PV Systems: Stand alone (SA) vs Grid Connected (GC)

• Very different design philosophy
• SA: availability key issue
  – Very complicated analysis, design, operation (interactions)
  – Worst case, longest cloudy period
  – Reliability (PV, diesel gen, storage) vs $
  – Loss of Load Probability (LLP)
    • LLP(%)= 100 - (% availability)
  – **Key parameter: Amp-hours @V_{BAT}**
  – Hybrid (diesel) for larger loads, hi reliability
• GC: annual or daily peak power
  – Total annual or offset peak power
  – **Key parameter: annual kW-hours**
  – LLP no concern, grid is backup, no power if grid down
2 Stand alone (SA) PV Systems with battery

FIGURE 2-3
A schematic of a basic DC stand-alone system in which the PV array is connected to the load and the battery bank via a voltage regulator.

FIGURE 2-4
A schematic of an AC/DC stand-alone PV system equipped with a voltage regulator, battery storage, and a DC-to-AC inverter.
2 Grid connected (GC) PV Systems

FIGURE 2-5
A schematic of an AC/DC stand-alone PV system with a voltage regulator, battery storage, an inverter, an auxiliary generator, and a battery charger.

FIGURE 2-7
A schematic of a utility-interactive PV system, which employs a power conditioner designed to make the power produced by the array compatible with that available on the utility grid.

Power Cond = inverter, MPT, display
Components (BOS) red=grid connected

- Charge controller (CC); “regulator”
  - Charge/discharge battery; regulates $V_{BAT}$
  - Protect over-charge/discharge
  - May have MPPT (Max Power Tracker, electronic psuedo load)
- Inverter (dc $\Rightarrow$ ac)
  - Modified square wave (limited appliances) or sine
  - Efficiency 85-95%
  - May have MPT and/or CC
  - GC or SA very different: synched to grid vs self-generating ac
- Batteries (efficiency=80-90%)
- Diesel generator
- Fuses, mounting rails, posts, wiring, ground rod, disconnects, smart system monitor
- NB: MPPT Tracking is electronic, 1-2 axis tracking is mechanical, they are totally different concepts, same term, same goal (max PV output)
**Grid connected sizing and goals**

- Very different from stand alone; grid is back-up
- Either max PV you can afford or max you can fit on roof
- Premium on efficiency; max output per area; not Thin Film
- Partial offset house load, typically not net PV energy
- Net metering: utility buys back at same price up to load
  - Rarely send you check if net positive energy (PV>load)
- Fixed tilt PV array, inverter (MPT), fuses, dc+ac switch
  - Data display/data log, second spinning meter
- Aesthetics (color, form factor, stand-off)
- Higher T since less circulation (stand-off)
- Few systems w/battery to store excess, backup select loads
  - Improve reliability, security, grid to charge/equalize battery
  - Increase cost, complexity, either 2 inverters (SA+GC) or few combo
Under federal law, utilities must allow independent power producers to be interconnected with the utility grid, and utilities must purchase any excess electricity they generate. - U.S Department of Energy
Residential PV project Gardner MA (mid 1990s)
2 kW grid connected to study PV-utility interaction
3 kW PV per apartment (Netherlands)
Track the sun: 1 and 2 axis flat plate and concentrator (APS)
Grid connection issues (<10 kW)

• Inverter/interconnection
  – Typically 240V AC output to interface with residential grid input
  – Codes: IEEE 929-2000, NEC Art. 690
  – Power quality, “islanding”, grounding
  – Line voltage: $88\% < V_{AC} < 110\%$ else inverter shut down <2sec
  – Freq: $59.3 < f < 60.5$ Hz, no dc
  – Off > 5 min after disturbance
  – Negligible EM interference
  – Component ground, GFI, disconnects

• Metering: where is PV connected
  – Util. side: no direct benefit to customer, (utility owns PV)
  – Cust. side: complicated (offset load); different financial arrangements
  – Answer: net metering (>35 states); not all meters allow 2-way
Grid connection issues (<10 kW)

• Net metering: billing agreement
• Interconnection: tech and legal issues
  – UL approved components, no inspectn<10 kW
  – Utility can req insurance, inspect conditional period, many barriers
  – Can deny power export to grid exceeding some limit (<100 kW)
• Customer side:
  – Rebate( $/kW), net meter offset kW-hr charges, 25-50% common
  – Tariff: Util pay **higher** $/kWhr (Germany 20 yr; NJ, CA new)
  – Encourages customer to maintain interest, output, quality assurance
  – verify ac performance; data log/display; both load and PV
  – Accumulate green RECs; bundle with other users; sell to util/corp
Inverter-to-PV: sizing factor

Common to undersize inverter $SF = \frac{P_{\text{INV}}}{P_{\text{PV}}}$

- Inverters $800/kW$, much cheaper than PV, so not cost

PV DC power rarely operates at rated (PR=0.8-0.9)

But sometimes PV exceeds inverter rating

Inverter thermal protection avoid damage

$SF = 70-150\%$ allow inverter limit losses <1% many locations

Limited choice of inverter sizes; cost effective for SF<1
Inverter-to-PV: sizing factor, meas vs calc

Top L: am (squares) pm (triangle)
Top R: Vdc for SF=55%
Bot R: Vdc for SF=100%
Effect of oversizing PV

MPPT increases $V$, move out on I-V curve, limit $P=\text{constant}$
Decrease $P$ even more to protect inverter from overheating
Large scale PV systems (>500 kW)

- Few in 80-90’s: demonstration, learning experience
- Unrealistic costs
  - Lower: Subsidized by utility/govt
  - Higher: data acq, worker facilities, testing new hardware, intentional variations
- Peak shaving or distributed generation
- Fixed tilt, 1 or 2 axis tracking
- Lessons learned (PVUSA)
  - PV: very low failure rate (<0.1%)
  - Inverter (PCU): high failure rate (but this was <2000)
  - Minimize on-site assembly
Utility PV Performance Evaluation

- Three parameters to characterize performance
  - See articles by Marion et al or Moore et al

- Reference Yield = solar resource for tilt, location
  - $Y_R = \text{plane of array (POA) irradiance/(1 kW/m}^2\text{)}$ in kWhrs/kW
  - Independent of PV size, temperature, dirt etc

- Final Yield = #hours at $P_{\text{STC}}$ to produce actual $E_{\text{AC}}$
  - $Y_F = \text{net ac energy/} P_{\text{STC}}\text{ in kWhrs/kW}$
  - Depends on inverter eff, wiring, temp, dirt, not sunlight

- Performance Ratio = $Y_F/Y_R = E_{\text{AC}}/(P_{\text{STC}} * \text{hrs POA})$
  - Actual vs expected energy
  - Independent of tracking, tilt, location (sunlight)
  - Depends on system performance, temp, dirt, invert eff, downtime
  - Equivalent to the “derating factor” used in my residential PV example
  - PR = 0.65-0.85 reported
**PVUSA: PV for Utility Scale Appls. (1986-?)**

- Utility/DOE/EPRI program to gain experience with PV
  - procurement, acceptance, rating, BOS, construction, safety, performance, AC qual., reliability, O+M, noise

- Two levels of installations
  - Emerging tech: <15kW
  - Mature tech: 100-500 kW
  - Total: 1800 kW, >35,000 modules

- With >15 yrs experience, summarized 2001
  - Output always < rated due to higher T
    - “PTC” replace STC; T @20°C+NOCT, not 25°C
  - PV/BOS cost was 50/50
  - Maintenance 1c/kWh (<<w/ more experience)
  - Module failure <0.1%
  - Inv. (dc/ac) efficiency=92±4%
  - Cap. Fac.= 10%(Win), 30%(Sum)
  - Delivery, installation time >> expected
Present day utility scale PV systems

- PR=0.75-0.85
- O+M costs 10X lower than PVUSA
- Increased PR and lower costs compared to residential or commercial rooftop
  - Higher voltage, higher eff inverters, lower installation $
  - TEP: $5/W for MW scale, $7/W residential
- Inverter reliability greatly improved
- $F (_{AC}/_{STC})$
  - Germany 900-1100 fixed, 1700 2 axis tracking
  - Arizona 1600-1700 fixed, 2000 1 axis track at tilt
Utility arrays: fixed or single N-S tracking
Carrisa Plains (CA): world’s 1st large PV site

- ARCO: supply PV/owner/installer, PG&E buyer
- 1984-85: ~ 5.5 MW
- 114,000 40W c-Si modules, 175 acre
- 760 2-axis trackers
- 90% w/ side reflector, 10% w/o
- Eff: 10.5% (1984), decrease to 8.5% (1987)
  - Encapsulant yellowing only w/ side reflectors
  - High temp degrade EVA plastic coating
  - Good lessons for PV industry/util.
- Disassembled, PV modules sold off
  - Worth more than energy they generated
PG+E peak shaving

• 2-axis tracking Cap Factor CF=30%
• PG&E redefined CF for peaking
  – 12:30-6:30 pm, May-Oct.
  – PV: 0, 30, 60° from due South
  – 60° best, close to 2 axis tracking
  – CF near 80%!! (when redefined for peak shaving period)
  – Shows that performance depends on definition of goal
Recent utility experience: Arizona Pub Serv

- 5 MW PV installed 1998-2003; 49 systems: 2-220 kW
- Fixed horizontal and latitude; 1 axis track horiz and lat tilts
- Metric #1: Annual Yield=$\text{kWhr}_{\text{AC}} / \text{kW}_{\text{DC}}$
  - Fix Horiz/Fix Lat/Track Horiz/Track Lat=1.0/1.11/1.37/1.52
- Metric #2: Annual Perf Ratio PR= $\text{kWhr}_{\text{AC}} / (\text{STC kW}_{\text{DC}} \times \text{hrs @1 sun})$
  - relates STC rated DC power and avg sunlight to actual AC power
  - Effect of T, dust, wiring, inverter eff,
  - PR=0.60-0.70 over 5 years for all 4 types of installation (tilt/ tracking)
- Actual costs (site prep, installation, etc); no finance, rebate
  - Fix Lat <10 kW: $7/W constant over 5 years
  - Tracking Horiz >90 kW: decreasing $8/W to $6/W ovr 5 years
  - O+M costs for track horiz: 0.35% of installed costs
- Conclude horiz tracking most cost effective
- Ref: Moore et al Progress in PV 13, 2005, 353-363
14 MW 2 Axis Tracking PV Plant

- Nellis AFB, Nevada; largest in US by factor of >5
- 70,000 PV modules, 140 acres, save $1M/yr in electric bill
11 MW Portuguese PV Plant

- On-line Jan 2007 near Lisbon (sunniest Euro location)
- land area $6 \times 10^5 \text{ m}^2$; 80 football field; 6 months to complete
- 52,000 Si modules; 1 axis tracking;
- GE Energy Financial Services; $75M;
- Powerlight (US) and local solar comp installed
6 MW Thin Film CdTe PV Plant

- On-line Mar 2007 in Leipzig, Saxony, DE; former mil airport
- First Solar (US) CdTe module area 6.7x10^4 m^2 (Eff=9%)
- Worlds largest thin film plant (CdTe!)
- Expect 5.7 M kW-hrs/yr (3.0 hrs equiv sun/day??)
- 40 MW plant underway nearby, also CdTe, former mil airport
Other Utility Scale PV sites

- Top 50 largest PV sites: 25 Spain, 20 Germany, 3 US, 1 Portugal, 1 Japan

- Spain
  - Several sites over 30 MW, largest 60 MW
  - Mostly 1 or 2 axis tracking, all ground mounted

- Germany
  - 5 sites roof mounted 3-5 MW, 15 ground mount

- US
  - 14 MW Nellis AFB, 8 MW Alamosa CO Jail (roof),
  - 4.6 MW Tucson EP

- Japan: 5 MW on Sharp (worlds largest manu)
0.5 MW Grid support for Dist Gen (DG)

- Kerman (central CA), PG&E project to eval DG
  - 10MW transformer, maxed out, end-of-dist line
  - Low growth in demand, good sun
- Besides providing peak power (PV only 5%)
  - Significant value even if not exact match to peak load
  - Lower temp of transformer ~4°C (less net power)
    - Correlates to increase life and output ~3-4% (400 kW)
- Economic analysis values PV at twice traditional energy production value
  - Avoided O+M costs, less losses
  - See table in article for other benefits
0.5 MW Kerman Single Axis Tracking
**PV as DG grid support**

Transmission line voltage vs distance showing step down transformers, power loss (*Resistance incr with Temp!*)

With PV: reduce demand, reduce V sag (loss) with less I, increase peak V;

Shows var. level PV power added to grid
Commercial flat roof installations
Large commercial flat roof PV critical issues

- Commercial rooftop PV syst 50-5000 kW range
- Minimal holes for mounting system (some have none!)
- Novel structures to mount modules, weights, interlock
- Flat vs tilt: orient, dirt/snow accum, drain, spacing (shadow)
- Air circulation: module temperature
- Crucial tradeoff: wind resistance vs weight (loading)
  - Retrofit: initial roof not built for weight
Commercial flat roof PV mounts: Old school
Commercial PV mounts: preform cement

- Low cost
- Easily manufactured
- PV held on with clips
- Light weight
- On “green” roof!!!
Commercial PV mounts: plastic

Gravel or bricks as ballast into base

Fig. 5: The SOLMAX, without ballast, accommodating 3 standards modules.
Large commercial flat roof PV: very light weight mounting (Sunpower)
Wilmington’s Solar Dock

- Developed by local building contractor (McConnell Energy Solution)
  - Al or SS structure to mount modules, interlock, 25° tilt
  - 2 cement block ballast, NO roof penetration! 90 mph wind
Solar Dock: brick ballast, external inverter opt
Commercial flat roof PV: cement block ballast
**Building Integrated PV: BIPV**

- Subsidize PV cost with avoided building matl cost
  - Granite exterior costs more than PV
- Value PV other than just energy
  - **Aesthetics, green statement**, DG (on-site)
  - Multiple functions: awning/shading, diffuse daylight, unique look
- Energy balance, costs, modeling; builder/customer buy-in
- Very little architect awareness in US; must be integrated at beginning; “bottom line” builders/customers
- Three main applications
  - Roof: integral replacement or added, skylight
  - Façade: opaque (cladding) or transp (atrium, gallery)
  - Component: windows, awning, louvres
- Must be compatible with existing building practice
  - Size, shape, color, grids, frame
  - Thin film vs Si wafer can be semitransp (diffuse daylight, façade) or opaque (outer wall, awning, roofing); active vs passive (summer shading); overheating vs daylight
BIPV Performance

• Performance issues
  – Non-optimum orientation (not S facing, vertical) → less output
  – Less circulation → higher Temp → less output
  – Interconnection: dispersed around building, non-uniform light, non-traditional arrangement, long runs of DC wiring
  – Shadowing unavoidable
  – May intentionally space cells to allow diffuse light, reduce cell area

• AC modules: integrate small inverter on each module
  – Only interconnecting 120/240 V AC, low current
  – Simpler installation, no DC wiring to central inverter
  – Inverter reliability and cost, less temperature control
  – Very limited commercial availability (2 companies)
Impact 2000 House 4 kW (1981, Boston)
Georgetown Univ 320 KW
(1984, Washington DC)
AP-Headquarter BIPV facade
BIPV façade modules

- APx spandrel panels
  - 42 cells / 138 Wp

- AP 106 glass/glass
  - 21 cells / 65 Wp
QH-façade system overview

APx solar arrays
single cryst. solar arrays
Inverter installation for facade

11 SWR 2500U SunnyBoy string inverters
Olympic Pool, 340 kW (Atlanta, 1996)
Coney Island Stillwell Subway Station 2005
Residential roof BIPV: Japan
**BIPV: Road Noise Barrier in EU**

- 100 kW roadnoise barrier on Swiss highway
  - 12 yrs, avg 1000 kW-hr/kWp
  - 2200 modules, 20 fail, 12 stolen
  - Cost: 40%PV, 10%PCU, 50%BOS
  - Public perception of ownership, high visibility
  - Close to population center
  - Reduce BOS costs with structure

- 1996 EU project to evaluate 6 styles of barrier, 10 kW each, mostly DE and SW, report written

- None cost-effective
**BIPV: Road Noise Barrier in EU**

- Road noise barrier on German highway

3. Prototype of Züblin AG / Dorfmüller GmbH (Germany)
   - Type: shingle, concrete elements
   - Location: A96, Ammersee (Munich, Germany)
   - In operation: since June 1997
   - (Photo by TNC AG)
BIPV: Road Noise Barrier in Germany

2. Prototype of ARGE Crimmitschau (Germany)
Type: zig zag, steel and glass
Location: A96, Ammersee (Munich, Germany)
In operation: since June 1997
(Photo by TNC AG)
Thin Film BIPV applications

Appearance preferred for building-integrated PV

85kW Shell Solar
Cu(InGa)Se₂ in Wales

216 Würth modules in Tübingen, Germany
TF BIPV applications: flexible a-Si

Flexible PV for roll-out rooftop installation (USSC triple junction/SS)
Flexible Thin Film a-Si PV Laminate
(Grand Valley Community College MI)
**BIPV window (Kaneka Corp JP)**

a-Si single junction on glass, 10% removal via laser

Achieve color neutral 10% transmission, not filtered through a-Si
MSK Corp (JP): laser cut BIPV window
Architectural a-Si semitransparent element
2 axis tracking solar sunflowers at CA winery by Steve Strong, famous US PV Architect