PV SYSTEMS TESTING AND CHARACTERIZATION

PV Modules and Systems Testing and Characterization

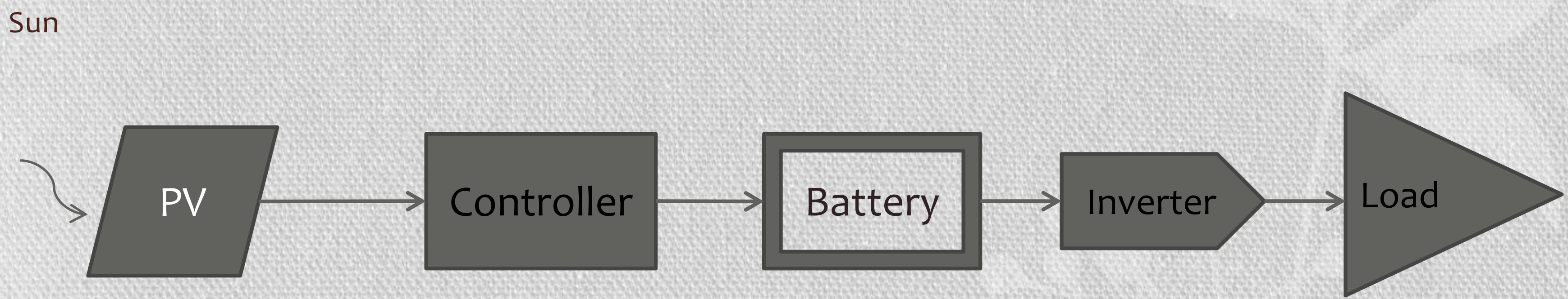
CEP Short Course
Nov. 26-28, 2014

Vaman Kuber,
NCPRE at IIT Bombay

Outline

- What is PV System?
- Basics of Systems
- Off-grid System Testing
- On-grid System Testing
- System Efficiency
- System DC Testing
- System AC Testing
- Energy Metering
- Solar Resource Testing
- Plant Functional Testing
- Plant Acceptance Testing
- Plant Performance Ratio
- Capacity Utilization Factor
- Plant Performance Testing
- Energy Generation
- SCADA
- Standards and Certification

PV System Concept

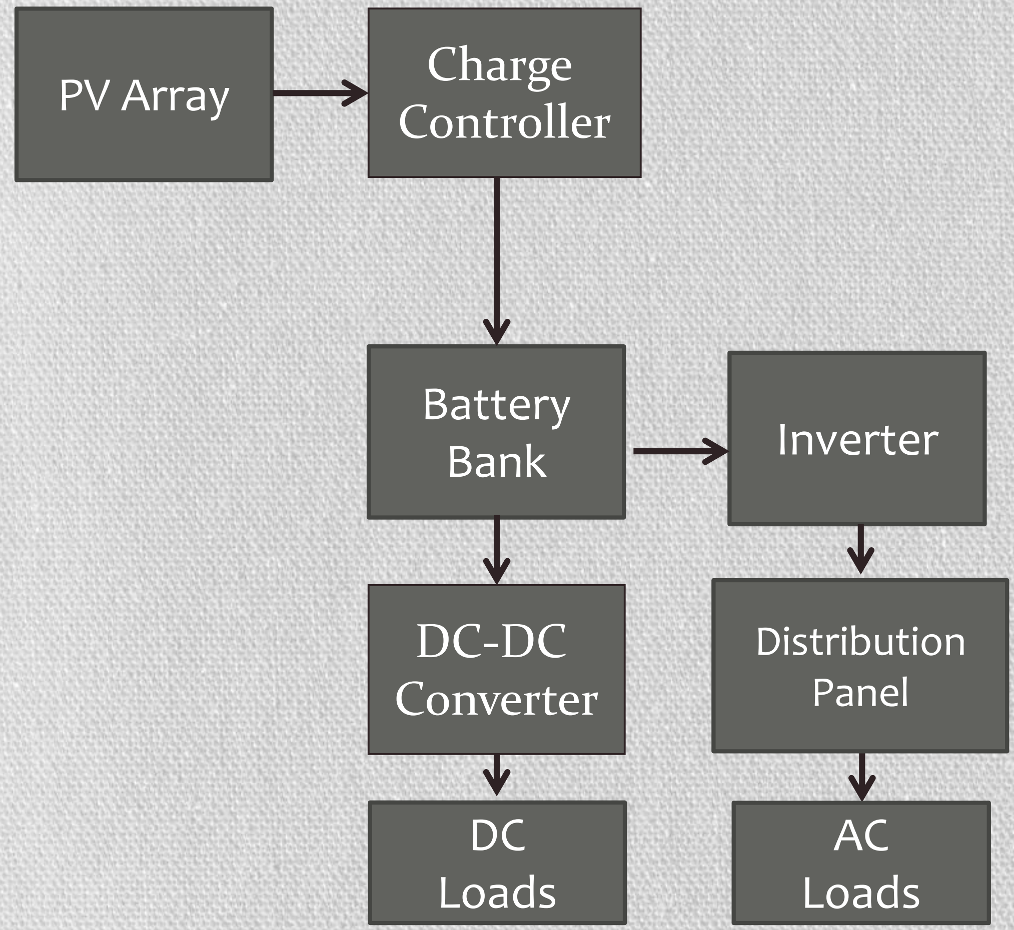


- Solar PV System converts sunlight to electricity
- System consists of PV modules, controller, battery and inverter.
- Balance of Systems (BoS) include array support structure, electrical wiring, safety, protection and switching devices.
- System Performance: How much energy is delivered to load at operating conditions compared to PV Energy produced at standard conditions?
- System performance depends on insolation, weather, PV modules, batteries, power conditioning components, load and their sizing/integration.
- System Testing , Certification and Warranty is paramount!

Solar PV System Configurations

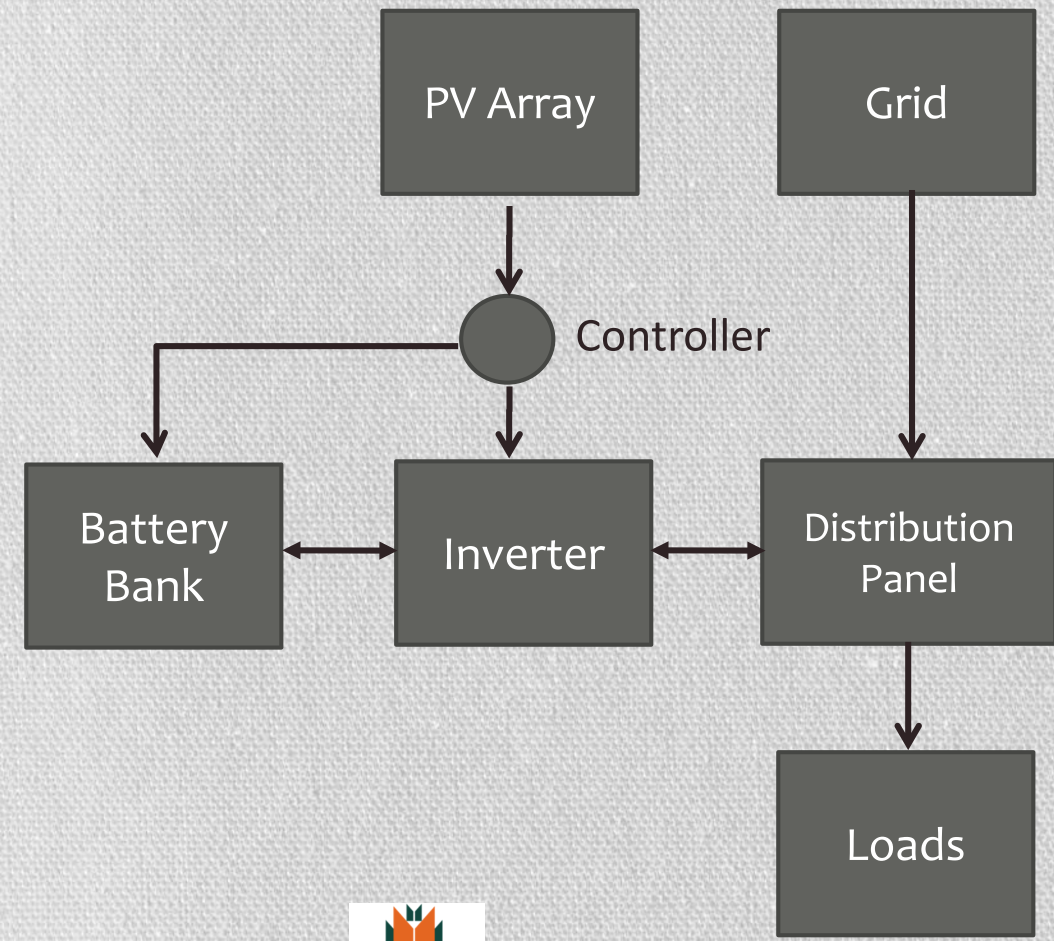
System Configuration	System Example
Off-grid/Grid-independent/Stand-alone System	Remote Household
Off-grid Hybrid System	Telecom Tower
Grid-support/Grid-dependent System	Rural or Semi-urban Home, Office, Industry
Grid-support Hybrid Power System	Hospital, Hotel
Grid-tied/Grid-connected/Grid-interactive System (Captive/Grid-feed)	***Roof-top plant, Ground based power plant***
Mini-grid/Micro-grid Power System	Local grid supplied to remote community

Off-grid System



- Energy storage mandatory
- DC and AC Systems
- **Components:** PV Array, Charge Controller, Battery Bank
- DC-DC Converter for DC Loads
- Inverter for AC Loads
- All DC PV

Grid-support System



- PV, Battery and Grid supply power to load
- PV and Grid both used to charge battery
- **Components:** PV Array, Inverter-Charger/PCU, Battery, AC Loads

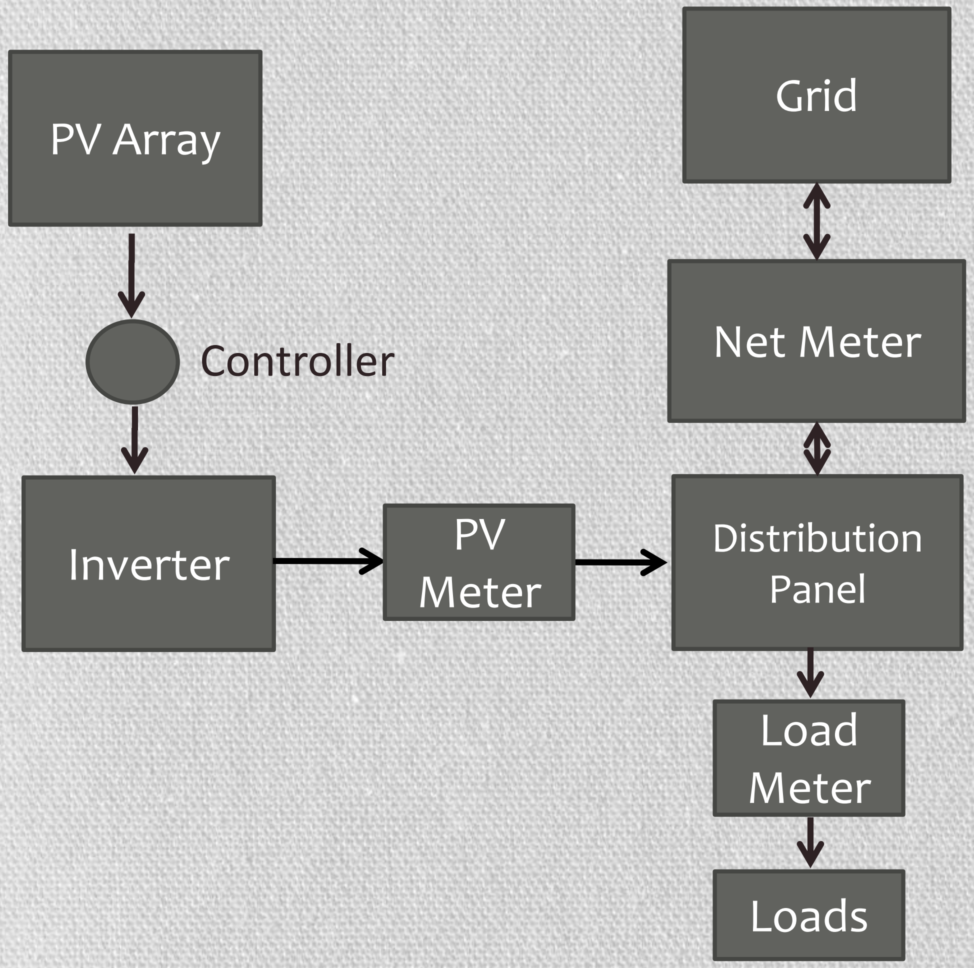
Off-grid System Testing

- Off-grid system: PV output, Battery input/output and Load output voltage, current and power are tested.
- Monitor battery input Wh to full charge and output Wh to cutoff level and evaluate battery efficiency.
- Battery SOC needs to be monitored for given load current and battery temperature. (Voc, Specific Gravity, Ah method)
- Energy delivered to load can be compared to rated PV energy for one battery cycle to determine system efficiency.
- Grid-support System: Load energy meter records PV, battery and grid energy. Additional grid energy meter is required to evaluate PV energy generation.

Off-grid PV System Optimization

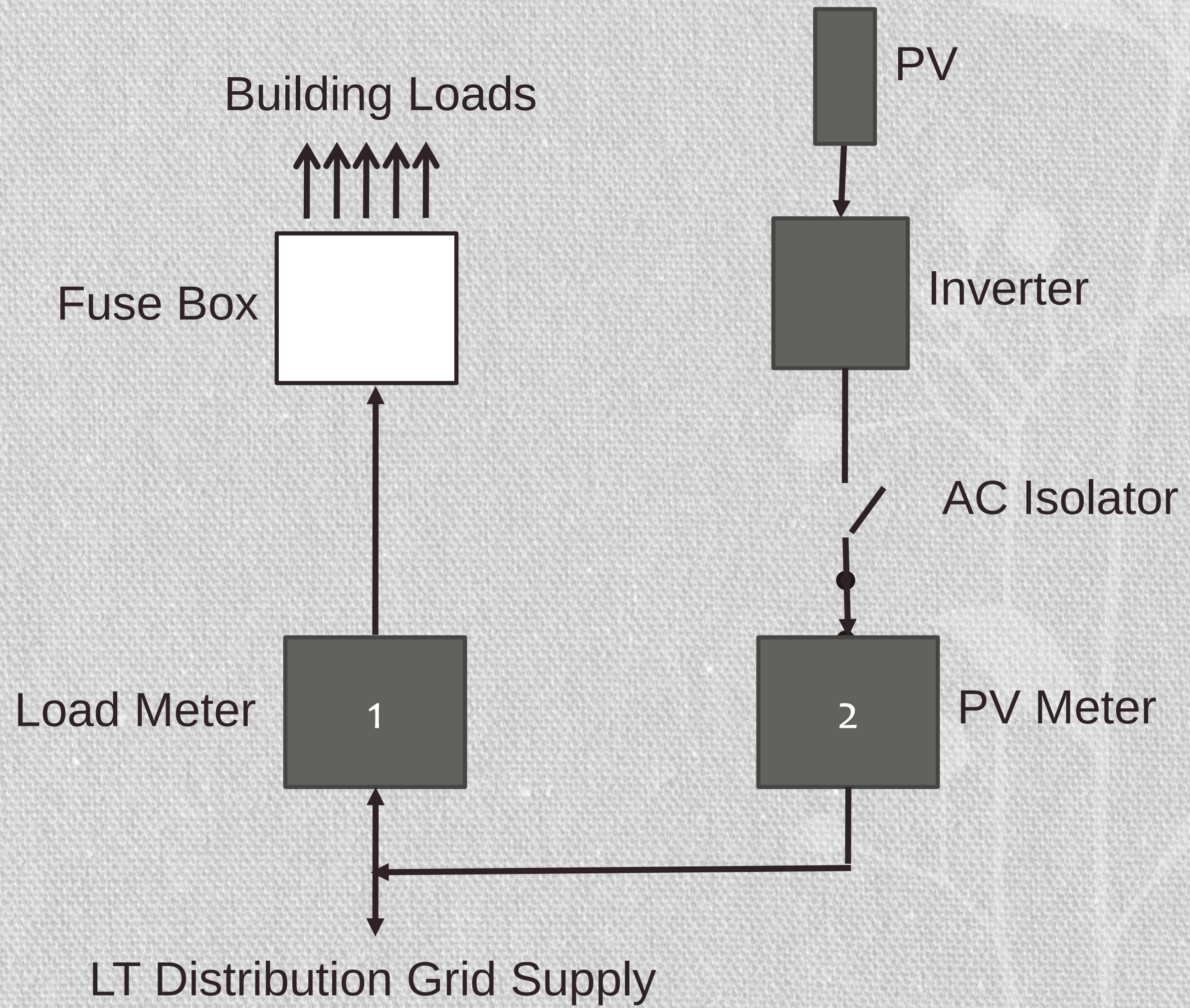
- System performance depends on optimum utilization of PV.
- PV charge current needs to be optimized for given battery State of Charge (SOC) and load profile for improved system performance.
- Adaptive Control to suit load Amp-hours, available PSH, PV output and battery SOC.
- Grid-support System:
  - Order of source priority needs to be PV, battery and grid for supply to load.
  - Order of source priority needs to be PV and grid for supply to battery.

Grid-tied System

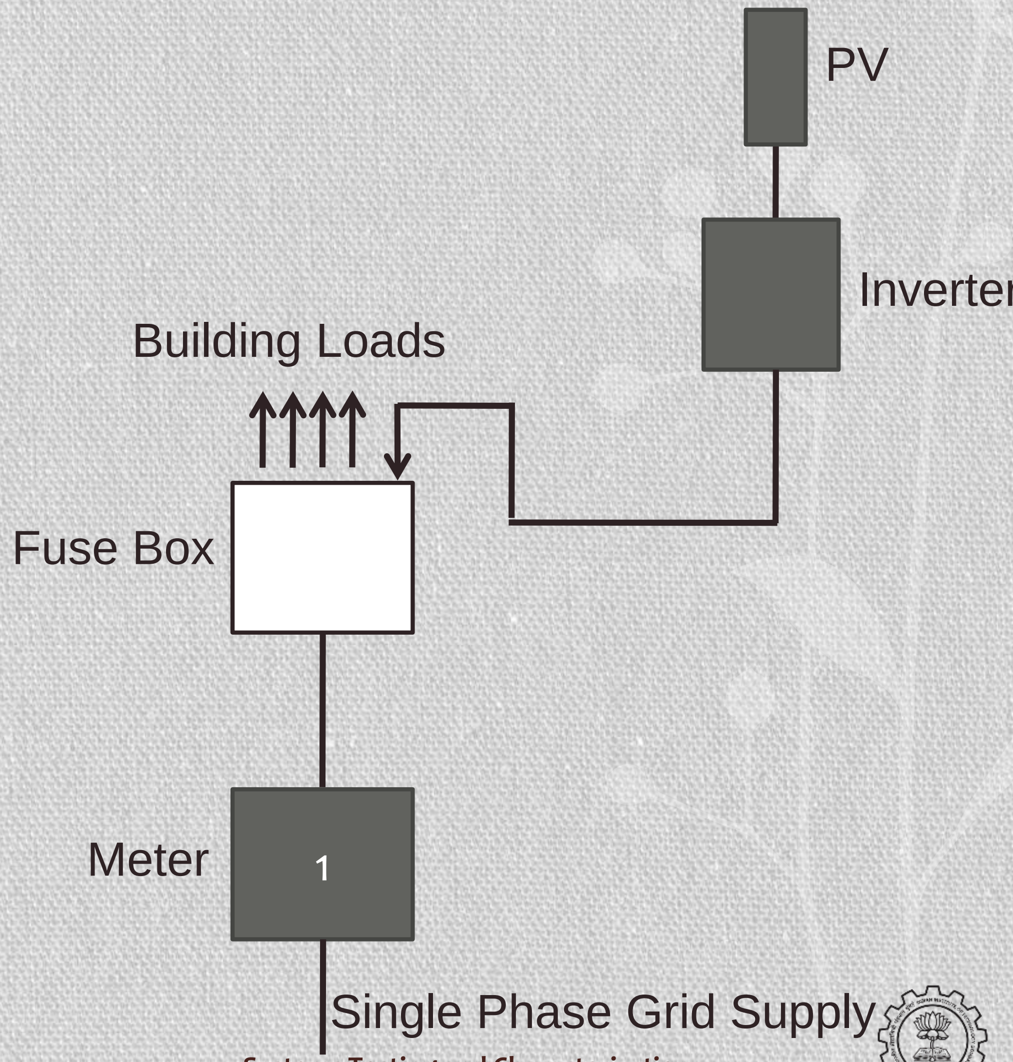


- **Components:** PV Array, grid connect inverter, energy meters
- PV energy is fed back into grid
- LT energy metering for captive loads
- HT transformer and metering for power evacuation.

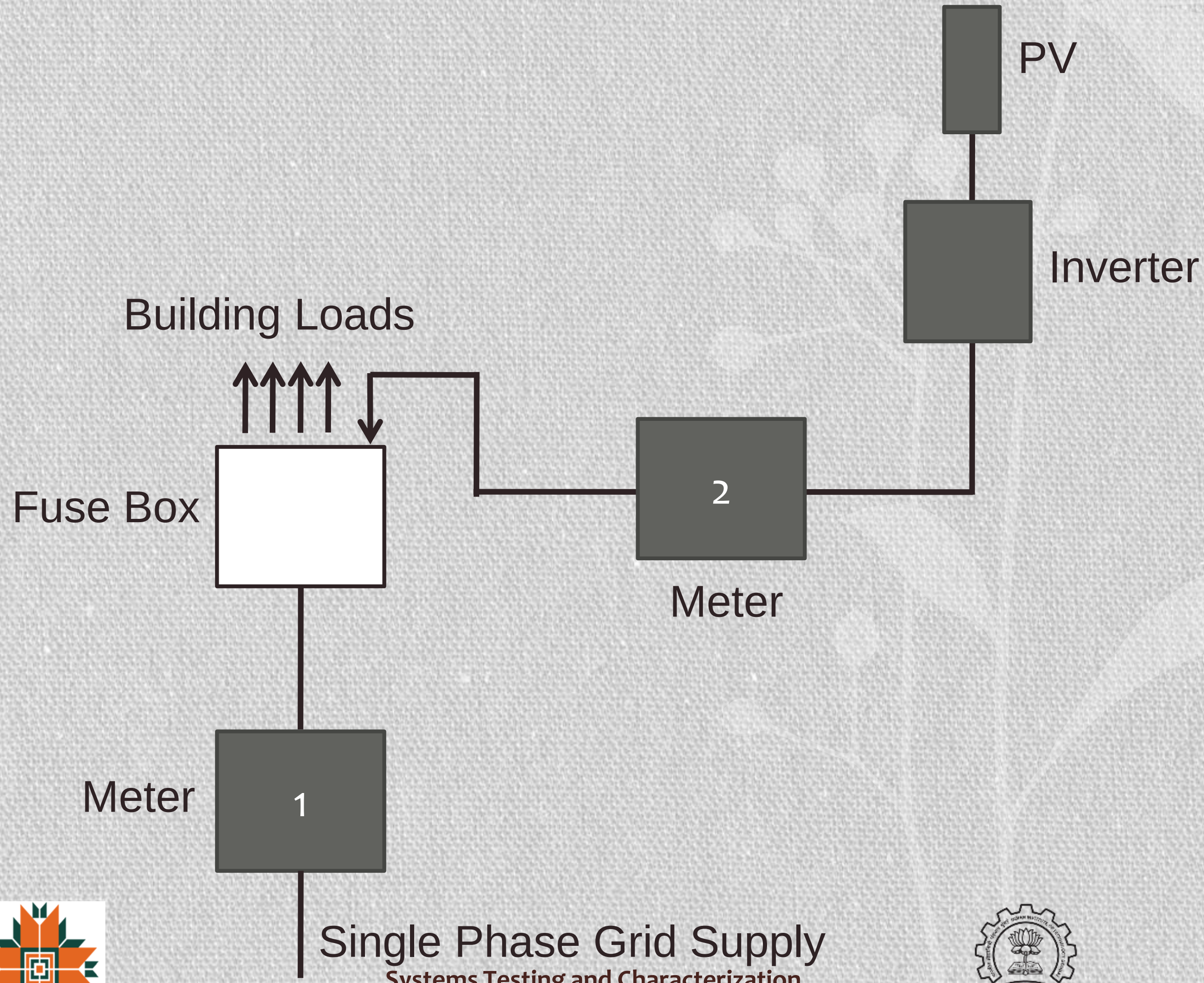
Grid Connection 1
Power Export-Two Meters



Grid Connection 2
Captive Power-Single Meter



Grid Connection 3
Captive Power-Two Meters



Grid-tied PV System Testing

- PV array output/Inverter input voltage, current and power
- Inverter output voltage, current and power
- Inverter efficiency = inverter output power/inverter input power

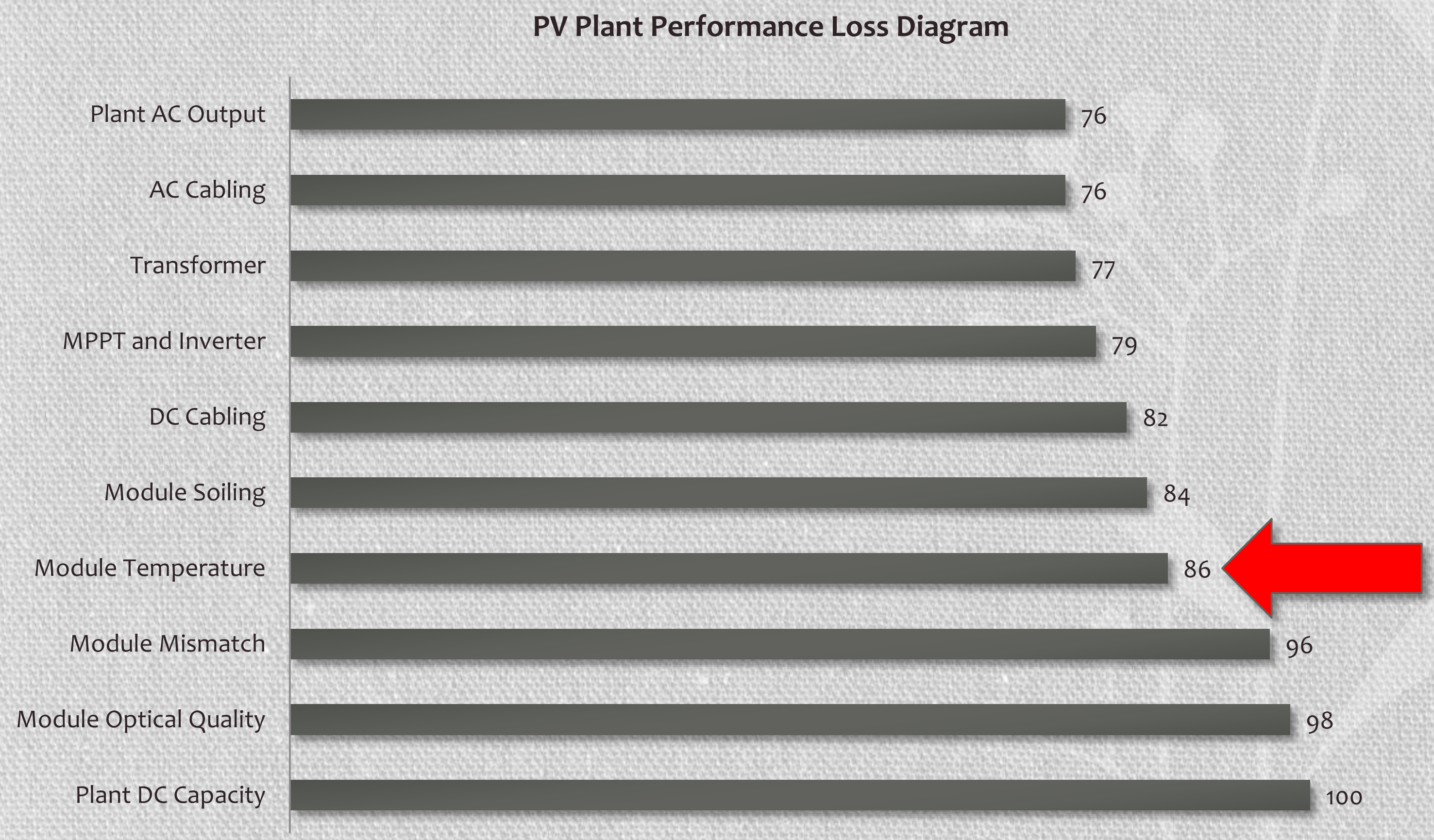
- PV generated energy at inverter output
- Energy consumed by local load
- Energy supplied to/drawn from grid

- Energy supplied to grid = PV Energy - Load Energy
- Energy drawn from grid = Load Energy - PV Energy

PV System Efficiency

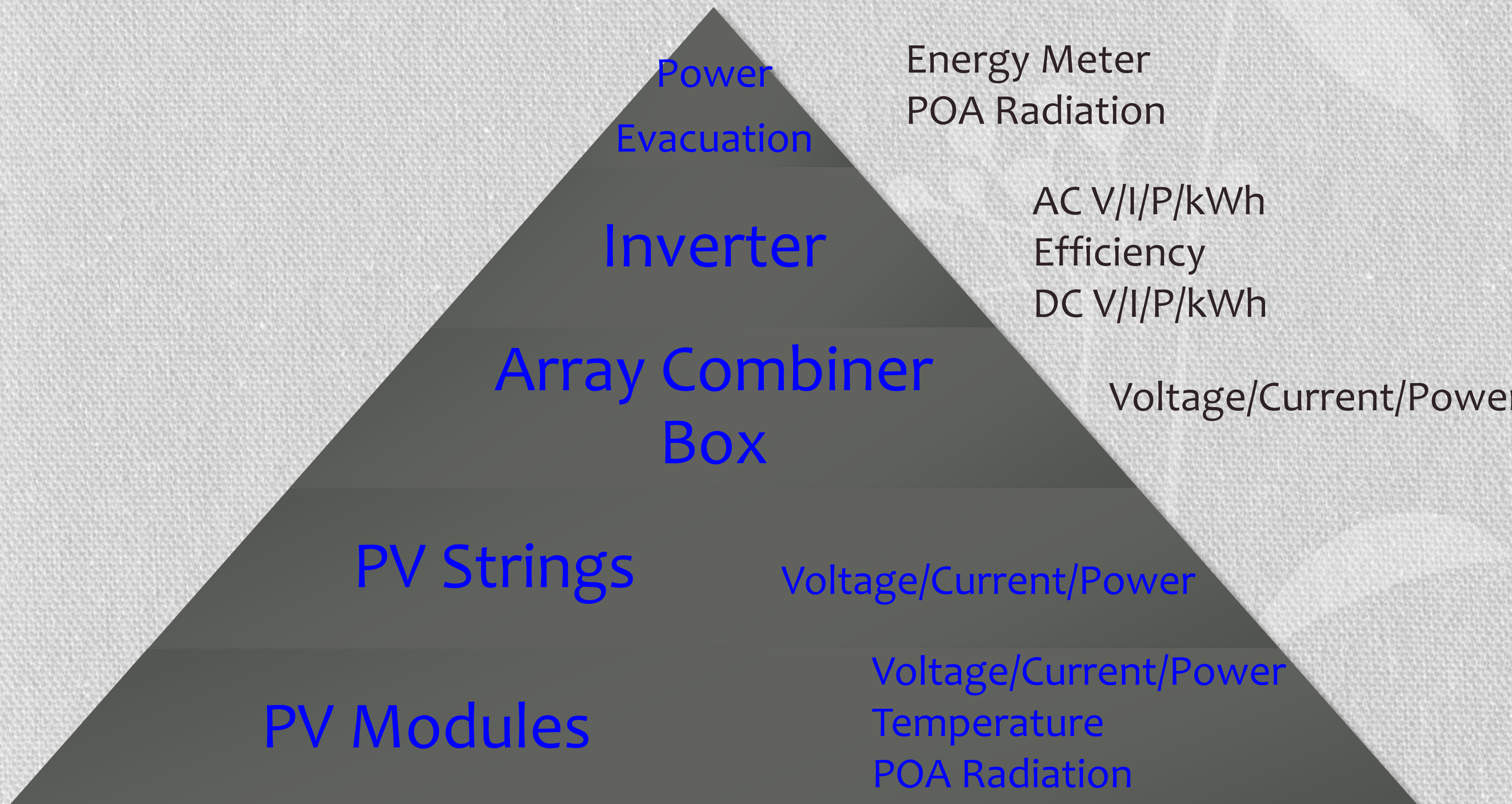
- Independent of PV conversion STC efficiency
- **Total system losses are sum total of individual component losses**
- **PV Technology** (c-Si/TF):
  NOCT efficiency, Tempco, response to low/diffuse light, degradation etc.
- **String and Array design:** module mismatch factors.
- **Balance of Systems Components**: MPPT and Inverter efficiency, DC Cabling, AC Cabling and transformer efficiency.
- **External factors:** quality of solar insolation (eg. Angle of incidence-IAM Factor, spectral content), ambient temperature, dust and other weather parameters.

System Loss Diagram



Plant Functional Tests

One-off Commissioning Tests



PV System DC Testing

- PV module Voc/Isc, I/V
- String Voc/Isc, I/V
- Array Vmp, Imp, Pmp at Inverter Input
- DC efficiency = Array Pmp at Inverter Input/DC rated power for given insolation
- Array Vmp, Imp and Pmp can be monitored at String Combiner/Minitoring Box (SCB/SMB).
- DC cable losses = Array Pmp at SCB - Array Pmp at Inverter Input
- DC earth resistance
- DC insulation resistance

PV System AC Testing

- Inverter output AC voltage, current and power
- Transformer output AC voltage, current and power
- Grid AC voltage, current and power
- AC efficiency = Power supplied to grid / Array Pmp at Inverter Input
- Inverter efficiency = Inverter output power / Array Pmp at Inverter Input
- Transformer Losses = Inverter output power – Transformer output power
- AC Cable Losses = Transformer output power – Power supplied to grid
- AC ground resistance
- AC insulation resistance

Example: Plant DC and AC Performance

- Available Solar Radiation in POA = 800 W/sqm
- DC rated power of Solar PV Array = 1000 kWp @ STC
- DC input power to Inveter = 680 kW
- AC output power of Inverter = 640 kW
- DC Performance Efficiency = 680/(1000x0.8) = 0.85
- AC Performance Efficiency = 640/680 = 0.94
- Plant Performance Efficciency = 640/(1000x0.8) = 0.80

MW PV Plant Performance Ratio

- **Governing Factors-Solar Insolation, Weather, System Loss Factors, O&M, Module Degradation, Plant Availability and Grid Conditions.**

- **Plant performance ratio (PR)**
- Measured Energy (kWh)/Modeled or Rated Energy (kWh)
- Modeled Energy = POA Irradiation (kWh/m^2) x Active Area of PV Array (m^2) x module efficiency
- Modeled Energy = Rated Array kWp x POA PSH

- PR independent of radiation
- PR useful in technology selection at a given location

Capacity Utilization Factor

- **Capacity utilization factor (CUF) or Plant Load Factor (PLF)**
- Measured Energy (kWh) / Potential Energy (kWh)
- Potential Energy = Installed Capacity (kWp) x (24 x 365) h
- CUF radiation dependent
- CUF measure of plant utilization, suitable in evaluating location

Example: Plant PR and CUF

- **Example 1:** Annual 2000 PSH, 1MWp PV plant, 16,00,000 kWh annual energy output
- Yearly average PR = 16,00,000/(1000x2000) = 80%
- Annual average CUF = 16,00,000/(1000x24x365) = 18.26%

- **Example 2:** Annual 1800 PSH, 1MWp PV plant, 14,40,000 kWh annual energy output
- Yearly average PR = 14,40,000/(1000x1800) = 80%
- Annual average CUF = 14,40,000/(1000x24x365) = 16.44%

Plant Performance Tests

- **Weekly/Monthly/Quarterly/Annual Performance Ratio based on SCADA.**
- Seasonal Variation in PR.
- Year-to-year performance test to understand **plant degradation rates.**
- Irradiation sensor installed in no-shadow zone and cleaned on daily basis is a must for accurate PR evaluation.
- Performance normalized for irradiance and ambient temperature.
- Co-relate predicted and actual performance (PI).
- **Compare plant performance between locations and technologies.**
- Demonstrate plant equipment and grid availability.
- **DC and AC PR Test to isolate Module/Inverter underperformance.**
- **Identify BoS and Power Evacuation Issues**

Test and Monitoring Equipment

- Digital Insulation Tester
- Digital Earth Resistance Meter
- Digital Temp. Monitor
- Digital Clamp DC/AC Multi-meter
- Power Analyzer.
- **DC/AC Energy Meters**
- Tilt/Sun-path/Shading-**Solmetric SunEye**
- Radiation, I/V-**Solmetric PV Analyzer/Daystar**
- Ground continuity, insulation resistance, OC voltage, SC current , Operational test-**Seaward PV Installation Test Kit PV100**-meets IEC 62446 test requirements
- PV Module Fault Detectors-String Tracer & **Cell Line Checker-Togami**
- **Thermo-graphic Camera-Fluke**
- Plant SCADA
- Radiation and Weather Monitor

Plant Acceptance Tests

- Functional Tests- one off pre-commissioning tests
- Runtime Operational Tests-5 to 10 days
- **Capacity** tests to measure plant size-need reference irradiance and weather conditions.
- **PR Tests:** 1 week, 1 month monitoring
- **Sensitivity to Seasonality**: Monthly tests to distinguish seasonal effects and PR issues.
- **Integrated PR** at effective temp. adjusted irradiance levels.

Energy Generation

- **Dependent on PR, Solar radiation, module degradation, plant and grid availability**
- Calibrated **POA global radiation** monitor to co-relate generation with solar insolation
- Specified power guarantee accounts for PV module degradation: 10% in first 10 years, 20% in 25 years
- First year generation and **average generation over life time**
- Grid availability and stability-Islanding protection and Inverter isolation, intentional islanding
- Plant monitoring, maintenance and availability
- Performance guarantee Vs. Generation guarantee

Plant Performance Guarantee

- Annual energy generation is the product of POA insolation, kWp rating and average annual PR.
- Higher radiation implies more generation when PR guarantee is offered unlike generation guarantee.
- Higher PR also implies more generation for a given solar resource.
- Generation guarantee undermines plant performance.
- PR guarantee is more beneficial to customer than CUF or generation guarantee.
- As PR is both a function of system efficiency and weather, measure of PR is an insufficient metric for performance guarantee with precise confidence intervals.
- Weather Corrected PR is a better choice for contract guarantee.

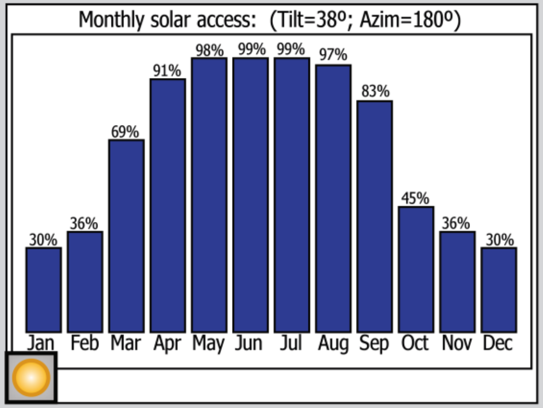
PV Plant Performance Index

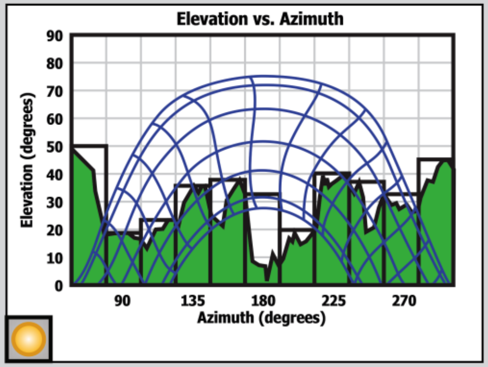
- Ratio of actual generation to expected generation over a time interval.
- PI is a dimensionless quantity.
- Common measures of 'Capacity Factor, Efficiency, PR, Availability' exhibit wider seasonal variation.
- Capacity Factor of PV plant is smaller in magnitude as the plant does not operate 24x7 unike coventional plants.
- PI is used for real time plant monitoring and long term analysis.
- PI is a useful index across range of technologies and locations.

Solar Resource Testing

- Compass to identify South direction and determine orientation of PV panels
- Angle Gauge to check tilt angle of roof/PV panel
- Solmetric Sun-eye: calibrated fish eye lens, electronic tilt and compass sensors, live annual sunpath survey, identification of shade-free area
- Pyranometer (Thermopile Sensor)-Global Horizontal and POA radiation Monitor
- Pyrheliometer-Direct Beam Radiation Monitor
- Pyranometer with shade arm-Diffuse radiation monitor
- Silicon Sensor-Global Horizontal and POA radiation monitor for PV technology deployed with matched spectral response
- Satellite data-NASA
- Meteonorm data-Satellite and ground based data interpolated between stations
- NIWE-approx. 100 ground based weather stations across india

Suneye-Solar Access and Obstruction Elevation





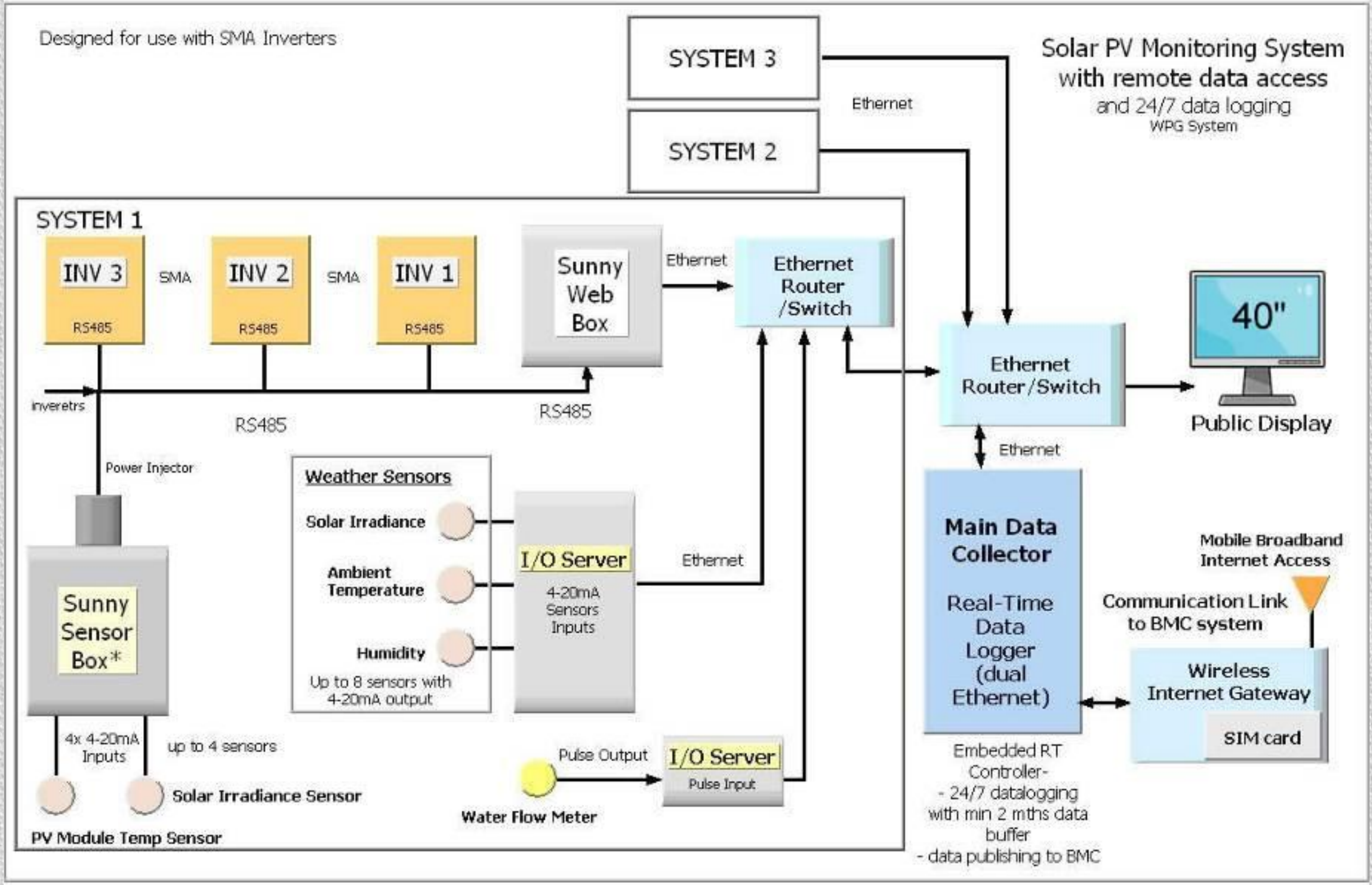
Alternative data views include monthly solar access and obstruction elevation vs. azimuth.

Source-Solmetric

PV Plant SCADA

- String Monitoring @ SCB or Inverter to monitor string voltage, current and power.
- Plant SCADA consists of various sensors and meters, internal communication devices, data acquisition system, external communication devices, data storage, display and report generation.
- Plant DC parameters: String/ Array voltage, current and power, ground current
- Plant AC parameters: Inverter output voltage, current, power, frequency, PF, DC injection, harmonics etc., ground current, plant generated energy.
- Weather parameters: Ambient temp, module back surface temp, wind speed, wind direction, humidity, GHI/POA solar radiation.

Solar PV Monitoring System Example



Source-SMA

MNRE System Test Guidelines

- PV Lighting System Specs
  - Individual component specs and certifications.
  - Dust to dawn operation @ 5.5 PSH is specified.
  - No system level tests (5 years system warranty) are specified.
- JNNSM phase 2 batch 2 guidelines: Test Specifications
  - Certifications required for PV modules, inverters and BoS components.
  - Remote monitoring of solar radiation, weather parameters, plant DC and AC power.
- System testing guidelines are required.
  - Co-relate power and energy output with solar radiation and weather.
  - DC and AC performance analysis.
  - System level design, installation and test standards.

System level Standards

- IEC 62548- Design (safety) requirements for photovoltaic (PV) arrays including d.c. array wiring, electrical protection devices, switching and earthing provisions. (off-grid and on-grid systems)
- IEC 62446: 2009 - Grid connected PV systems – minimum requirements for system documentation, commissioning tests, and inspection.
- IEC 61724 - Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis.
- IEC 62124- PV standalone systems design verification- Check functionality, autonomy and ability to recover after periods of low state of charge of the battery.

PV GAP and Certification

- PV Global Acceptance Program (GAP)-1998.
- PV Quality Mark for PV components and PV Quality Seal for systems.
- IEC International Standards for safety, quality and performance.
- Aging and impact resistance, endurance, and energy efficiency testing ensures long term reliability.
- New Owners- IECEE (CB-FCS Program) and Electrosuisse in Switzerland.
- EPIA/SEIA award PV GAP mark/seal based on VDE Certifications.
- First Solar MW plant recently awarded PV GAP Quality Seal for the first time.

Large Scale PV Power Plant Performance Evaluation

- Based on generation data, array/inverter monitoring, radiation data and plant field visit.
- Analyze energy generation data for 1-2 years.
- Co-relate plant PR with PV and Inverter Technology.
- Study effects of BoS, Systems Integration, Installation, O&M on plant performance.
- Develop models for PV and Inverter technology, location and environment.

Conclusion

- PV components testing and certification is mandatory.
- PV system level testing and certification is required for optimization of plant performance.
- Plant functional and acceptance tests identify short term under performance issues.
- Plant long term performance tests help compare actual irradiance and performance with predicted values.
- Plant long term performance tests also required to understand plant degradation rates as well as location and technology specific energy generation.
- Performance improvement translates to reduced energy cost, faster payback and bankability of project.

Thank You

and

Enjoy

1MW Plant Visit!