PV SYSTEMS

Today

- PV systems engineering
- Remote applications
- *(PV sizing)*

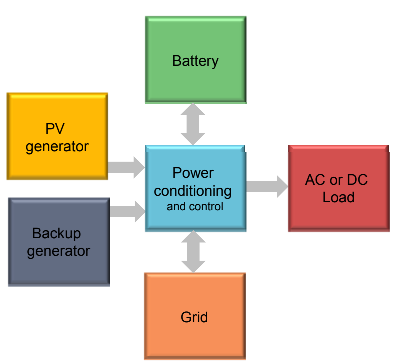
Extra class (6/11/2009: 2pm)

- Building integrated photovoltaics (BIPV)
- Concentration photovoltaics (CPV)

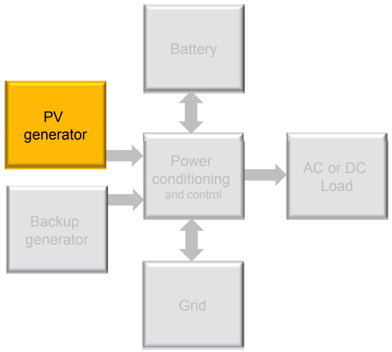
PV SYSTEMS

- PV generator
  - Mismatch and/or shading
  - Temperature effect
- Energy storage
  - Lead acid batteries
- Power conditioning and control
  - Charge controler
  - Inverter

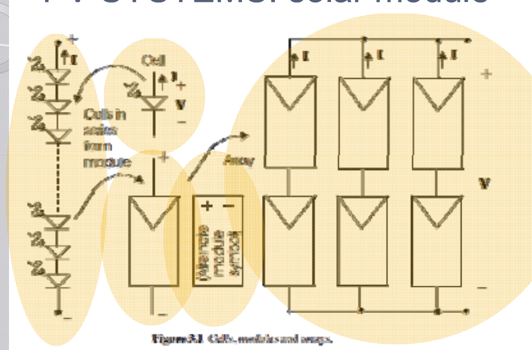
PV SYSTEMS



PV SYSTEMS



PV SYSTEMS: solar module



PV SYSTEMS: solar module

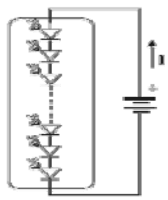
In a module, solar cells usually connected in **series**.

- For a 12V battery:
  - Not optimum irradiation: 16V
  - Fill factor (80%): 20V
  - Each cell (0.6V) x n = 20V

    n = 33-36 cells in series

PV SYSTEMS: solar module

When the PV module is not illuminated



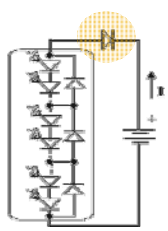
Example:
33 cells
Saturation current: 10-10A
Battery: 12.8V
Voltage across each cell: 12.8/33=388mV
Current: 0.32mA (use diode equation)

The battery will discharge during nightime!

More cells in series: lower voltage across each cell, lower reverse current

PV SYSTEMS: solar module

When the PV module is not illuminated



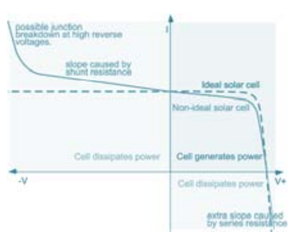
Example:
33 cells
Saturation current: 10-10A
Battery: 12.8V
Voltage across each cell: 12.8/33=388mV
Current: 0.32mA (use diode equation)

The battery will discharge during nightime!

More cells in series: lower voltage across each cell, lower reverse current
Or use a **blocking diode**

PV SYSTEMS: solar module

When **one cell** is not illuminated?

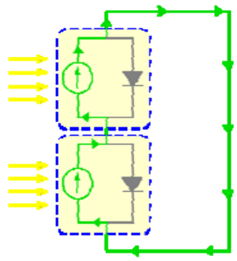


PV SYSTEMS: solar module

When **one cell** is not illuminated?

Matched solar cells in series:

Cells are in short circuit so:
- Current = Isc
- Voltage = 0V



PV SYSTEMS: solar module

When **one cell** is not illuminated?

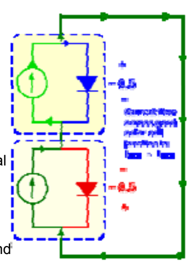
Mismatched solar cells:

Because series connection, current is dominated by 'poor' cell: $I = Isc_2$ ($< Isc_1$)

'Extra' current (Isc_1-Isc_2) flows through 'good' cell (forward bias).

The 2 cells are short-circuited so the total voltage is still 0V.

'Poor' cell becomes reverse bias and dissipates 'extra' current. If string is long one will get above breakdown voltage and then **hotspot!**



PV SYSTEMS: solar module

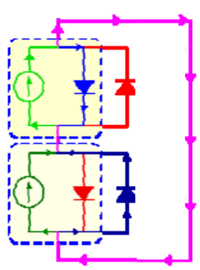
When **one cell** is not illuminated?

Mismatched solar cells, usind **bypass diode**

'Good' cell is forward bias and shaded cell is reverse bias.

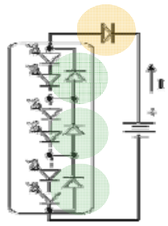
Bypass diode of the good cell is reversed biased (no effect).
Bypass diode of the shaded cell is forward bias and conducts current.

Shaded cell is reverse biased But only to about -0.5V, avoiding any hotspots.



PV SYSTEMS: solar module

Blocking and bypass diodes!



PV SYSTEMS: solar module

- Module parameters are defined for **standard conditions**
  - Irradiance: $1kW/m^2$
  - Spectral distribution: AM1.5
  - Cell temperature: 25ºC

PV SYSTEMS: solar module

- V_{oc} sensitive to cell temperature:

$$\frac{dV_{OC}}{dT} = -2.3 \times n \quad (mV/^{o}C)$$

- **Normal Operating Cell Temperature (NOCT)**
  - Irradiance: $0.8kW/m^2$
  - Spectral distribution: AM1.5
  - Ambient temperature: 25ºC
  - Wind speed: <1m/s
- The **cell temperature** T_c for a given ambient temperature T_a and irradiance G (kW/m^2) is:

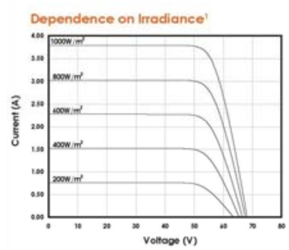
$$T_c - T_a = \frac{NOCT - 20}{0.8} G$$

PV SYSTEMS: solar module

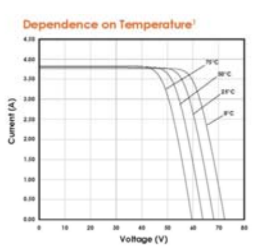
Electrical Specifications

Model	HIT Power 195 or HIP-195BA19
Rated Power (Pmax)[1]	195 W
Maximum Power Voltage (Vpm)	55.3 V
Maximum Power Current (Ipm)	3.53 A
Open Circuit Voltage (Voc)	68.1 V
Short Circuit Current (Isc)	3.79 A
Temperature Coefficient (Pmax)	-0.348% / °C
Temperature Coefficient (Voc)	-0.189 V / °C
Temperature Coefficient (Isc)	1.96 mA / °C
CEC PTC Rating	181.1 W
Cell Efficiency	19.3%
Module Efficiency	16.8%
Watts per Ft.[2]	15.6 W
Maximum System Voltage	600 V
Series Fuse Rating	15 A
Warranted Tolerance (-/+)	-0% / +10%

PV SYSTEMS: solar module



PV SYSTEMS: solar module



PV SYSTEMS: solar module

Mechanical Specifications

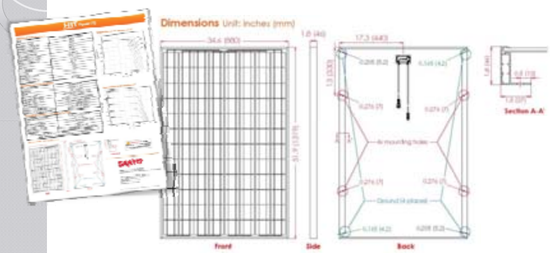
Internal Bypass Diodes	4 Bypass Diodes
Module Area	12.49 Ft.² (1.16m²)
Weight	33.07 Lbs. (15kg)
Dimensions LxWxH	51.9x34.6x1.8 in. (1319x880x46mm)
Cable Length -Male/+Female	30.7/24.8 in. (780/630mm)
Cable Size / Connector Type	No.12 AWG / MC4™ Locking Connectors
Static Wind / Snow Load	60PSF (2880Pa) / 39PSF (1867Pa)
Pallet Dimensions LxWxH	53x35x77 in. (1346x897x1952mm)
Quantity per Pallet / Pallet Weight	34 pcs. / 1166 Lbs. (530kg)
Quantity per 20', 40', and 53' Container	340 pcs., 714 pcs., 918 pcs.

Operating Conditions & Safety Ratings

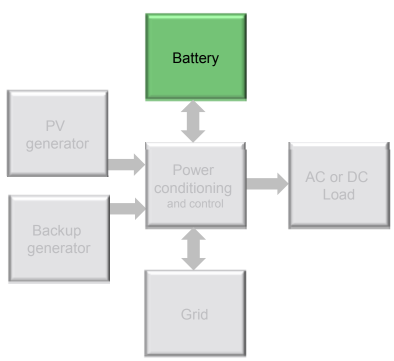
Ambient Operating Temperature	-4°F to 115°F (-20°C to 46°C)²
NOCT	113°F (45°C)
Hail Safety Impact Velocity	1" hailstone (25mm) at 52 mph (23m/s)
Fire Safety Classification	Class C
Safety & Rating Certifications	UL 1703, cUL, CEC
Limited Warranty	5 Years Workmanship, 20 Years Power Output

[1]STC: Cell Temp. 25°C, AM1.5, 1000W/m² [2]Monthly average low and high of the installation site.
Note: Specifications and information above may change without notice.

PV SYSTEMS: solar module



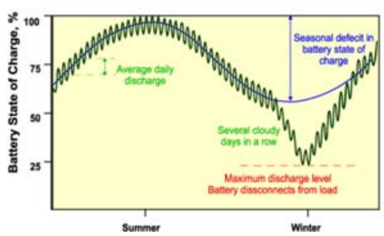
PV SYSTEMS



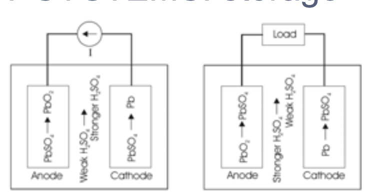
PV SYSTEMS: storage

Energy stored	Technology	Remarks
Mechanical	Pumped water	PV pumping; or Large-scale storage solution
	Compressed air	Large-scale storage solution
	Flywheel	Under development for small (short) systems
Electromagnetic	Electric current in superconducting ring	Potentially interesting for 'high temperature' superconductors
Chemical	Batteries	Most common for PV
	Hydrogen	Under development

PV SYSTEMS: storage



PV SYSTEMS: storage



a. Charging process   b. Discharging process

CHARGING

Anode: $PbSO_4 + 2H_2O \rightarrow PbO_2 + 4H^+ + SO_4^{2-} + 2e^-$

Cathode: $PbSO_4 + 2e^- \rightarrow Pb + SO_4^{2-}$.

DISCHARGING

Anode: $PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$

Cathode: $Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$.

PV SYSTEMS: storage

- **Gassing** – when overcharged, hydrogen ions combine with free electrons and are converted into gaseous hydrogen
- **Sulphatation** – formation of large lead sulphate crystals at the plate
- **Stratification** – non-uniform electrolyte distribution
- **Electrode corrosion** – accelerated at higher temperatures

PV SYSTEMS: storage

AVOID OPERATION...	TO PREVENT...
High voltages during charge	Corrosion, water loss
Low voltages during discharge	Corrosion
Deep Discharge	Sulphation, dendrite growth
Extended period w/o fully carge	Sulphation
High temperature	All ageing processes
Stratification of the electrolyte	Sulphation
Very low carge current	Sulphation

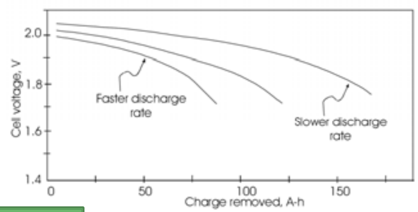
PV SYSTEMS: storage

Charging/discharging should be reversible, but there are **losses**:

- Internal resistance loss (IR^2): lower performance for higher currents (also depends on operating temperature)
- Hydrogen escape = energy loss

Overall efficiency: **~90%**

PV SYSTEMS: storage



Higher C/x means
Higher currents thus
Higher heat losses and
Less useful energy

Battery capacity: C
Battery (dis)charge rate: C/x

R. Messeger *Photovoltaic System Engineering*, 2nd Ed. (2003) CRC Press, Washington

PV SYSTEMS: storage

- Warm batteries are capable of storing more charge than cold batteries

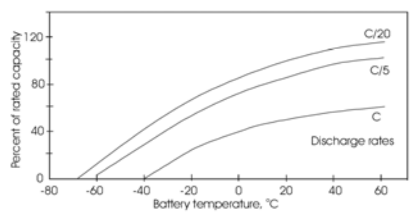


Figure 3.12 Effect of temperature and discharge rate on available energy from a lead-acid battery.

R. Messeger *Photovoltaic System Engineering*, 2nd Ed. (2003) CRC Press, Washington

PV SYSTEMS: storage

- Lifetime sensitive to depth of discharge

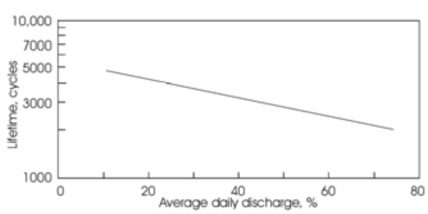
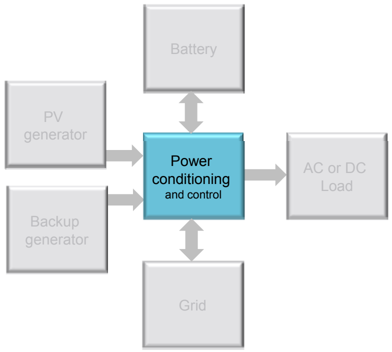


Figure 3.13 Lead-acid battery lifetime in cycles vs. depth of discharge per cycle [1].

R. Messeger *Photovoltaic System Engineering*, 2nd Ed. (2003) CRC Press, Washington

PV SYSTEMS: control



PV SYSTEMS: control

Charge regulator

- Load disconnect/reconnect voltage
  - User satisfaction *vs* battery lifetime

    may acommodate warming signal (30' in advance) and/or "manual bypass" for special occasions
- End-of-charge/Reposition voltage
  - full charge (high V) *vs* corrosion and water consumption (low V)
- Protection against reverse current leakage

PV SYSTEMS: control

- Adjusting the load to the PV system point of maximum power

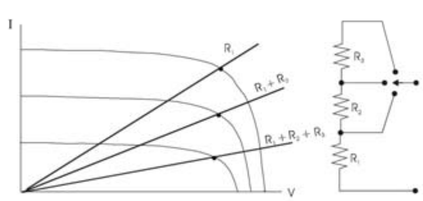


Figure 3.17 Varying a resistive load to track maximum power from a PV array.

PV SYSTEMS: control

Maximum power tracker

(DC/DC converter)

- Ensures maximum power transfer to load

$$V_R = \sqrt{P_{max} R}$$

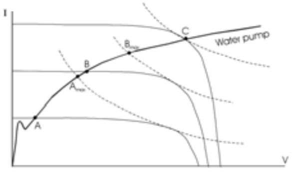


Figure 3.27 Pump and PV I-V characteristics, showing the need for use of MPT.

R. Messeger *Photovoltaic System Engineering*, 2nd Ed. (2003) CRC Press, Washington

PV SYSTEMS: control

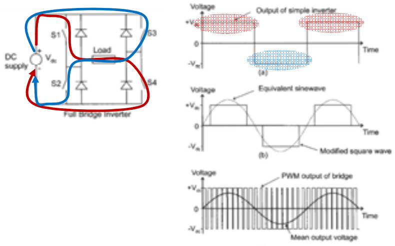
Inverter

(DC/AC converter)

- Variable frequency for PV pumping systems
- Self-commutating fixed frequency for isolated distribution grid
- Line-commutated fixed frequency for grid connection applications

PV SYSTEMS: control

Inverter



PV SYSTEMS: control

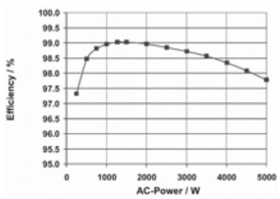
Inverter

- Inverter efficiency: $\eta = P_{AC} / P_{DC}$

To make comparison of different inverters and/or inverters that are operating under different climatic conditions possible:

$$\eta_{EURO} = 0.03\times\eta_{5\%} + 0.06\times\eta_{10\%} + 0.13\times\eta_{20\%} + 0.10\times\eta_{30\%} + 0.48\times\eta_{50\%} + 0.20\times\eta_{100\%}$$

(Efficiency index = percent of rated power)



REMOTE APPLICATIONS

- PV economics
- Rural electrification
- Water pumping
- Health care systems
- Other remote applications

PV ECONOMICS

- High capital cost
- No fuel cost
- Low maintenance cost
- High reliability (= low replacement cost)
- System output depends on location

PV ECONOMICS

- **Life cycle cost**: sum of all costs over lifetime, at today's money
- **Payback time:** time it takes for total cost to be paid for by system benefits/revenues
- **Rate of return:** magnitude of benefits expressed as a percentage on initial investment

PV ECONOMICS

- **Period of analysis:** lifetime of longest lived system under comparison
- **Excess inflation (i):** rate of price increase above (or below) general inflation
- **Discount rate (d):** rate (relative to inflation) at which money would increase in value if invested
- **Capital cost:** total initial cost
- **Operation and maintenance:** amount spend yearly in keeping system operational
- **Fuel costs:** annual fuel bill
- **Replacements costs:** cost of replacing each component at the end of its lifetime.

PV ECONOMICS

M. Kolhe, S. Kolhe, J. C. Joshi, *Economic viability of stand-alone solar photovoltaic system in comparison with diesel-powered system for India* , Energy Economics, **24**:2 (2002)155-165

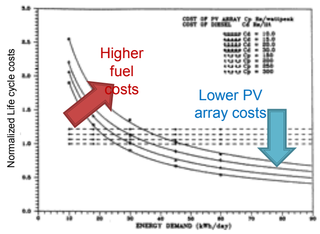


Fig. 3: PV and diesel system life-cycle cost comparisons for different PV array and diesel cost as a function of energy demand.

PV ECONOMICS

M. Kolhe, S. Kolhe, J. C. Joshi, *Economic viability of stand-alone solar photovoltaic system in comparison with diesel-powered system for India* , Energy Economics, **24**:2 (2002)155-165

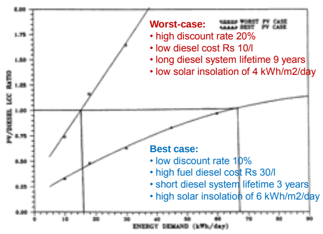


Fig. 4: Sensitivity to PV and diesel system life-cycle costs to the best and worst PV conditions as a function of energy demand.

RURAL ELECTRIFICATION

- Lighting and power supply for remote buildings (mosques, farms, schools, mountain huts, etc.)
- Remote villages
- Battery charging stations
- Portable power for nomads

RURAL ELECTRIFICATION

Different **deployment strategies**

- Donations
- Cash sales
- Consumer credit
- Fee-for-service

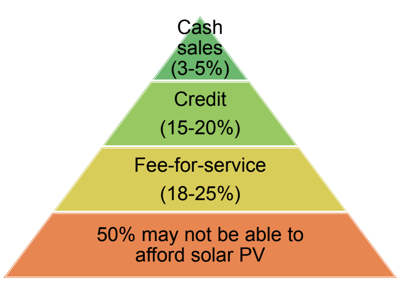
RURAL ELECTRIFICATION

- **Donations**
  - ✓Low initial cost for user
  - ✓Economies of scale
  - ✓Rapid deployment
  - ✘Lack of user commitment
  - ✘No funding for maintenance/replacements
- **Cash sales**
  - ✓User choice
  - ✓User commitment
  - ✓'Modular' purchasing
  - ✘Cheap/low quality/undersized components
  - ✘High- and middle class access only

RURAL ELECTRIFICATION

- **Donations**
  - …
- **Cash sales**
  - …
- **Consumer credit**
  - Dealer extended credit or micro-credit
- **Fee-for-service**
  - Economies of scale

RURAL ELECTRIFICATION



Data from: M.T. Eckhartet al *Financing PV growth*, Chpt 24 in *Handbook* …, Ed. A. Luque, S. Hegedus, John Wiley & Sons, USA (2003)

RURAL ELECTRIFICATION

- **Model deployment: 2 case studies**
  - Kenya – Cash sale
  - Zambia – Fee-for-service (ESCO)

SHS: Solar Home Systems

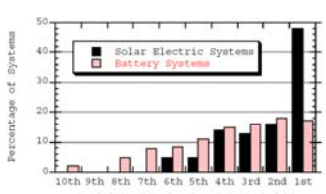
Cash sales deployment model

Technology type	Median wealth rank	Typical initial cost ($US)	Cost per kWh ($US/kWh)
Solar electric system	10%	200-600	0.25-1.0
Rural grid connection	17%	50-1500	0.08
Lead acid battery system	29%	50-100	1.0-1.5
Dry cell batteries	46%	5-30	50-100
Kerosene lighting	50%	2-20	n/a

A. Jacobson, *Connective Power: Solar Electrification and Social Change in Kenya*, PhD Thesis, University of California, Berkeley (2004)

SHS: Solar Home Systems

Cash sales deployment model



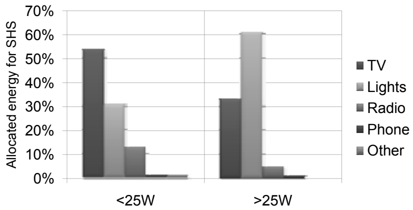
- Solar electrification market in Kenya is driven by the purchasing power of the rural middle class, in particular rural teachers (30%)
- 'Modular' deployment: one gets a battery before buying a small PV module

A. Jacobson, *Connective Power: Solar Electrification and Social Change in Kenya*, PhD Thesis, University of California, Berkeley (2004)

SHS: Solar Home Systems

Cash sales deployment model

- Main use of small SHS is TV! Light comes 2nd choice – only for 'larger' systems



A. Jacobson, *Connective Power: Solar Electrification and Social Change in Kenya*, PhD Thesis, University of California, Berkeley (2004)

SHS: Solar Home Systems

Cash sales deployment model

- Low quality equipment

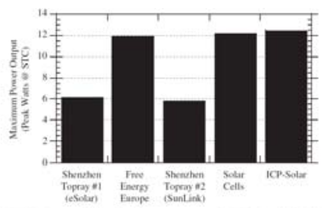


Fig. 5. Average stabilized maximum power output for five brands of 14 W rated amorphous silicon solar modules sold in Kenya. (Maximum Power at Standard Test Conditions, STC, of 1000 W/m^2 and 25 °C.)

A. Jacobson, D.M. Kammen, *Evaluating product quality in the Kenyan solar photovoltaics industry*, Energy Policy 35 (2007) 2960-2968

SHS: Solar Home Systems

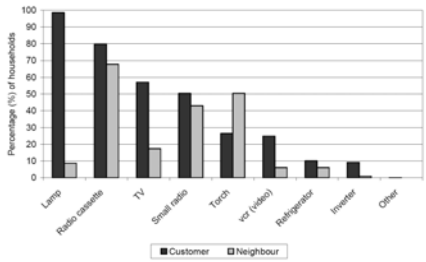
Fee-for-service deployment model

- **Access to SHS service**
  - 90% of households have 'formal income' (teachers, etc)
  - Better light quality but not cheaper
- **'Standard 'package':**
  - 50Wp module + battery + charge regulator
  - Equipment quality below specs (e.g. Siemens batteries)
- **Moderate/low rate of income-generation**
  - 13% willing to start a new activity enabled by SHS
  - most popular: shop
- **'Solar trap'**
  - Protests over long-term exclusion from grid connection

M. Gustavsson, *Solar Energy for a Brighter Life - A Case Study of Rural Electrification through Solar Photovoltaic Technology in the Eastern Province, Zambia*, PhD Thesis, University of Goteborg (2008)

SHS: Solar Home Systems

Fee-for-service deployment model



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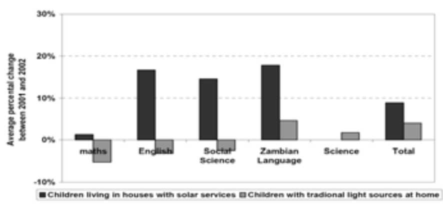
SHS: Solar Home Systems

Fee-for-service deployment model



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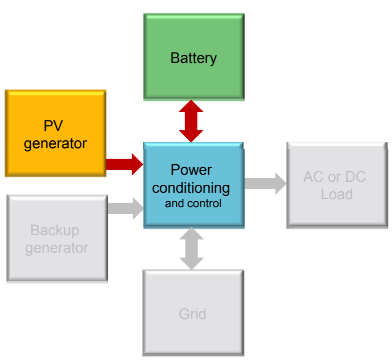
SOLAR HOME SYSTEMS



SOLAR HOME SYSTEMS

- Certified PV modules (no need for bypass diode)
- Support structures
  - at least 10 years of outdoor exposure
  - withstand winds of 120 km/h
- Tilt angle: latitude ± 10º
- Manual tracking: 2-3 positions/day, moving from East to West)
  - ✓ (Slight) performance improvement
  - ✓ Promotes user participation
  - ✘ Risk of damage
  - ✘ Risk of energy loss due to poor or no adjustment

"Universal technical standard for solar home systems" Thermie B SUP 995-96, EC-DGXVII, 1998

SOLAR HOME SYSTEMS

- Automotive batteries (SLI)
  - ✓ Cheap
  - ✓ Widely available
  - ✓ Locally produced
    - Economic & socially convenient
    - Recycle
  - ✘ Short lifetime
    - use larger capacity
    - use lower electrolyte density (1.24 instead of 1.28g/cl)
    - replace thin electrodes (>2mm)

SOLAR HOME SYSTEMS

- Maximum **depth of discharge**:
  $0.3 < Depth_{max} < 0.6$
- **Useful capacity** (C_U) < Nominal capacity (C_B)
  $C_U = C_B \times Depth_{max}$
- C_U = 3-to-5 days x daily energy consumption
  *Depth of discharge in **daily cycle**:*
  $0.06 < Depth < 0.2$

SOLAR HOME SYSTEMS

- $Depth_{max}$ = 0.3-0.5
- n x Load / $Depth_{max}$ < C_B

Load = 12 Ah
Dry place: n = 3 days
Isc = 3.3 A
C: 72 Ah < C_B
R: 120 Ah < C_B

Load = 12 Ah
Wet place: n = 5 days
Isc = 3.3 A
C: 120 Ah < C_B
R: 200 Ah < C_B

• NOC (number of cycles before residual capacity less than 80% CB) > 200
• Self discharge < 6%/month

SOLAR HOME SYSTEMS

- Voltage losses:
  - PV modules → charge regulator < 3%
  - Battery → charge regulator < 1%
  - Charge regulator → load < 5%
- Minimum section of copper cable (12V)

  $S(mm^2) = 0.3 \times length\ (m) \times I_M(A) / \Delta V(\%)$

SOLAR HOME SYSTEMS

- Energy performance
  - Loss of load probability (LLP)
  - Performance ratio(= useful energy / max theoretical energy)

    includes losses in module (temperature, mismatch), self consumption of charge regulator, battery efficiency, etc.
- Energy requirement (typical)
  - 40-50Wp
  - 120-160Wh/day

  Lighting, radio, TV

  (for refrigerator, fans, etc, larger systems required)

SOLAR HOME SYSTEMS

- Sizing:
  - PV generator capacity
    $CA = \eta\ A\ Gd / L$
  - Storage capacity (days)
    $CS = CU / L$

η – efficiency
A – Area
Gd – daily irradiation
L – (load) daily consumption
CU – useful battery capacity

- Rules of thumb
  - Energy produced during worst month can, at least, equal demand of the load (CA = 1)
  - Battery useful capacity should allow 3-to-5 days of autonomy (3 < CS < 5)

SOLAR HOME SYSTEMS

Proper sizing using Loss-of-load-probability method (LLP)

- R. Posadillo, R. López Luque, *Approaches for developing a sizing method for stand-alone PV systems with variable demand,* Renewable Energy 33:5 (2008)1037-1048
- E. Lorenzo, *Energy collected and delivered by PV modules,* in Handbook of Photovoltaic Science and Engineering, ed. A. Luque , S. Hegedus (2003)

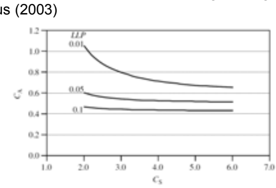


Figure 20.23 Reliability maps: Generator capacity C_A versus storage capacity C_S with the reliability *LLP* as parameter

SOLAR HOME SYSTEMS

- No shadows on modules, at least 8h/day, centred at noon, all year
- Pedestal mounting preferable
- If on roof: 5cm gap for air circulation
- Battery locked but accessible
- And…
  - Avoid different bolts/screws to minimise tools
  - Use fluorescent tubes available locally
  - All materials (screws, connectors, etc) in SHS kit
  - etc.

SOLAR HOME SYSTEMS

Flexibility:

- Any component may be substituted by similar component (even from different supplier)
- Increasing system size:
  - PV modules in parallel (check wiring sizes and regulator maximum current)
  - Batteries in parallel?
    - Not more than 2 identical batteries
    - Old and new batteries OR 2 non-identical batteries may not be connected in parallel

WATER PUMPING

- Pumping for drinking water
- Pumping for irrigation
- De-watering and drainage
- Ice production
- Saltwater dessalination
- Water purification
- Water circulation in fish farms

WATER PUMPING

- Solar pumps
  - Hydraulic energy (kWh/day) =

    = volume required (m^3/day) x head (m) x water density x gravity

    = 2.725 x 10^{-3} x volume required (m^3/day) x head (m)
  - Solar array required (kWp) =

$$\frac{\text{Hydraulic energy (kWh/day)}}{\text{Average daily solar irradiation (kWh/m}^2\text{/day) x F x E}}$$

F (mismatch factor) = 0.85

E (subsystem efficiency) = 0.25 – 0.4

Example
25m^3/day
20m head
requires 800Wp
at Sahel

Sizing example: W. Stuart, *Applied Photovoltaics*., London, Earthscan Publications (2006) Appendix H

WATER PUMPING

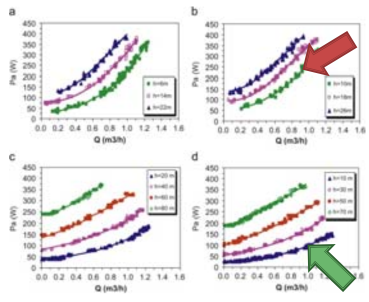


Fig. 3. Electrical power versus flow rate: (a) and (b) centrifugal pump, and (c) and (d) displacement pump.

A. Hamidat and B. Benyoucef, *Systematic procedures for sizing photovoltaic pumping system using water tank storage*, Energy Policy 37:4 (2009) 1489-1501

WATER PUMPING

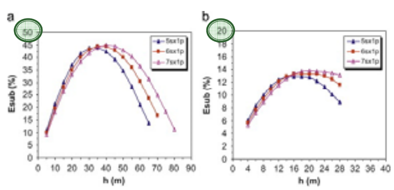


Fig. 4. The subsystem efficiency, the peak power of the photovoltaic array:
(a) DC motor with a positive displacement pump and (b) AC motor with a centrifugal pump.

A. Hamidat and B. Benyoucef, *Systematic procedures for sizing photovoltaic pumping system using water tank storage*, Energy Policy 37:4 (2009) 1489-1501

WATER PUMPING

- Maximum point tracker:
  DC/DC converter to track pump input I/V

Figure 3.27 Pump and PV I-V characteristics, showing the need for use of MPT.

R. Messeger *Photovoltaic System Engineering*, 2nd Ed. (2003) CRC Press, Washington

HEALTH CARE SYSTEMS

- Lighting in rural remote clinics
- UHF transreceivers between health centres
- Vaccine refrigeration
- Ice pack freezing for vaccine carriers
- Sterilisers
- Blood storage refrigerators

OTHER REMOTE APPLICATIONS

- Remote communications: Radio repeaters, Remote TV & radio receivers, Mobile radios, Emergency phones
- Remote weather measuring
- Earthquake monitoring
- Road sign lighting
- Navigations buoys
- Boat power supply
- Corrosion protection systems
- Calculators

SOLAR HOME SYSTEMS

Further reading

- E. Lorenzo, *Photovoltaic Rural Electrification,* Progress in Photovoltaics: Research and Applications, 5:1 (1997) 3-27
- J.M. Huacuz, L. Gunaratne, *Photovoltaics and development* in Chpt 23 in Handbook of Photovoltaic Science and Engineering, Ed. A. Luque, S. Hegedus, John Wiley & Sons, USA (2003)
- "Universal technical standard for solar home systems" Thermie B SUP 995-96, EC-DGXVII, 1998
- M. Gustavsson, *Solar Energy for a Brighter Life - A Case Study of Rural Electrification through Solar Photovoltaic Technology in the Eastern Province, Zambia,* PhD Thesis, University of Goteborg (2008)
- A. Jacobson, *Connective Power: Solar Electrification and Social Change in Kenya,* PhD Thesis, University of California, Berkeley (2004)
- M. Bond, R.J. Fuller and Lu Aye, *A policy proposal for the introduction of solar home systems in East Timor,* Energy Policy, 35:12(2007) 6535-6545