Power Management in Renewable Energy Microgrids with Hybrid Storage

Carlos Bordons

Systems Engineering and Automaticon Dpt.

University of Seville, Spain

Centre of Research Excellence
for Advanced Cooperative Systems

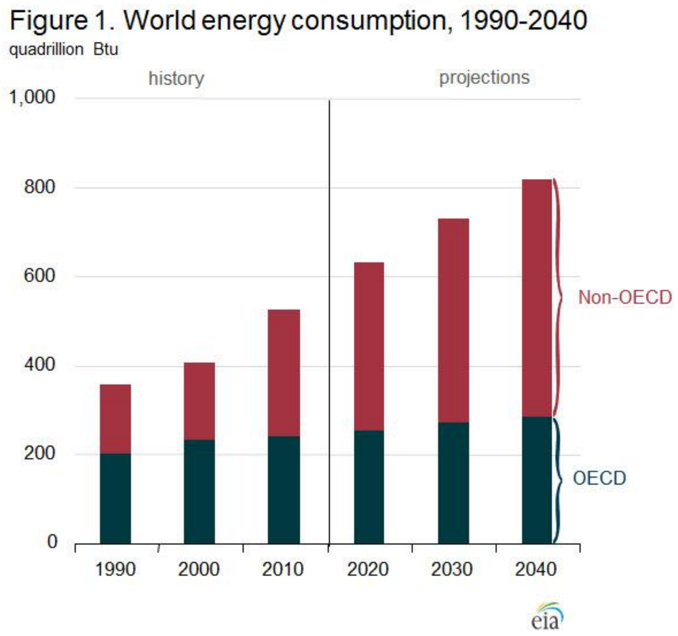
Abstract

- Power Management in micro-grids with **renewable sources** (wind and solar) and hybrid (**hydrogen and electricity**) storage
- Focus on the control methodology: open issue
- Model predictive control
- Implementation on a laboratory plant
- Assessment by KPI
- Control objectives: power balance, durability, economic profit, etc.

Outline

1. **Setting the Context**
2. Microgrids
3. Experimental testing facility: HyLab
4. Model Predictive Control for µGrid Power Management
5. Extended control objectives
6. Concluding remarks

The demand for energy, especially for electricity, has increased exponentially for years



Source: U.S. Energy Information Agency

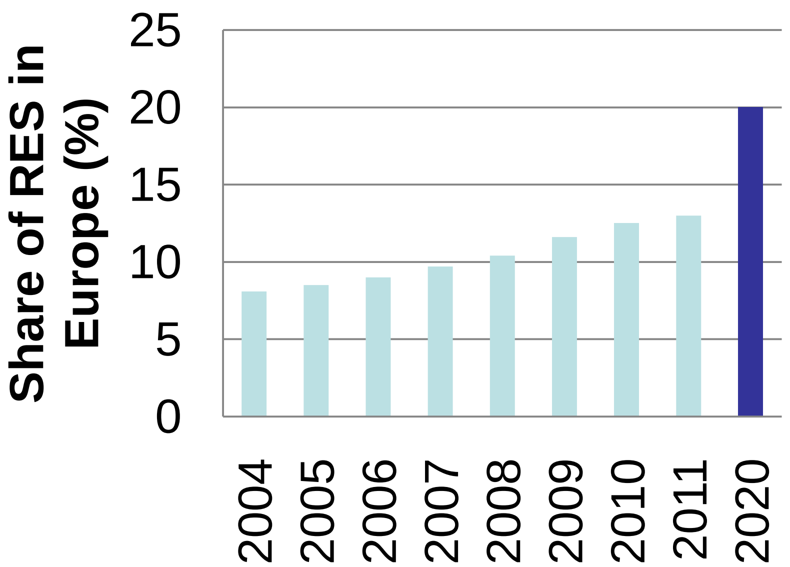
We need more energy and it needs to be cleaner → Renewable Energy sources can be a solution

Government regulations

- **Energy mandates**
  - ❑ USA → 20-33%
  - ❑ EU's 20-20-20 → 20%

2020

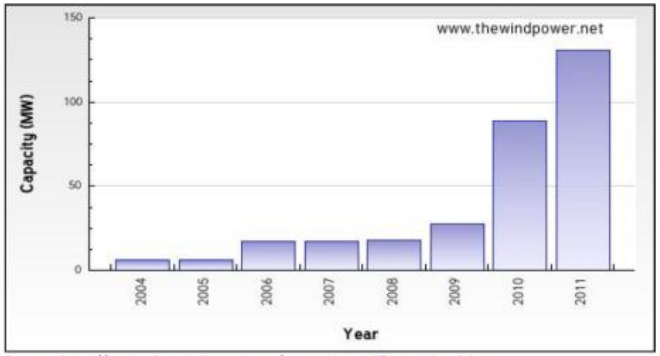
- **Environmental regulations and security of supply**
  - Coal plants phase-out
  - Nuclear phase-out (Germany, Italy, Japan, Swi tzerland, Austria, Sweden. .etc.)



Source: Eurostat

Wind and solar energy

Wind power installed in Croatia



Source: http://www.thewindpower.net/country_en_45_croatia.php

Mail Online

Home | News | U.S. | Sport | TV&Showbiz | Femail | Health | Science | Money | Video

News Home | Arts | Headlines | Pictures | Most read | News Board

Wind farms paid £30 million a year to stand idle because the grid can't cope with all the energy they produce

- Wind farms paid millions when National Grid is unable to use their energy
- Last weekend alone energy firms were paid £3.1million to switch off

By NICK MCDERMOTT

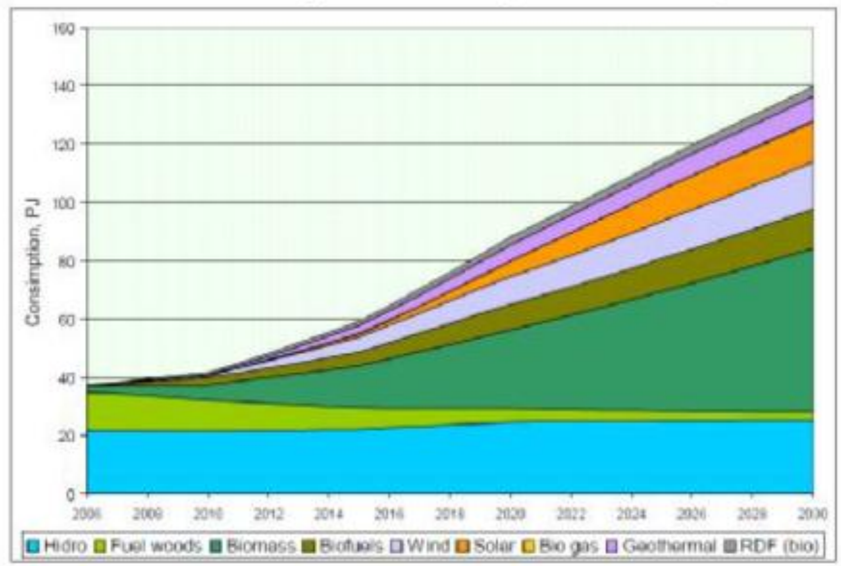
PUBLISHED: 21:33 GMT, 9 August 2013 | UPDATED: 09:32 GMT, 25 September 2013

The New York Times **Business**

THE ENERGY CHALLENGE

Wind Energy Bumps Into Power Grid's Limits

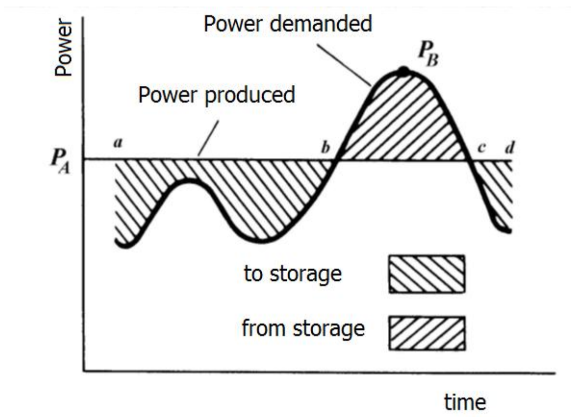
Structure of renewable energy sources to 2020 (with a view to 2030)



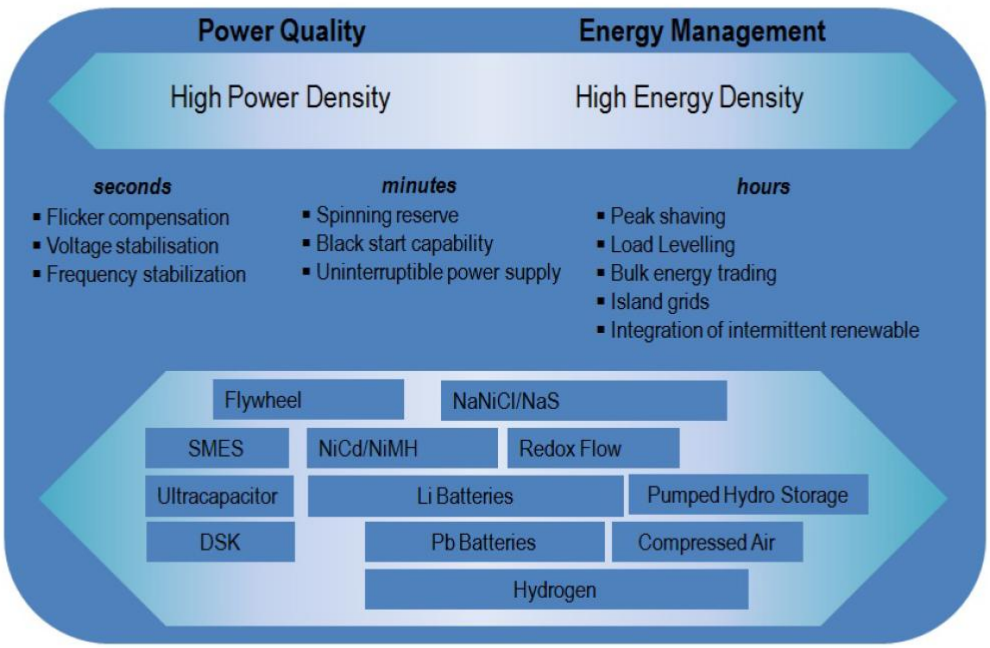
> **Wind farms in Pacific Northwest paid to not produce**
>
> Oversupply of renewable power

Energy storage must become an integral element of the renewable adoption strategy

Electricity Energy storage



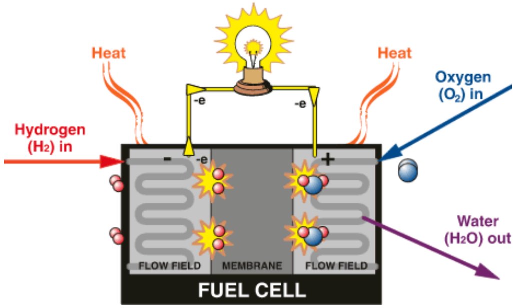
- Cover a range of time scales
- H2, batteries, ultracapacitor, flying wheels, etc.
- Different dynamics-different term. Complementary



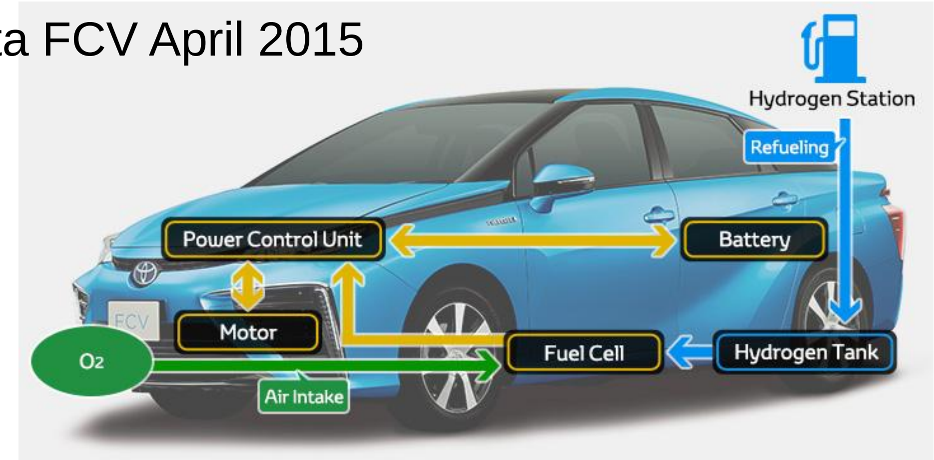
Storage allows a non-dispatchable generator (RES) to be dispatchable

Storage must be operated in an optimal way

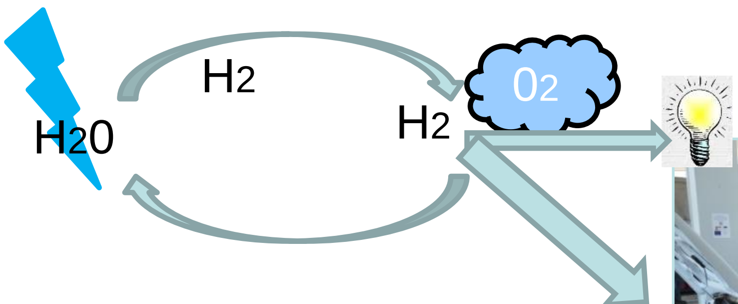
Hydrogen can be an option: **high energy density** and **high power density**



Also for FCHVs:
Toyota FCV April 2015

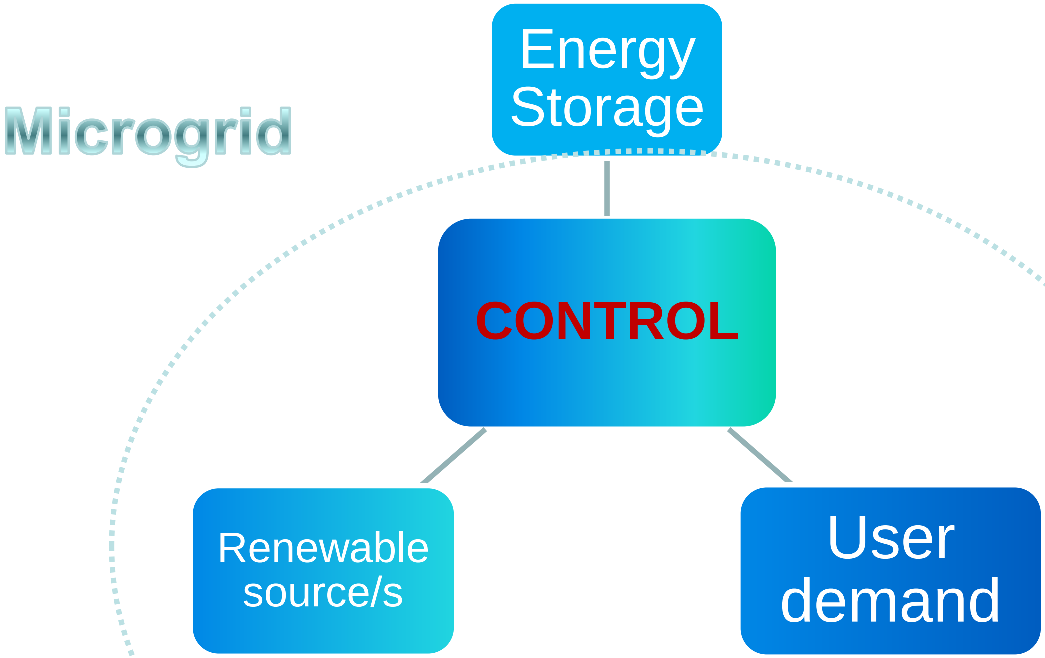


"The Green Hydrogen Cycle"



Hybrid storage in vehicles (batteries + H2 tanks)

Distributed and mobile storage



Challenges:
- Maintain energy security for end-users
- Stabilize the electrical grid so as to avoid disconnections of wind farms and solar fields
- Make RES dispatchable

Control system must guarantee:
- Efficiency
- Lifetime
- Economic
- Safety

Outline

1. Setting the Context

2. Microgrids

3. Experimental testing facility: HyLab

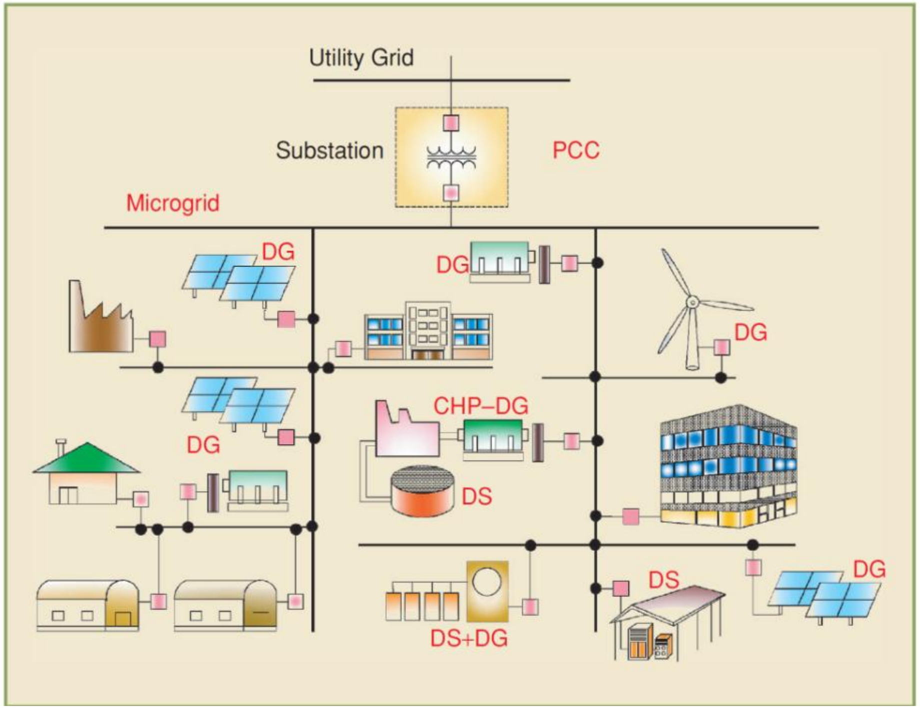
4. Model Predictive Control for µGrid Power Management

5. Extended control objectives

6. Concluding remarks

Microgrid

- Portion of an electric power distribution system that includes a variety of **DER** units and different types of **end users** of **electricity and/or heat.**
- DER (Distributed Energy Resource) units:
  - Distributed generation (DG)
  - Distributed storage (DS) .
- It can work in Islanded/grid-connected mode
- AC or **DC** microgrid



Control objectives in microgrids (AC/DC)

- Supply and demand **balancing**
- Power **quality**: avoid variations as harmonic distortion or sudden events as interruptions or even voltage dips.
- In isolated mode: **Voltage** and **frequency** management
- Economic benefit
- **This talk focuses on DC microgrids**

Manipulated the dispatchable units in the proper way

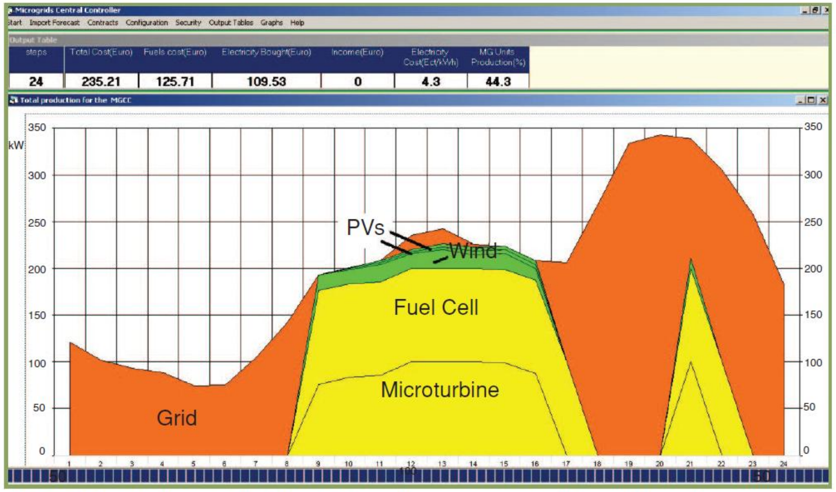


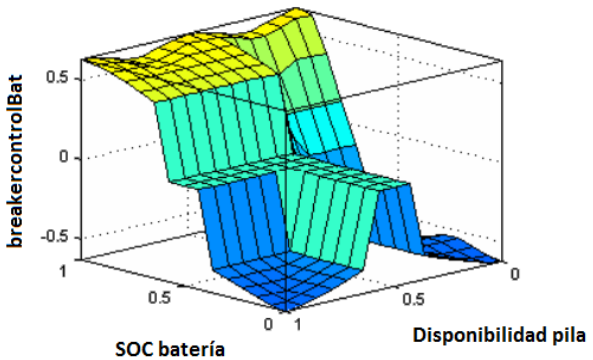
figure 14. Display of DER dispatch and energy imported from the grid.

400 kW Microgrid

Control techniques applied to microgrids

In the last ten years, experience has demonstrated that **system performance is highly subject to the control strategy**

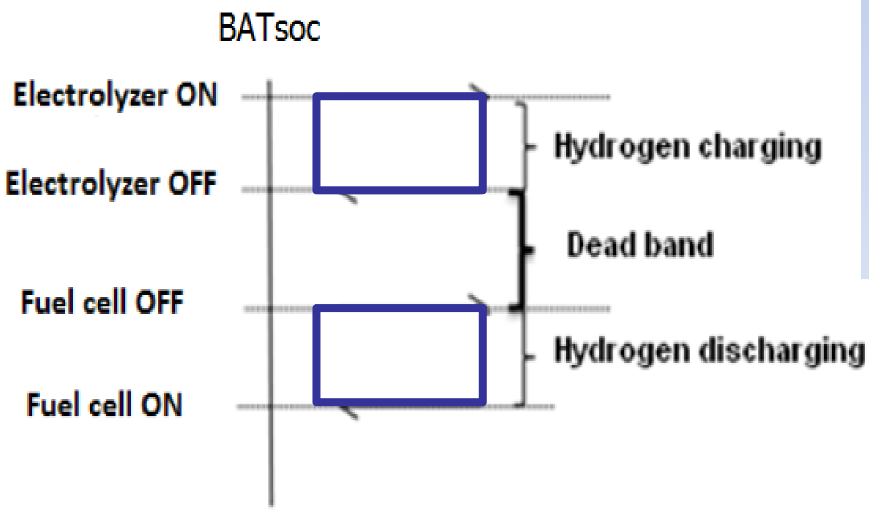
- HYSTERESIS BAND CONTROL (Ulleberg, 2003), (Ghosh, 2003), (Ipsakis, 2008)
- NEURAL NETWORK (López, 2007)
- FUZZY LOGIC (Bilodeau, 2006), (Stewart, 2009) (Hajizadeh , 2009)
- DROOP CONTROL (Vasak, 2014)
- MODEL PREDICTIVE CONTROL (Del Real, 2007) (Baotic, 2014)

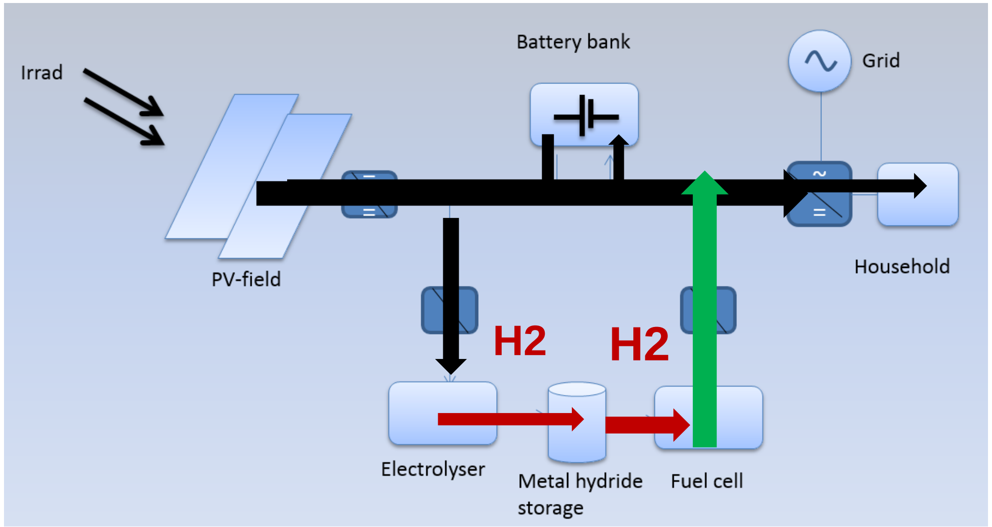


Challenges translated into innovative control strategies that **can benefit efficiency and cost reduction** to make this technology more competitive.

Hysteresis band technique

The whole operation is based on the battery's state of charge (SOC)





PV: non-dispatchable
FC: dispatchable

Very simple and reliable

Non optimal
Low efficiency
Equipment degradation

Open issues

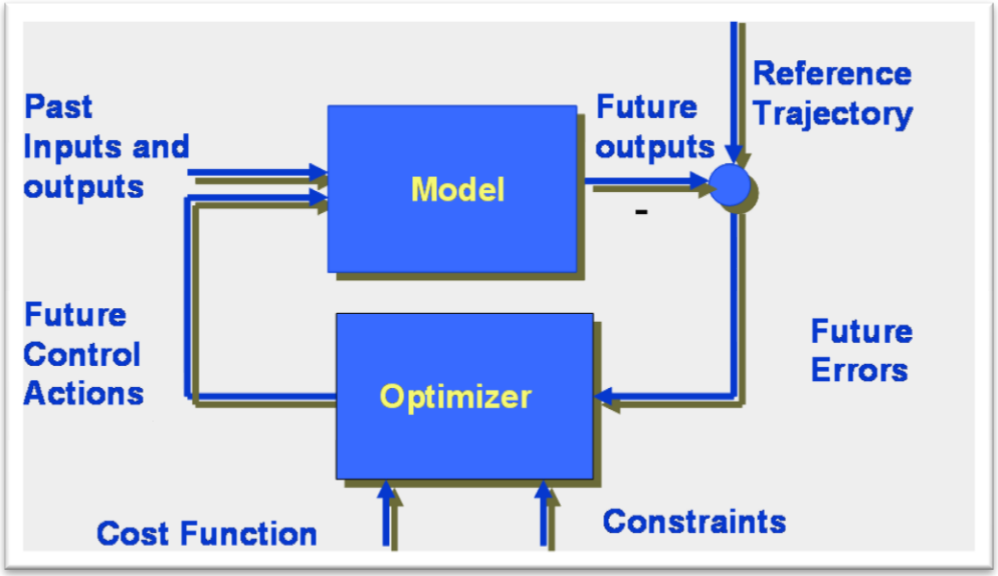
- Is heuristic control the cause of premature **degradation**?
- Which are the different ways of operating the equipment in a µG? What are the best ways? Can we quantify the **goodness** of a control strategy?
- Why **optimal** control has not been developed and demonstrated in hydrogen µGs? Can it provide solutions?
- What are the steps towards the **development and validation** of an optimal controller?
- What are the greatest technical **challenges** facing H2-microgrids optimal control?

?

Model Predictive Control in microgrids

- The use of MPC technique allows to **maximize** the economical benefit of the microgrid, **minimizing** the degradation causes of each storage system, fulfilling the different system constraints.
- MPC can be used for
  - Dispatch/Schedule
  - Power quality/service

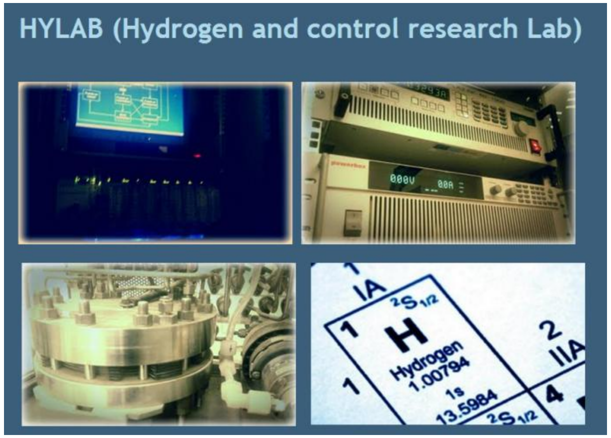
Optimization over a future receding horizon using a dynamic model of the plant



Outline

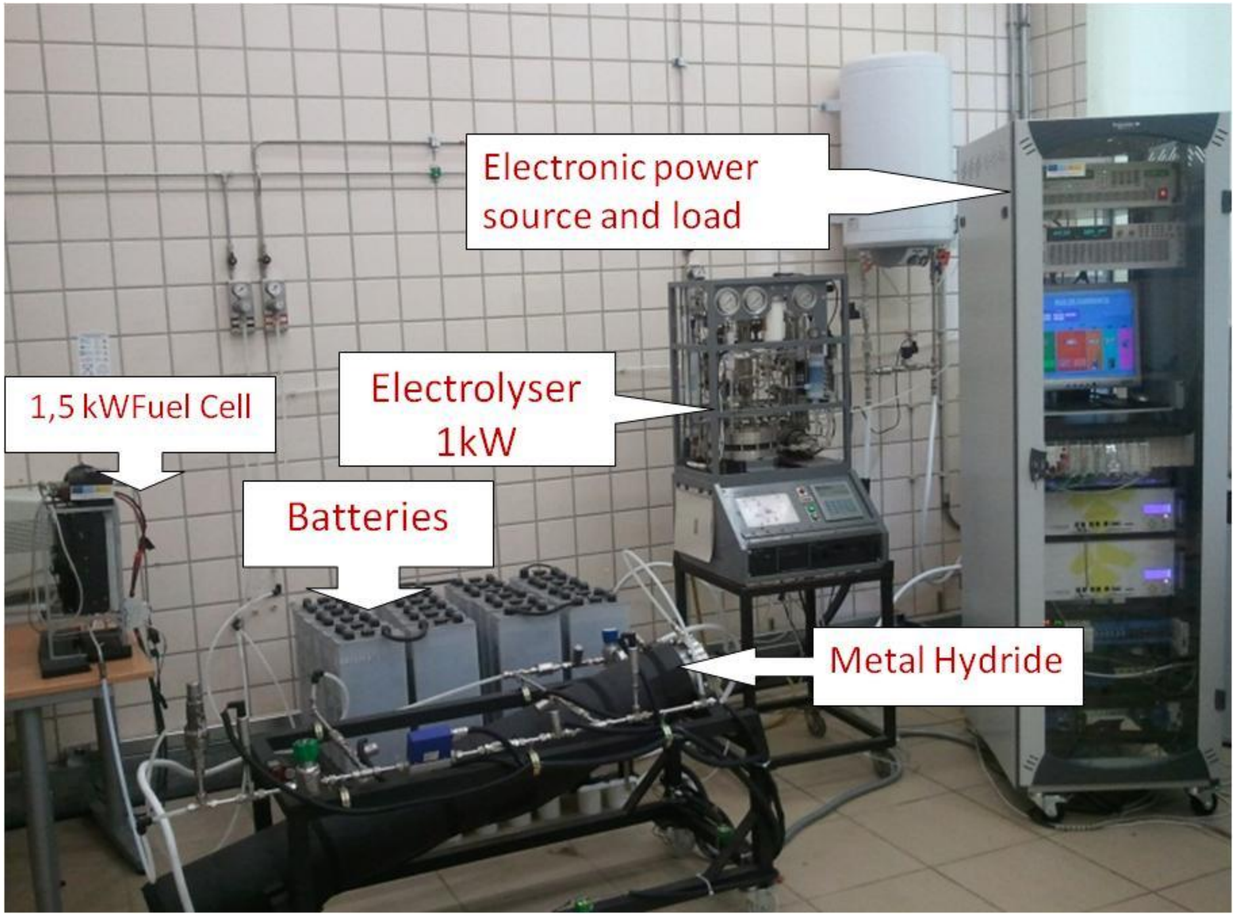
1. Setting the Context
2. Micrograds
3. **Experimental testing facility: HyLab**
4. Model Predictive Control for µGrid Power Management
5. Extended control objectives
6. Concluding remarks

System Overview



https://sites.google.com/site/laboratorioh2/

DC microgrid



Other RES-H2 Demonstration Projects

Wind- hydrogen

Project name	Year	Country
HARI	2004	UK
UTSIRA	2004	NORWAY
ITHER	2005	SPAIN
RES2H2	2005	GREECE
PURE	2005	UK
SOTAVENTO	2007	SPAIN
RES2H2	2007	SPAIN
PEIP	2008	CANADA
HIDROLICA	2009	SPAIN
R. Island P.	2010	CANADA
HYDROGEN OFFICE	2010	UK

PV- hydrogen

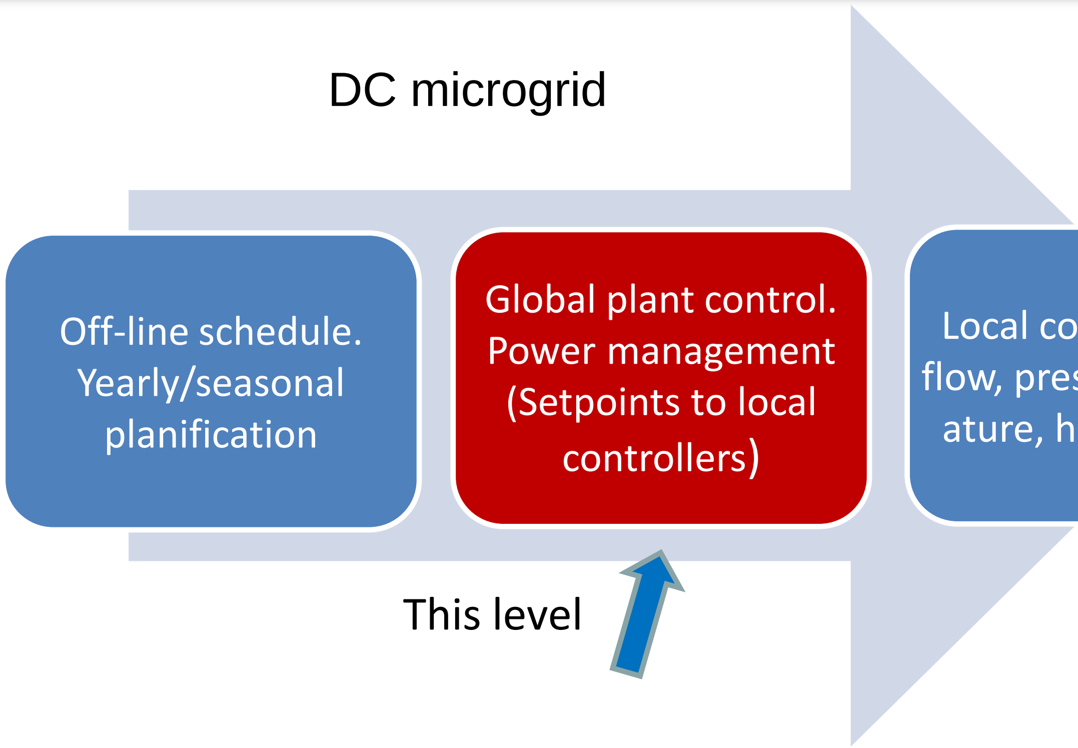
Project name	Year	Country
FIRST	2002	SPAIN
HARI	2002	U.K
HRI	2001	CANADA
INTA	1997	SPAIN
PHOEBUS	1993	GERMANY
SAPHYS	1994	ITALY
SCHATZ	1989	USA
Solar house	1992	ITALY
Solar hydrogen pilot	1990	FINALAND
SWB	1989	GERMANY
CEC	2007	USA
LARES	2014	CROATIA

Definition of Key Performance Indicators

- Percentage of Non-Satisfied Demand (%NSD)
- Fuel Cell and Electrolyser number of start-stop events (START-STOP)
- Percentage of Unused eNErgy from renewables (%UNE)
- Metal Hydride hydrogen storage Level (MHL)
- Batteries State Of Charge (SOC)
- Fuel Cell and Electrolyser running time (t_{fc},t_{ez})
- Hydrogen produced/consumed ratio (rH2)
- Fuel Cell and electrolyser operating constraints trespassing event (e-Alarm)
- Fuel Cell and Electrolyser average efficiency (η_{ez}, η_{fc})
- Efficiency of energy path (η_{path})
- Plant operating cost (O&MC)

Luis Valverde. "Energy management in systems with renewable sources and energy storage based on hydrogen using model predictive control", PhD Thesis, University of Seville, 2013

Control in the microgrid



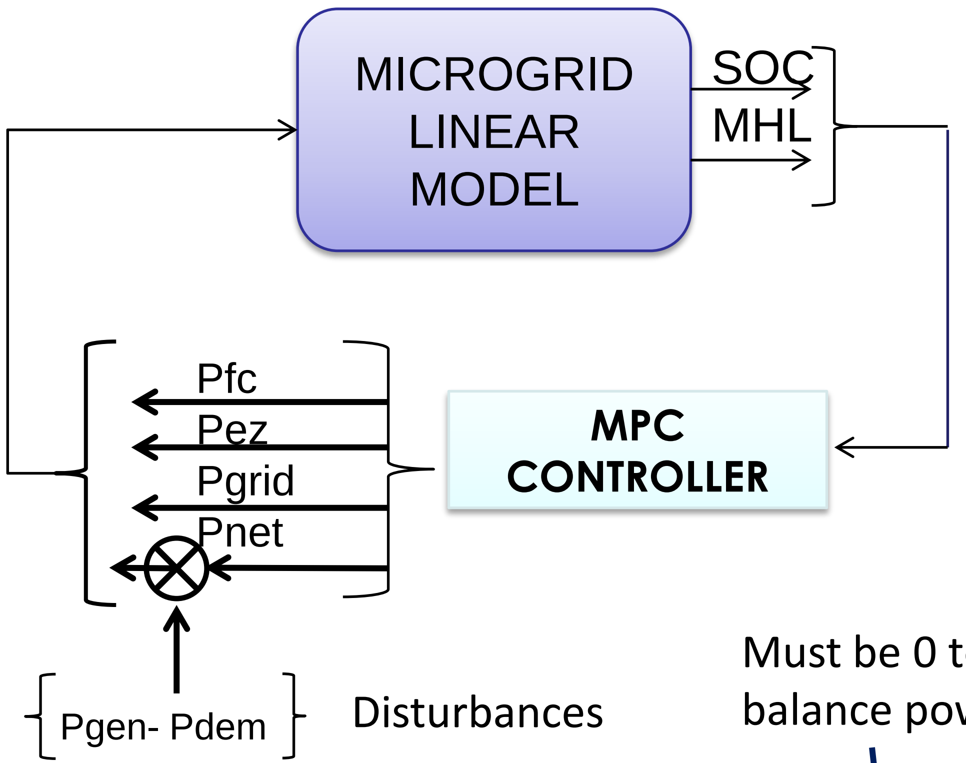
Since the generated (renewable) power does not fit the demanded load, the controller must compute the setpoints to the local controllers of FC, ELZ and grid **in order to balance the power**

Try to optimize some KPIs

Outline

1. Setting the Context
2. Microgrids
3. Experimental testing facility: HyLab
4. **Model Predictive Control for µGrid Power Management**
5. Extended control objectives
6. Concluding remarks

Control Scheme



Must be 0 to balance power

Power in the battery bank:

$$P_{bat} = P_{gen} - P_{dem} + P_{fc} - P_{ez} + P_{grid} + P_{net}$$

MPC Inputs (CVs):

Battery SOC

Metal Hydride Level

MPC:

Constraints

Cost function minimization

MPC outputs (MVs):

FC Power

ELZ Power

Grid Power

Net Power (slack)

Cost function

The behavior of the MPC is defined by the **cost function** (Objective)

3 weighted objectives

- ❑ Power balance
- ❑ Keep storage levels (H2 and electricity)
- ❑ Protect equipment from intensive use

The first group of weighting factors controls which equipment is used first

$$J = \sum_{k=1}^{Nu} \alpha_1 P_{fc(t+k)}^2 + \alpha_2 P_{ez(t+k)}^2 + \alpha_3 P_{grid(t+k)}^2 + \alpha_4 P_{net(t+k)}^2 +$$

$$+ \boxed{\beta_1} \Delta P_{fc(t+k)}^2 + \boxed{\beta_2} \Delta P_{ez(t+k)}^2 + \boxed{\beta_3} \Delta P_{grid(t+k)}^2 + \boxed{\beta_4} \Delta P_{net(t+k)}^2 +$$

$$+ \sum_{k=1}^{N} \gamma_1 \left(SOC_{(t+k)} - SOC_{ref} \right)^2 + \gamma_2 \left(MHL_{(t+k)} - MHL_{ref} \right)^2$$

The second group (β) is set to protect the equipment from intensive use

The group penalizes the error in reference tracking in order to give flexibility to the plant operation

Different set of parameters for different objectives (or operating conditions: sunny, cloudy, etc.)

Controller constraints and implementation

Constraints: power and power rates limits. Storage limits

$$P_{ez,min} = 100W \le Pez \le 900W = P_{ez,max}$$

$$P_{fc,min} = 100W \le Pfc \le 900W = P_{fc,\max}$$

$$P_{grid,min} = -2500kW \le Pgrid \le 6kW = P_{grid,\max}$$

$$\mathrm{P_{net,min}} = -2500\ \mathrm{W} \le \mathrm{Pnet} \le 6\ \mathrm{kW} = \mathrm{P_{net,max}}$$

$$\Delta \mathrm{P_{fc,min}} = -20\ \mathrm{W/s} \le \Delta \mathrm{Pfc} \le 20\ \mathrm{W/s} = \Delta \mathrm{P_{fc,max}}$$

$$\Delta \mathrm{P_{fc,min}} = -20\ \mathrm{W/s} \le \Delta \mathrm{Pfc} \le 20\ \mathrm{W/s} = \Delta \mathrm{P_{fc,max}}$$

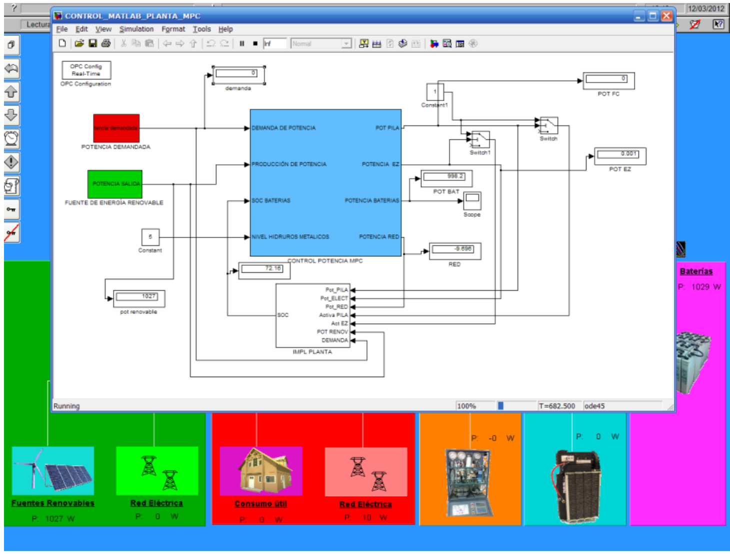
$$\Delta \mathrm{P_{net,min}} = -2500\ \mathrm{W/s} \le \Delta \mathrm{Pnet} \le 6000\ \mathrm{W/s} = \Delta \mathrm{P_{net,max}}$$

$$\Delta \mathrm{P_{grid,min}} = -1000\ \mathrm{W/s} \le \Delta \mathrm{Pgrid} \le 1000\ \mathrm{W/s} = \Delta \mathrm{P_{grid,max}}$$

$$\mathrm{SOC_{min}} = 40\ \% \le \mathrm{SOC} \le 75\ \% = \mathrm{SOC_{max}}$$

$$\mathrm{MHL_{min}} = 10\ \% \le \mathrm{MHL} \le 90\ \% = \mathrm{MHL_{max}}$$

Implementation



Matlab/Simulink→ PLC Real-Time control

Quadratic Programming

Controller design

Linear model for control purposes

$$x(t)=\begin{pmatrix} I^* \\ I_{chr} \\ I_{dis} \\ m_{Hnet} \end{pmatrix}(t);\quad u(t)=\begin{pmatrix} P_{fc} \\ P_{ez} \\ P_{grid} \\ P_{net} \end{pmatrix}(t)$$

$$y(t)=\begin{pmatrix} SOC \\ NHM \end{pmatrix}(t)$$

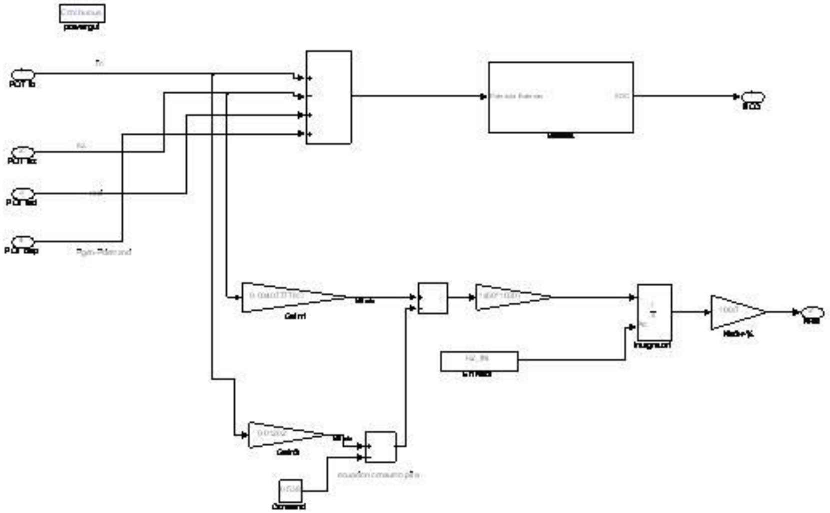
State Space model

Linearized

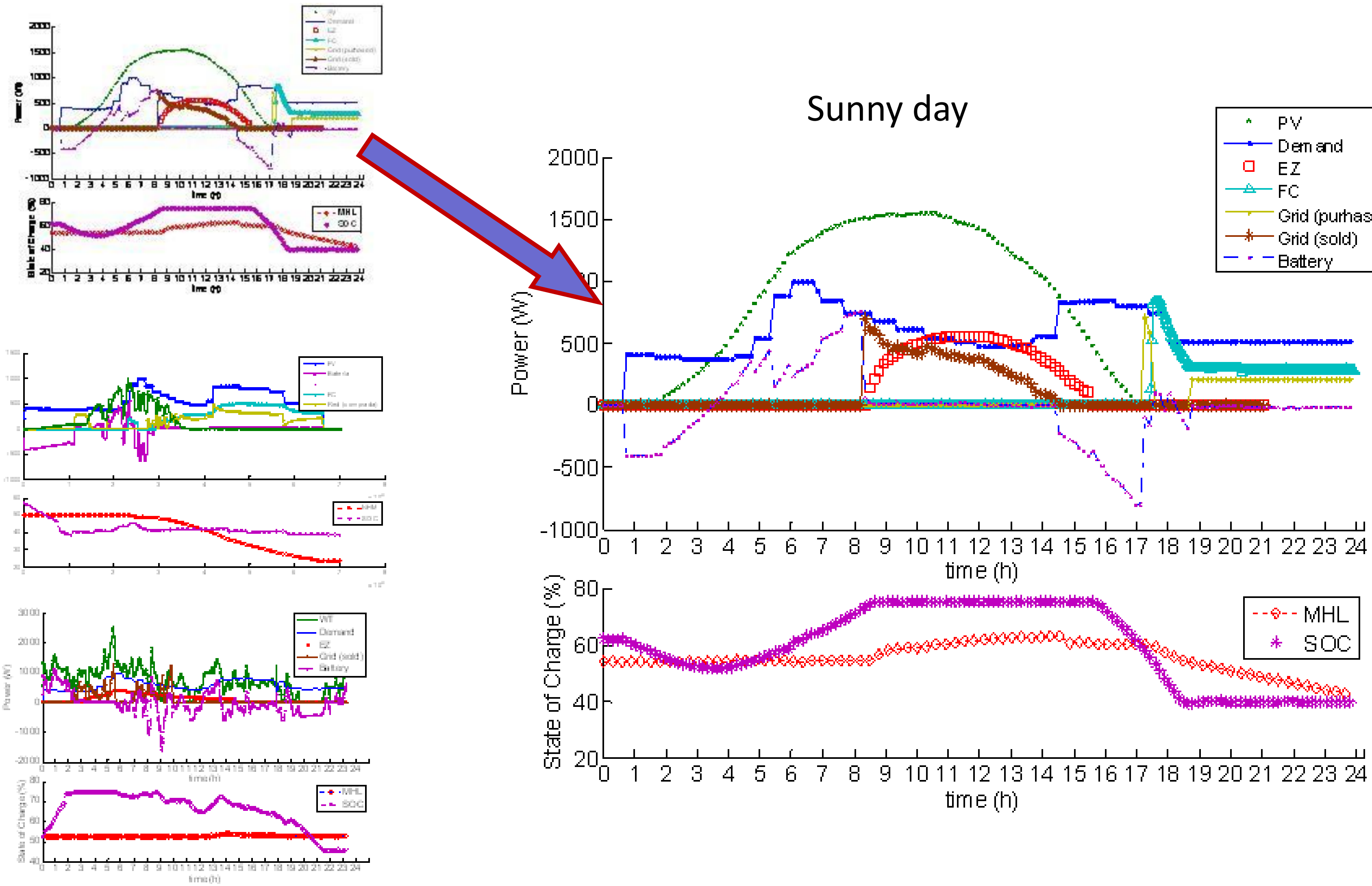
Uncertainties

$$A=\begin{pmatrix} -0.1000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.0868 \end{pmatrix}\quad ;\quad C=\begin{pmatrix} 0 & -0.0002 & 0 & 0 \\ 0 & 0 & 14.2857 & 0 \end{pmatrix}$$

$$B=\begin{pmatrix} -0.0208 & 0.0208 & -0.0208 & -0.0208 \\ -0.0208 & 0.0208 & -0.0208 & -0.0208 \\ -0.0000 & 0.0000 & 0 & 0 \\ 0.0001 & -0.0001 & 0.0001 & 0.0001 \end{pmatrix}\quad ;\quad D=\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$



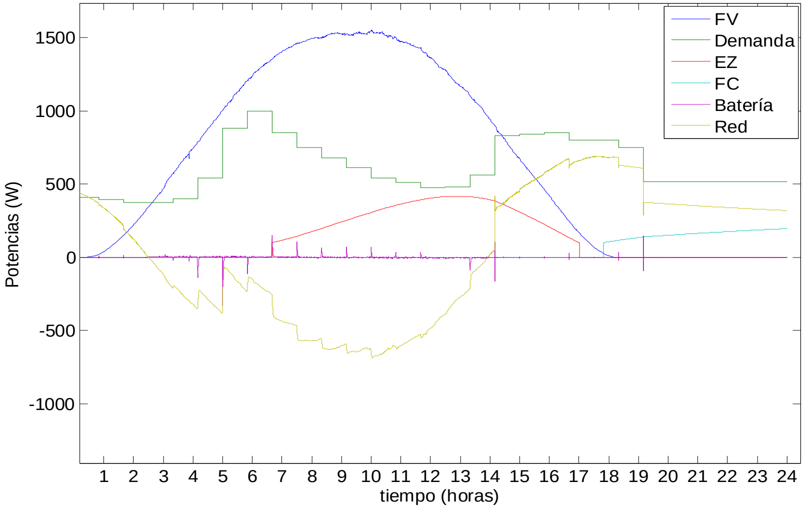
Experimental validation

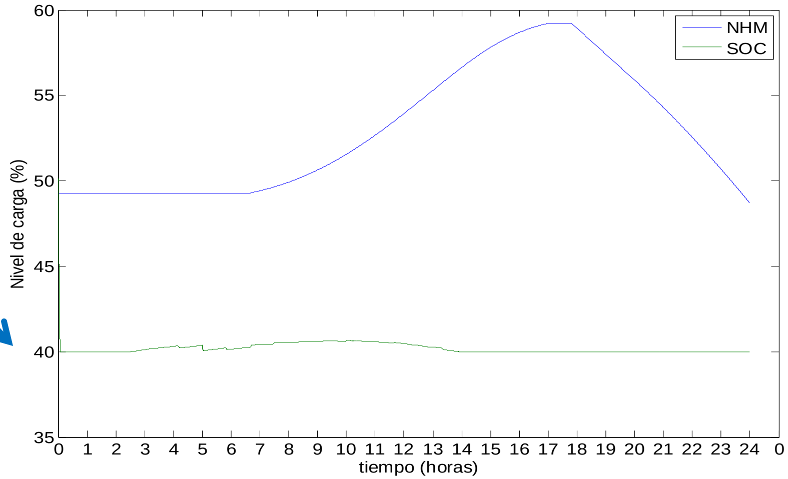


Weighting factors

The weights can be changed to fulfill other objectives or change priorities

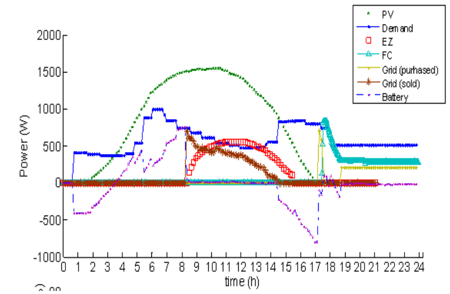
- SOC tracking
- Setpoint at 40%
- The power developed by other unit changes accordingly
- Solved by a centralized QP

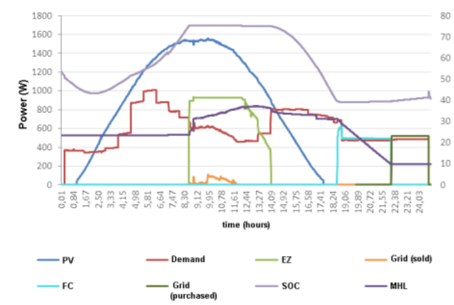




Comparison with traditional control

MPC	**Heuristic control**
Fewer start-up/shut down (25% fewer) START-STOP	Uncontrolled start-up/shut downs
Variable power →More energy stored (+5% MHL)	Variable power→ more energy but equipment damage (intensive use) Fixed power → low efficiency
Smooth power references η_{ez}, η_{fc}	Directly absorbs wind/solar fluctuations
Higher equipment efficiency (low currents) η_{path}	Low equipment efficiency (unless specific operating mode)
Lower operational cost (-30%) O&MC	**Higher cost**



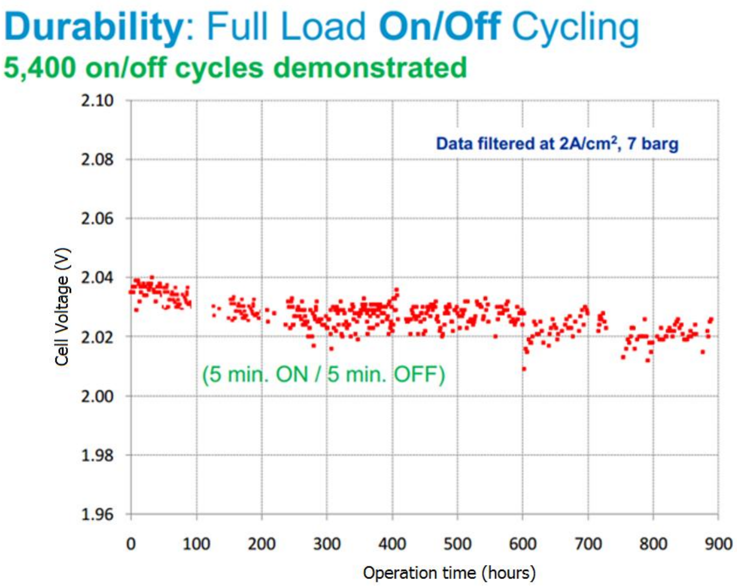


Outline

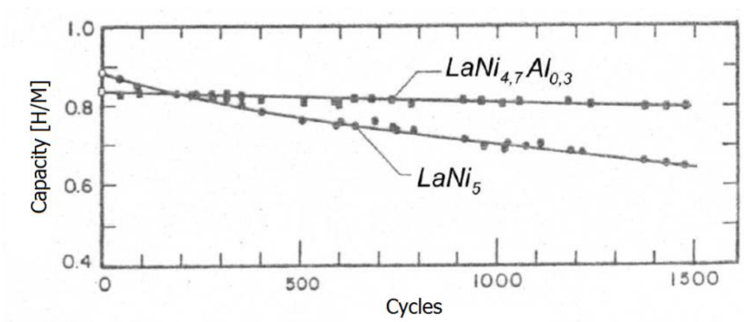
1. Setting the Context
2. Microgrids
3. Experimental testing facility: HyLab
4. Model Predictive Control for µGrid Power Management
5. **Extended control objectives**
6. Concluding remarks

Durability, O&M costs, optimal schedule

- Reformulate the MPC problem
- Durability is an important issue in ESS



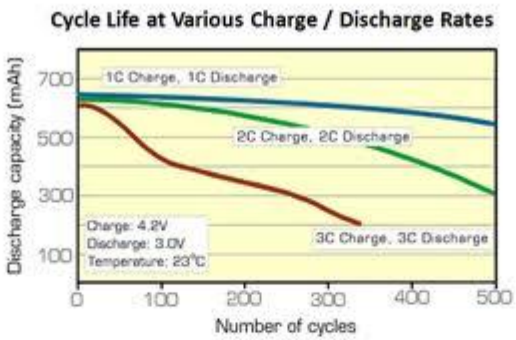
Metal hydride storage



Include degradation in the cost function

- Batteries: Manufacturers of batteries quantify the life of this ESS as a function of the number of the charge and discharge cycles.
- Ultracapacitor: similar.

$$
\begin{aligned}
J_{bat} = \sum_{h_i=1}^{24} \Big(& \frac{\mathrm{CC}_{bat}}{2 \cdot Cycles_{bat}} P_{bat,ch}(h_i) \cdot T_s \cdot \eta_{bat,ch} \\
& + \mathrm{Cost}_{degr,ch} \cdot P^2_{bat,ch}(h_i) \\
& + \frac{\mathrm{CC}_{bat}}{2 \cdot \mathrm{Cycles}_{bat}} \frac{P_{bat,dis}(h_i) \cdot T_s}{\eta_{dis,bat}} \\
& + \mathrm{Cost}_{degr,dis} \cdot P^2_{bat,dis}(h_i) \Big)
\end{aligned}
$$



.

Hydrogen

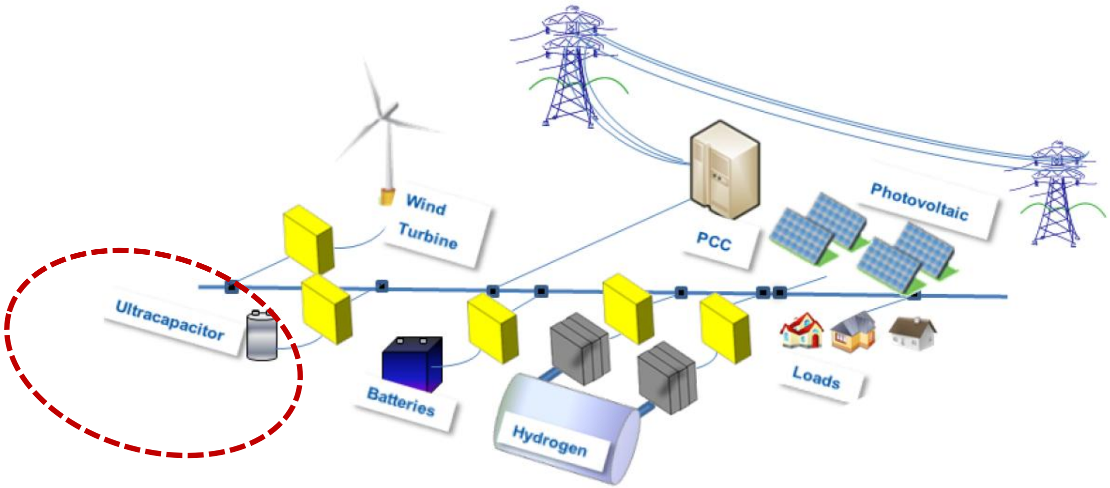
- Manufacturers of electrolyzers and fuel cells give the life expression of this kind of systems as a function of the number of working life. **Start up and shut down cycles** and **fluctuating load** conditions can affect seriously to these devices.
- Logical variables included: on/off states (δ) startup and shutdown states (σ)

$$\sigma_j^{on}(t_k) = max(\delta_j(t_k) - \delta_j(t_{k-1}), 0)|_{j=elz,fc}$$
$$\sigma_j^{off}(t_k) = max(\delta_j(t_{k-1}) - \delta_j(t_k), 0)|_{j=elz,fc}$$

$$J_{elz}(h_i) = \left(\frac{\mathrm{CC}_{elz}}{\mathrm{Hours}_{elz}} + \mathrm{Cost}_{o\&m,elz}\right)\delta_{elz}(h_i) +$$
$$\mathrm{Cost}_{startup,elz} \cdot \sigma_{elz}^{on}(h_i) + \mathrm{Cost}_{shutdown,elz} \cdot \sigma_{elz}^{off}(h_i)$$
$$+ \mathrm{Cost}_{degr,elz} \cdot \vartheta_{elz}^2(h_i)$$
$$J_{fc}(h_i) = \left(\frac{\mathrm{CC}_{fc}}{\mathrm{Hours}_{fc}} + \mathrm{Cost}_{o\&m,fc}\right)\delta_{fc}(h_i) +$$
$$\mathrm{Cost}_{startup,fc} \cdot \sigma_{fc}^{on}(h_i) + \mathrm{Cost}_{shutdown,fc} \cdot \sigma_{fc}^{off}(h_i)$$
$$+ \mathrm{Cost}_{degr,fc} \cdot \vartheta_{fc}^2(h_i)$$

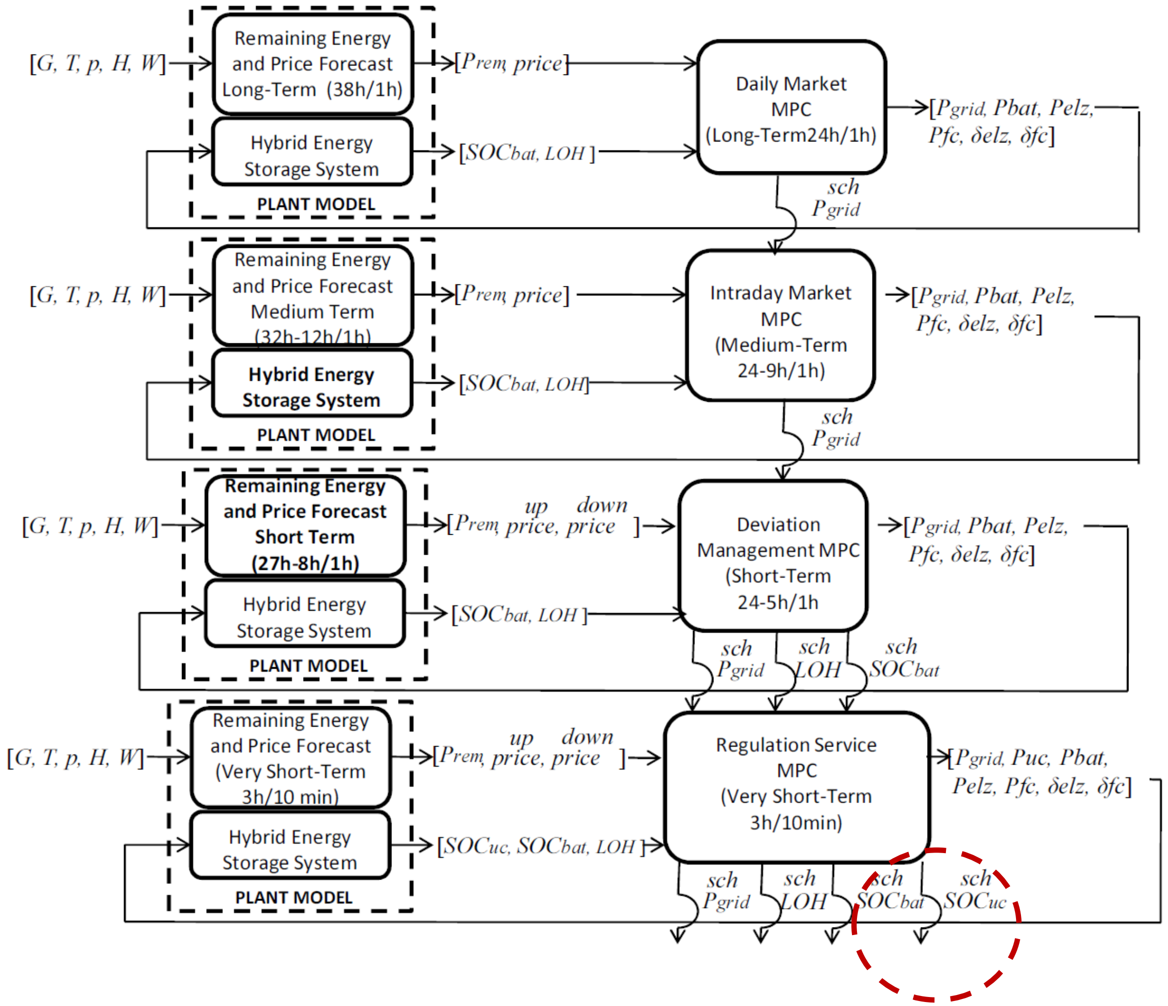
Optimal schedule

- Microgrid at CNH2 (not at full operation yet)
- **Optimal scheduling policy** linked to the time-varying price of energy. The results show an optimal behaviour of the microgrid whose **non-dispatchable generation is converted into dispatchable using the ESS.**
- The microgrid operator can act as a conventional power plant (gas, coal, etc.) and participate in the auction process



Participation in the markets

- The horizon schedule determines also the most appropriate ESS technology to be used.
- Durability included
- As well as the deviation schedule penalty with respect to the main grid
- Four level-cascaded MPC
- Forecast of available energy and electricity prices is included in the controller



MPC using MLD: MIQP

Logical constraints (example)

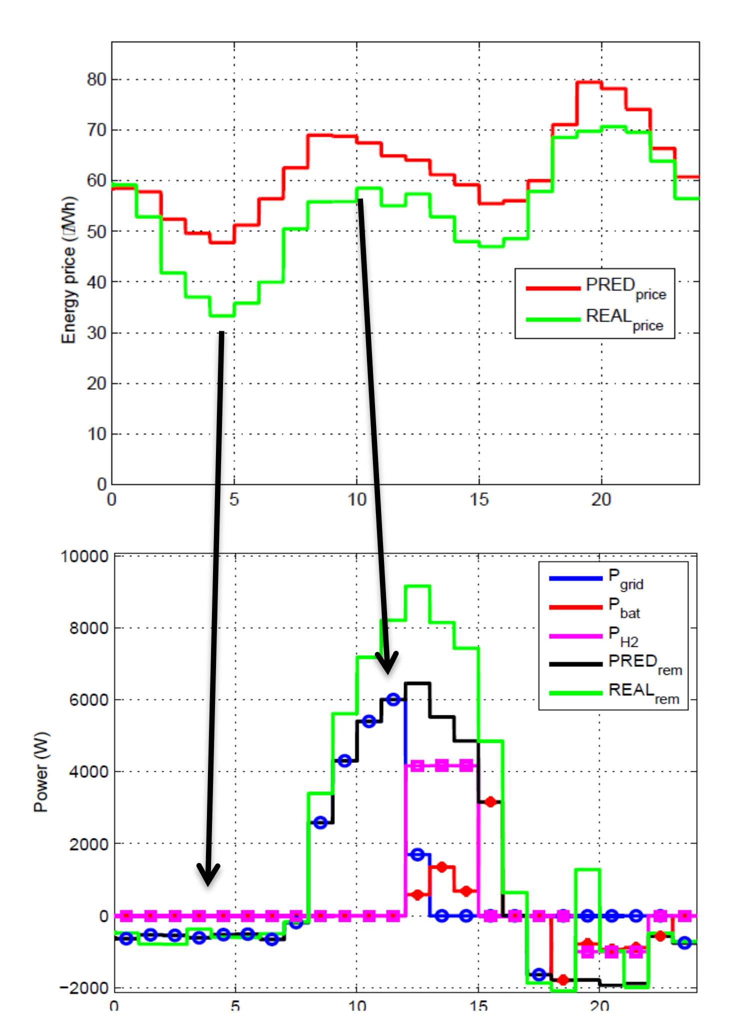
$$0 \le \delta_{sale}(t_k) + \delta_{pur}(t_k) \le 1$$
$$P_{sale}(t_k) - P_{pur}(t_k) = P_{grid}(t_k)$$
$$P_{grid}^{min}\delta_{sale}(t_k) \le P_{sale}(t_k) \le P_{grid}^{max}\delta_{sale}(t_k)$$
$$P_{grid}(t_k) - P_{grid}^{max}(1-\delta_{sale}(t_k)) \le P_{sale}(t_k)$$
$$P_{sale}(t_k) \le P_{grid}(t_k) - P_{grid}^{min}(1-\delta_{sale}(t_k))$$
$$0 \le \delta_{ch,i}(t_k) + \delta_{dis,i}(t_k) \le 1|_{i=uc,bat}$$
$$P_{ch,i}(t_k) - P_{dis,i}(t_k) = P_i(t_k)|_{i=uc,bat}$$
$$P_i^{min}\delta_{ch,i}(t_k) \le P_{ch,i}(t_k) \le P_i^{max}\delta_{ch,i}(t_k)|_{i=uc,bat}$$
$$P_i(t_k) - P_i^{max}(1-\delta_{ch,i}(t_k)) \le P_{ch,i}(t_k)|_{i=uc,bat}$$
$$P_{ch,i}(t_k) \le P_i(t_k) - P_i^{min}(1-\delta_{ch,i}(t_k))|_{i=uc,bat}$$
$$0 \le \delta_{elz}(t_k) + \delta_{fc}(t_k) \le 1$$
$$-\delta_i(t_k) + \sigma_i^{on}(t_k) \le 0|_{i=elz,fc}$$
$$-(1-\delta_i(t_k-1)) + \sigma_i^{on}(t_k) \le 0|_{i=elz,fc}$$
$$\delta_i(t_k) + (1-\delta_i(t_k-1)) - \sigma_i^{on}(t_k) \le 1|_{i=elz,fc}$$
$$-\delta_i(t_k-1) + \sigma_i^{off}(t_k) \le 0|_{i=elz,fc}$$
$$-(1-\delta_i(t_k)) + \sigma_i^{off}(t_k) \le 0|_{i=elz,fc}$$
$$\delta_i(t_k-1) + (1-\delta_i(t_k)) - \sigma_i^{off}(t_k) \le 1|_{i=elz,fc}$$

$$P_i^{min}\delta_i(t_k) \le z_i(t_k) \le P_i^{max}\delta_i(t_k)|_{up,down}^{i=pur,sale,elz,fc}$$
$$P_i(t_k) - P_i^{max}(1-\delta_i(t_k)) \le z_i(t_k)|_{up,down}^{i=pur,sale,elz,fc}$$
$$z_i(t_k) \le P_i(t_k) - P_i^{min}(1-\delta(t_k))|_{up,down}^{i=pur,sale,elz,fc}$$
$$-\delta_i(t_k) + \chi_i(t_k) \le 0|_{i=elz,fc}$$
$$-\delta_i(t_{k-1}) + \chi_i(t_k) \le 0|_{i=elz,fc}$$
$$\delta_i(t_k) + \delta_i(t_{k-1}) - \chi_i(t_k) \le 1|_{i=elz,fc}$$
$$\Delta z_i^{min}(\chi_i(t_k)) \le \vartheta_i(t_k) \le \Delta z_i^{max}(\chi_i(t_k))|_{i=elz,fc}$$
$$\Delta z_i(t_k) - \Delta z_i^{max}(1-\chi_i(t_k)) \le \vartheta_i(t_k)|_{i=elz,fc}$$
$$\vartheta_i(t_k) \le \Delta z_i(t_k) - \Delta z_i^{min}(1-\chi_i(t_k))|_{i=elz,fc}$$
$$(P_{grid}(h_i,m_j) - P_{grid}^{sch}(h_i)) \le P_{grid}^{max} - P_{grid}^{max}\cdot\delta_{down}(t_k)$$
$$(P_{grid}(h_i,m_j) - P_{grid}^{sch}(h_i)) \ge \epsilon + (-\epsilon)\cdot\delta_{down}(t_k)$$
$$-(P_{grid}(h_i,m_j) - P_{grid}^{sch}(h_i)) \le P_{grid}^{max} - P_{grid}^{max}\cdot\delta_{up}(t_k)$$
$$-(P_{grid}(h_i,m_j) - P_{grid}^{sch}(h_i)) \ge \epsilon + (-\epsilon)\cdot\delta_{up}(t_k)$$
$$\varphi_i - \sum_{s_j=0}^{s_j=\varphi_i}(\lambda_i(t_k-s_j)) \le M - M\delta_i|_{i=elz,fc}$$
$$\varphi_i - \sum_{s_j=0}^{s_j=\varphi_i}(\lambda_i(t_k-s_j)) \ge \epsilon + (m-\epsilon)\delta_i|_{i=elz,fc}$$

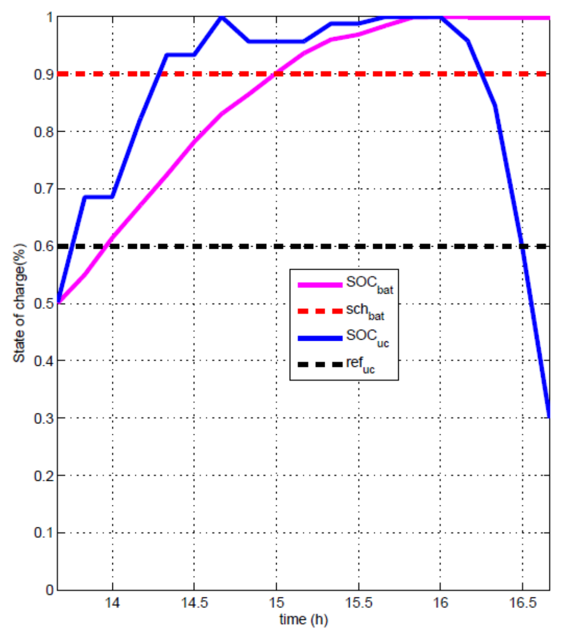
In order to capture both **continuous/discrete dynamics** and switching between different **operating conditions,** the plant is modelled with the framework of Mixed Logic Dynamic (**MLD**). The problem is solved using MIQP (Mixed Integer Quadratic Programming).

Some results

- Daily market forecast
- Daily market controller schedule
- Purchase to the grid when price low. Sell when price high
- Constants setpoint to ELZ y FC to minimize degradation
- This will be recomputed.



(zoom)



Outline

1. Setting the Context
2. Microgrids
3. Experimental testing facility: HyLab
4. Model Predictive Control for µGrid Power Management
5. Extended control objectives
6. **Concluding remarks**

Concluding remarks

- A remarkable lack of applications of advanced Control Strategies → Experimental validation needed
- KPI to assess control methodologies
- MPC showed outstanding features in power management: smooth operation, lower cost, higher lifetime
- Changes in tuning parameters- logical constraints can help fulfil different objectives
- Durability and O&M Cost can be included as control objectives
- Non-dispatchable RES can be converted into dispatchable using the ESS and advanced control. Optimal economic schedule can be achieved
- Open issues for research

Open lines for research

- AC microgrids
- Dispatchable microgrids in the pool market
- Contribution of (up-to-now) non-dispatchable RES to frequency regulation (virtual inertia)
- Grids of microgrids (SoS)
- Microgrids for EVs: Distributed storage (electricity and H2). V2G
- New paradigm of power network

Power Management in Renewable Energy Microgrids with Hybrid Storage

Carlos Bordons

University of Seville, Spain

Thanks to Luis Valverde and Félix García