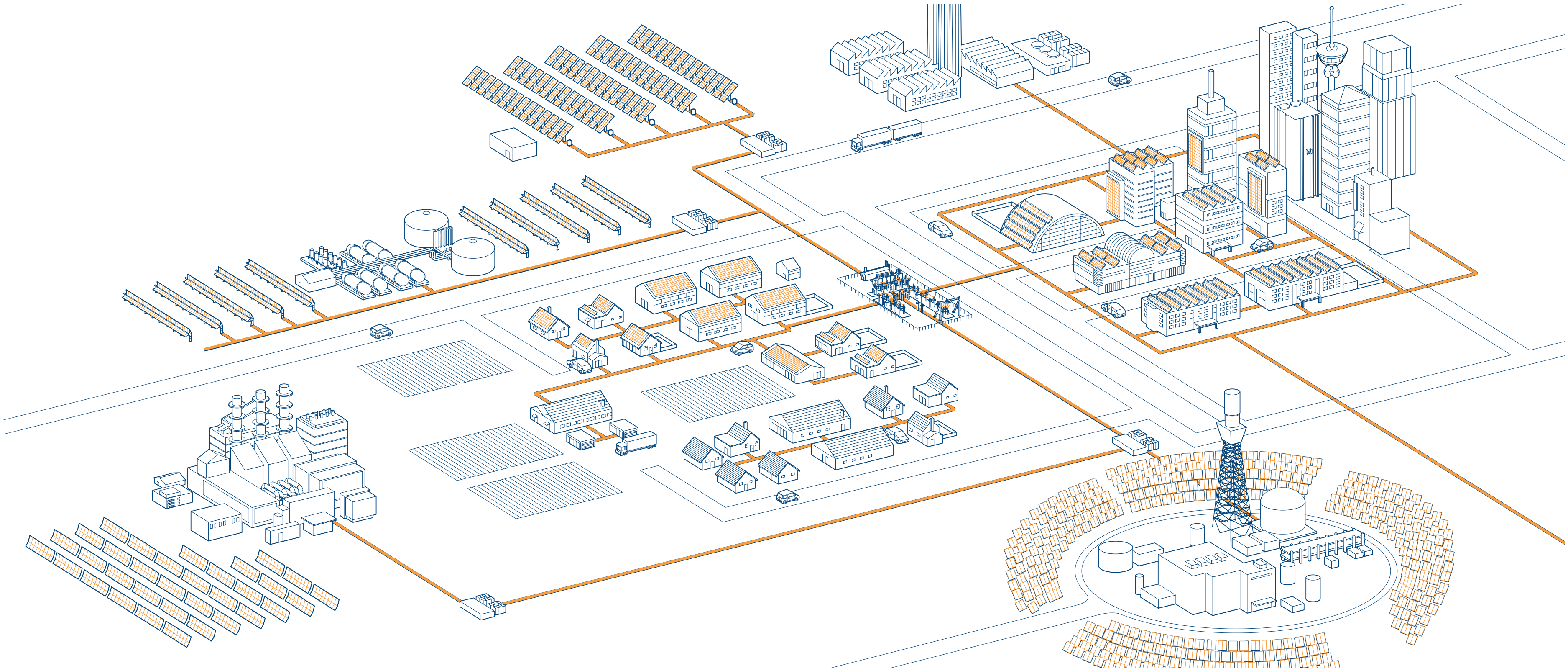
Internet of Energy

The revolution of distributed generation: from environmental energy harvesting to integration of renewables in smart micro-grids



Paolo Tenti

Department of Information Engineering, University of Padova

Outline

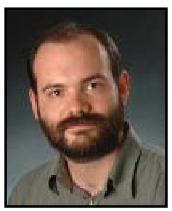
- **Part I: Energy Harvesting Research @ UniPD+UniUD**
  - **Energy Harvesting: Introduction and Foreseeable Applications**
  - **Research Lines**
- **Part II: Integration of distributed renewable energy sources in low-voltage smart microgrids**
  - **Distributed generation scenario**
  - **Microgrid Architecture**
  - **Role of Power Electronics**
  - **Microgrid control**
  - **Case studies**
  - **Conclusions**

Part I: Energy Harvesting Research @ UniPD and UniUD

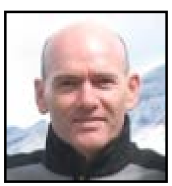
Research in Energy Harvesting @ UniPD+UniUD: People and Departments

Paolo Mattavelli
Associate Professor
DTG, UniPD

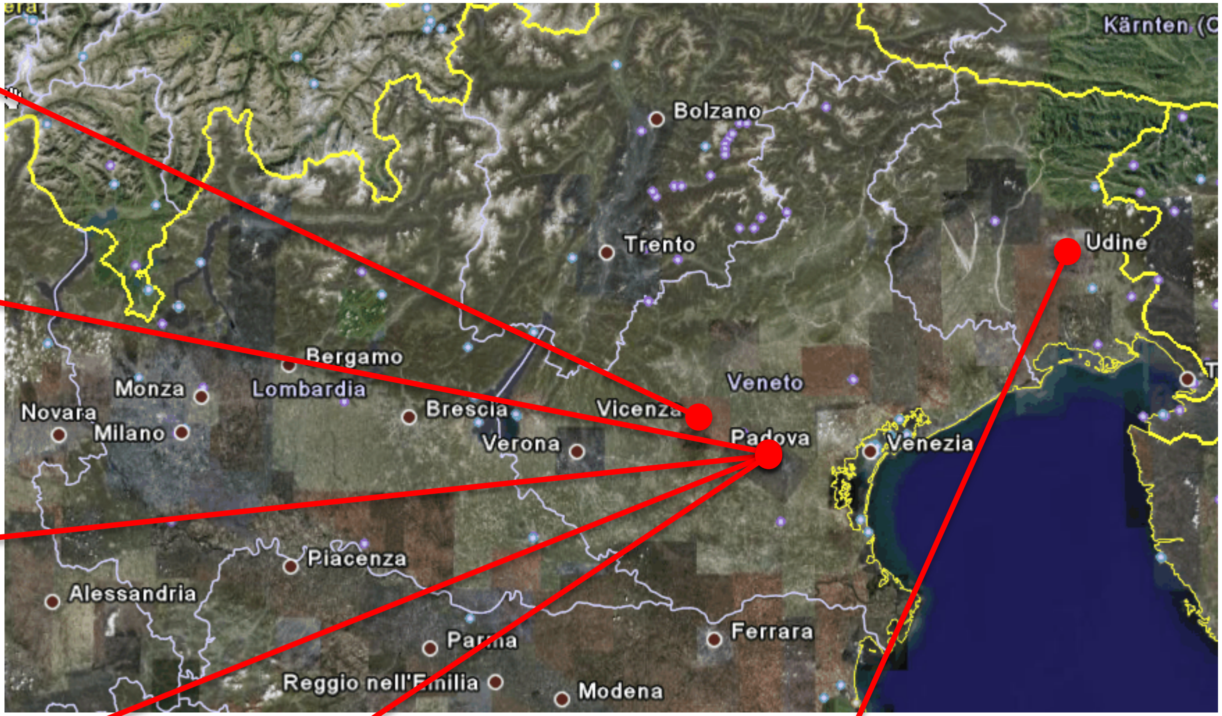
Simone Buso
Associate Professor
DEI, UniPD



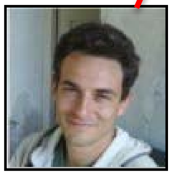
Luca Corradini
Assistant Professor
DEI, UniPD



Giorgio Spiazzi
Associate Professor
DEI, UniPD



Paolo Tenti
Full Professor
DEI, UniPD



Stefano Saggini
Assistant Professor
DIEGM, UniUD

http://pelgroup.dei.unipd.it/people

Small-Scale Energy Harvesting

- General idea is to absorb, locally store and reuse ambient energy from various types of sources such as:
  - Solar, using photovoltaic micropanels,
  - RF, using rectifying antennas,
  - Thermal, using thermoelectric generators,
  - Mechanical, using piezoelectric as well as magnetic devices

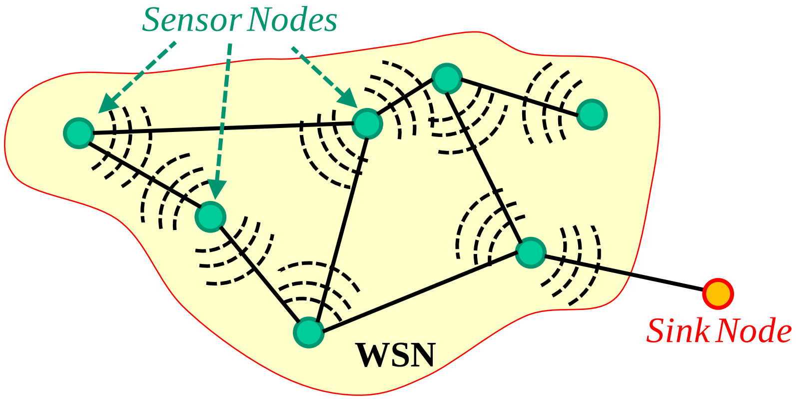
- Purpose is to operate low-power devices such as sensor nodes and small actuators

Typical Energy Sources

Source	Harvester	Typical Voltage	Typical Power	Challenge
Solar	Photovoltaic Micropanel	0.5 V per cell	Up to 15 mW/cell (outdoors)	Low-complexity MPPT
Mechanical	Piezoelectric Device	Tens of volts AC @ open-circuit	Tens of mW	Complex Impedance ➔ load-source matching
Mechanical	Magnetic Device	Few volts	Wide range	Maximum energy extraction
RF	Rectenna	< 1 V @ Matched conditions	Hundreds of μW to few mW	Coupling
Thermal	Thermoelectric Generator	0.2 mV/K per cell	Hundreds of μW to few mW	Ultra-low voltage source

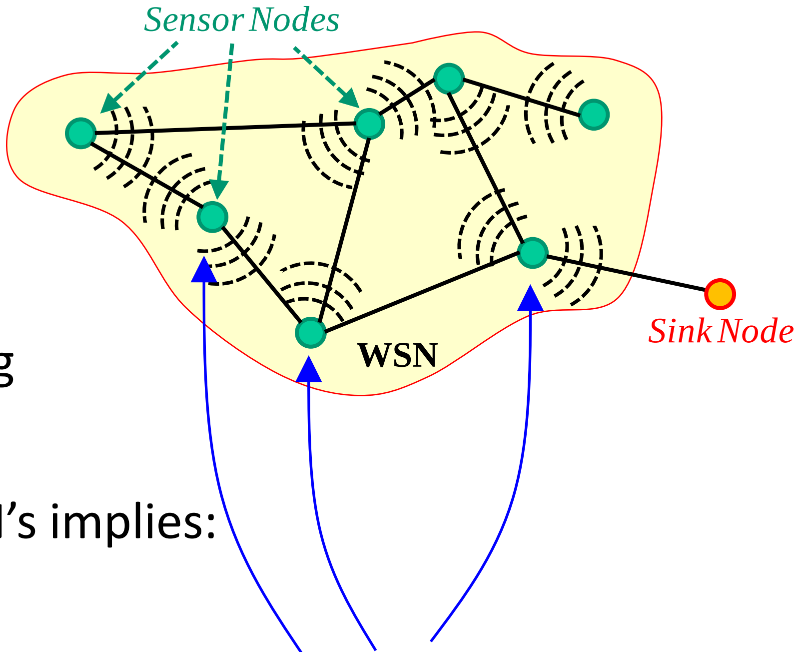
Motivating Example: Large Wireless Sensor Networks

- Function of a WSN:
  - Sense and sample a scalar field (Temperature, pressure, humidity, motion, vibration, etc…)
  - Route sensed information to a central unit or *sink node*
- Large WSN: tens to hundreds of nodes



Motivating Example: Large Wireless Sensor Networks

- Application areas:
  - Industrial: machine monitoring, fault diagnostics / prevention
  - Residential: surveillance, efficient building control
  - Environmental: landslide monitoring and prevention



- Practical deployment of large-scale WSN's implies:
  - Zero-maintainance nodes ("Fit and forget" approach)
  - Prolonged sensor lifetime (several years)
  - Low $/Wh

Research Trend:
Embed energy harvesting capabilities into each sensor node

Other Fields of Applicaton of the Energy Harvesting Paradigm

Wearable technologies and gadgets

Amiigo wirelessly-charged wristband tracks a number of health parameters

Avionics

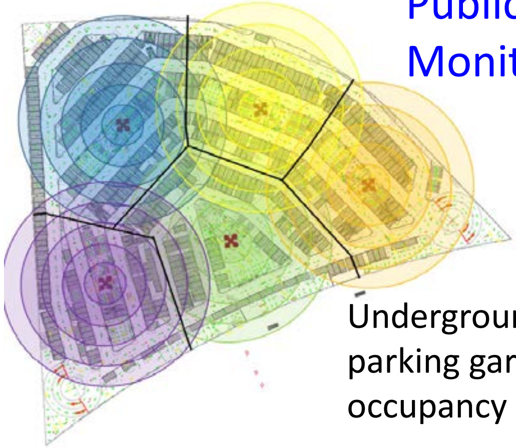
EH-based wireless engine monitoring vs. conventional wired monitoring

@ 2011 Rolls Royce

Automotive

Rooftop PV's,
Regenerative braking,
EH Dampers, Tire Pressure Monitoring Systems

Public Places Monitoring

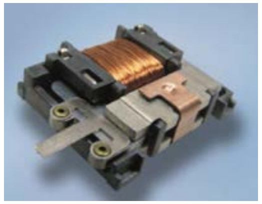


Underground parking garage occupancy monitoring

@ 2011 PowerLeap

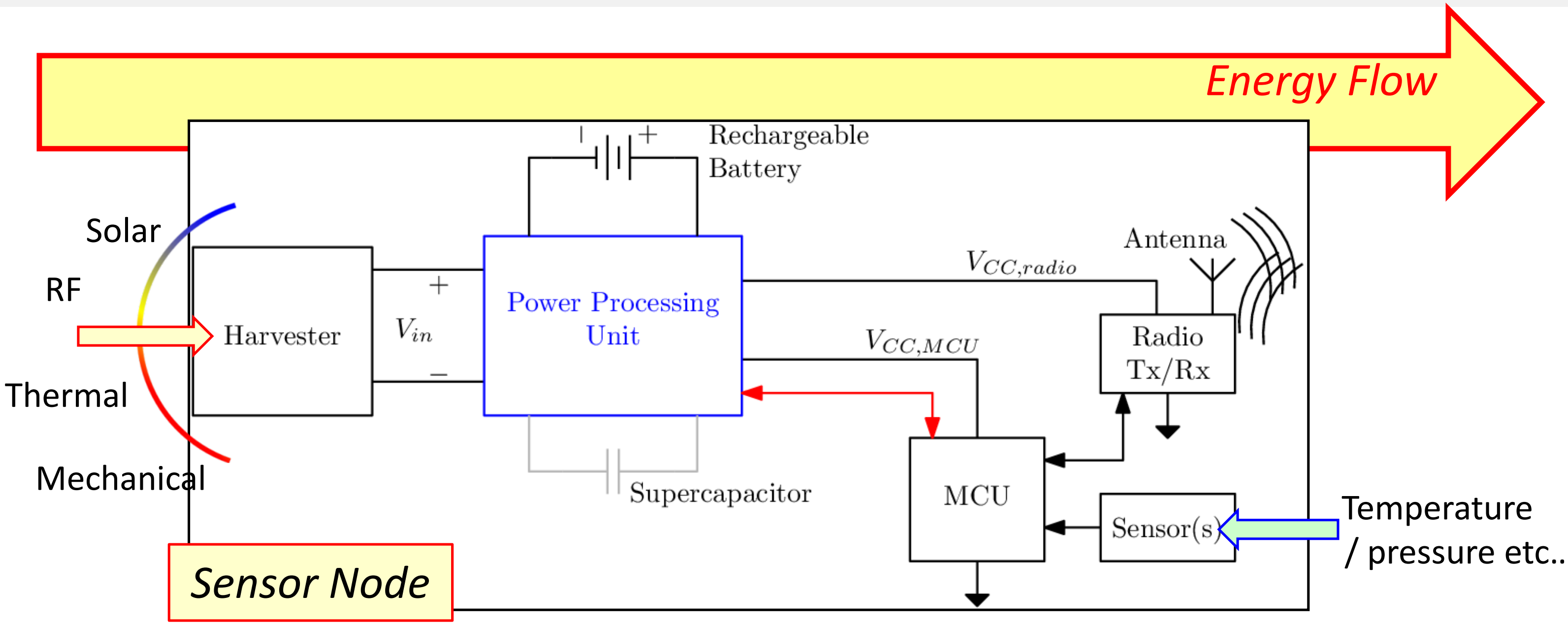
Wireless Switches for Building Control

EnOcean ECO-200 Wireless Switch



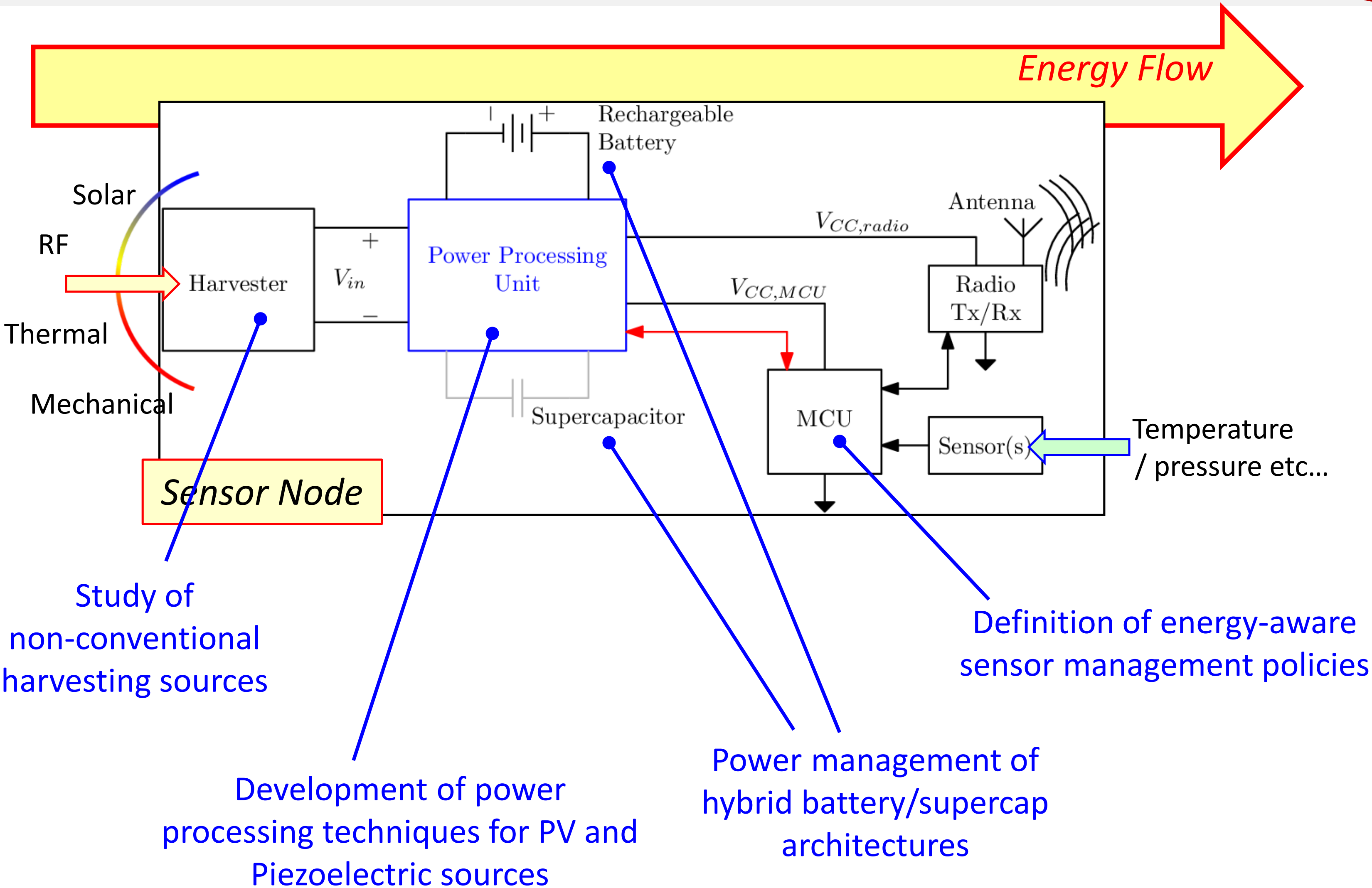
@ 2012 EnOcean

The Harvesting-Based Wireless Sensor Node

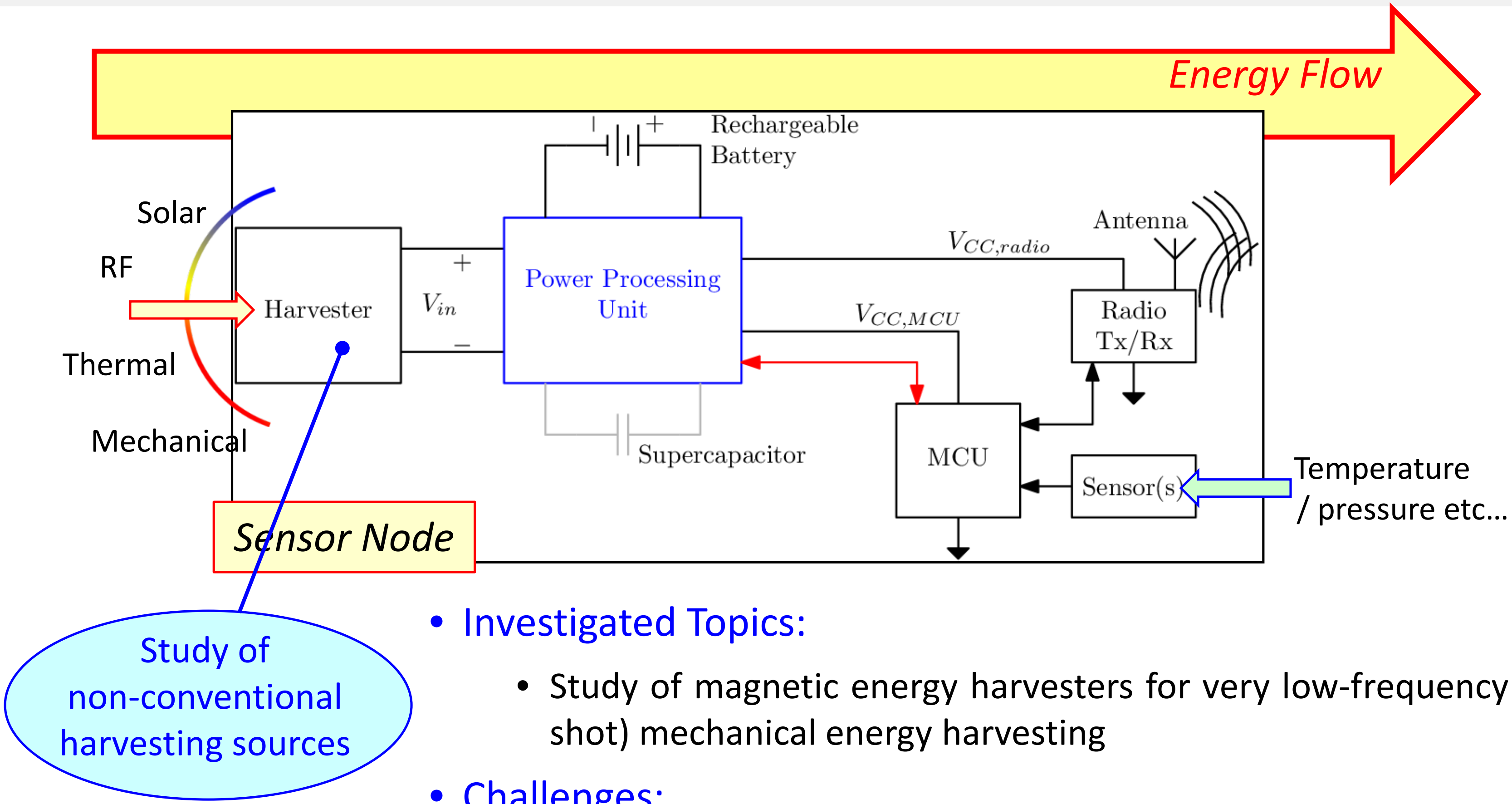


- Building blocks:
  - Energy harvester
  - Storage units: secondary (micro)battery, optional supercapacitor
  - Power Processing Unit:
    - Source Matching
    - Storage management
  - Sensor loads: Microcontroller Unit (MCU), Transceiver, Sensor(s)

Energy Harvesting Research Lines at UniPD and UniUD

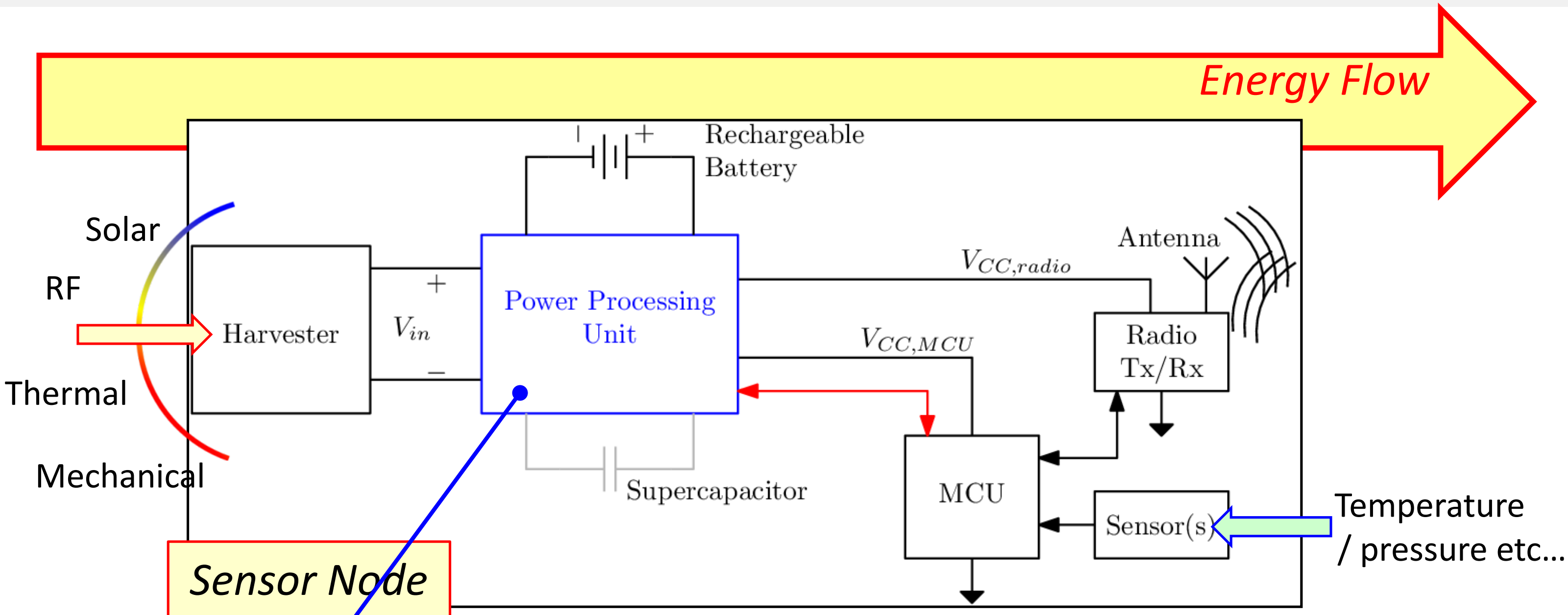


Non-conventional Harvesting Sources



- Investigated Topics:
  - Study of magnetic energy harvesters for very low-frequency (or one-shot) mechanical energy harvesting
- Challenges:
  - Source characterization
  - Harvester design for optimized energy extraction under realistic battery voltage constraints
  - Different solutions required for continuous vs. one-shot operation

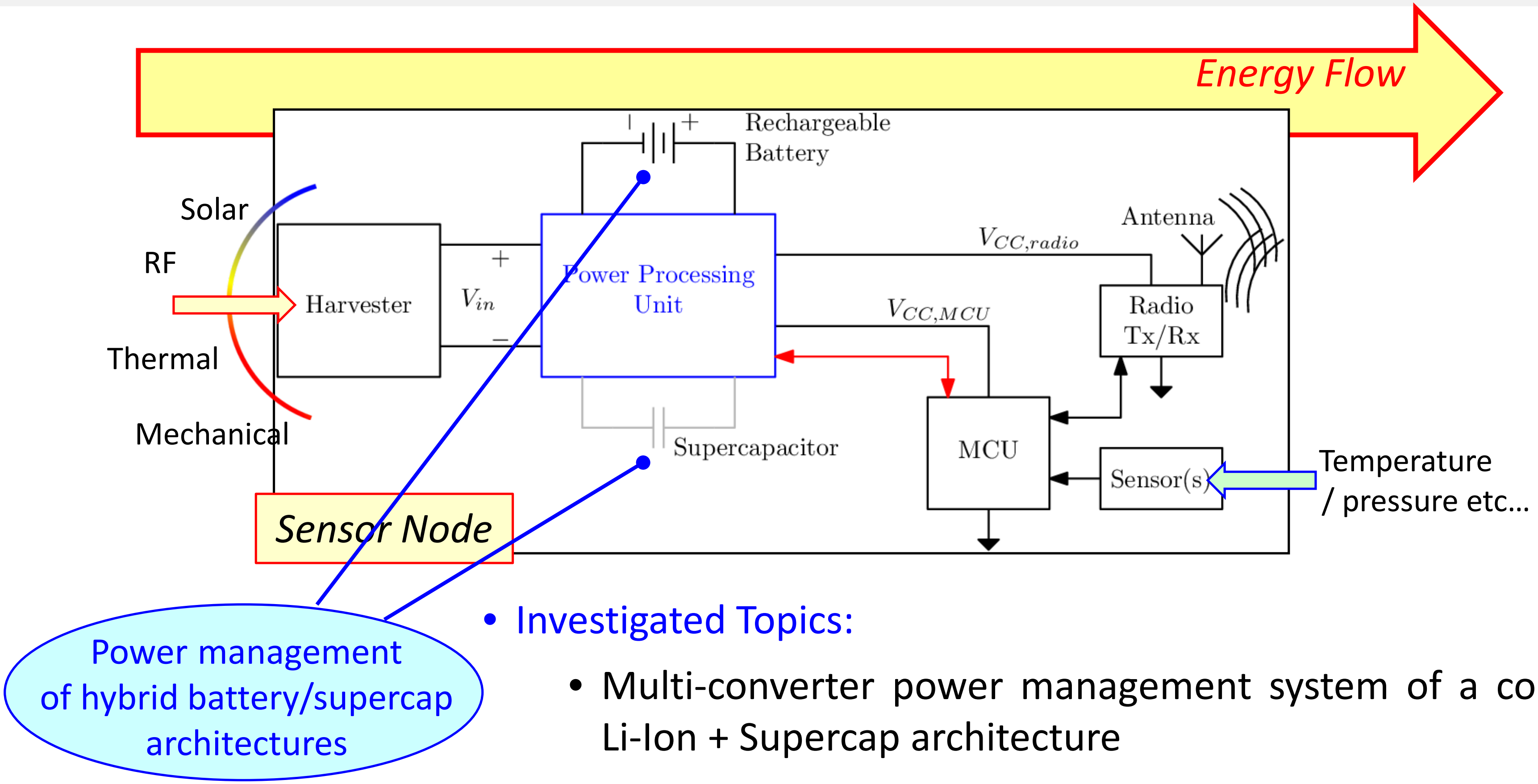
Power Processing Techniques



Development of power processing techniques for PV and Piezoelectric sources

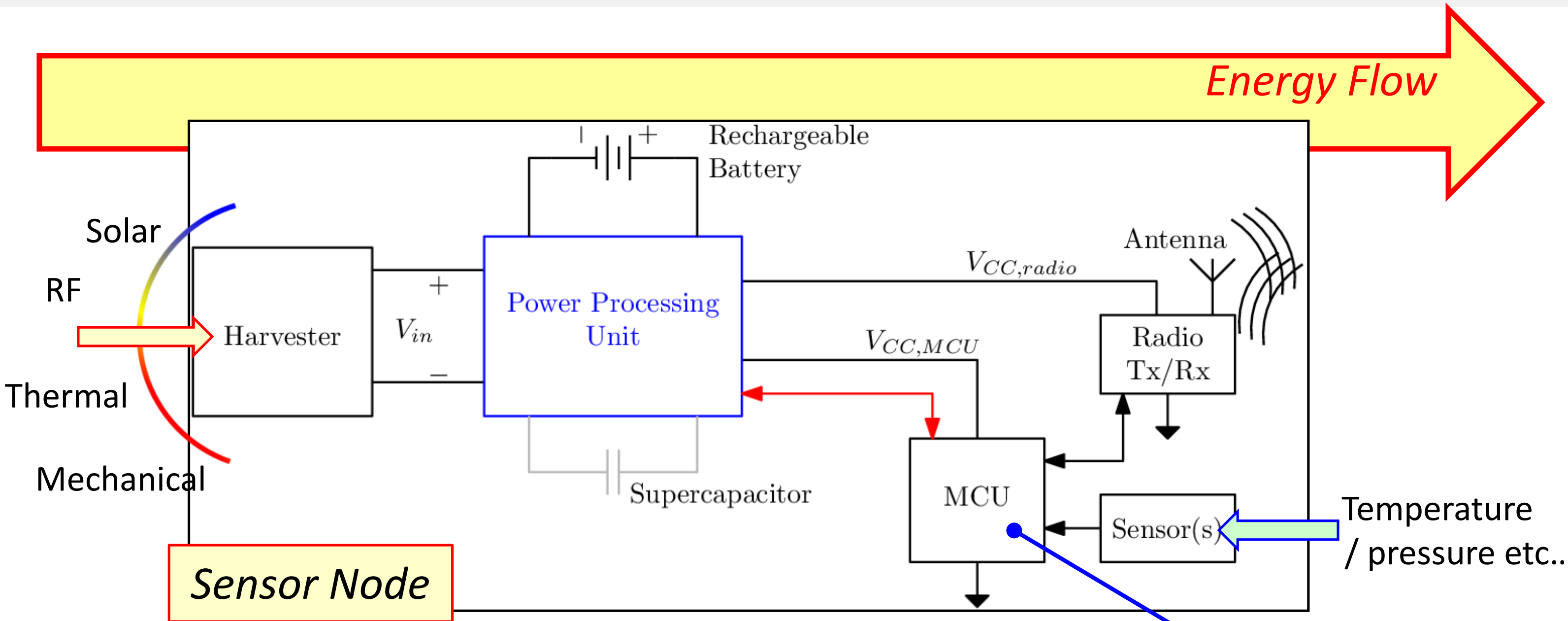
- Investigated Topics:
  - Maximum power point tracking for PV and Piezo sources
- Challenges:
  - Low-complexity algorithm required due to limited power budget
  - Two-parameter load matching required: voltage / switching rate (PV) or load equivalent R and L (Piezo)

Power Management of Hybrid Systems



- Investigated Topics:
  - Multi-converter power management system of a combined Li-Ion + Supercap architecture
- Challenges:
  - Best exploitation of batteries (low power, large Wh) and supercaps (high power, low Wh) in hybrid systems
  - Prolong / optimize battery lifetime

Energy-Aware Sensor Management



Definition of energy-aware sensor management policies

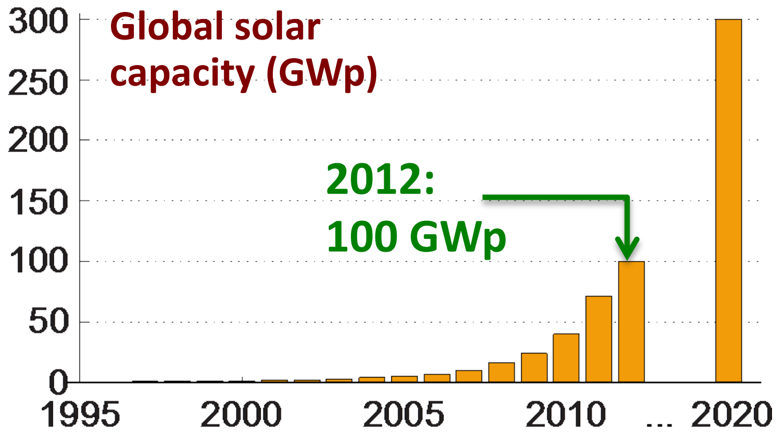
- Investigated Topics:
  - Exploitation of SoC information *at network level* for:
    - Improved battery management (depth of discharge vs. degradation)
    - Understanding quality of service vs. energy autonomy tradeoffs
- Challenges:
  - Development and study of Markovian models for sensor management including battery degradation and SoC information

Ongoing Activities

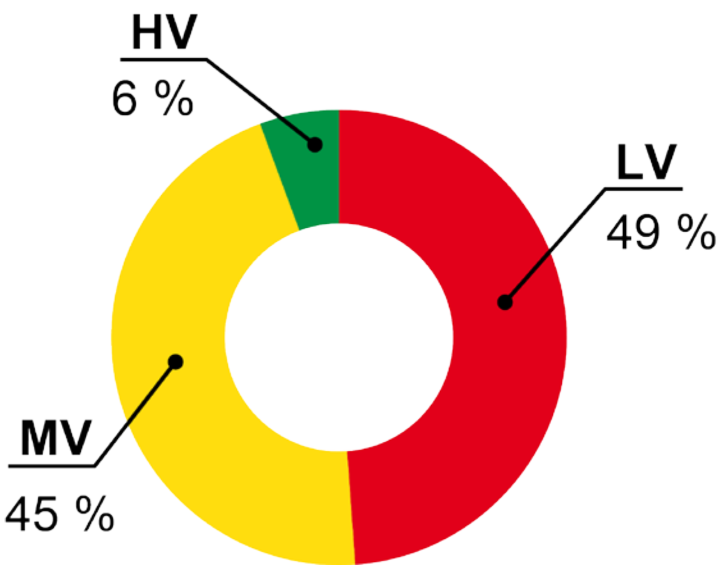
- Study of electronic oscillators for cold-start operation from ultra low-voltage sources (e.g. thermoelectric)
- Maximum power harvesting of industrial thermal waste using thermoelectric panels
- Optimized energy harvesting circuits for wireless switches

Part II: Integration of distributed renewable energy sources in low-voltage smart microgrids

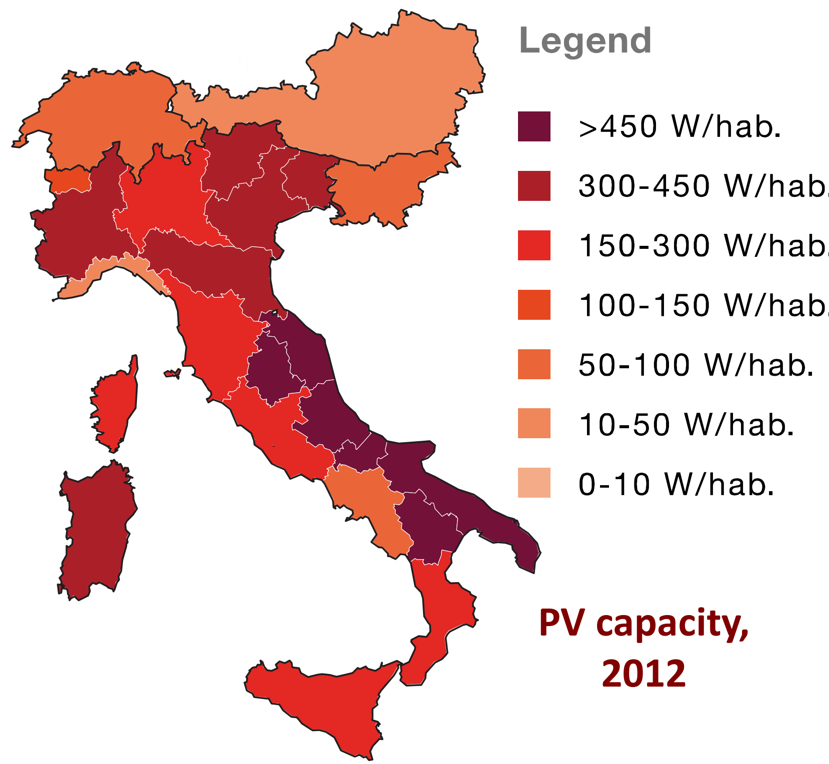
PV Installations in Europe / Italy



- High densitity of distributed generation
- 49% **Low Voltage (LV)** installations
- **Further increase** up to 300 GW in 2020



Source: www.pvgrid.eu

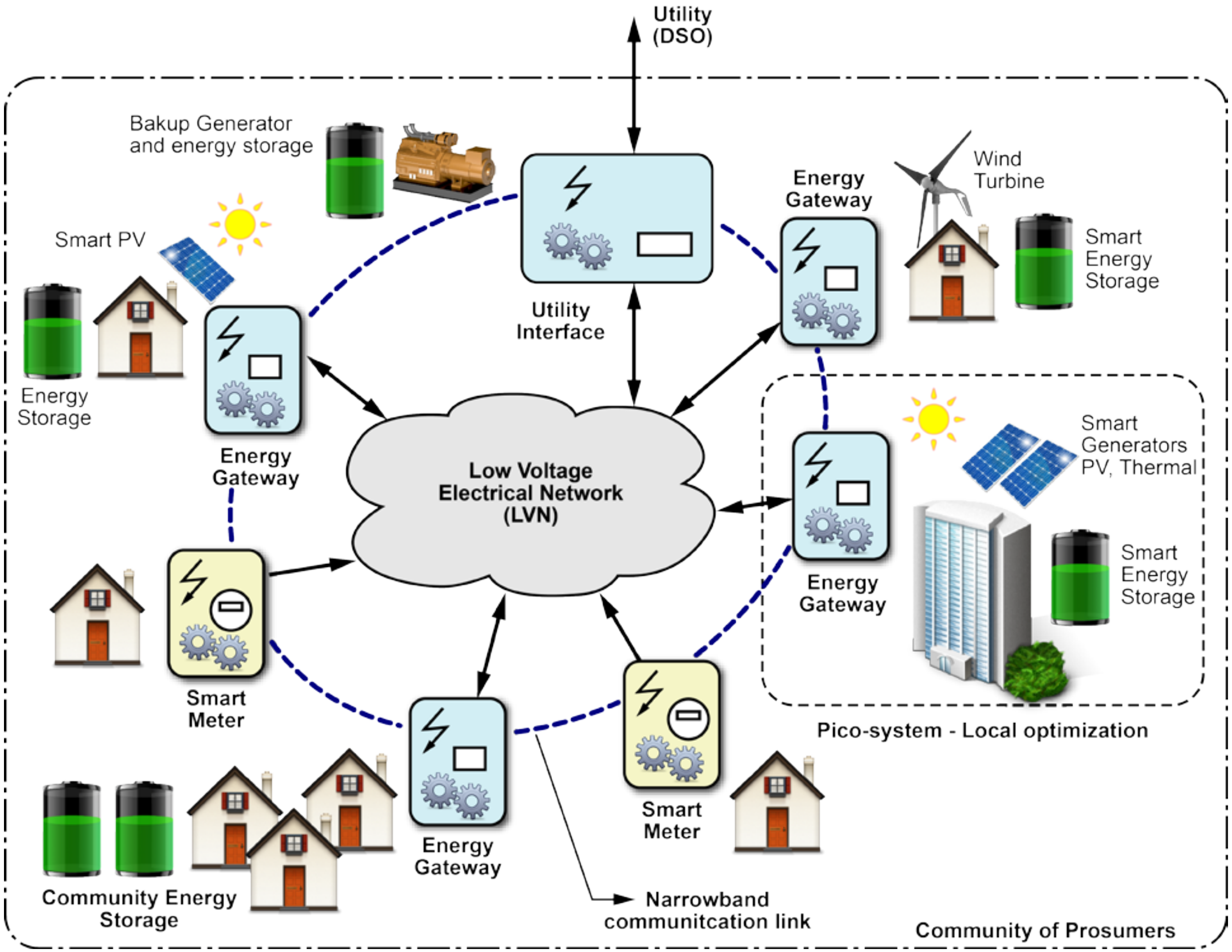


PV capacity, 2012

Effects of PV penetration in LV Grids

- **Intermittent** power generation
- Possible **overload** of distribution lines due to uncontrolled power sharing
- Alteration of **voltage profiles** due to local power injection
- Possible detrimental **interaction** among distributed generation systems
- Reduction of **power quality** due to circulation of reactive currents, injection of unbalanced power by single-phase equipment, increase of THD due to resonances
- Other issues: protection, islanding detection…
- **Solution: to aggregate distributed loads and power sources to form LV microgrids, where energy resources are shared so as to improve local and global performances, i.e., energy efficiency, power quality, robustness against faults and transients, etc.**

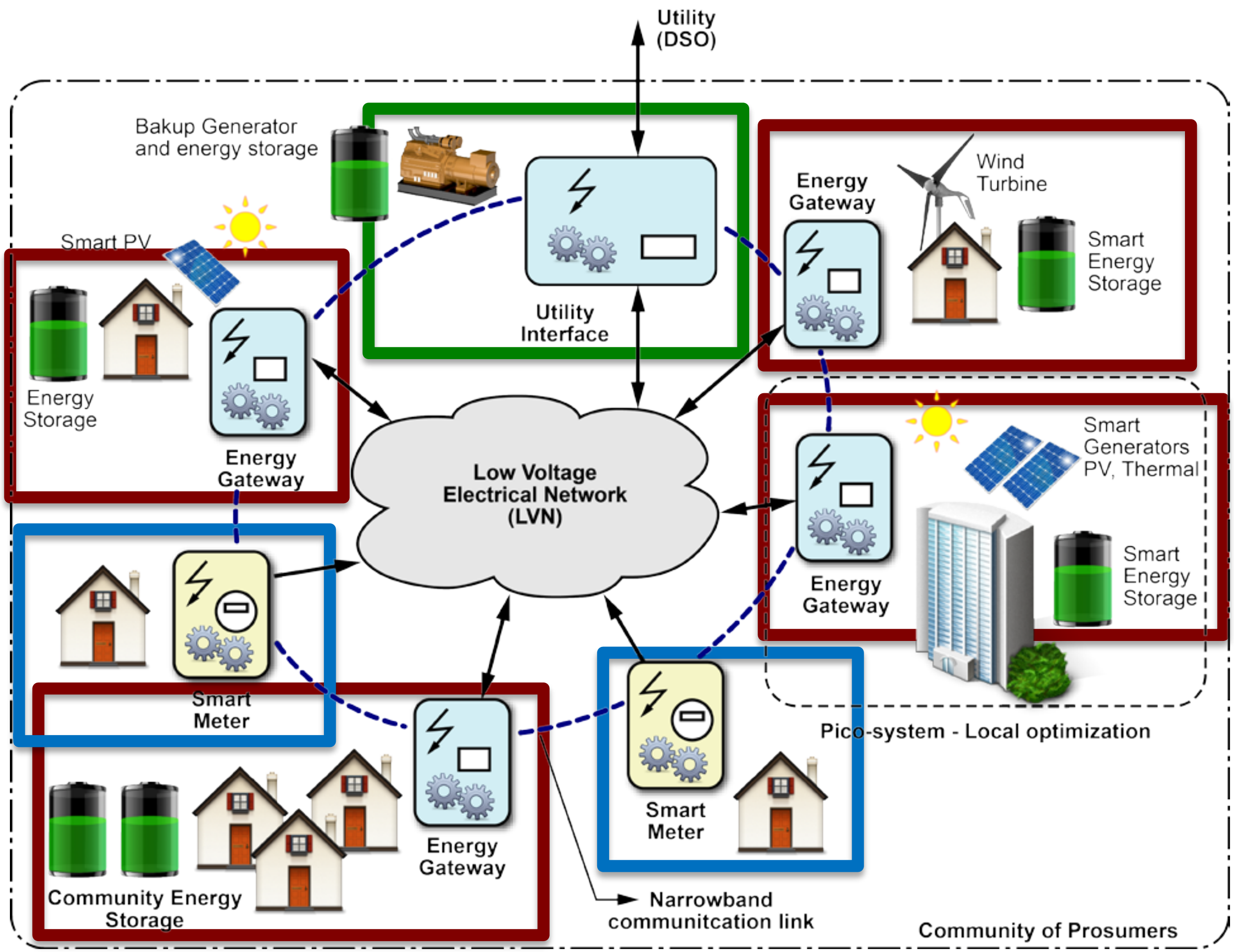
LV Microgrid Architecture



Elements:

- LV distribution grid
- ICT infrastructure
- Passive loads
- Distributed (renewable) power sources
- Energy storage devices
- Smart meters
- **Energy gateways** (EG)
- **Utility Interface** (UI)

Role of Power Electronics



Energy Gateways

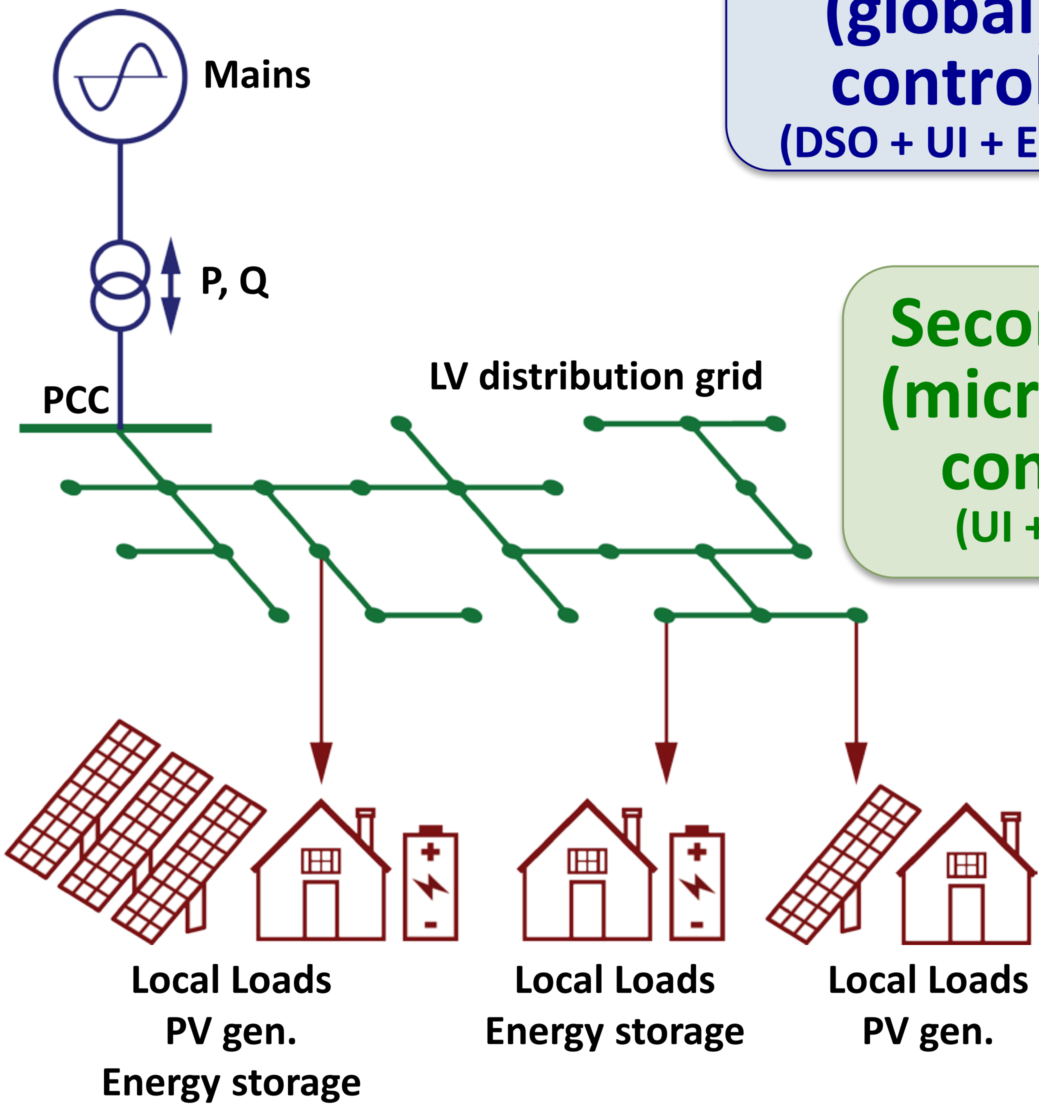
- Interface local sources and grid
- Behave as current sources
- Perform as control slaves (two-way communication to UI)

Utility Interface

- Interfaces microgrid and mains
- Behaves as voltage source
- Performs as control master (two-way communication to SMs, EGs and DSO)

The Utility Interface is the key element to ensure safe dynamic operation of the microgrid and effective interaction with the mains

Control Hierarchy



Tertiary (global) control
(DSO + UI + EGs)

- Optimization of interaction between microgrid and mains: harmonic, reactive and unbalance compensation, demand response, fault management, islanding detection and management, etc.

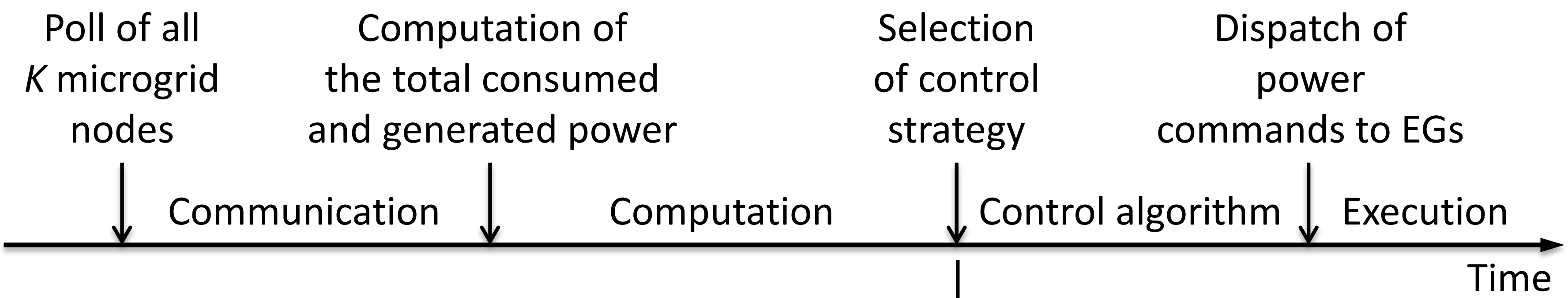
Secondary (microgrid) control
(UI + EGs)

- Load power sharing
- Full exploitation of DERs
- Reduction of distribution and conversion loss
- Optimization of μG operation on-grid and off-grid, black start …

Primary (local) control
(EGs)

- Management of local energy sources (smoothing of power profiles, control of ES device, …)
- Reactive and harmonic compensation of local loads
- Local voltage stabilization
- Emergency supply to local loads

Power-based control of microgrid



A_n

P_{Ln}, Q_{Ln}

P_{Gn}

$E_{in,n}^{max}, E_{out,n}^{max}$

$P_{Gn}^{min}, P_{Gn}^{max}$

$P_{Sn}^{min}, P_{Sn}^{max}$

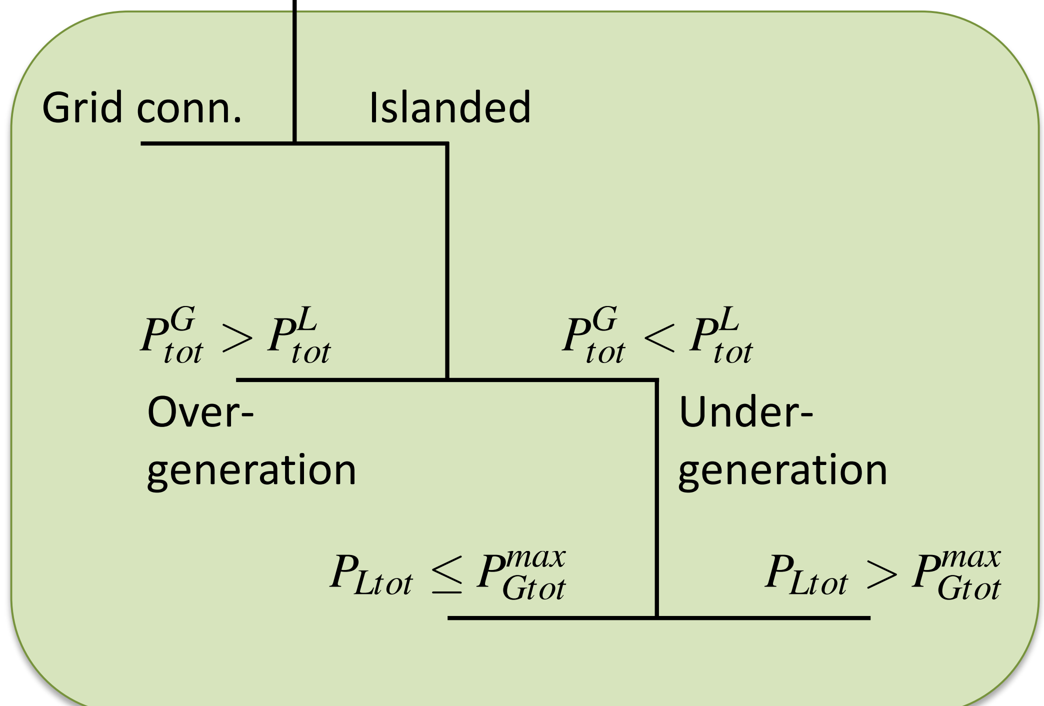
$$P_{Ltot} = \sum_{k=1}^{K} P_{Lk} = $$

$$= \sum_{m=1}^{M} P_{Lm} + \sum_{n=1}^{N} P_{Ln}$$

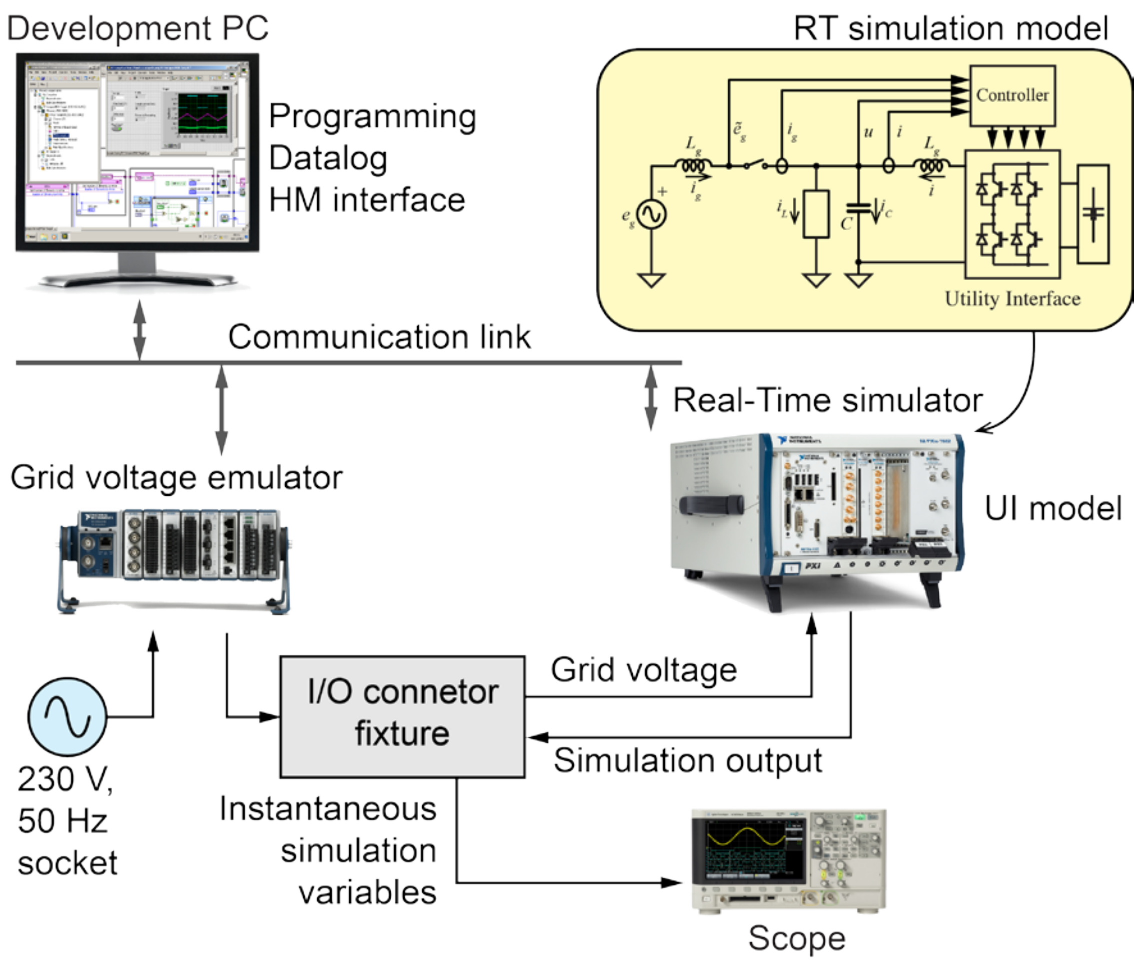
$$P_{Gtot} = \sum_{n=1}^{N} P_{Gn}$$

$$P_{Gtot}^{min} = \sum_{n=1}^{N} P_{Gn}^{min}$$

$$P_{Gtot}^{max} = \sum_{n=1}^{N} P_{Gn}^{max}$$

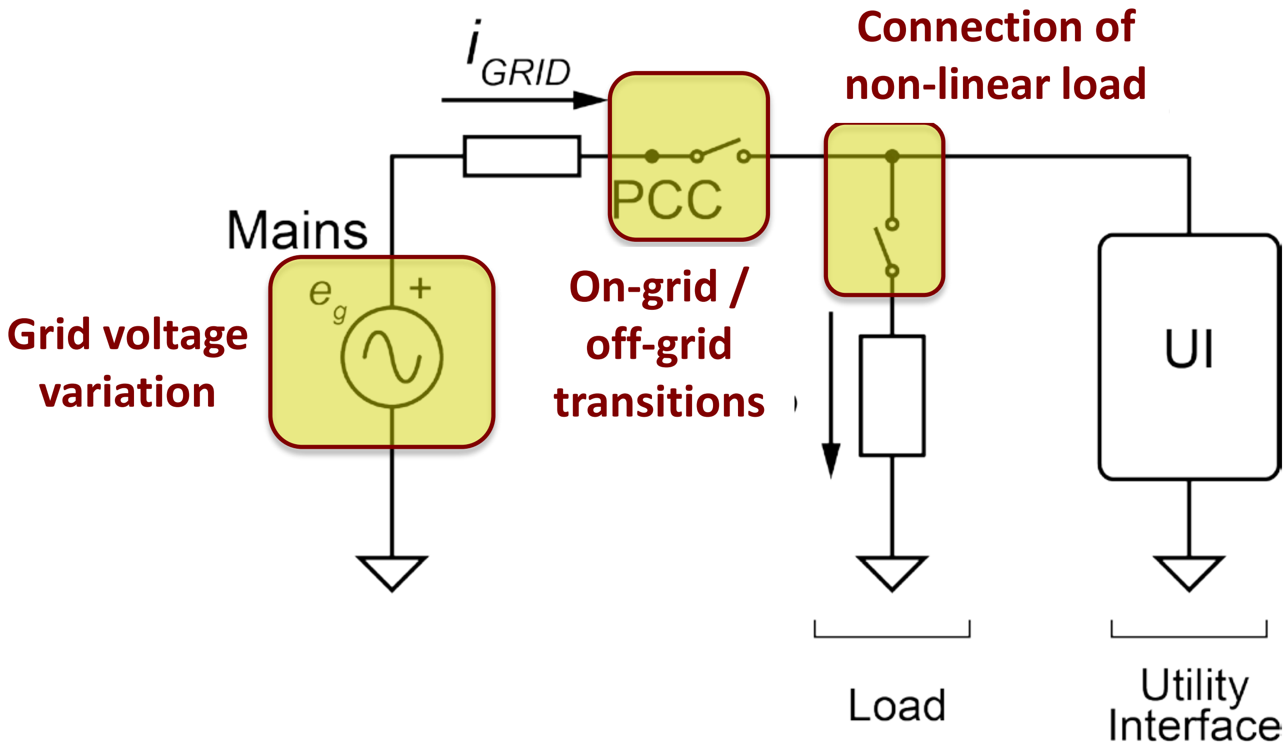


Real-Time Simulation Setup

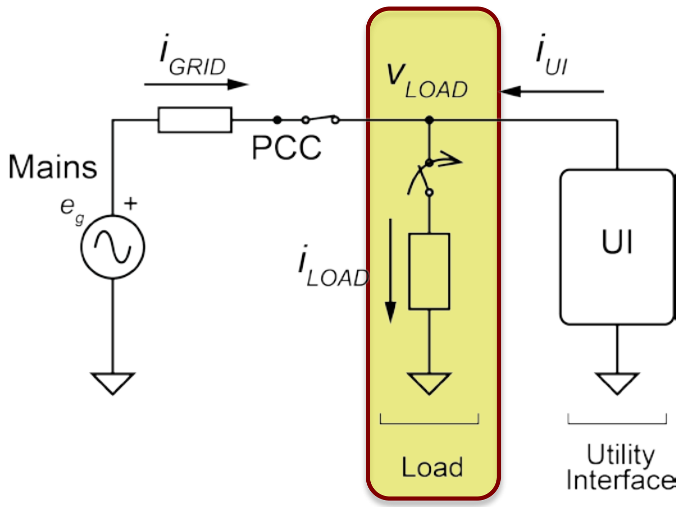


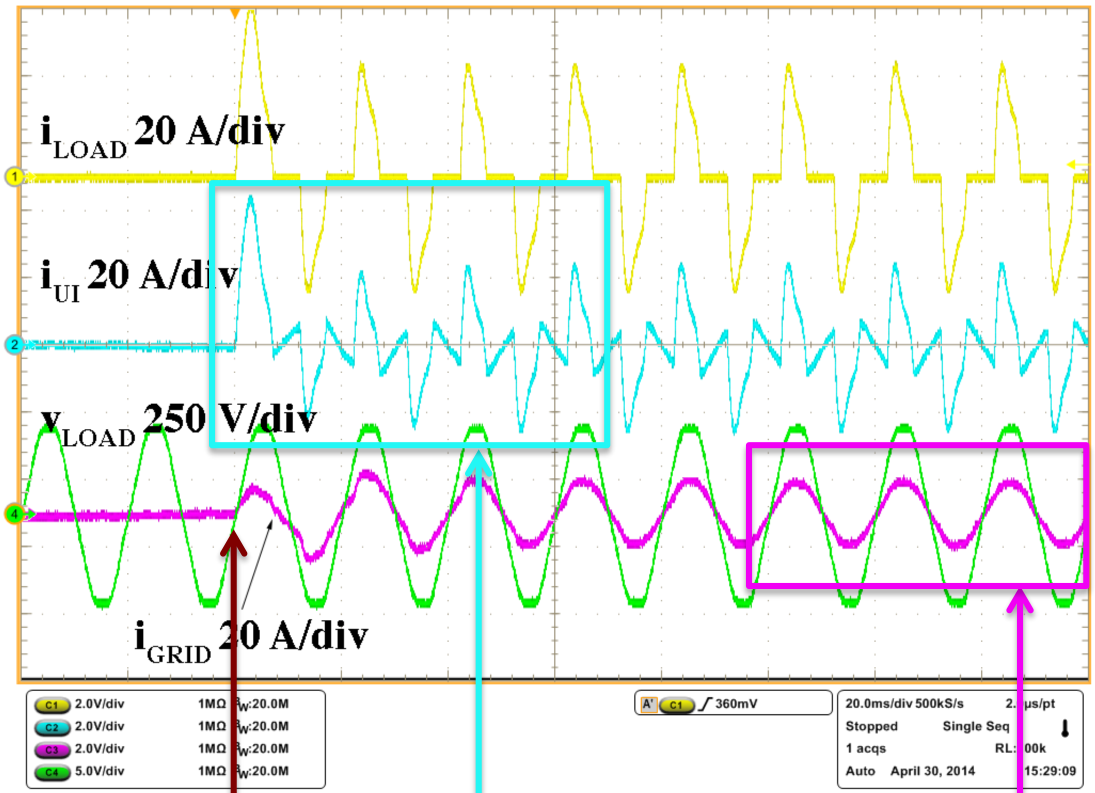
Dynamic operation of Utility Interface

- Connection of non-linear load
- Variation of grid voltage
- Transition from grid-connected to islanded operation and *vice-versa*



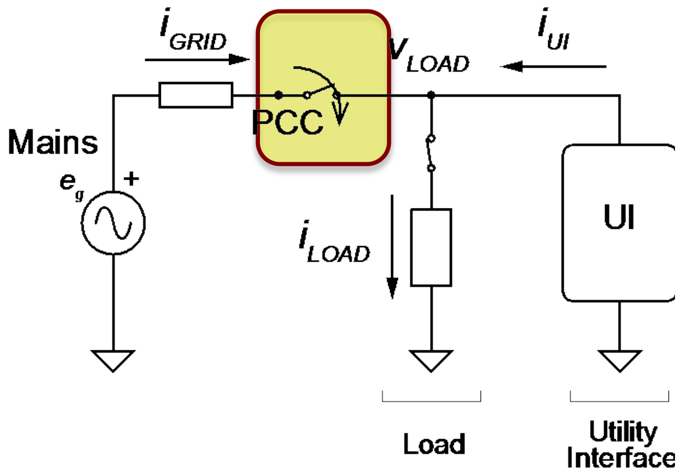
Connection of non-linear Load

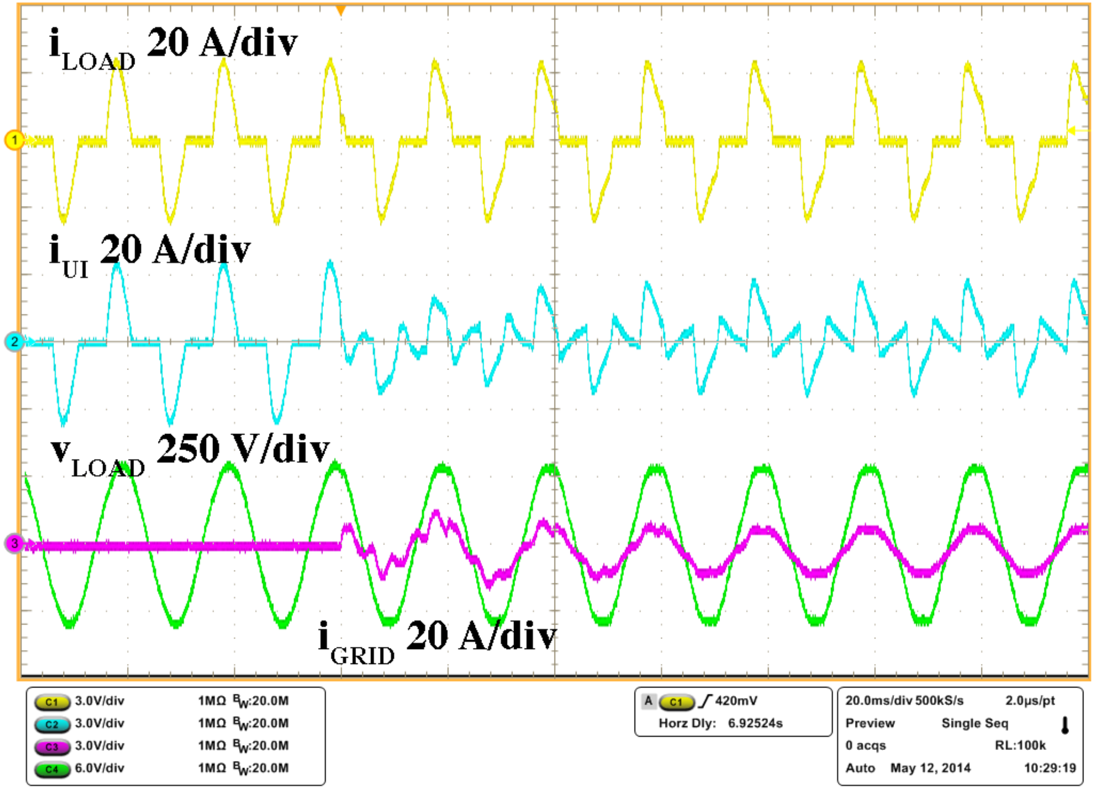




- **Connection of non-linear load**
- **UI compensates only for distorting currents** generated by the load
- Load power fed by the grid at **unity power factor**

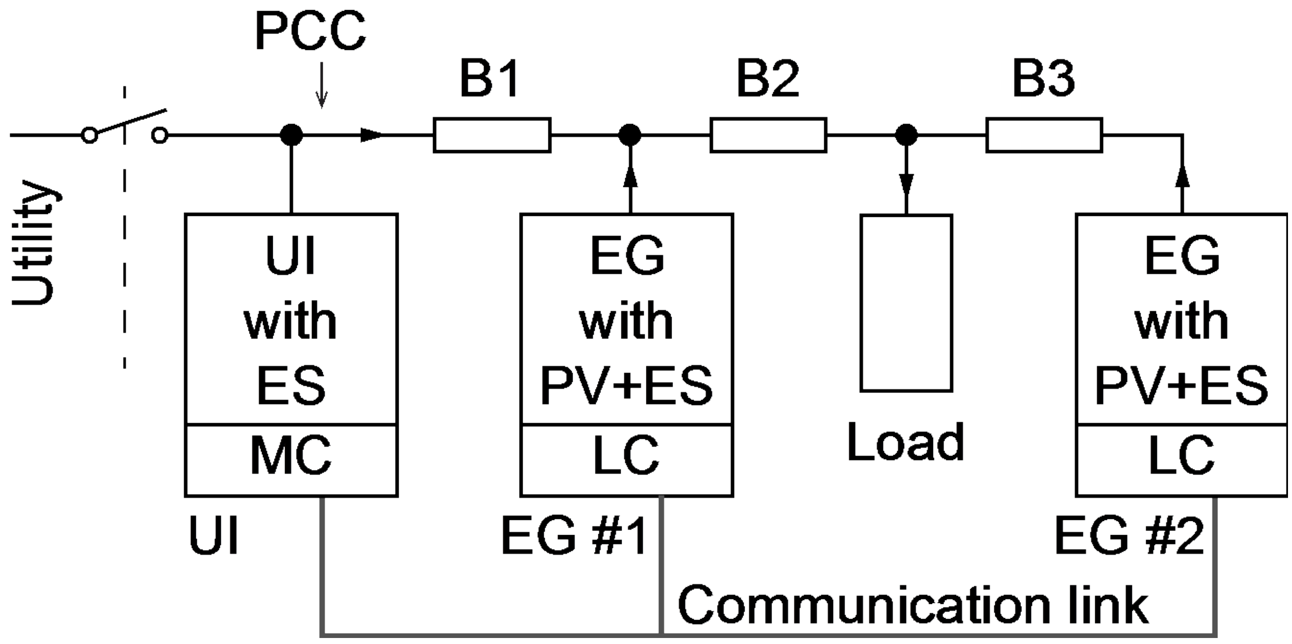
Return to grid-connected operation





- Reconnection to main grid (& black start)
- UI voltage keeps synchronized with grid voltage
- Grid current adapts in few line cycles and shows limited deviations

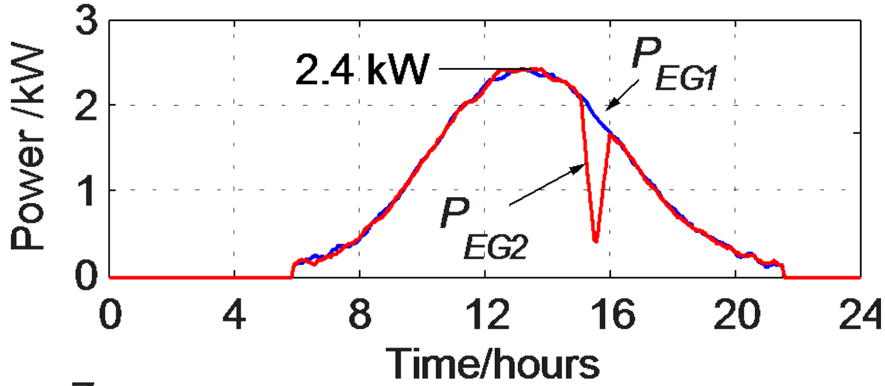
Case study – Distribution efficiency

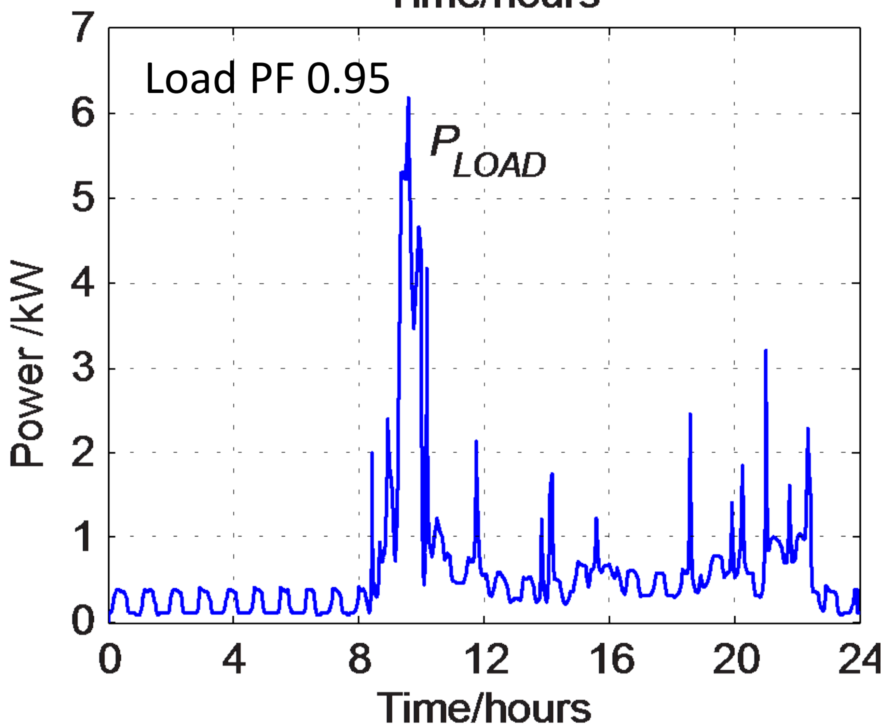


Power System Parameters

V_{grid}	f_{grid}	P_{load}	Z_{B1}	Z_{B2}	Z_{B3}
230 V	50 Hz	6 kW	0.17 + i0.04 Ω	0.26 + i0.06 Ω	0.71 + i0.16 Ω

Power generation and consumption





Typical data of residential installations:

- **generation** and **load** profiles
- **inverter** and **energy storage** parameters

	EG_1	EG_2
A_{EG}	4.2 kVA	5.0 kVA
E_{ES}	3.6 kWh	5.4 kWh
$P_S^{out(max)}$	2 kW	3 kW
$P_S^{in(max)}$	1 kW	1.5 kW
η_{EG}, η_{ES}	0.95, 0.92	0.95, 0.92

Micro-grid performance

- **Power-based control** significantly **reduces reactive power flows** at PCC and **total distribution loss**
- **Automatic overvoltage limitation** maintains **voltages within specified limits**, though affecting total energy production
- Proper management of energy storage improves distribution efficiency and voltage stability as well

	Produced Energy (kWh)	Distribution losses (kWh)	v_{EG2} max overvoltage (%)	Power Factor at PCC (W/VA)
No control	36.5	0.83	5.5	0.93
Power-based control	34.1	0.65	4.0	1.00
Power-based control + Energy storage	34.2	0.47	4.0	1.00

LV Microgrids: a win-win solution

Low-voltage microgrids equipped with Utility Interfaces feature:

- prompt adaptation to load and line variations
- management of intentional and non-intentional islanding
- voltage and fault ride-through capability
- black start and fault recovery
- reactive, harmonic and unbalance compensation
- management of interaction with DSO (demand response, fault recovery, intentional islanding …)

Final users (prosumers) take advantage of:

- Energy savings, reduced electricity bill, increased power quality
- Upgrade of role in the electrical market, increased negotiation capability

DSOs and ESCOs take advantage of :

- Aggregation of end-users into efficient and programmable macro-users
- Participation of end-users to investments for distributed energy management and storage
- Increased operation flexibility and efficiency of distribution networks

Conclusions

- Distributed generation, from small environmental sources to residential renewable energy, is experiencing a huge diffusion worldwide.
- This will dramatically change some traditional and consolidated markets, like electric distribution, and open entirely new and pervasive application domains, like wireless sensor networks and microgrids.
- The expected investments on distributed generation technologies in the next decade are very high (tens of $B in North-America, Europe, China, Japan, Korea ..) , under the pressure to reduce carbon footprint, preserve environment and improve health and quality of life.
- Key elements of such innovations are power electronic devices and systems, that can provide distributed and effective power management at low cost, high efficiency and compactness.