Solar energy conversion

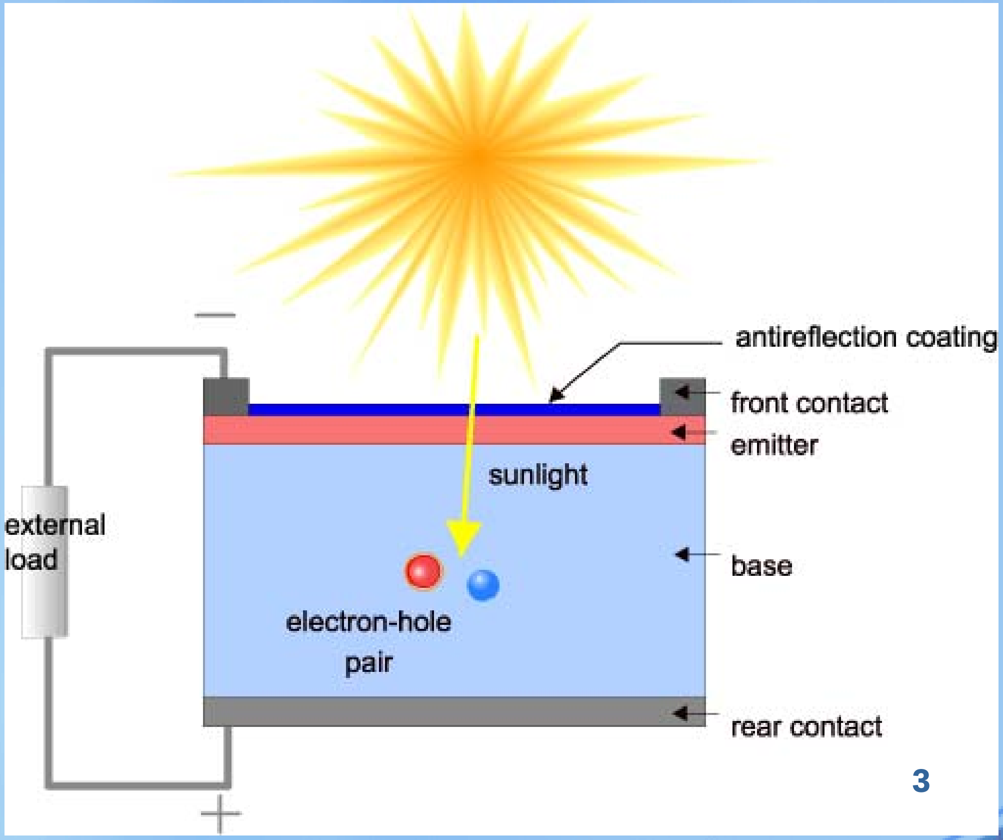
- **Convert sunlight into heat** used for building or water heating
  - Solar pool heating and solar water heaters
- Two ways to **convert sunlight into electricity**
  - Solar thermal electricity generation
  - Utilizing ~1% of the earth's deserts to produce solar electric energy would provide more electricity than is being produced by fossil fuels

Photovoltaics - Simple explanation

- 1. Photons (sunlight) hit the solar panel and are absorbed by semiconducting materials.
- 2. Electrons (negatively charged) are knocked loose from their atoms, allowing them to flow through the material to produce electricity. Complementary positive charges are also created (holes) and flow in the direction opposite of the electrons.

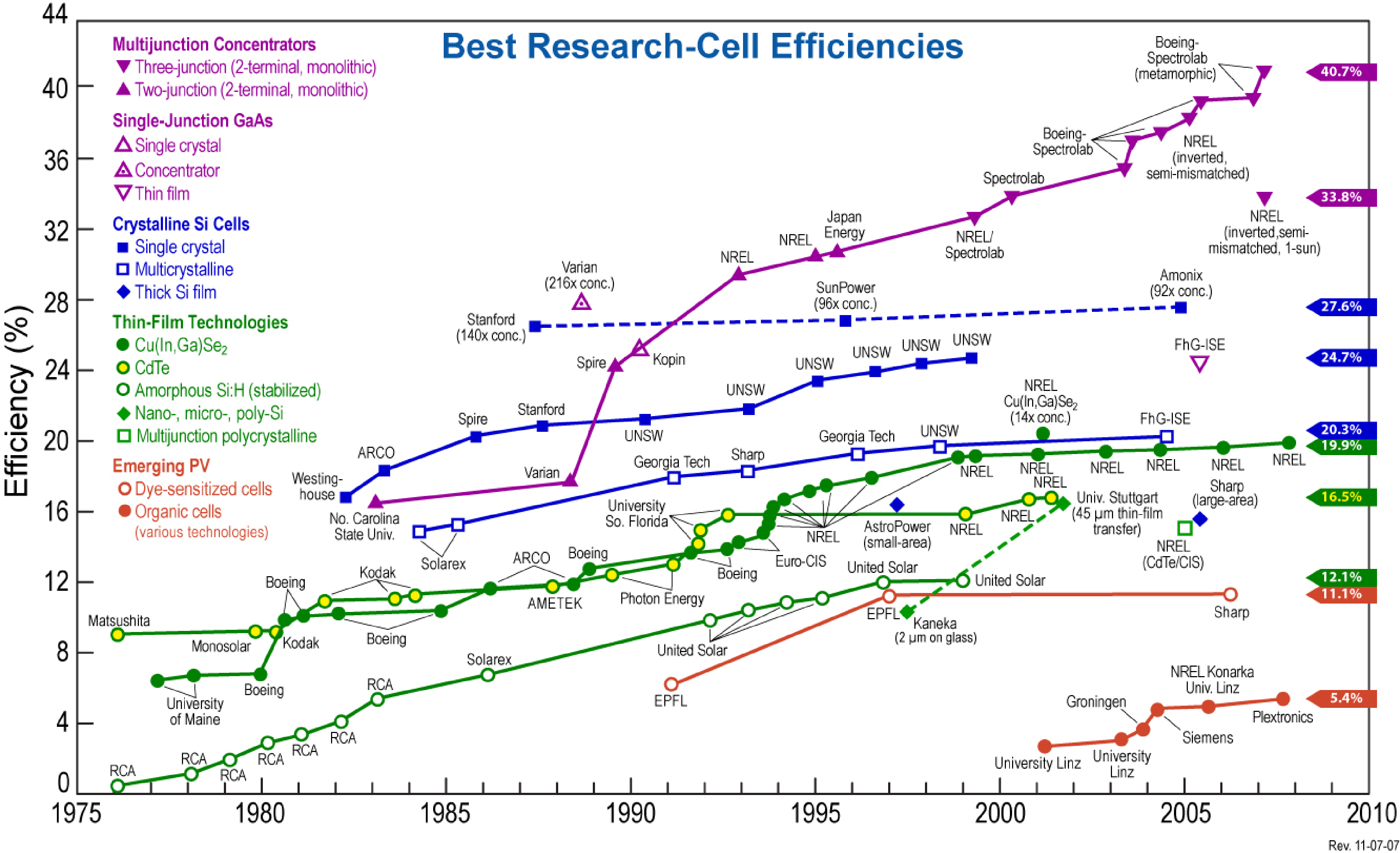
Solar cell fundamentals

- Over 95 % of all solar cells are made from Silicon (Si).
- Dope Si fort solar cell production.
- Positive charge carriers (p-doped).
- Negative charge carriers (n-doped).
- p-n-junction.



Still the problem: efficiency

- Solar cell efficiencies vary from ~ 6% for amorphous silicon-based solar cells to ~ 41% with multiple-junction research lab cells.
- Solar cell energy conversion efficiencies for commercially available multicrystalline Si solar cells are ~ 14-19%.
- High efficiency cells are not always the most economical.
- 30% efficient multijunction cell based on exotic materials might well cost one hundred times as much as an 8% efficient amorphous silicon cell in mass production, while only delivering about four times the electrical power.


Best Research-Cell Efficiencies
Efficiency (%)
44
40
36
32
28
24
20
16
12
8
4
0
1975
1980
1985
1990
1995
2000
2005
2010
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Single-Junction GaAs
Single crystal
Concentrator
Thin film
Crystalline Si Cells
Single crystal
Multicrystalline
Thick Si film
Thin-Film Technologies
Cu(In,Ga)Se2
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly-Si
Multijunction polycrystalline
Emerging PV
Dye-sensitized cells
Organic cells
(various technologies)
Boeing-Spectrolab (metamorphic)
40.7%
Boeing-Spectrolab
NREL (inverted, semi-mismatched)
Spectrolab
33.8%
NREL (inverted,semi-mismatched, 1-sun)
Japan Energy
NREL
NREL
NREL/ Spectrolab
Varian (216x conc.)
SunPower (96x conc.)
Amonix (92x conc.)
Stanford (140x conc.)
27.6%
Spire
Kopin
UNSW
UNSW
UNSW
UNSW
FhG-ISE
24.7%
UNSW
NREL Cu(In,Ga)Se2 (14x conc.)
Spire
Stanford
UNSW
FhG-ISE
20.3%
19.9%
ARCO
Georgia Tech
UNSW
Westing-house
Varian
Georgia Tech
Sharp
NREL
NREL
NREL
NREL
NREL
NREL
NREL
Sharp (large-area)
16.5%
University So. Florida
NREL
AstroPower (small-area)
NREL
NREL
Univ. Stuttgart (45 µm thin-film transfer)
No. Carolina State Univ.
NREL (CdTe/CIS)
Solarex
ARCO
Boeing
Euro-CIS
Kodak
Boeing
United Solar
United Solar
12.1%
Boeing
AMETEK
Photon Energy
11.1%
Matsushita
Monosolar
Kodak
Boeing
EPFL
Kaneka (2 µm on glass)
Sharp
United Solar
Solarex
RCA
Boeing
EPFL
NREL Konarka Univ. Linz
University of Maine
Groningen
5.4%
Plextronics
Siemens
RCA
RCA
RCA
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RCA
RCA
RCA
University Linz
University Linz
Rev. 11-07-07

Generations of solar cells

- Solar Cells are classified into three generations.
- At present there is concurrent research into all three generations
- First gen. technologies account for 89% of 2007 production.
- Large-area, high quality and single junction devices.
- Single junction silicon devices are approaching the theoretical limiting efficiency of 33%
- High production costs - unlikely to achieve cost parity with fossil fuel energy generation.

- Second generation materials use new manufacturing techniques (vapor deposition, electroplating).
- 2nd generation technologies are faulted for “poor” conversion efficiencies and despite high Si prices were unable to gain significant market share.
- Most successful 2nd generation materials have been cadmium telluride (CdTe), copper indium gallium selenide, amorphous silicon, and micromorphous silicon.
- Materials are applied in thin films to supporting substrates (glass, ceramics) reducing material mass and costs
- In 2007 CdTe production represented 4.7% of total market share, thin film silicon 5.2%

- Third generation technologies enhance poor electrical performance of thin film technologies while maintaining low production costs.
- Current research is targeting conversion efficiencies of 30-60%
- There are a few approaches to achieving these high efficiencies:
  - Multiple junction devices.
  - Modifying incident spectrum (concentration).
  - Use of excess thermal generation to enhance voltages or carrier collection.

Solar Modules

- A photovoltaic module is a packaged interconnected assembly of solar cells.

Solar thermal energy

- Harness solar energy from heat.
- Low, medium, or high temperature collectors.
- Low temperature collectors are flat plates generally used to heat swimming pools.
- Medium-temperature collectors are also flat plates but are used for creating hot water for residential and commercial use.
- High temperature collectors concentrate sunlight using mirrors or lenses and are generally used for electric power production.

- BrightSource Energy made purchase agreement with Pacific Gas and Electric in 3/2008 for 900MW of electricity and is developing solar power plants in SoCal (construction of the first plant in 2009).
- In June 2008, BrightSource Energy dedicated Solar Energy Development Center in Israel.
- Working power plant in Spain with capacity of 11MW and 15MW plant is under construction in Spain.
- In South Africa, a 100MW solar power plant is planned
- NREL estimated that by 2020 electricity could be produced from power towers for 5.47 ₡/kWh and for 6.21 ₡/kWh from parabolic troughs.

Capabilities at UD

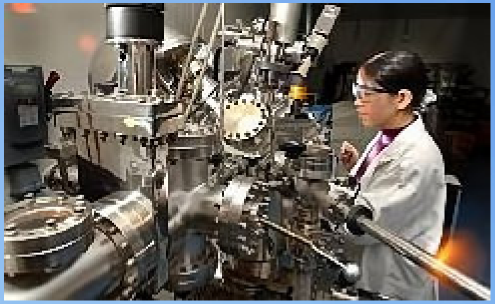
- **Research**
  - Institute for Energy Conversion (IEC)
  - Solar Power Program in EE
  - Polymer Solar Cell research in ChE
- **Education**
  - Solar Hydrogen IGERT
  - REU Program in ChE
- **Energy Institute**

Institute of Energy Conversion

Powering the 21st Century

- Thin-film photovoltaic cells and educates students with expertise in photovoltaics
- Established in 1972
- In 1980, IEC developed the first thin film solar cell to exceed 10 percent efficiency.
- In 1982, new 40,000 square foot laboratory
- In 1992, IEC became Center of Excellence for Photovoltaic Research and Education.
- In 1996, Prof. Robert W. Birkmire, became fourth director.
- Today, IEC is one of the few laboratories in the world with expertise in Si, CdTe and CuInSe2 based solar cells.

- **Design, fabrication and analysis of solar cells made from thin-film semiconductor materials**
  - CdTe, CuIn diselenide, amorphous Si, Si on low cost substrates
- **Process Equipment Design and Operation**
  - Development of laboratory scale reactors
  - Provide basis for commercial scale reactor design.
  - Photochemical vapor deposition reactors for state-of-the-art amorphous silicon solar cells.



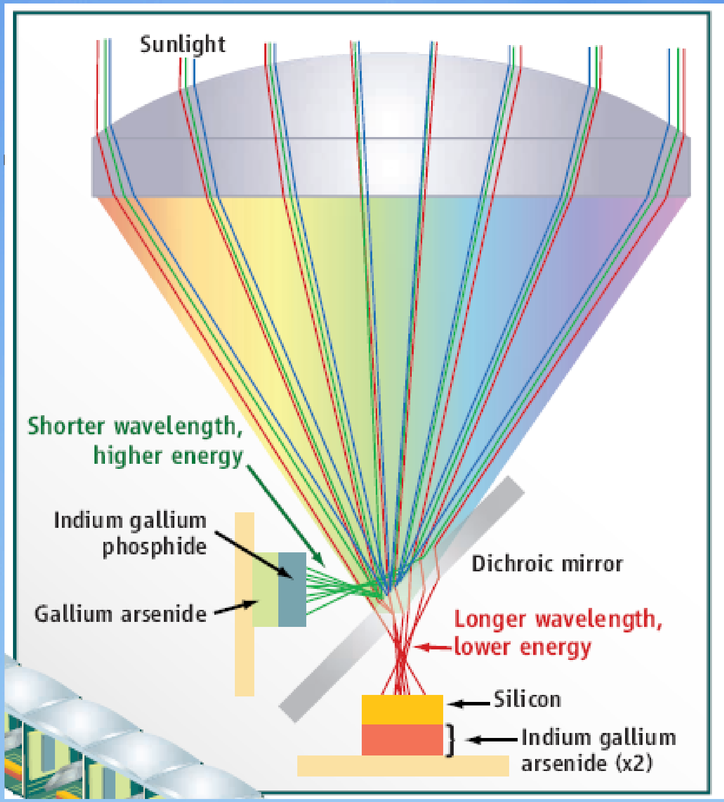
- **Thin Film Deposition Capabilities**
  - Roll-to-Roll inline deposition systems
  - Elemental evaporators & CVD reactors
  - Plasma enhanced chemical vapor deposition
  - Electron beam evaporation & RF/DC magnetron sputtering
- **Material Characterization Capabilities**
  - Amray 1810T Digital Scanning Electron Microscope
  - UV-visible-IR Spectrophotometer with integrating sphere
  - Wide Angle X-ray Diffractometer
  - XPS system with load-lock sample preparation chamber
  - Scanning Probe Microscopy
- **Device Analysis Capabilities**

Consortium for Very High Efficiency Solar Cells

- 15 univ., corps. and labs
  - DuPont, BP Solar, Corning Inc., LightSpin Technologies and Blue Square Energy.
- In 2005, the consortium received $13 mio. in funding for the initial phase.
- Develop and produce 1,000 Very High Efficiency Solar Cells that operate at efficiencies of at least 50 percent for application in high-tech military.
- *The creation of affordable, high-efficiency solar cells is a challenge in that it presents not a single problem but a complex set of interrelated problems.*
- High performance crystalline silicon solar cell platform with integrated optical design.

Solar cells

- Cells operates with conc. sunlight.
- Novel technology that adds innovations to high-performance crystalline Si solar cell.
- Consortium has achieved a combined solar cell efficiency of 42.8%.



DuPont Solar Project

- Next phase of the DARPA project
- UD-led team joins DuPont on project worth as much as $100 million.
- 42.8% is a significant advance and demonstrates an important milestone on the path to the 50 percent efficiency goal.
- DARPA initiated next phase by funding the newly formed DuPont-UD Consortium to transition the lab-scale work to a prototype model.
- 3-year effort could be worth as much as $100 million, including industry cost-share.

- **Chemical Engineering**
  - Development of novel catalysts for hydrogen generation
- **Chemistry and Biochemistry**
  - High efficiency electrolysis
- **Economics and Policy**
  - Climate change policy and impacts on competitiveness of renewables
  - Economic modeling of renewables
- **Electrical and Computer Engineering**
  - In GaN solar cells
  - Liquid/semiconductor and polymer/semiconductor solar cells and electrochemical solar cells
  - Silicon solar cells

- **Materials Science**
  - Interface science, chemistry and its effect on charge transfer.
  - Photoelectron spectroscopic charactizations of electronic materials and their interfaces
- **Mechanical Engineering**
  - Thermo-chemical methods for hydrogen production
  - PEM Fuel Cells for next generation Hybrid Vehicles
- **Physics and Astronomy**
  - Nanostructural high efficiency solar cells including molecular beam epitaxy quantum dot and quantum well solar cells
  - Properties of gases on carbon nanotubes and other carbon structures

Examples for other programs

- MIT/Eni program
  - $50 mio. over 5 years
  - Part of the MIT Energy Initiative
- Florida Solar Energy Center
  - State's energy research institute
- University of Johannesburg and German IFE Solar Systems
  - $81.3 million

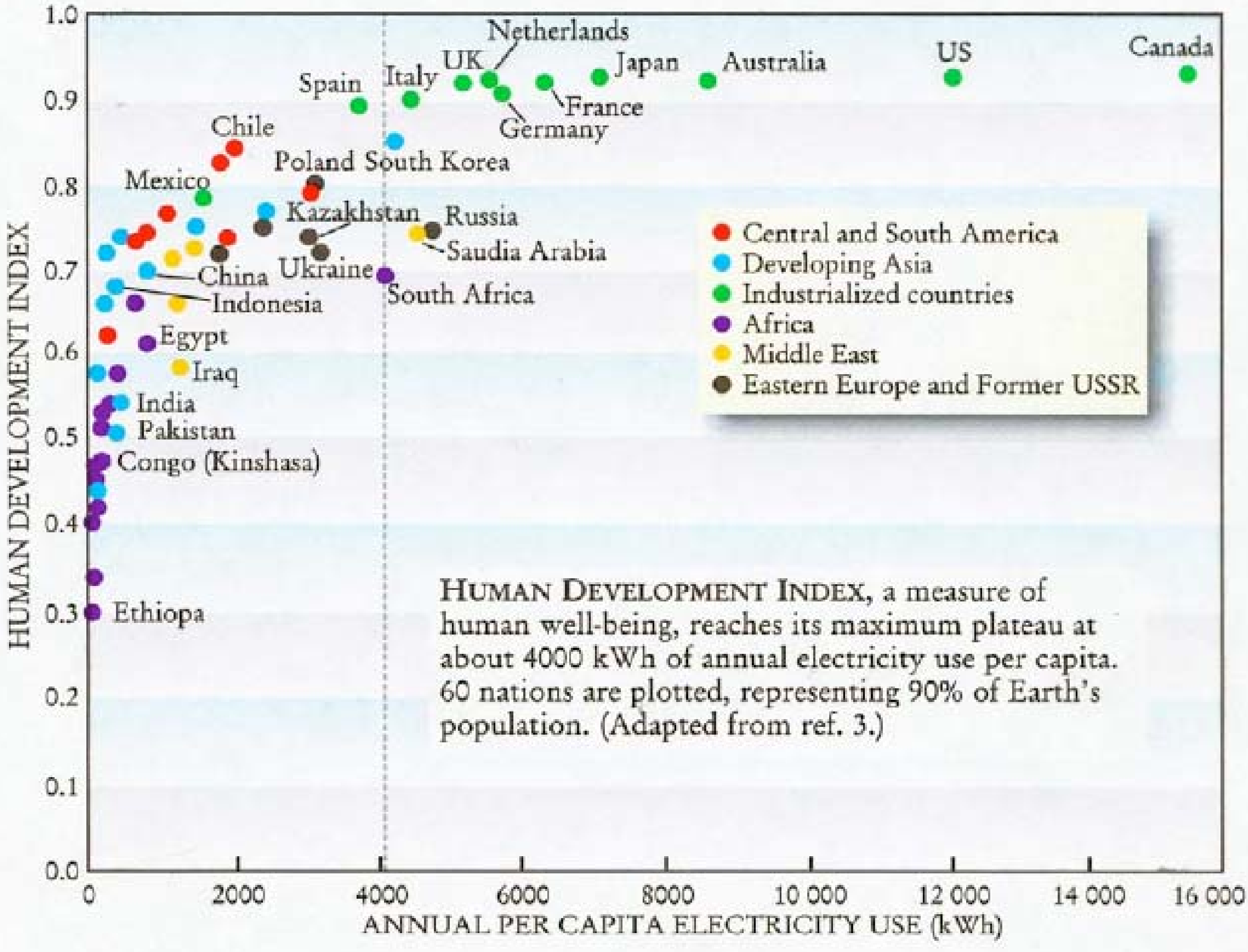


Figure 1.2. Human development index vs. per capita electricity use for selected countries. Taken from S. Benka, *Physics Today* (April 2002), pg 39, and adapted from A. Pasternak, Lawrence Livermore National Laboratory rep. no. UCRL-ID-140773.