NREL
National Renewable Energy Laboratory

Systems-Driven Approach: PV Models & Tools

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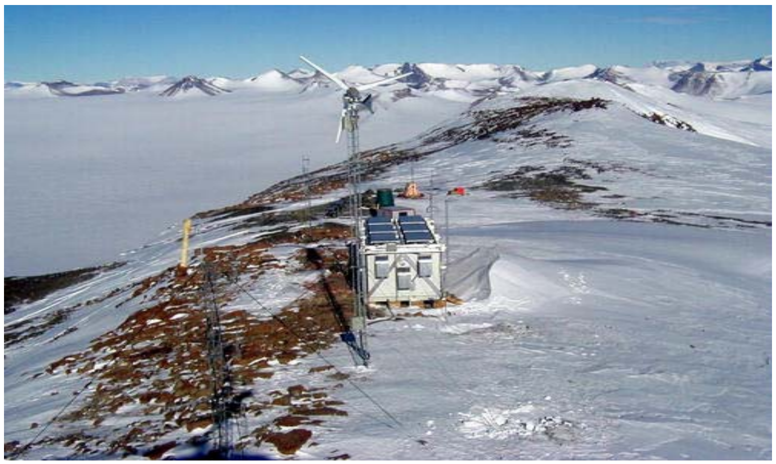
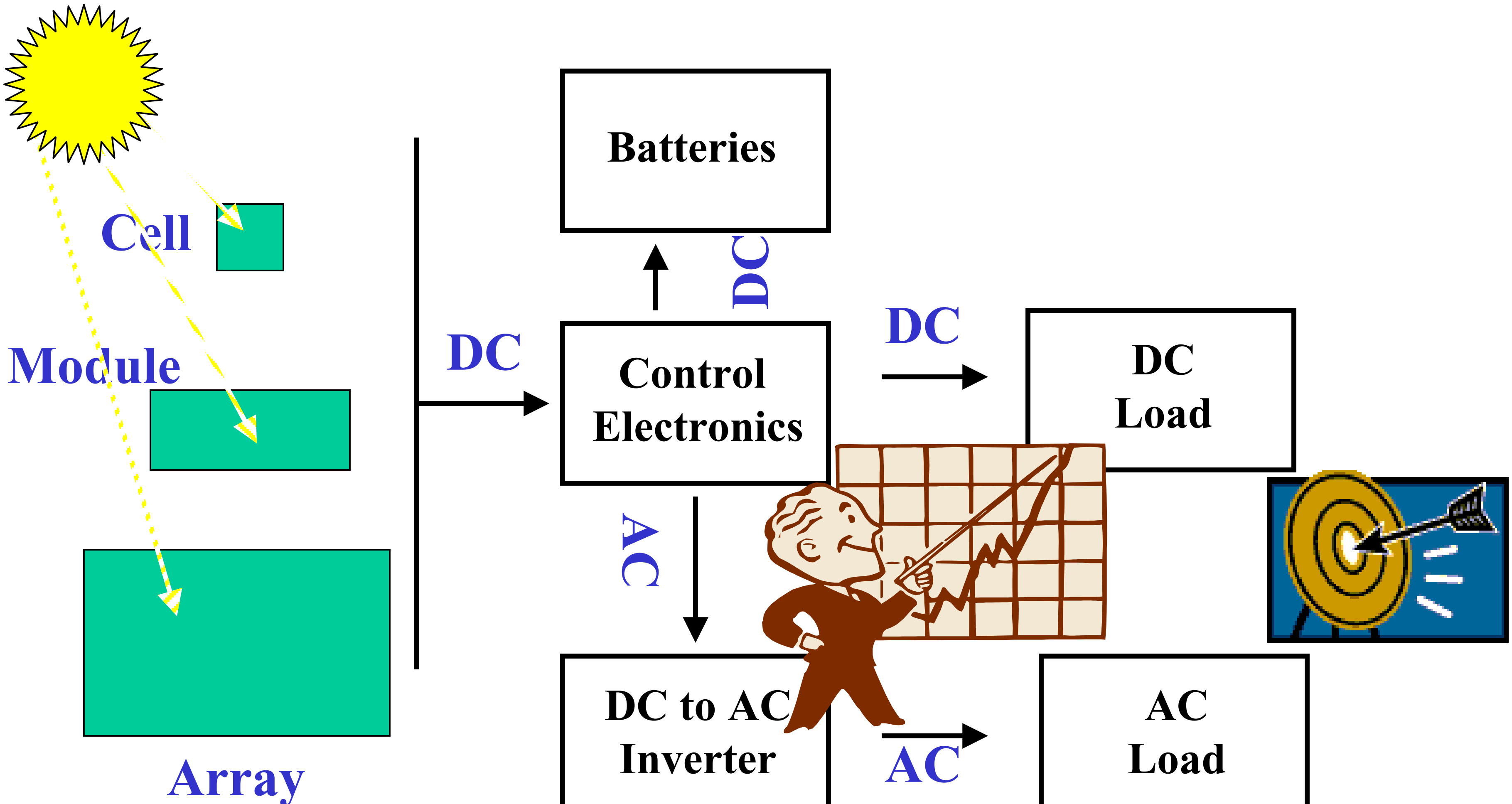
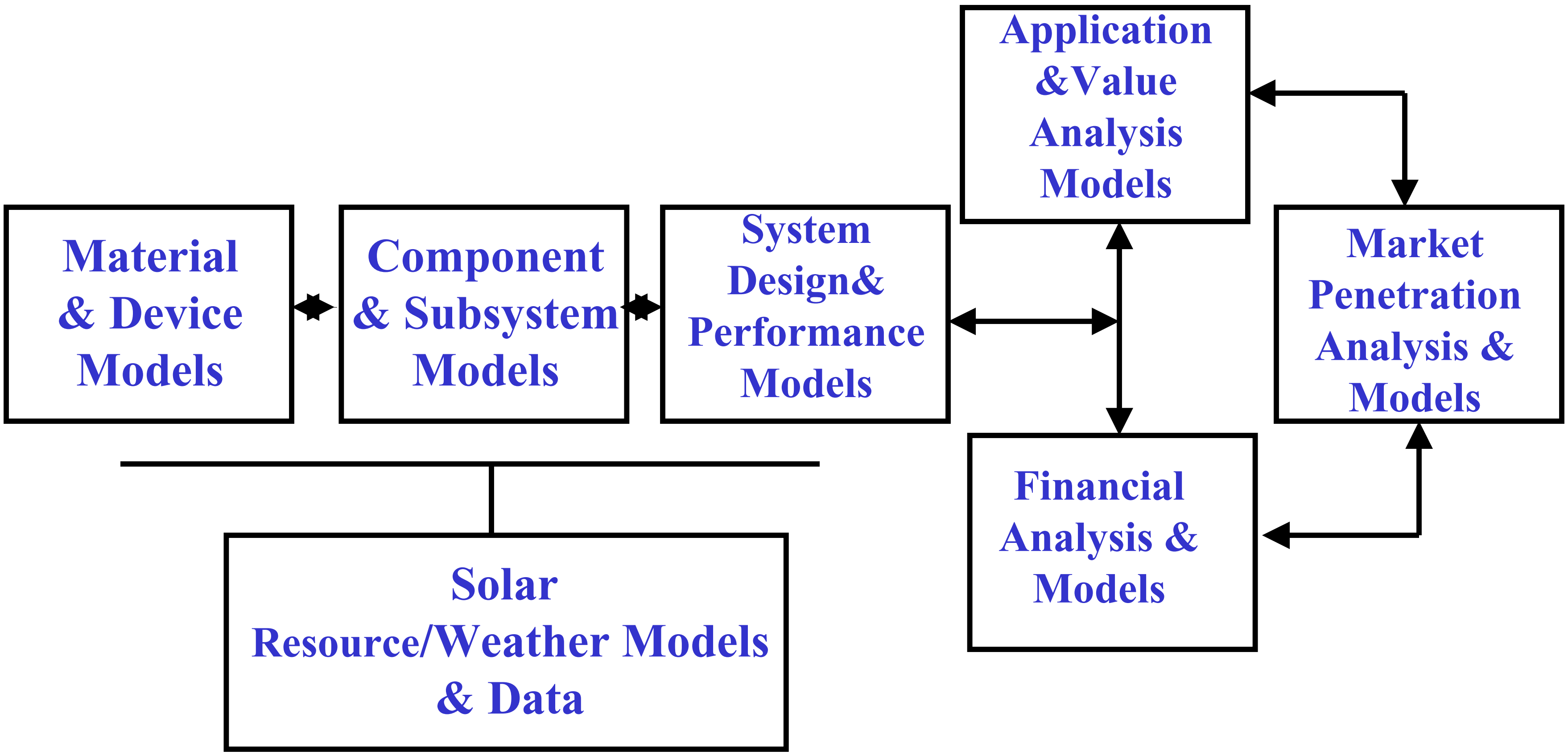
The Scope of PV Products/Applications/Models/Tools



PV System Configurations/Components: Simple to Complex



Models and the PV Technology--Market Chain



Materials and Devices Models

What/Who	Description/Input	Output
Solid State Theory (NREL, and Others)	First principle calculations of semiconductor material properties: atomic number/structures	Scientific understanding of optical,structural, defect, interfacial, & alloying properties:Predictions of New Materials.
PC-1D (Purdue, SNL, UNSW, others)	1-dimensional electronic modeling package for single-junction solar cells: material parameters (resistivity, lifetime, absorption, etc.)	Current-Voltage characteristics of device and sensitivity to various parameters.
AMPS (Penn State)	Similar to above, but can be used for multijunctions; uses many more material parameters(defect distributions, etc.)	Current-Voltage characteristics of device and sensitivity to various parameters.
PV-OPTICS (NREL)	Ray tracing & wave optics for light absorption in a material/device; 3-D, can handle multijunctions & metal optics	3-D generation function of carriers in device..can use this in PC-1D & AMPS to predict I-V characteristics & sensitivities.
NEWORK(NREL)	Electronic engineering model to predict device performance resulting from spatial inhomogeneities in a cell or effects of cell-to-cell variations in a module	Solar cell or module performance; understanding of effects of inhomogeneities.

Component and Subsystem Models

- Models for modules, power conditioners, batteries, and other components.

- Typically provide component performance and cost information based on input design parameters.

- Models based on empirical data also widely used.

NOTE: Many firms have their own proprietary models.

Module Manufacturing Cost Models

What/Who	Description/Input	Output
IPEG/SAMICS/SAMIS (JPL)	Developed for x-Si manufacturing (feedstock, crystal growth, wafering, cell fabrication, module packaging, testing): inputs are factory size, equipment, material costs, O&M costs, processes (yields, throughputs, etc.), labor, etc. Simple user interactive inputs with extensive data base in program.	Module manufacturing costs & sensitivities to various parameters (efficiency, feedstock cost, cell process or module packaging alternatives, etc.)
Thin-Film Manufacturing Cost Models (Research Triangle Institute, EPRI, NREL, industry)	Similar to above for specific thin-film technologies; equipment & material costs, processes, labor, overhead, etc.	Module manufacturing cost & sensitivities to various parameters. Most of industry models are proprietary.

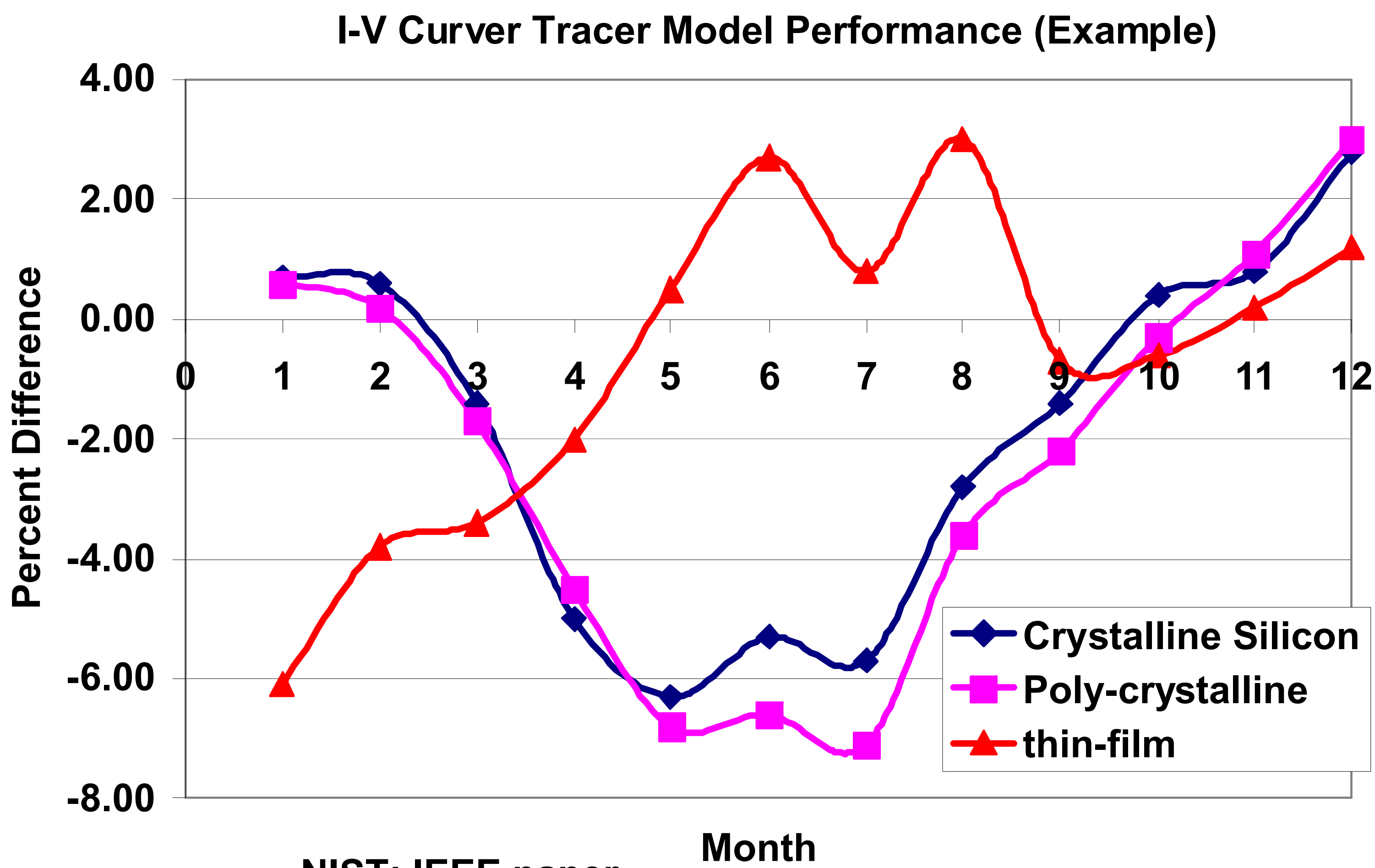
PV Module Performance Models

- Basic - Power equation adjusts power for irradiance and temperature.

- Advanced - Models complete I-V curve and corrects for irradiance, temperature, angle-of-incidence, and solar spectrum. Examples: IVTracer (Sandia) and MER model (NREL)

Advanced PV Module Performance Models

- Inputs: Irradiance, temperature, wind speed, solar spectrum or air mass, and technology-specific module characteristics.
- Output: Complete I-V Curve, Isc, Voc, Imp, Vmp, Pmax, FF.
- Typical Accuracy: For hourly values, MBE <3% and RMSEs of <6%.



NIST: IEEE paper.

PV System Design and Performance Models

- The models provide PV/hybrid system design and /or performance information for specific applications and sites.

- Inputs: TMY weather/solar-resource, PV module, inverter, battery, and wiring specifications; electric loads; and costs.

- Outputs: D.C. and A.C. energy(hourly, daily, monthly, annual), battery state of charge, energy cost, lifecycle cost analysis.

PV System Design & Performance Subroutines

- Solar irradiance incident on modules
- PV cell temperature
- D.C. power and energy
- Inverter efficiency
- A.C. power and energy
- Charge controller efficiency
- Battery state of charge
- Economics

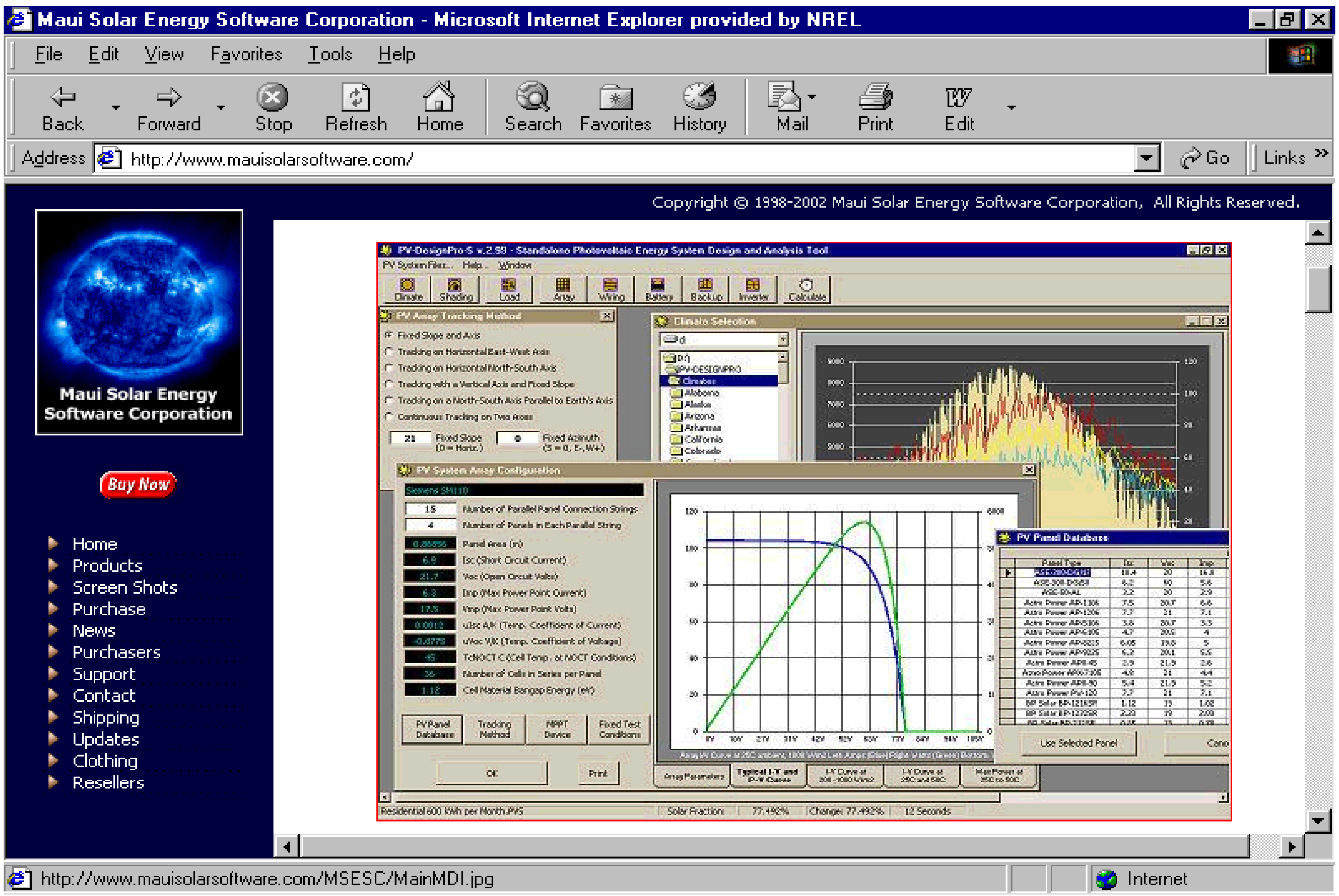
PV System Design & Performance Models

Several have been developed over a span of 30 years, with continued development to meet various needs. Examples include:

- **PVFORM (SNL)**
- **TRNSYS (Univ. of Wisconsin)**
- **PVWATTS (NREL)**
- **PV-DesignPro (Maui Solar Energy)**
- **Manufacturers, System Integrators, Companies develop and use their own, proprietary, models as tools specific to their products/systems.**

<u>If used correctly/appropriately,</u> <u>with accurate inputs/data</u>, these models can be used to produce good designs and projections of delivered electricity and costs. As new component technologies become available, subroutines have to be updated/modified.

PV-DesignPro Screen Shot



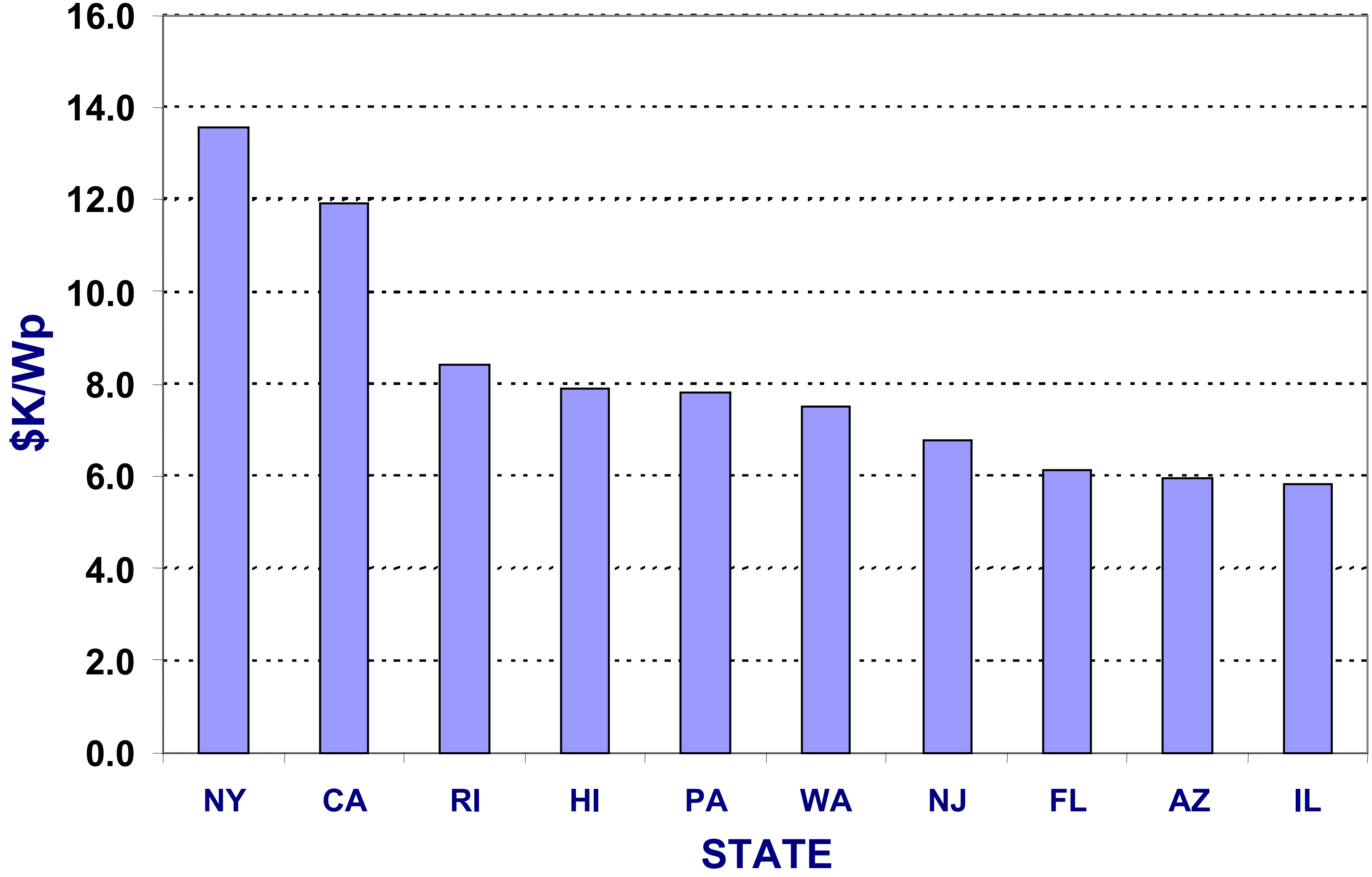
PV Applications and Value Analysis Models

These models look at the requirements of specific applications for PV and hybrid systems, and analyze the value of such systems relative to competing options, including consideration of factors such as:

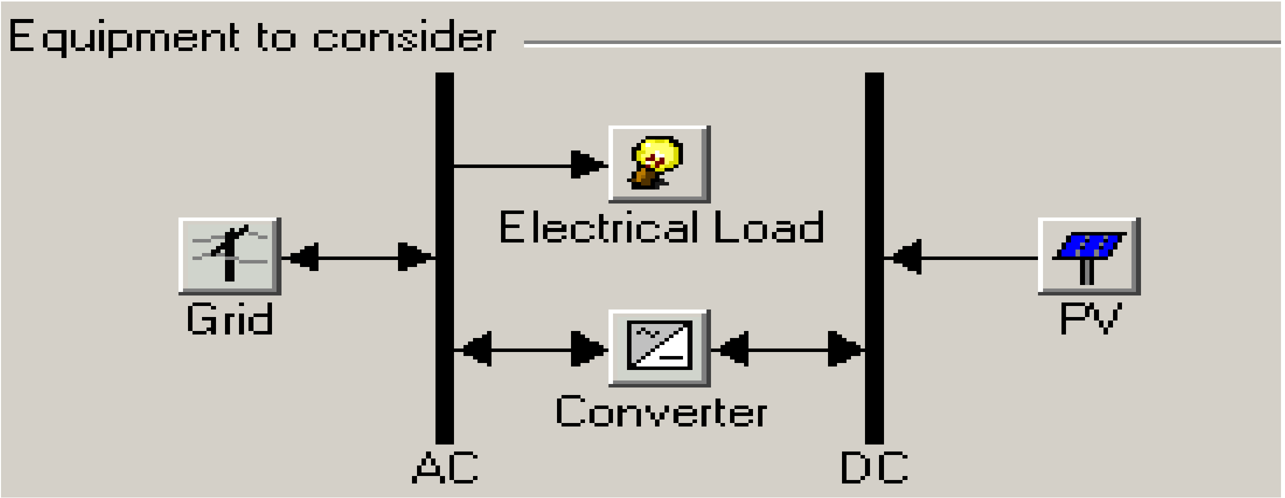
- **Resources**
- **Environmental and climate benefits (e.g. CO_2 mitigation)**
- **Security and reliability benefits.**

PV Applications and Value Analysis Models
-Examples-

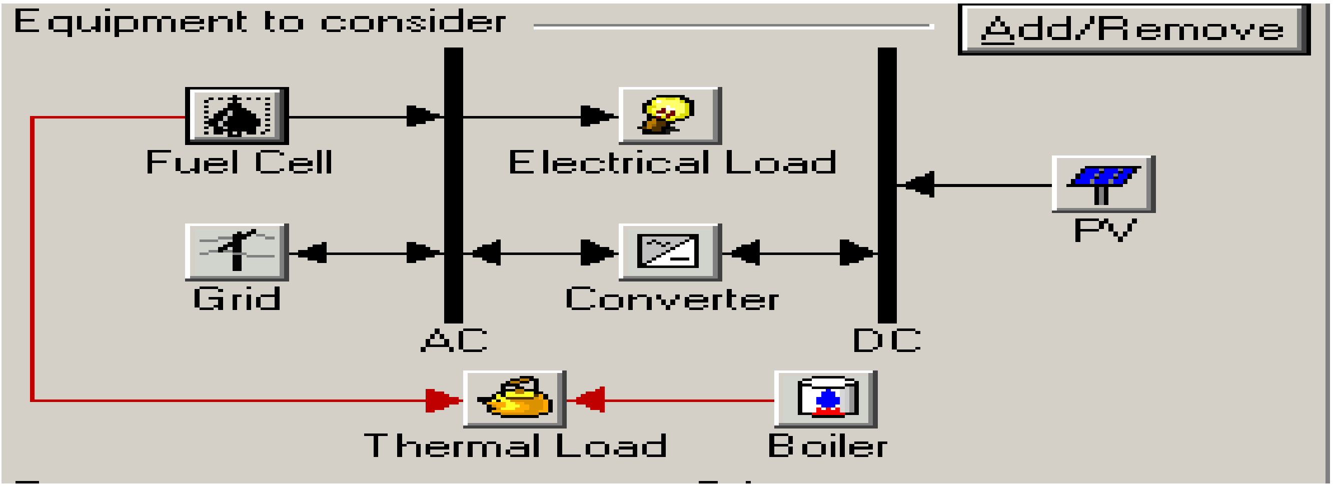
Residential PV Breakeven Turn-key Value Analysis



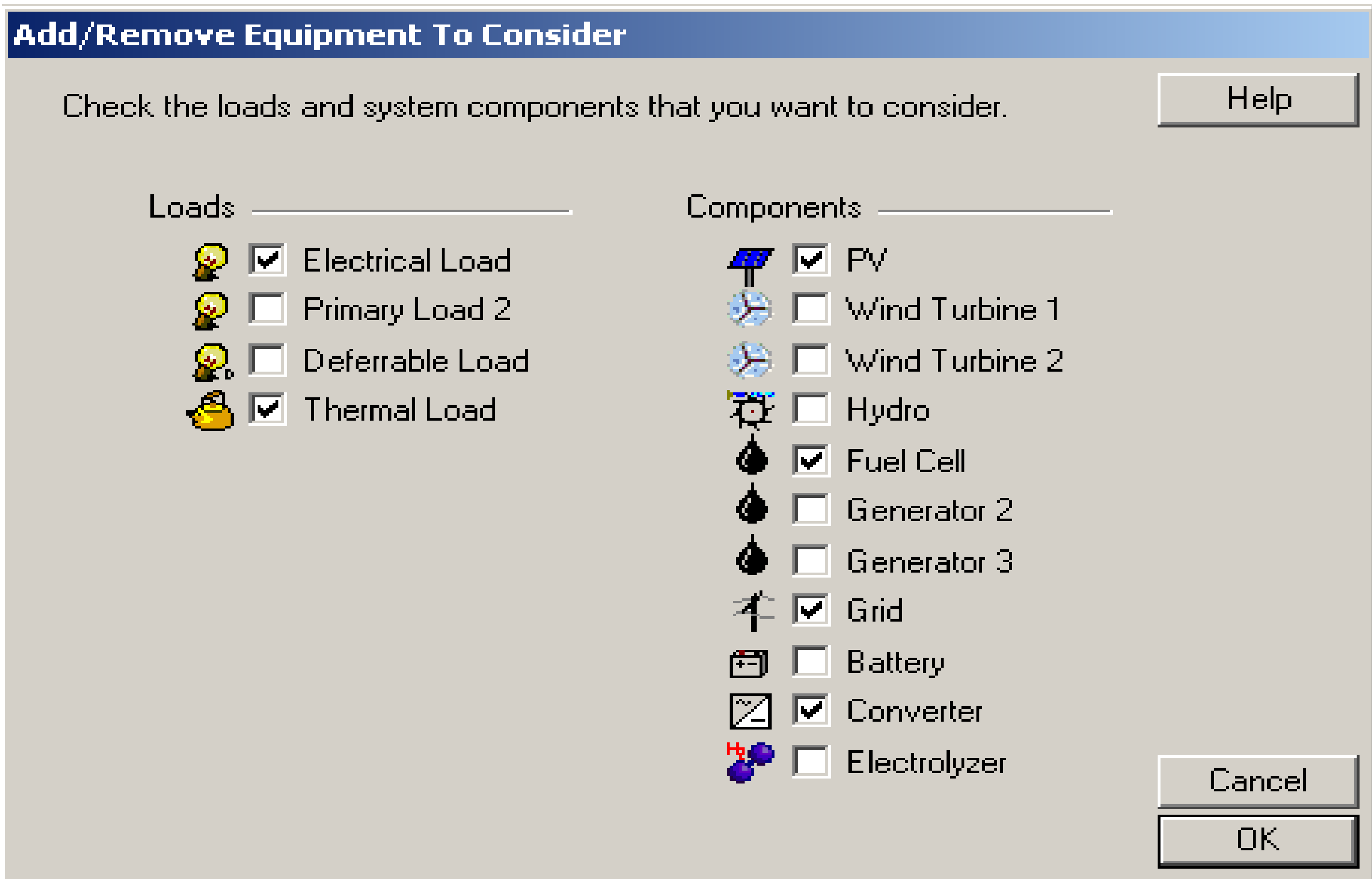
HOMER Model: NREL



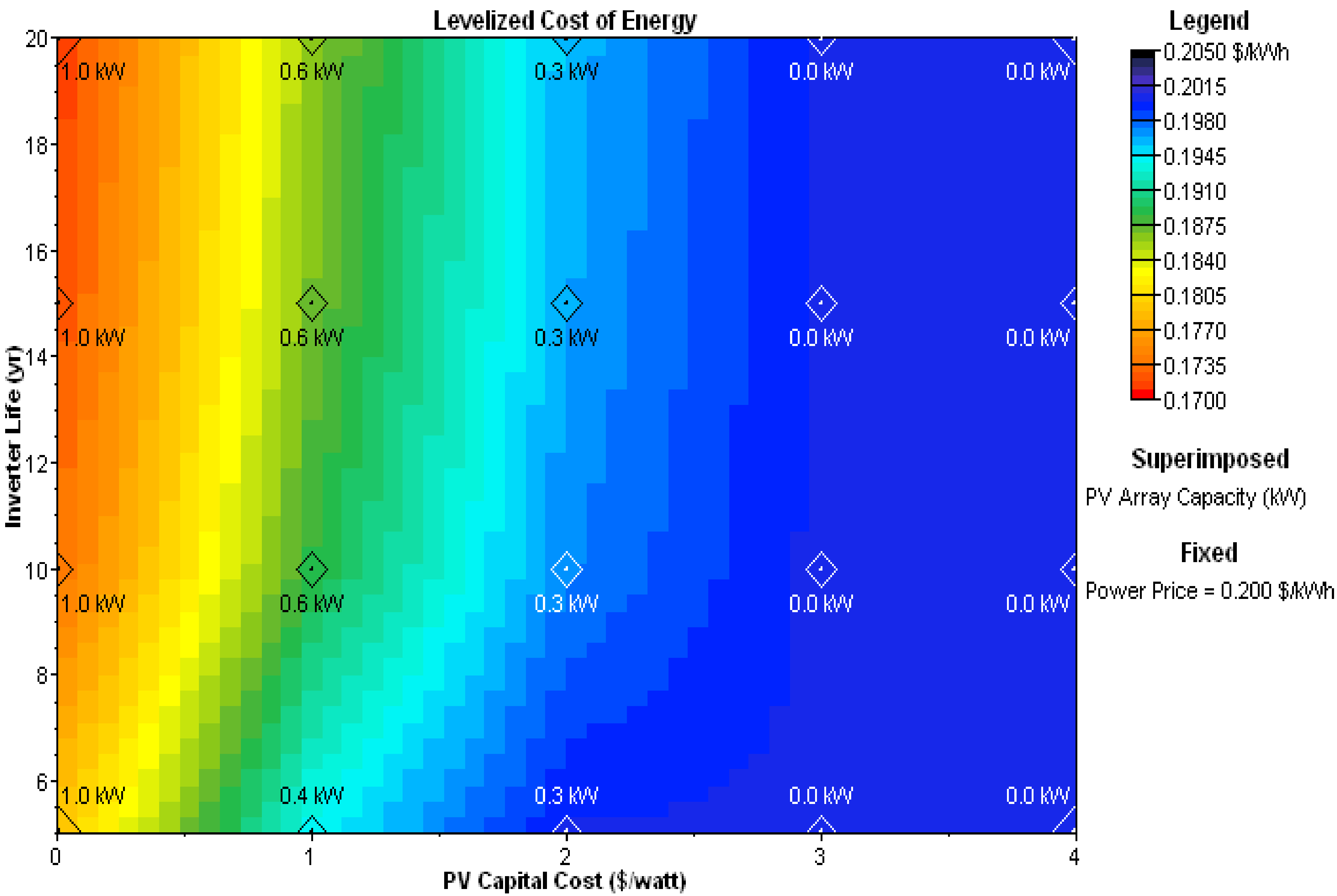
HOMER can compare many potential configurations and hybrids



Potential Components in HOMER: User Selected.



Example of Output of HOMER Model



Financial Models and Tools

- These models calculate levelized costs or rates of return on PV systems.
- Inputs include PV system performance and cost characteristics along with assumptions about financial parameters such as interest rates, taxes, depreciation schedules, subsidies, etc.
- Current information on state-level taxes and subsidies is critical.

Examples of Financial Models & Tools

FATE 2P & RETFinance (PERI & NREL)

Spreadsheet, cash flow models that can calculate levelized energy costs or rates of return. Use technology and resource characteristics and financial parameters as inputs.

DESIRE Database (NC Solar Institute)

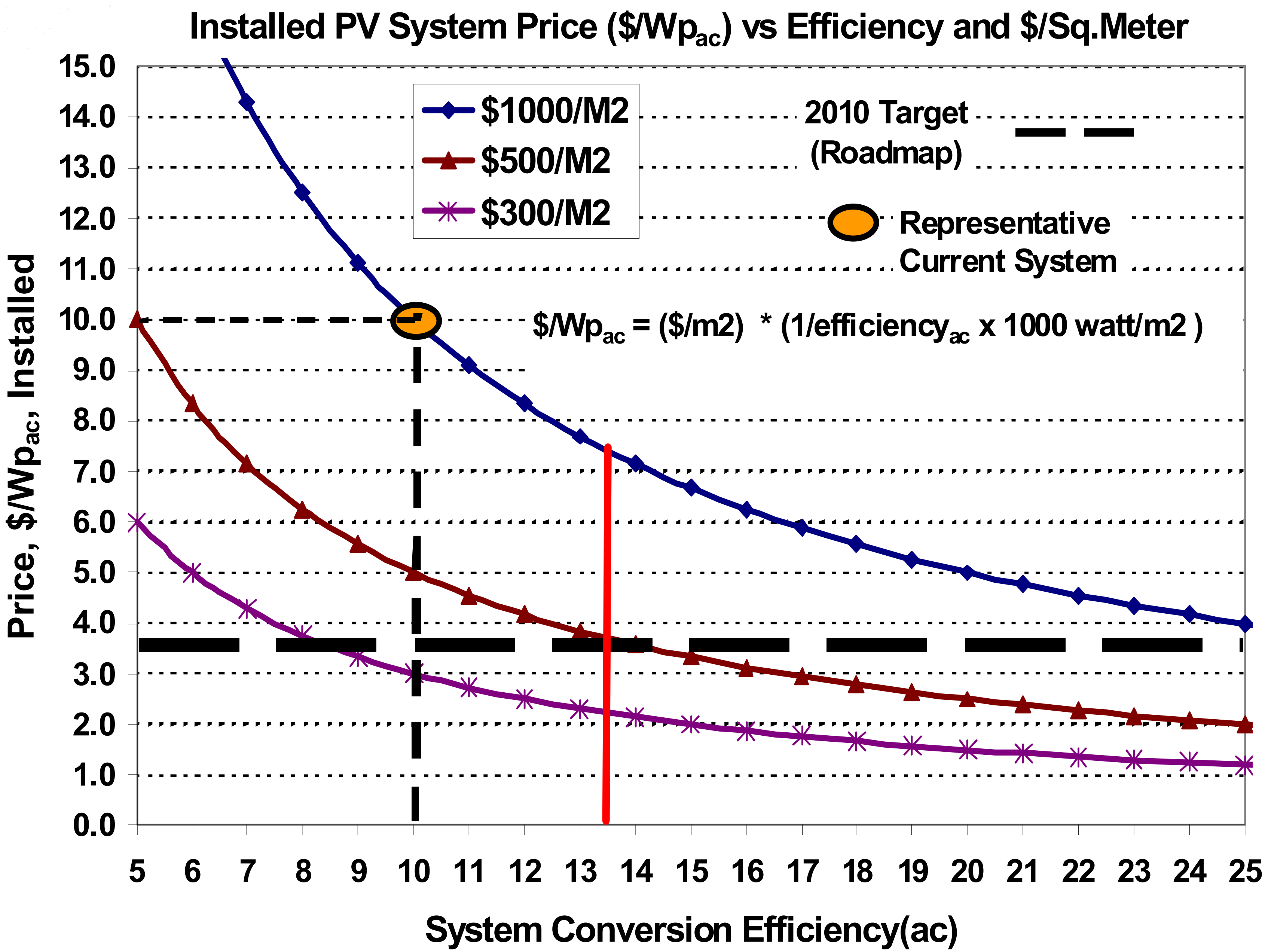
Information on subsidies for renewables by State.

Financial Model: Levelized Cost of PV Electricity $/kWh. EPRI TAG (Technical Assessment Guide).

EC= [FCR/8760*CF]*[INDC]*[A($MSQMD+$MSQBS+$KWBS]
+ A*G*CRF[$MSQOM/8760*CF]

Important System Characteristics and/or Subroutine Models

- **A= 1/(Average Insolation)*(System Efficiency)**
- **System Efficiency= (BOS Efficiency)*(Module Efficiency)**
- **$MSQMD: Module costs in $/sq.meter.**
- **$MSQBS: BOS area-related costs in $/sq.meter**
- **$KWBS: BOS power-related costs in $/kW**
- **$MSQOM: Annual operation and maintenance costs in $/sq.meter-year**
- **CF: Annual system capacity factor (ratio of energy produced divided by the product of peak capacity times the # of hours per year).**
- **CRF: Capital recovery factor..a function of discount rate and system lifetime.**



Installed PV System Price ($/Wp_ac) vs Efficiency and $/Sq.Meter
$1000/M2
$500/M2
$300/M2
2010 Target
(Roadmap)
Representative
Current System
$/Wp_ac = ($/m2) * (1/efficiency_ac x 1000 watt/m2)
Price, $/Wp_ac, Installed
System Conversion Efficiency(ac)
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
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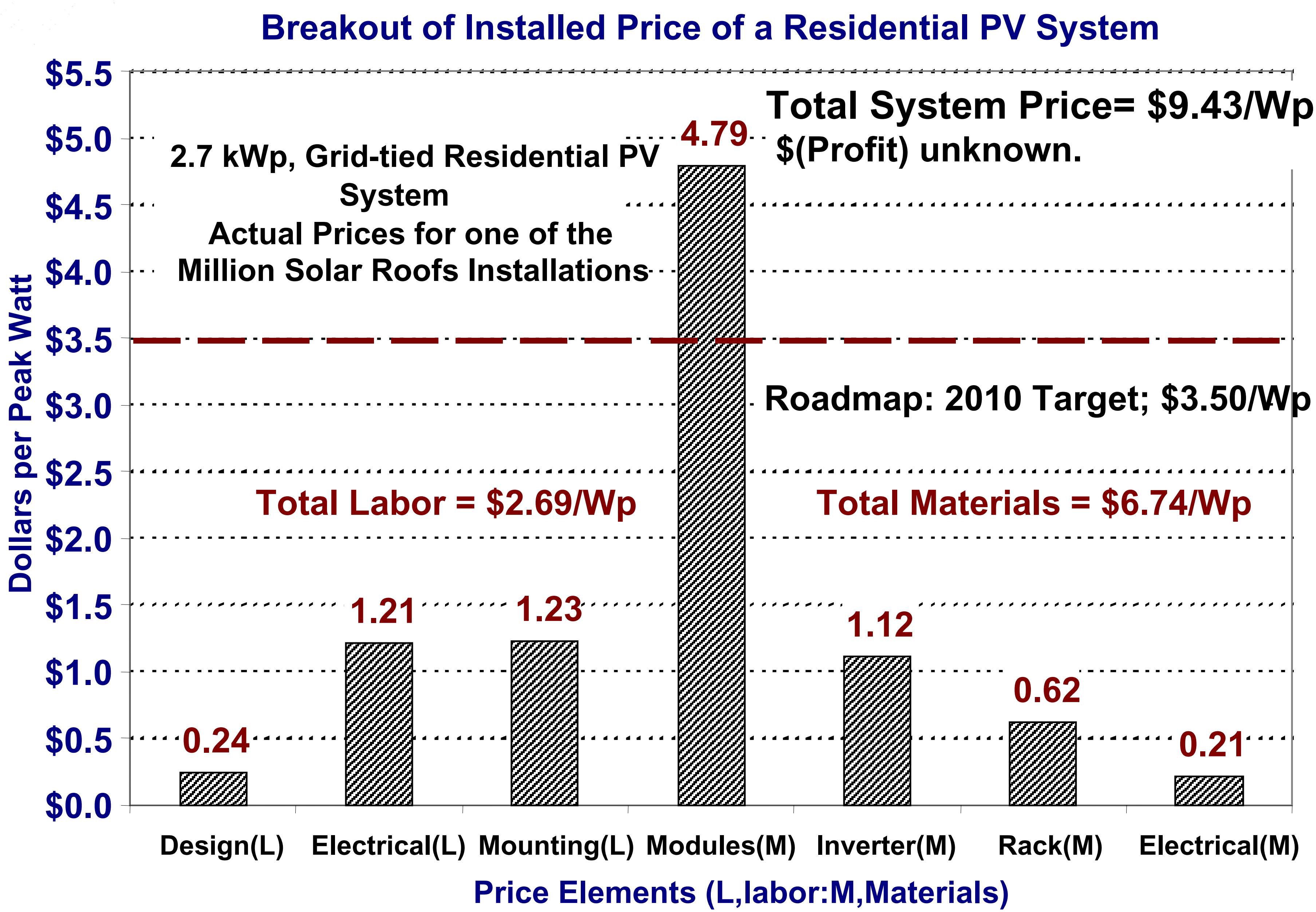
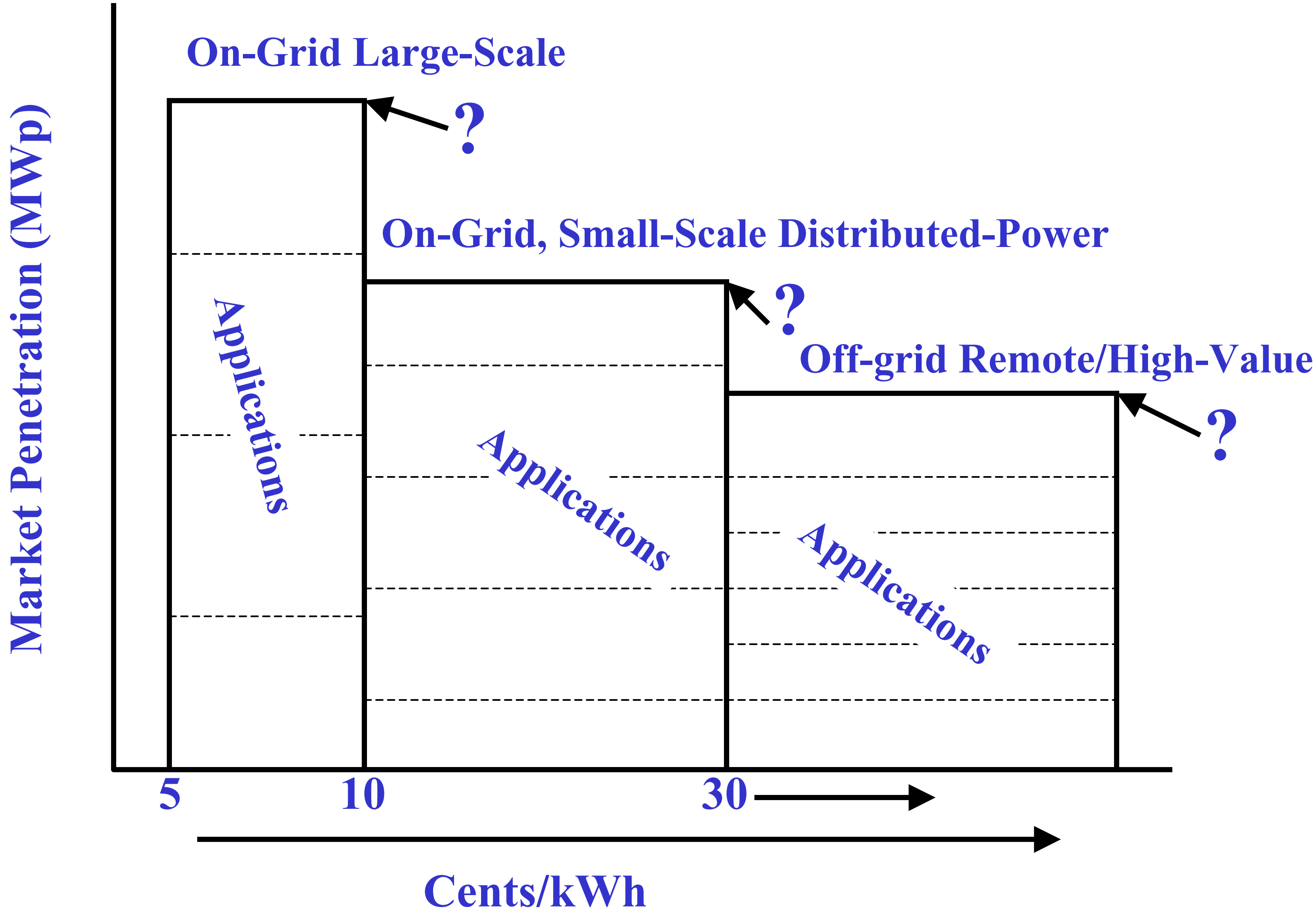


Breakout of Installed Price of a Residential PV System
Total System Price= $9.43/Wp
$(Profit) unknown.
2.7 kWp, Grid-tied Residential PV System
Actual Prices for one of the Million Solar Roofs Installations
Roadmap: 2010 Target; $3.50/Wp
Total Labor = $2.69/Wp
Total Materials = $6.74/Wp
$5.5
$5.0
$4.5
$4.0
$3.5
$3.0
$2.5
$2.0
$1.5
$1.0
$0.5
$0.0
Dollars per Peak Watt
0.24
1.21
1.23
4.79
1.12
0.62
0.21
Design(L)
Electrical(L)
Mounting(L)
Modules(M)
Inverter(M)
Rack(M)
Electrical(M)
Price Elements (L,labor:M,Materials)

Market Penetration Models/Tools

Concept of Goal of Market Penetration Analysis & Projections



Examples of Market Penetration Models

NEMS: (EIA)

Multi-region model for the U.S. energy economy, used for Annual-Energy-Outlook and other national energy analyses

MARKAL: IEA/Energy Technology Systems Analysis Programme

Developed over the past 20 years, used in over 40 countries. Addresses all "energy carriers"/primary-supplies, conversion & processing, and end-use demands. Optimization routine selects, from each of the sources, energy carriers, and transformation technologies to produce a least cost solution to user-defined goals/end-points.

SGM & MiniCam: PNNL

Long-range(2100), global energy models for climate change analysis. Very limited technology representation

Under Development: NREL

Detailed market penetration models for wind and PV that reflect actual market conditions, e.g. load-matching and peak values, intermittency, transmission requirements.

Industry/Investors: Proprietary

Detailed, usually technology/product specific, market(s) potential and sensitivity analyses used to support investment/development strategies (short and long-term).

PV "Advisor Model" ?