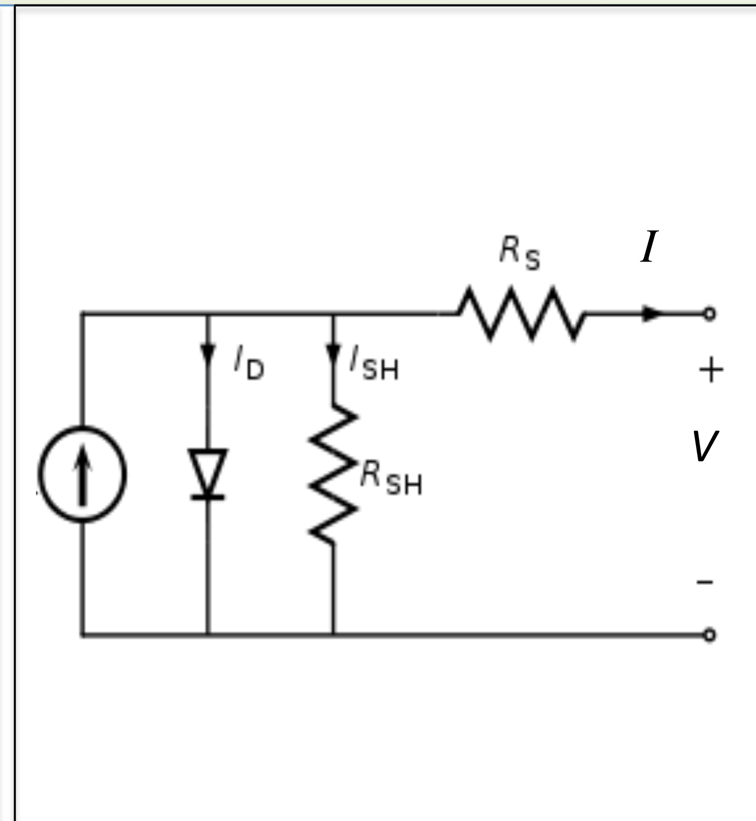
Modeling Dye-Sensitized Solar Cells

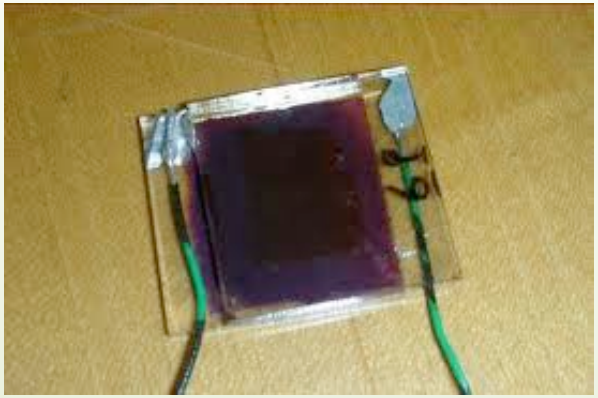
Equivalent Circuit of Photoconversion

Energy Diagram



Equivalent Circuit





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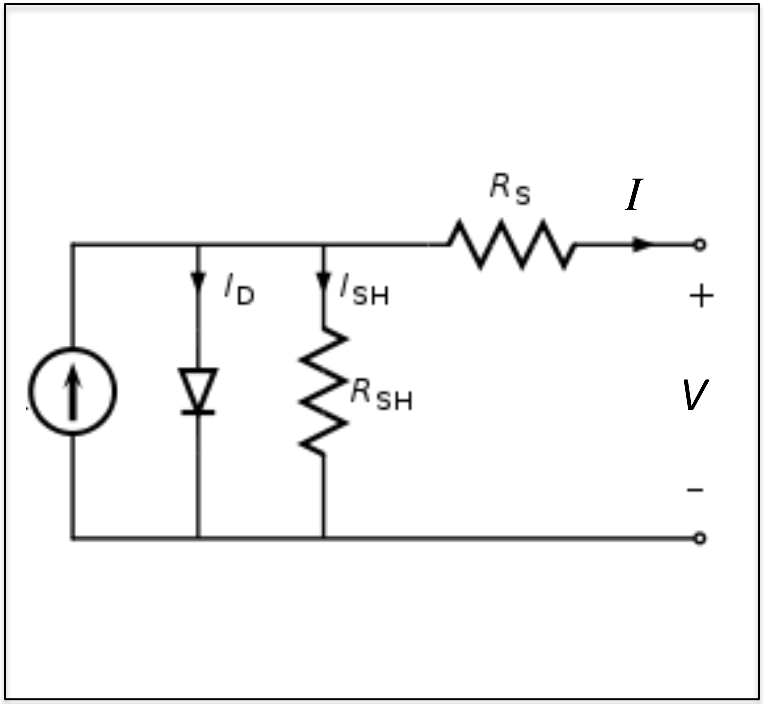
Modeling Dye-Sensitized Solar Cells

Photoconversion: Output Current

Equivalent Circuit

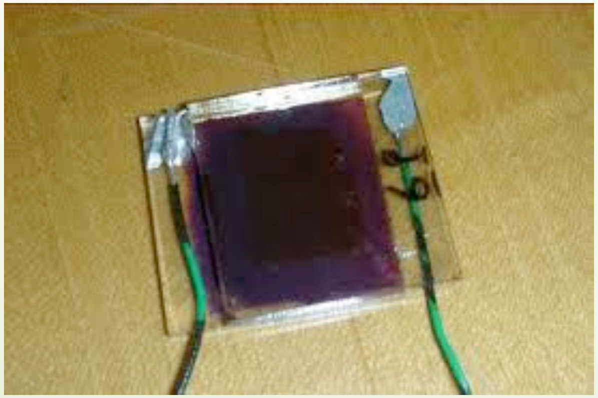


Characteristic I-V Curve

Output Current: $I = I_L - I_D - I_{SH}$

$$I = I_L - I_0\left\{\exp\left[\frac{q(V+IR_S)}{nkT}\right] - 1\right\} - \frac{V+IR_S}{R_{SH}}.$$

Open Circuit Voltage: $V_{OC} \approx \frac{kT}{q}\ln\left(\frac{I_L}{I_0}+1\right).$



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Modeling Dye-Sensitized Solar Cells

Photoconversion Efficiency: Redox Couple

Exercise 1 (due Thursday Sept 25, 2014):

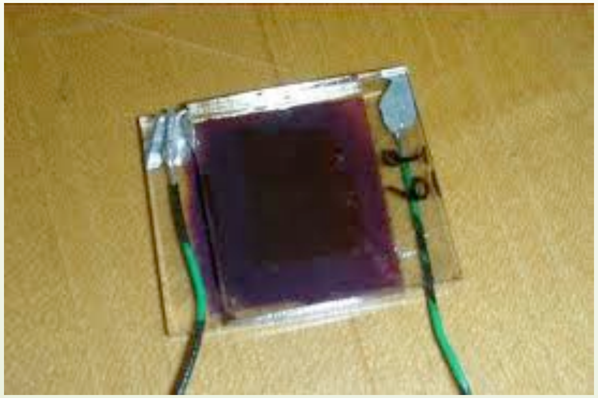
Consider a dye-sensitized solar cell (DSSC) with an equivalent circuit with the following parameters:

- Photogenerated current density: J_L=16.7 mAmperes/cm^2
- Specific series resistance: R_S = 2.0E-4 KΩ*cm^2
- Specific shunt resistance: R_{SH} = 100 KΩ*cm^2
- Open circuit voltage (Volts): $V_{oc} = E^0(I^-/I_3^-) - E_{CB} + \Delta V(pH)$
- Reverse saturation current density: $J_0=J_L\ 10^{-10}$ mAmperes/cm^2
- Diode ideality factor times kT/q= 0.0259 Volts: $nkt=V_{oc}/\log(J_L/J_0+1)$

(a) Compute the I-V characteristic at pH=7.75 assuming $E^0(I^-/I_3^-)$=350mV, and $\Delta V(pH)$=60mV*pH+E_{CB} relative to the hydrogen standard electrode (HSE).

(b) Compute the light-to-electrical power conversion % efficiency (η) of the DSSC, assuming that incident sunpower P_i = 1 kW m^{-2}.

(c) Compute η for an analogous DSSC, where the redox couple I^-/I_3^- has been replaced by a redox pair X^-/X_3^- with $E^0(X^-/X_3^-)$=150mV.



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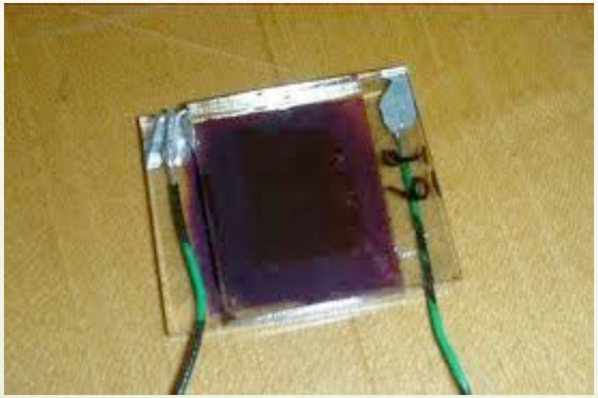
Modeling Dye-Sensitized Solar Cells

Photoconversion Efficiency: Redox Couple

Solution to Exercise 1 (standard fortran):

```
      PROGRAM main
      PARAMETER(npt=100)
      dv=2.4/(npt-1)
      pmax=-1.
      DO i=1,npt
         v=(i-1)*dv
         rv=rj(v,rkt)
         IF(rv.GT.(-10.0)) THEN
            p=v*rv
            PRINT *,p
            IF(p.GT.pmax) THEN
               pmax=p
               vmax=v
               rmax=rv
            END IF
            WRITE(10,22) v,rv
         END IF
      END DO
      PRINT *, "n(ideality factor)", rkt/0.0259
      WRITE(11,22) 0,rmax
      WRITE(11,22) vmax,rmax
      WRITE(11,22) vmax,0.
      PRINT *, "PCE(eta*100)=",pmax
 22   FORMAT(2(e13.6,2x))
      END
```

```
FUNCTION rj(v,rkt)
c
      rjl=16.7  ! current density
      rs=2.0E-4 ! specific series resistance
      rsha=100. ! specific shunt resistance
      Voc=0.42+0.35+0.045+0.3 ! Voc
      rj0=rjl*1.0E10 ! Rev. sat. curr. Density
C     ideality factor times kT/q= 0.0259 Volts
      rkt=Voc/log(rjl/rj0+1.)
      DO i=1,5
         IF (i.EQ.1) rj=rjl
         rj=rjl-rj0*(exp((v+rj*rs)/rkt)-1.)
     1      -(v+rj*rs)/rsha
      END DO
      RETURN
      END
```



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Conventional Solar Cells

Cost and Space Requirements

Exercise (Current Scenario) (due Thursday Sept 25, 2014):

Considering that the current US energy consumption is at a rate of 3.5 TWatts:

(1) What percentage of the US energy consumption is supplied by solar panels?

(2) What percentage of the electricity in Germany is supplied by solar panels?

(3) How much would the solar panels cost to supply the US with 3.5 Twatts?

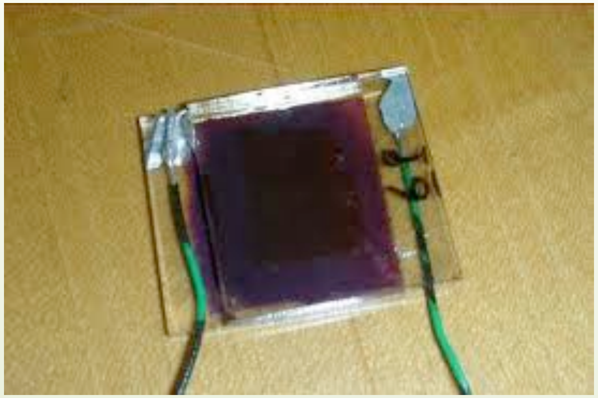
(4) How does that cost compare to the US military budget?

(5) How much area would the solar panels take to supply 3.5 TWatts?

(6) What percentage of the electricity in CT comes from nuclear reactors?

(7) Where are the nuclear power plants?

(8) When was the last time a hurricane hit the coast of CT?



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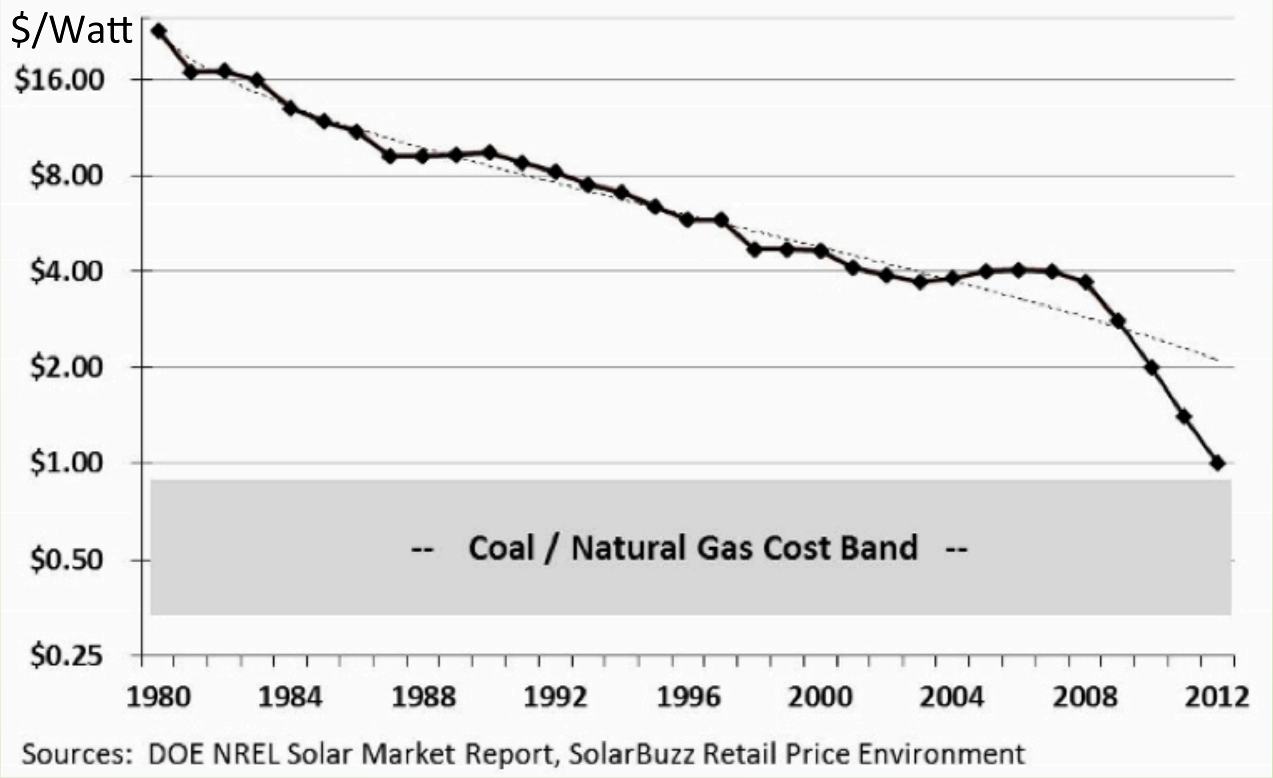
Plummeting Solar Module Cost

PV Parity?

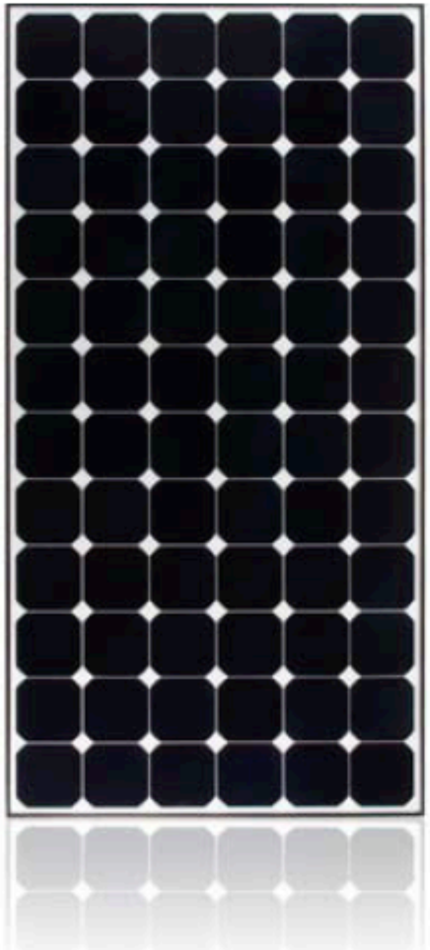


"what is certain is that we're headed for parity with fossil fuels (the gray area in the graph), and then solar will beat them..." Michael Graham Richard, May 1, 2013

Considering $1/Watt

230 SOLAR PANEL

EXCEPTIONAL EFFICIENCY AND PERFORMANCE



Cadmium telluride

SUNPOWER

$1\ KWatt/m^2\ \ 18.5/100 = 185\ W/m^2$

BENEFITS

Highest Efficiency

Panel efficiency of 18.5% is the highest commercially available for residential applications

$11.2/0.185 = 60.5\ m^2$ /person

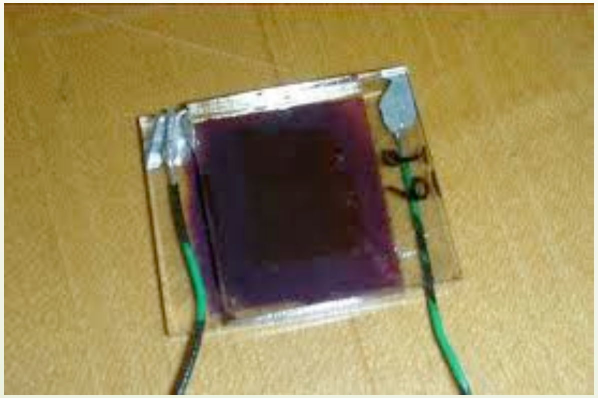
Solar Panel for Current U.S. Energy Consumption Size and Cost

- ✓11.2 KWatts/person = 3.5 10^{12} Watts (3.5 Twatts)
  - ✓Cost of solar panels: $11,200 /person = [$3.5 Trillions]

2012 U.S. military budget = $2,064/person [$0.646 Trillion]

2011 Ivanpah BrightSource Energy = $5.1/person

WASHINGTON (Army News Service, July 8, 2010) --"We view energy security as a critical mission-enabler and an operational imperative, which can provide the Army with an essential tactical advantage," said Jerry Hansen, the Army's senior energy executive, during a bloggers roundtable discussion, July 7, at the Pentagon. "Our Army installations, our tactical operations, Soldier training -- all require secure and uninterrupted access to energy."



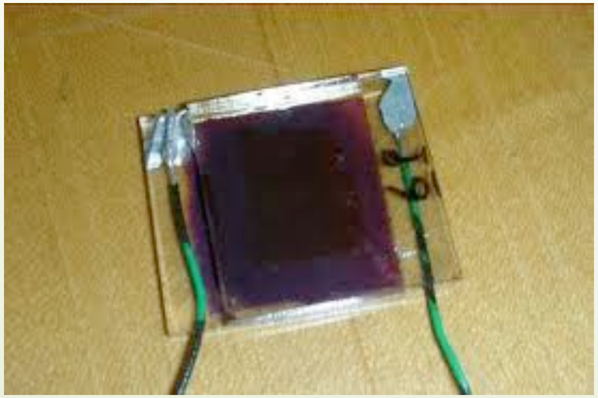
Modeling Photovoltaic Solar Cells

U.S. Energy Consumption

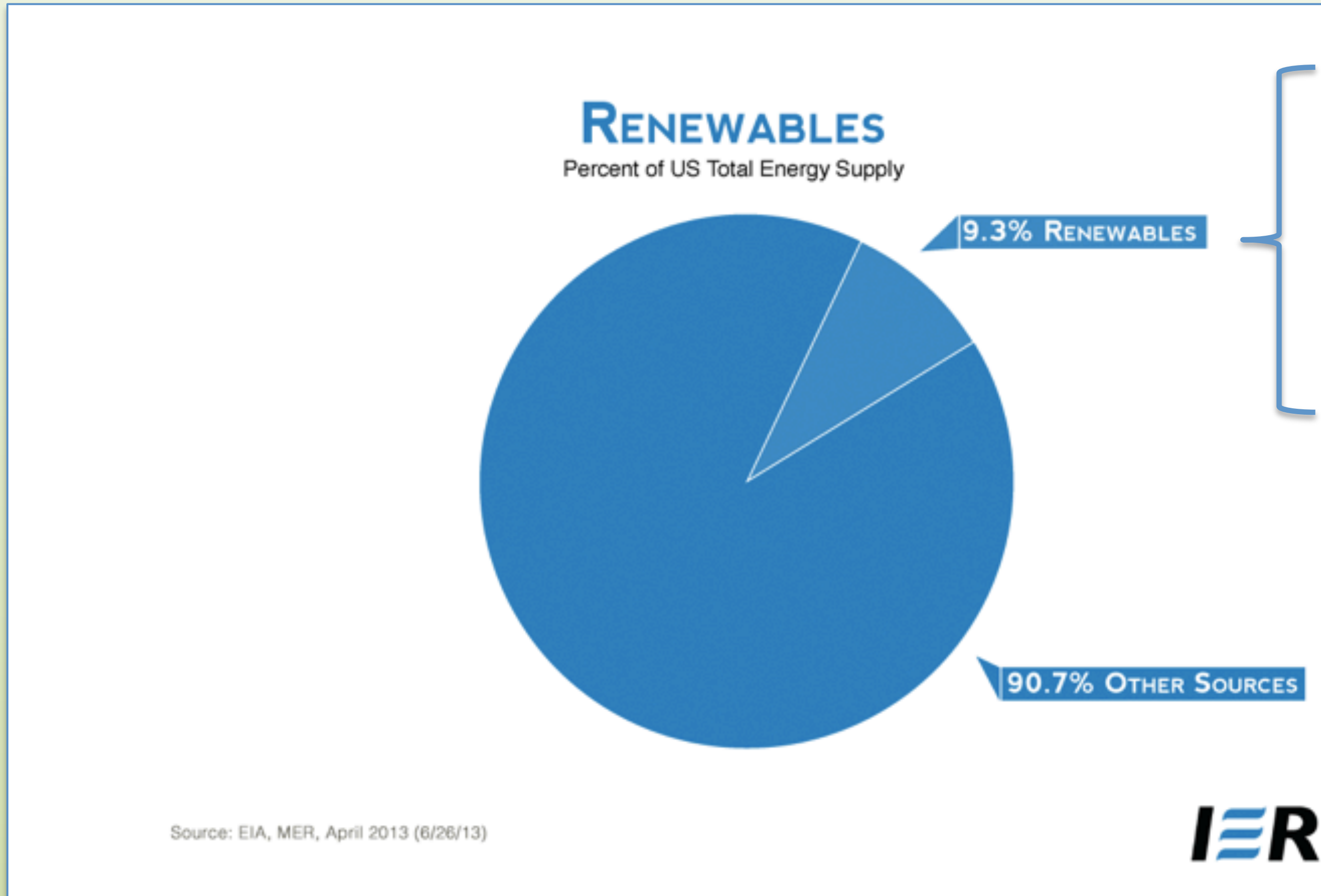
✓11.2 KWatts/person = (3.5 TWatts)

- Each person consumes energy, on average, at a rate comparable to the energy consumption of 11 window air conditioners, or 110 light bulbs (100 Watts each).

- Sunlight shines on earth at an average flux rate of 1.0 KWatt/m^2. Therefore, the average flux of solar energy shining on 11.2 m^2 (120 ft^2) corresponds to the average energy consumption per capita.



2012 U.S. Renewable Energy Consumption



Hydropower 2.8%
Biomass Wood 2.0 %
Biomass Waste 0.5%
Biomass Biofuels 2%
Wind 1.4%
Geothermal 0.1%
Solar 0.2%

April 11, 2011. DOE Finalizes $1.6 Billion Loan Guarantee for BrightSource Energy

U.S. DEPARTMENT OF ENERGY
LOAN PROGRAMS OFFICE

IVANPAH Solar Electric Generating System | BrightSource | nrg | Google

IVANPAH: World's Largest Solar Thermal Plant

[As World's Largest Solar Thermal Plant Opens, California Looks to End Solar Wars]()

July 12, 2013. In a few weeks, the largest solar plant of its kind in the world will start producing power in California's Mojave Desert.

The [Ivanpah Solar Electric Generating System]() will supply both Northern and Southern California, inching the state one step closer to its ambitious renewable energy goal.