CLEAN ENERGY SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY
An Initiative of the Clean Energy Ministerial

INTERNATIONAL SOLAR ALLIANCE

CARBON TRUST

International Solar Alliance Expert Training Course

Introduction to Technical Integration of PV

In partnership with the Clean Energy Solutions Center (CESC)

Dr Pol Arranz-Piera, Dr Oriol Gomis-Bellmunt

September 2019

Supporters of this Expert Training Series

INTERNATIONAL SOLAR ALLIANCE

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Overview of Training Course Modules

This Webinar is the **Introduction** to Module 4

Expert Trainer: Dr Pol Arranz-Piera

Brief Profile:

- Projects Director and Senior Engineer at AIGUASOL, an international energy consulting, engineering and R&D firm
- Previous experience includes Trama Tecnoambiental (TTA) and URS Corp. (currently AECOM)
- 20+ years of experience in the renewable energy and energy efficiency sectors, covering nearly 40 countries in Europe, The Americas, Africa, the Middle East and Asia
- Associate researcher and lecturer at the Technical University of Catalonia (UPC) on electricity services planning, solar and biomass technologies.

Expert Trainer: Prof Oriol Gomis-Bellmunt

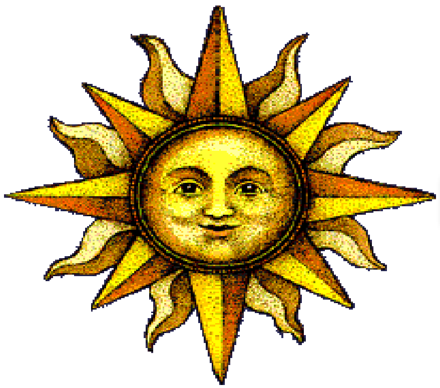
- Professor in the Electrical Power Department of Technical University of Catalonia (UPC)
- Directive board member of the research group CITCEA-UPC, where he leads the group of power systems dominated by power electronics, including renewable energy (PV and wind), HVDC transmission systems and other power converter based systems (energy storage, EV chargers)
- 20+ years of experience in the fields of renewable energy, power electronics and power systems. Involved in a number of research projects and contracts of technology transfer to industry.
- Coauthor of 3 books, 7 patents and > 100 journal publications, mainly in the field of power electronics in power systems and grid integration of renewables.

Index

- Basics of PV systems or plants
- Levels of integration of PV systems
- Highlights of the 7 webinars on Technical integration of PV systems

Solar radiation and PV modules

Solar Radiation



PV Module

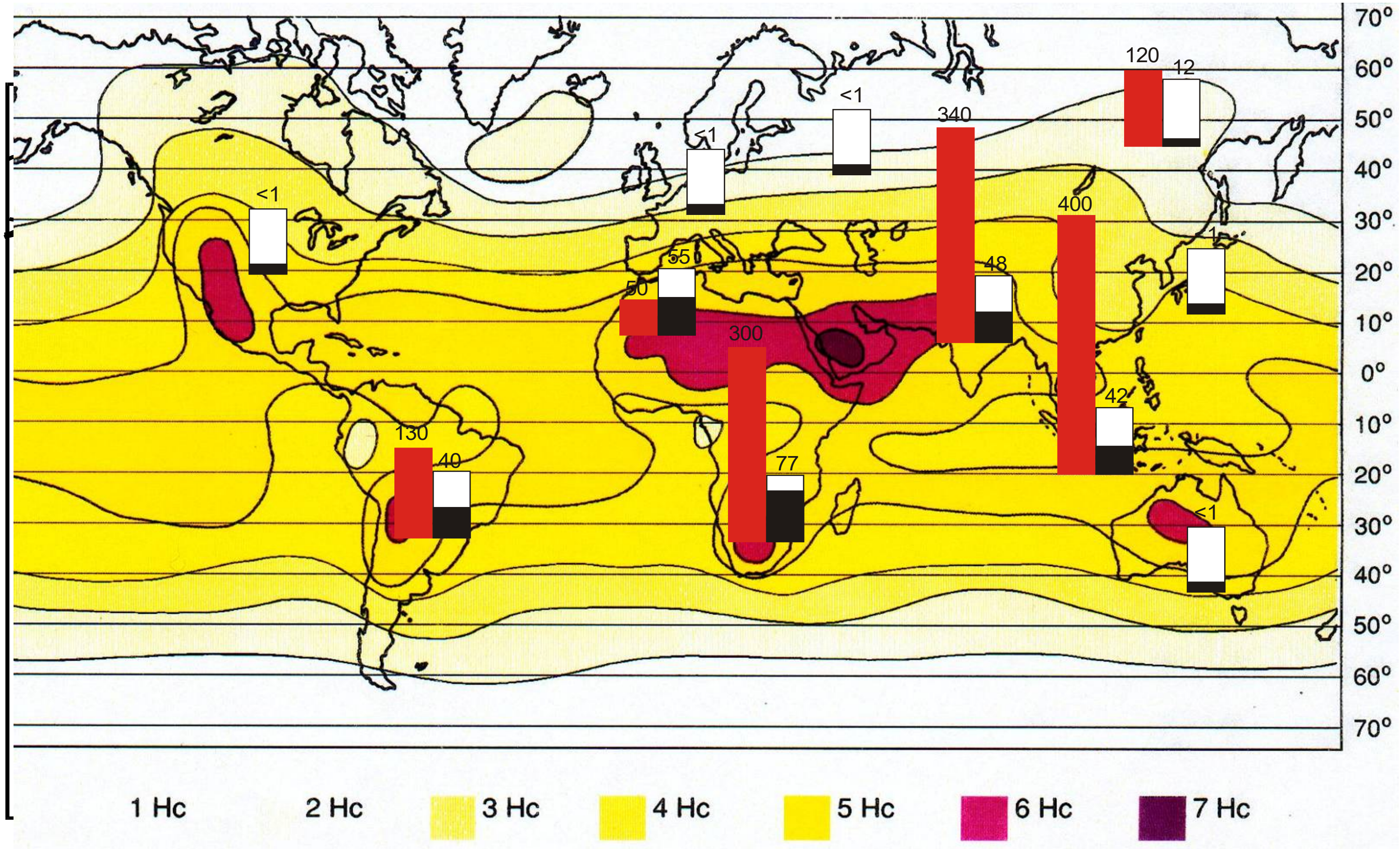
Electrical Power
(Type: DC)

Solar cells are rated at 1000 W/m^2

Incident Solar Irradiance (Instantaneous Power Density): [W/m^2]

The Earth continuously receives about 154 x 10^9 MW from the Sun.

Solar energy – Universal resource



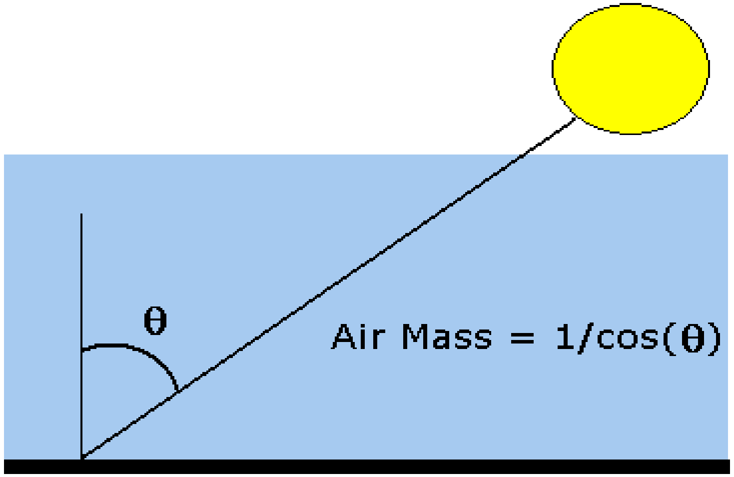
Solar radiation concepts

- Irradiance W/m^2
- Irradiation Wh/m^2
- Nominal Power Capacity: Electrical power at the maximum power point on Standard Test Conditions (STC):

- Irradiance 1000 W/m^2
- Temperature 25ºC
- "Air Mass 1,5" (AM=1,5)

"Watt-peak(Wp): Nominal power of a PV Module on STC"

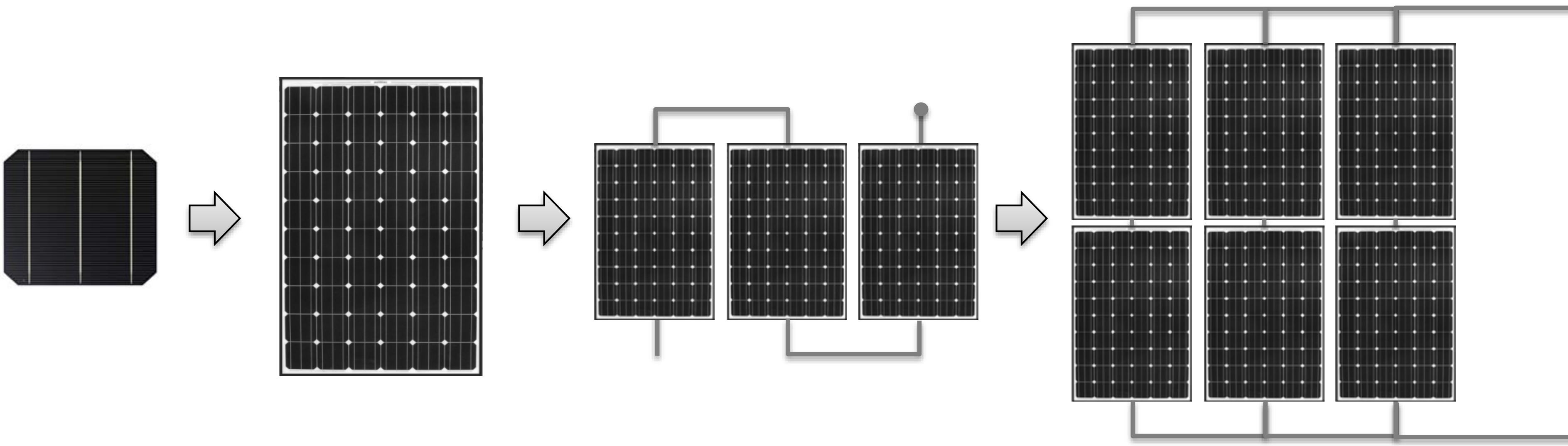
Direct Radiation →



Diffuse Radiation: Due to refraction of solar light on atmosphere (called skylight, diffuse skylight, or sky radiation)

PV is modularity

The heart of every PV system is the array of photovoltaic modules



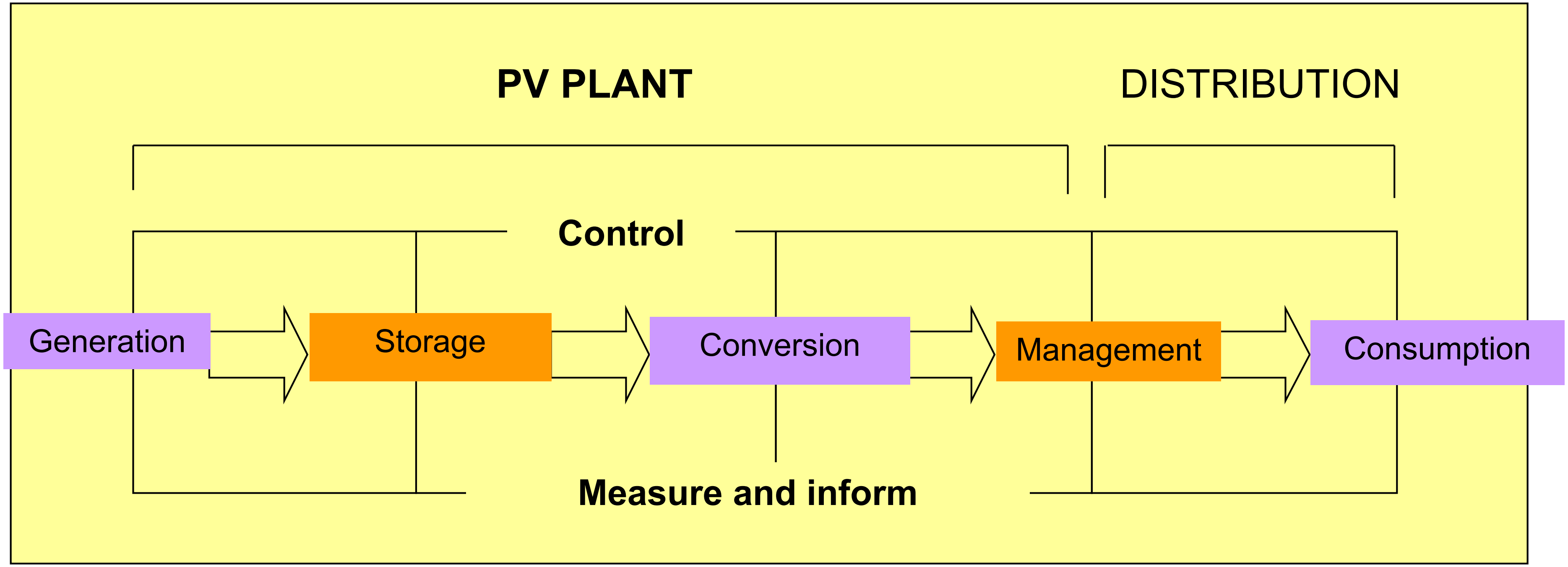
Cell

Module
Cells in series

String
Modules in series

Array
Strings in parallel

PV plants are more than PV modules…



Integration of PV systems

What is an Integrated PV system?

PV systems shall be comprehensive projects and NOT ONLY installations

✓ Integration INTO BUILDINGS:

1. Integration into Buildings operations Determination of responsibilities & Monitoring operation process at mid and long term
2. Social Use of PV Integrate society on BIPV projects
3. And on Architecture...

✓ Integration BEYOND BUILDINGS

Integration into buildings

Sheikh Zayed Learning Center
Al Aïn Zoo (Abu Dhabi)

Stadtwerke
Konstanz Energy
Cube (Germany)

COMSA-EMTE HQ
(Barcelona)

Integration beyond buildings

- The relevant topics associated with the integration of solar PV system beyond buildings is discussed one the following seven webinars:
  1. Technical integration of PV into Distribution Grids
  2. Distribution network planning with distributed PV
  3. Transmission network planning with increased PV and other Variable Renewable Energy
  4. Smart Grids and PV Integration
  5. Remote controlled curtailment options for solar PV system integration
  6. Advanced inverters for PV system integration
  7. Grid code development for PV system integration

Context: Integration of PV plants into current grids

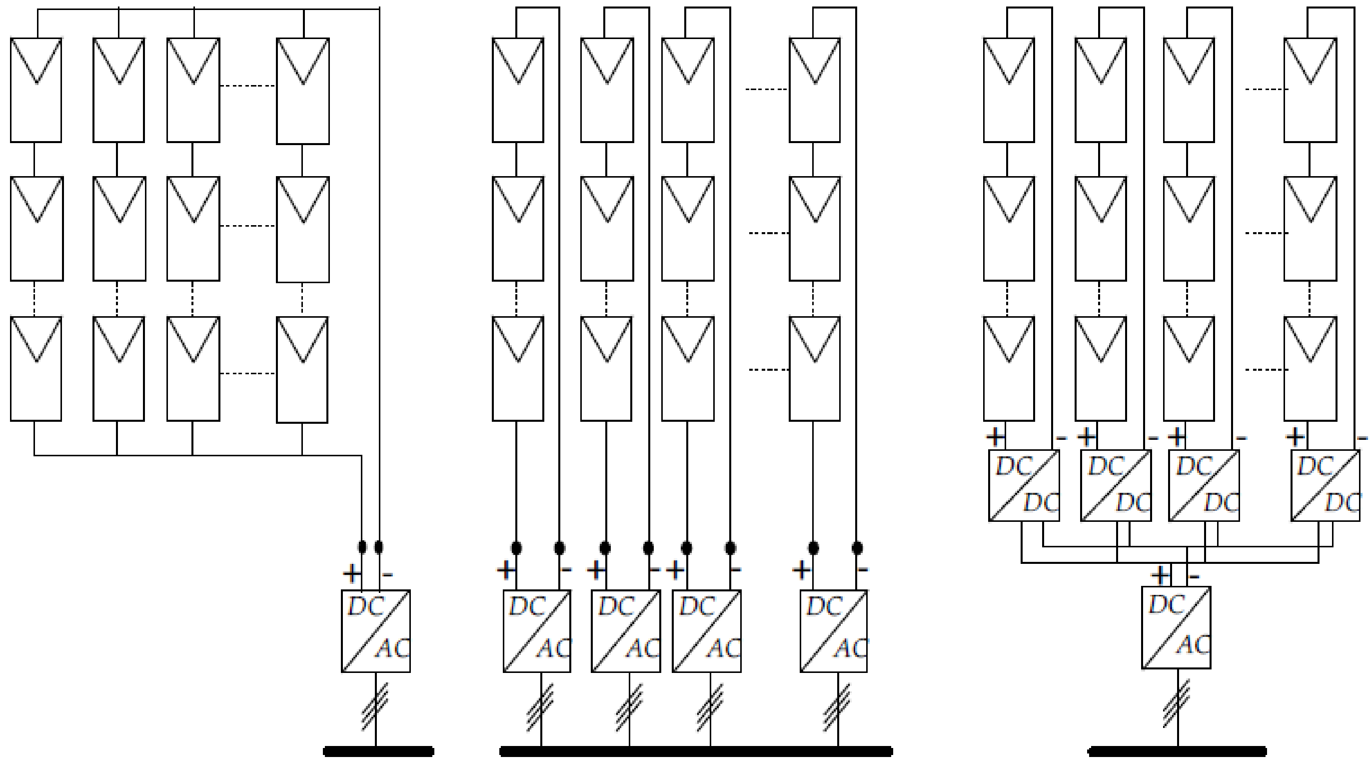
- Power systems are experiencing a deep transformation; new actors and novel technical approaches, largely driven by a global concern to rise the renewable fraction in today's generation mix.

- Massive penetration of renewables (PV and wind) has raised the concern of system operators. PV power plants are required to not only generate power when the resource is available (farms), but also to be operated as power plants supporting the power system.

Flexibility in PV power plants layout

- There are a number of possible topologies for arranging the power inverters, including central, string and multi-string.
- Collection systems for PV power plants can be implemented with radial, ring or star systems.
- PV power plant collection is typically designed at medium voltage.
- Additional equipment is needed: transformers, switchgear and in some cases reactive power equipment and energy storage systems.

Typical Topologies for PV Systems integration



Inverter topology	P (kW)	Vin mppt dc (V)	Vout ac(V)	f (Hz)
Central	100-1500	400-1000	270-400	50, 60
String	0.4-5	200-500	110-230	50, 60
Multistring	2-30	200-800	270-400	50, 60
Module Integrated	0.06-0.4	20-100	110-230	50, 60

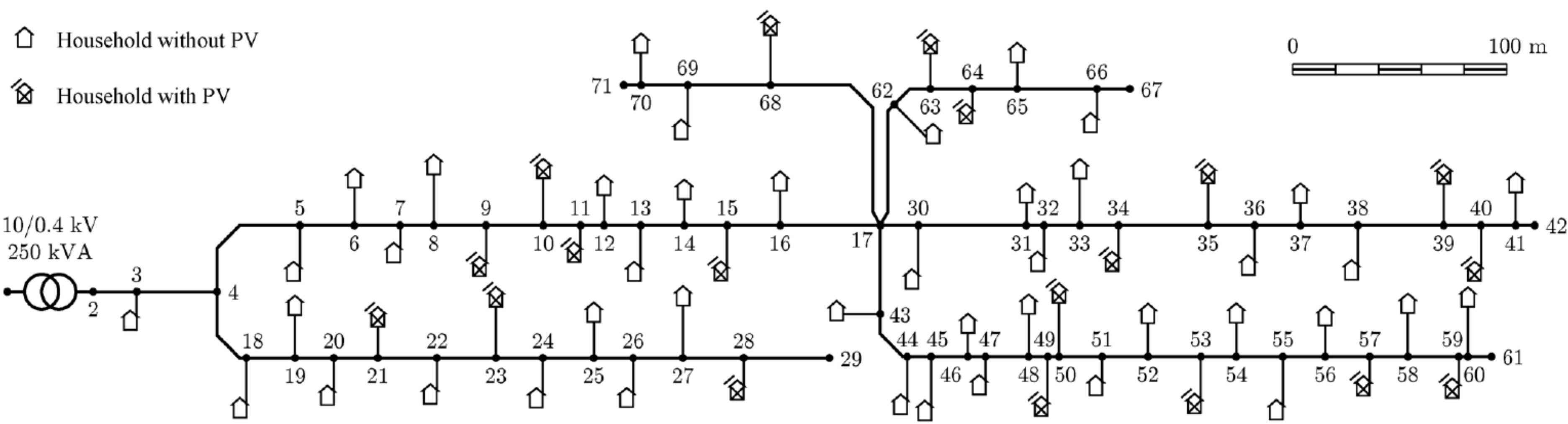
A Cabrera doctoral thesis, UPC 2017

PV systems impact on Distribution grids

- PV power plants can be installed in the distribution network as distributed energy sources.
- PV plants can contribute to reduce or increase the loading of the lines.
- PV plants have an impact on the overall system voltage, which needs to be studied.
- Energy storage system or flexible loads can be integrated with PV systems.

Energy storage as a strategy to increase PV systems penetration

- Energy storage can be useful to reduce overloads in the distribution network, while providing support to the voltage control in the distribution system.
- It can be analyzed as an optimization approach addressing multiple objectives, such as peak shaving and voltage control.



Tant et al. “Multiobjective Battery Storage to Improve PV Integration in Residential Distribution Grids” IEEE Trans Sustainable Energy

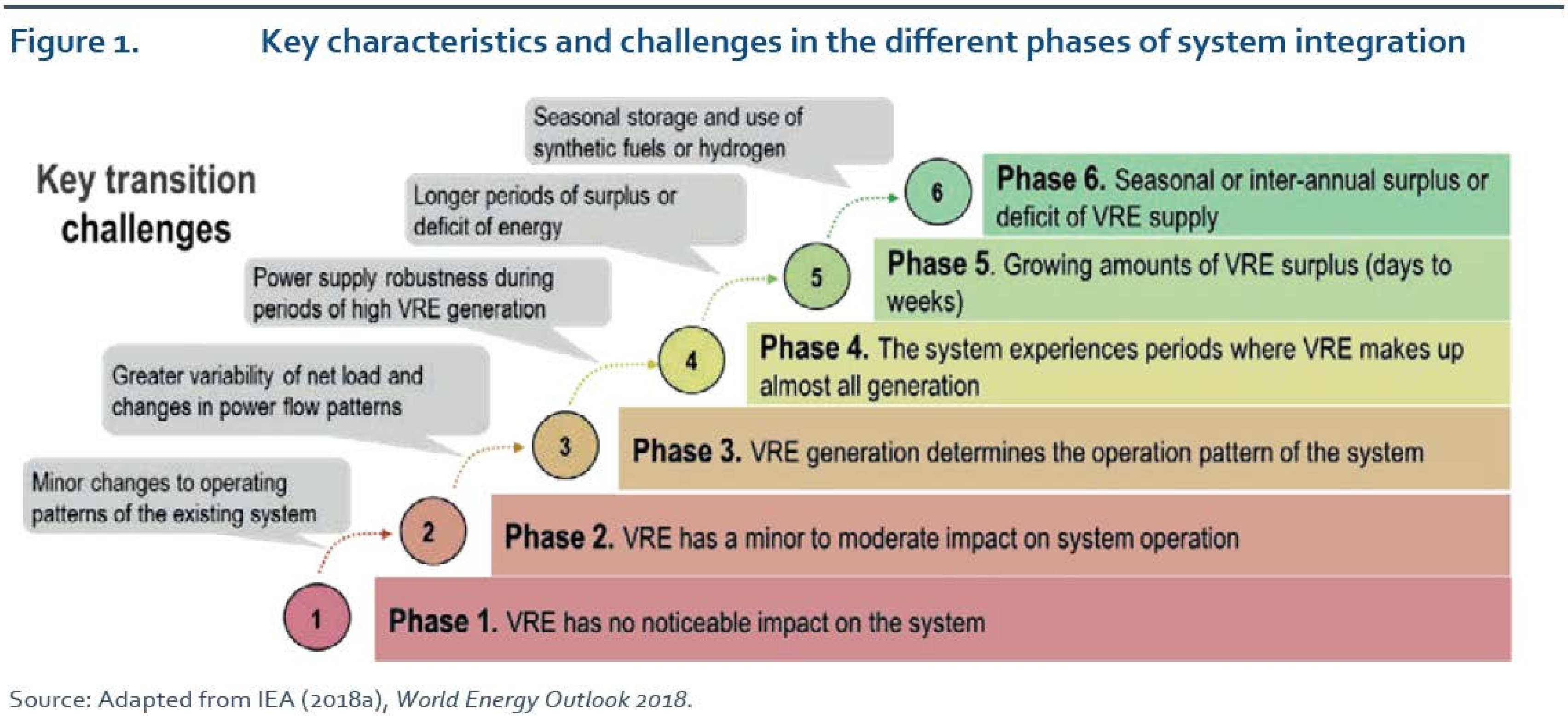
Challenges to the Transmission system

- PV generation has strong variability and limited predictability. This is an important difference with conventional thermal and hydro power generation with controllable output.

- PV power plant output varies periodically in different time scales (years, seasons, days)

- High penetration of PV generation is a challenge for the transmission system:
  - Demand-generation balancing
  - Frequency fluctuations
  - Voltage and power flow issues
  - Short term additional costs and how to offset them

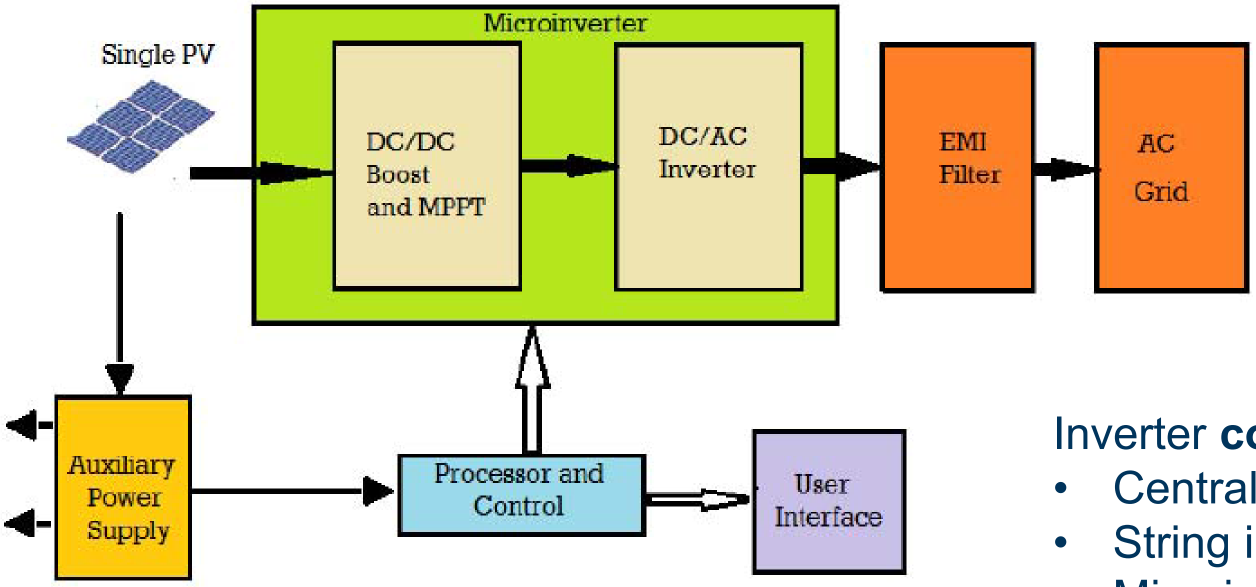
Evolution of large scale PV integration impacts on the Transmission system



IEA (2019), "Status of Power System Transformation 2019"

PV system components are key in solar PV systems integration

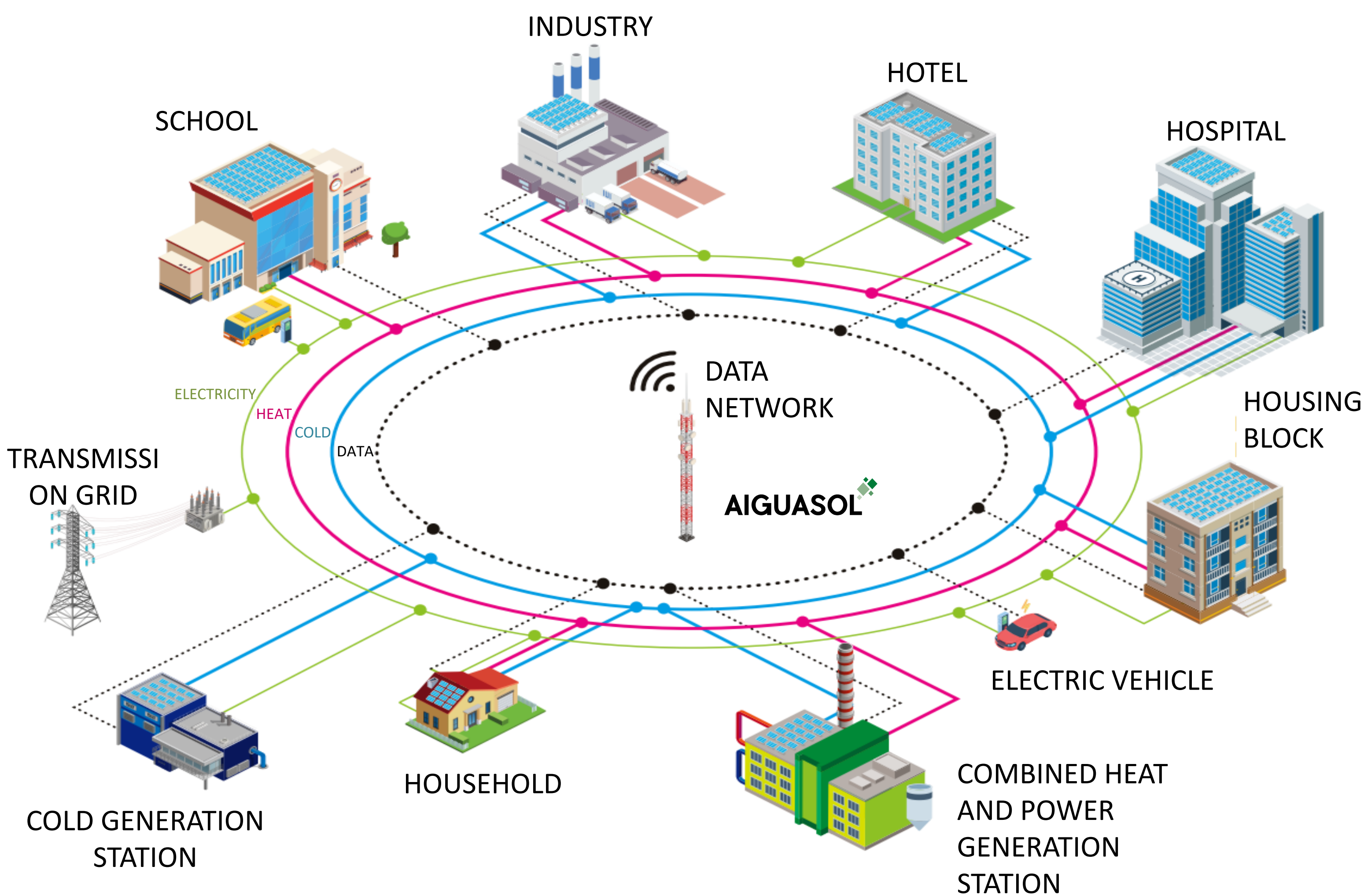
Two-way flows of power and communication are required between smart grids and solar PV systems. The solar PV system is managed by the **inverter** that transforms DC voltage into AC.



Inverter **cost comparison**:

- Central inverter: 0.08 US$/Wac
- String inverter: 0.12-0.15 US$/Wac
- Microinverter: 0.40 US$/Wac

The role of solar PV in Smart Grids



Industry focus areas of Smart Grids & PV

- Distributed energy systems:
  - Micro (i.e. prosumers) to large solar PV and other renewable generators
  - Energy storage, Electric vehicles
- Transmission and distribution grid management: Grid monitoring, control and security
- Increase consumer choices and markets (Demand/response, dynamic pricing)
- Advanced software and hardware: Energy dashboards, controllers, sensors and smart appliances
- Communication systems:
  - Smart meters to transmit energy consumption/generation data to utilities
  - Control centers at the utility
  - Power Line Communications (PLC) or Wireless mesh networking to transmit data to control center

Communications and Control of PV power plants are essential

- The system operator receives information on the PV power plant state and sends set-points related to active and reactive power exchange.

- A typical example is a command of active power curtailment, to avoid congestions in the power system.

- The set-points of the grid-code requirements can be also adjusted through this communications channel.

- The power plant controller of the PV power plant is the **responsible to coordinate the required actions internally in the plant.**

Inverters: the “brains” of PV systems integration

Solar PV Inverters convert the DC output of photovoltaic (PV) solar panels or strings of panel into a AC current which is injected to the grid (or load).

Solar PV inverters have the following functions:

- DC/AC conversion and voltage adaptation
- Maximum power point tracking
- Anti-islanding protection
- Synchronization with the grid
- Support to the grid where the PV system is connected

Grid code requirements need to be adapted to facilitate PV integration

- **Grid codes** are the **requirements** imposed by the **power system operators** that a **power plant** must **accomplish** to be connected (and to sell energy) to the grid.

- These requirements are detailed in a document **(Grid code)** that details which is the behavior of the power plant both in steady state conditions and during transient operation.

- For instance, in Spain the connection of wind power is defined in the Operational Procedure (PO) documents PO 12.2 y el PO 12.3.

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Items covered in each webinar

AIGUASOL

CITCEA UPC

tta Trama TecnoAmbiental

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Technical integration of PV into Distribution Grids

- ✓ Topologies for PV power plants
- ✓ Panel / String / central inverters for PV power plants
- ✓ Analysis of PV power plant layouts
- ✓ Auxiliary equipment for PV power plants
- ✓ Integration of energy storage

Distribution network planning with distributed PV

- ✓ PV plants as distributed energy sources in the distribution network
- ✓ Distribution network planning
- ✓ Impact on line loading and system voltages.
- ✓ Integration with storage and flexible loads.
- ✓ Example studies

Transmission network planning with increased PV and other Variable Renewable Energy

- ✓ Challenges for the transmission systems and the system operation
- ✓ Key Impacts of PV systems penetration in the planning of Transmission networks
  - ➢ Impact of system flexibility on curtailed energy
  - ➢ Impact on reserves
- ✓ Uncertainty of Cost impact – need for further analyses
- ✓ Case studies

Smart Grids and PV Integration

- ✓ Why do we need Smart Grids?
- ✓ Definition of Smart Grids
- ✓ Traditional VS Smart Grids
- ✓ Focus Areas of Smart Grids
- ✓ Smart Grid Technologies and Components
- ✓ Solar PV Designs for Smart Grid Integration
- ✓ Advantages of Smart Grids
- ✓ Barriers to Smart Grids
- ✓ Cost and Benefits of Smart Grids
- ✓ Case Studies

Remote controlled curtailment options for solar PV system integration

- ✓ Remote control of PV power plants
- ✓ Structure of power plant controllers
- ✓ PPC for reactive power control
- ✓ PPC for active power control
- ✓ Examples

Advanced inverters for PV system integration

- ✓ Basics of converters
- ✓ Electric circuits fundamentals
- ✓ Solar inverters functionalities
- ✓ I-V and P-V characteristics
- ✓ Maximum power point tracking
- ✓ Control principles
- ✓ Single / two stage inverters
- ✓ Galvanic isolation / Anti-islanding detection

Grid code development for PV system integration

- ✓ Context: the electrical power system
- ✓ From PV farms to PV power plants
- ✓ Grid codes
- ✓ Voltage support
- ✓ Frequency support
- ✓ Inertia emulation
- ✓ Black-start
- ✓ Ramp control

Thanks for your attention!

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