A Composable Framework for Real-Time Control of Active Distribution Networks with Explicit Power Setpoints

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Keynote speech – Shandong Univ. Symposium on Smart Grids

May 18th, 2015

Joint work with
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EPFL Laboratory for Communications and Applications and Distributed Electrical Systems Laboratory

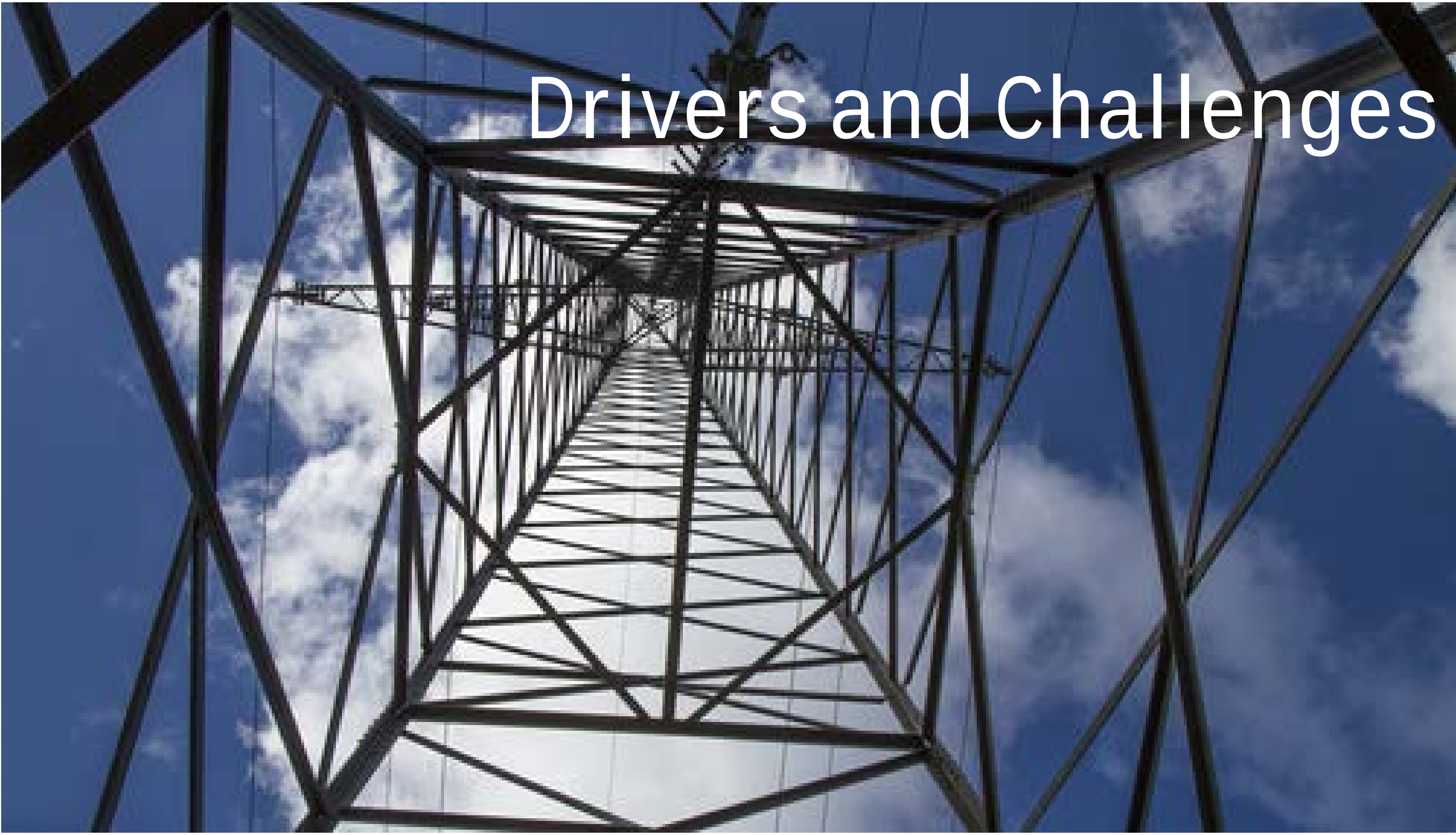
References

A. Bernstein, L. E. Reyes Chamorro, J.-Y. Le Boudec and M. Paolone
A composable method for real-time control of active distribution networks with explicit power set points. Part I: Framework
Accepted in Electric Power Systems Research, p. 1-11, 2015.
doi:10.1016/j.epsr.2015.03.023

L. E. Reyes Chamorro, A. Bernstein, J.-Y. Le Boudec and M. Paolone
A composable method for real-time control of active distribution networks with explicit power set points. Part II: Implementation and validation,
Accepted in Electric Power Systems Research, p. 1-16, 2015.
doi:10.1016/j.epsr.2015.03.022

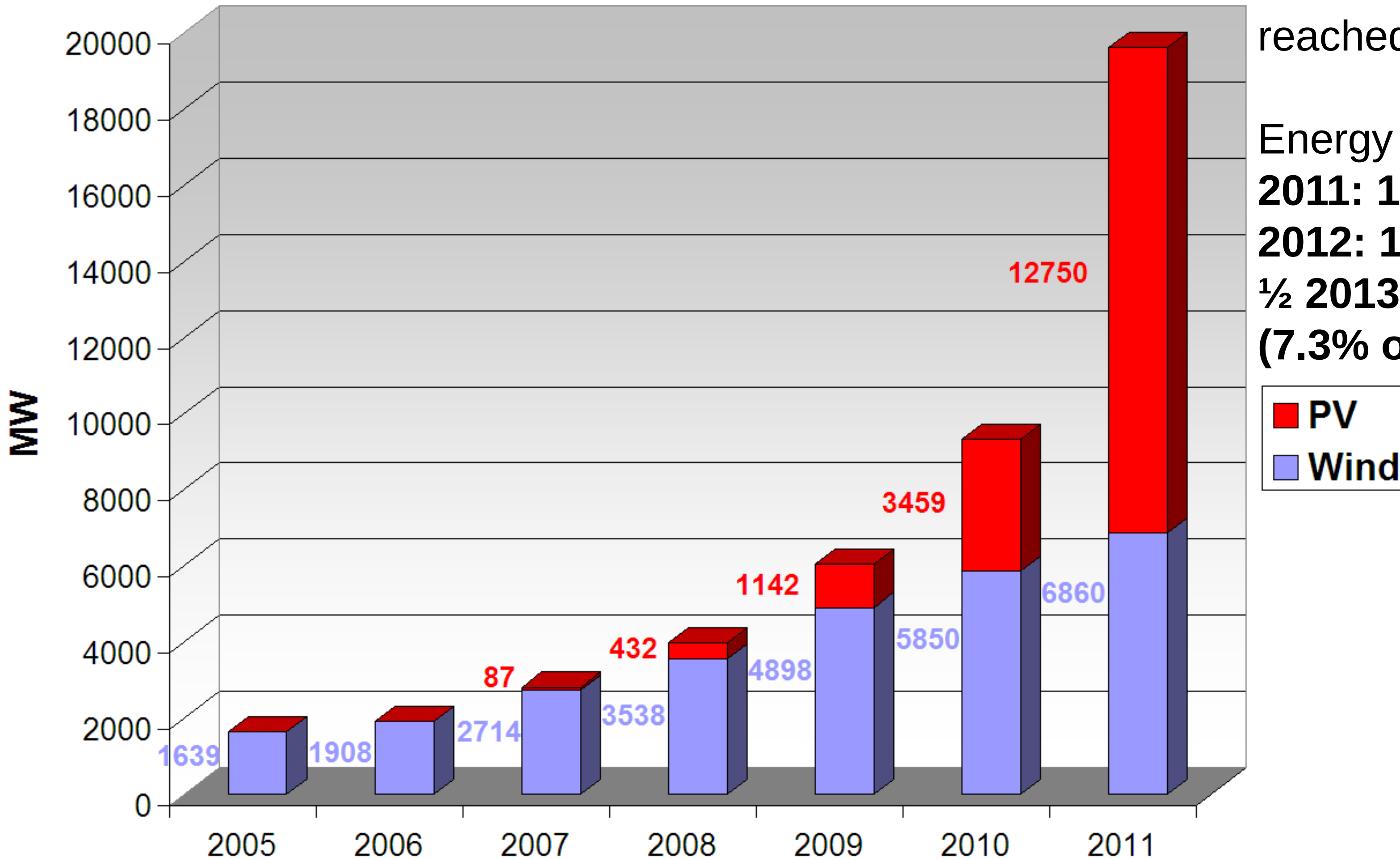
http://smartgrid.epfl.ch

Outline



The Drivers

Grow rate of decentralized energy resources: the case of Italy



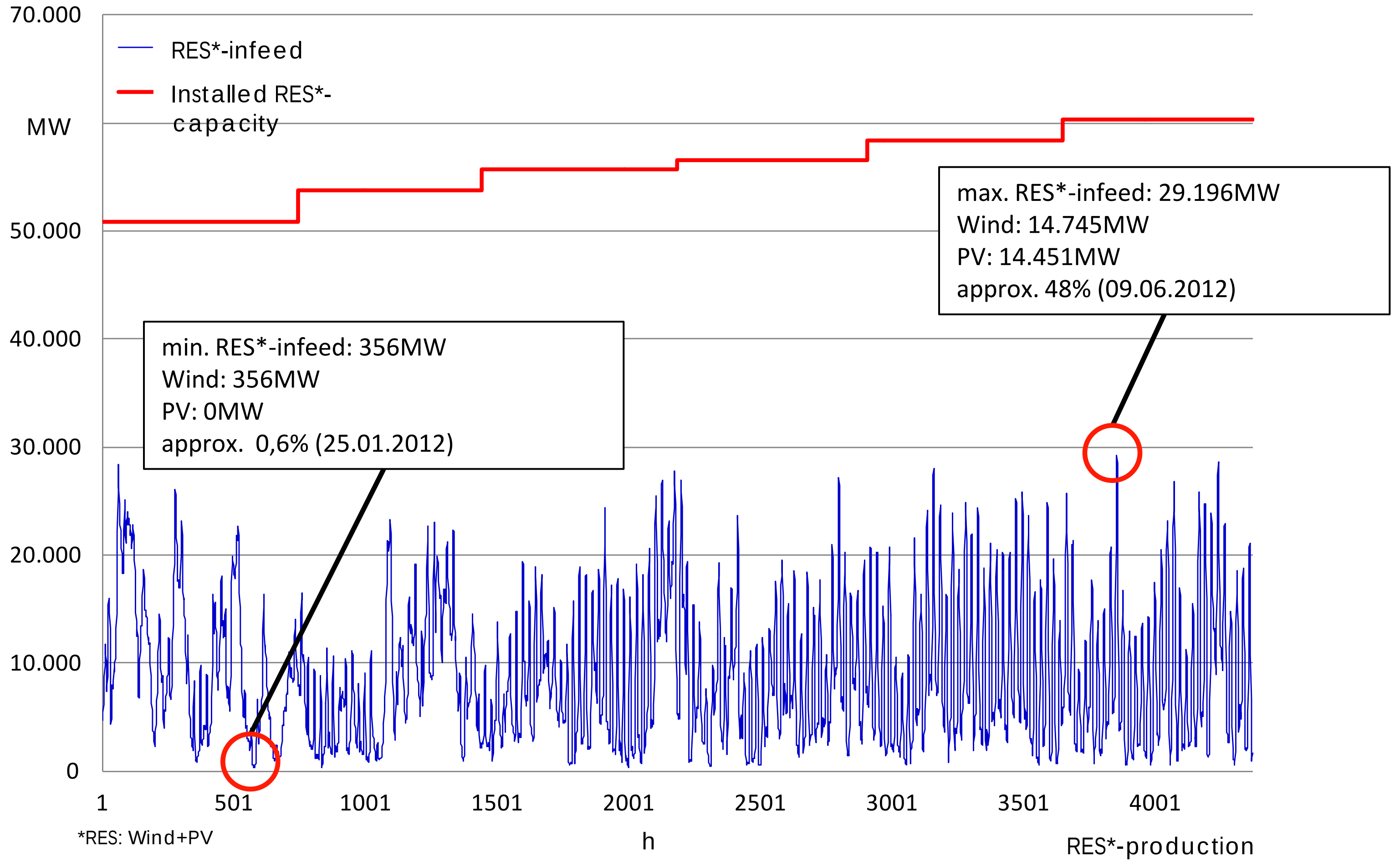
In **April 2013**, the **PV** installed capacity has reached **16.5 GWp**

Energy prod:
2011: 10.7 TWh
2012: 18.8 TWh
½ 2013: 13.8 TWh
(7.3% of the demand)

The Drivers

Seasonal volatility Jan 1st – Jun 30th (Wind+PV)
Installed capacity vs real infeed: the case of Germany

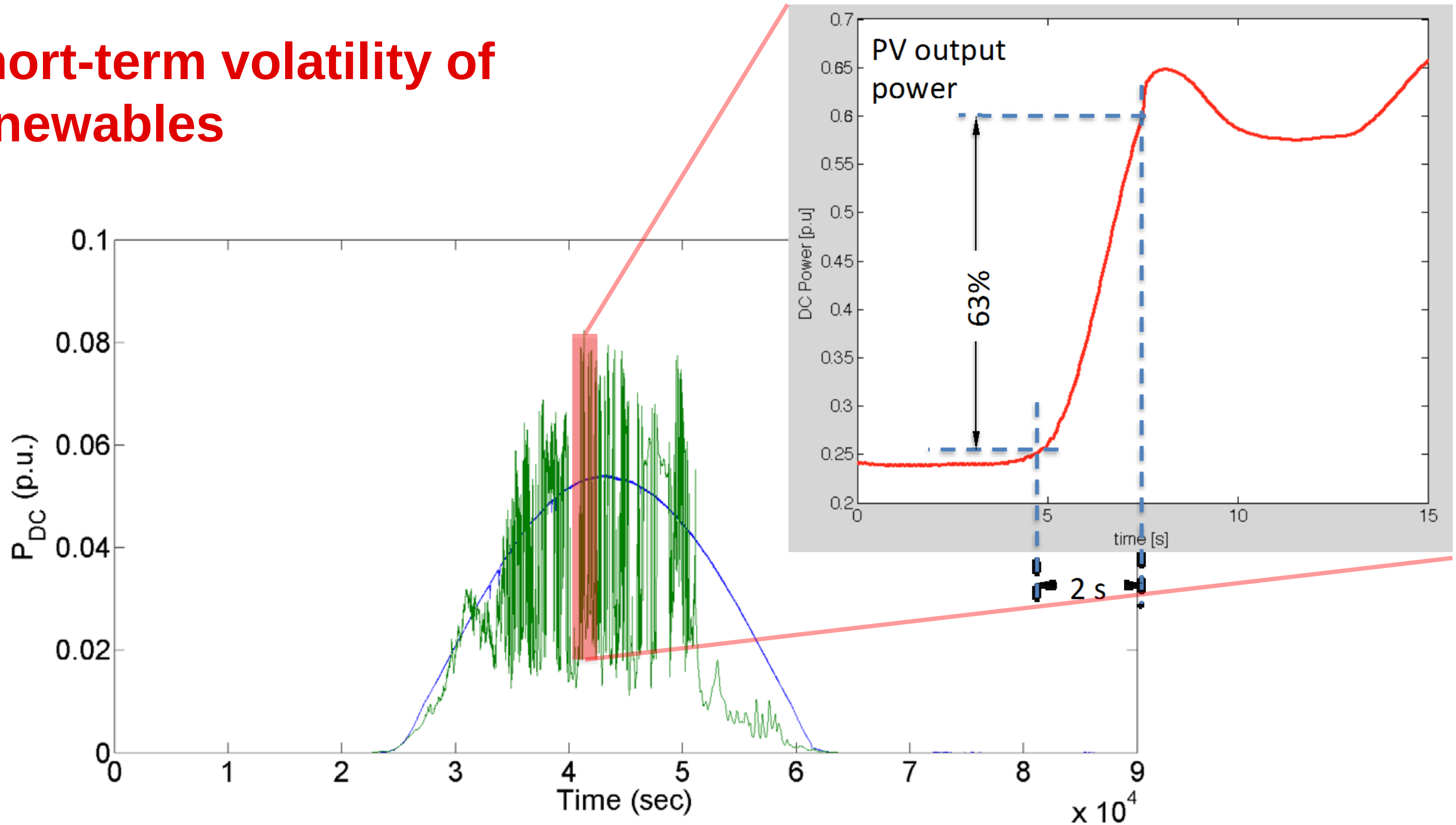
Source: G. Vanzetta



*RES: Wind+PV

The Drivers

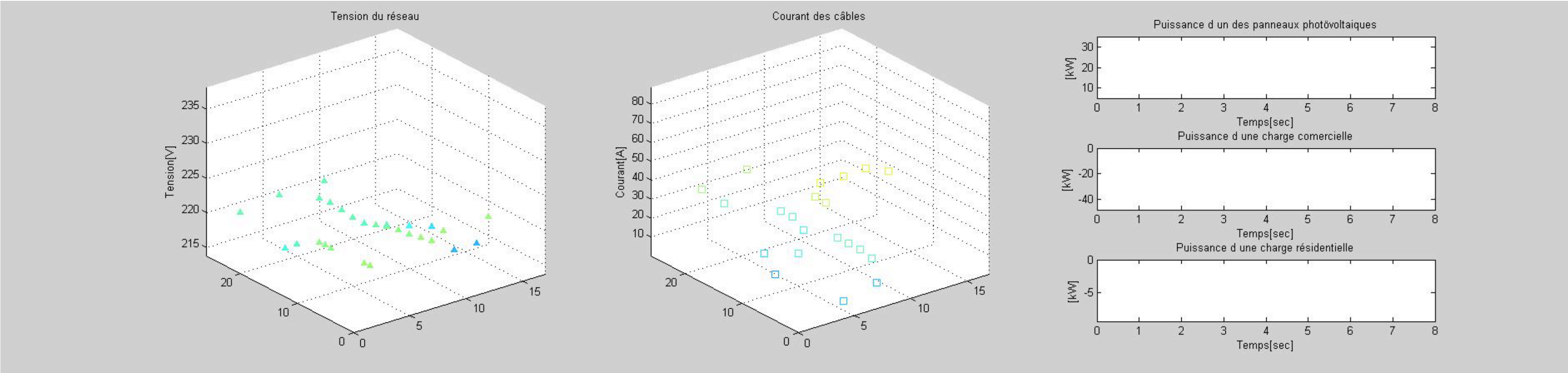
Short-term volatility of renewables

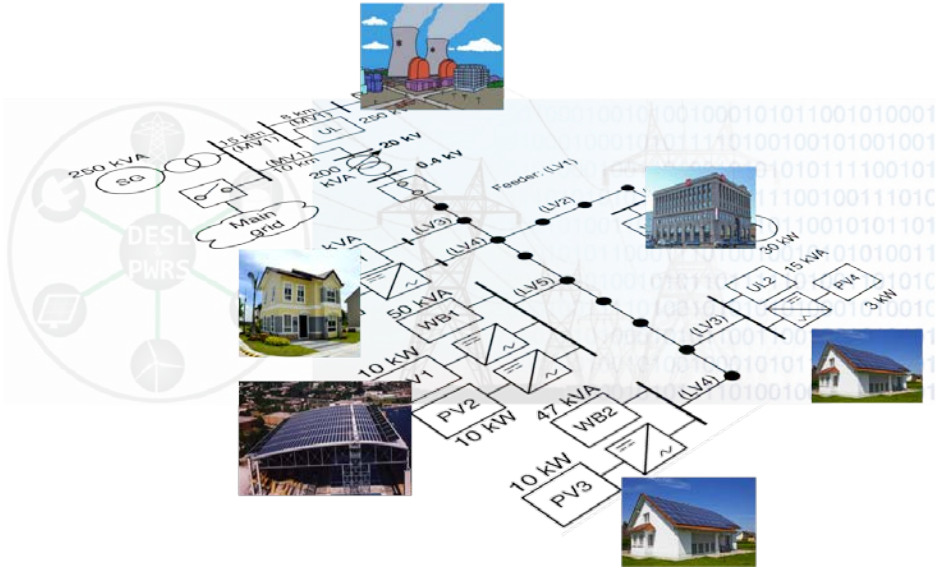


Data coming from the EPFL-DESL.

The Challenges

Line congestions and voltage quality in microgrids



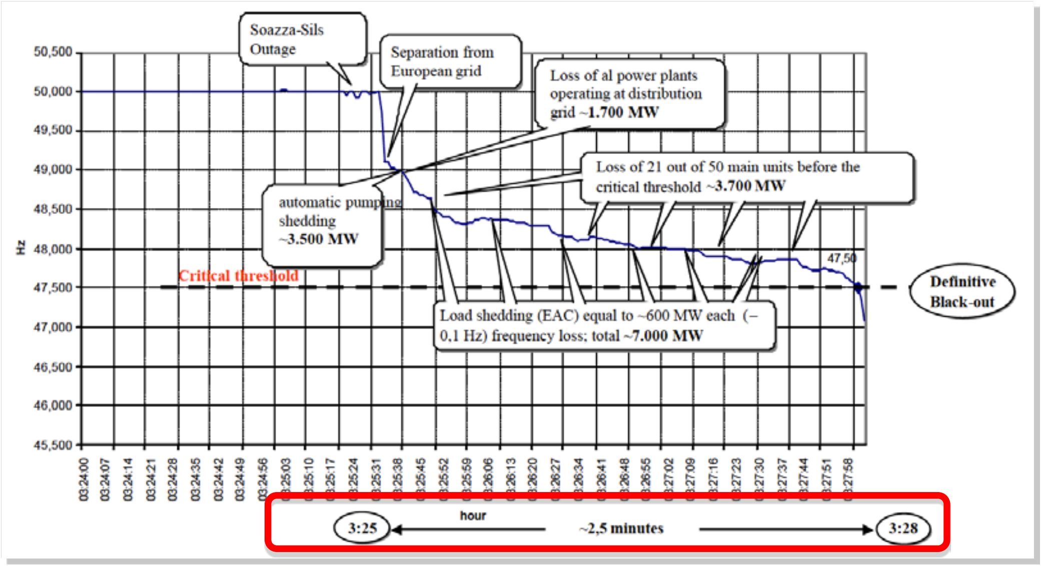


The Challenges

The issue of the inertia-less systems

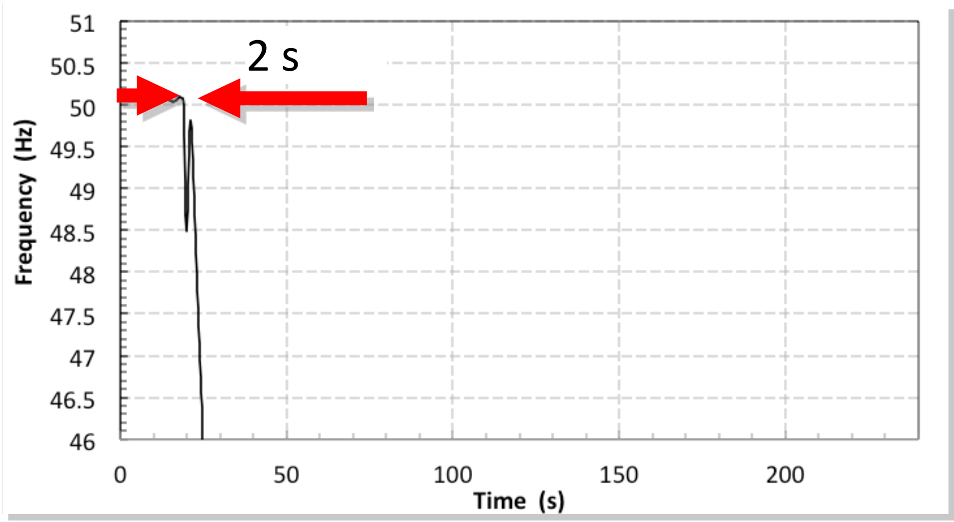
2003 blackout in Italy frequency trend

Source: UCTE Interim Report of the Investigation Committee on the 28 September 2003 Blackout in Italy



2009 blackout during the islanding maneuver of an active distribution network

Source: A. Borghetti, C. A. Nucci, M. Paolone, G. Ciappi, A. Solari, “Synchronized Phasors Monitoring During the Islanding Maneuver of an Active Distribution Network”, IEEE Trans. On Smart Grid, vol. 2 , issue: 1, march, 2011, pp: 70 – 79.



The Challenges

Challenges for grids

- participation of distributed generation to frequency and voltage support (**Virtual Power Plant**)
- autonomous small scale grids with little inertia
- quality-of-service in distribution networks

Solutions

- fast ramping generation (for the bulk grid)
- local storage, demand response in conjunction with **real time control** of local grids

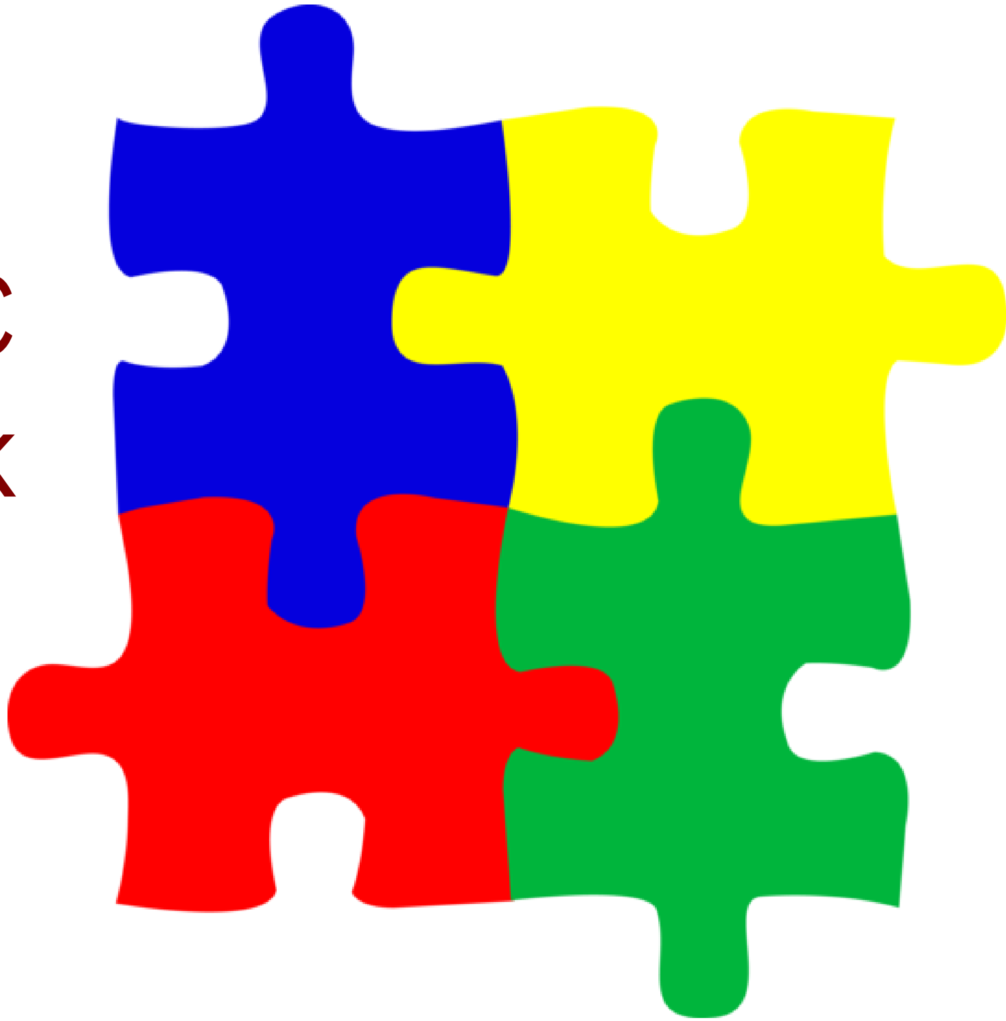
The Challenges

Real-time control of local grids

- Typically done with **droop controls** (f and V)
- Problems:
  - system does not know the state of resources (e.g., state-of-charge of a battery, temperature of a building)
  - all problems made global
- Alternative: **optimal explicit control of power setpoints**
  - **mathematically complex**
  - **radical change in grid operation**

Outline

The COMMELEC framework



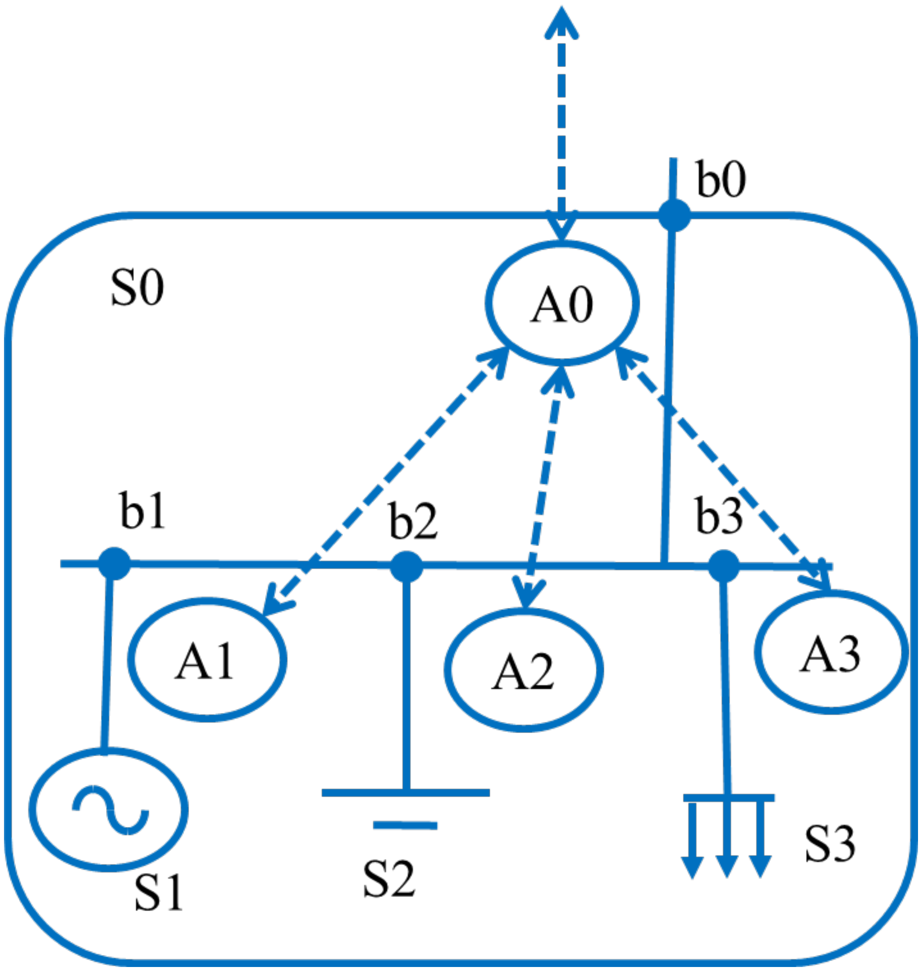
Design criteria

- Adoption of inexpensive platforms (embedded controllers)
- Do not build a monster of complexity (bug-free)
- Scalability
- Composable (i.e. built with identical small elements)

COMMELEC's Architecture

- **Software Agents** associated with devices
  - load, generators, storage
  - grids

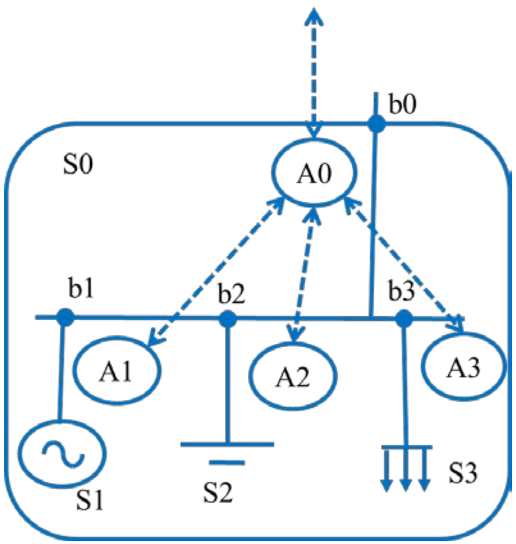
- **Grid agent sends** explicit ***power setpoints*** to devices' agents



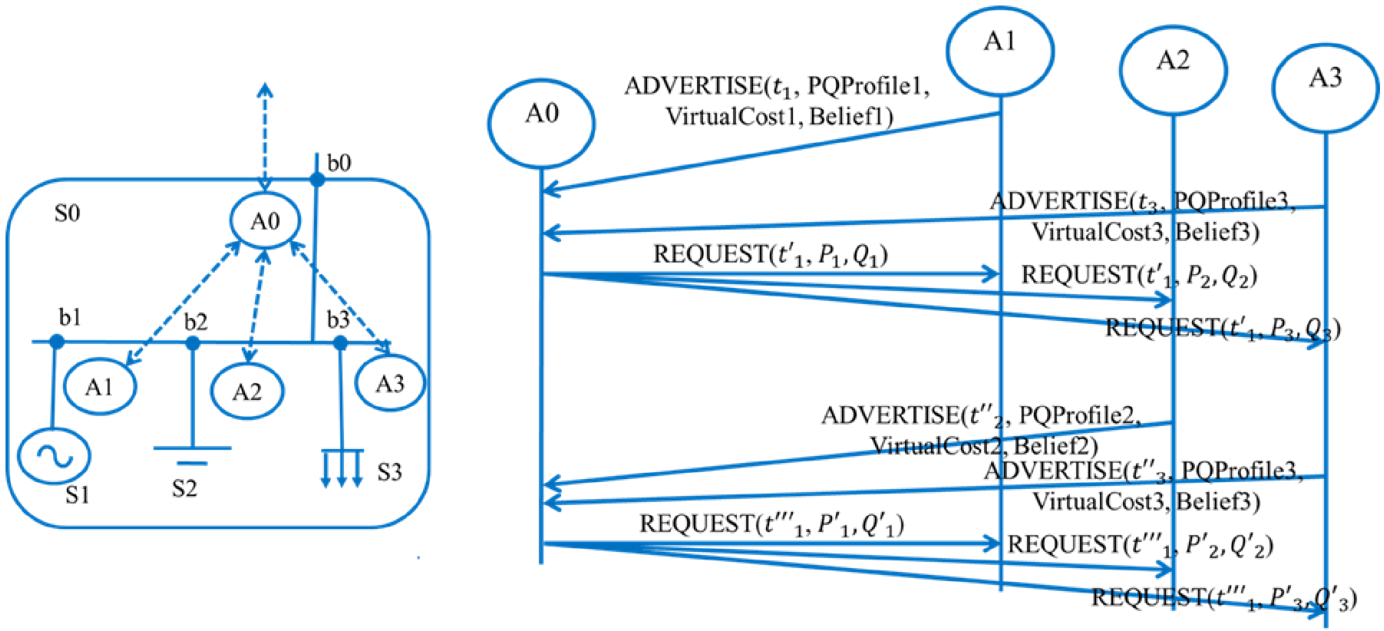
COMMELEC's Architecture – Resources and Agents

- Resources can be
  - **controllable** (sync generator, battery)
  - **partially controllable** (PVs, boilers, HVAC, TCLs)
  - **uncontrollable** (load)
- Each resource is assigned to a resource agent
- Each grid is assigned to a grid agent

- **Leaders and followers**
  - resource agent is follower of a grid agent
  - LV grid agent is follower of MV agent



COMMELEC's Architecture – The Protocol



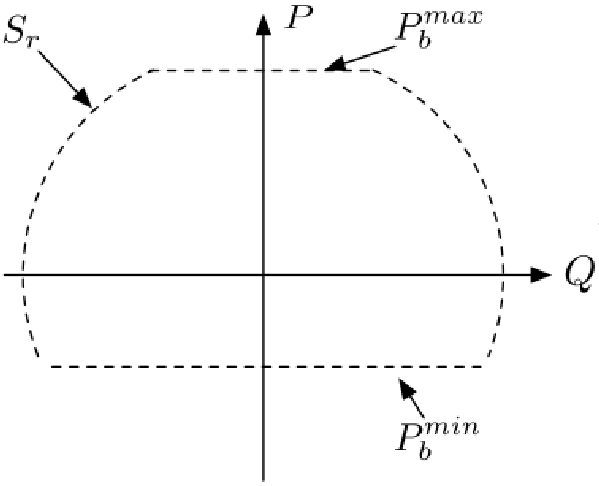
- Every agent **advertises** its state (example each 100 ms) as a ***PQt profile***, a ***virtual cost*** and a ***belief function***
- Each Grid agent computes optimal setpoints and sends them as **requests** to resource agents.

COMMELEC's Architecture – The PQt Profile

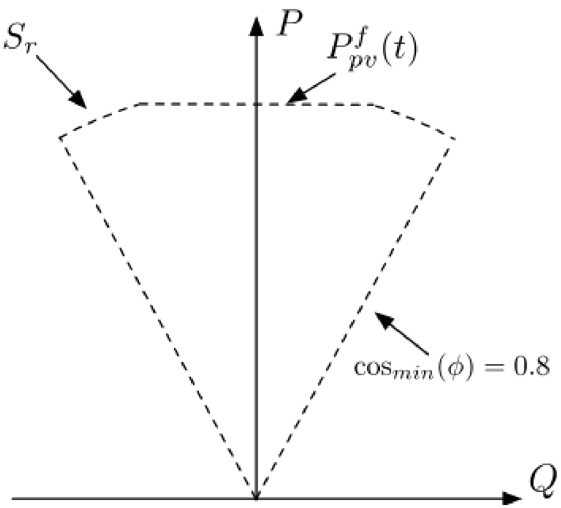
PQt profile: constraints on active/reactive power setpoints

Examples of *PQt* profiles

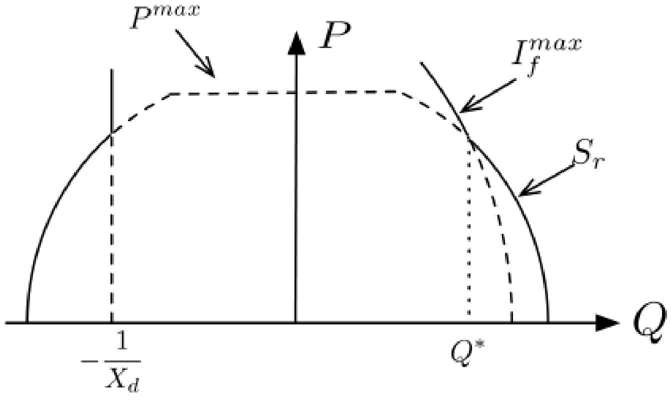
Battery



PV plant



Synchronous Generator



COMMELEC's Architecture – The Virtual Cost

Virtual cost: proxy for the resource internal constraints

I can do P,Q in the next t

It cost you (virtually) $C(P,Q)$

Example:

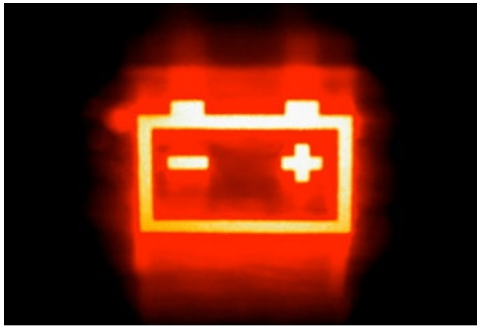
If (State-of-Charge) is 0.7

I am willing to inject power

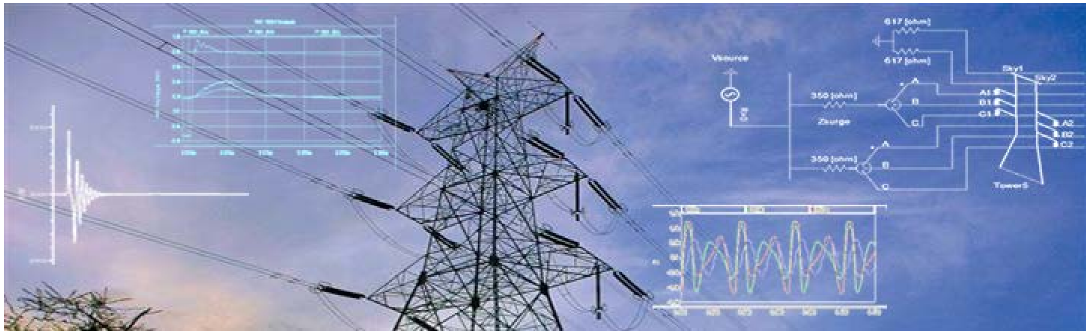
If (State-of-Charge) is 0.3,

I am interested in absorbing power

Battery agent

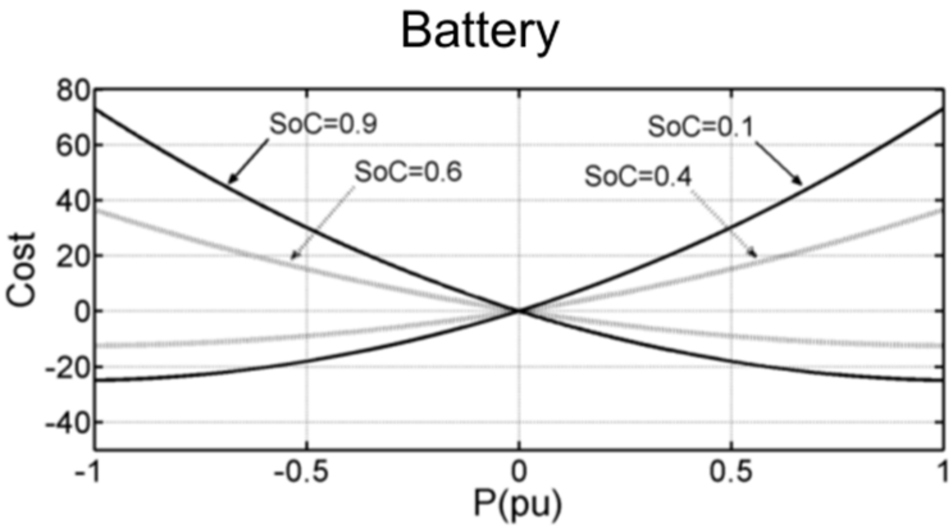


Grid agent

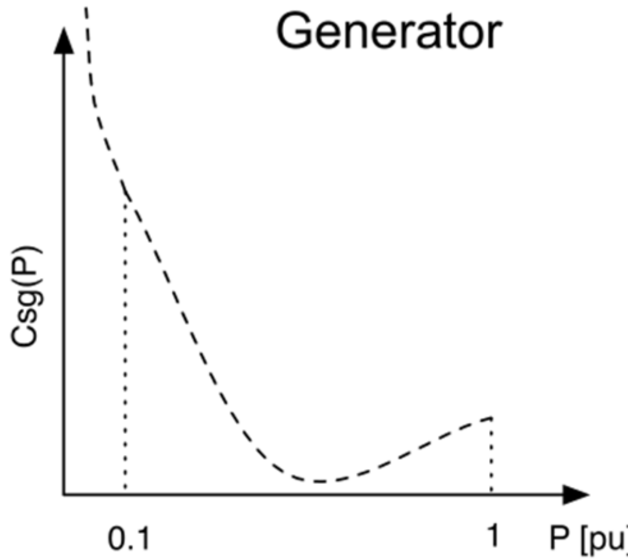


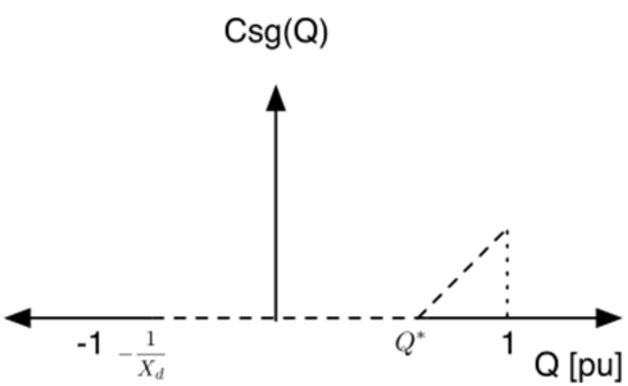
COMMELEC's Architecture – The Virtual Cost

Examples of virtual costs



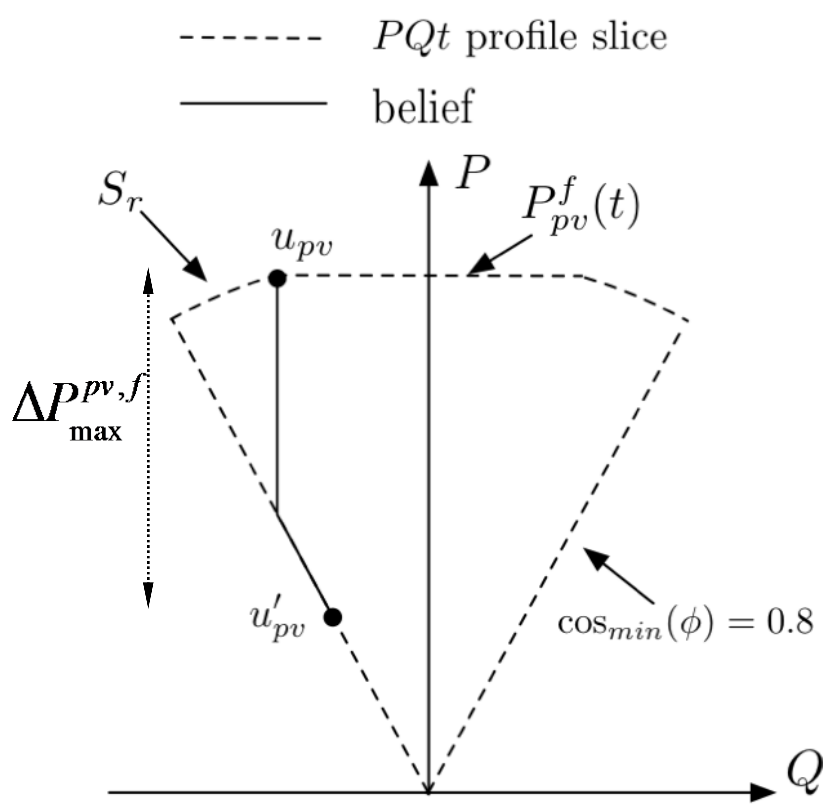
$$C_b(Q) = 0$$





COMMELEC's Architecture – The Belief Function

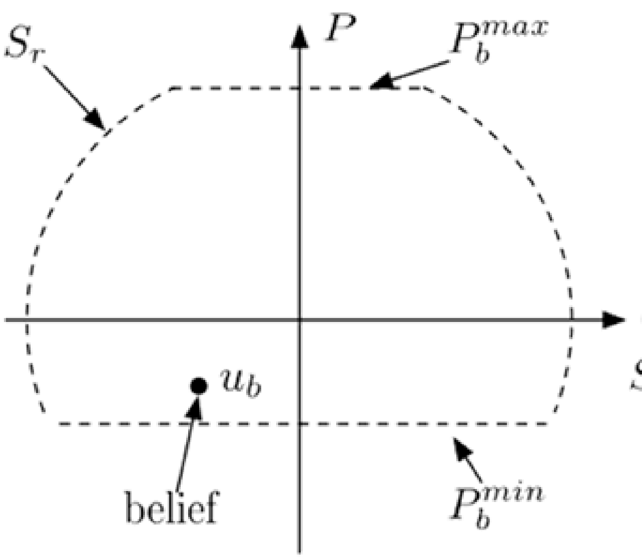
- Say grid agent requests setpoint (P_{set}, Q_{set}) from a resource
- Actual setpoint **will, in general, differ**
- The ***belief function*** is exported by a resource agent with the semantic: resource implements $(P,Q) \in BF(P_{set},Q_{set})$
- It gives bounds on the actual (P,Q) that will be observed when the follower is instructed to implement a given setpoint.
- Essential for safe operation.



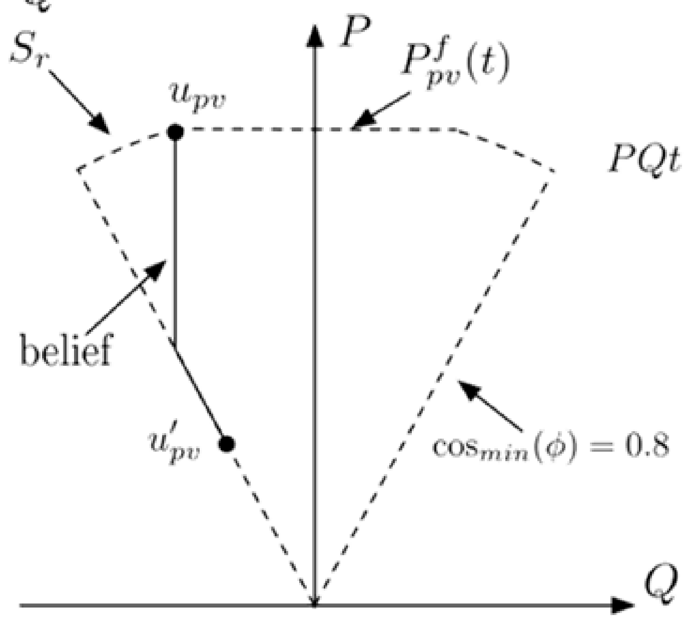
COMMELEC's Architecture – The Belief Function

Examples of belief functions

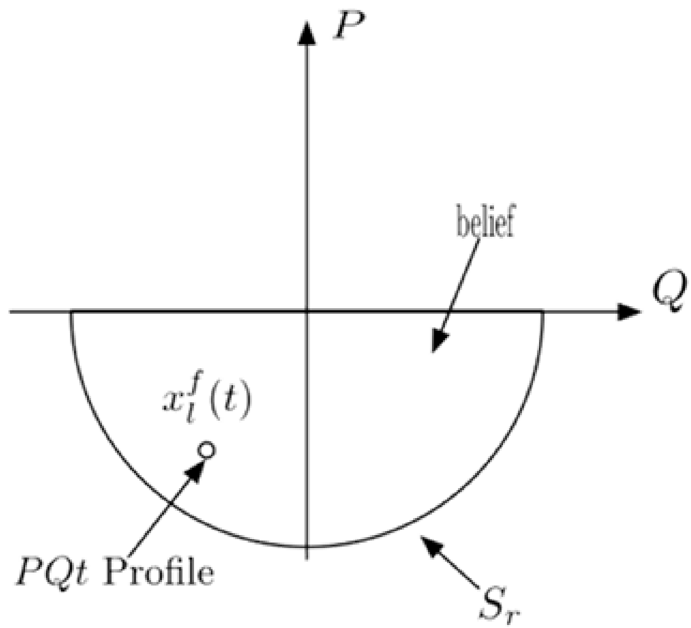
Battery



PV plant



Load



COMMELEC's Architecture – The Grid Agent's Job

- **Leader agent (grid agent)** computes setpoints for followers based on
  - the state of the grid
  - advertisements received from the resources

The Grid Agent attempts to minimize

Cost of power flow at point of common connection

$$J(\mathbf{x}) = \sum_i w_i C_i(x_i) + W(\mathbf{z}) + J_0(\mathbf{x}_0)$$

Virtual cost of the resources

Penalty function of grid electrical state z (e.g., voltages close to 1 p.u., line currents below the ampacity)

The Grid Agent **does not see the details of resources**

a grid is a collection of devices that export PQt profiles, virtual costs and belief functions and has some penalty function

problem solved by grid agent **is always the same**

COMMELEC's Architecture – The Grid Agent's Job

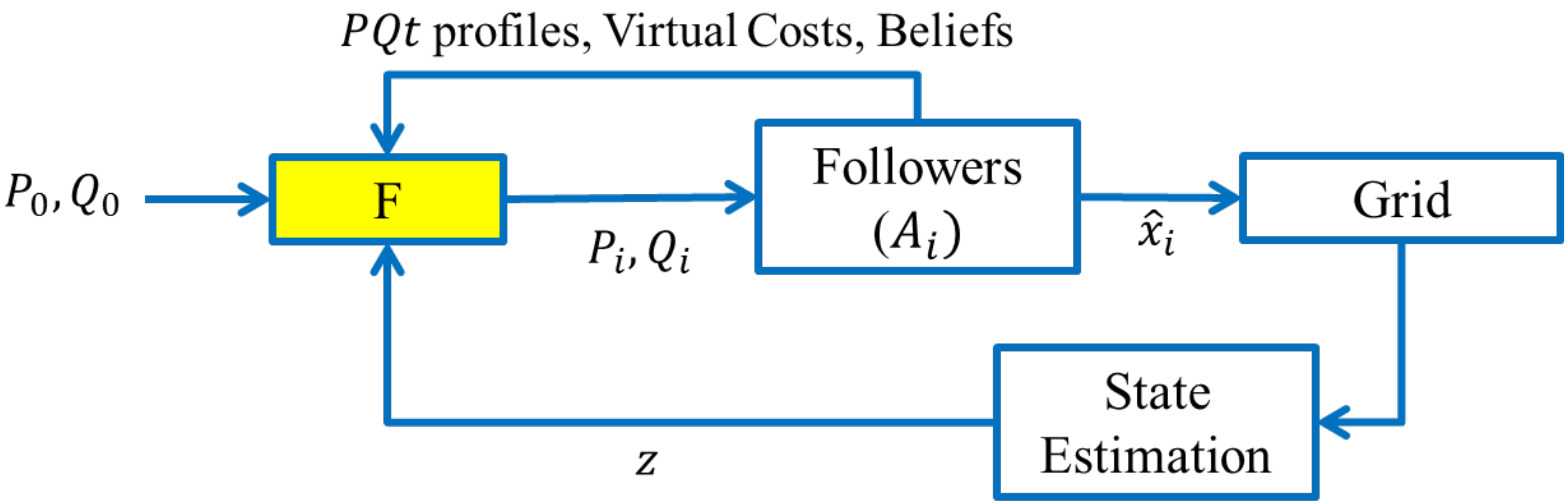
- **Objective function is a weighted combination of**
  - followers costs
  - the cost of grid quality of service
  - the cost of deviation from the request (in our case study, LV grid agent only)
- **Gradient-based approach**
- **Given the current (measured/estimated) setpoint** $\hat{\mathbf{x}} = \left(\hat{P}_i, \hat{Q}_i\right)$ **the computed next setpoint is given by**

$$\mathbf{x} = \mathrm{Proj}\left(\hat{\mathbf{x}} + \Delta\mathbf{x}\right)$$

Here:

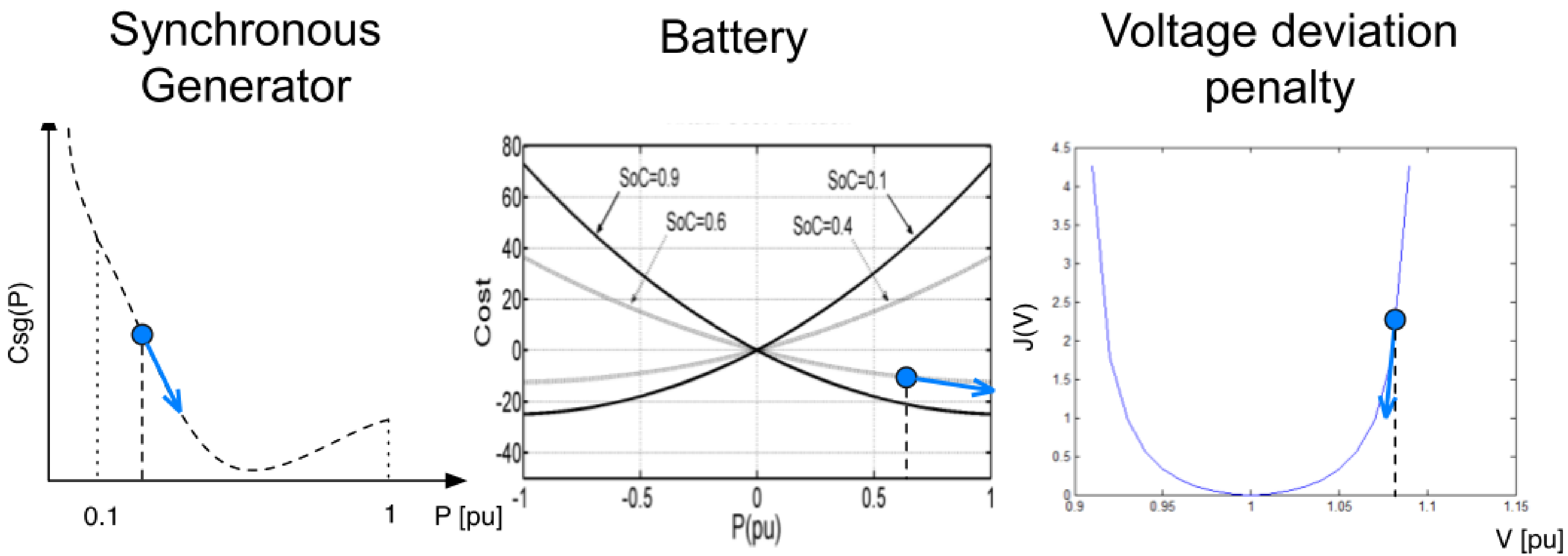
- $\boldsymbol{\Delta}\mathrm{x}$ is a vector in the direction opposed to the direction of the gradient of the overall objective function
- $\mathbf{Proj}\{\}$ is the **projection to safe setpoint**.

COMMELEC's Architecture – The Grid Agent's Job

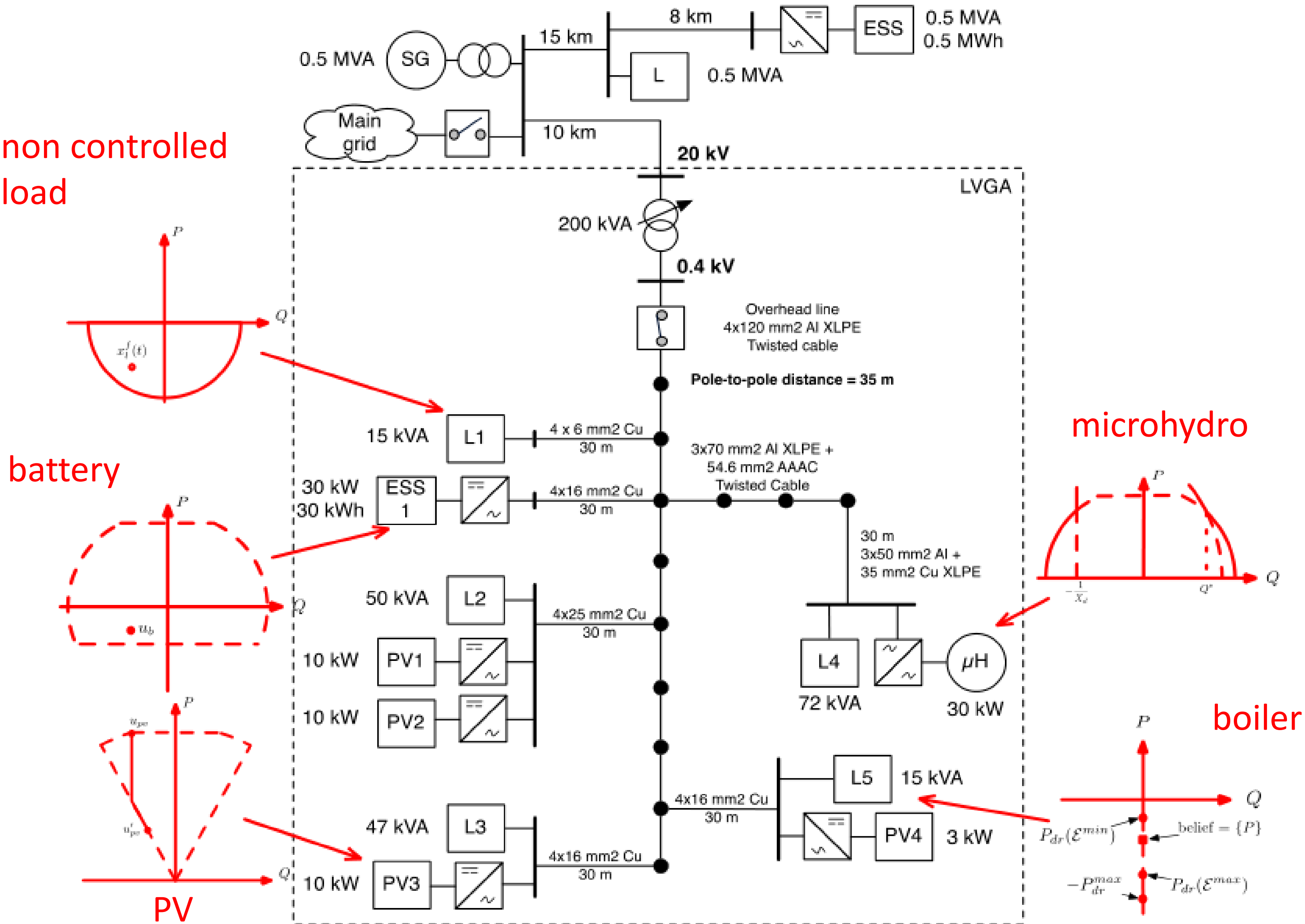


COMMELEC's Architecture – The Grid Agent's Job

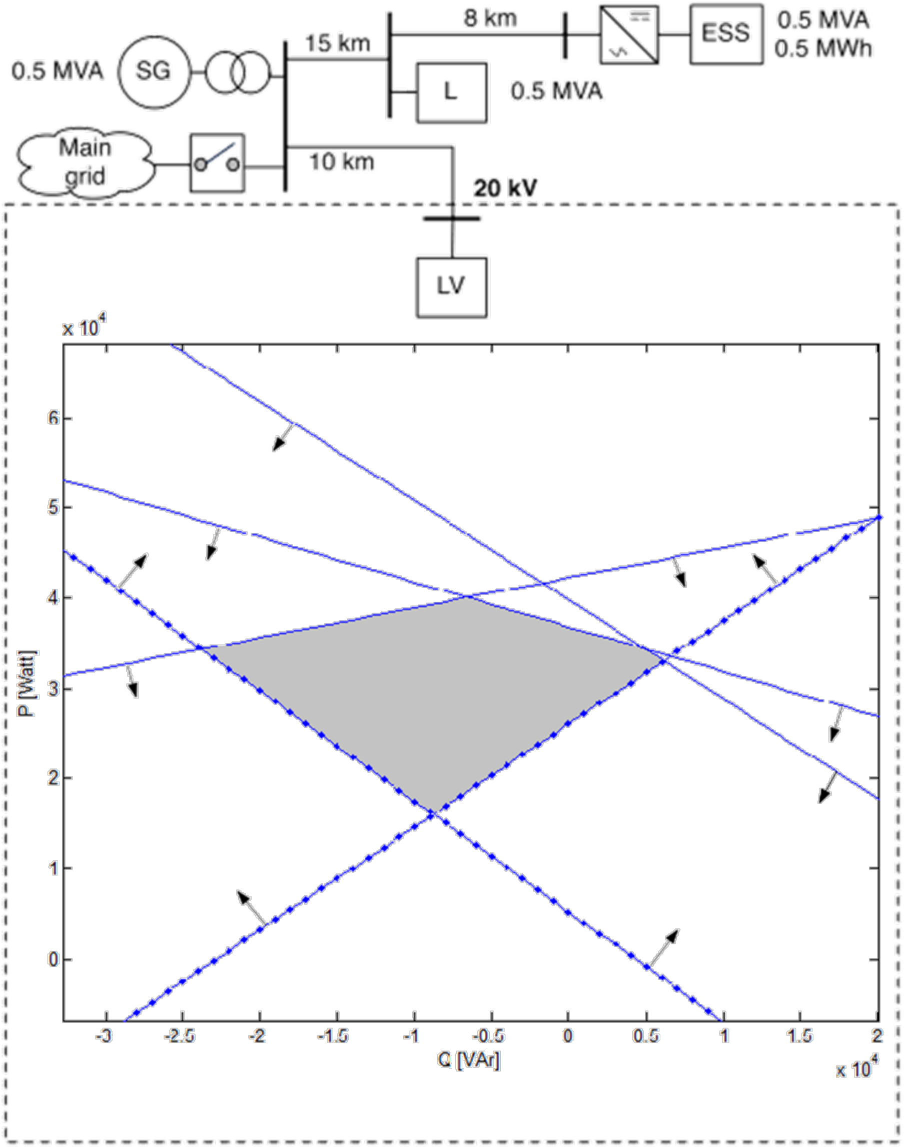
Setpoint Computation by Grid Agent involves gradient of overall objective = sum of virtual costs + penalty



COMMELEC's Architecture – Aggregation, Composability



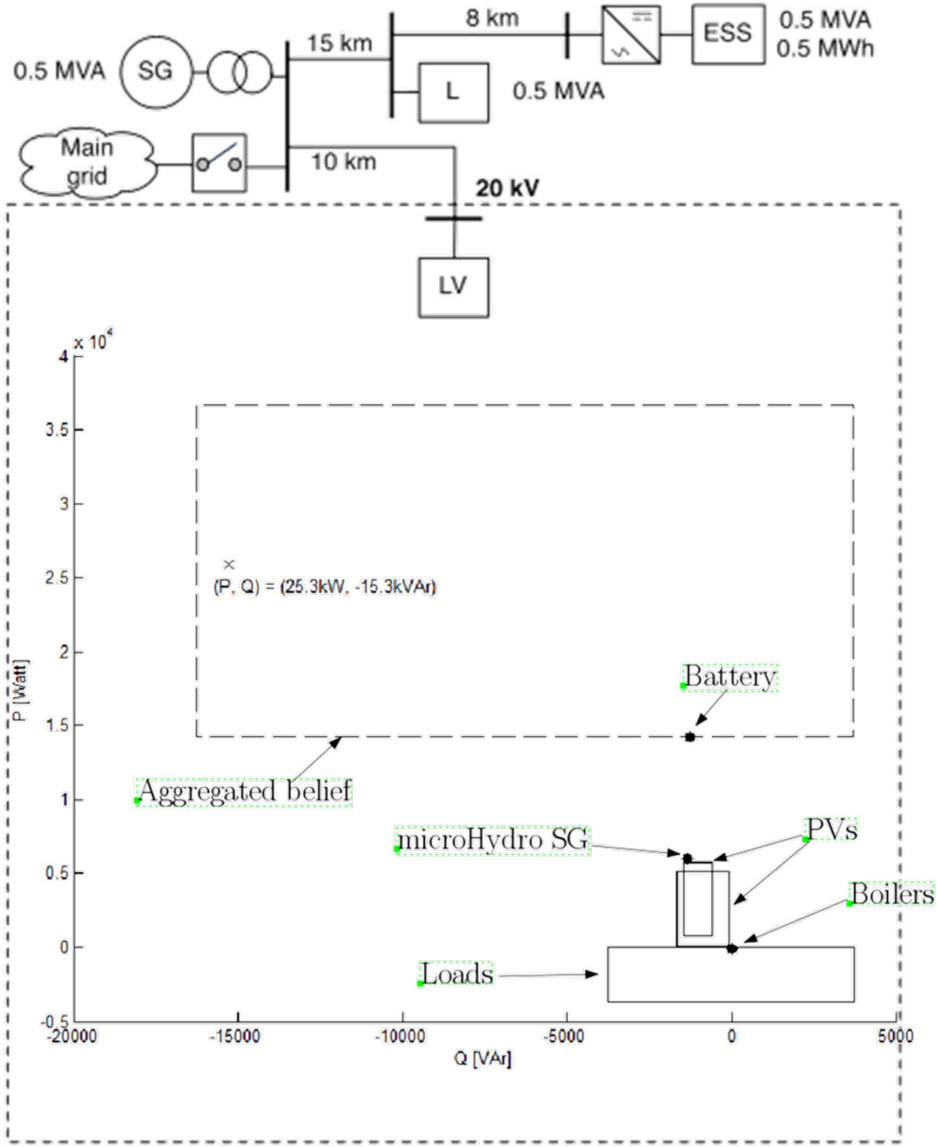
COMMELEC's Architecture – Aggregation, Composability



Aggregated
***PQt* profile**

safe approximation (subset of true aggregated *PQt* profile)

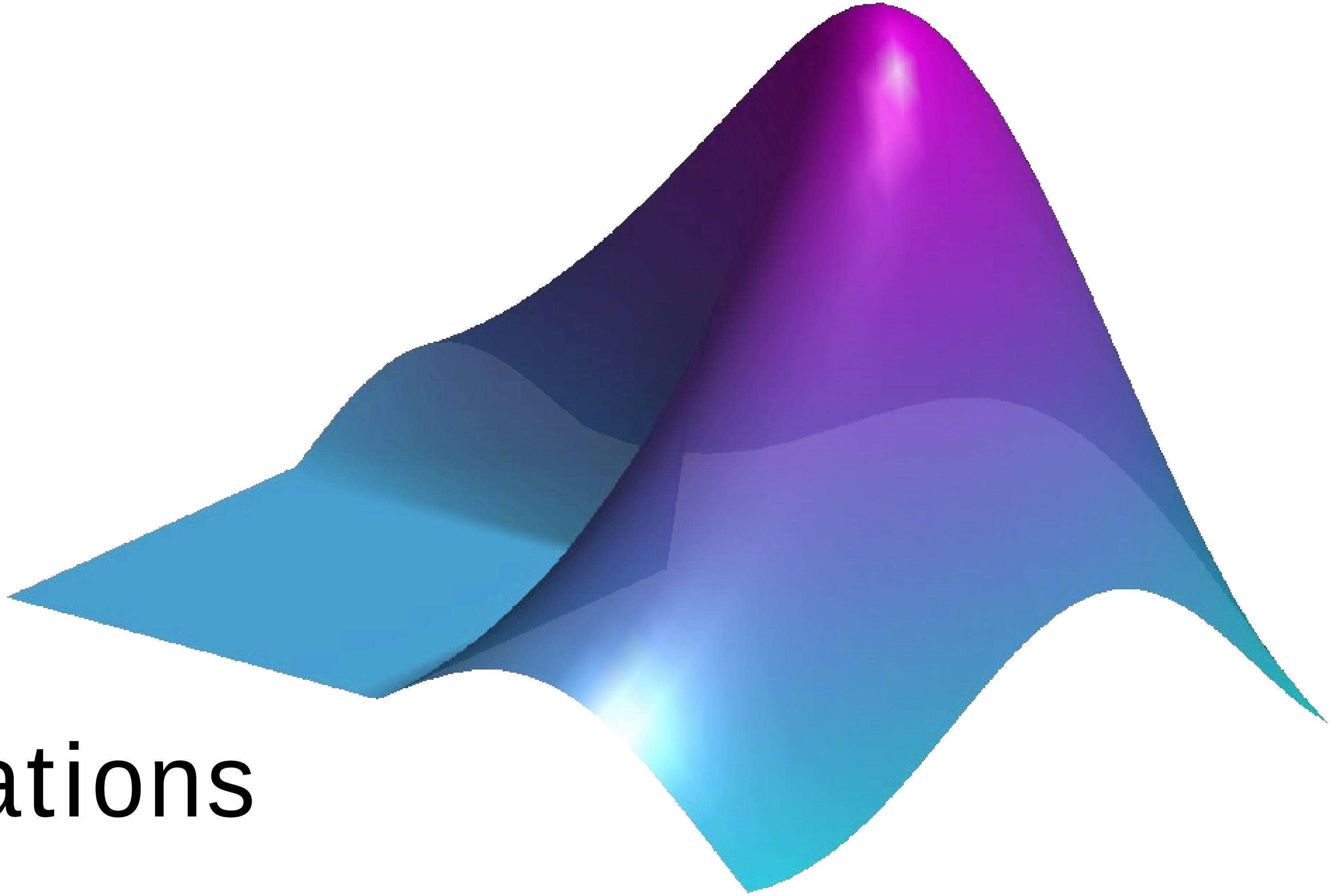
COMMELEC's Architecture – Aggregation, Composability



Aggregated belief

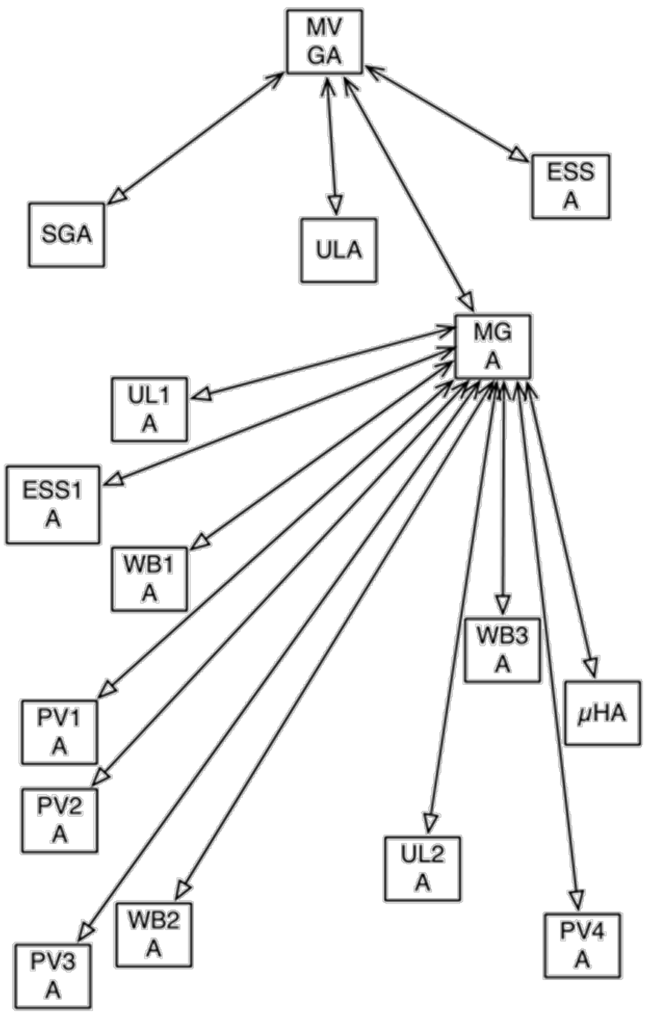
safe approximation (superset of true aggregated belief)

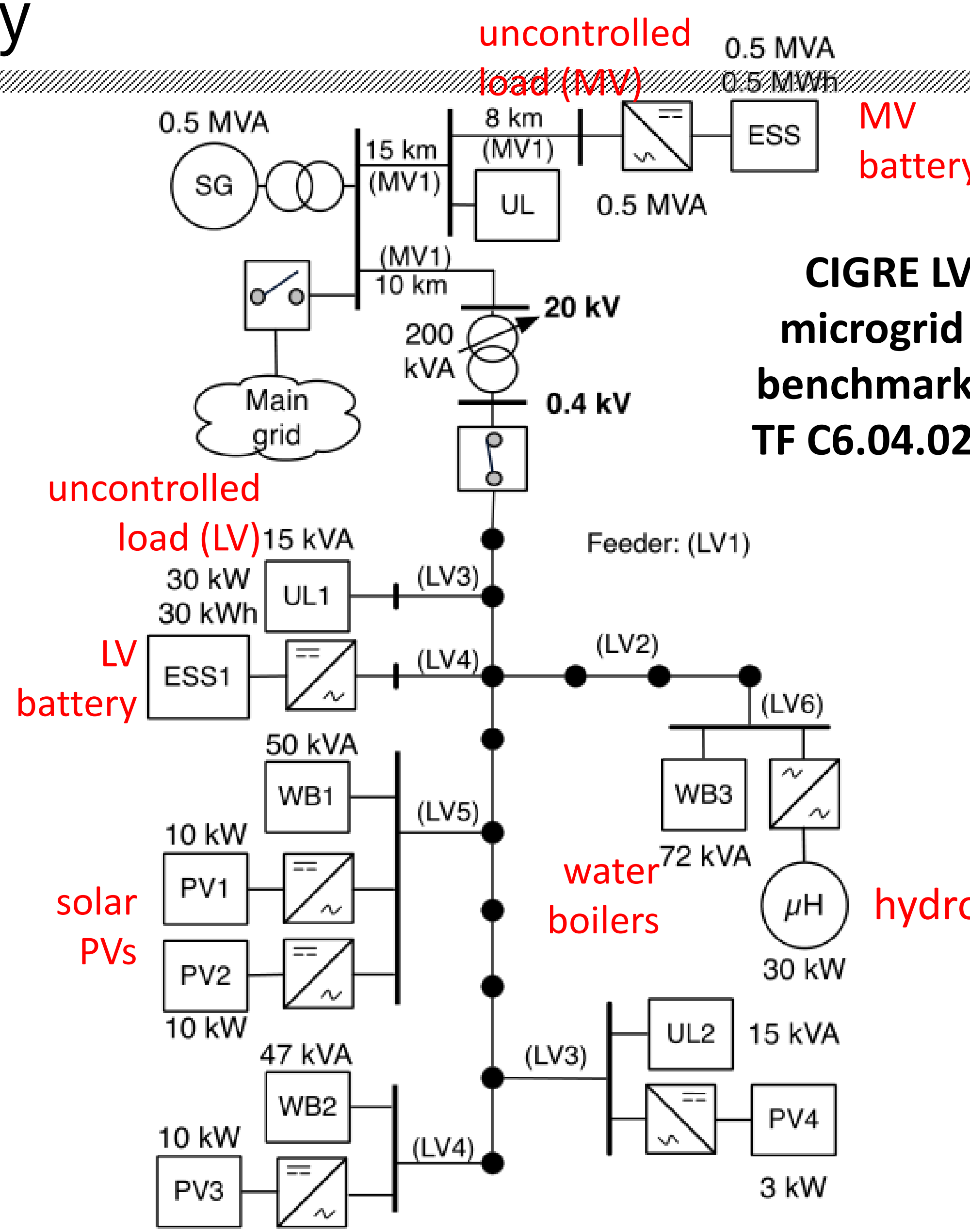
Outline



Simulations

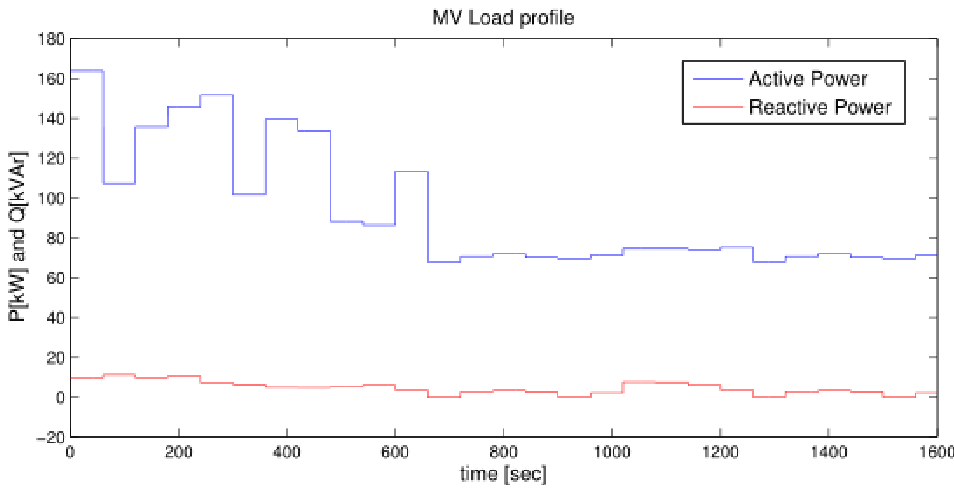
Simulations – Case Study

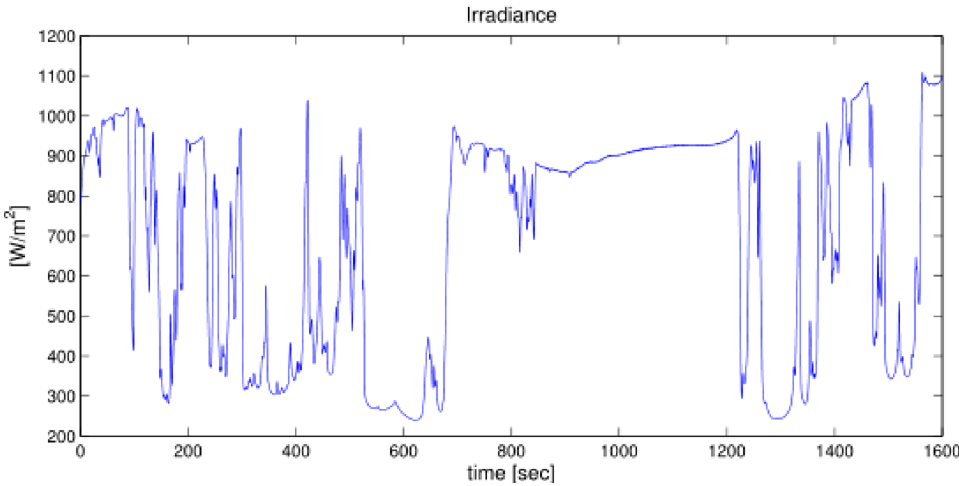




Simulations – Case Study

- **Sources of randomness**
  - solar irradiation
  - uncontrolled load
- **Storage**
  - batteries
  - water boilers
- **Data: traces collected at EPFL in Nov 2013**
- **Performance Metrics**
  - distance of node voltages to limits
  - state of charge
  - renewable curtailed
  - collapse/no collapse





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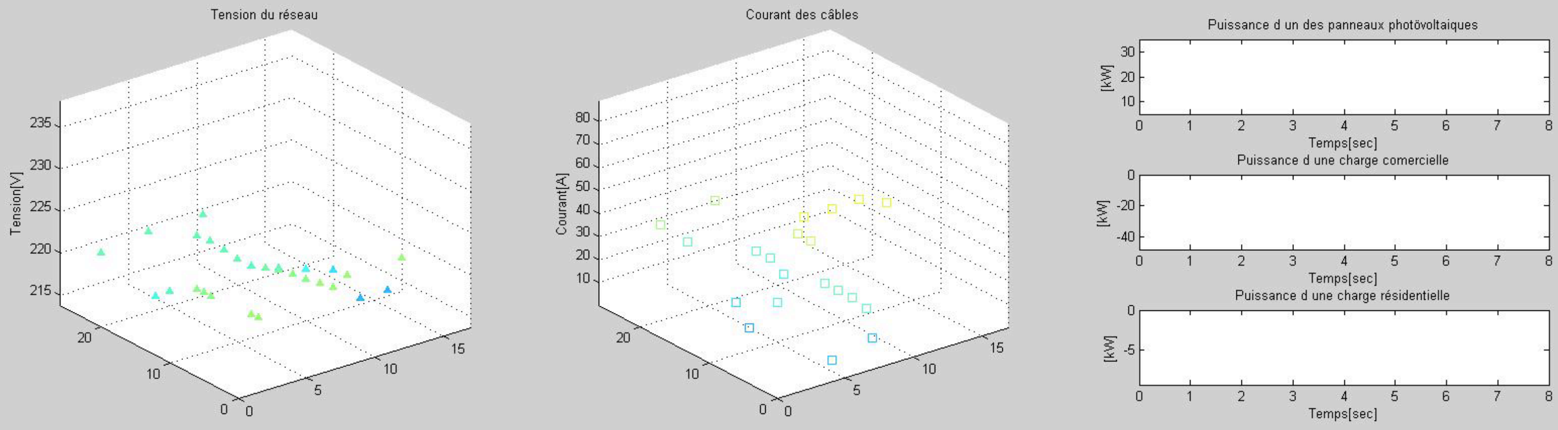
Comparison with classical droop controls

Commelec

Primary droop control on frequency

Primary and secondary frequency controls

Droop control



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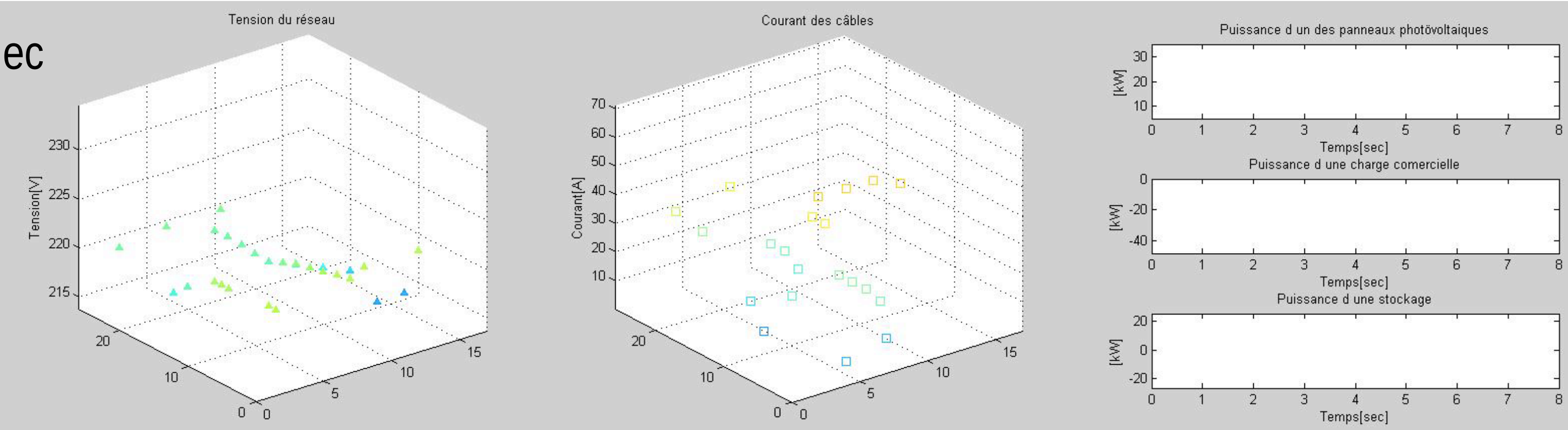
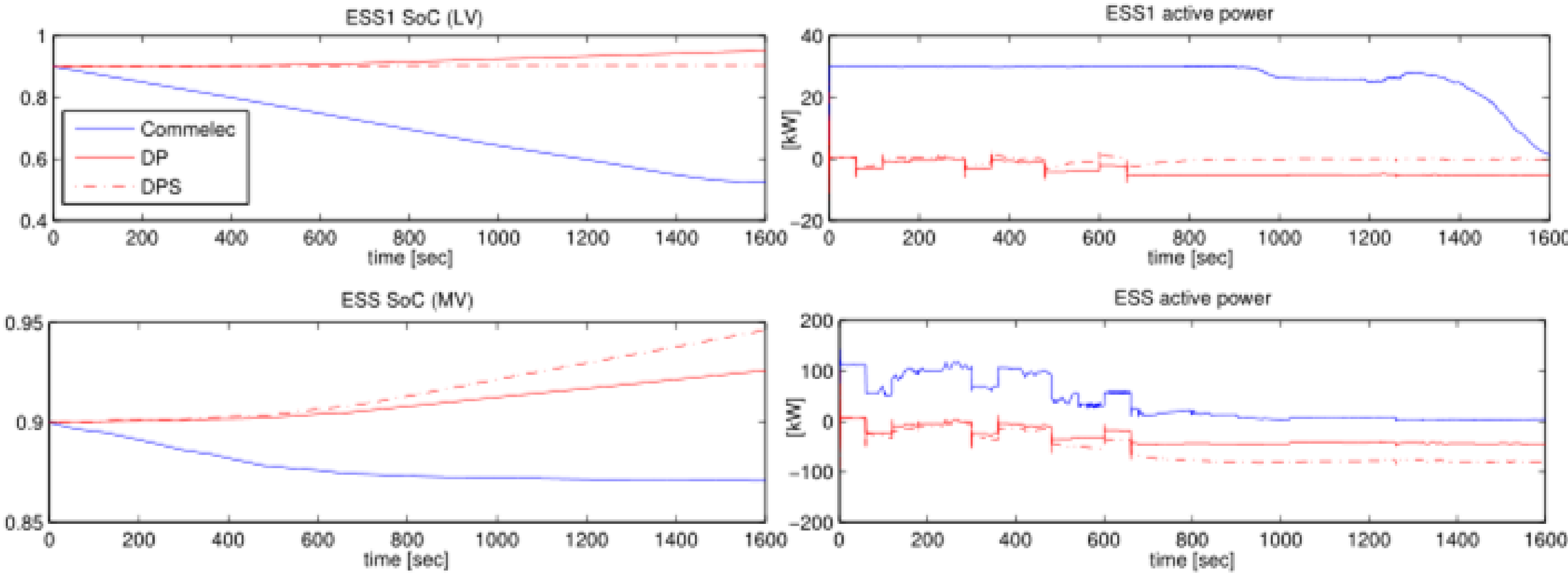


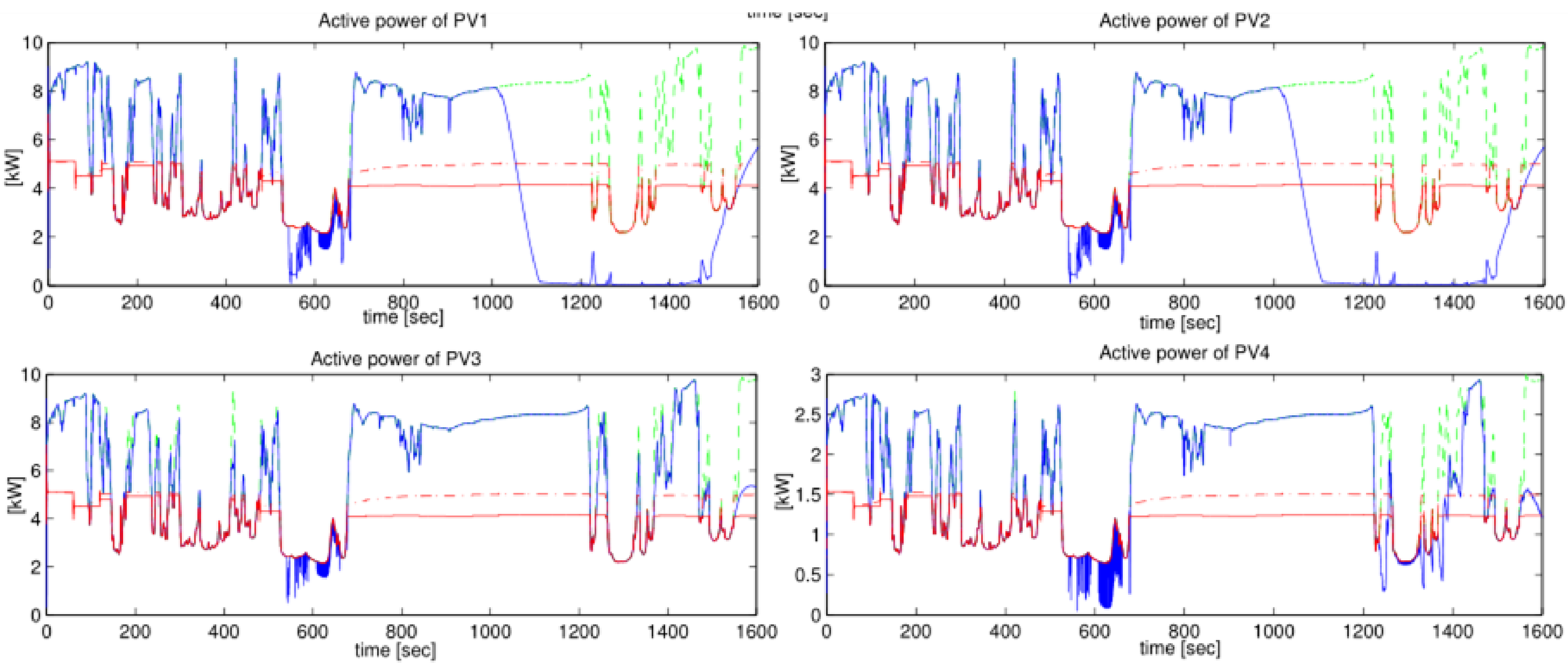
Simulations – Results

ESS1 and ESS2 are driven to their midpoints



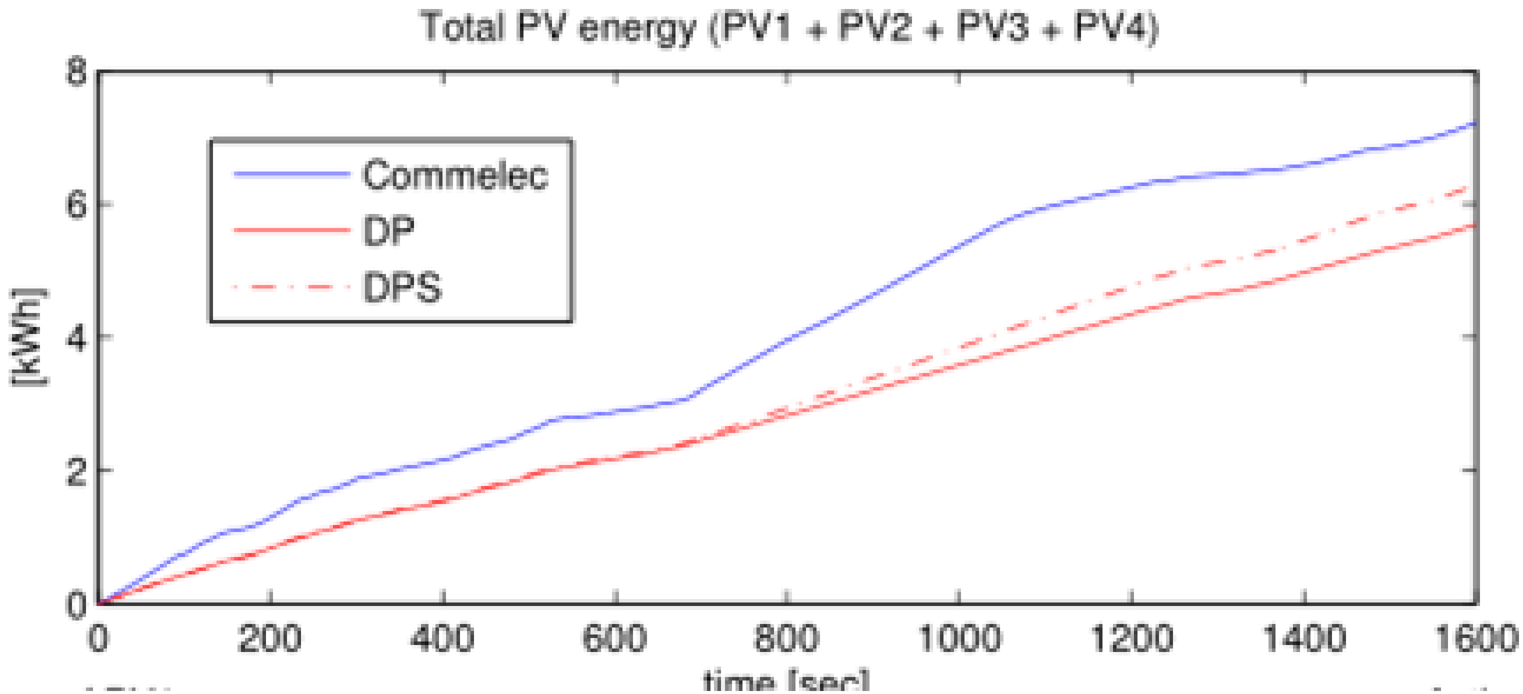
Simulations – Results

Reduced Curtailment of Renewables



Simulations – Results

Reduced Curtailment of Renewables

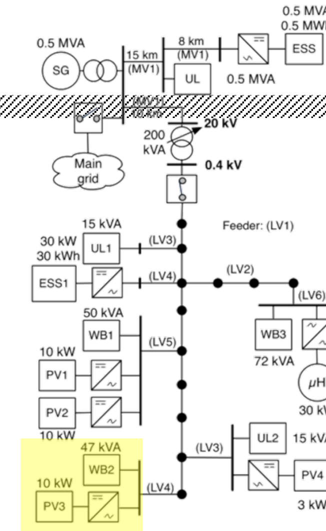


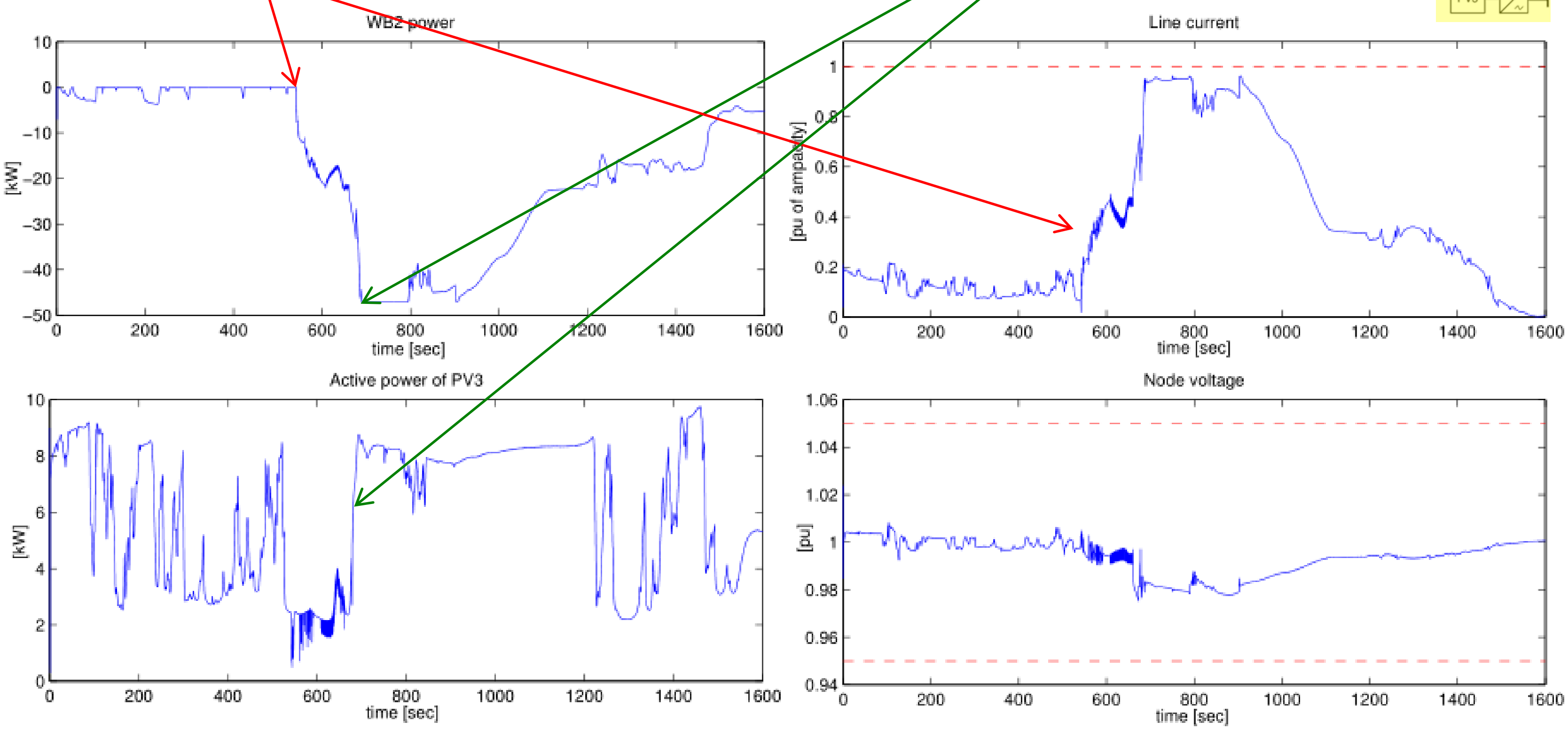
Simulations – Results

Local power management

Boiler WB2 charges at full power because PV3 produces

Boiler WB2 starts because WB1 stops at mid power due to line congestion





Outline

Conclusions

Conclusions

Separation of concerns

Resource Agents

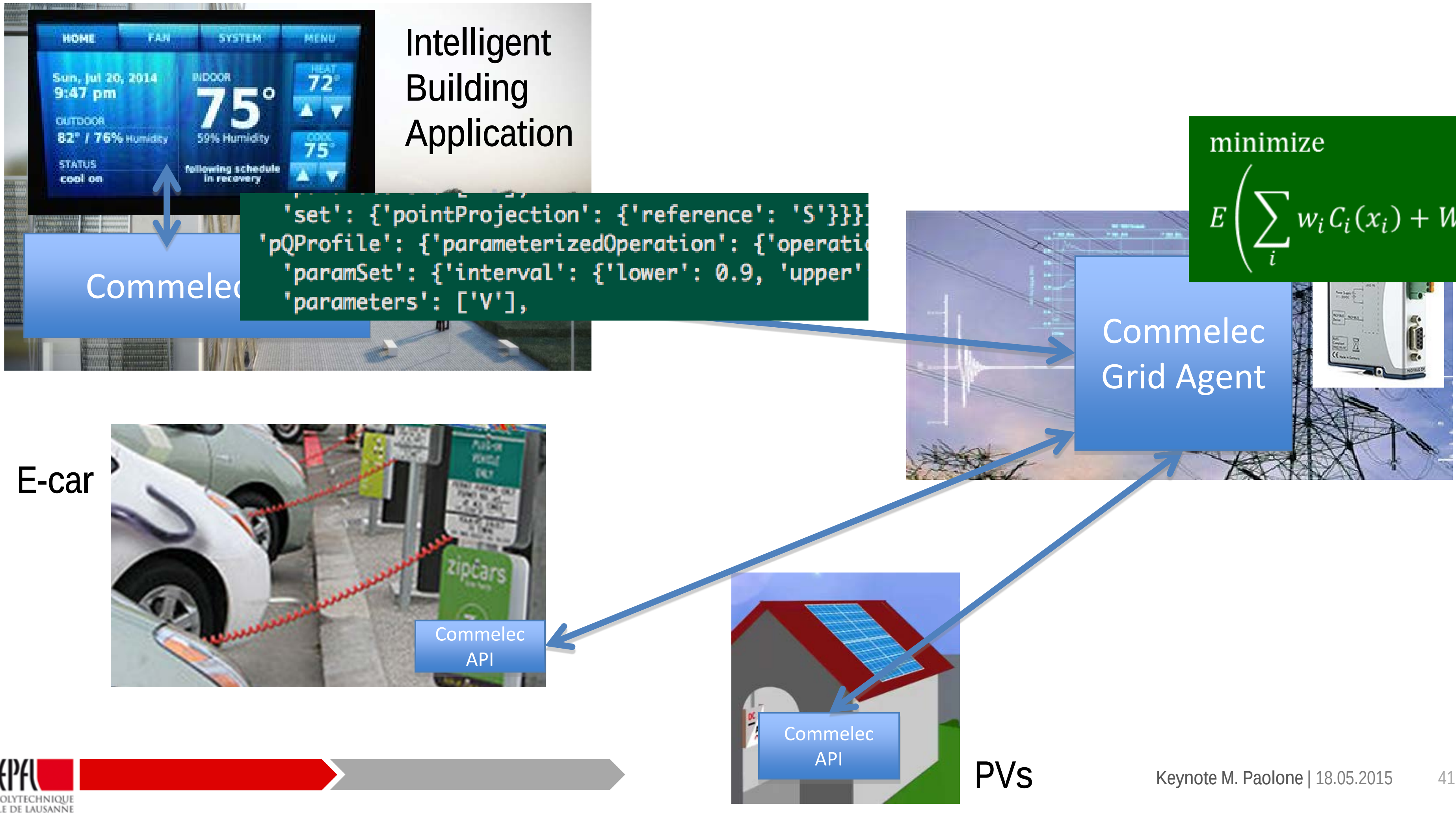
- Device-dependent
- Simple:
  - translate internal state of a resource into a virtual cost
  - implement setpoint received from a grid agent

Grid Agents

- Complex and real-time
- All identical
- Steer the grid to the safe/optimal point of operation
- Capable to abstract the state of an entire grid to the upper one

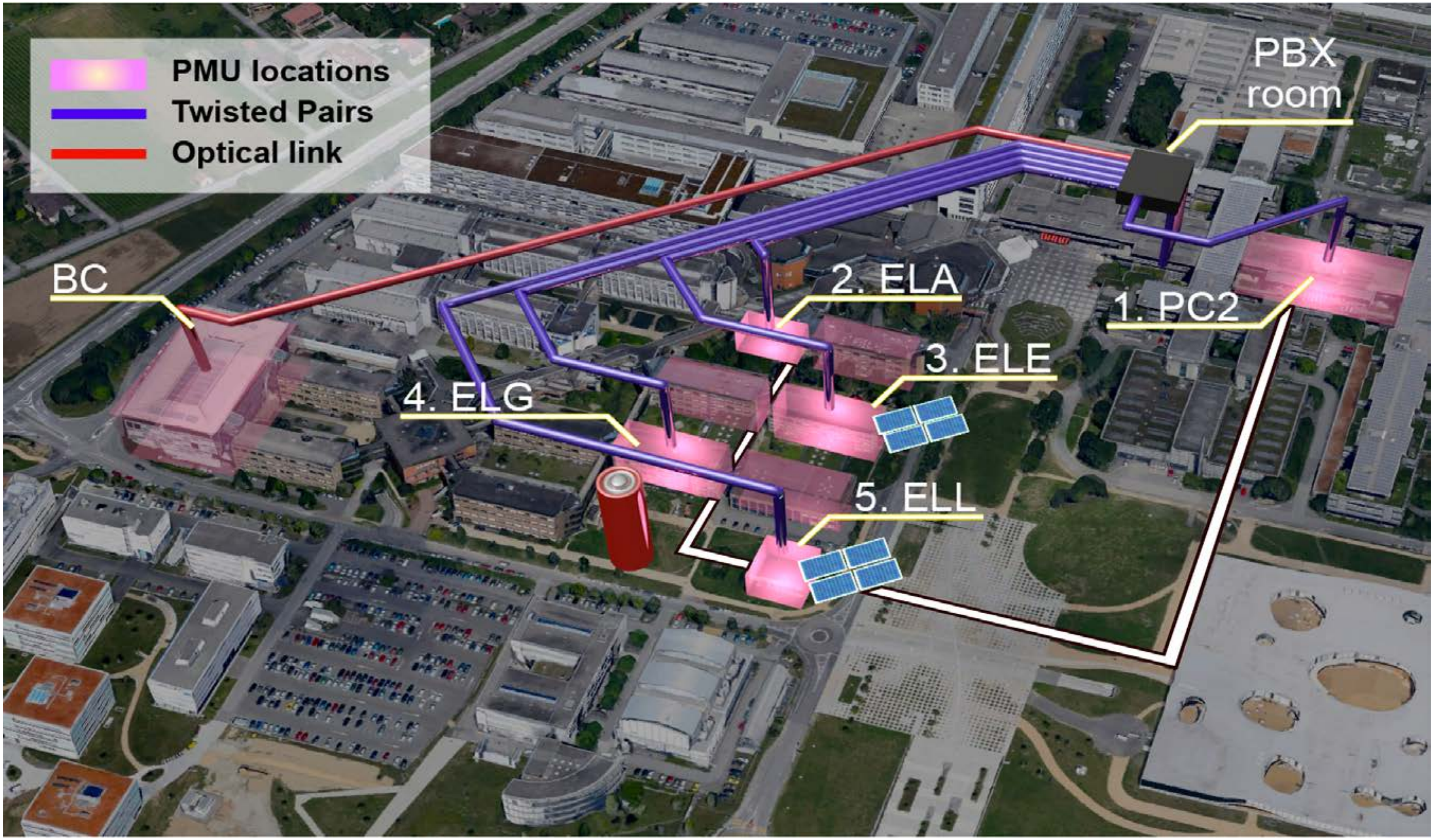
Conclusions

An operative system for electrical grids: resource control uses the Commelec API (open source) and does not need to be aware of the grid



Conclusions

Ongoing validation on the EPFL campus (see http://smartgrids.epfl.ch)



Conclusions

- Commelec is a practical framework for the automatic control of distribution systems (microgrids) with massive presence of stochastic resources
  - exploits available resources (storage, demand response) to avoid curtailing renewables while maintaining the local grid in safe operation
- The framework is designed to be robust and scalable
  - separation of concerns between resource agents (simple, device specific) and grid agents (all identical)
  - a simple, unified protocol that hides specifics of resources
  - aggregation for scalability

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Prof. Mario Paolone keynote speech

1st Int. Symposium on Smart Grids Methods, Tools and Technologies

Shandong Univ., Jinan, China, May 18th, 2015

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