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

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International Solar Alliance Expert Training Course

PV power plants layouts

CITCEA UPC

In partnership with the Clean Energy Solutions Center (CESC)

Professor Oriol Gomis-Bellmunt

September 2019

Supporters of this Expert Training Series

INTERNATIONAL SOLAR ALLIANCE

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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.
- Supervision of 18 doctoral theses and >60 Bachelor and Master theses.

4. Technical Integration of Solar	Introduction to Technical Integration of Solar PV
	Smart grids and PV Integration
	Solar PV Inverters
	PV power plants layouts
	Grid support to the grid from PV power plants - Grid codes
	Power plant controllers
	Planning - Distribution network with distributed PV
	Planning - Transmission network with large scale PV power plants

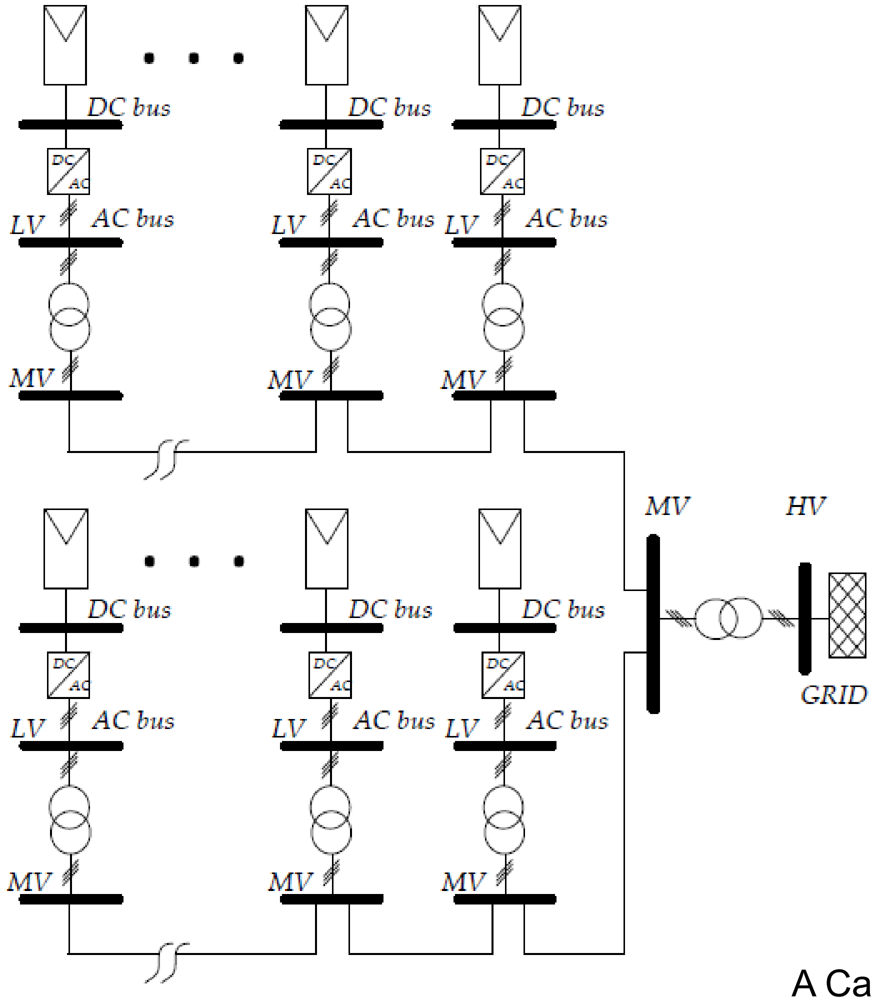
Outline

- 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

Collection systems for PV power plants

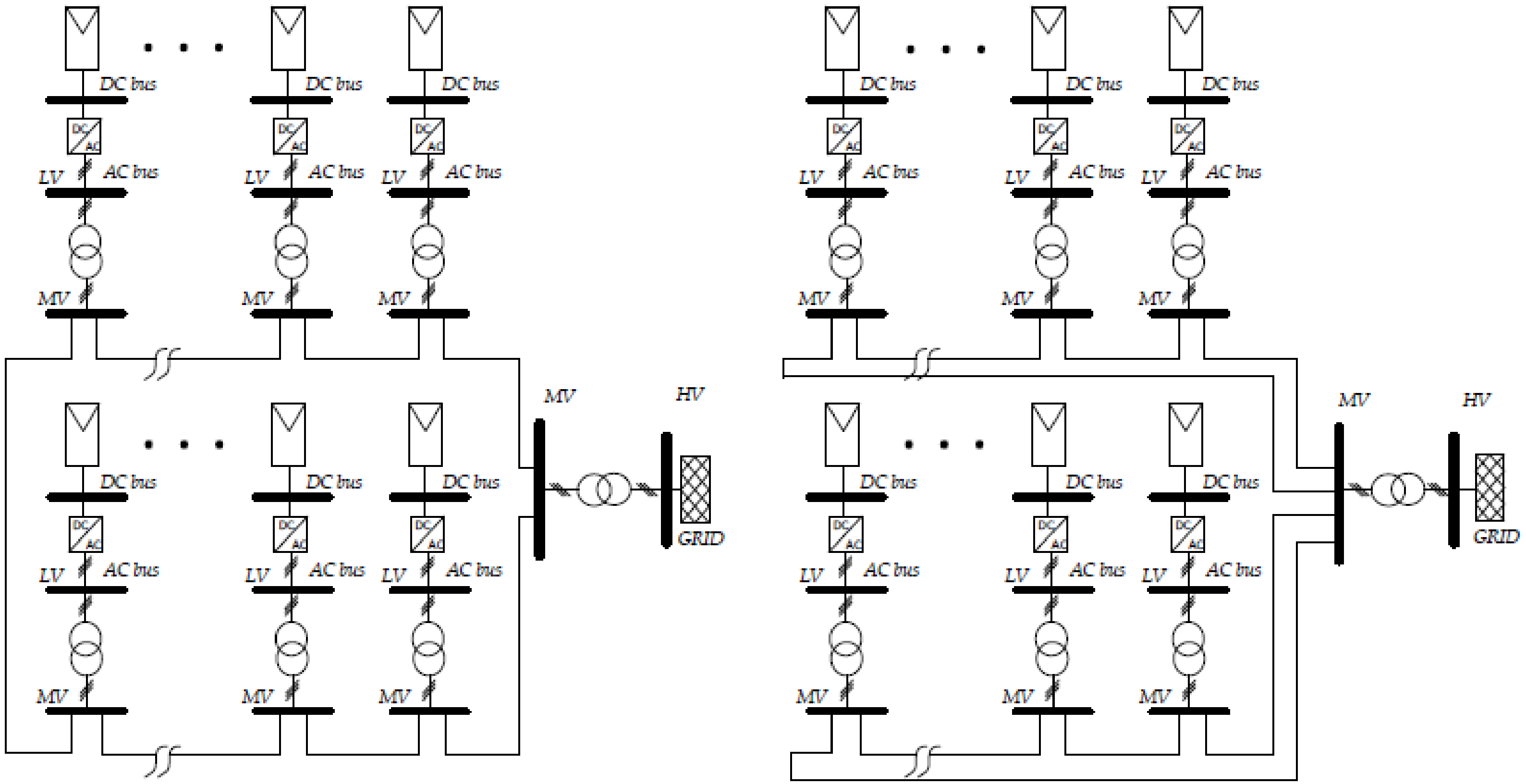
- Collection in typically addressed with a medium voltage AC network.
- The network can have a radial, ring or star structure.
- DC collection is an alternative which is being investigated. It could provide some advantages, but it requires more power electronics converters to adapt the voltages. In this case, large DC-AC inverters at medium voltage would be needed to interconnect with the main grid.

Radial collection configuration



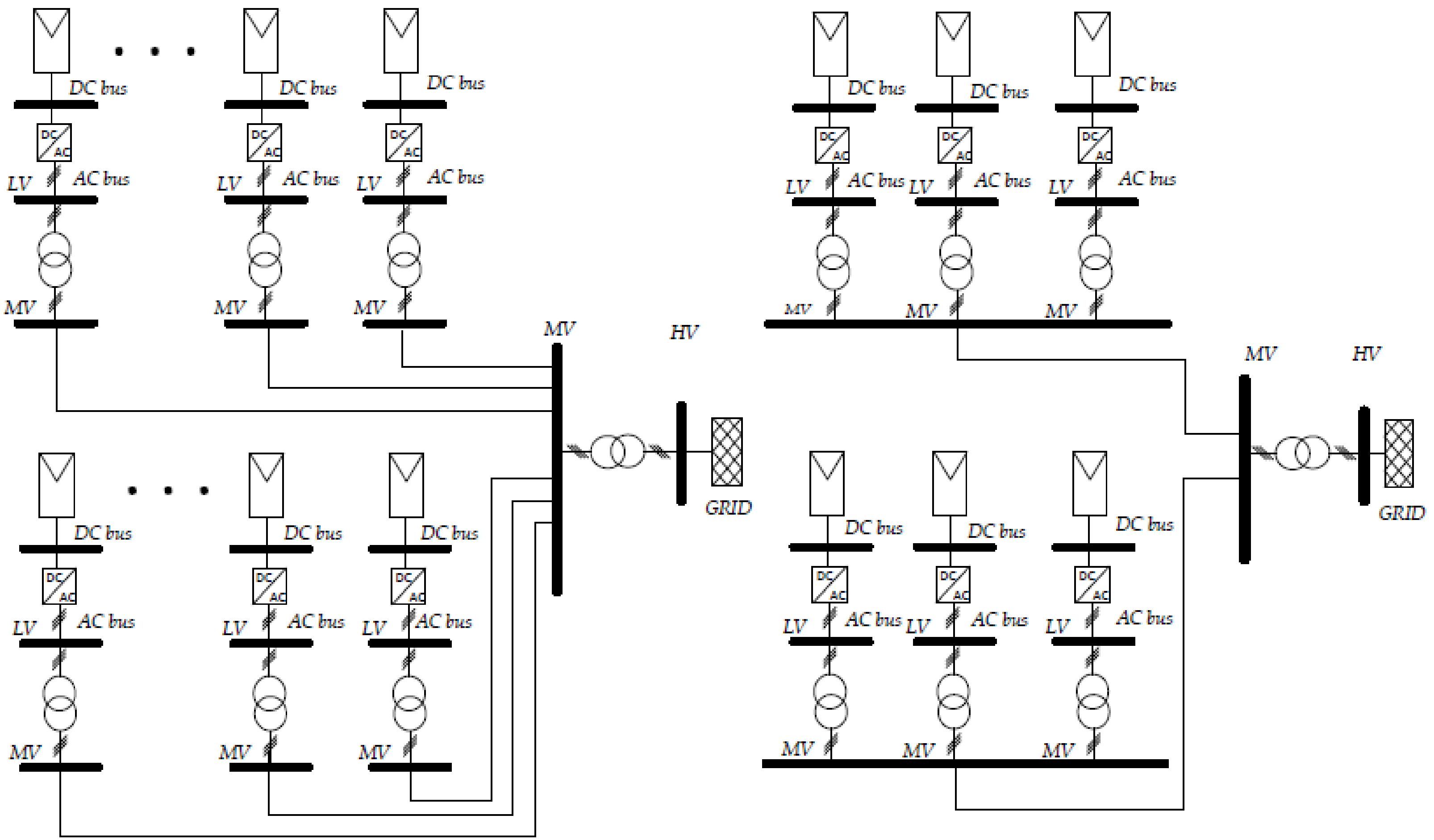
A Cabrera doctoral thesis, UPC 2017

Ring collection



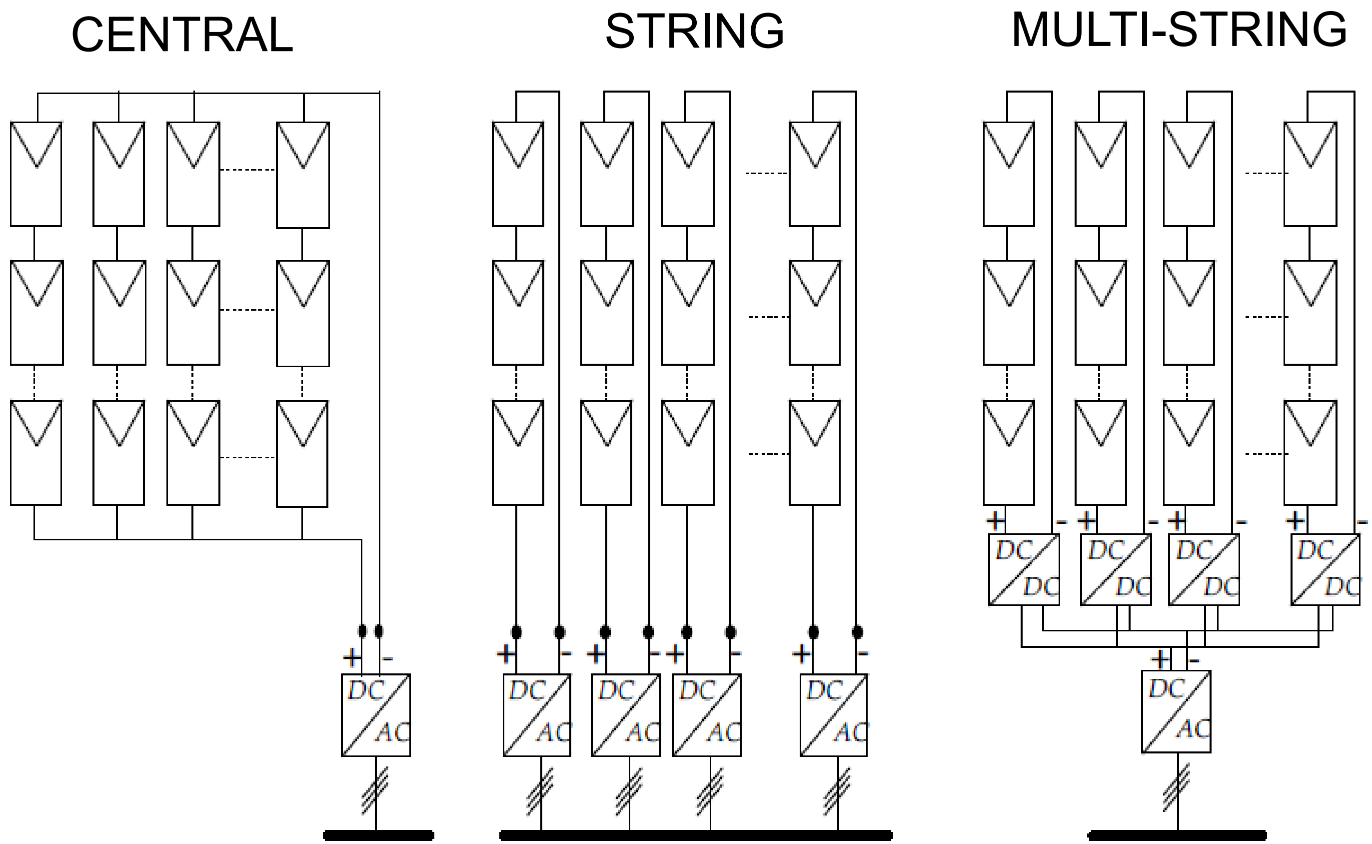
A Cabrera doctoral thesis, UPC 2017

Star collection



A Cabrera doctoral thesis, UPC 2017

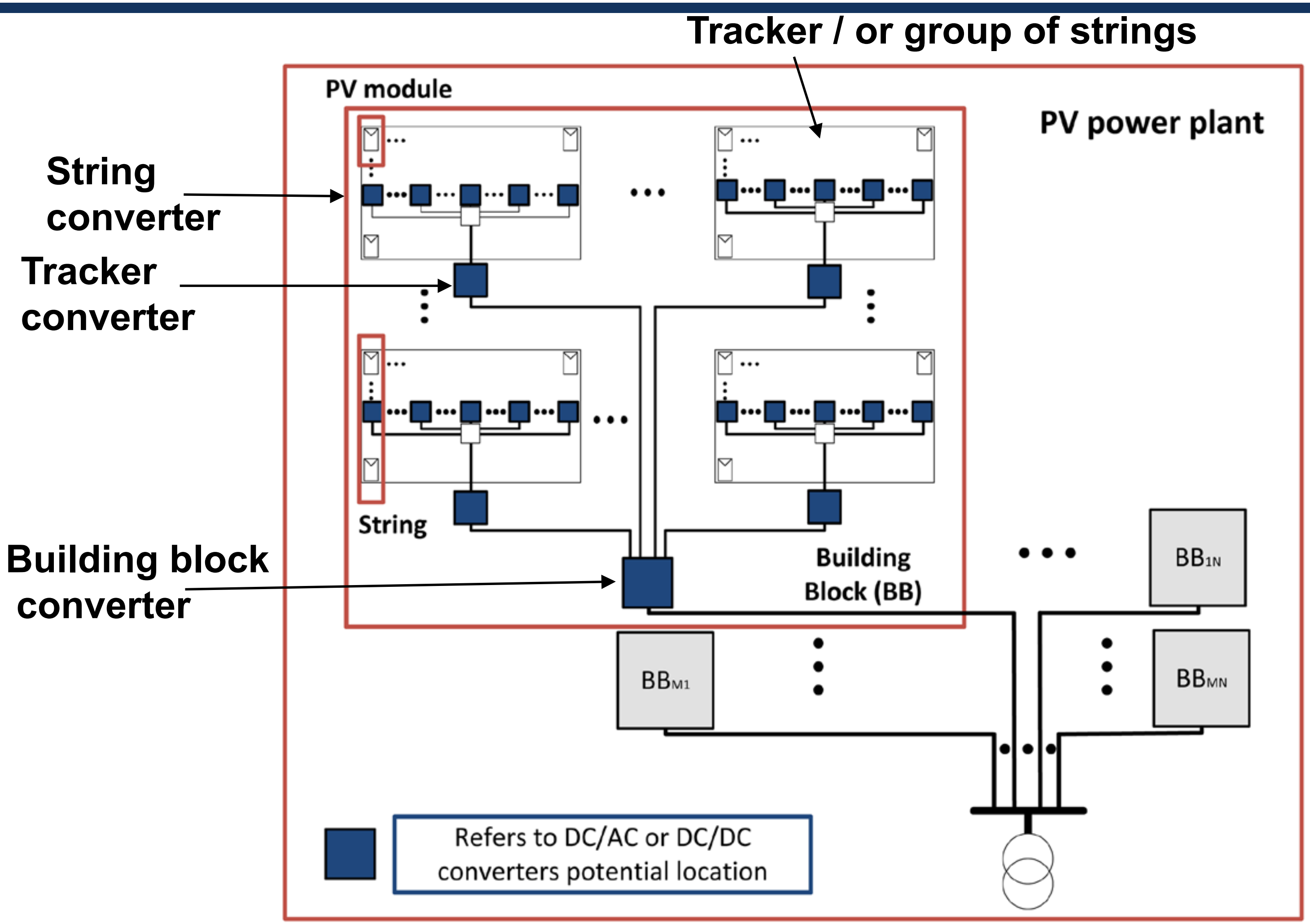
Topologies



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

Analysis of PV power plants



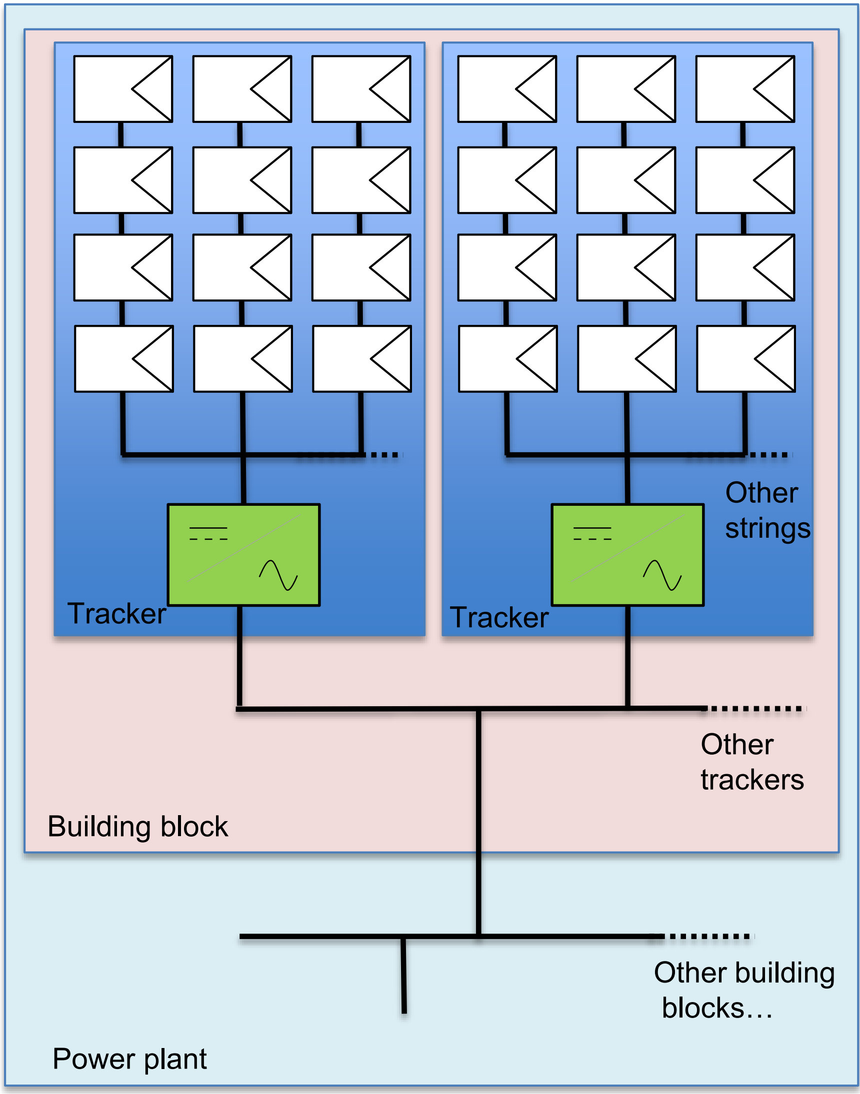
De Prada et al "Technical and Economic comparison of various electrical collection grid configurations for large PV power plants" IET 2017

PV1 Central inverter per tracker

Group of PV modules connected in series forming strings which in turn are connected in parallel, through string diodes, to a central inverter per tracker.

Key characteristics:

- power losses due to a centralized MPPT,
- mismatch losses between the PV modules
- losses in the string diodes
- poor reliability since an unscheduled inverter failure leads to the energy loss of a whole tracker or array.
- low investment costs
- easy installation

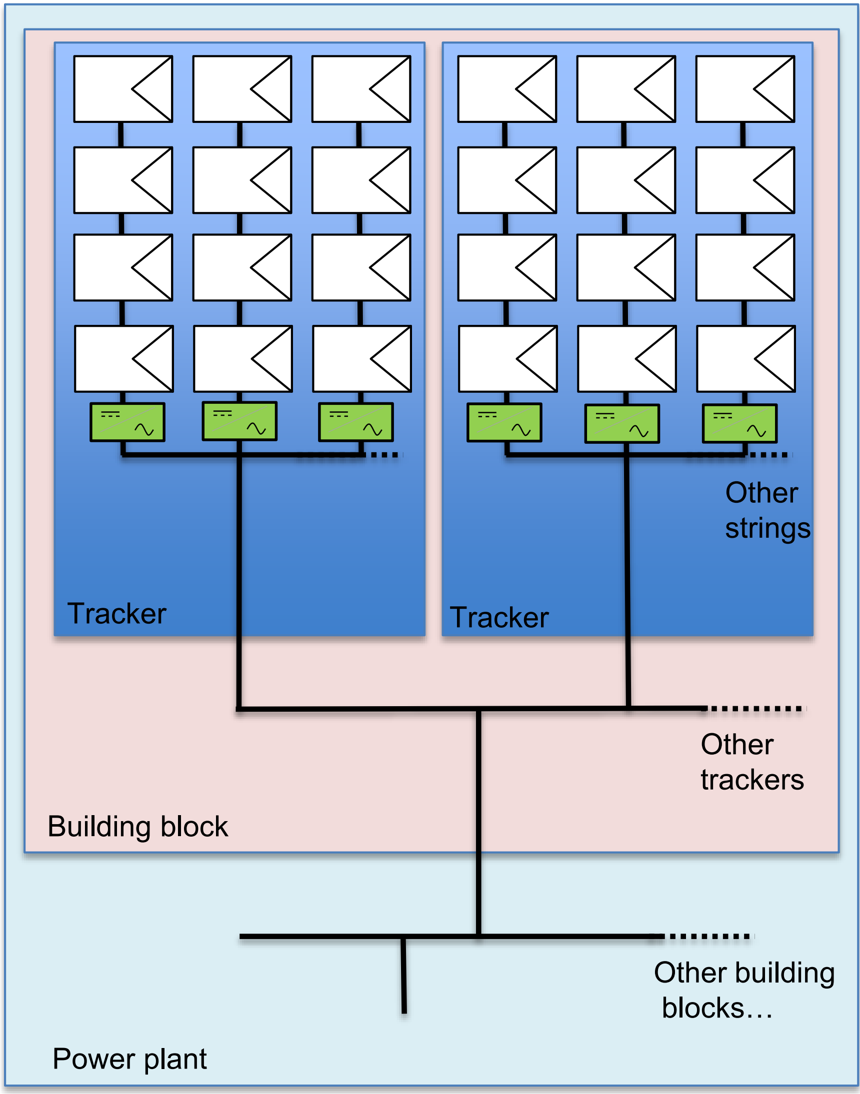


PV2 String inverters

String inverters are installed in the PV plant.

Key characteristics:

- No losses associated with string diodes
- Each inverter provides MPPT on a string level (This is especially useful for those cases where modules are installed with different orientation or have different specifications)
- It increases reliability in comparison with PV1 since a failure of a string inverter do not imply the loss of the total PV power plant, but only a small part.
- It increases the cost and complexity compared with the previous one.

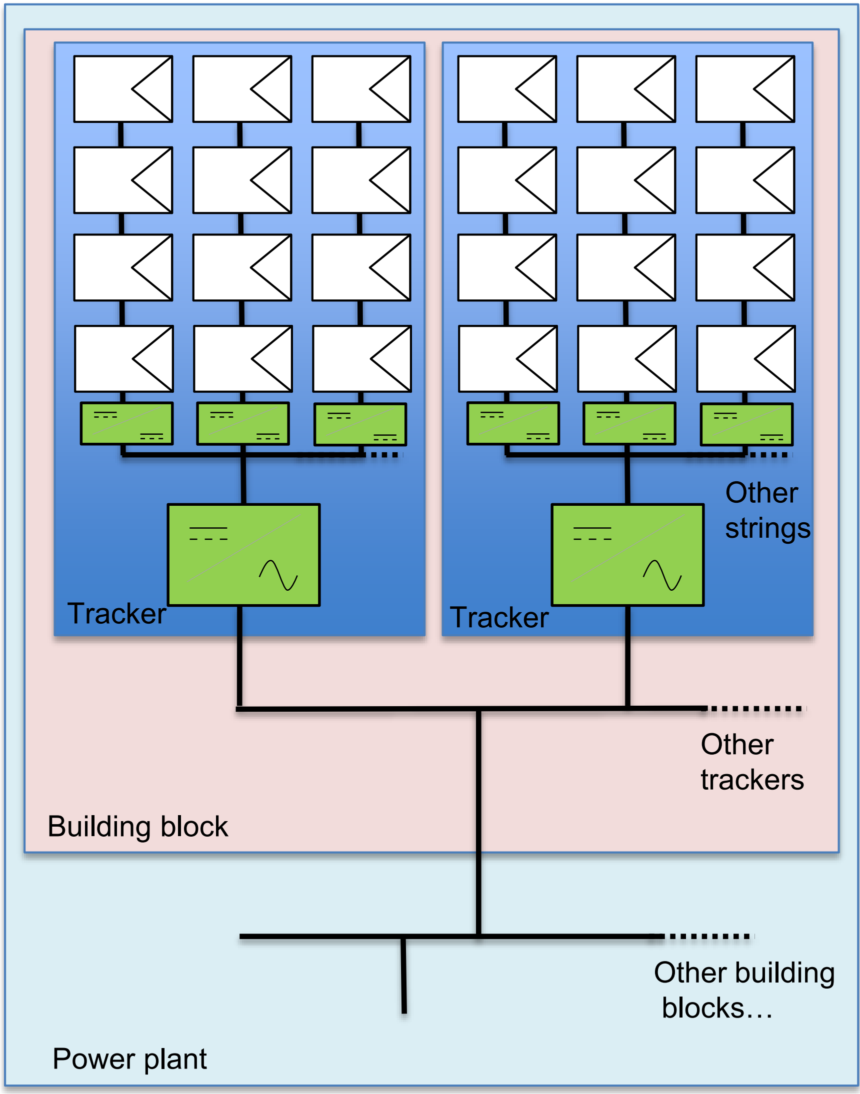


PV3 Multi-string inverter

Several strings are interfaced with their own DC/DC converters which are connected to a common central inverter.

Key characteristics:

- Compared to PV1 it improves the energy yield efficiency.
- nominal values, size or type of PV modules as well as strings with
- Suitable to connect strings with different orientations or different degree of shadings.
- DC/DC converters increase the voltages, so that both wiring
- costs and the costs associated with cable losses are reduced as well.
- It increases the investment costs on the converters compared with both PV1 and PV2.

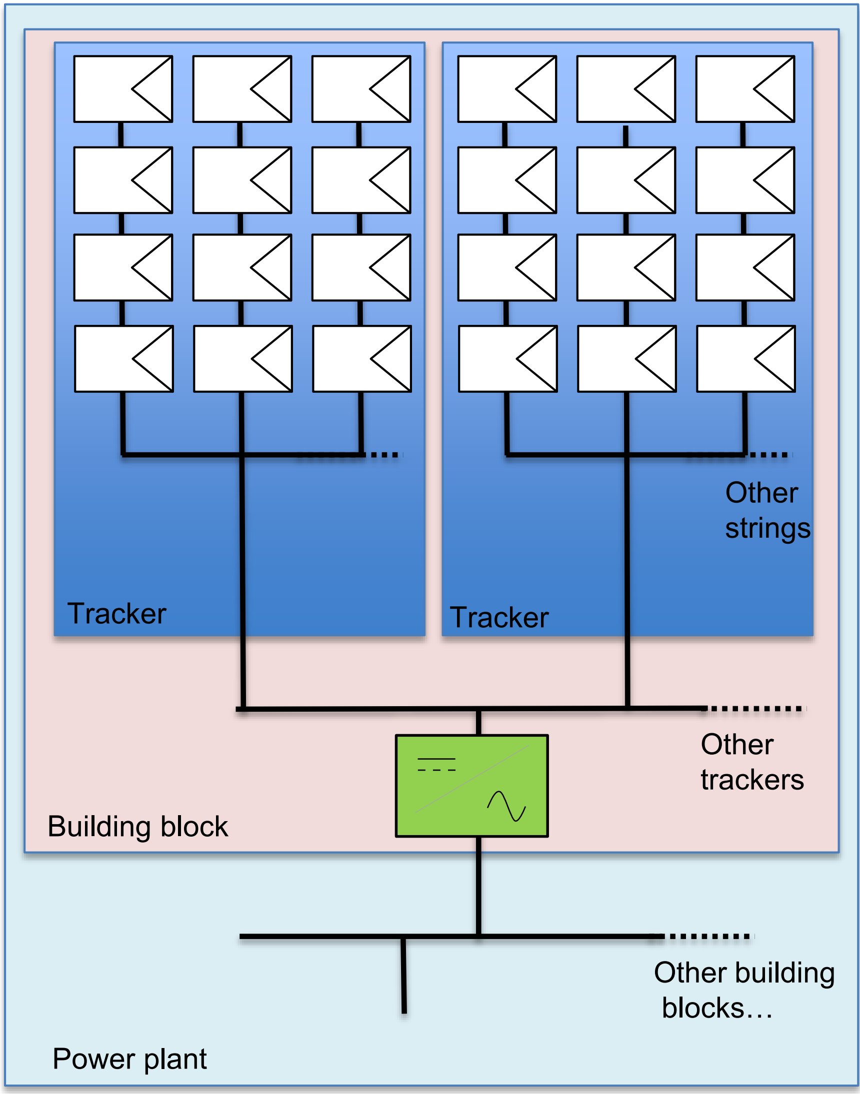


PV4 Central inverter per BB

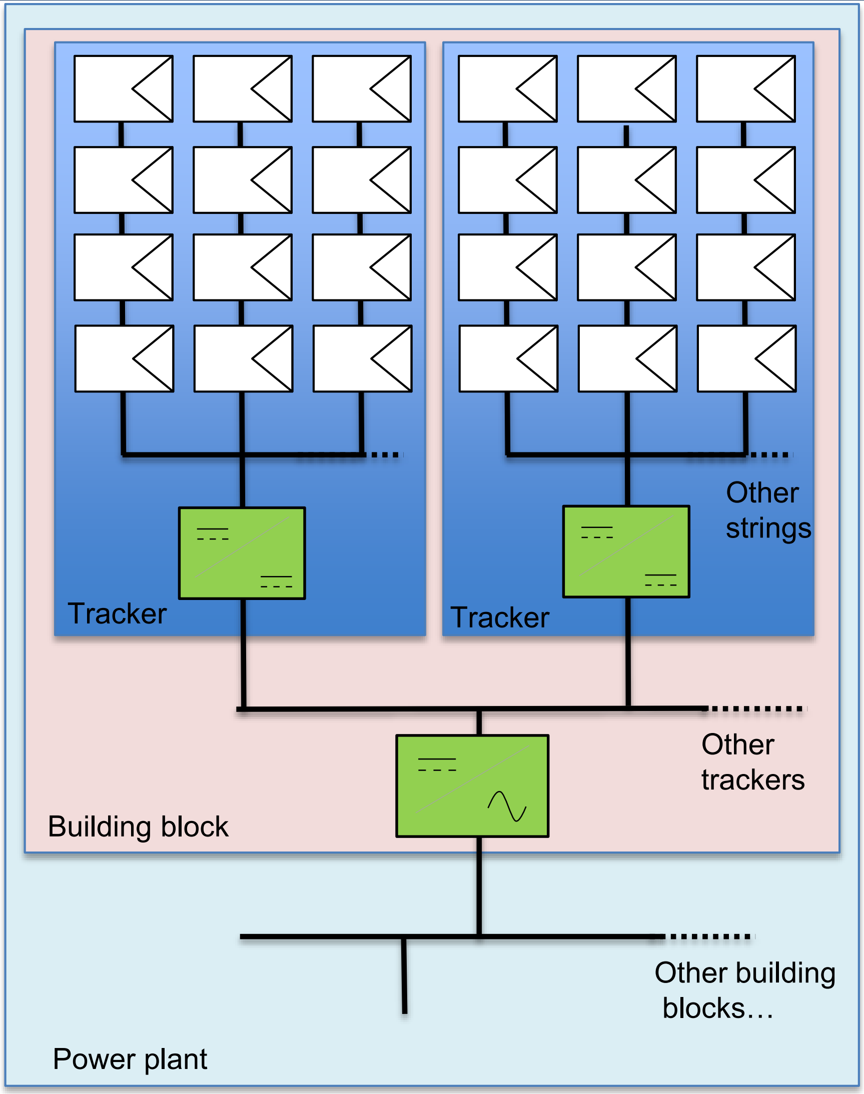
One central inverter per each building block.

Key characteristics:

- Complexity of installation and investment costs are substantially decreased
- Energy yield efficiency is diminished
- Reliability losses of this particular PV configuration are higher than in previous cases.



PV5 Tracker DC-DC and BB inverter



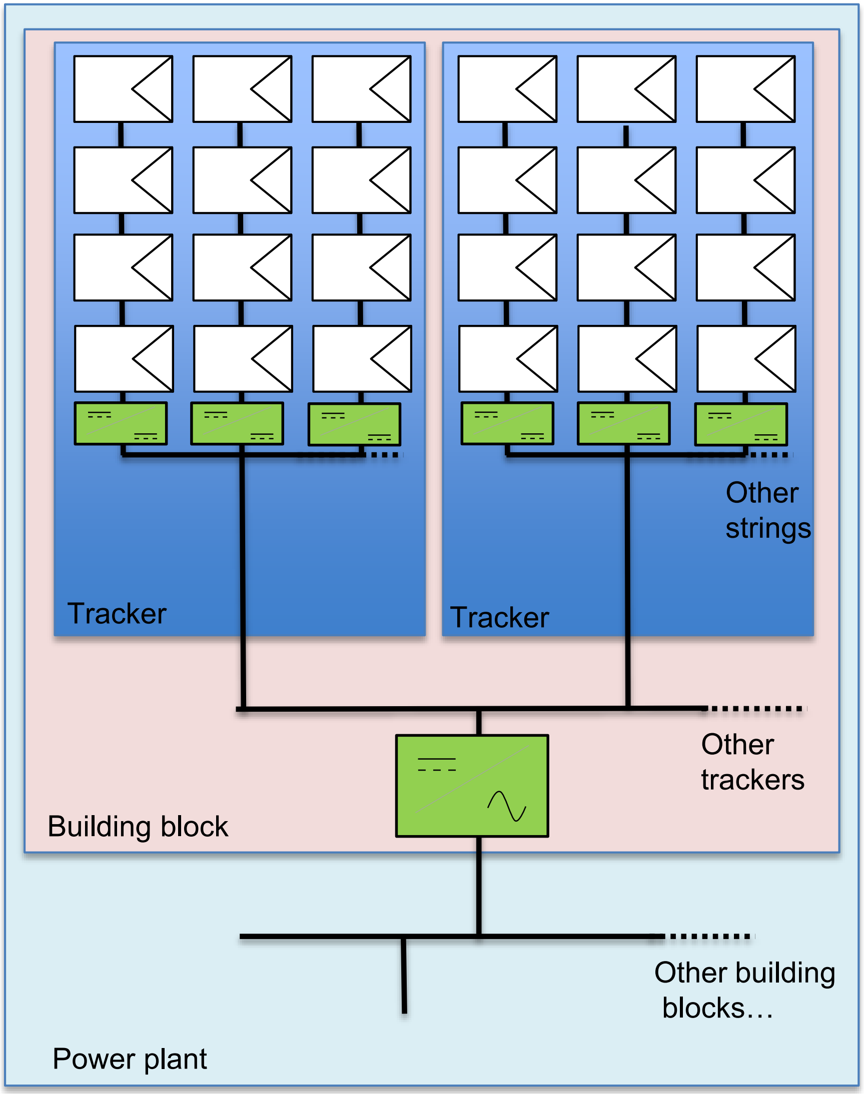
PV5 Tracker DC-DC and BB inverter

Combination between PV1 and PV4. Each tracker is connected to a DC/DC converter which performs an MPPT control strategy similar to the aforementioned central inverter of PV1 topology. Likewise, each building block has installed one central inverter which connects the DC outputs of all DC/DC converters and delivers the AC power to the point of common coupling (PCC).

Key characteristics:

- Enhanced energy yield efficiency by reducing the MPPT losses in comparison with PV4 configuration without increasing the investment costs and the complexity of installation of the system.
- Inclusion of DC/DC converters allows to step up the voltage thus reducing cable losses beyond the tracker's output.
- PV configuration presents similar drawbacks as PV1 topology in terms of high mismatch losses between the PV modules and significant MPPT losses within each tracker, as well as, alike reliability losses as PV4 due to the lack of power of an entire building block in case of failure of a single central inverter.

PV6 String DC-DC and BB inverter



PV6 String DC-DC and BB inverter

Adapted combination between PV2 and PV4 concepts. Each string of each tracker is controlled by a dedicated DC/DC converter which provides MPPT control. All the string inverters are connected to a common centralized inverter.

Key characteristics:

- It avoids losses associated with string diodes and increases the energy yield efficiency by decreasing the mismatching losses and partial shading losses.
- Main drawback on its high cost and complexity of installation due to the large number of electronic devices required.

Analysis (parametres)

Location	NREL Golden, Colorado, USA		
latitude, deg.	39.742 North		
longitude, deg.	105.18 West		
elevation, m	1828.8		
time zone	GMT-7		
PV capacity, MW_p	1	50	200
number of PV modules	4860	243,000	972,000
number of strings	243	12,150	48,600
number of trackers	9	450	1800
number of BBs	1	50	200
module area, m^2	7776	388,800	1,555,200
tilt angle, deg.	30		
PV module technology	Si-poly		
lifetime, years	25		

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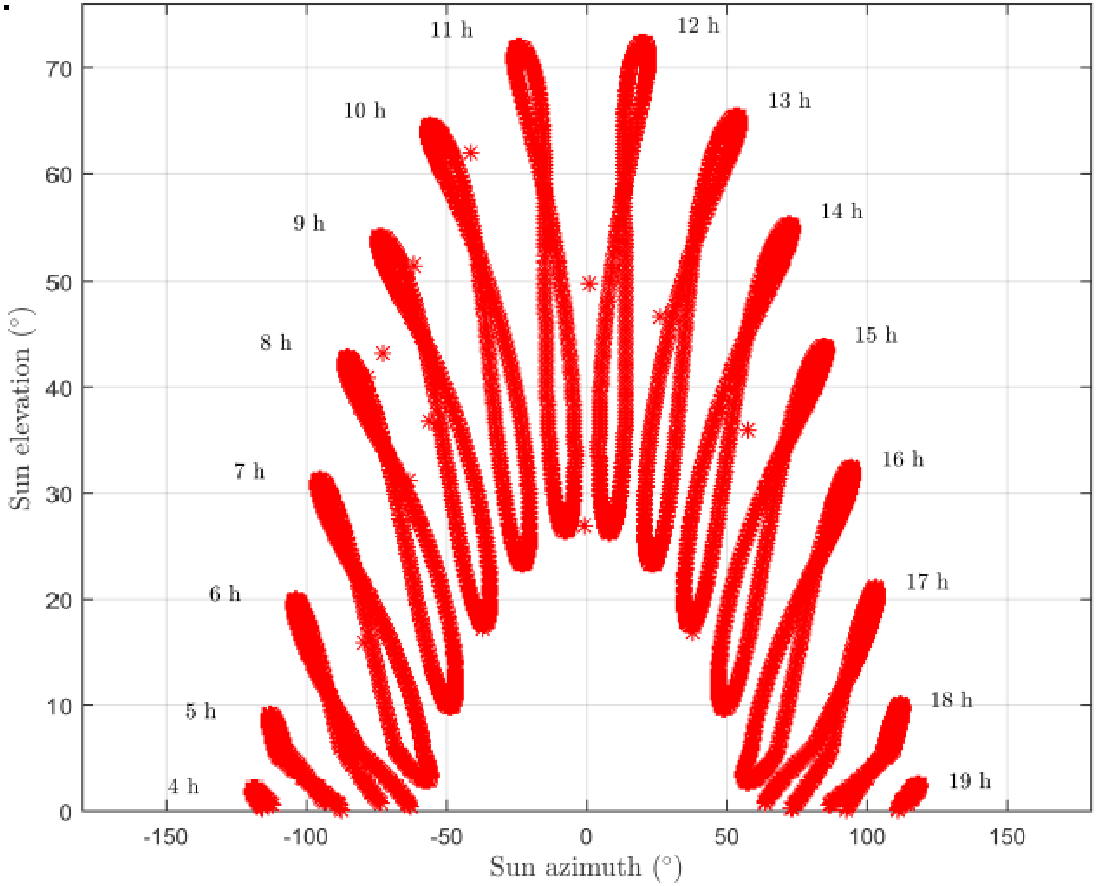
Meteorological data applied

Sun azimuth versus elevation angles, for each hour of a whole year.



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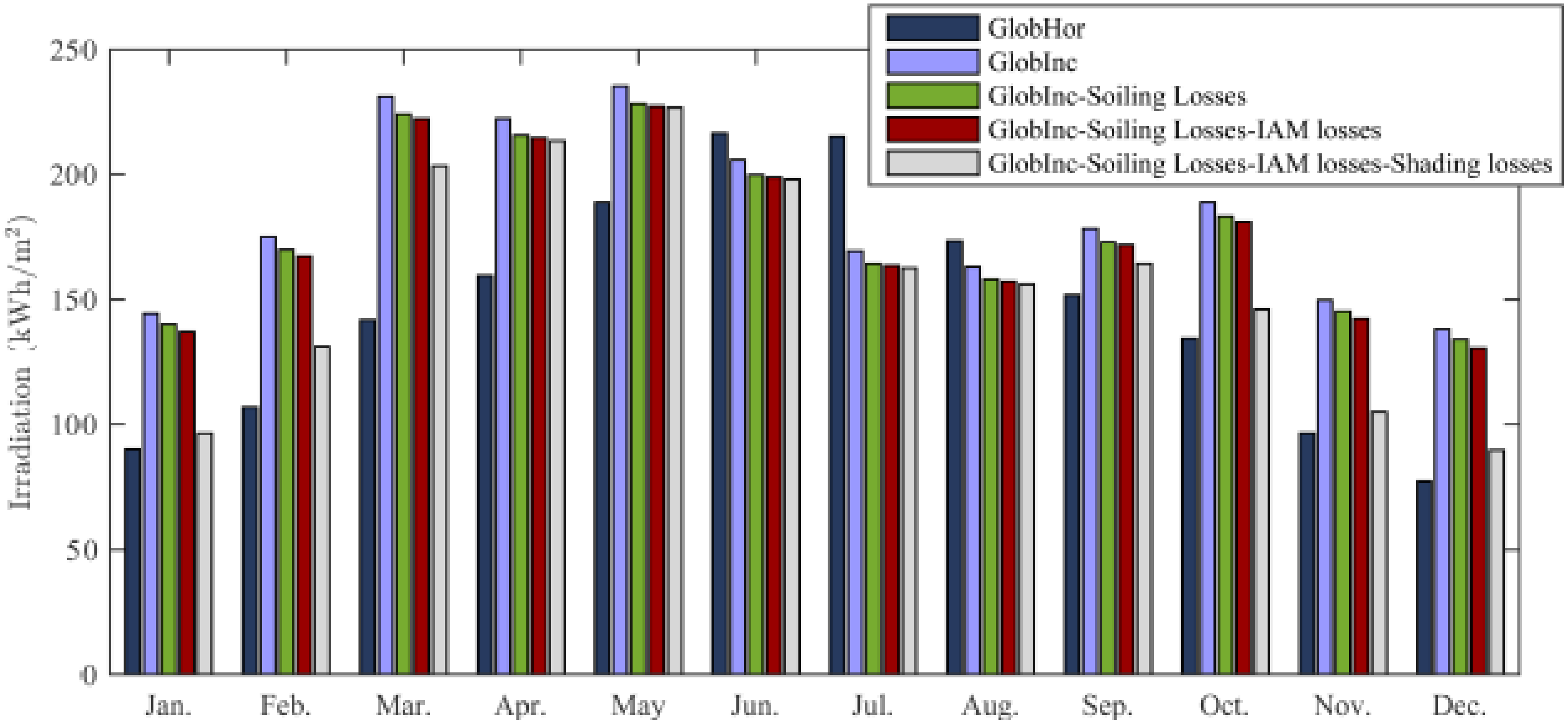
Meteorological data applied



Horizontal and incident global irradiation considering soiling, IAM factor and shading losses over a whole year.

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Performance ratio (PR)

- PR is defined as

$$PR = \frac{E_{grid}}{G_{inc}\rho_{nom}}$$

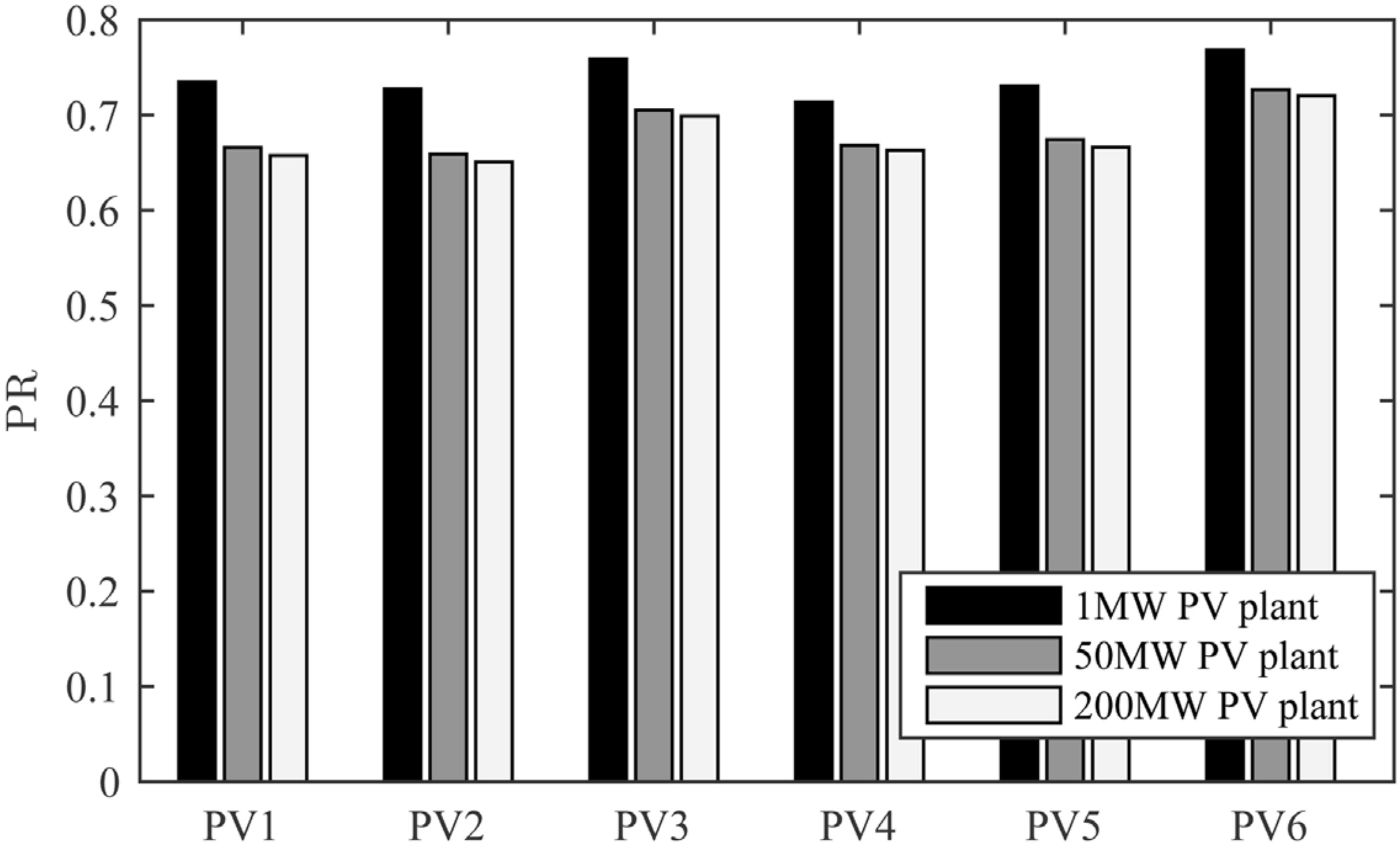
where

- E_{grid} is the energy delivered to the grid considering all the losses within the PV power plant
- G_{inc} is the irradiation in the plane of array
- ρ_{nom} is the array efficiency

The difference is due to different losses:

- Soiling, Incidence angle modifier (IAM), Shading, PV conversion , MPPT, Aging, Inverter, Cables, Transformers, Reliability.

Results - PR



Technical and economic results obtained: PR calculated for all PV configurations and capacities considered (1, 50 and 200 MWp)

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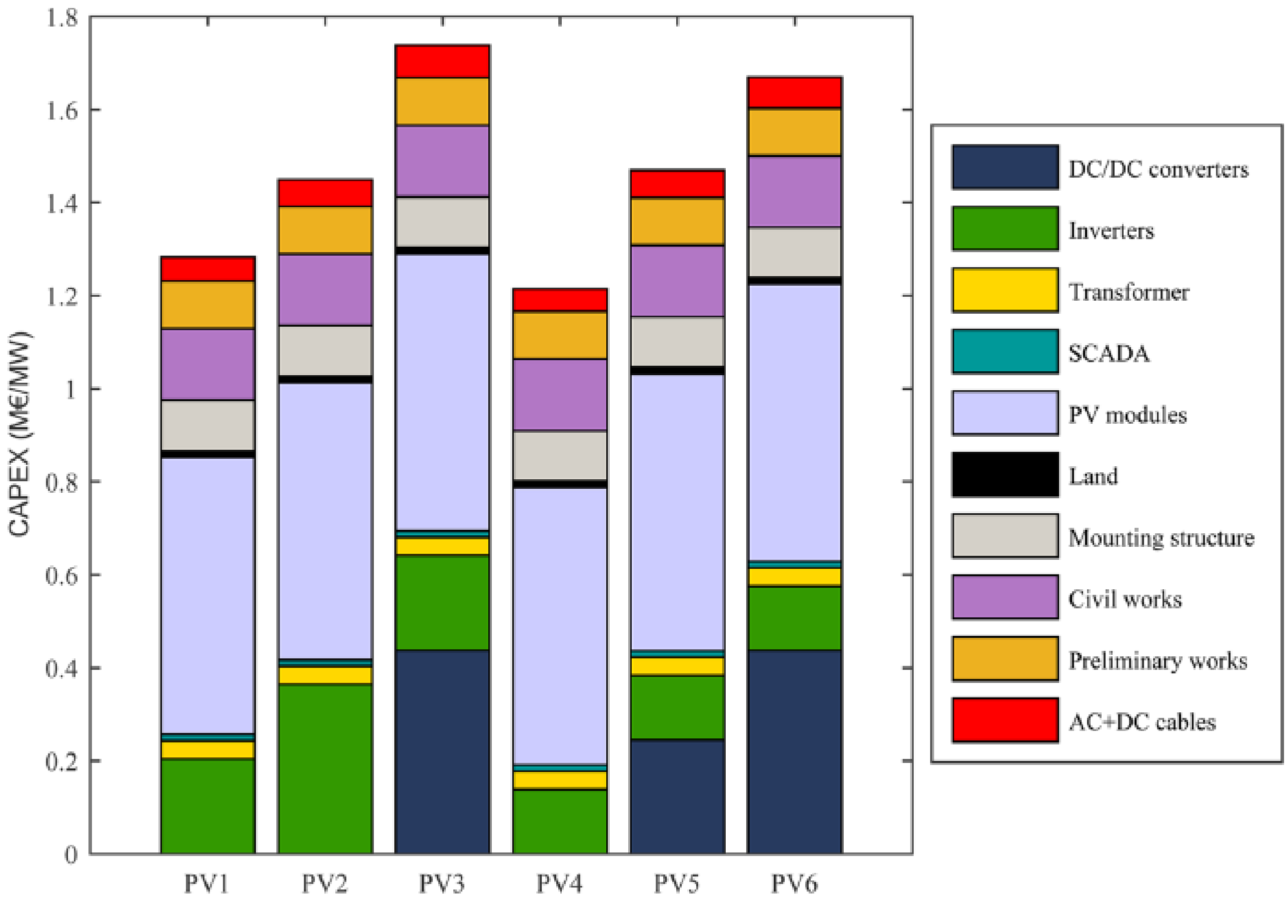
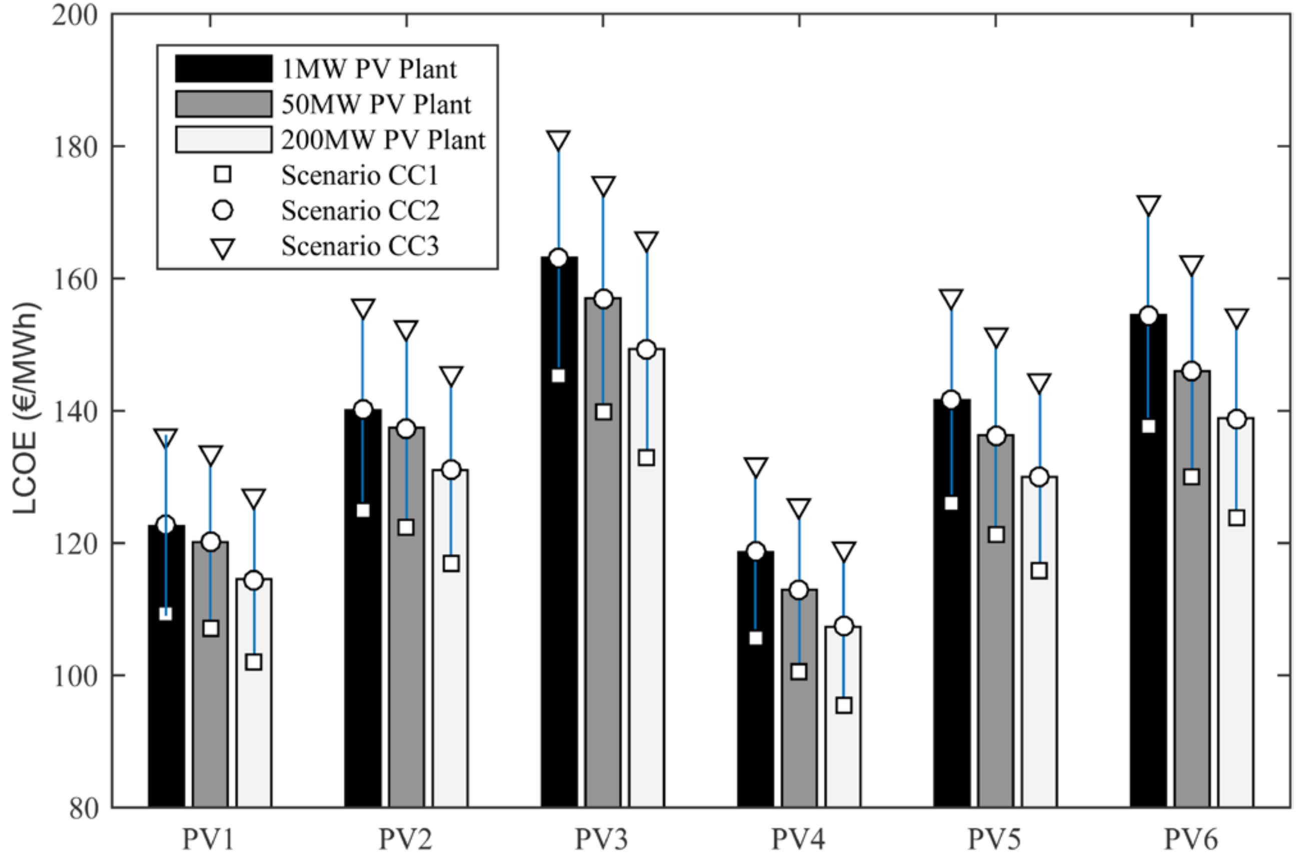
Results - CAPEX



Breakdown of CAPEX per MW considering the scenario 2

De Prada et al "Technical and Economic comparison of various electrical collection grid configurations for large PV power plants" IET 2017

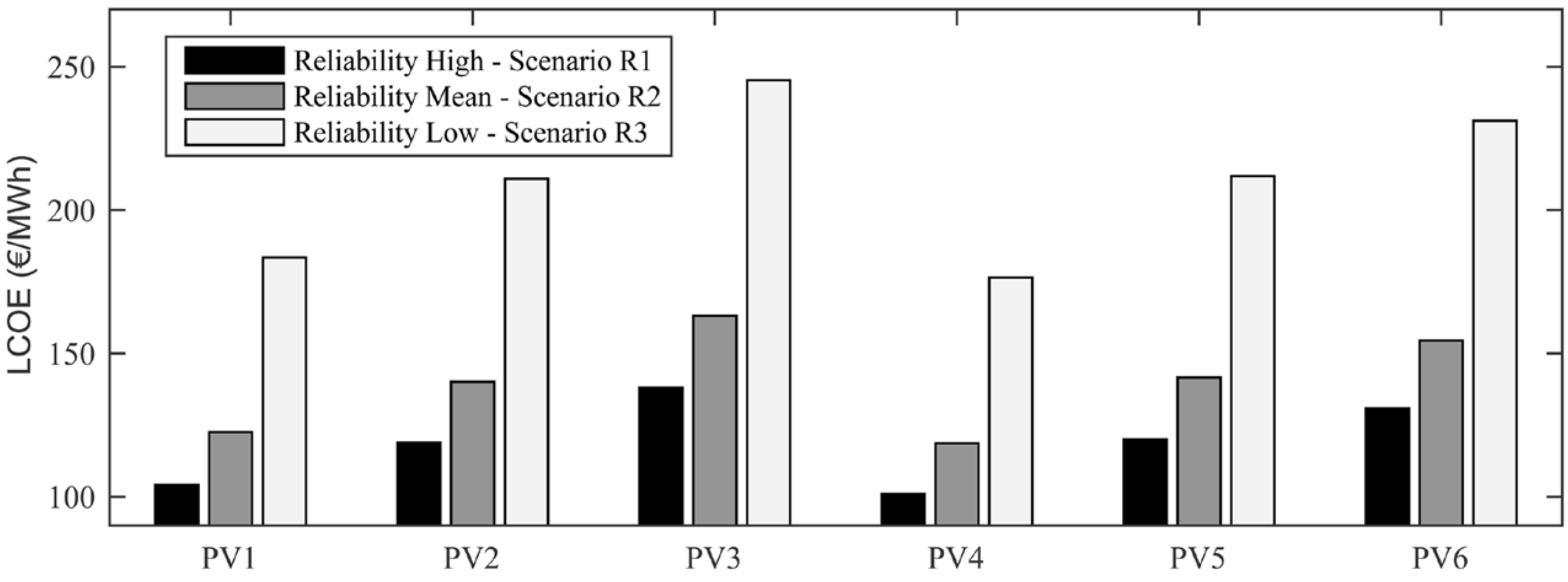
Results - LCOE



LCOE computed for all PV plant configurations varying PV plant capacity (1, 50 and 200 MWp) and component costs (CC1, CC2 and CC3)

De Prada et al “Technical and Economic comparison of various electrical collection grid configurations for large PV power plants” IET 2017

Results - LCOE

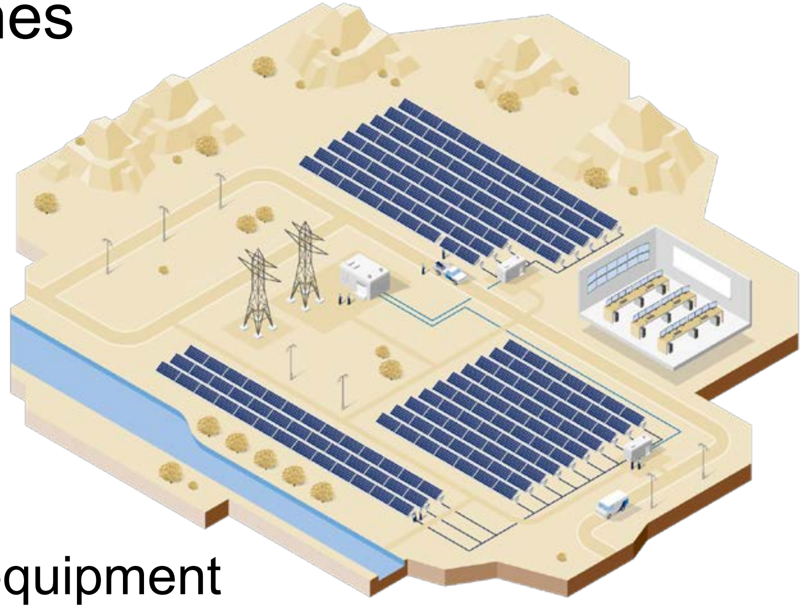


LCOE computed for all PV plant configurations varying components reliability (R1, R2 and R3)

De Prada et al "Technical and Economic comparison of various electrical collection grid configurations for large PV power plants" IET 2017

Equipment for PV power plants

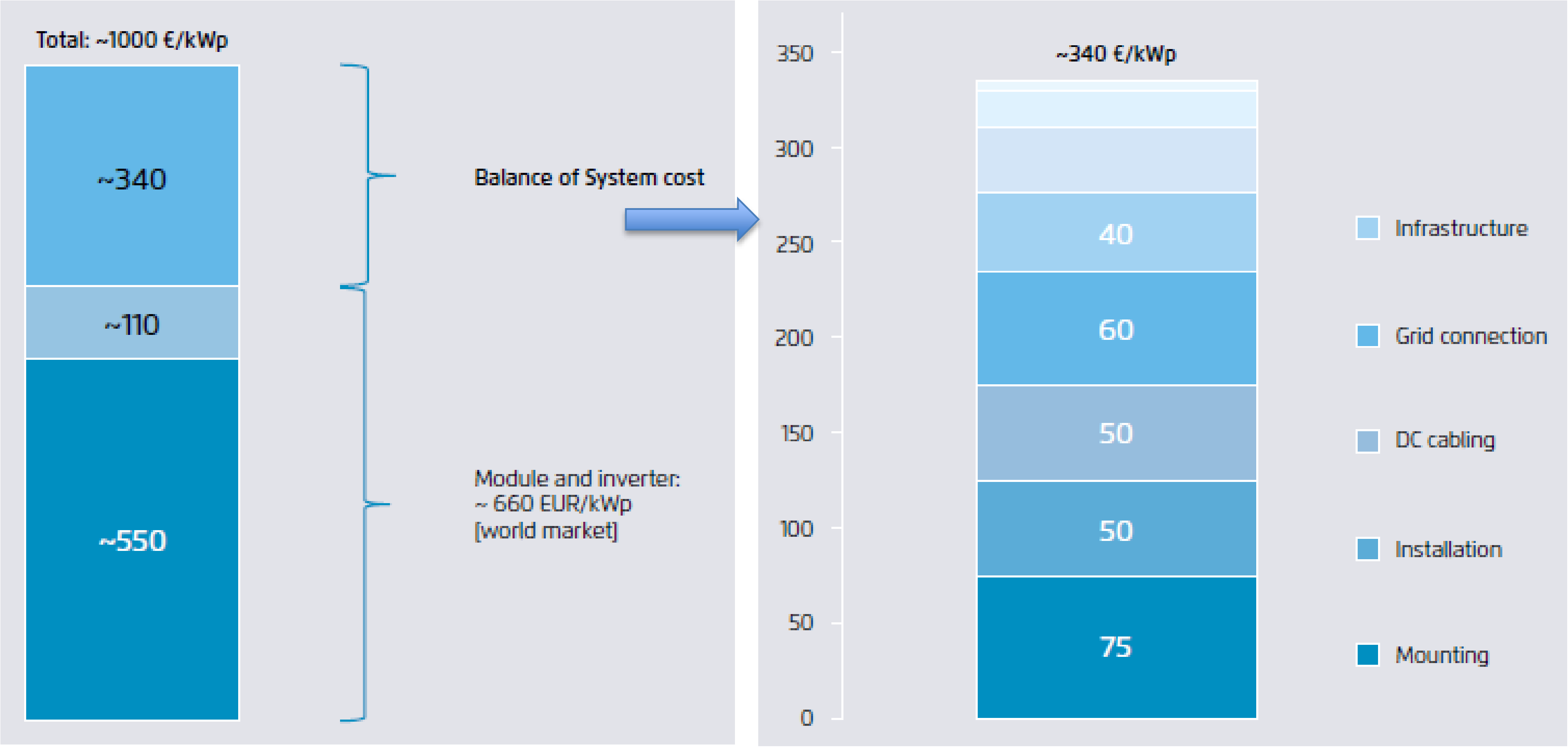
- In addition to PV panels and inverters, PV power plants require the following equipment:
  - Interconnection cables and lines
    - DC strings
    - AC Grid connection
  - Grid connection equipment
    - Protection equipment
    - Electrical switchgear
    - Power Transformers
    - Reactive power compensation equipment
  - Energy storage systems (when needed)



Source: Skytron

Cost distribution

Overview of (2015) total system cost for ground-mounted PV systems



Current and Future Cost of Photovoltaics, Fraunhofer ISE

Stand-alone PV power plants

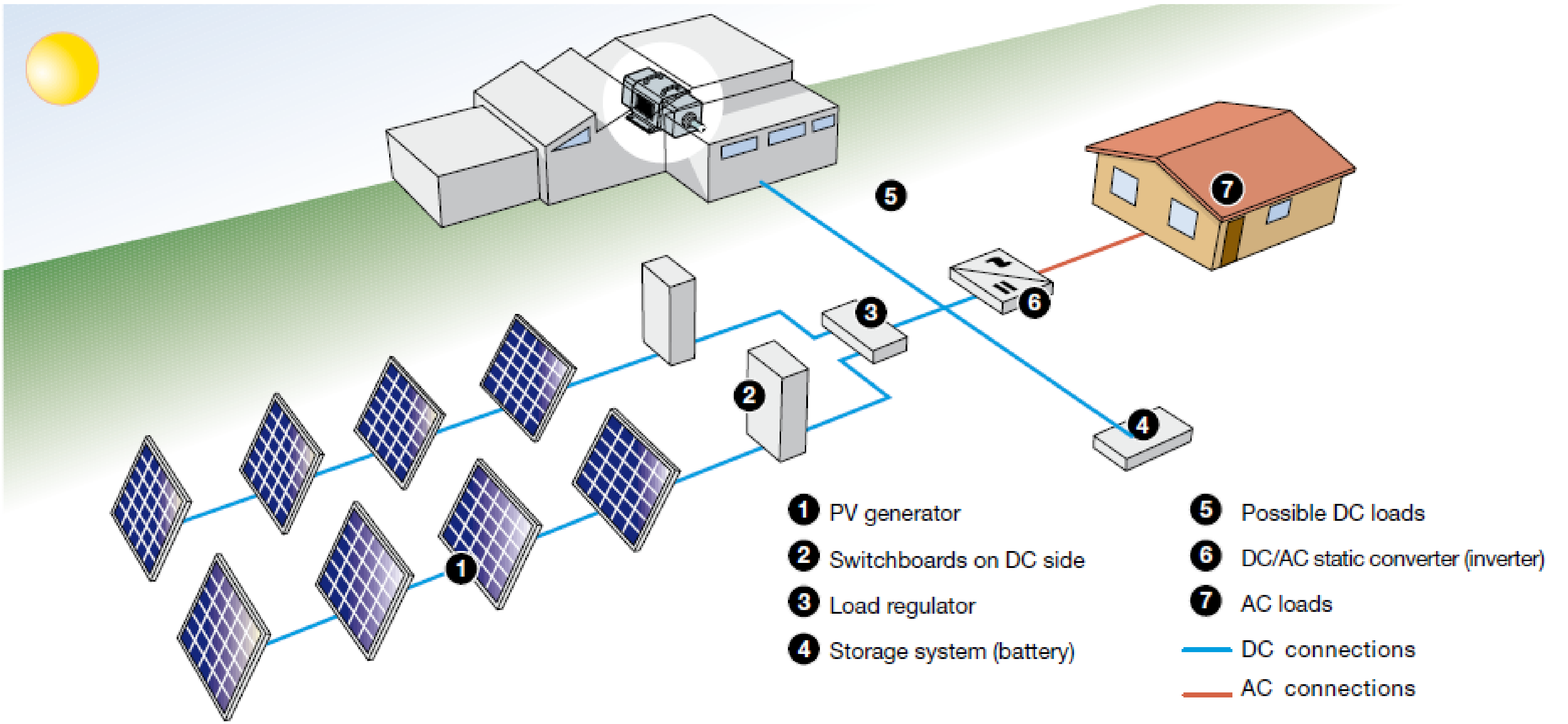


ABB Technical application paper No 10 – PV plants

Grid connected PV power plants

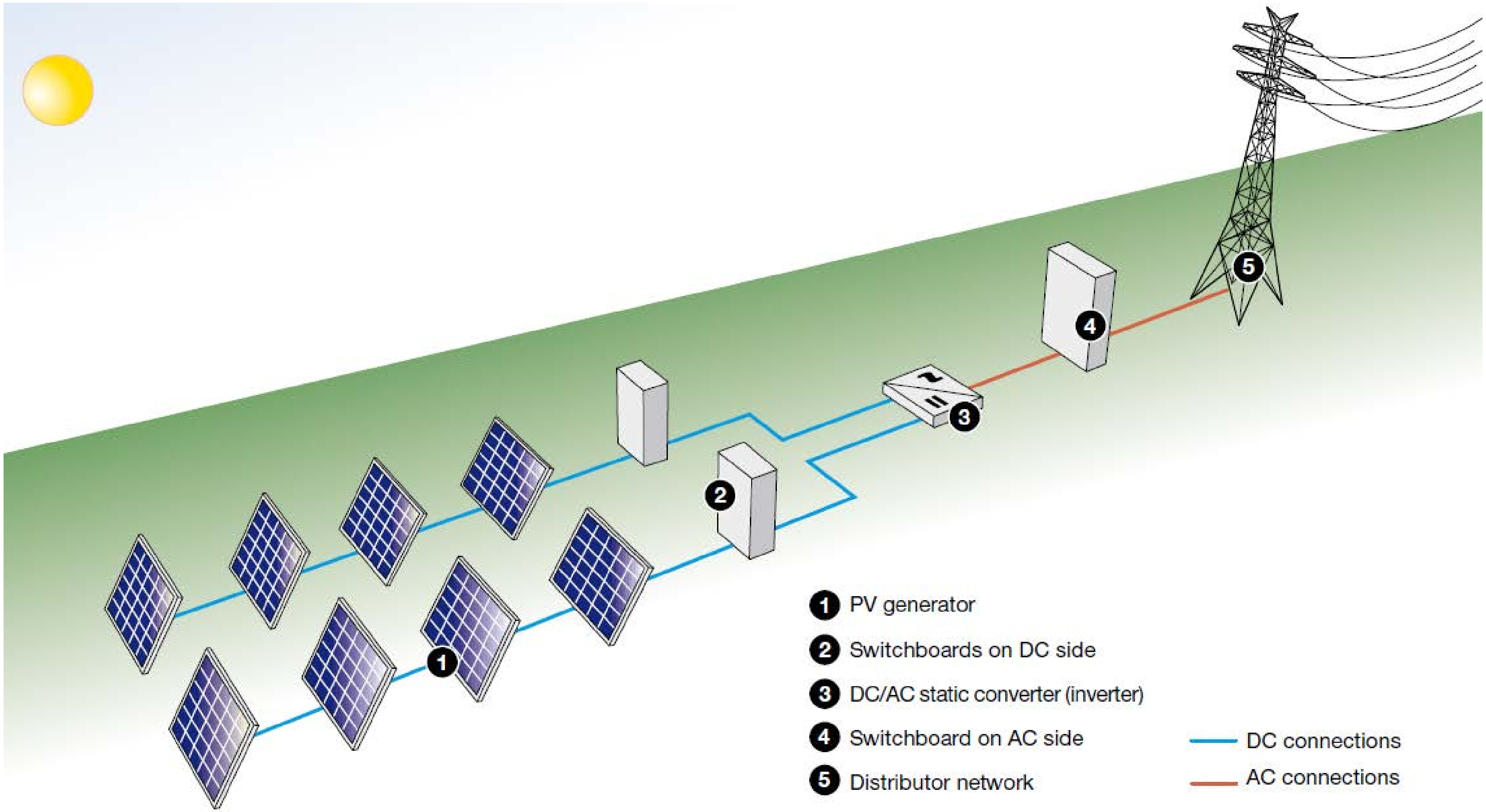
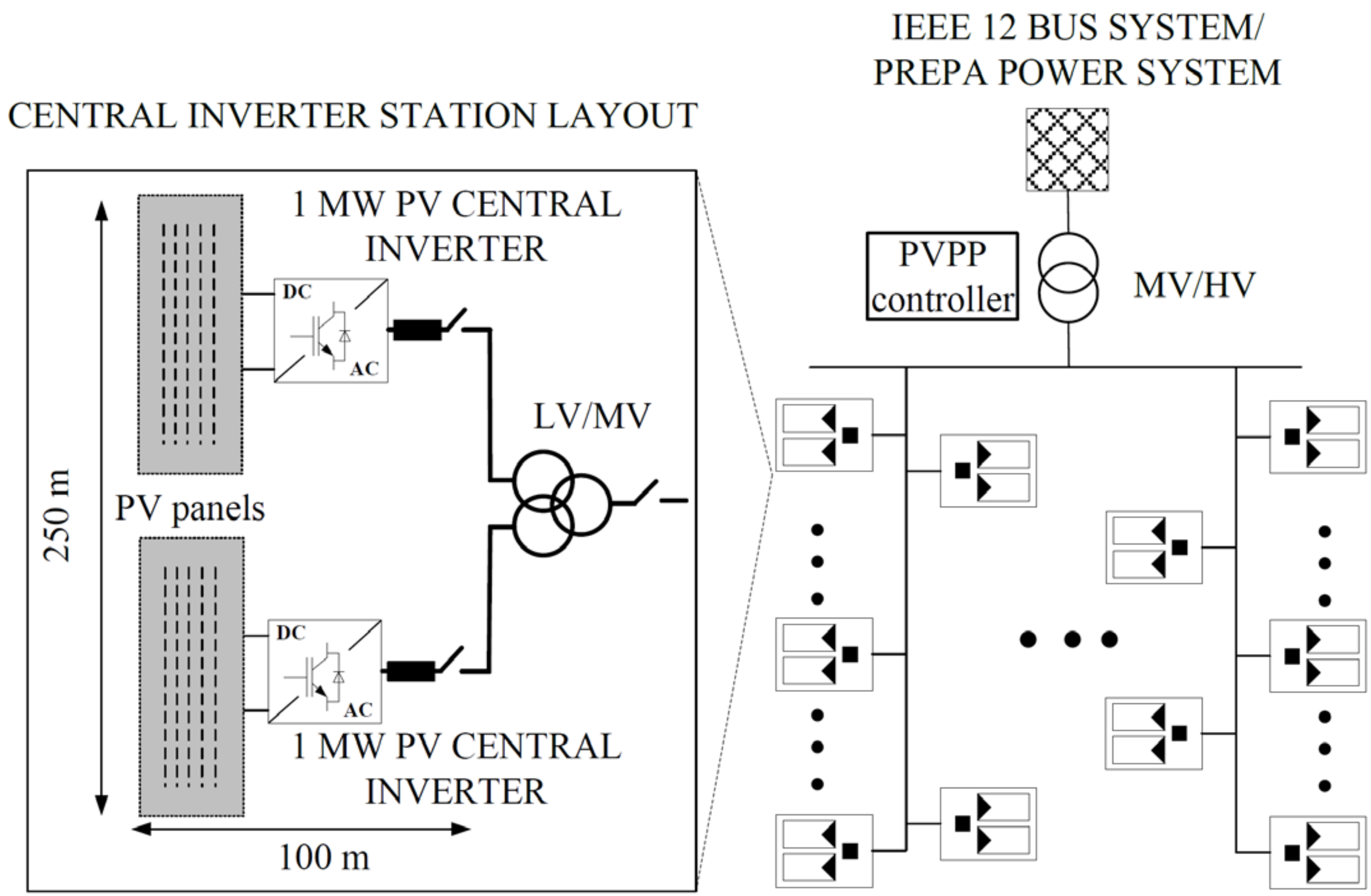


ABB Technical application paper No 10 – PV plants

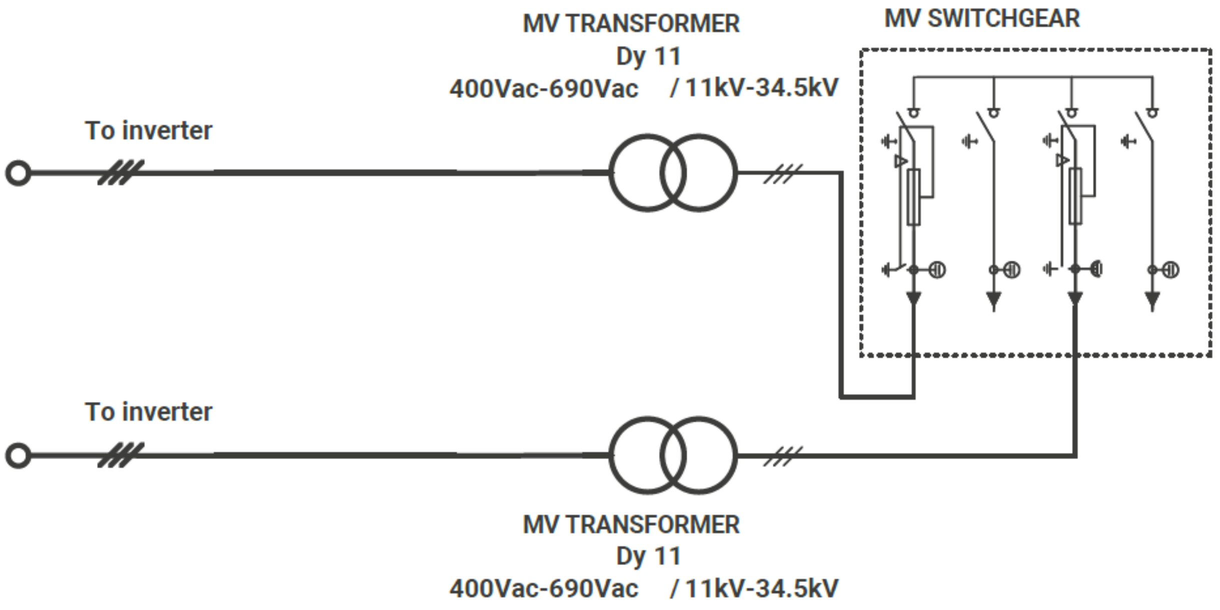
Large PV power plants



Energinet.dk ForskEl project no.10648

Transformers and switchgear

- Low to medium voltage AC Transformers for each inverter (or pair of inverters)
- Single or double feeder configuration

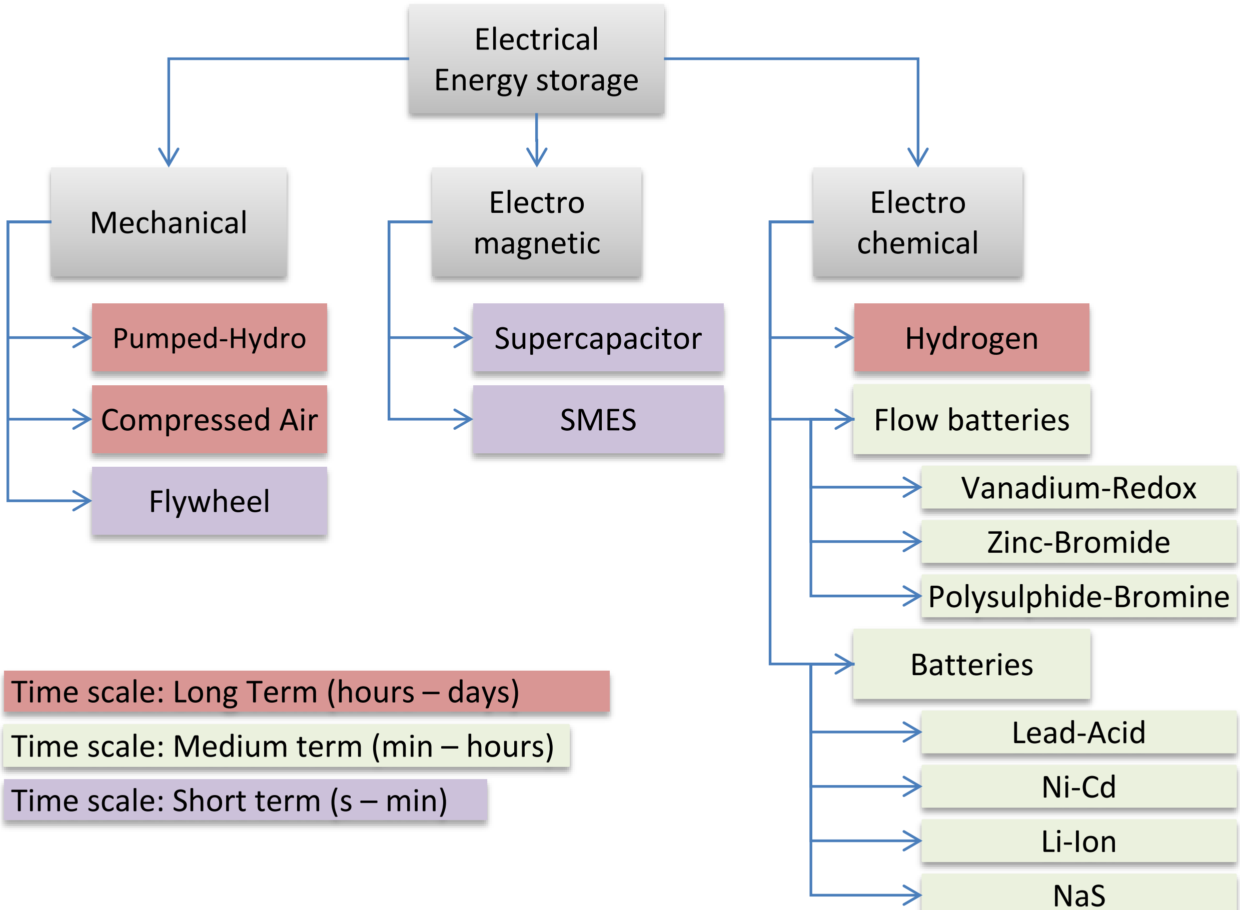


power-electronics.com

Reactive power

- Additional reactive power provision can be needed in some projects.
- It can be provided with:
  - Capacitor banks, if there are no dynamic requirements.
  - SVC (static VAR compensator), if the reactive power needs to be adjusted dynamically.
  - STATCOM (static synchronous compensator), if reactive power needs to be adjusted dynamically and reactive current needs to be ensured also in fault conditions.
- In some applications we can use capacitor banks for the bulk reactive power provision and a STATCOM for the regulation.

Energy storage systems - General description



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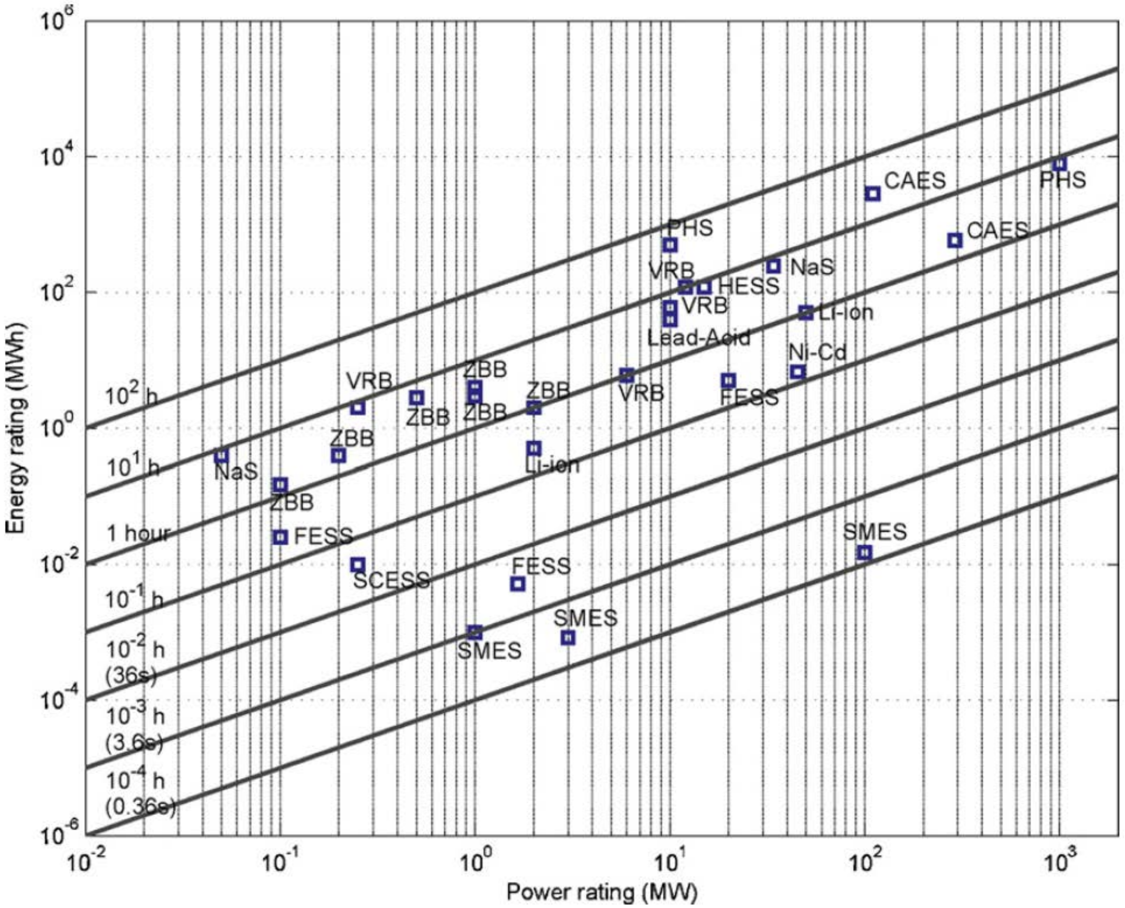
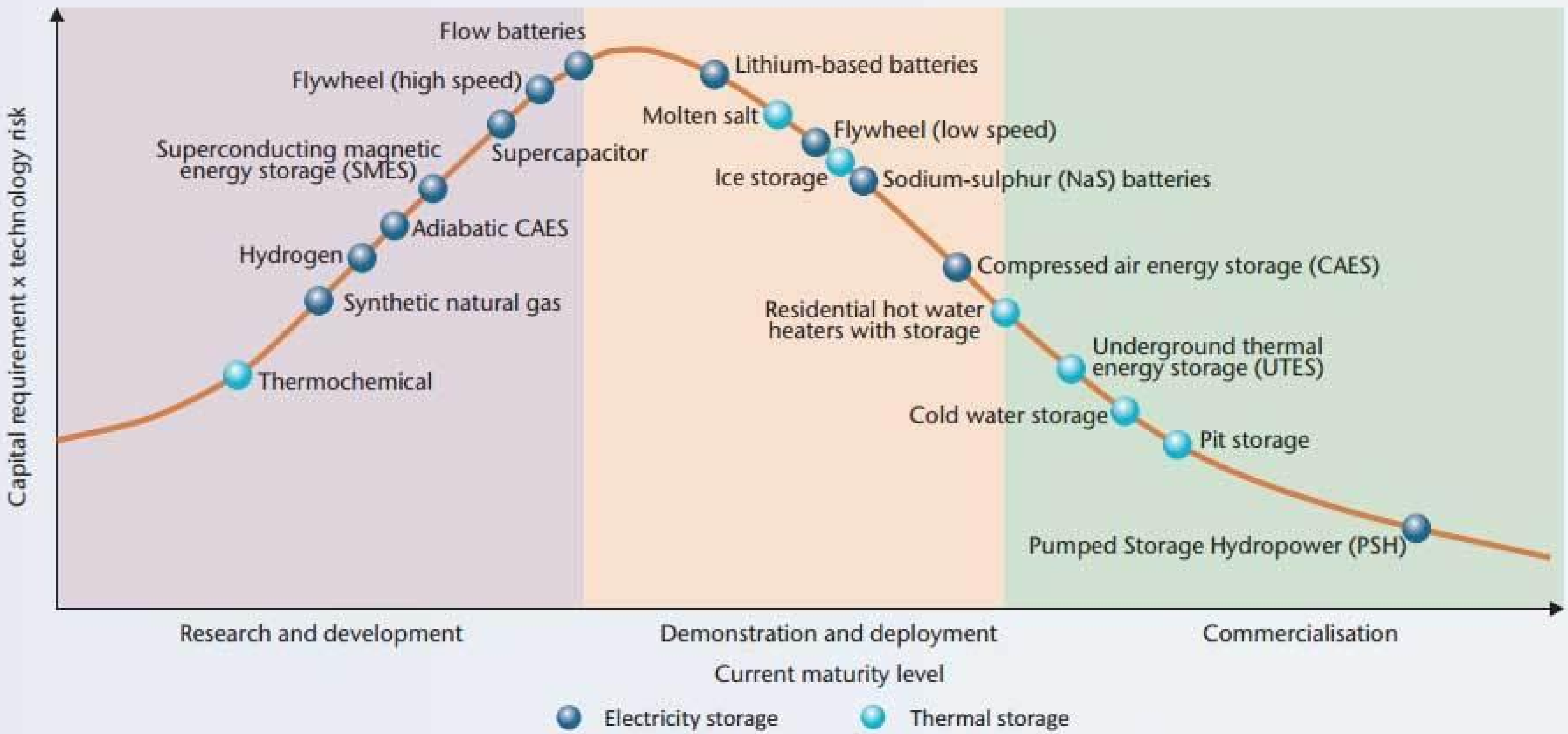
Energy storage systems - General description



Source: F. Díaz-González, A. Sumper, O. Gomis-Bellmunt, R. Villafáfila-Robles. A review of energy storage technologies for wind power applications. Renewable and Sustainable Energy Reviews 2012(16)

Energy storage systems - General description



Source: Decourt, B. and R. Debarre (2013), "Electricity storage", *Factbook*, Schlumberger Business Consulting Energy Institute, Paris, France and Paksoy, H. (2013), "Thermal Energy Storage Today" presented at the IEA Energy Storage Technology Roadmap Stakeholder Engagement Workshop, Paris, France, 14 February.

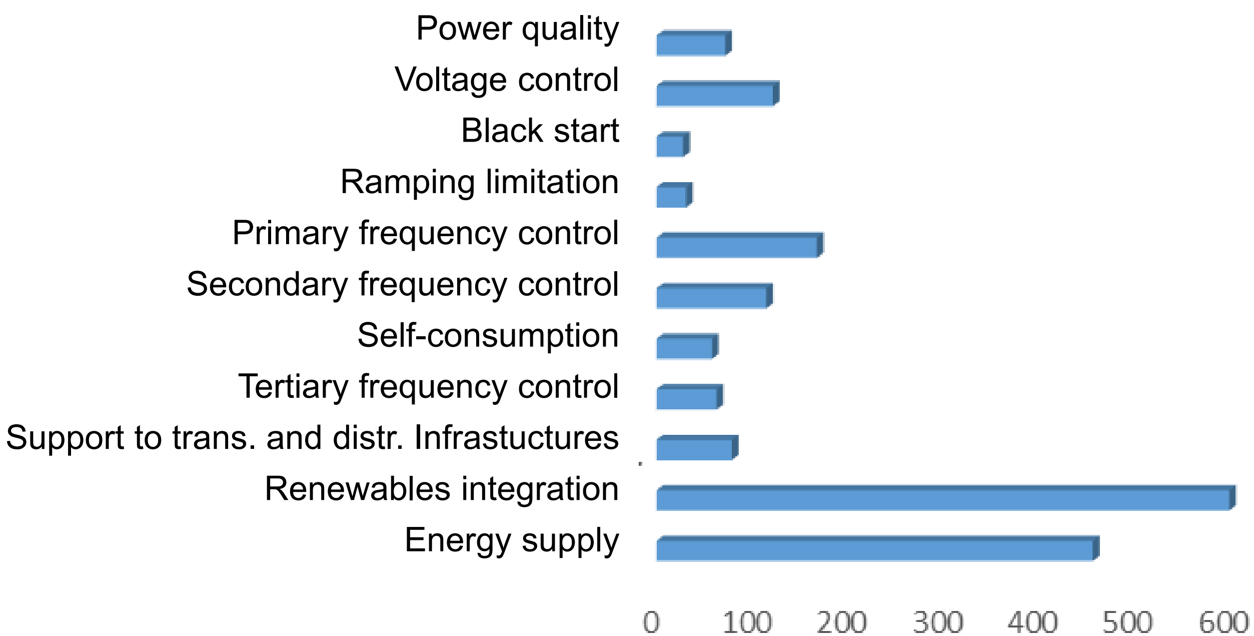
Energy storage systems - Applications

	Full power duration of storage	Pumped Hydro	Hydrogen	Compressed Air	Vanadium Redox	Zinc Bromine	Polysulphide Bromide	Sodium Sulphur	Lead Acid	Nickel Cadmium	**Lithium Ion**	SMES	Flywheel	Supercapacitor
Fluctuation suppression	≥ 1 min				v	v	v	v		v	**v**	v	v	v
Low Voltage Ride Through	≥ 1 min				v	v	v	v	v	v	**v**	v	v	v
Voltage control	≥ 1 min				v	v	v	v	v	v	**v**	v	v	v
Oscillation damping	≥ 1 min		v		v	v	v	v	v	v	**v**	v	v	v
Spinning reserve	≥30 min	v	v	v	v	v	v	v	v	v	**v**	v	v	
Load following	1-10 h	v	v	v	v	v	v	v	v	v	**v**			
Peak shaving	1-10 h	v	v	v	v	v	v	v	v	v	**v**			
Transmission curtailment	5-12 h	v	v	v	v	v	v	v						
Time shifting	5-12 h	v	v	v	v	v	v	v						
Unit commitment	h-days	v	v	v										
Seasonal storage	≥120 days	v	v	v										

Source: F. Díaz-González, A. Sumper, O. Gomis-Bellmunt, R. Villafáfila-Robles. A review of energy storage technologies for wind power applications. Renewable and Sustainable Energy Reviews 2012(16)

Energy storage systems – Number of research projects worldwide

Research focuses on the application of energy storages for the grid integration of renewables.



Data: DOE Global Energy Storage Database, http://www.energystorageexchange.org/

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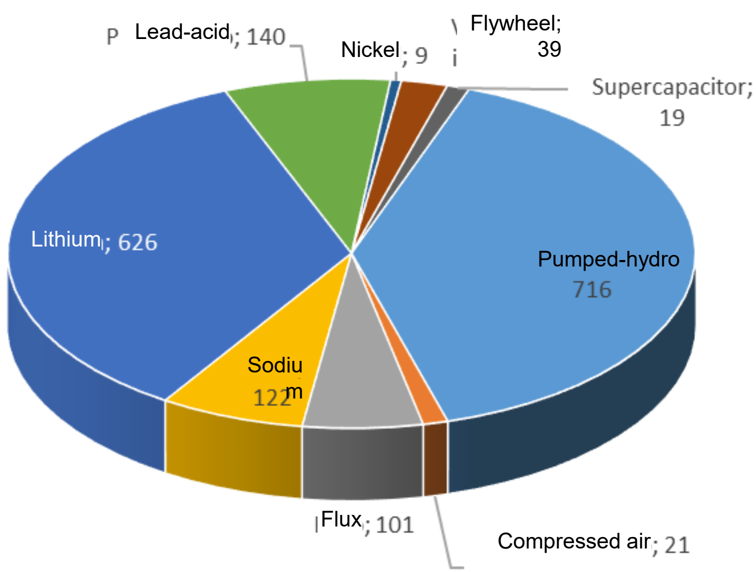
Energy storage systems – projects worldwide

The intense research activities should favor a dramatic cost reduction of lithium-ion batteries in a short term, thus favoring a generalized deployment of this technology in the electrical power system and the electro mobility fields.

The European Commission (and other organizations such as EASE and EERA) proposed in their technology roadmaps the objective of decreasing by a factor of 5 the current cost of lithium-ion batteries by 2030.



Data: DOE Global Energy Storage Database, http://www.energystorageexchange.org/

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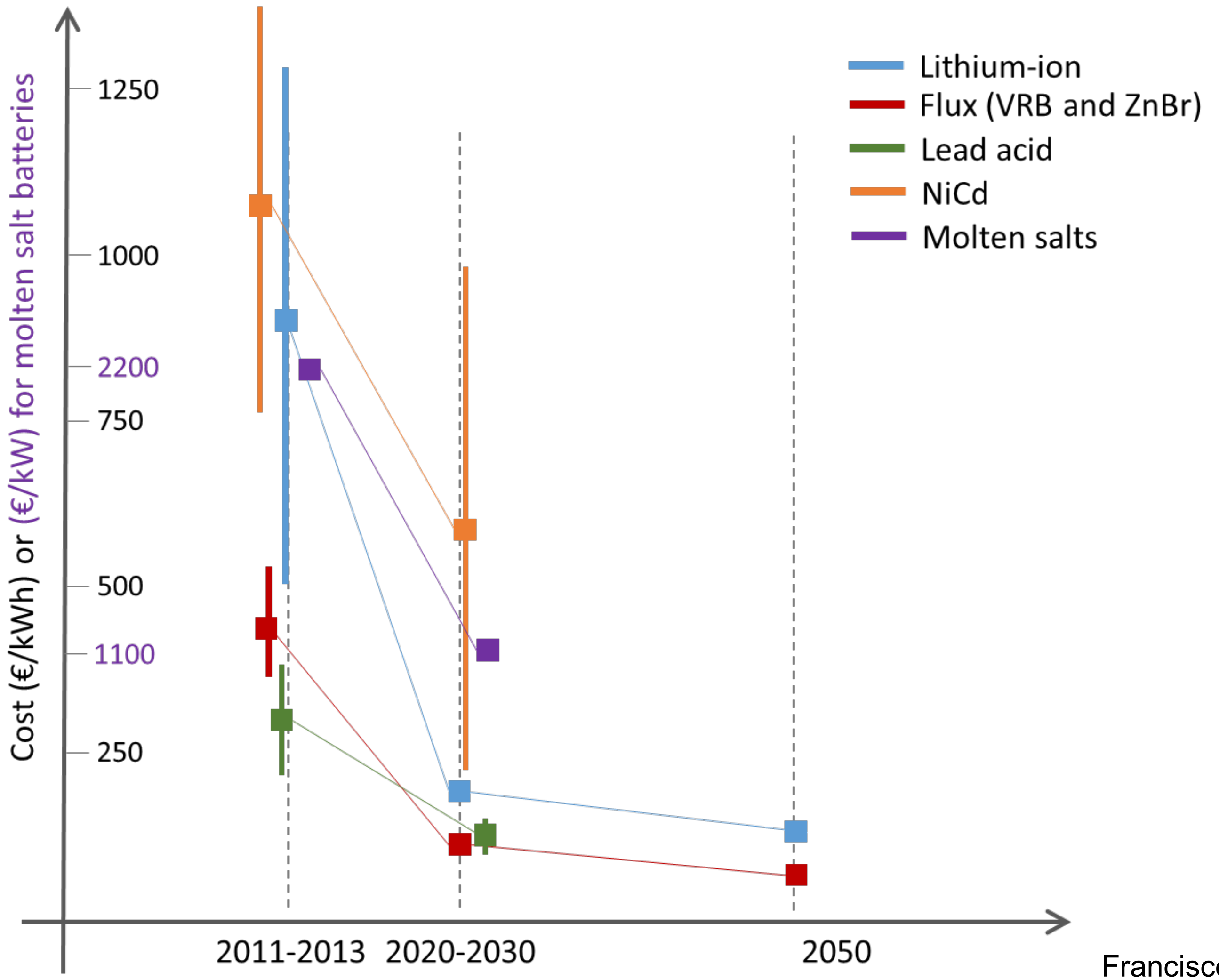
Energy storage systems – expected dramatic cost reduction



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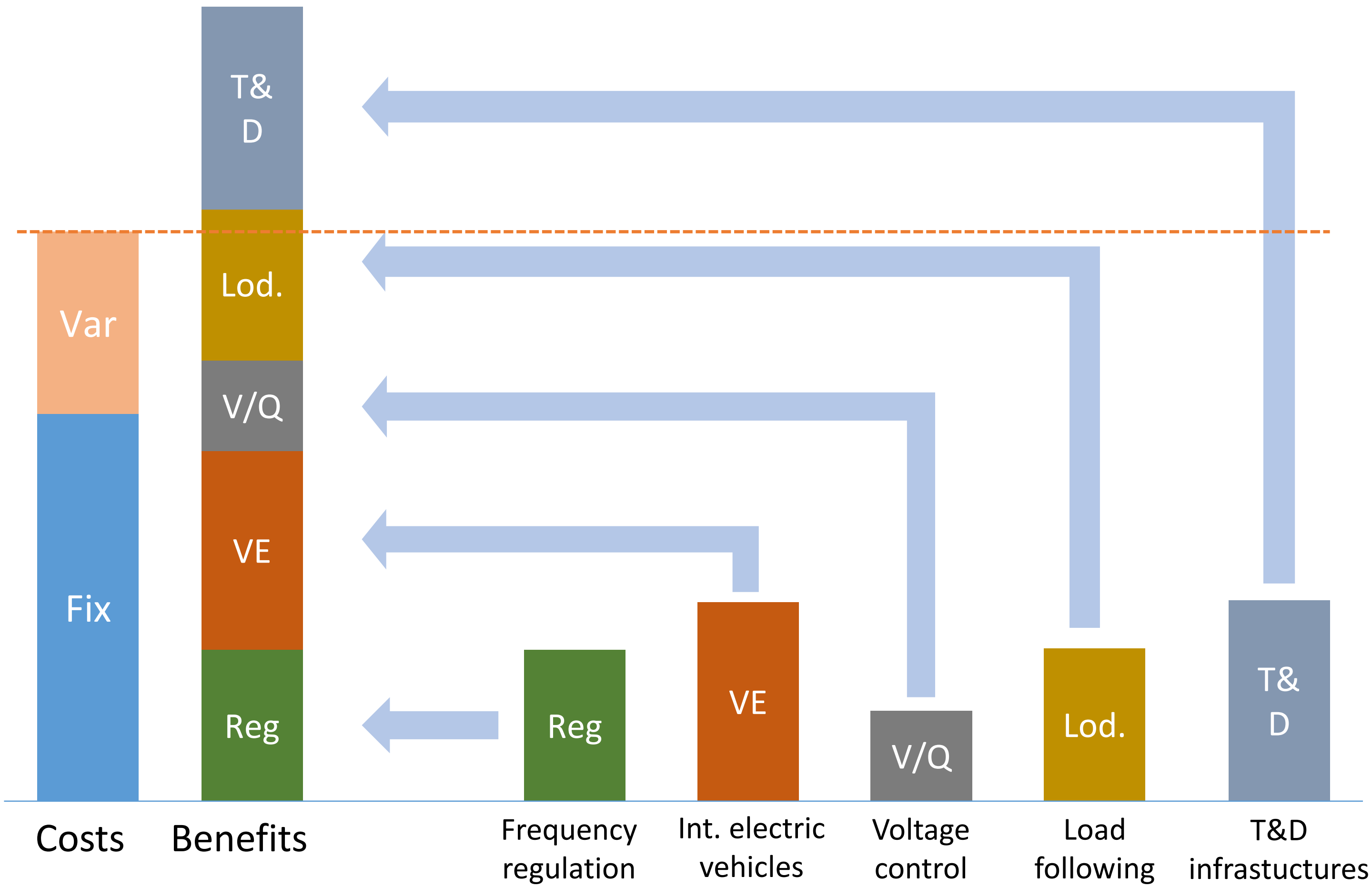
Energy storage systems – Business models. Vision



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Summary

- 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.
- There are a number of possible topologies for arranging the power inverters, including central, string and multi-string.
- Additional equipment is needed: transformers, switchgear and in some cases reactive power equipment and energy storage systems.

Thanks for your attention!

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