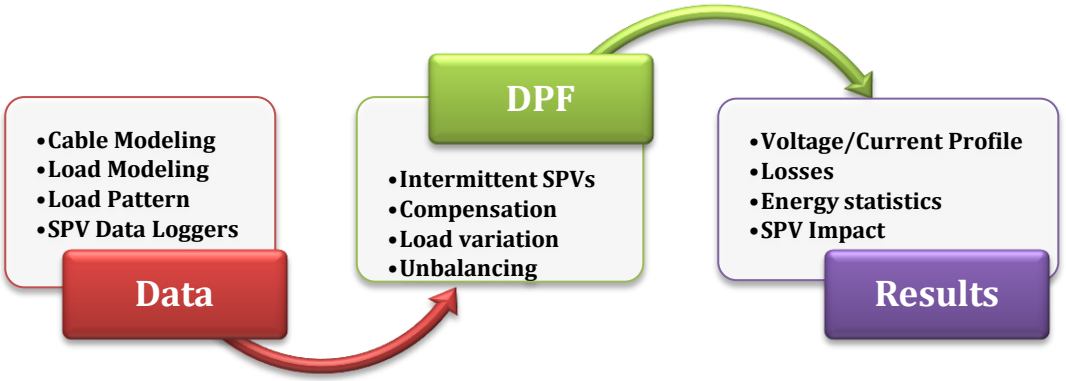
Indian Institute of Technology
Gandhinagar, India

# Integration of Distributed Solar PV Generations into Secondary Distribution Grid

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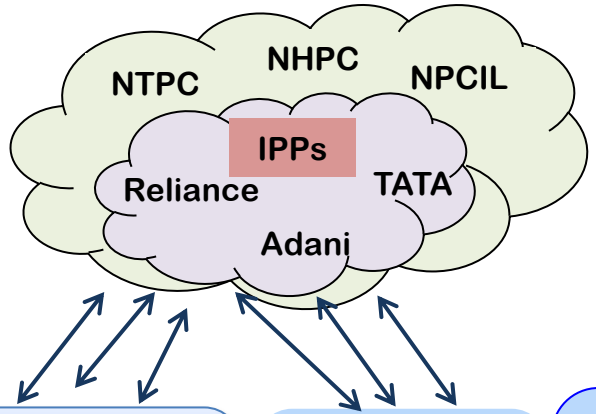
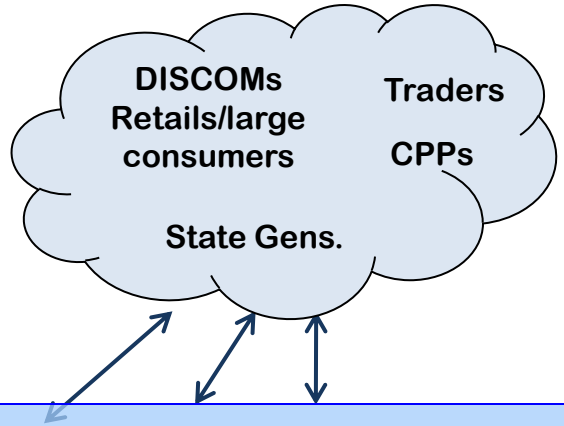
IIT Gandhinagar, Gujarat
Email: naran@iitgn.ac.in

# Electricity Market Operation in India




**Long Term Market**

12-25 Yr

**Medium Term Market**

3months -3 Years

**Short Term Open Access**

| Bilateral Transaction | Collective Transaction | Day Ahead Transaction | Contingency Transaction |
|---|---|---|---|
| 3 month ahead | Day Ahead ahead | After Clearance of PX | On the day of operation |

IEX INDIAN ENERGY EXCHANGE India's No.1 Power Exchange

PXIL Transforming Power Markets

**Schedules**

System operation Injections/drawals adjustment

**Balancing Market ( UI )**
**( Real Time Operation )**

# Motivation: ABT

## Capacity Charges

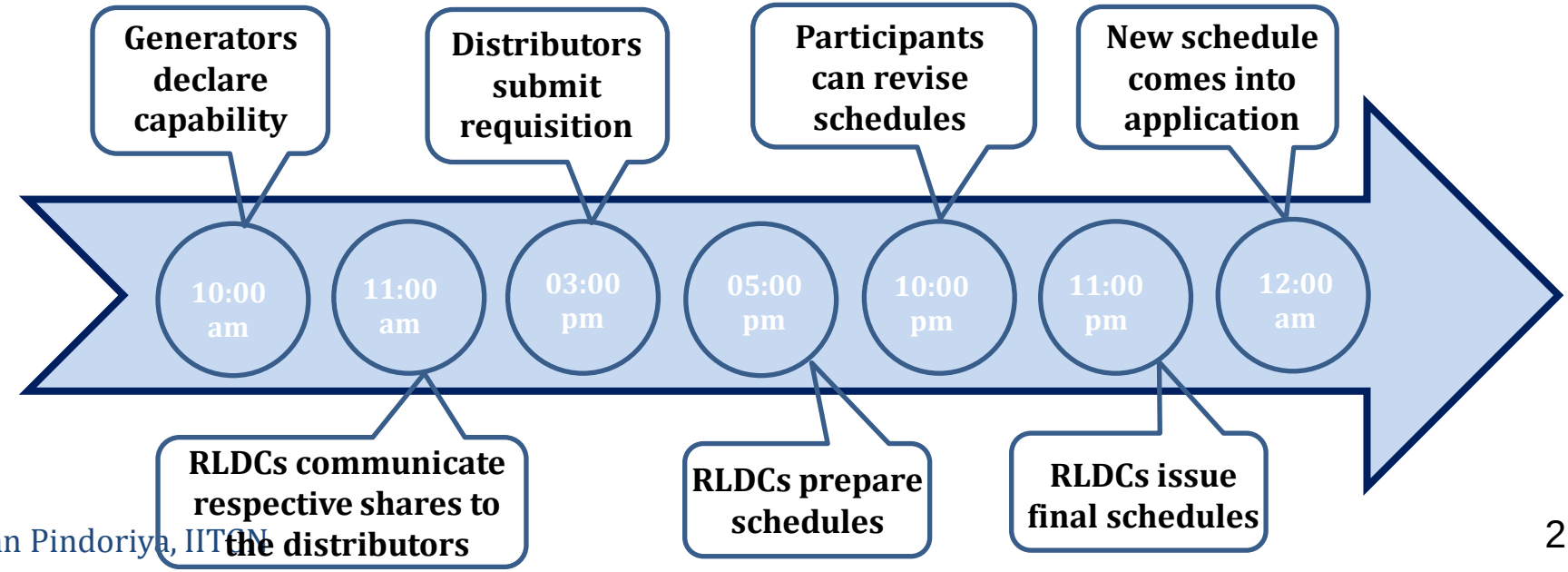
- Fixed costs comprising of interest on loan and working capital, return on equity, O&M expenses, insurance, taxes and depreciation
- Dependent on the availability of the plant

## Variable Charges

- Energy charge charged as per the fuel consumption
- Dependent on the schedule of the day and not on the actual generation

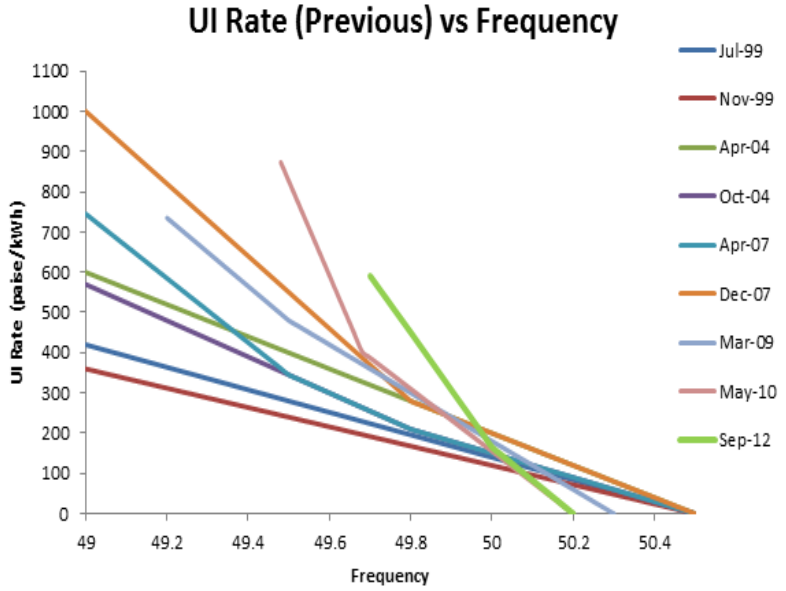
## Charges of Deviation (COD)

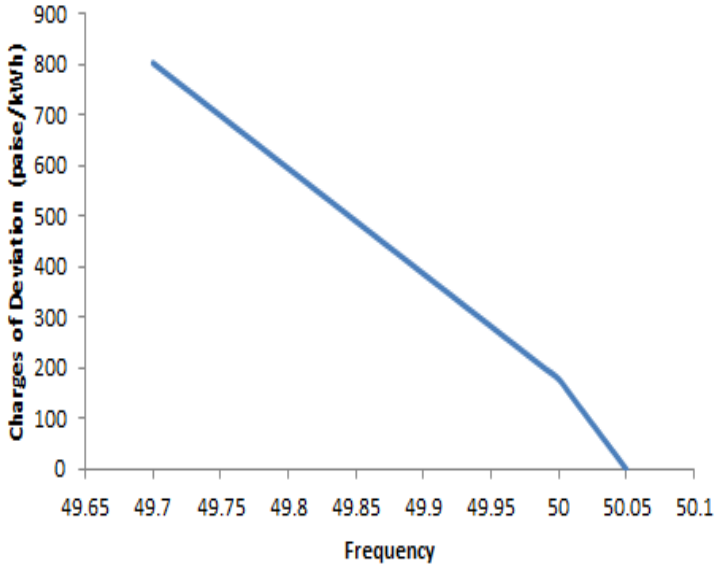
- Payment for deviations from schedule
- Dependent on system frequency



# Motivation: UI/Charges of Deviation

- Known as Unscheduled Interchange (UI) Charges till 17th Feb 2014
- Varies inversely with system frequency



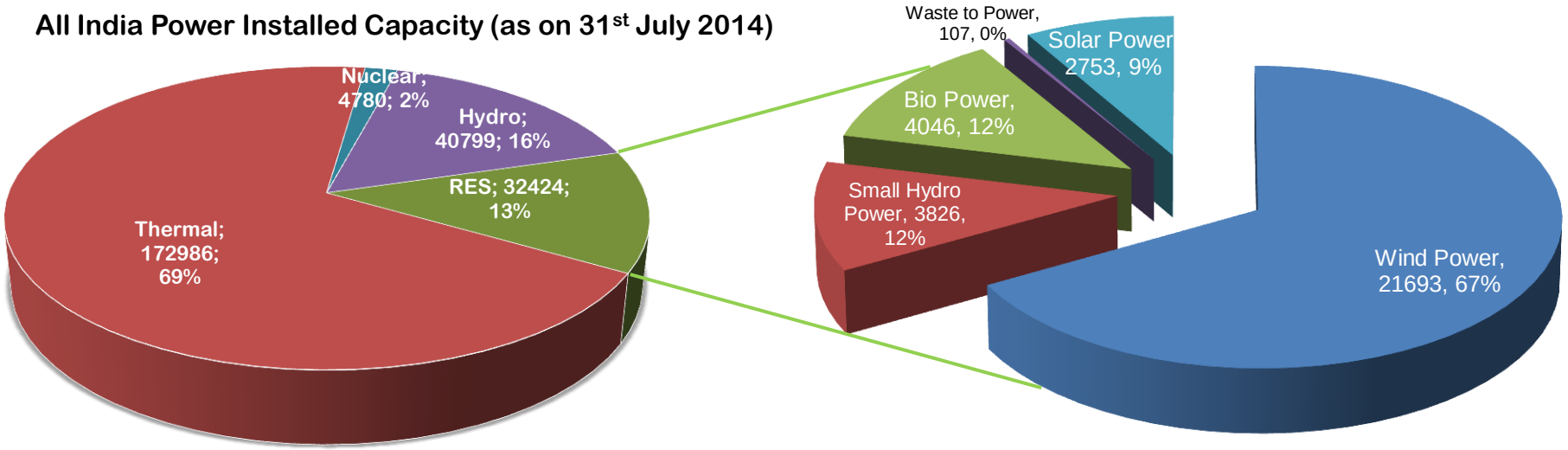

No over drawl is allowed. Overdrawl @ 16.48 Rs / KWh i.e. 100% additional charge of Freq 49.70 Hz

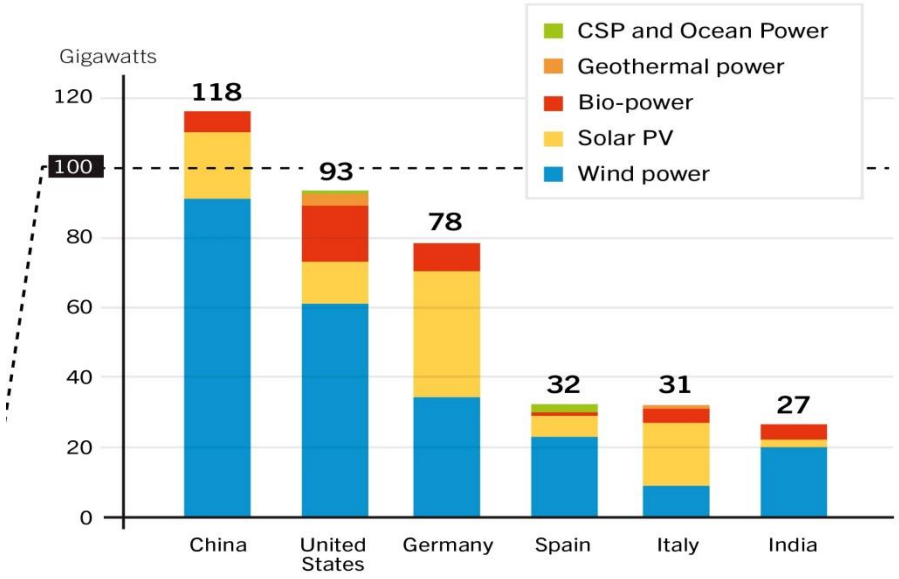
| Frequency range | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 49.70 | 49.75 | 49.80 | 49.85 | 49.90 | 49.95 | 50.00 | 50.05 | 50.10 |
| Rate in Rs per KWh | | | | | | | | |
| 8.24 | 6.99 | 5.94 | 4.90 | 3.86 | 2.82 | 1.78 | 0.00 | 0.00 |

Under drawl / over injection Penalty @ 1.78 per KWh

# Power Scenario in India

**All India Power Installed Capacity (as on 31st July 2014)**

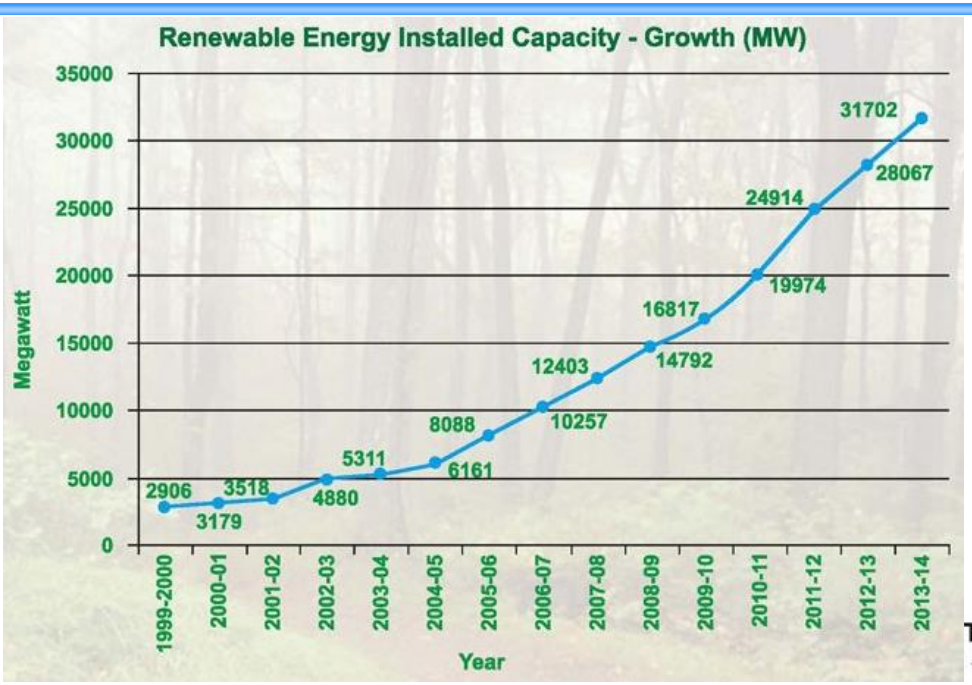





*Status Report* (Paris: REN21 Secretariat).

# Power from Renewable Energy Sources

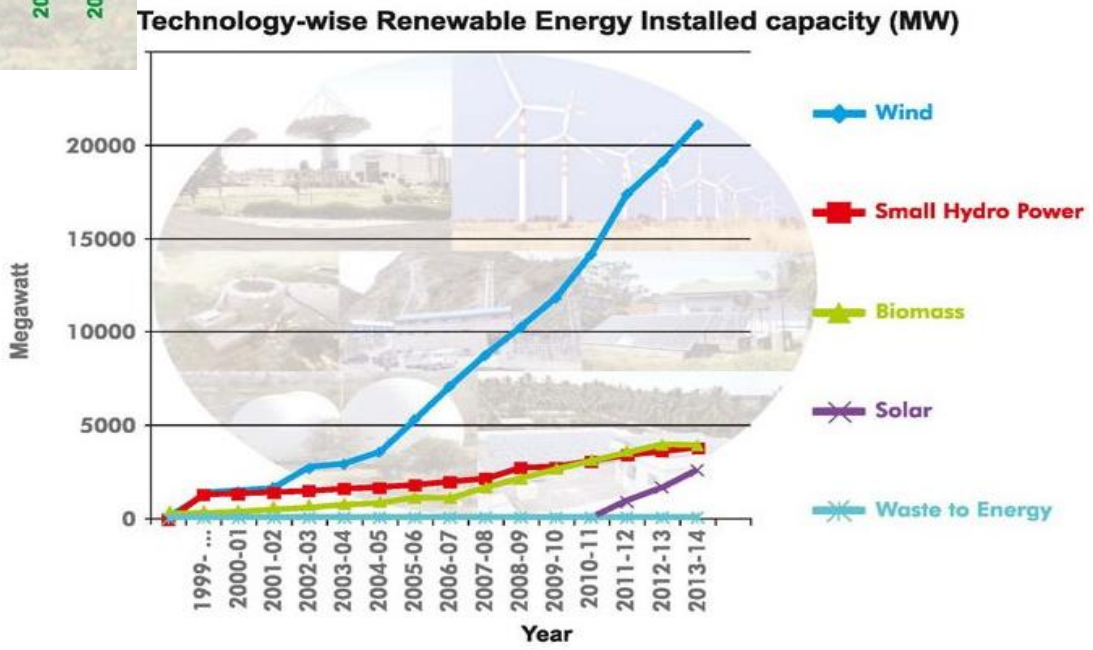



**RE based power generation :**
**~ 20% growth in last 5 years**

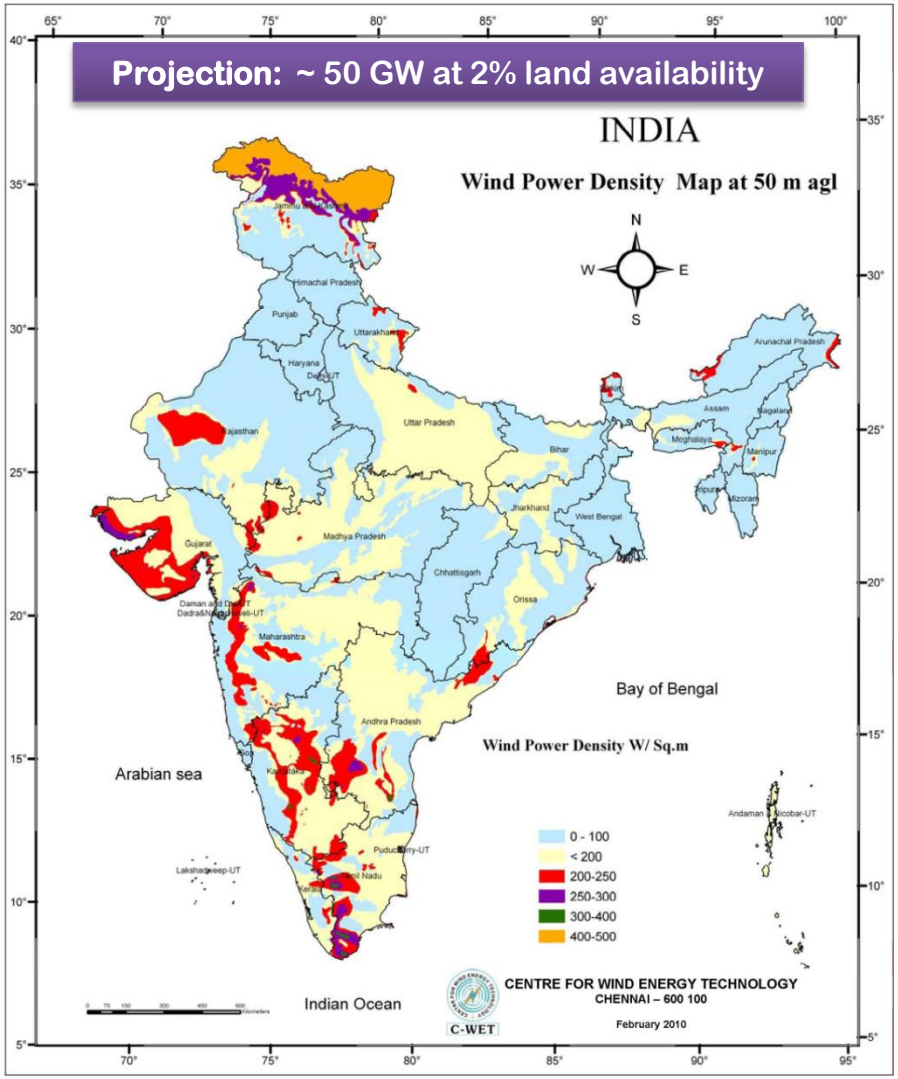
**Wind energy (21,132 MW) continues to dominate - 67 % of total RE**

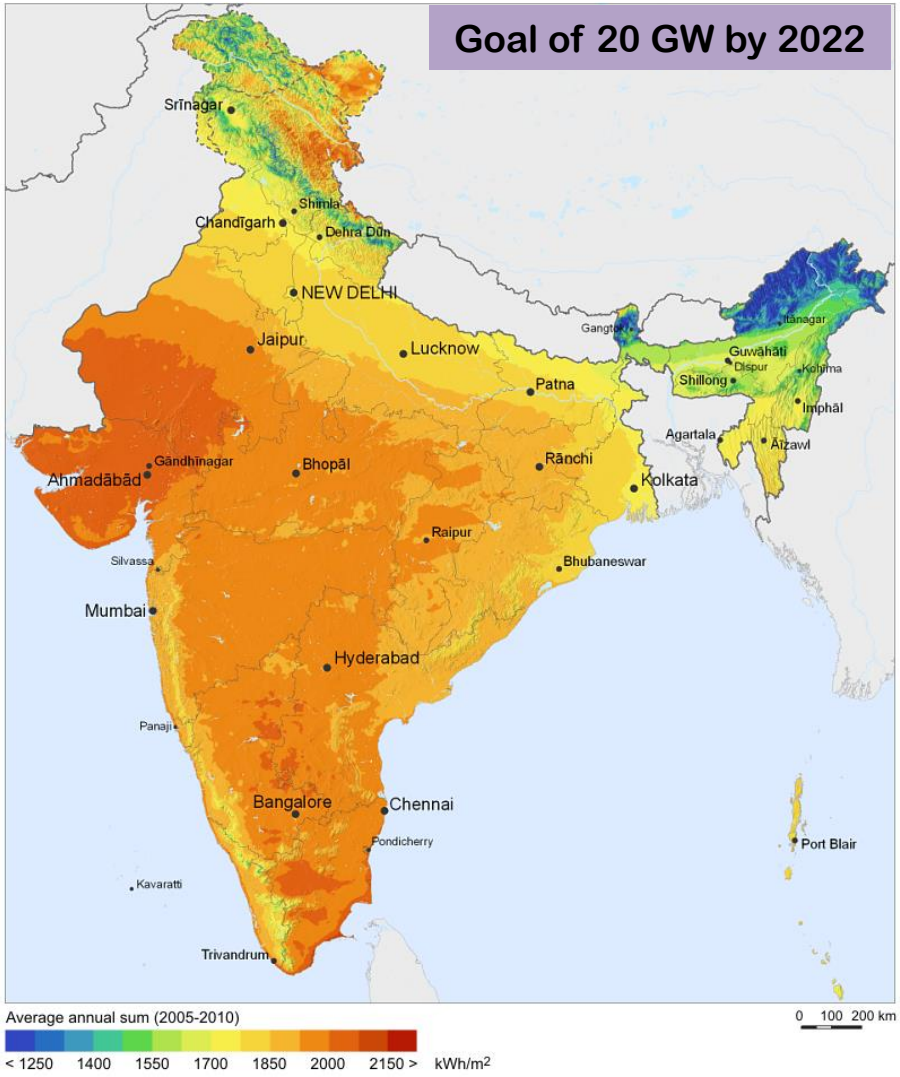
**Solar power : 2,647 MW**

**As on 31st March 2014**



# Wind and Solar Energy Sources

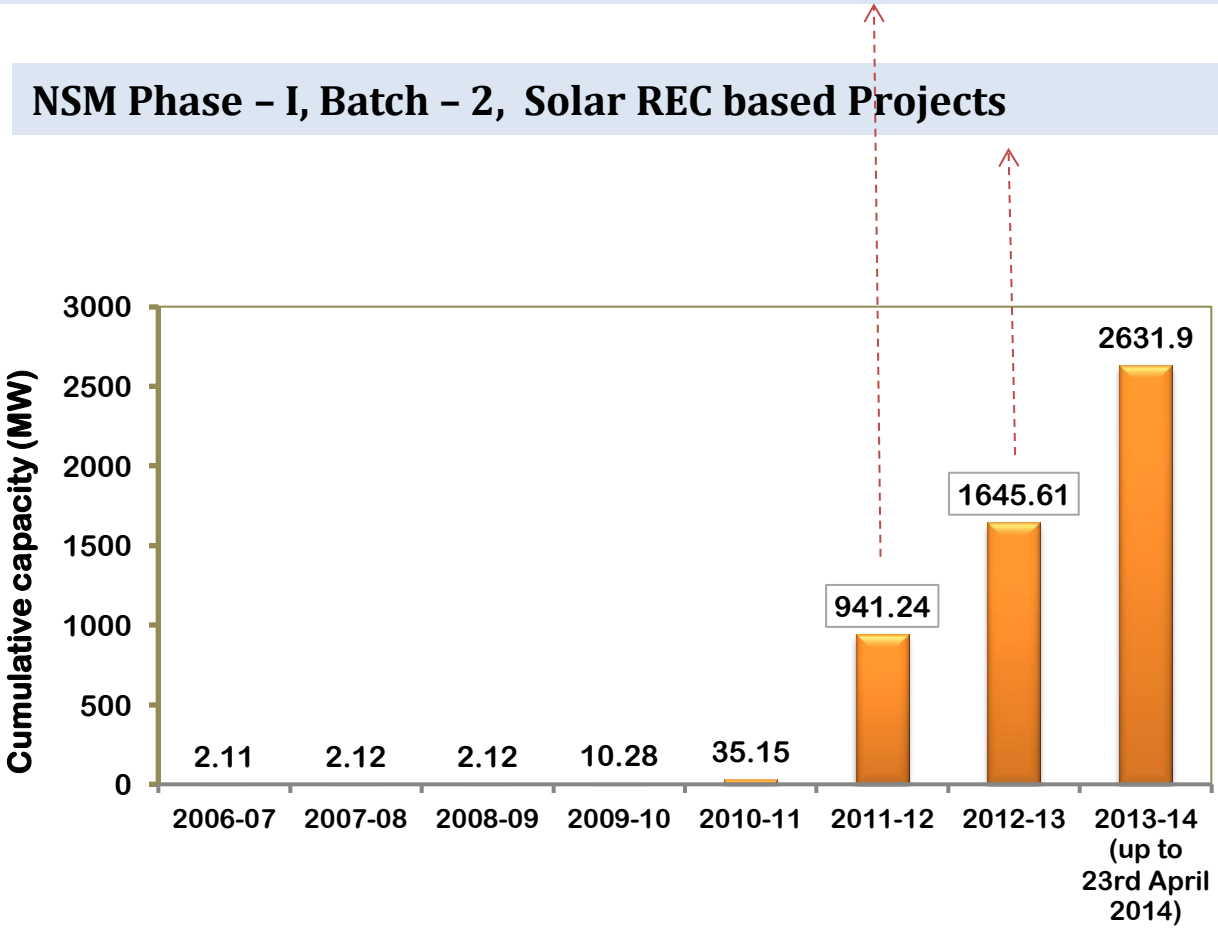


# Cumulative Capacity Addition of Solar Power

**NSM Phase – I, Batch – 1, Projects under Gujarat Solar Policy**

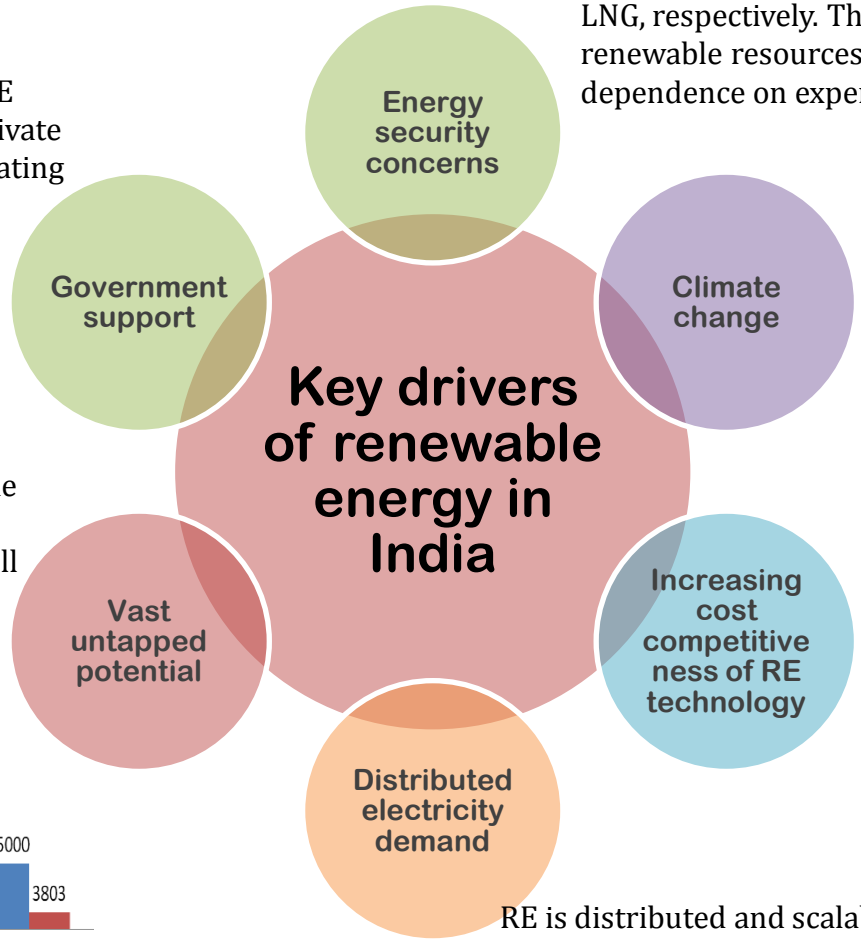
**NSM Phase – I, Batch – 2, Solar REC based Projects**




| Sr. No. | States | Installed Capacity (MW) |
|---|---|---|
| 1 | Andhra Pradesh | 131.84 |
| 2 | Arunachal Pradesh | 0.0025 |
| 3 | Chhattisgarh | 7.1 |
| 4 | Delhi | 5.15 |
| 5 | Goa & UT | 8.66 |
| 6 | Gujarat | 916.4 |
| 7 | Haryana | 10.3 |
| 8 | Jharkhand | 16 |
| 9 | Karnataka | 31 |
| 10 | Kerela | 0.025 |
| 11 | Madhya Pradesh | 347.17 |
| 12 | Maharashtra | 249.25 |
| 13 | Odisha | 30.5 |
| 14 | Punjab | 16.85 |
| 15 | Rajasthan | 730.1 |
| 16 | Tamil Nadu | 98.36 |
| 17 | Uttarakhand | 5.05 |
| 18 | Uttar Pradesh | 21.075 |
| 19 | West Bengal | 7.05 |
| Total | | 2631.88 |

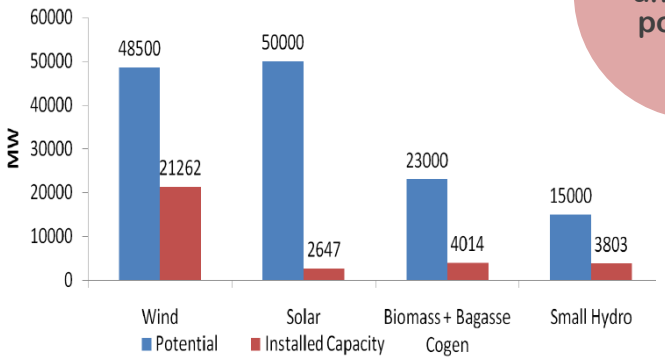
India ranks 4th and 6th globally as the largest importer of oil, and of petroleum products and LNG, respectively. The increased use of indigenous renewable resources is expected to reduce India's dependence on expensive imported fossil fuels.

Promoting the adoption of RE resources by encouraging private sector investment and mandating the use of RE generation




NAPCC – promoting the understanding, adaption and mitigation of climate change, energy efficiency and resource conservation

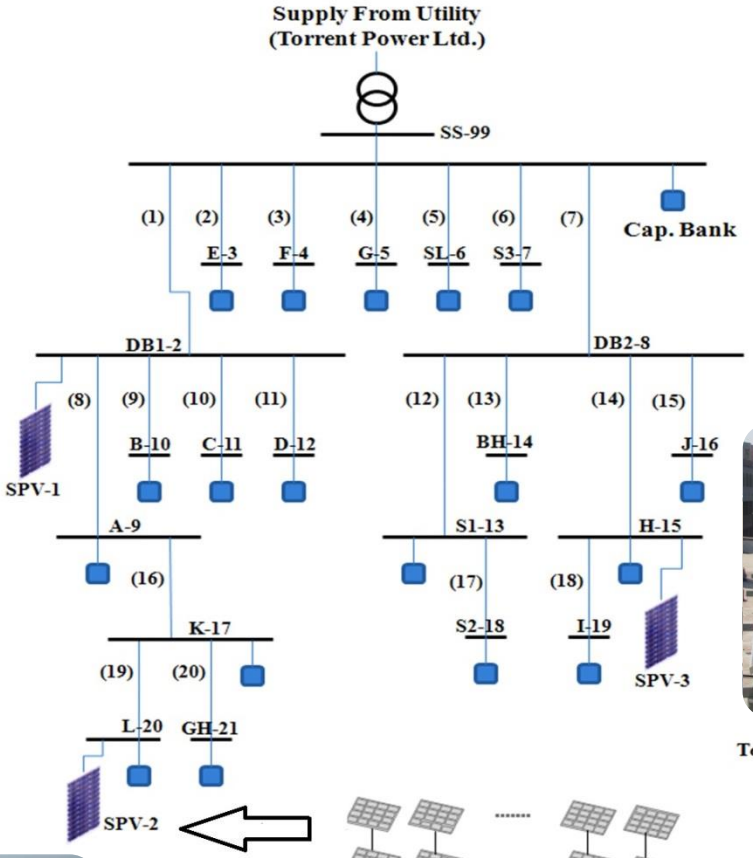
Ample opportunities for the establishment of land-based RE generation as well as for offshore wind farms



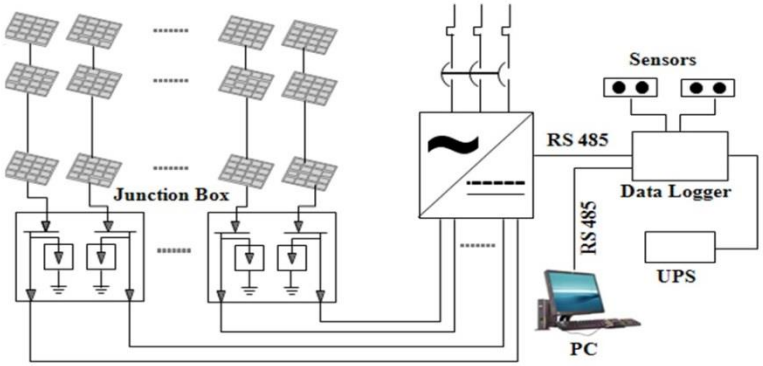

RE is distributed and scalable resource, making it well suited to meet the need for power in remote areas, which lack grid and road infrastructure

# Power Distribution Network of IITGN-VGEC Campus

**100 kW Multi-crystalline**
PV plant, 25 kVA x 4 inverters, ABB





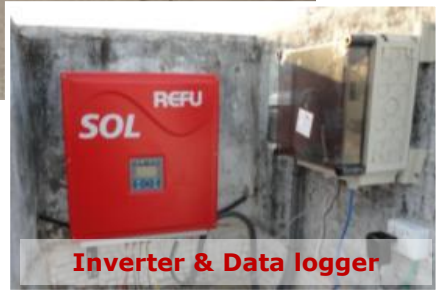



# 10 $kW_p$ Solar PV (Thin-film, CIS) System



**Pyranometer and Irradiance sensors with module temperature sensor**


**Ambient temperature sensor**




**PV Inverter** (REFU*sol* 010K)

**Data logger** (Solar-Log 200)

**PV module**

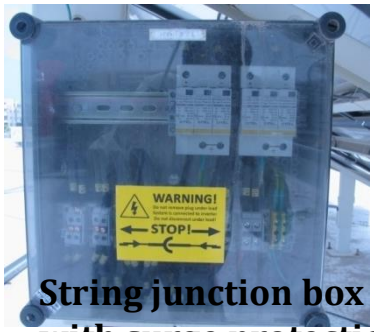
| | |
|---|---|
| Manufacturer | : Solar Frontier, Japan |
| Type | : CIS (SF150-L) |
| Nominal value | : 150 $W_p$ |

(http://www.solar-frontier.com)

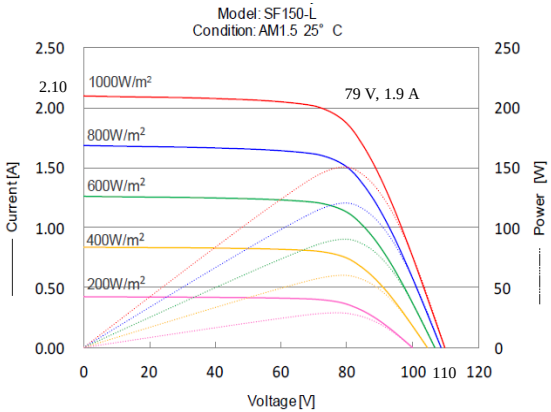
**Installation conditions**

| | |
|---|---|
| Inclined angle | : 25˚ |
| Orientation | : South |

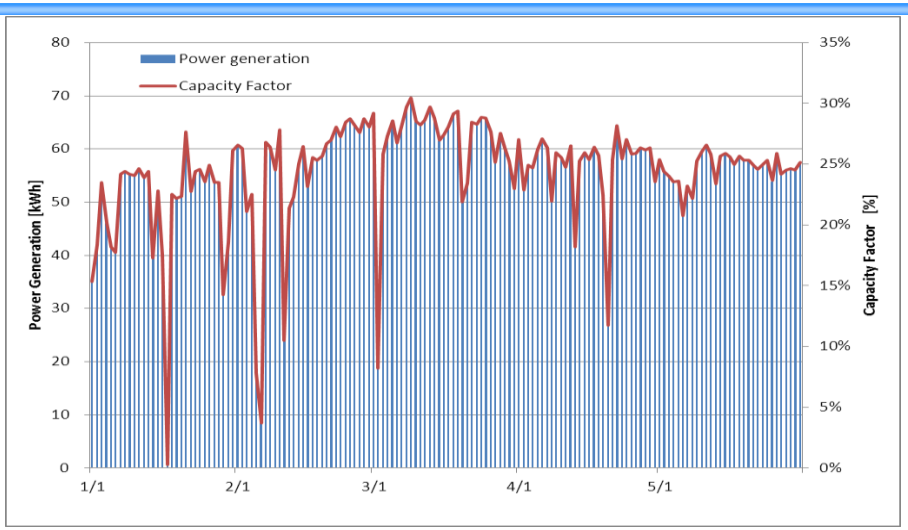
**Installed in January 2012**



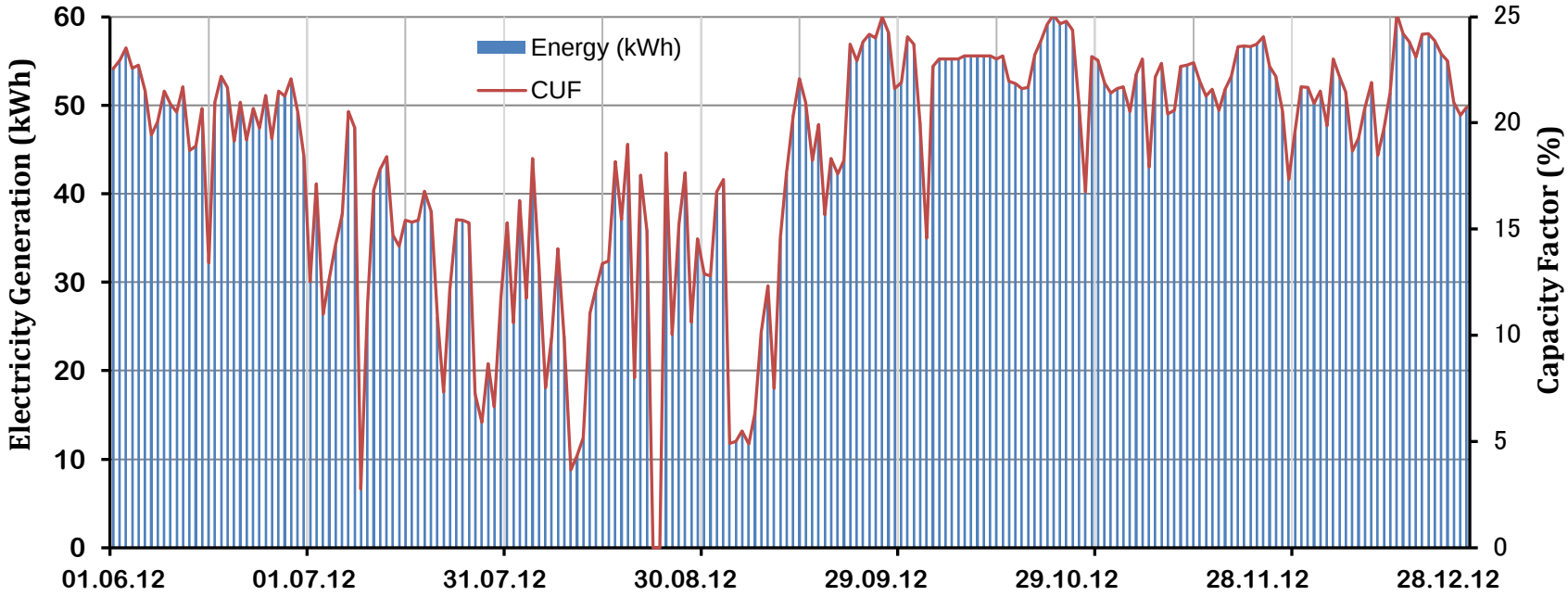

**String junction box with surge protection**



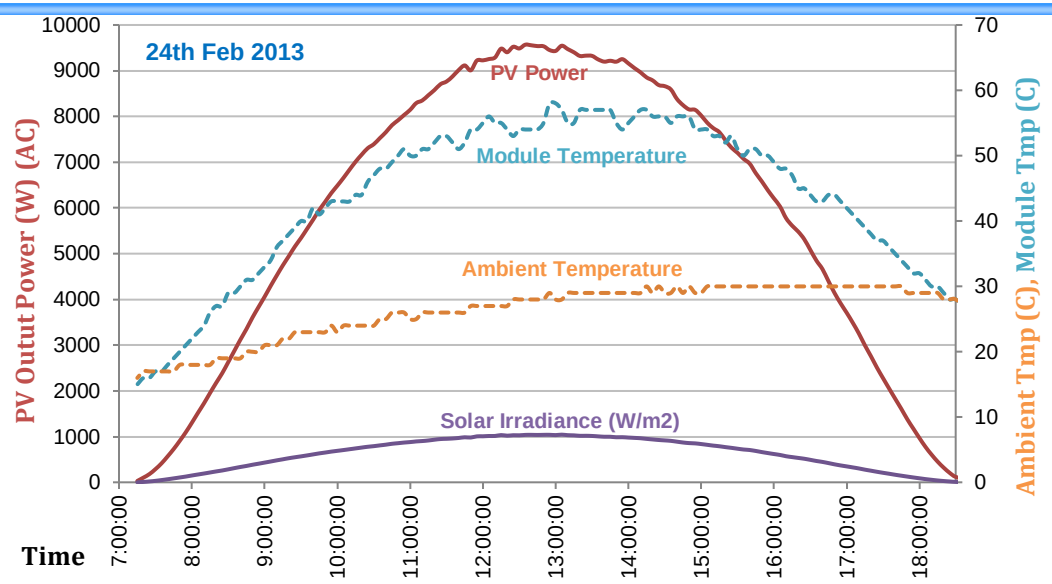
# 10 $kW_p$ Solar PV (Thin-film, CIS) System

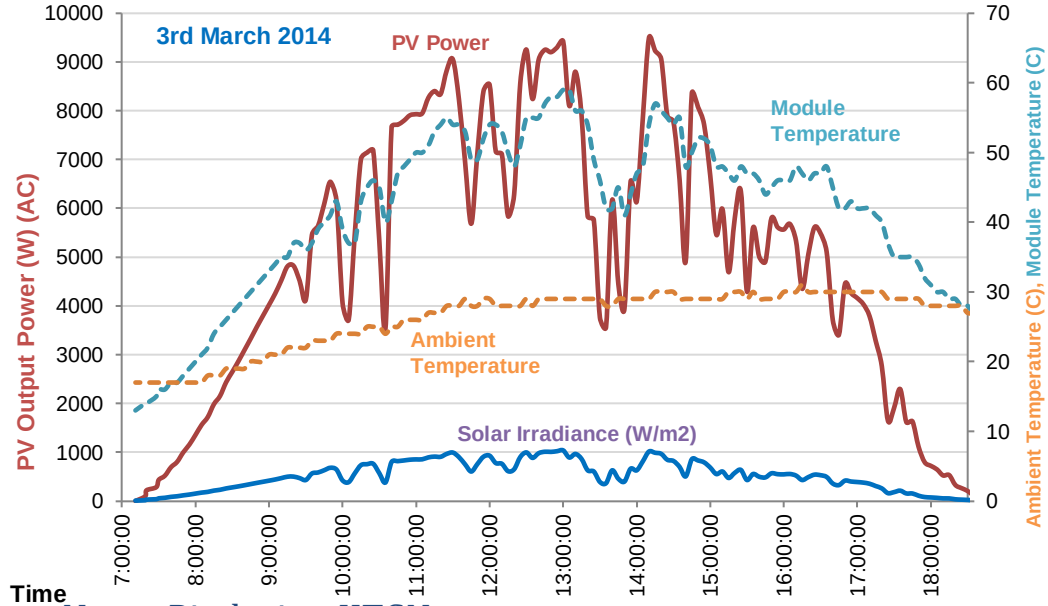



Solar PV system performance from January to May & June to December in 2012



# 10 $kW_p$ Solar PV (Thin-film, CIS) System

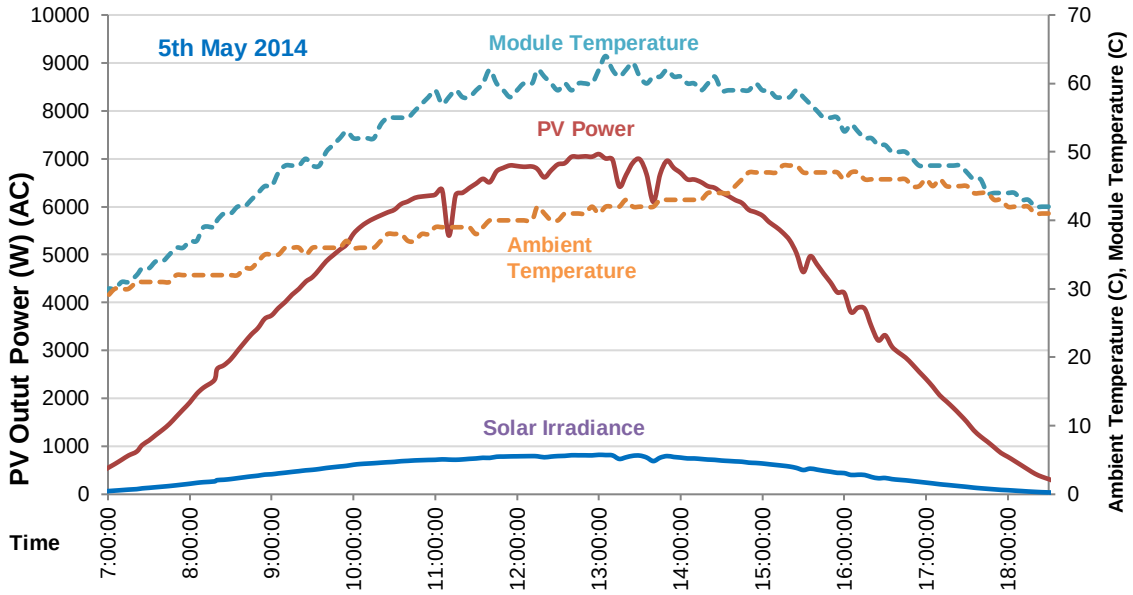



## Solar PV Profile over a day

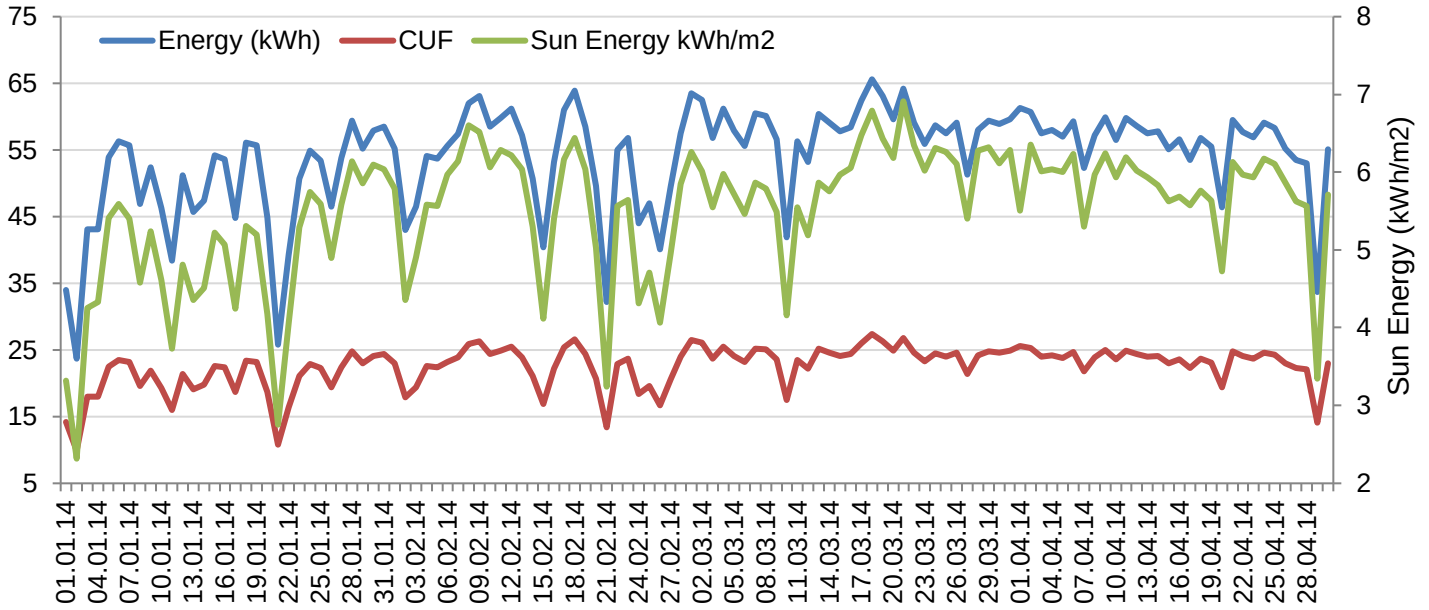
| Date | Time | Pac (W) | Energy (Wh) | Pdc (W) | Vdc (V) | Vac (Vph) | SolIrr (W/m2) | Tmp Mod | Tmp Amb | DaySumIrr (Wh/m2) |
|---|---|---|---|---|---|---|---|---|---|---|
| 24.02.13 | 13:35:00 | 9246 | 39500 | 9373 | 628 | 248 | 1009 | 57 | 29 | 3998 |
| 24.02.13 | 13:30:00 | 9323 | 38700 | 9449 | 628 | 249 | 1018 | 57 | 29 | 3923 |
| 24.02.13 | 13:25:00 | 9328 | 37900 | 9453 | 627 | 249 | 1022 | 57 | 29 | 3846 |
| 24.02.13 | 13:20:00 | 9321 | 37200 | 9450 | 627 | 249 | 1021 | 57 | 29 | 3770 |
| 24.02.13 | 13:15:00 | 9402 | 36400 | 9531 | 628 | 248 | 1031 | 55 | 29 | 3694 |
| 24.02.13 | 13:10:00 | 9471 | 35600 | 9599 | 630 | 249 | 1035 | 55 | 29 | 3616 |
| 24.02.13 | 13:05:00 | 9545 | 34800 | 9674 | 630 | 250 | 1046 | 57 | 28 | 3538 |
| 24.02.13 | 13:00:00 | 9432 | 34000 | 9558 | 628 | 249 | 1037 | 58 | 28 | 3460 |
| 24.02.13 | 12:55:00 | 9450 | 33200 | 9579 | 628 | 248 | 1043 | 58 | 29 | 3382 |
| 24.02.13 | 12:50:00 | 9533 | 32400 | 9667 | 632 | 248 | 1042 | 55 | 28 | 3305 |
| 24.02.13 | 12:45:00 | 9537 | 31700 | 9674 | 634 | 247 | 1040 | 54 | 28 | 3226 |
| 24.02.13 | 12:40:00 | 9554 | 30900 | 9702 | 634 | 247 | 1042 | 54 | 28 | 3148 |
| 24.02.13 | 12:35:00 | 9568 | 30100 | 9712 | 636 | 248 | 1041 | 54 | 28 | 3069 |
| 24.02.13 | 12:30:00 | 9485 | 29300 | 9627 | 637 | 247 | 1032 | 54 | 28 | 2990 |
| 24.02.13 | 12:25:00 | 9522 | 28500 | 9679 | 640 | 247 | 1034 | 53 | 28 | 2912 |
| 24.02.13 | 12:20:00 | 9403 | 27700 | 9545 | 637 | 247 | 1024 | 54 | 27 | 2834 |
| 24.02.13 | 12:15:00 | 9481 | 26900 | 9621 | 636 | 247 | 1037 | 55 | 27 | 2756 |
| 24.02.13 | 12:10:00 | 9288 | 26400 | 9427 | 634 | 246 | 1018 | 55 | 27 | 2679 |

# 10 $kW_p$ Solar PV (Thin-film, CIS) System

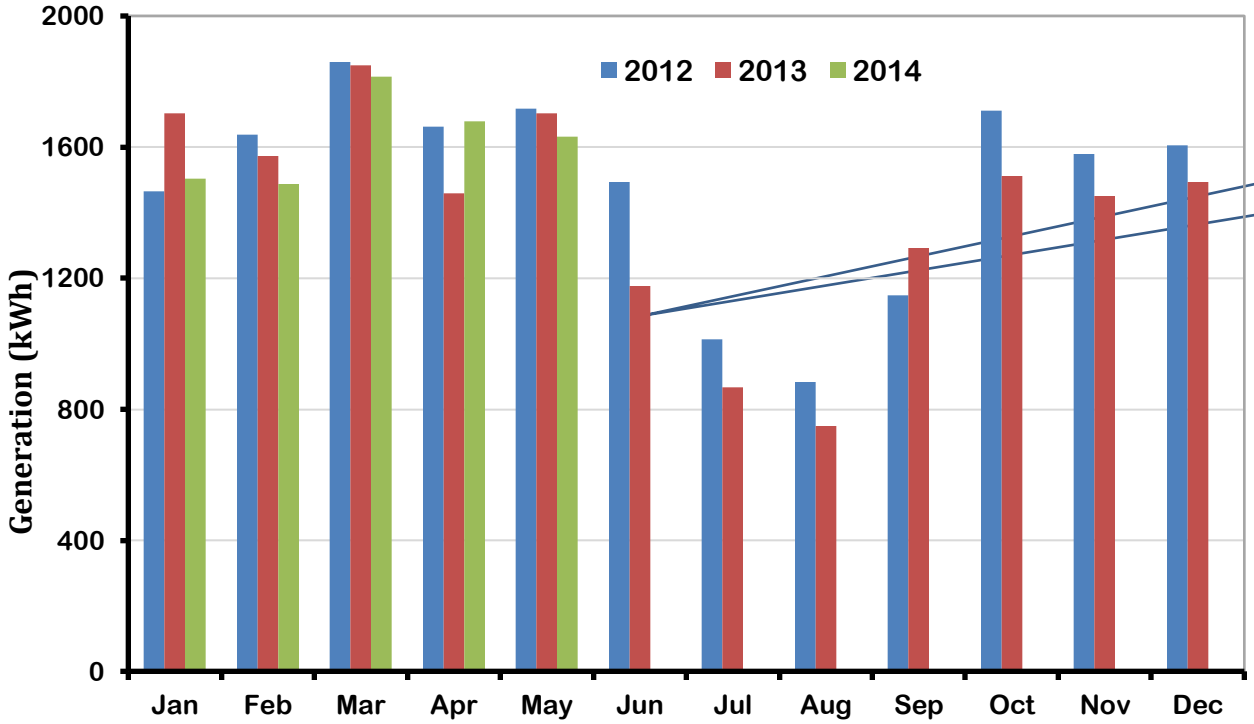



## Statistical (Average) performance (so far in 2014)

- **Energy: 54 kWh/day**
- **Sun Energy: 5.5 kWh/m²/day**
- **CUF: 22.5**



# 10 $kW_p$ Solar PV (Thin-film, CIS) System




Rain started in June month in 2013 whereas it was started in July in 2012

- It has been observed that *winter season is most favorable* weather condition for solar PV power generation
- Energy generation in *March month is the highest* across the year
- The performance in *rainy season (July-Sept) is so much intermittent* which essentially drops the total power generation in this season

# 10 $kW_p$ Solar PV (Multicrystalline Silicon) System


Pyranometer and Irradiance sensors with module temperature sensor





PV Inverter (REFU*sol* 010K)

**PV module**

Manufacturer : Jain Photovoltaic
Type : JJ – M660
Nominal value : 230 $W_p$

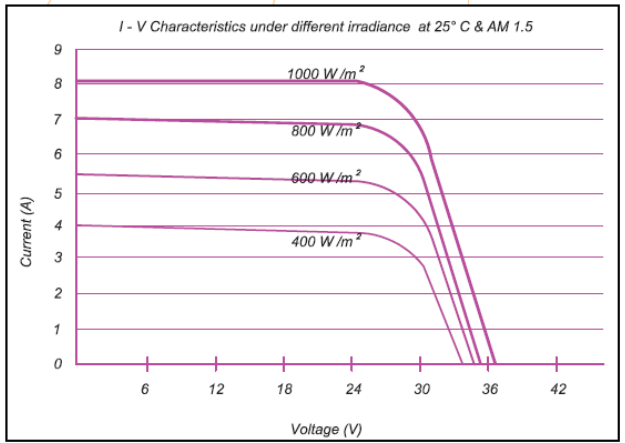
(http://www.jains.com/Solar/jain%20jyot/Models%20-%2010%20to%20230%20watt.htm)

**Installation conditions**

Inclined angle : 21°
Orientation : South

**Installed in February 2012**

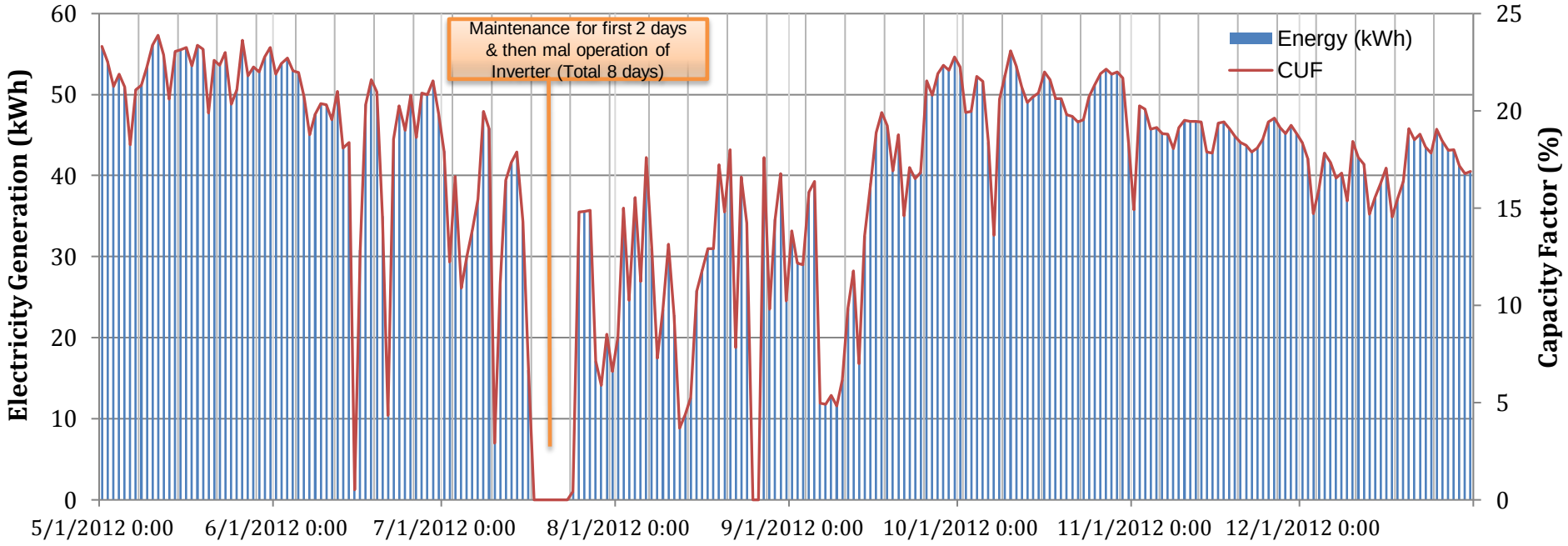
Naran Pindoriya, IITGN




| | |
|---|---|
| $P_{max}$ | 230 $W_p$ |
| $V_{mpp}$ | 30.26 V |
| $I_{mpp}$ | 7.55 A |
| $V_{oc}$ | 36.35 |
| $I_{sc}$ | 8.15 |

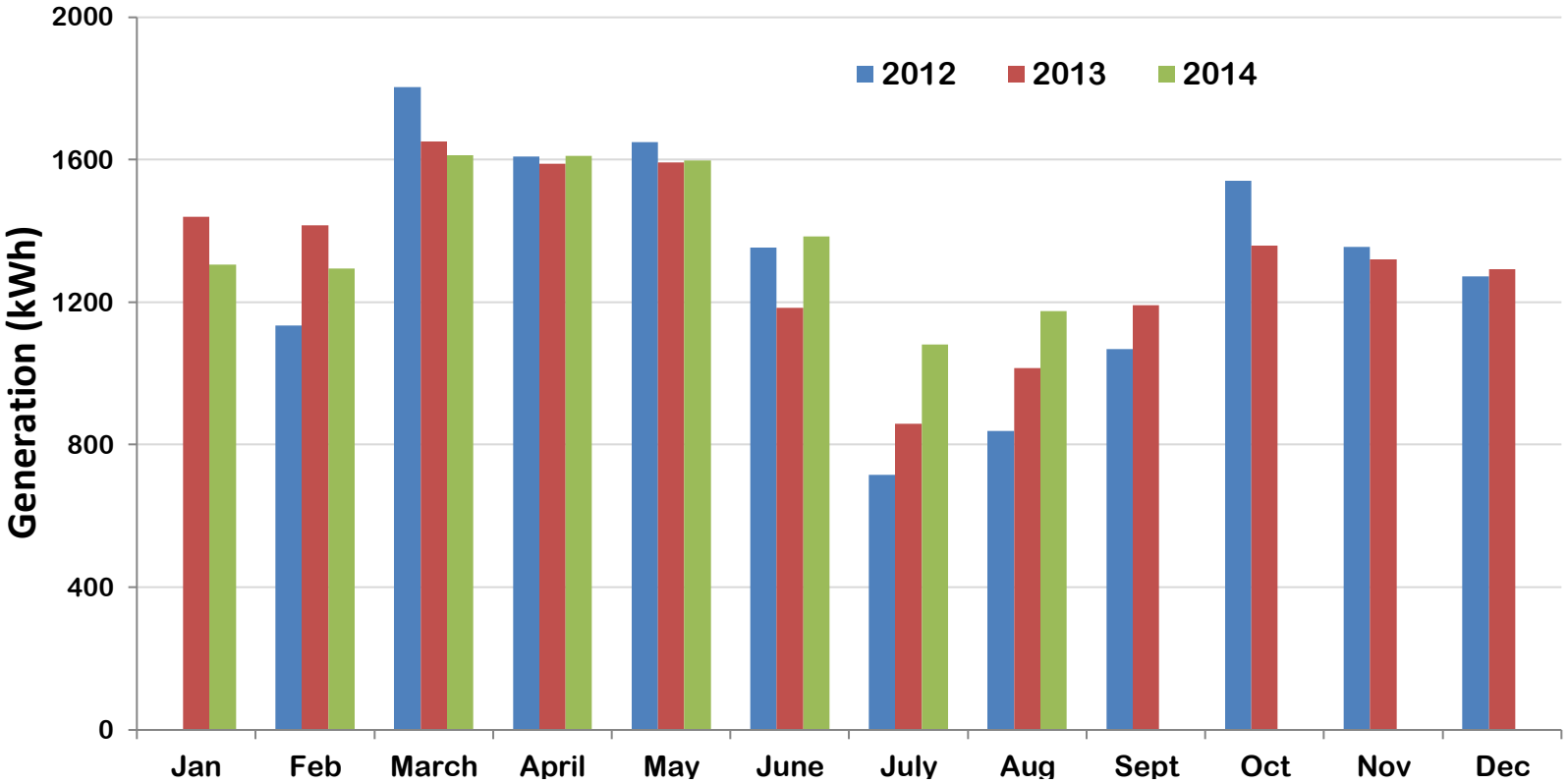
# 10 $kW_p$ Solar PV (Multicrystalline Silicon) Rooftop System

## Solar PV system performance from May to December in 2012

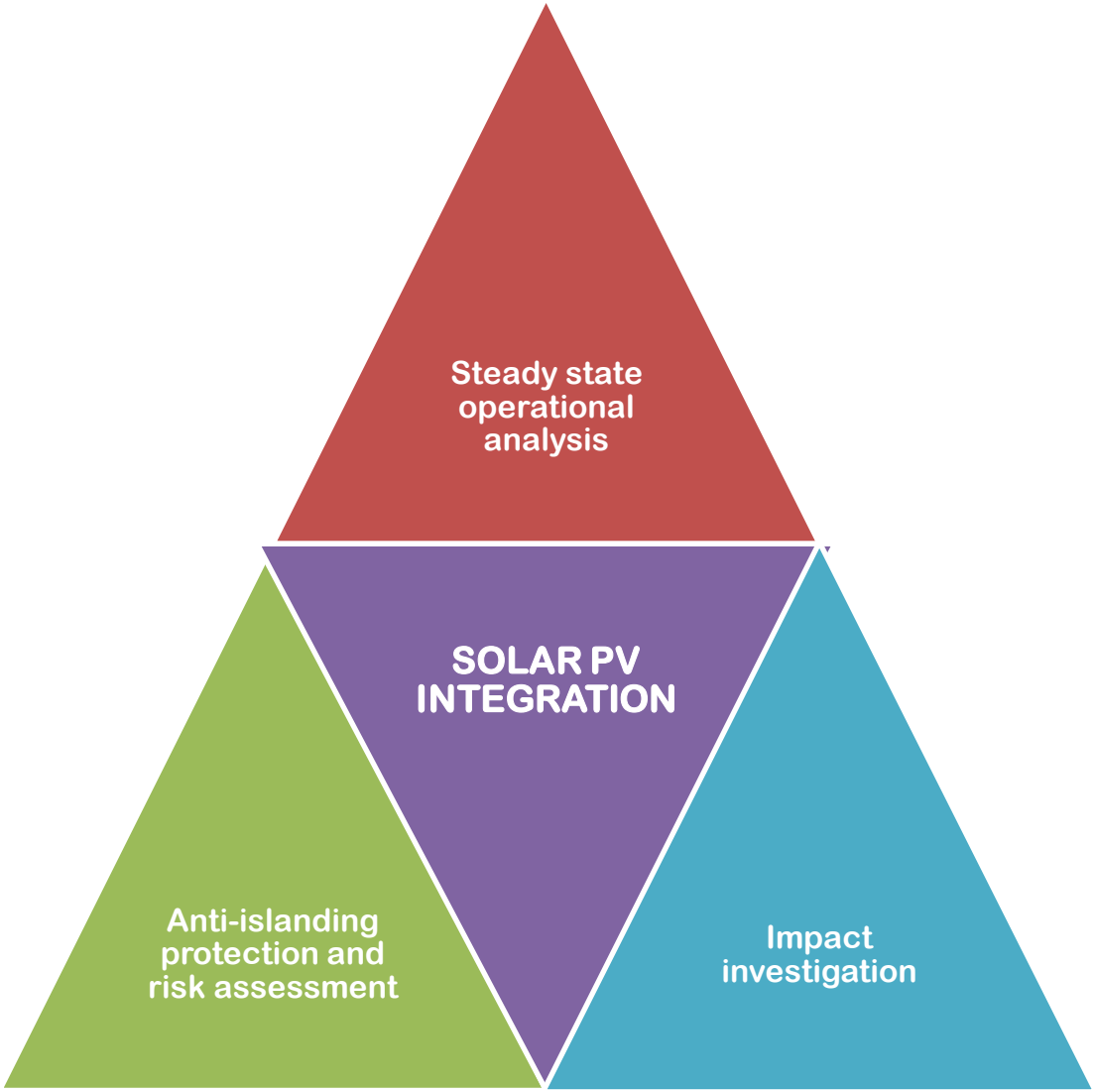



Operational failure sometimes happened because of unstable distribution grid conditions

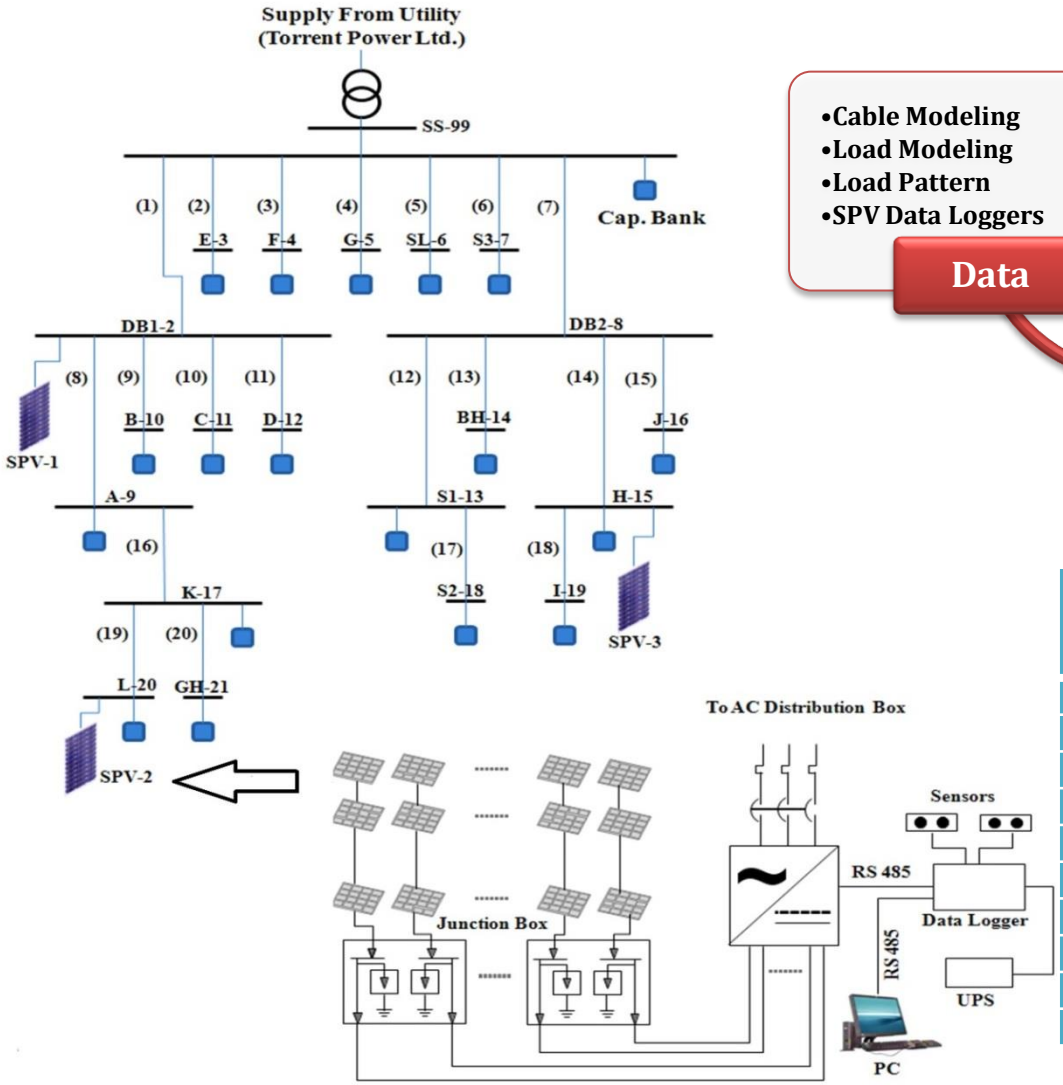
# 10 $kW_p$ Solar PV (Multicrystalline Silicon) System

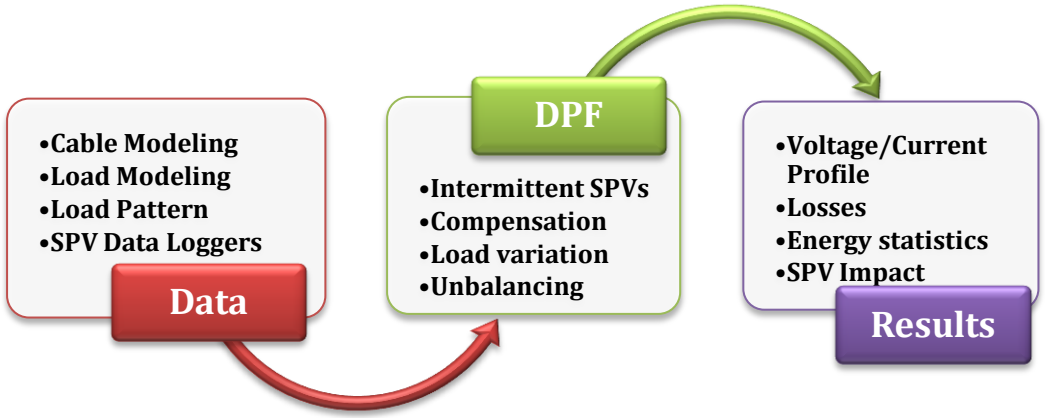



- Energy generation in ***March month*** is the highest across the year
- The performance ***in rainy season (July-Sept) is so much intermittent*** which essentially drops the total power generation in this season


Steady state operational analysis
SOLAR PV INTEGRATION
Anti-islanding protection and risk assessment
Impact investigation

# The Impact Investigation Exercise




| Node | Lighting Loads | Air Conditioners | Single Phase Motors | Electronic Loads |
|---|---|---|---|---|
| 3 | 4% | 82% | 9% | 5% |
| 7 | 5% | 86% | 6% | 3% |
| 9 | 6% | 78% | 4% | 11% |
| 13 | 12% | 65% | 10% | 13% |
| 14 | 25% | 57% | 8% | 10% |
| 15 | 8% | 72% | 7% | 12% |
| 17 | 5% | 88% | 6% | 1% |
| 18 | 9% | 78% | 8% | 5% |
| 20 | 6% | 74% | 5% | 15% |
| 21 | 25% | 54% | 11% | 10% |

Kalpesh Joshi and N.M. Pindoriya, "Impact Investigation of Rooftop Solar PV System: A Case Study in India," *2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, Berlin, October 14-17, 2012, pp. 1-8.

# The Impact Investigation Exercise

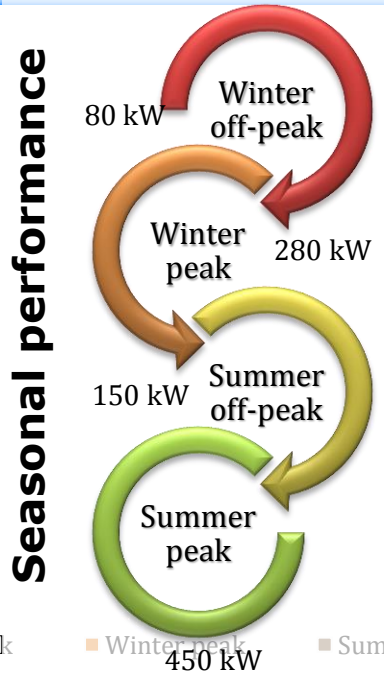
**Case 1**
- Base case study
- Balance load, without capacitor compensation and solar PV generation

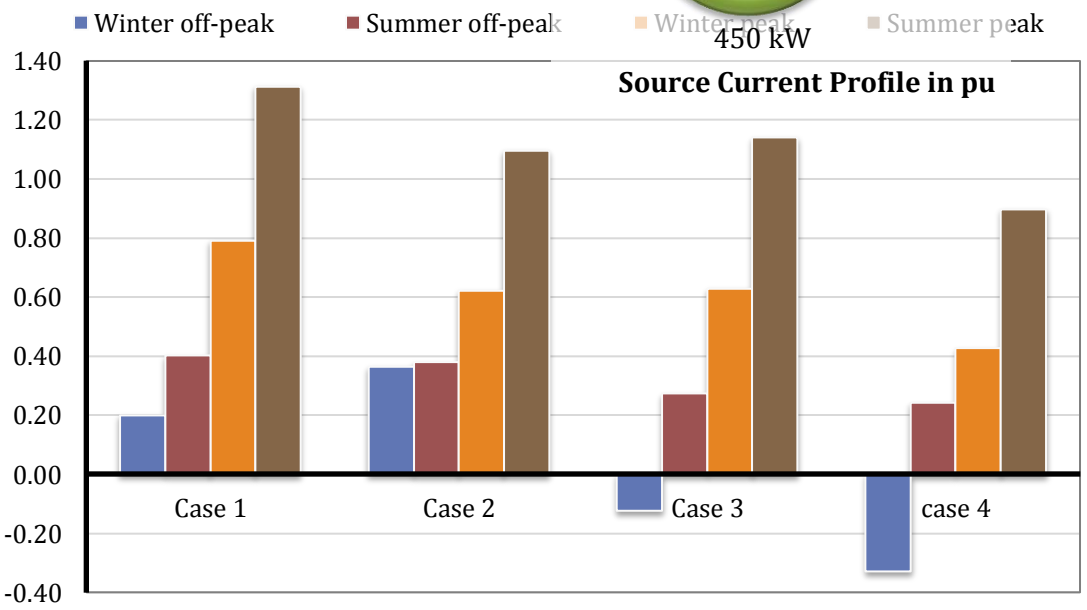
**Case 2**
- With capacitor compensation
- Balance load, without solar PV generation

**Case 3**
- With solar PV generation
- Balance load, without capacitor compensation

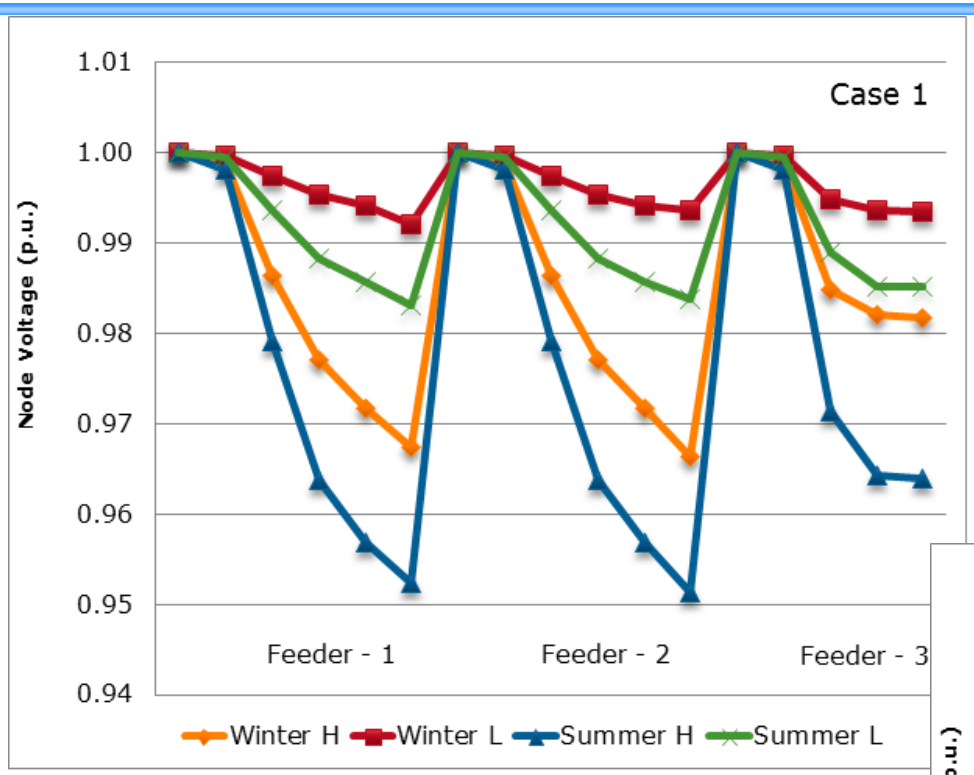
**Case 4**
- With capacitor compensation & solar PV generation
- Balance load

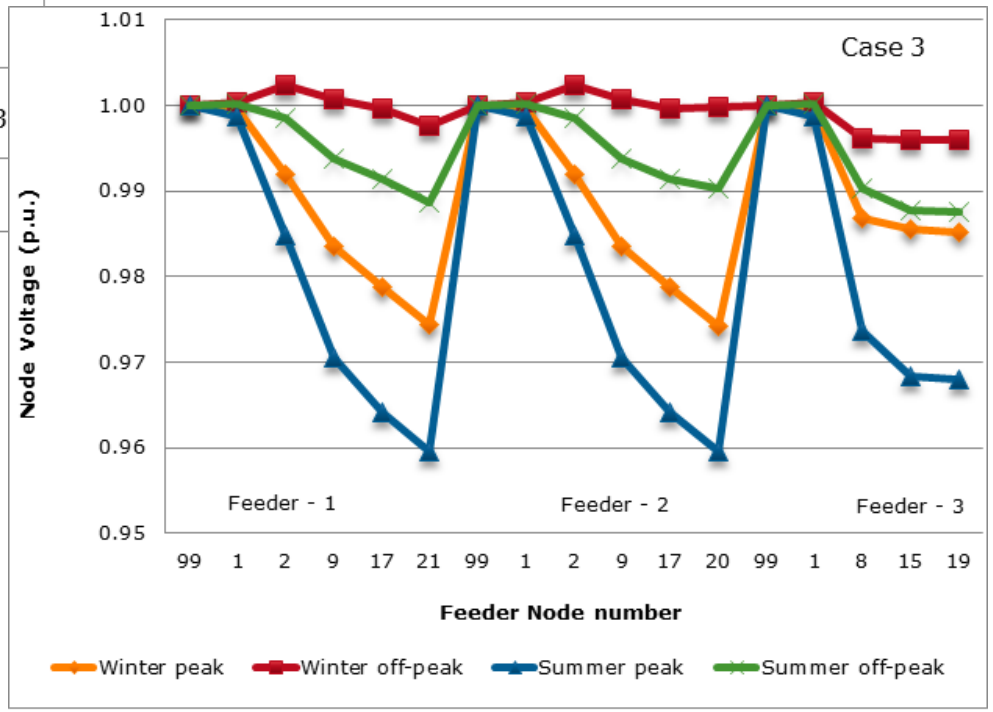
**Case 5**
- Unbalance load
- With capacitor compensation & solar PV generation



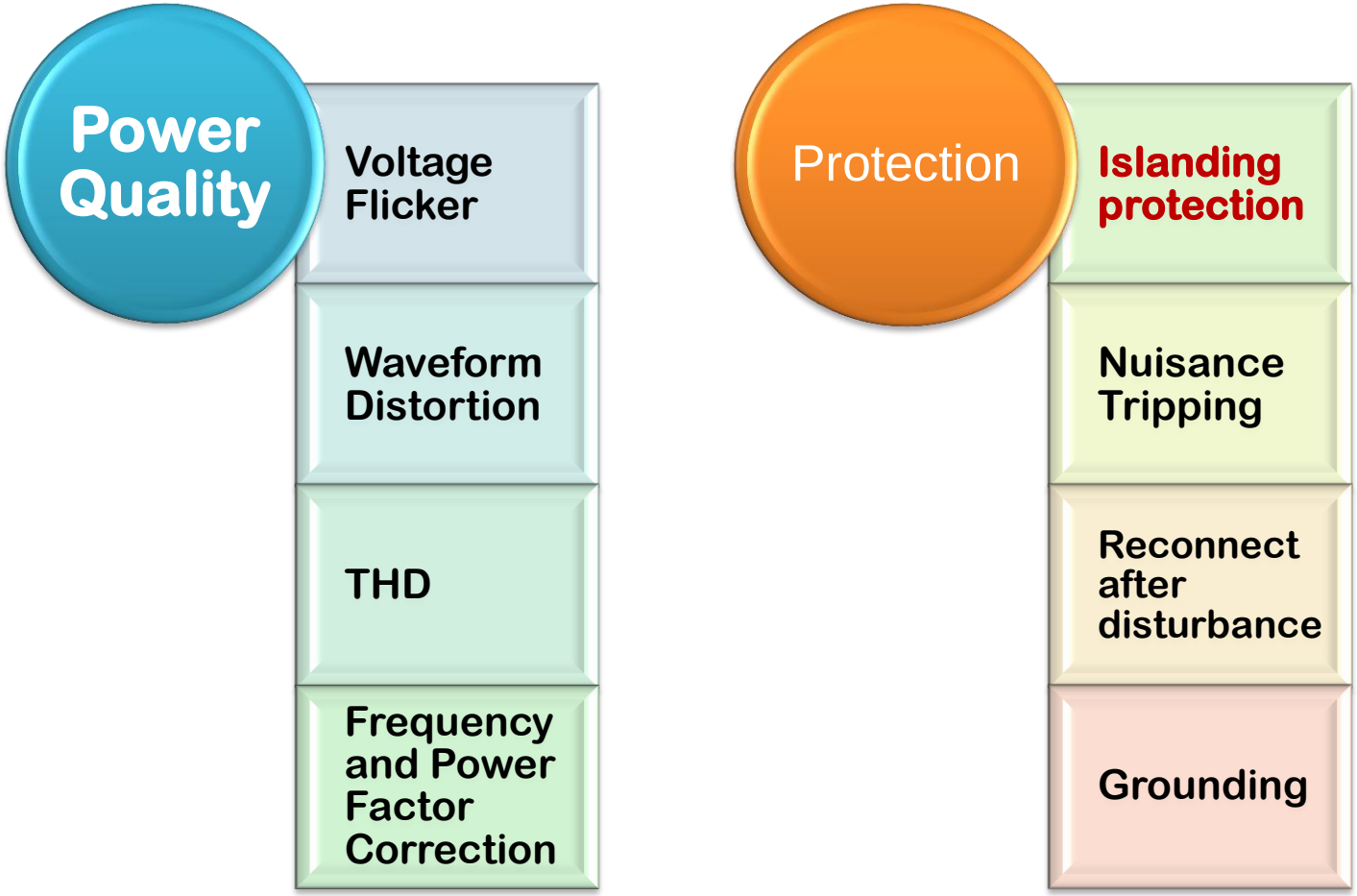



# The Impact Investigation Exercise



# Technical issues in solar PV integration with utility distribution grid




*IEEE Recommended Practice for Utility Interface of PV systems*, IEEE Standard 929-2000

## Power Quality Constraints

Response to Abnormal Voltages

| RMS voltages at PCC | Maximum trip time |
|---|---|
| V <50% | 6 cycles (0.12 sec) |
| 50% <V <88% | 6 cycles (0.12 sec) |
| 88% <V <110% | Normal operation |
| 110% <V <137% | 120 cycles (2.4 sec) |
| 137% <V | 6 cycles (0.12 sec) |

THD<5% of fundamental frequency

| Odd harmonics | Limit % | Even harmonics | Limit % |
|---|---|---|---|
| $3^{rd} - 9^{th}$ | <4 | $2^{nd} - 8^{th}$ | <1 |
| $11^{th} - 15^{th}$ | <2 | $12^{th} - 16^{th}$ | <0.5 |
| $17^{th} - 21^{st}$ | <1.5 | $18^{th} - 22^{nd}$ | <0.375 |
| $23^{rd} - 33^{rd}$ | <0.6 | $24^{th} - 34^{th}$ | <0.15 |

## Islanding Condition

Islanding detection time

| | |
|---|---|
| 10 cycles (0.2 sec) or less | 50 % mismatch in P<br>Load p.f. <0.95 (lead or lag) |
| 2 seconds | Q.F. <2.5<br>Load p.f. >0.95 (lead or lag) |

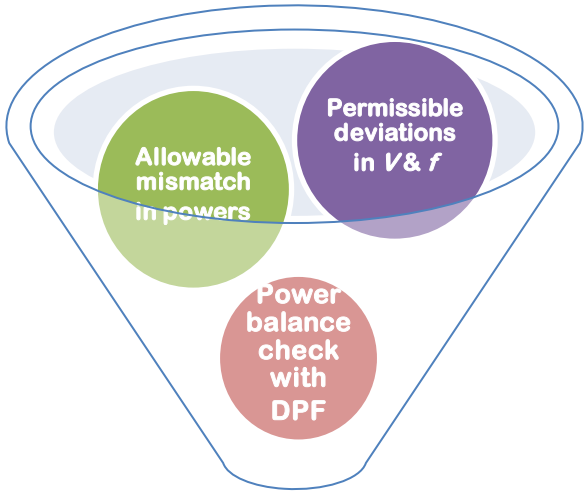
Islanding scenario in Indian conditions:

| | |
|---|---|
| Quality Factor | 1.6 to 2.5 |
| Voltage Threshold | 80% <V <110% |
| Frequency Threshold | 47.5 Hz <f <50.5 Hz |
| Active Power Threshold | $-17.36\% < \frac{\Delta P}{P} < 56.25\%$ |
| Reactive Power Threshold | $-27\% < \frac{\Delta Q}{P} < 4.925\%$ |
| Total Harmonic Distortion | THD <4.92% |

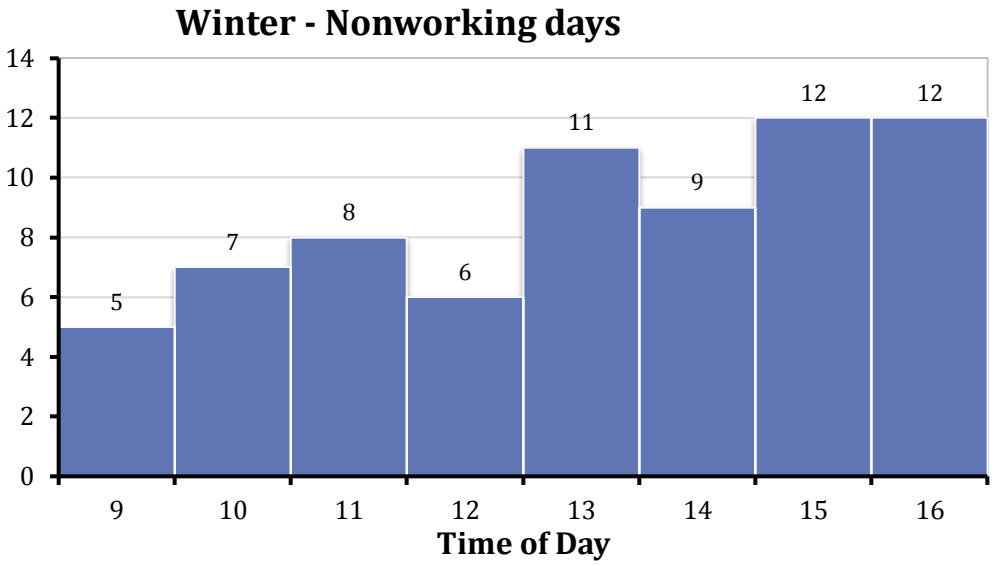
# Risk Assessment of Unintentional Islanding Exercise

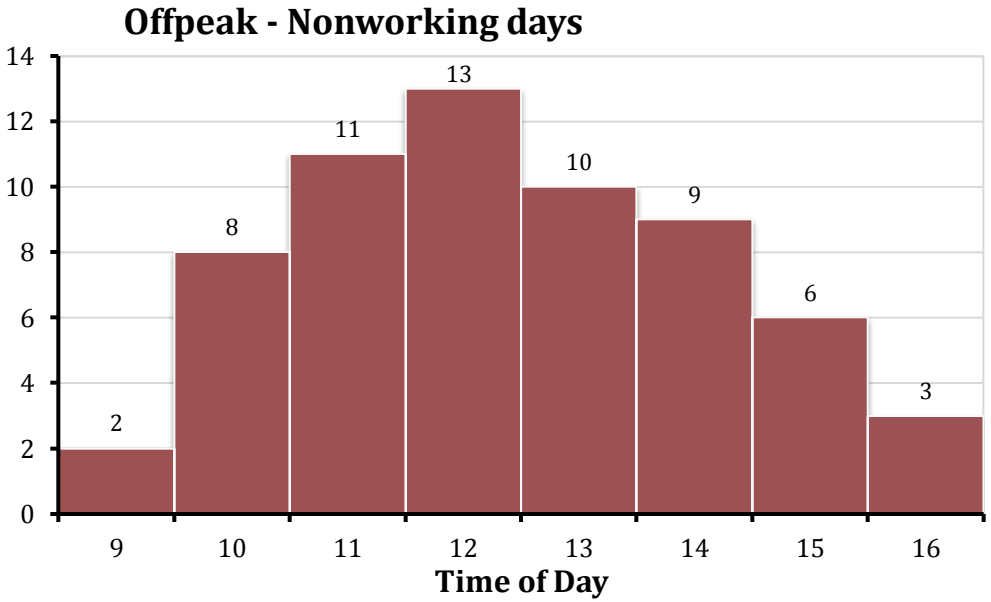
## What is Unintentional Islanding ???

**Process of elimination and identification of probable scenarios for unintended islanding**




**Most Probable Days and Time of Day (ToD) for formation of island**



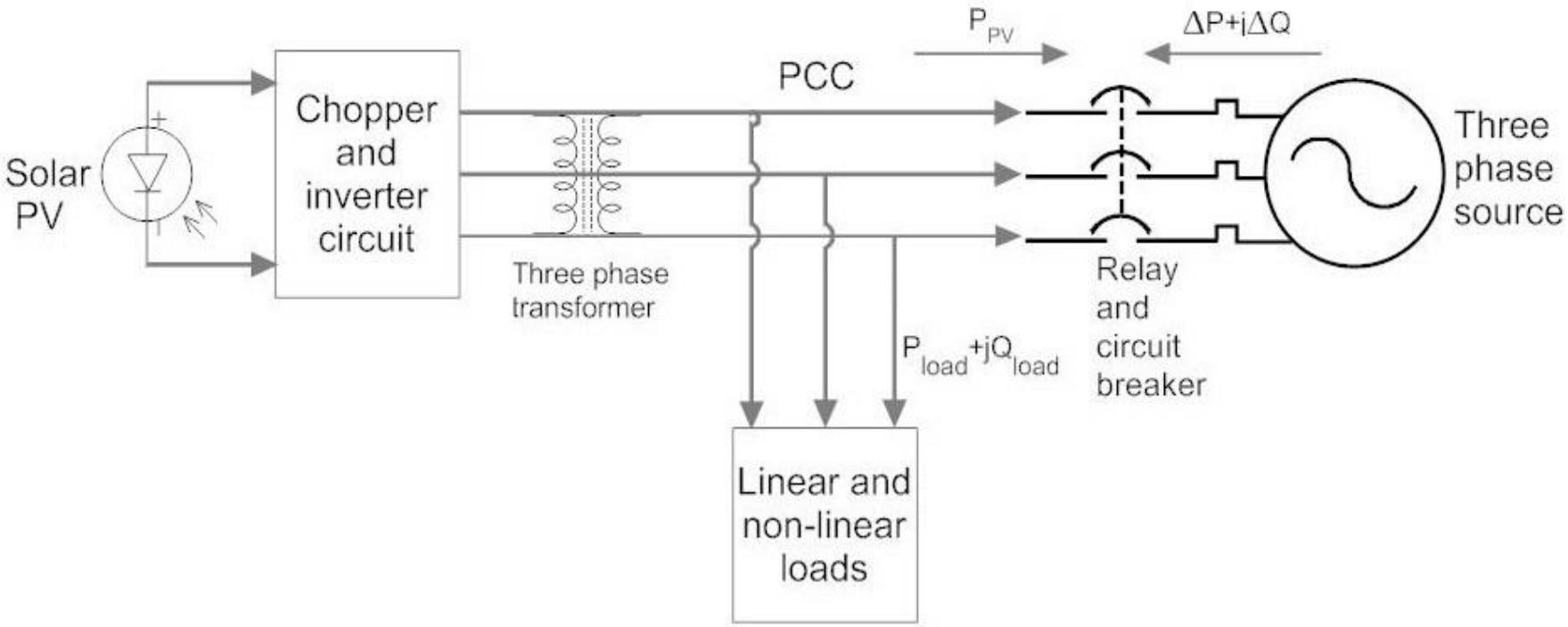
# Goals for successful grid integration

*Detection of islanding and disconnection* of the PV system from the utility, regardless of the initial state of the system, perturbations, composition of the load

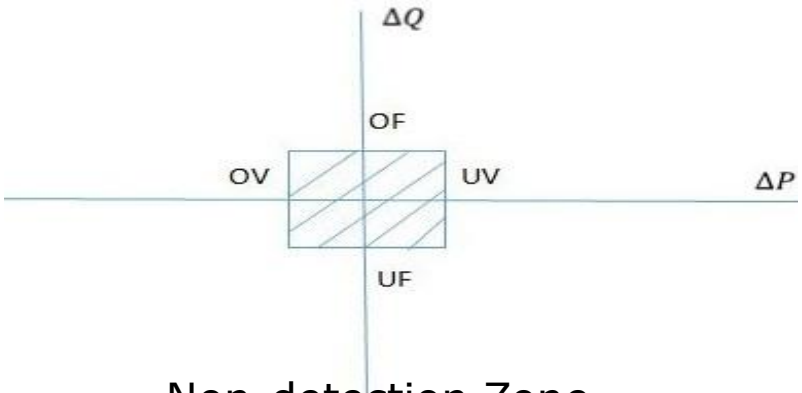
*Detection of islanding which is sufficiently fast* to guarantee safety and safeguard the reliability and integrity of the utility and PV systems

Disconnection of the PV system only when islanding is actually occurring (*no nuisance trips*)

# Anti-Islanding Protection

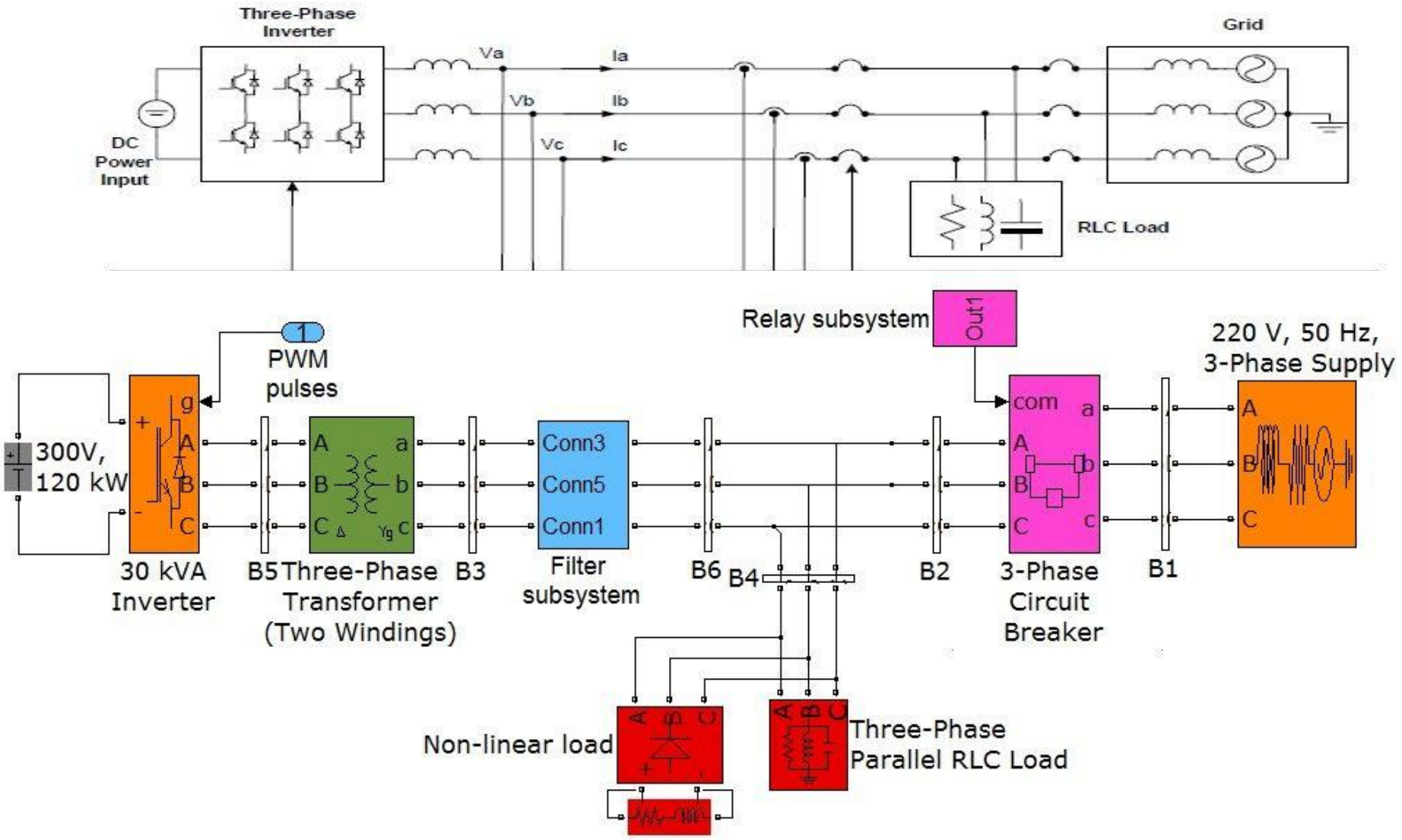



| $\Delta P > 0$ Under voltage relay | $\Delta P < 0$ Over voltage relay | $\Delta Q > 0$ Over frequency relay | $\Delta Q < 0$ Under frequency relay |
|---|---|---|---|



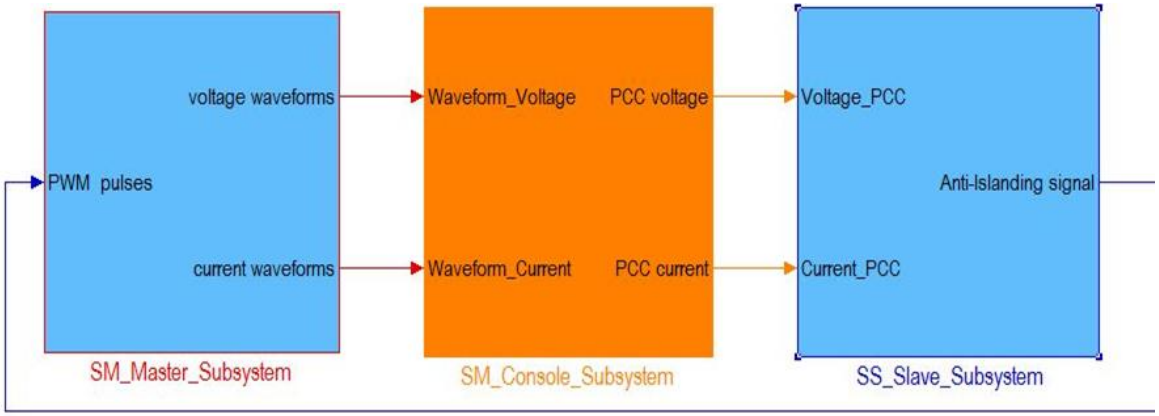

Non-detection Zone

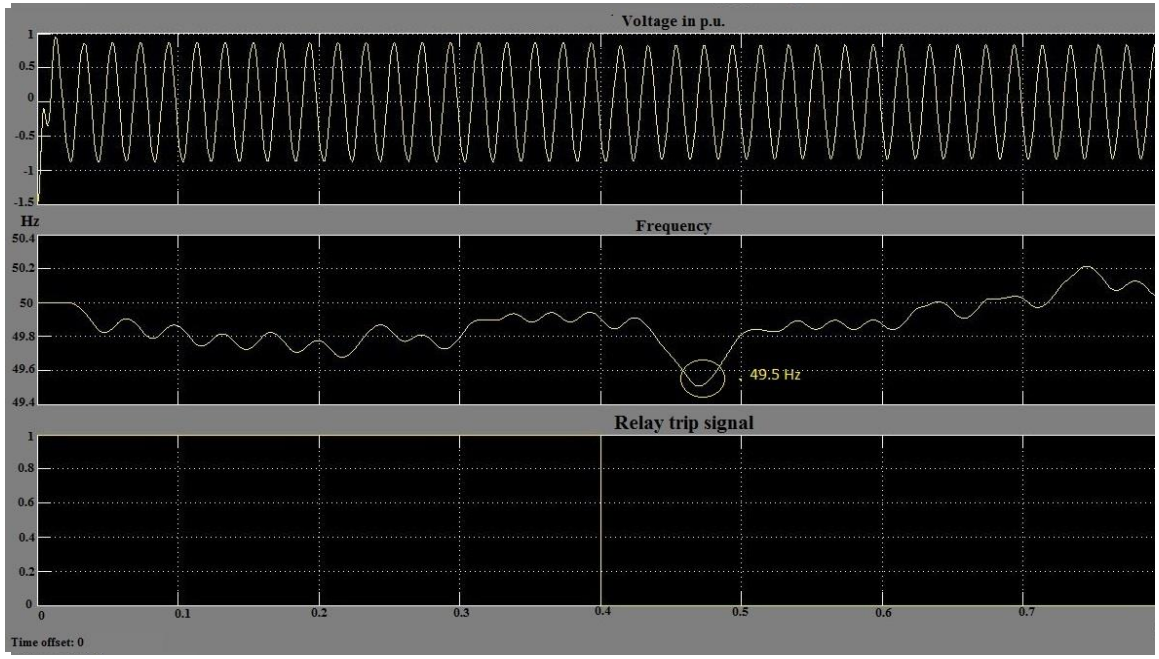
# Anti-Islanding Protection



# Anti-Islanding Protection

## Real time digital simulation



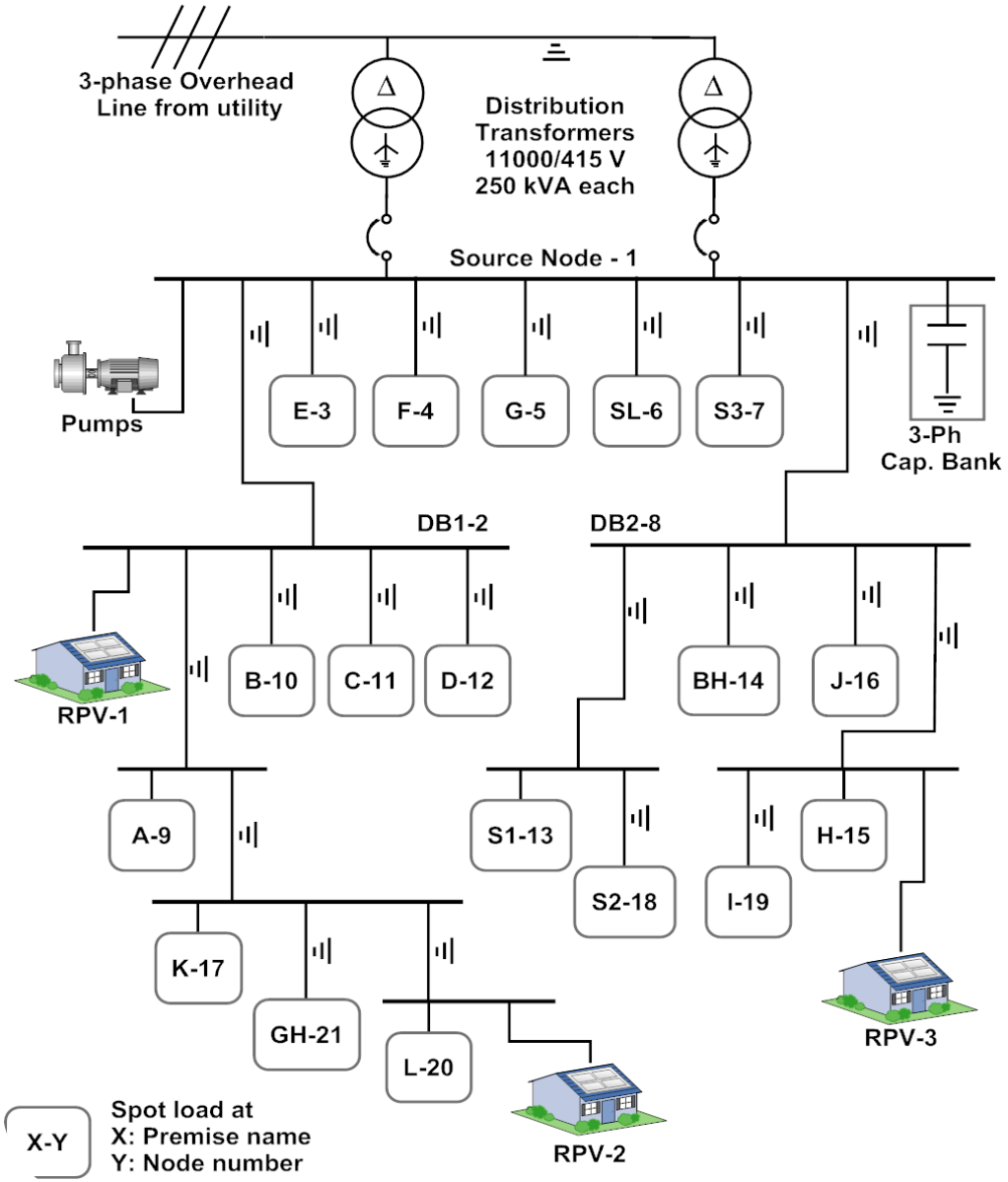

# Unbalance Distribution Network Operations with PV Generation

## Unbalance Distribution Networks under Study

**IITGN-VGEC Network –**

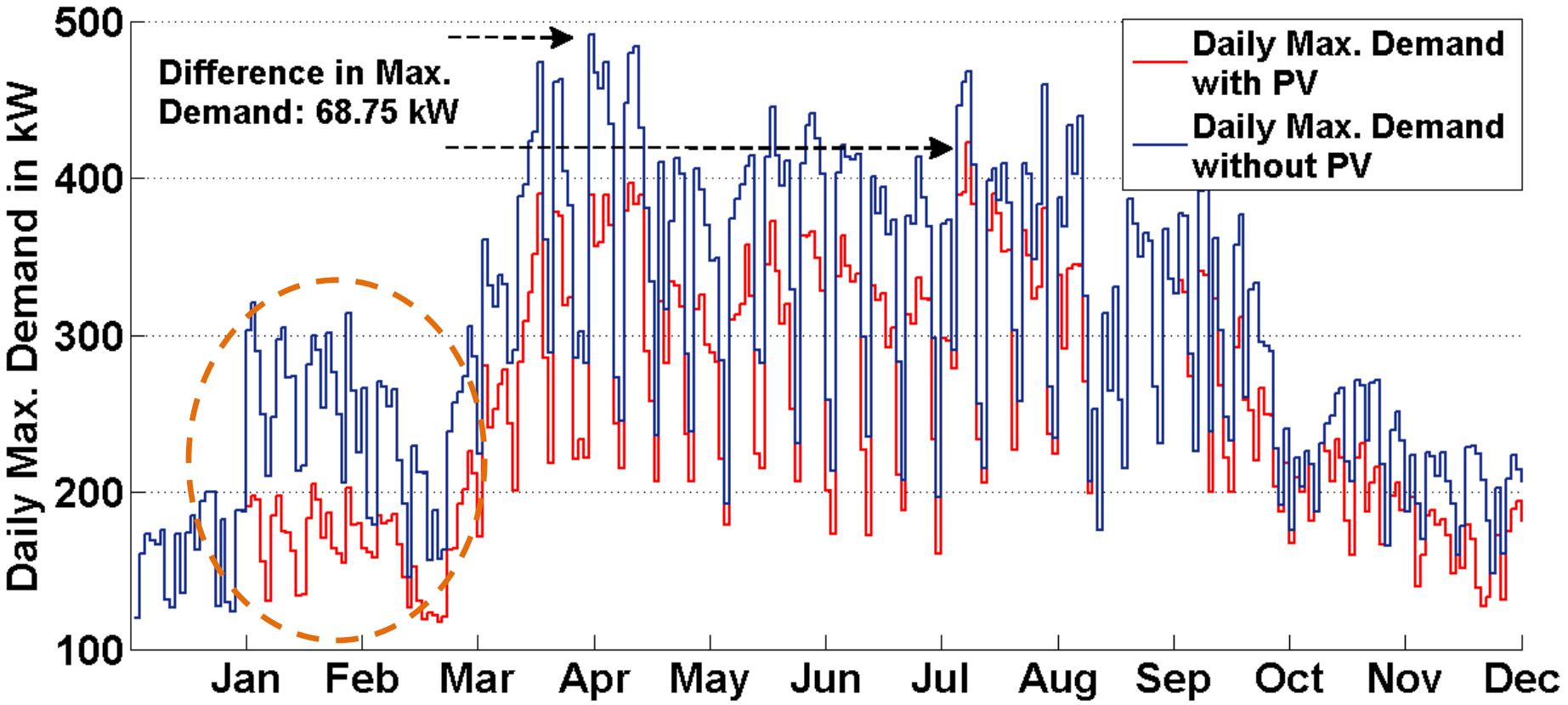
**An underground cable-fed actual spot network in India with 3 roof-top PV plants**

**21 Node Network, 400 V, small & spot network**



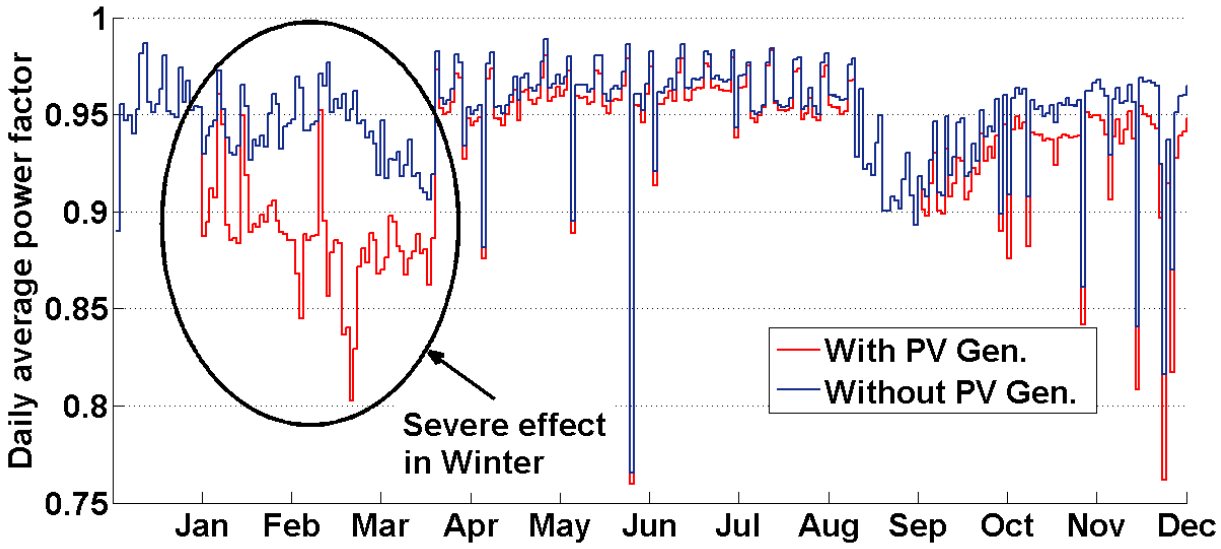
# Unbalance Distribution Network Operations with PV Generation (IITGN-VGEC)

Daily peak demand – with and without PV generation



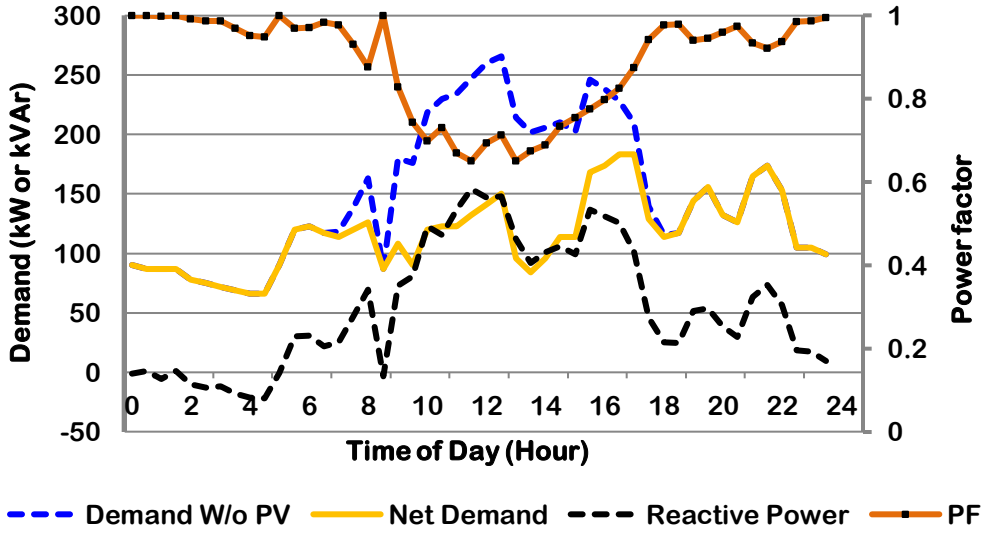

maximum reduction in peak demand occurs in the months of February and March. However, the year-round net reduction in peak demand is found to be 68.75 kW.

# Unbalance Distribution Network Operations with PV Generation (IITGN-VGEC)




average power factor consistently stays below 0.9 (lagging) during the months of February, March and partly April in the year 2012

- The drop in average power factor is shown expanded for a typical day (February 27, 2012).
- The real power demand sinks during sun-shine hours due to real power injection from RPVs. Inverters of all RPVs are set to operate at unity power factor.

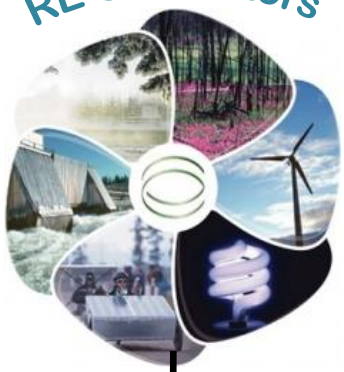


# Renewable Energy Trading

**Cost of electricity through RE generation**

- **Cost equivalent to conventional resources**
- **Cost for "GREEN" Attributes**

RE Generators



| | |
|---|---|
| Solar PV | • 12-15 Rs/kWh for first 12 years<br>• 3-5 Rs/kWh for next 13 years |
| Solar Thermal | • 9-11 Rs/kWh for first 12 years<br>• 3 -4 Rs/kWh for next 13 years |
| Wind | 3-5 Rs/kWh |

Unbundling of REC from electrical energy

**REC Option**

**Feed-in-Tariff (FiT)**

**Electricity**

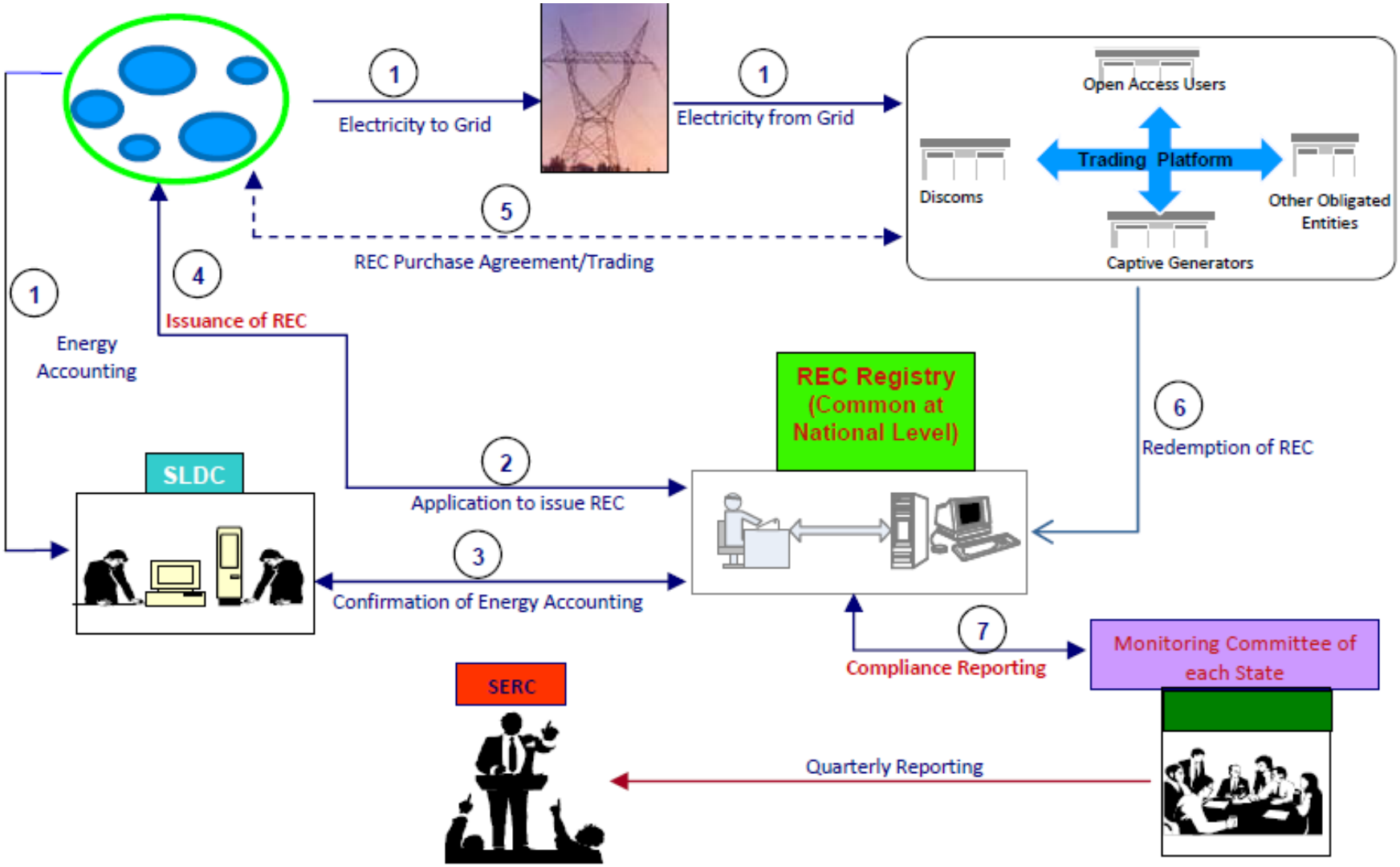
- **Electricity sale at market price**
- **Sale of electricity to obligated entities at price ≤ average price**

**Green attributes**

- **REC (Solar and non-solar)**
  - **Sale of REC at PXs**

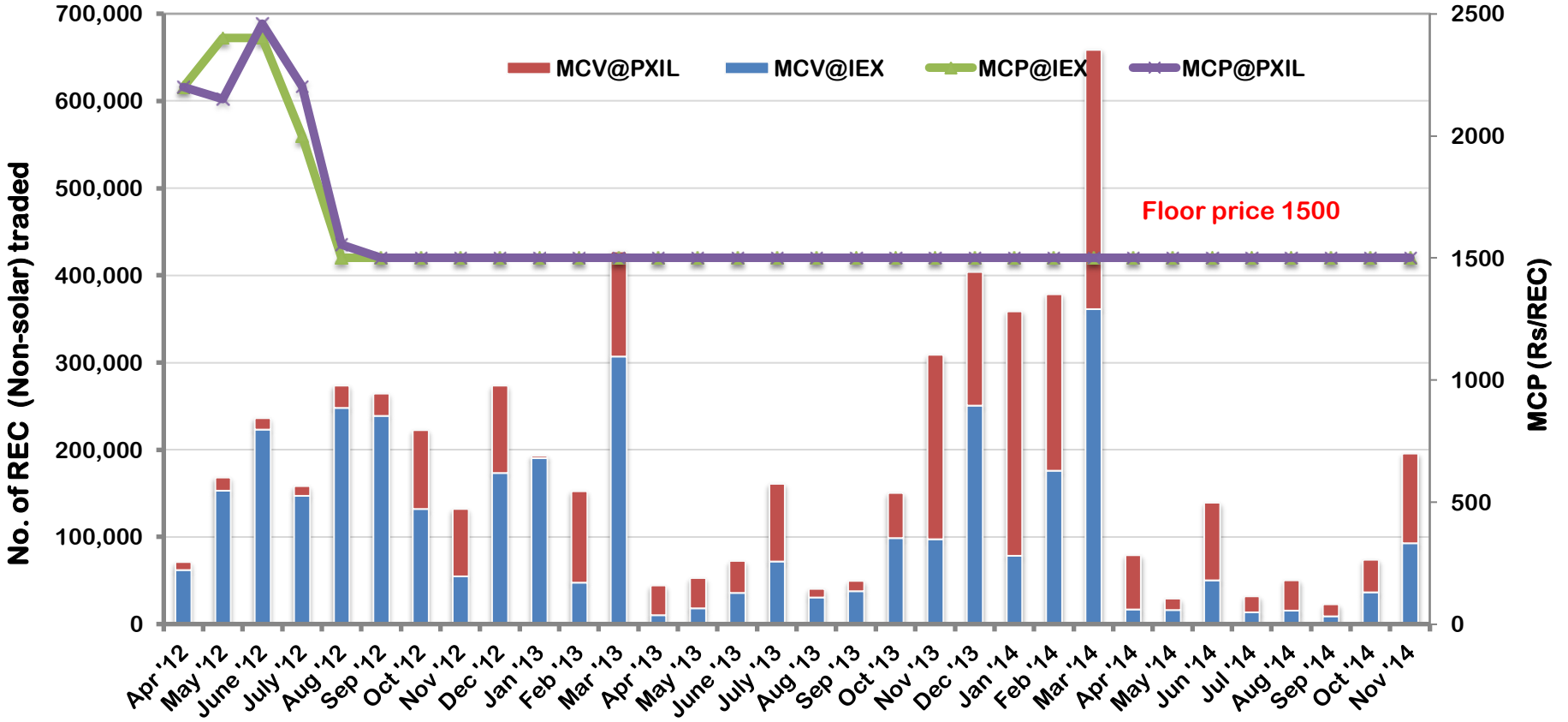
**Sale of electricity to *obligated entities* (DISCOMs, CPPs, OA consumers) at preferential tariff**

# Operational Framework for REC



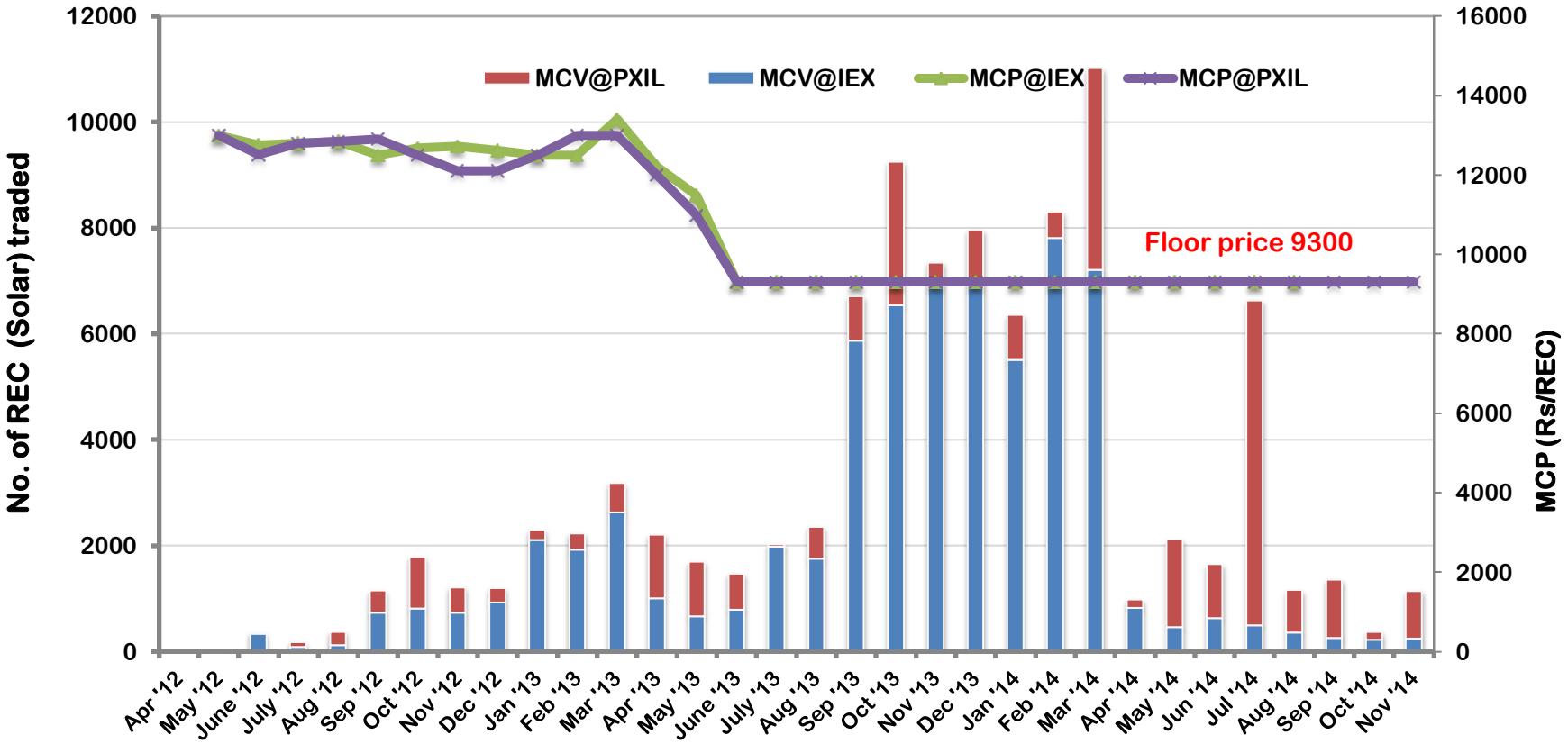

**Source: MNRE**

# Non-solar REC Trading




| Non-Solar REC (Rs/REC) | Forbearance Price | Floor Price |
|---|---|---|
| | 3300 | 1500 |

# Solar REC Trading




| Solar REC (Rs/REC) | Forbearance Price | Floor Price |
|---|---|---|
| | 13,400 | 9300 |

# Thank You !