Control of Fuel Cells

Controle de células de combustível

Carlos Bordons

Fuel Cell Control Lab

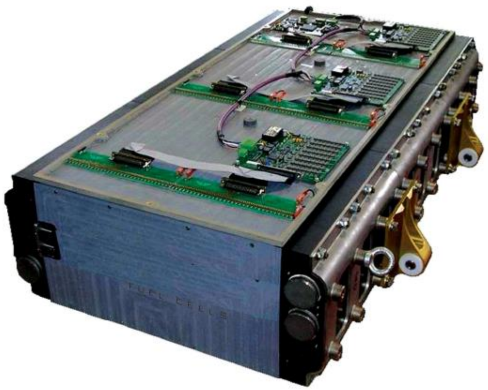
Systems Engineering and Automation Department / ENGREEN
University of Seville, Spain

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
AGENCIA ESTATAL DE INVESTIGACIÓN

Abstract & Outline

This talk presents an overview of the fundamentals of **automatic control of fuel-cell based systems**, focusing on the application of Model Predictive Control (**MPC**) as an advanced control technique suited to this kind of systems. Including some **experimental results**

1. Introduction
2. Fuel Cell Control
3. Mobile applications
4. Integration in Microgrids
5. Concluding remarks



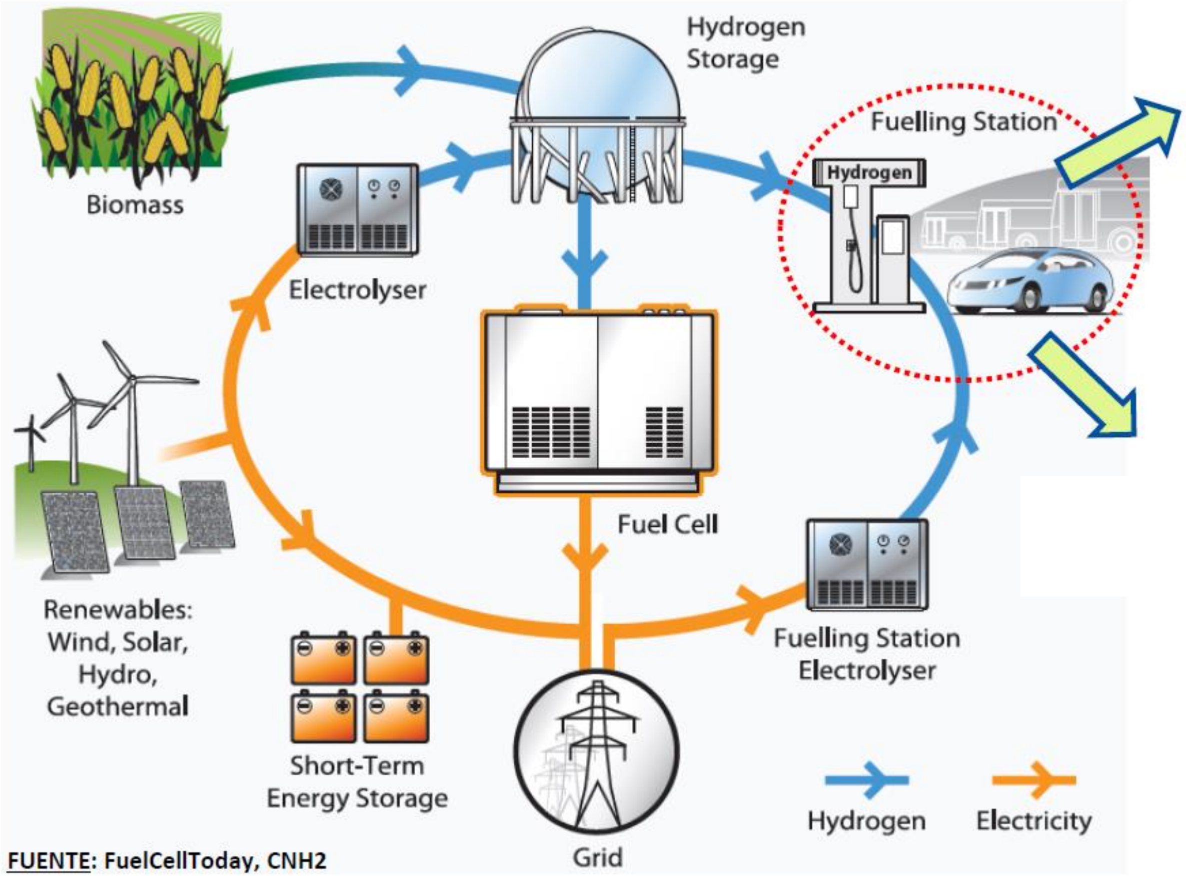
1. Introduction

- Fuel cells have experienced a considerable development in the last years: good candidates for clean electricity generation both in stationary and automotive applications.

- Fed with hydrogen. Water and heat are by-products

- Many open issues related to fields such as materials, electrochemistry, manufacturing or maintenance, automatic control being one of the most important ones

Green Hydrogen

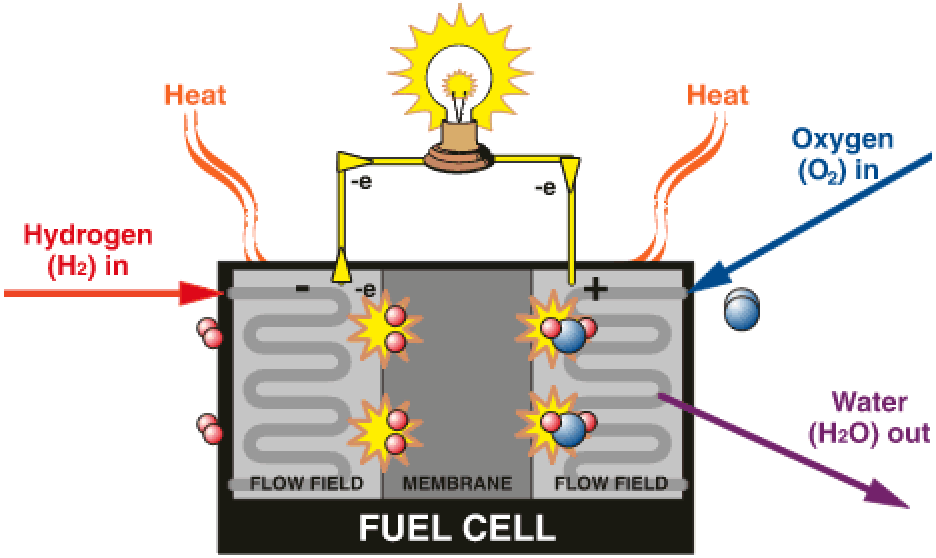


FUENTE: FuelCellToday, CNH2

FCEV

Fuel cells

- Electrochemical systems that generate electric power from fuel. **Direct conversion**, no thermodynamic cycle (no Carnot limit)
- Several kinds of FC: SO (Solid Oxide), MC (Molten Carbonate), PA (Phosphoric Acid), **PEM** (Polymer Electrolite Membrane), etc.
- This talk is focused on PEM fuel cells. See* for modeling and control of SOFCs



PEM: automotive industry, handheld electronic devices or stationary power generation

Low temperature, fast response, high power density…

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*Huang, D., Yutong, Q. and Murshed, M. *Solid oxide fuel cell: Perspective of dynamic modeling and control.* Journal of Process Control 21 (2011) 1426-1437.

Outline

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2. **Fuel Cell Control**
3. Mobile applications
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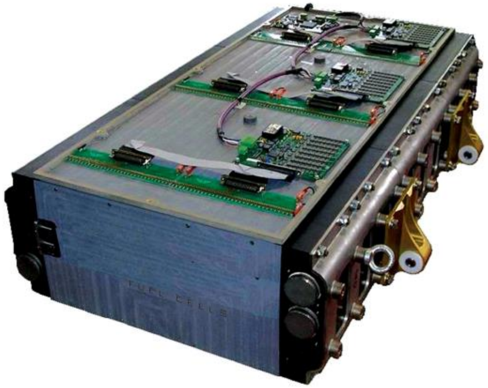


2. Control of Fuel cell systems

Design of control systems for fuel cell based systems:

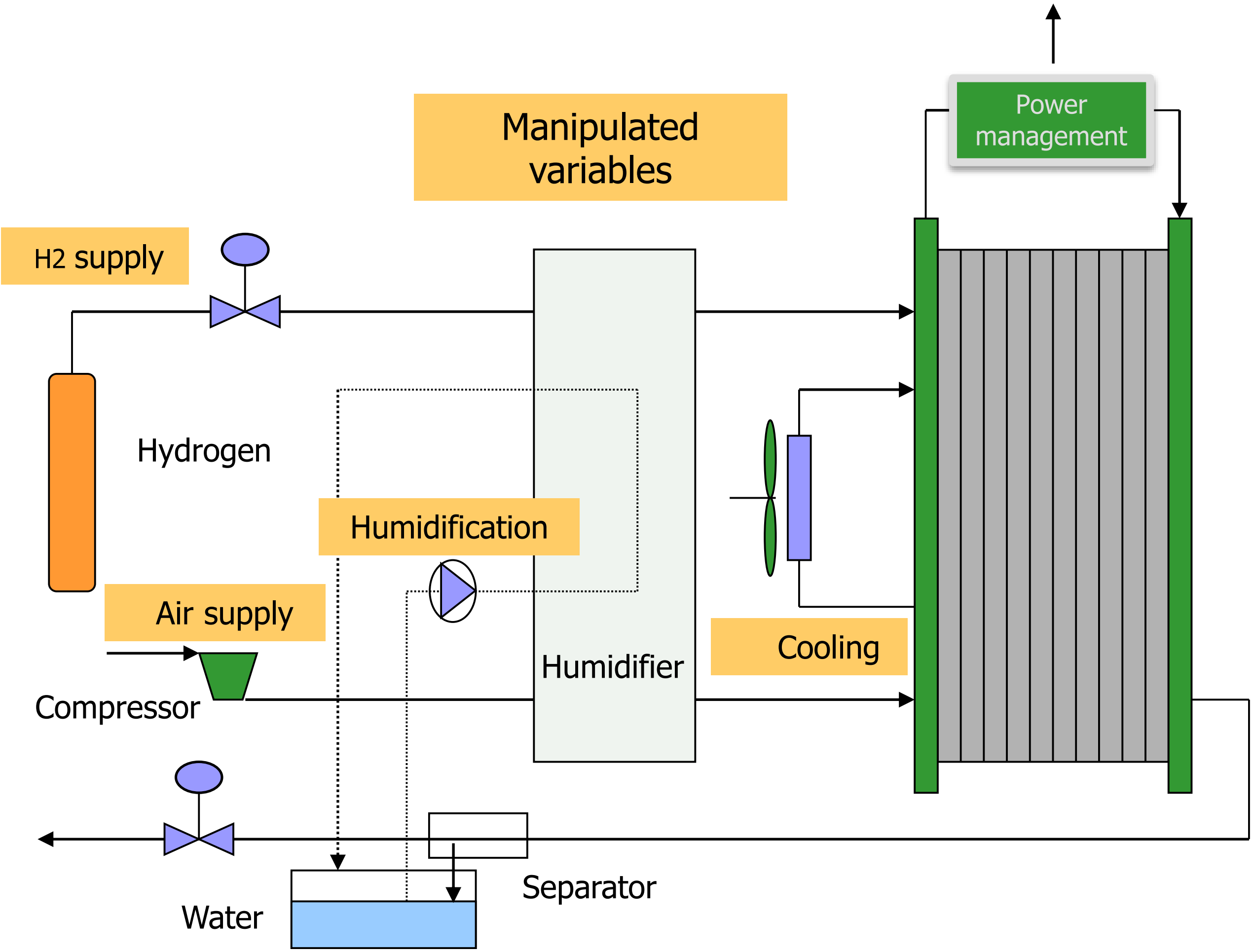
- **Air supply** control (Stefanopoulou, Thountong, Arce, Bao, Riera, Chang, Danzer, Sun, Kunusch, etc.)
- **Temperature** control and **water management** (*Karnik, Chen, Peng, Ahn, Choe, Arce, Pereira, Stefanopoulou, etc.*)
- **Hybrid** fuel cell systems *(Thountong, Chandler, Rodatz, Choi, Turpin, Del Real, Pera, etc.*)
- **Automotive** applications *(Rodatz, Guzzella, Sciarreta, Stefanopoulou, Suh, Arce, Serra, etc.*)
- Control of **electronic converters** for FC (*Rodriguez, Geyer, Franquelo, Leon, Kouro, etc.*)
- **Integration** in Renewable Energy Systems/**Microgrids** (*García-Torres, Wang, Guerrero, Ulsberg,*)

+17,000 papers on the subject in the last ten years (Google Scholar)

Control of PEM Fuel Cells

Low-level control,
main control loops: fuel/air feeding, humidity and temperature

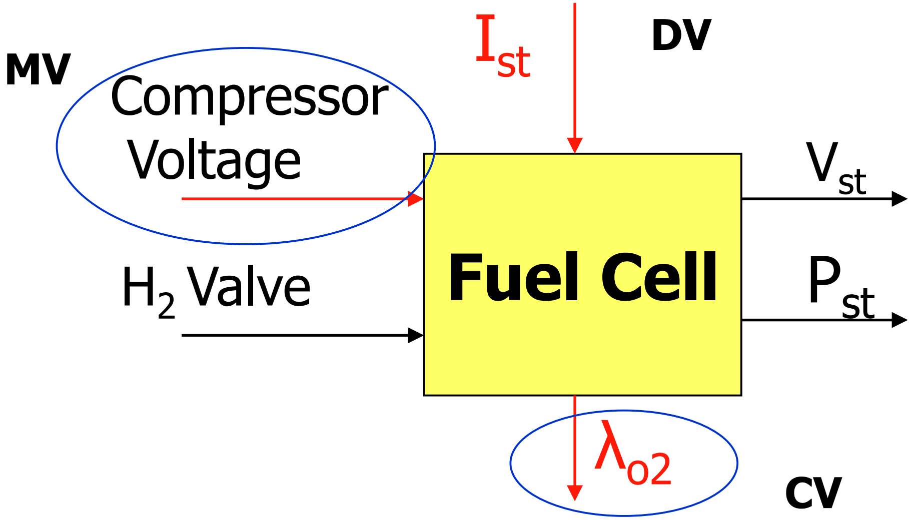
High-level control, whole system, integrating the electrical conditioning, storage. BOP (Balance of Plant)



Airflow control

- Objective: supply in an effective way the necessary flow of reactants, providing a good transient response and minimizing auxiliary consumption:
  - Manipulate the compressor to track a desired λ_{O2}
  - Setpoint and control strategy selection

- Important: keep the **oxygen excess ratio**. *Starvation* danger
- Control the flow of oxygen



$$\lambda_{O2} = \frac{W_{O2,in}}{W_{O2,react}}$$

Optimal value for λ_{O2}

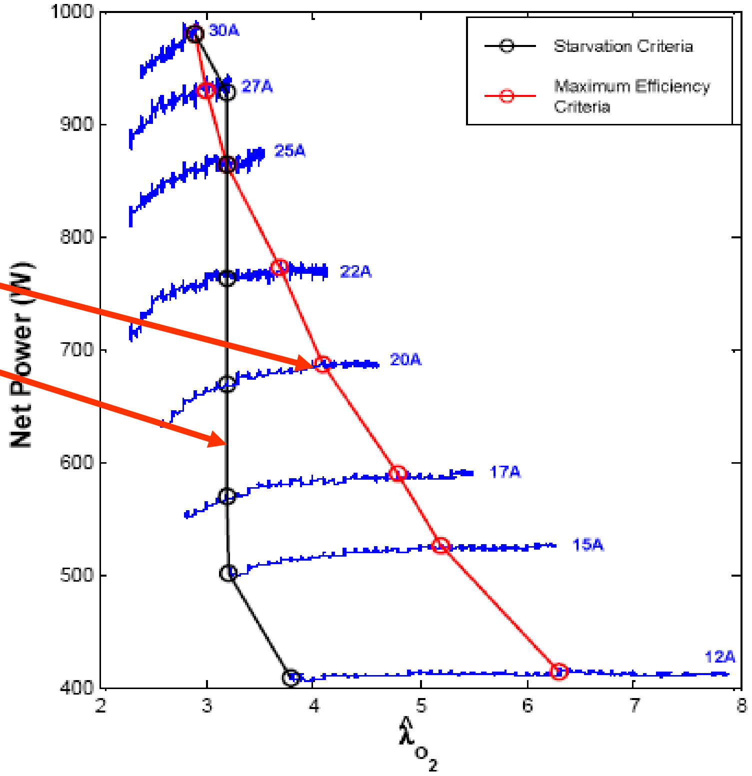
Control criterium: maximum efficiency

Setpoint choice depending on load

Existing controllers: constant excess ratio (constant values depending on the FC size)

Net power: $P_{net} = P_{FC} - P_{aux}$

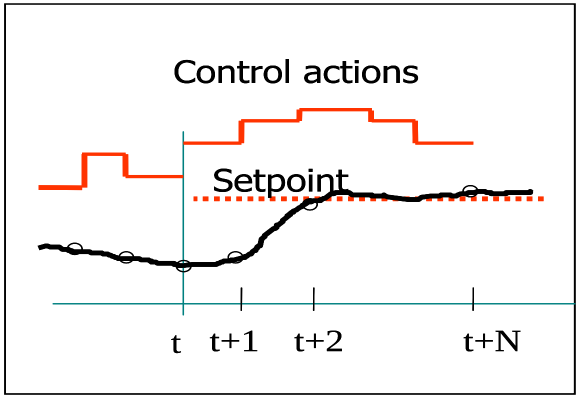
Higher flow implies more power but also more losses. ***Trade-off***



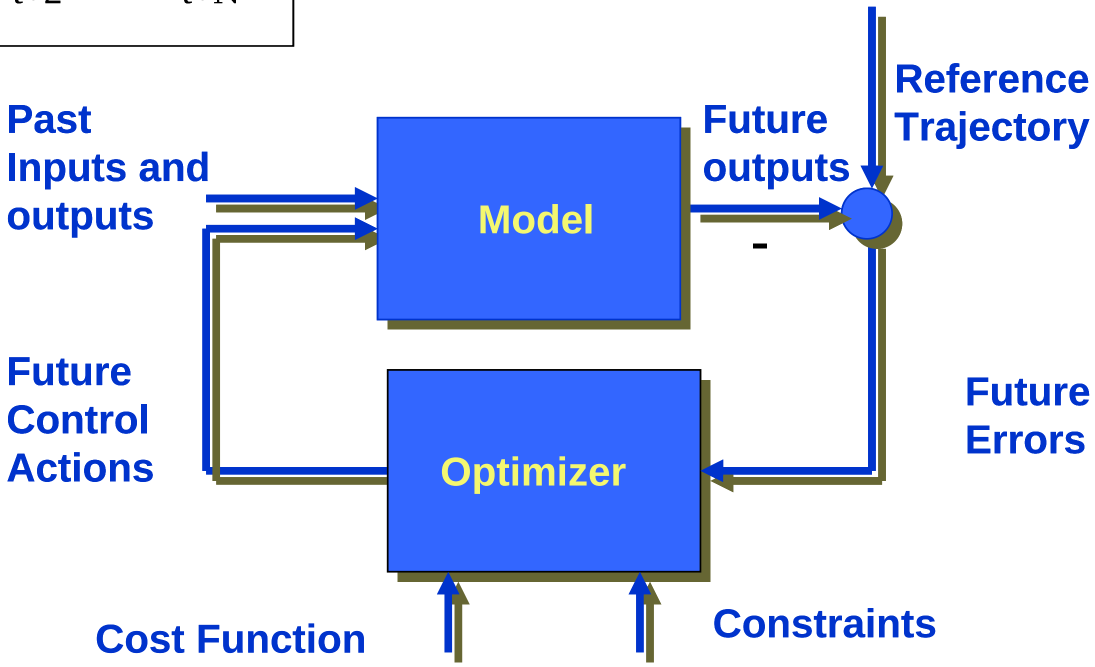
Real-Time Implementation of a Constrained MPC for Efficient Airflow Control in a PEM Fuel Cell. Alicia Arce, Alejandro J. del Real, Carlos Bordons and Daniel R. Ramírez, *IEEE Transactions on Industrial Electronics* (2010)

Operational optimization and real-time control of fuel-cell systems . J. Hasikos, H. Sarimveis ∗, P.L. Zervas, N.C. Markatos. Journal of Power Sources 193 (2009) 258–268

Control strategy: Model Predictive Control



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



Past Inputs and outputs

Model

Future outputs

Reference Trajectory

-

Future Control Actions

Optimizer

Future Errors

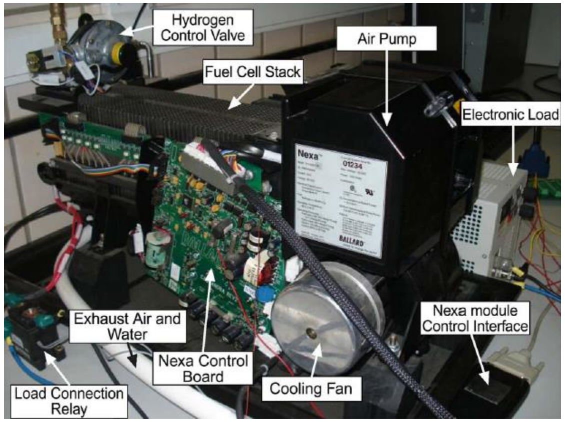
Cost Function

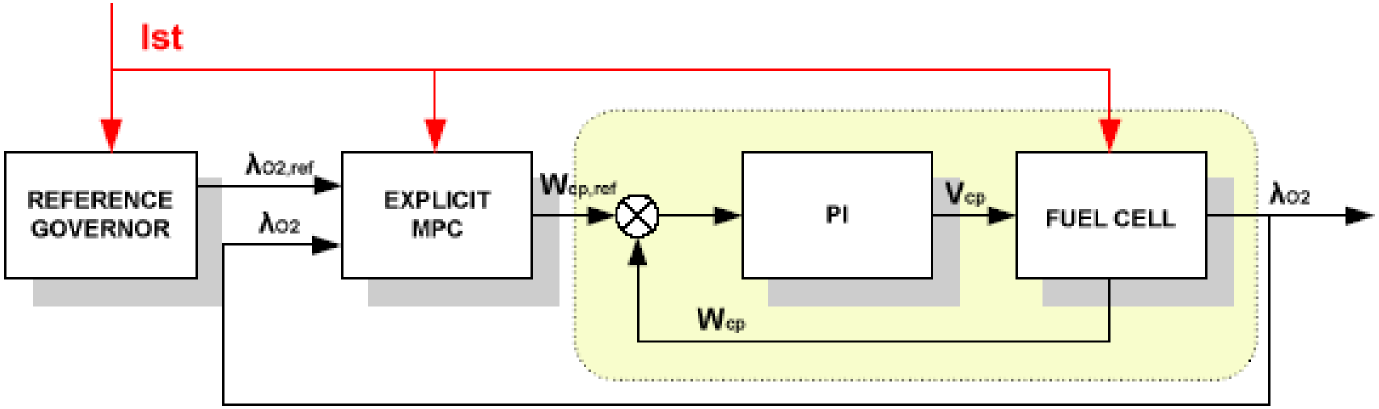
Constraints

MPC for airflow control

- Airflow control for maximum efficiency
- Satisfying oxygen starvation avoidance
- Based on a constrained explicit MPC
- Suitable for real-time implementation (low computational demands)
- Master-Slave
- Reference governor for λ_{O2} choice

Ballard Nexa, 1200 W





Constrained Predictive Controller

$$J = \sum_{j=N_1}^{j=N_2} \left[y(t+d|t) - w(t+d|t)\right]^2 + \sum_{j=1}^{j=N_u} \lambda(j) \cdot \left[\Delta u(t+j-1)\right]^2$$

Subject to:

$$V_{min} \leq V_{cp} \leq V_{max}$$

Input constraint (physical limits)

$$\lambda_{O_2,min} \leq \lambda_{O_2} \leq \lambda_{O_2,max}$$

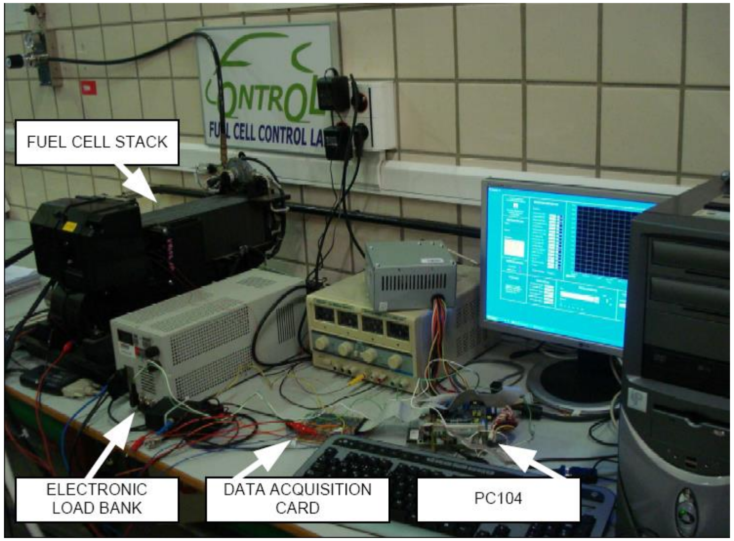
Desired output constraint

- Implicit **feed-forward effect.** Demanded current is the disturbance (measurable):

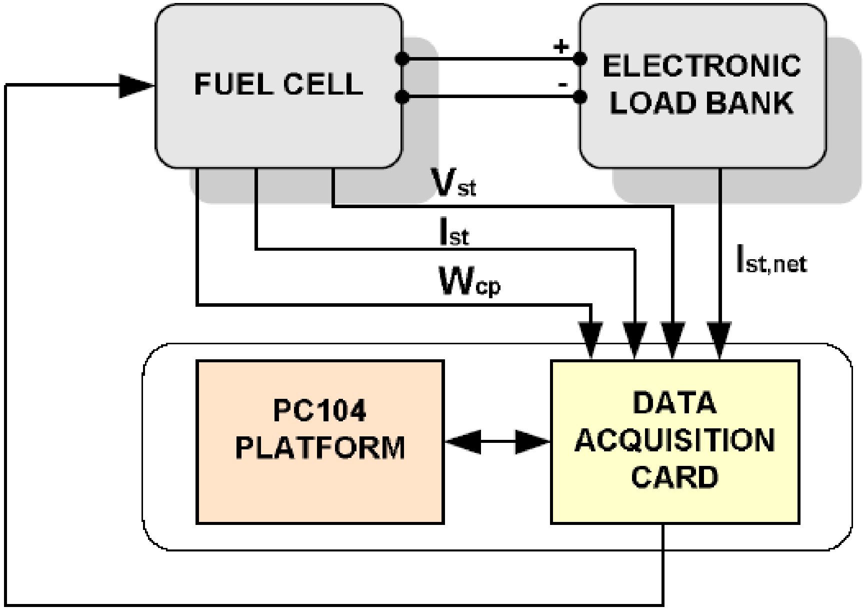
$$J = (G \cdot u + H \enclose{circle}{\cdot v} + f - w)^T \cdot (G \cdot u + H \cdot v + f - w) + \lambda \cdot u^T \cdot u$$

- Sampling time according to system dynamics: 10 milliseconds

Experimental setup

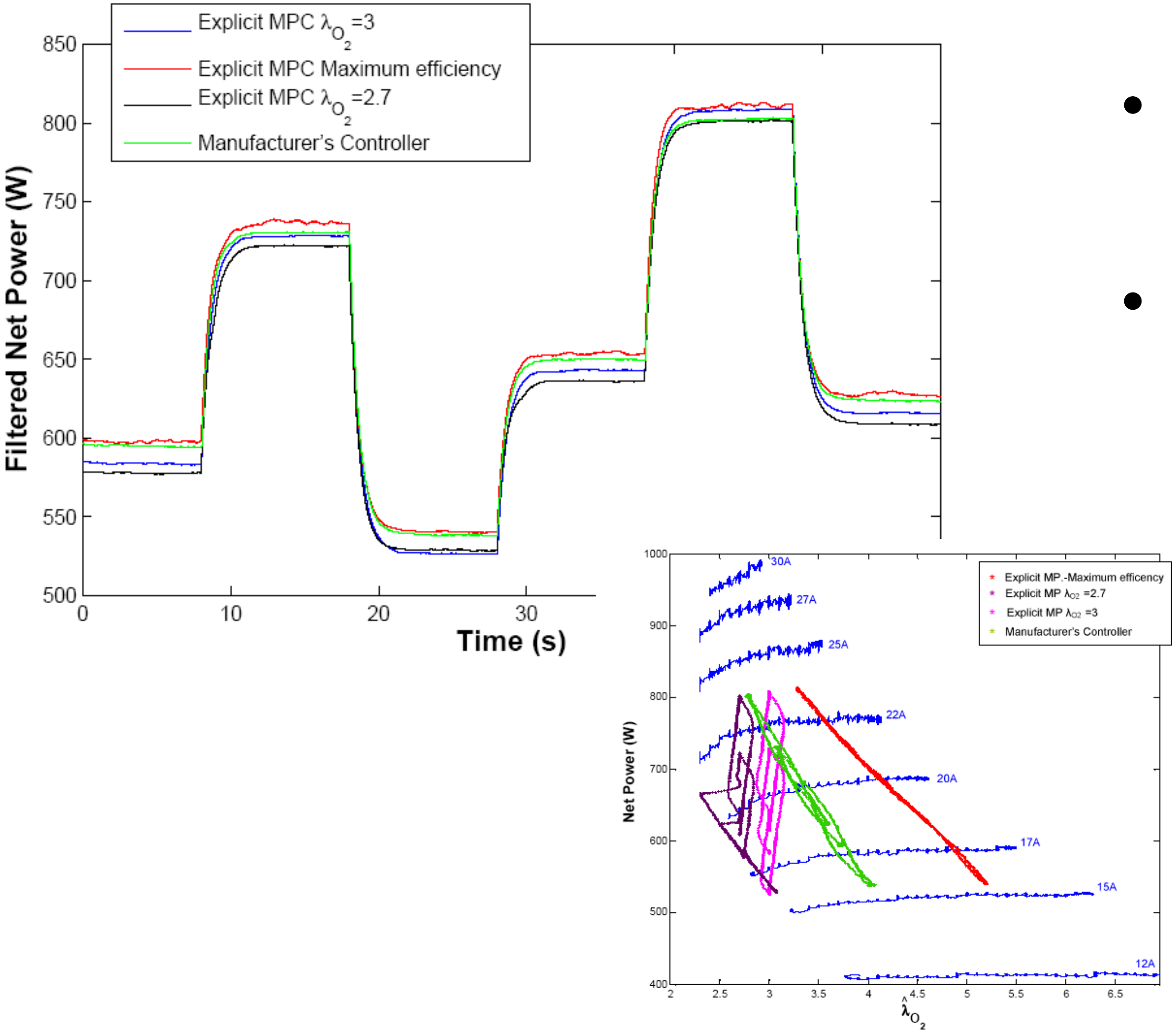


Nexa built-in controller **overriden**



- Explicit MPC (221 regions)
- Horizons: 4 (small)
- Embedded controller PC-104
- Average exec time: 0.245 ms

Results



- Allows performance improvements of 5%.
- Improved transient responses compared to those of the manufacturer's control law.

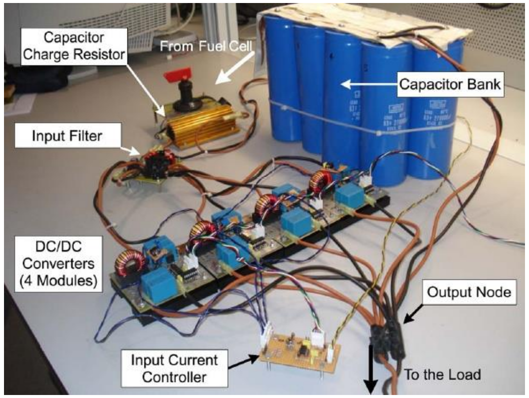
Need of buffer storage

- Model Predictive Controllers can provide good **transient behavior** to setpoint changes and **optimize efficiency**.

However:

- The fuel cell system shows a much faster transient behavior with respect to **changes in the stack current** than to changes in the **compressor motor voltage**.
- These different dynamics make it physically impossible to avoid the characteristic **peaks** in the oxygen excess ratio after abrupt changes in the load current
- A reduction of these **peaks** could be achieved by using additional batteries or ultracapacitors supplying the demanded peaks in the stack current.

The use of storage (capacitor bank) allows ***smooth transients,*** which **increase FC lifetime** and prevents from starvation

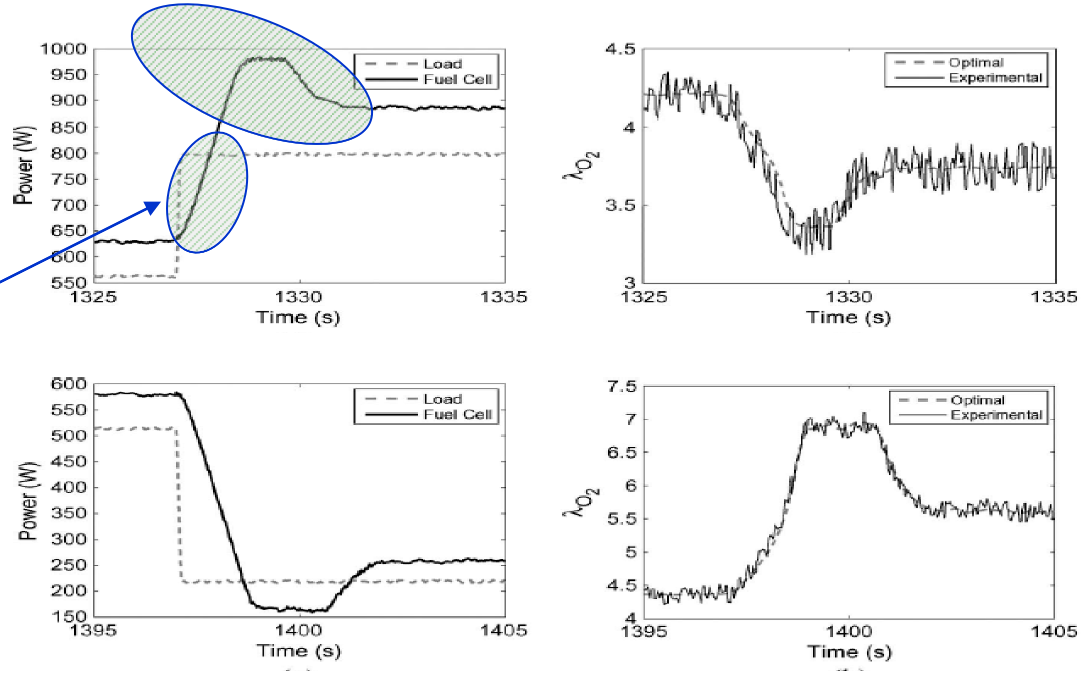


Minimum Fuel Consumption Strategy for PEM Fuel Cells. C. Ramos-Paja, C. Bordons, A. Romero, R. Giral and L. Martínez-Salamero. IEEE Transactions on Industrial Electronics, vol. 56, No 3, 2009

Response. Power transients

Energy excess supplied by the FC to restore the capacitors energy and bus voltage

Energy supplied by the capacitors



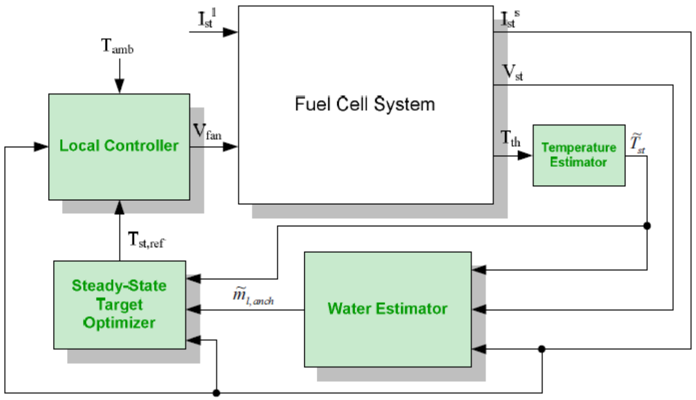
In power transients:

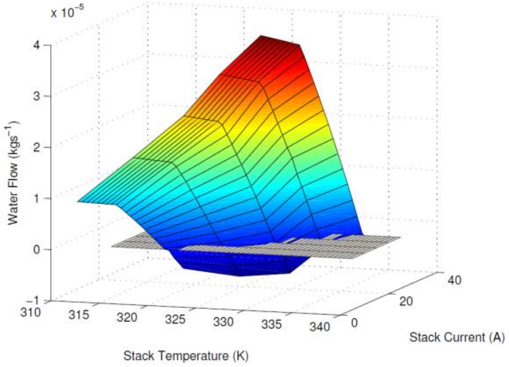
- The capacitor initially supplies the power to the load
- Then the FC setpoint is moved to the new steady state (with a ***limited power slope*** and ***optimum oxygen excess ratio***)

Degradation and water management

It is observed that the liquid **water content** inside the anode channel is strongly related to temporal and permanent **degradation** processes such as flooding and corrosion phenomena.

- Therefore **water management** is important for proper operation
- Water depends on temperature: **temperature controller** needed (indirect control). **Slower dynamics** than air supply
- A steady-state target optimizer which calculates the temperature setpoint profiles that minimize the stack degradation



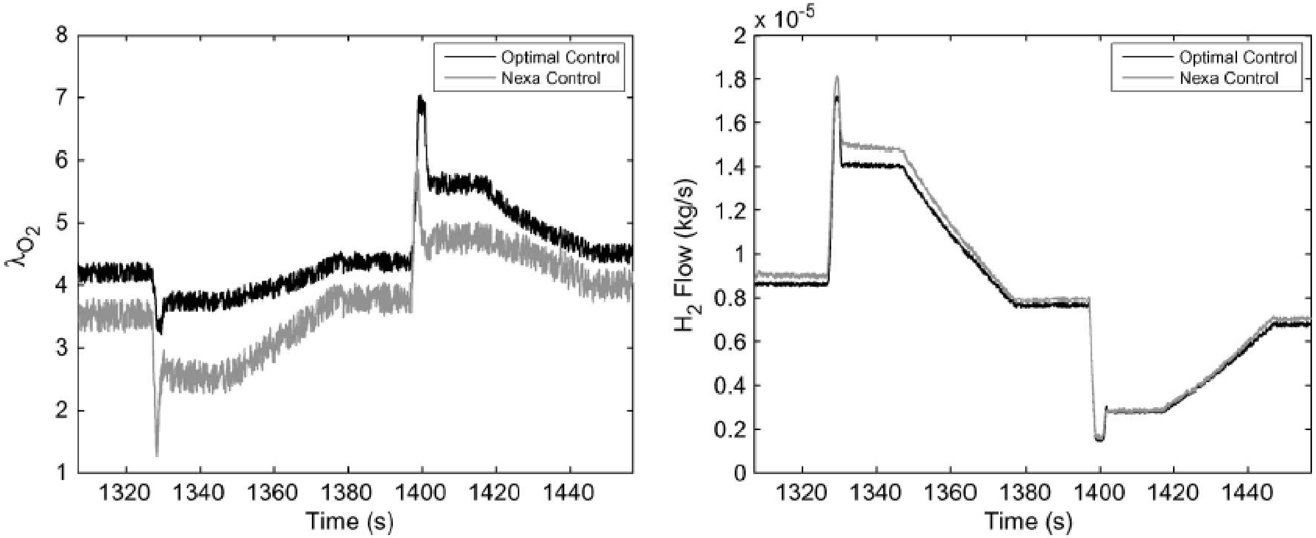


. 1. Steady-state liquid water flow against stack temperature and current

Water Management in PEM Fuel Cells: Controllability Analysis and Steady-state Optimization for Temperature Control. Arce, A., Bordons, C. and A. J. Del Real. 18th IFAC World Congress , 2011.

Development and experimental validation of a dynamic thermal and water distribution model of an open cathode proton exchange membrane fuel cell. Strahl, S., Husar, A, and M. Serra. Journal of Power Sources 196 (2011) 4251–4263.

Experimental results



- **Safe and smooth operation (no peaks)**
- Optimal profile control being 5% (average) more efficient than the Nexa internal control in this particular case (7% improvement around 800 W).
- 18.7 minutes extended operation for a hydrogen cylinder of 240 g

A good control policy can save fuel!

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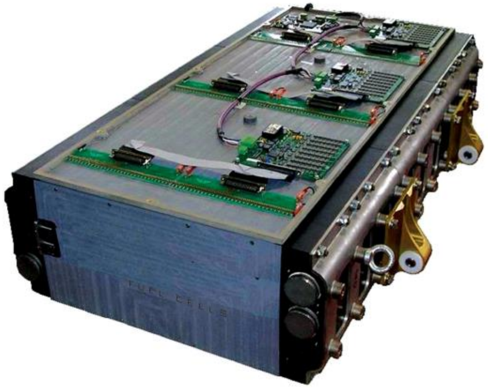


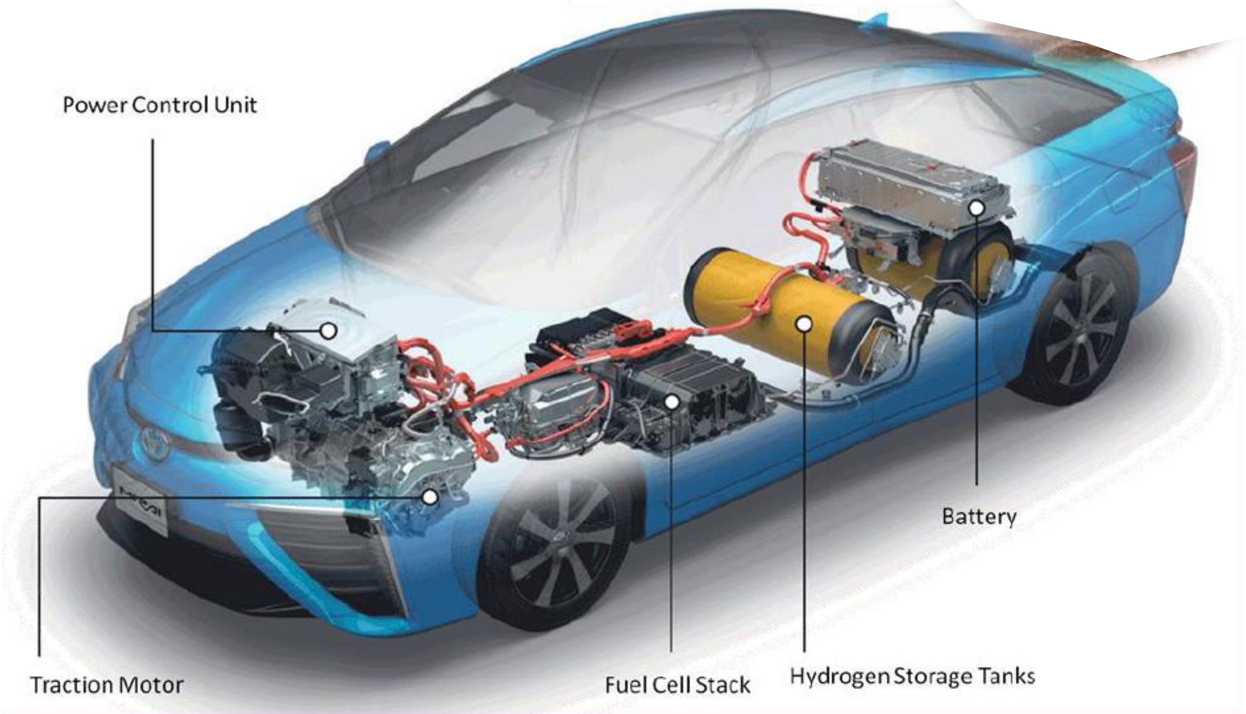
Fuel Cell Electric Vehicle (FCEV)

Toyota Mirai (50,000 USD)

Toyota Mirai breaks 1,000-kilometre range barrier

11 June 2021

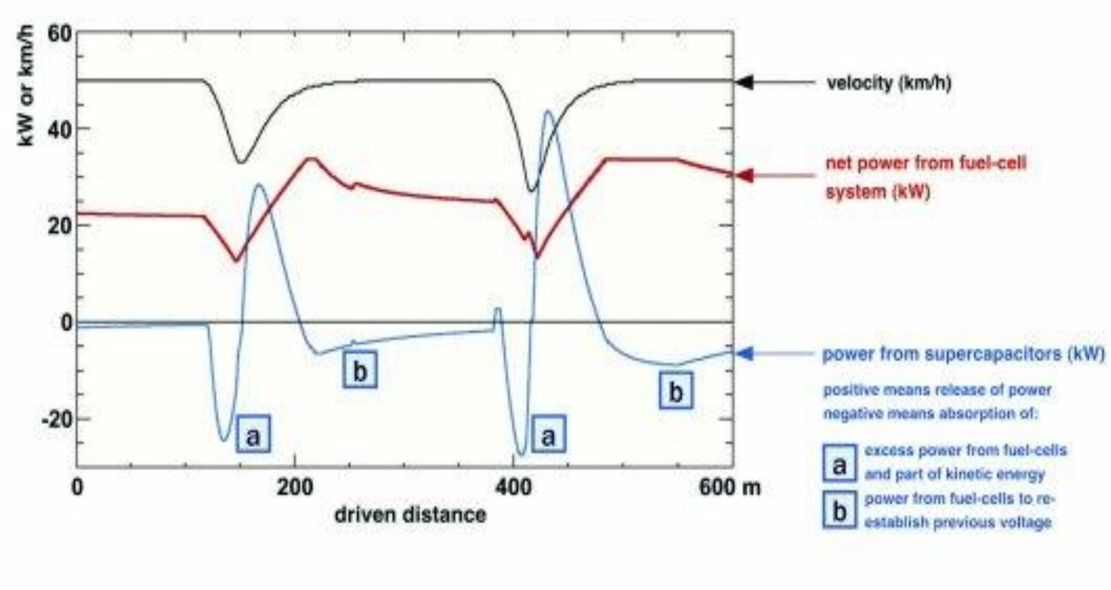
5,5 kg of Hydrogen
Refuelling time: 5 minutes



FUENTE: Toyota, Mercedes, BMW, Hyundai, Honda

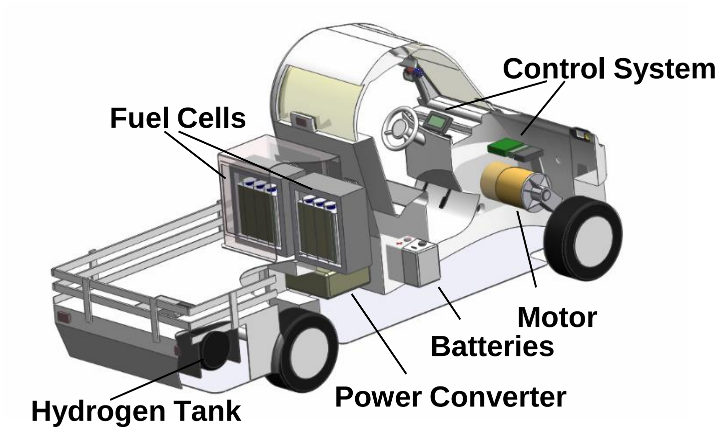
Hybrid propulsion

- Manage of two energy sources: fuel cell and battery/ultracapacitor
- Different dynamic responses
- Like ICE hybrid vehicles



Need of an on-board real-time control system

Some prototypes



- Based on a commercial platform
- Fuel cell: 56 kW
- PMSM motor 66 kW
- Hydrogen storage: 90 l at 350 bar
- Li-ion batteries 15 kWh
- 2 ECUs: PC104 with QNX

FOX: 4 in-wheel motors

- FC as range extender
- Hydride storage. Fast replacement
- Stability control

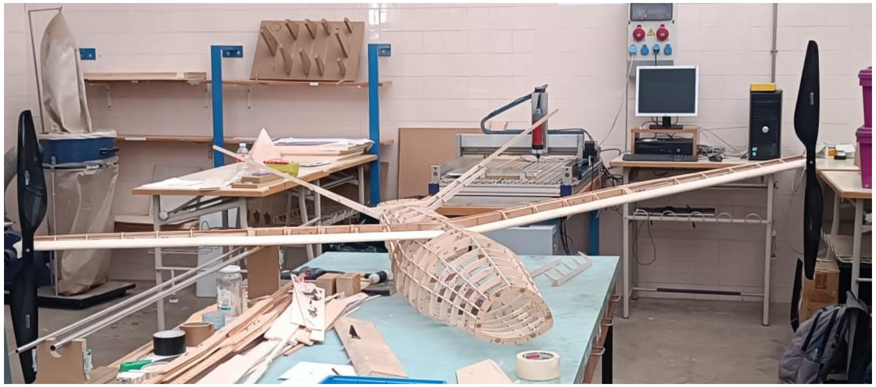
Unmanned vehicles

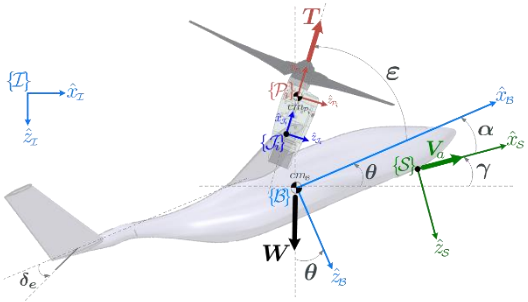
- Ground
- Underwater

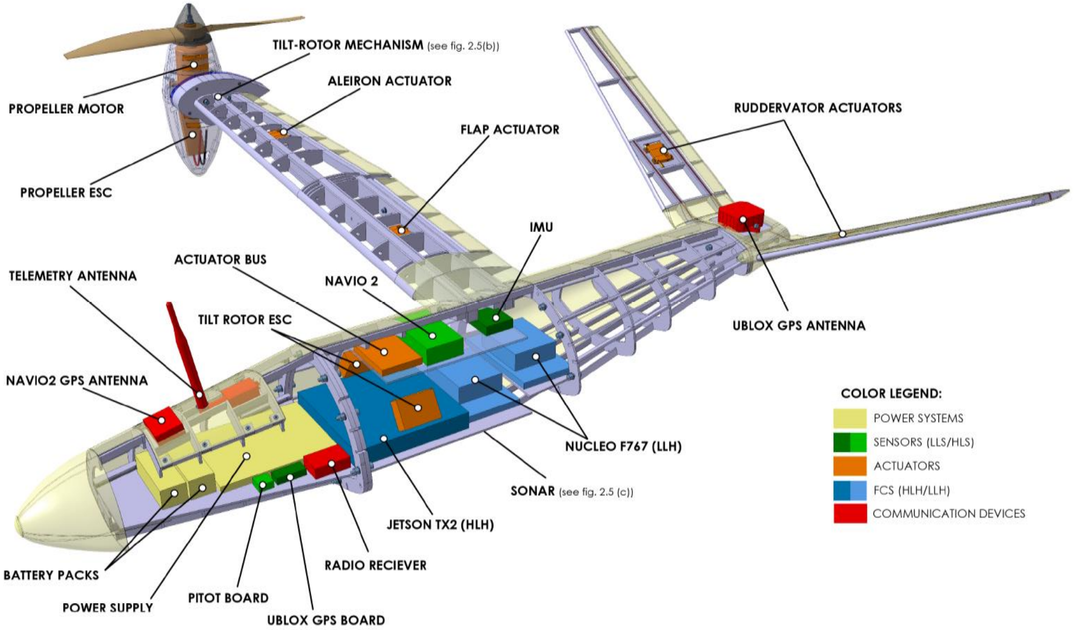
- Original electric vehicles: small endurance
- Increase energy density
- Fuel cell allows **range** extension and fast **charge**

Aerial: UAVs

Emergentia Project (US, UFSC, UFMG)
Tilt-rotor configuration
Extended endurance with Hydrogen

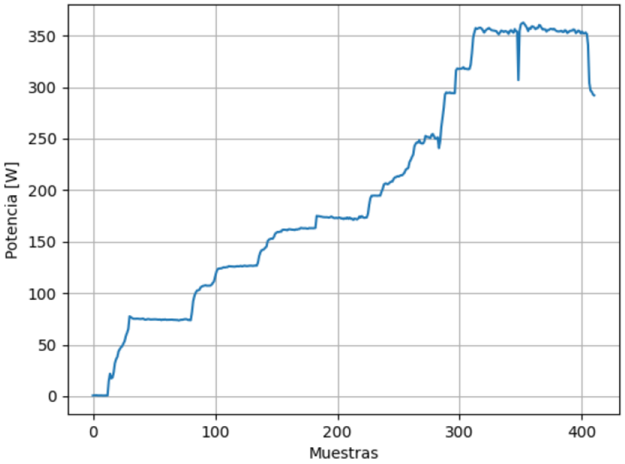




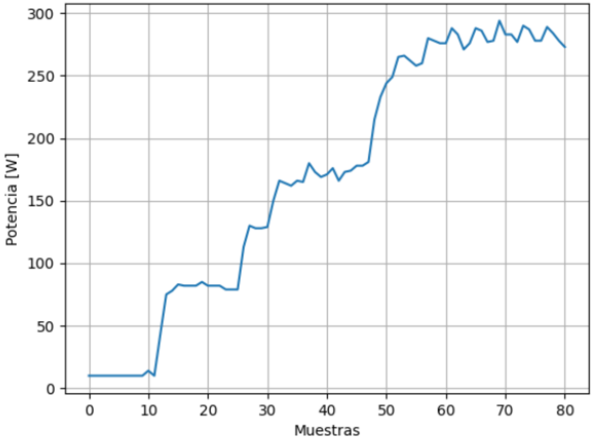


Emergentia Project

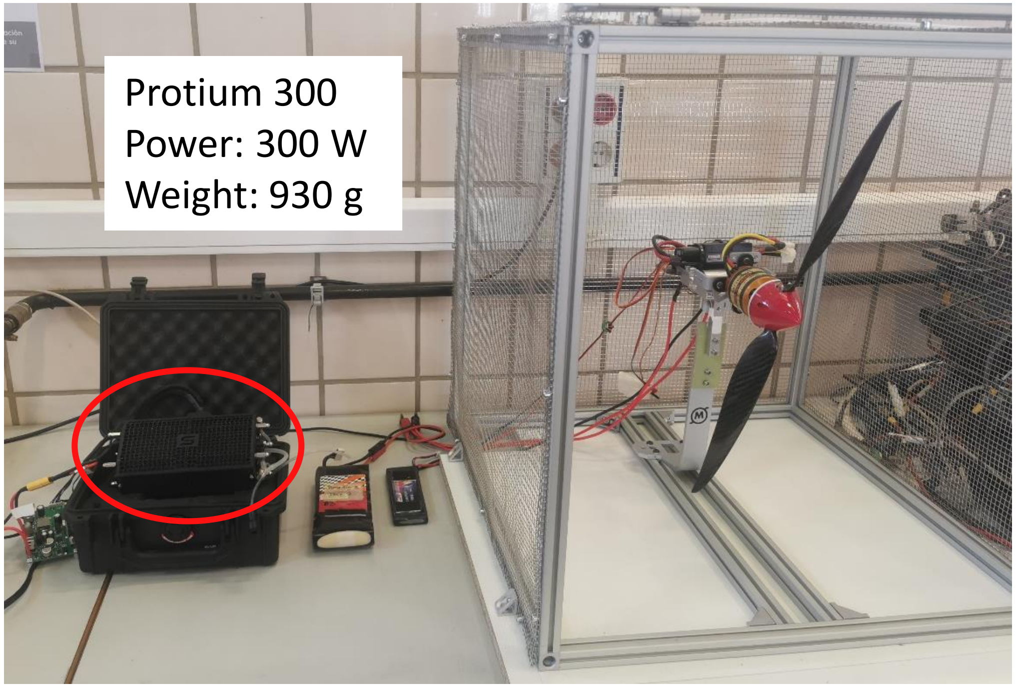
Static testbed. Ready to be onboard



(a) Lectura de Potencia en RCBenchmark.



(b) Evolución de la Potencia en Protium-300.



Protium 300
Power: 300 W
Weight: 930 g

- FC supplies the main demand (300 W) and the battery compensate the peaks
- DC/DC converter for battery operation at 24 V (optimal power of FC)
- Up to now: threshold control tested

Algorithms for hybrid propulsion

- Heuristic (based on rules or on maps)
- ECMS (Equivalent Consumption Minimization Strategies), based on Pontryagin principle
- MPC:
  - Model: state space. The dynamics is given by the storage devices and energy balance
  - Cost function: minimize the use of Hydrogen
  - Constraints: avoid sudden changes in power of FC

  - Expanded for microgrids (see next section)

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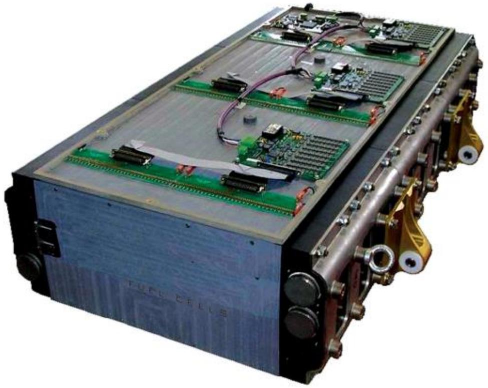
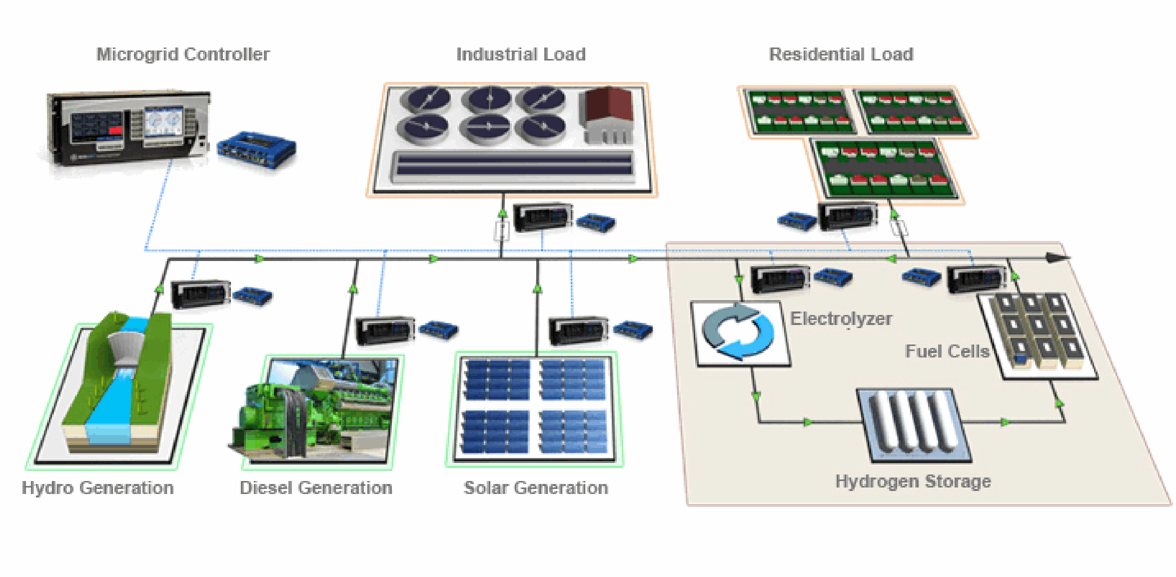


Stationary use of FCs: Microgrids

- Microgrid: portion of a power system that includes a variety of **DER** units and different types of end users. Different types of energy: electricity, thermal, gas, H2, etc.
- DER (Distributed Energy Resource) units:
  - Distributed generation (DG)
  - Distributed storage (DS) .
- Also known as Multi Carrier Energy Systems
- It can work in islanded/grid-connected mode



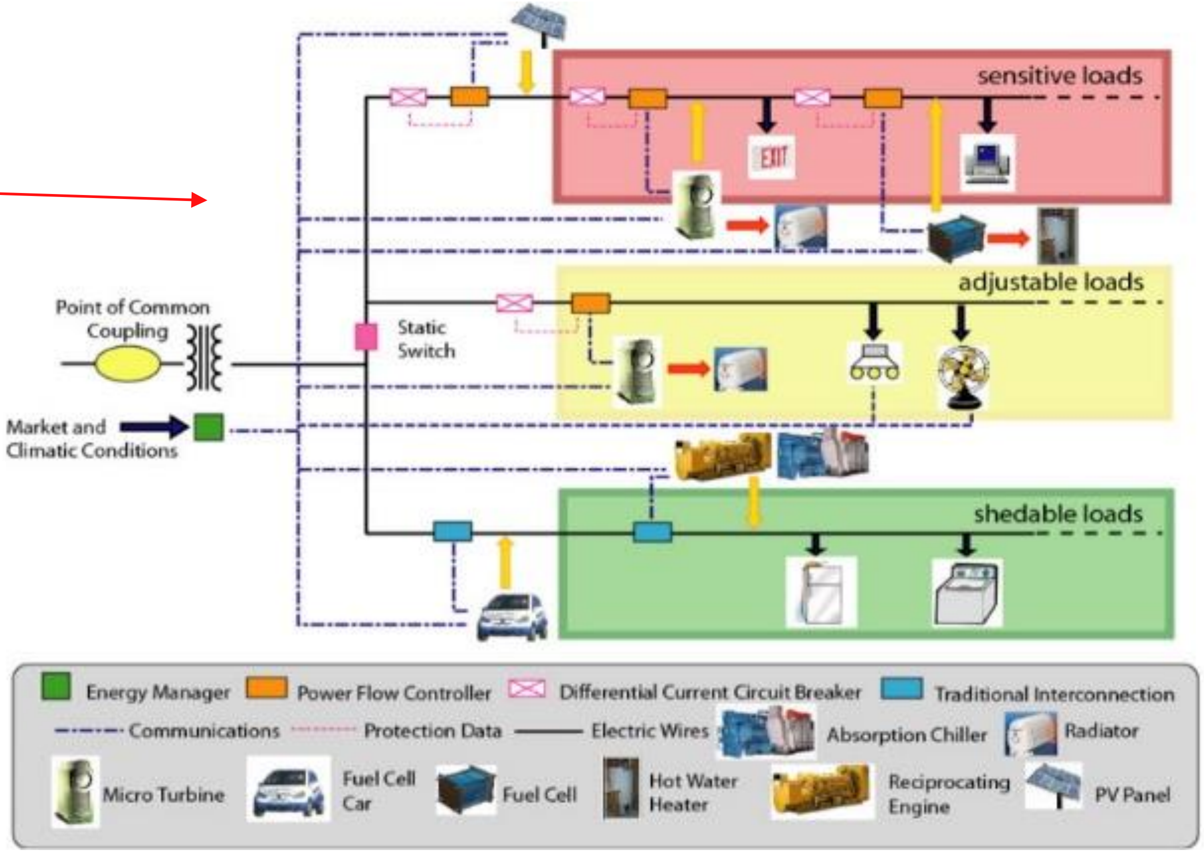
How to operate it?

- When to store energy?
- When to use stored energy?
- Buy/sell to grid?
- (Dis)connect units?
- Islanded?

Lasseter, R. H. Microgrids. IEEE Power Eng Soc Transm Distrib Conf, 2002

Examples

- District
- Factory
- Hospital
- University Campus
- Hybrid vehicles (nanogrid)



Sugar Cane Factory is also a microgrid*

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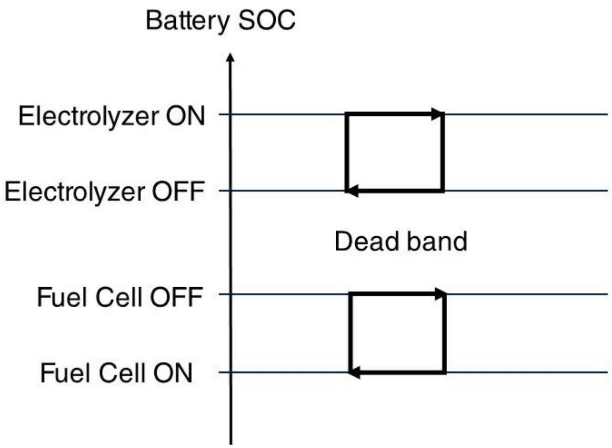
*Optimal operation of hybrid power systems including renewable sources in the sugar cane industry. MM Morato, PRC Mendes, JE Normey-Rico, C. Bordons. IET Renewable Power Generation, 2017

Control techniques applied to microgrids

- ☐ Hysteresis Band Control (Ulleberg, 2003; Ghosh, 2003; Ipsakis, 2008)
- ☐ Neural Networks (López, 2007)
- ☐ Fuzzy Logic (Bilodeau, 2006; Stewart, 2009; Hajizadeh , 2009)
- ☐ Droop Control (Vasak, 2014)
- ☐ **Model Predictive Control** (Del Real, 2007; Baotic, 2014; Garcia-Torres, 2016; Parisio, 2016)

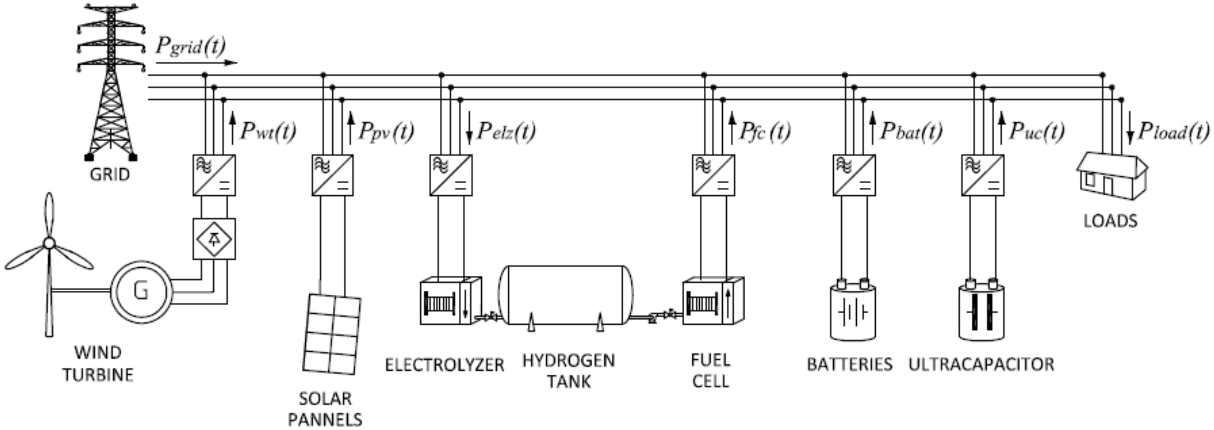


The use of MPC technique allows to **maximize the economical benefit** of the microgrid, **minimizing the degradation** causes of each storage system, fulfilling the different system **constraints**

Experience has demonstrated that system performance is highly subject to the control strategy. MPC has shown >30% reduction in operational costs*

*Integration of Fuel Cell Technologies in Renewable-Energy-Based Microgrids Optimizing Operational Costs and Durability. L. Valverde, C. Bordons, F. Rosa. IEEE Trans on Industrial Electronics, 2016.

MPC of microgrids. EMS



Energy Management System (EMS):

Since the generated (renewable) power **does not fit** the demanded load, the controller must compute the setpoints to the local controllers of ESSs (Energy Storage Systems) and grid **in order to balance the power in the best way**

Cost associated to use of Renewable Energy and ESS

Controlled Variables:

Battery/uC SOC

Hydrogen LOH

MPC:

Constraints

Cost function minimization

Manipulated Variables:

FC Power

ELZ Power

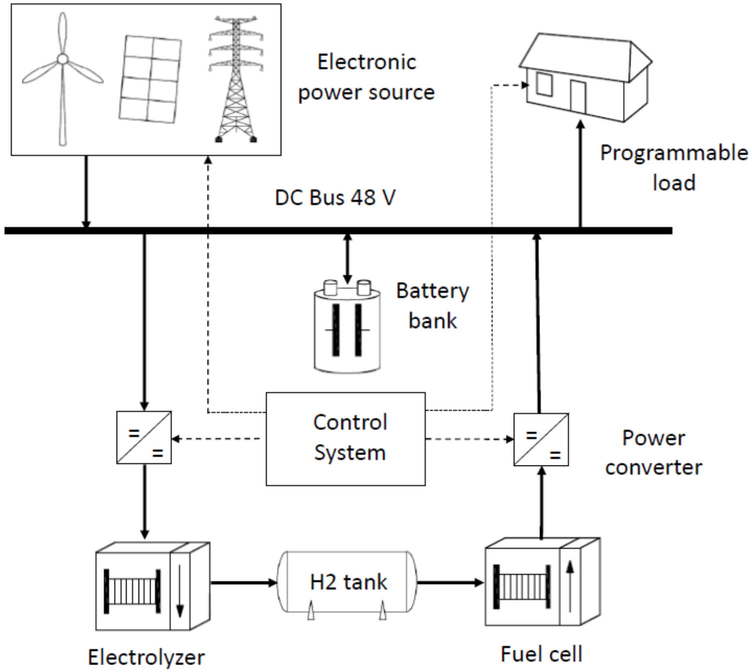
Bat/uC Power

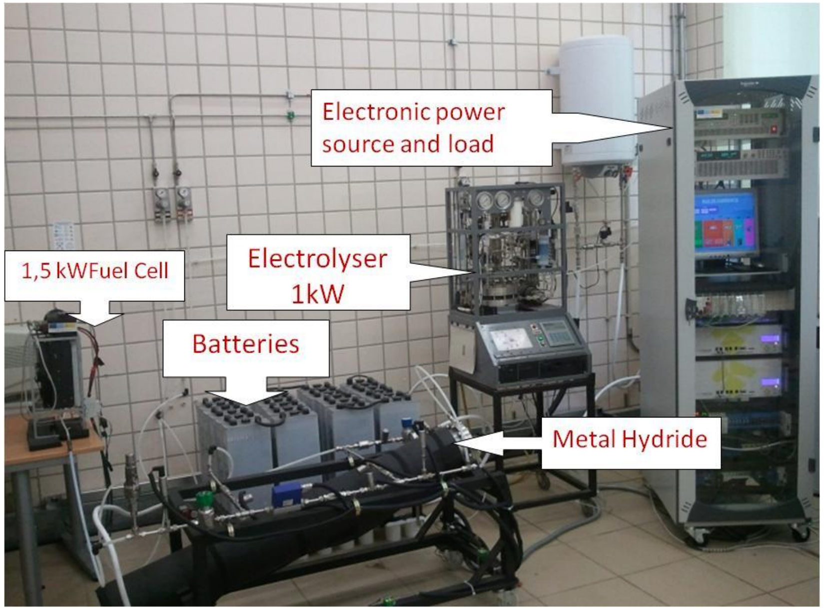
Grid Power

Model Predictive Control of Microgrids. Bordons, García-Torres and Ridao. Springer, 2020

Laboratory-scale microgrid

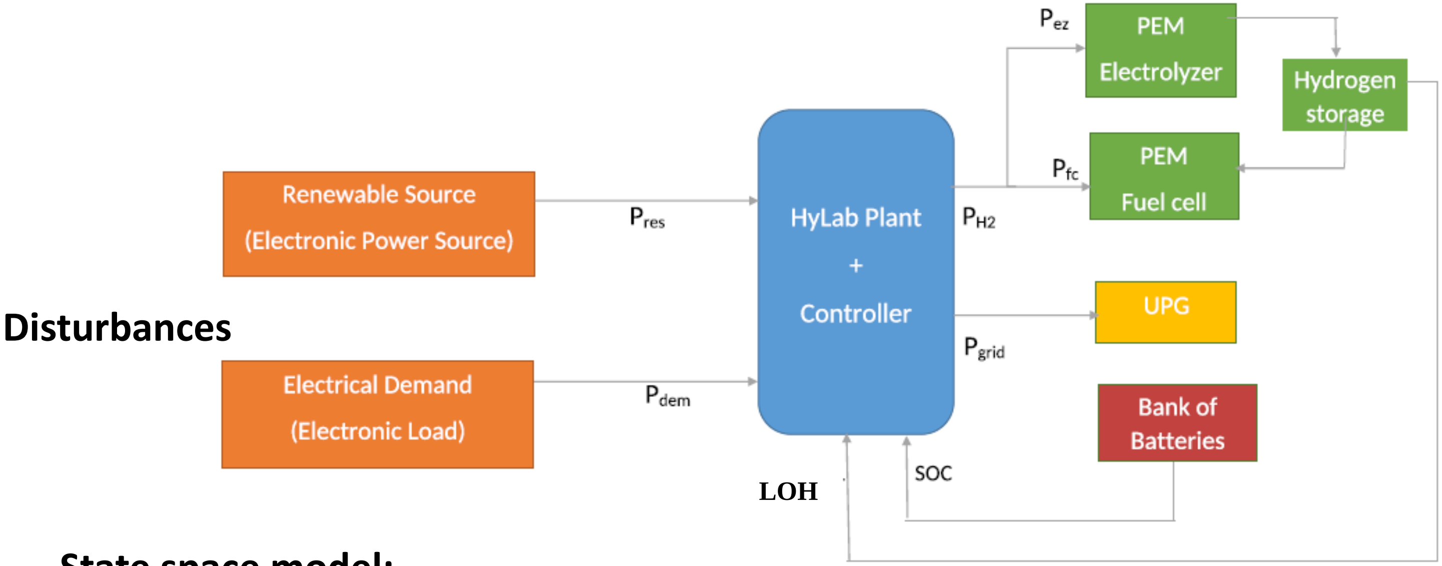
DC microgrid (Hylab)





Energy Management Strategies in hydrogen Smart-Grids: A laboratory experience. L Valverde, F Rosa, C Bordons, J Guerra. International Journal of Hydrogen Energy.

Microgrid Scheme



State space model:

$$SOC(t+1) = SOC(t) - \frac{\eta_{bat} T_s}{C_{\max}} P_{bat}(t)$$

$$LOH(t+1) = LOH(t) + \frac{\eta_{elz} T_s}{V_{\max}} P_{elz}(t) - \frac{T_s}{\eta_{fc} V_{\max}} P_{fc}(t)$$

Power in the battery bank (balance):

$$P_{bat}(t) = P_{load}(t) + P_{elz}(t) - P_{fc}(t) - P_{grid}(t) - P_{gen}(t)$$

MPC Cost function

3 weighted objectives

- ☐ **Minimize the use of grid**
- ☐ **Protect equipment from sudden changes**
- ☐ **Keep storage levels (H_2 and electricity)**

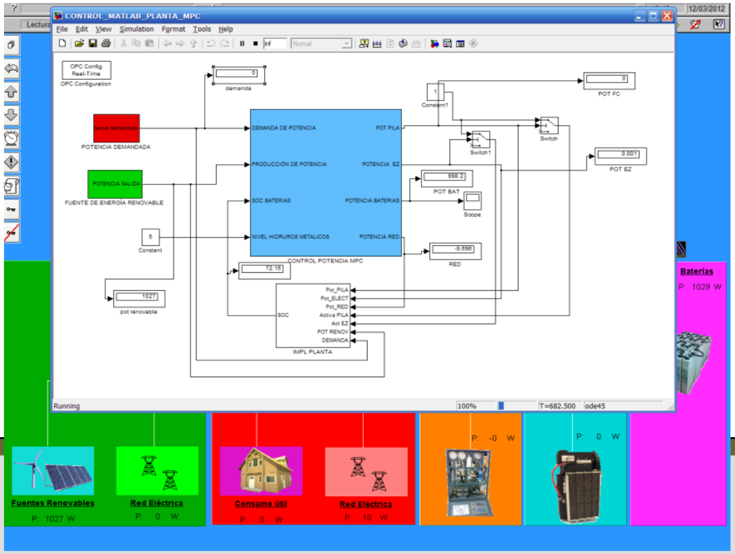
$$J=\sum_{k=1}^{N_c}\alpha_1 P_{fc}^2(t+k)+\alpha_2 P_{elz}^2(t+k)+\alpha_3 P_{grid}^2(t+k)+\alpha_4 P_{bat}^2(t+k)+$$
$$+\beta_1\Delta P_{fc}^2(t+k)+\beta_2\Delta P_{elz}^2(t+k)+\beta_3\Delta P_{grid}^2(t+k)+\beta_4\Delta P_{bat}^2(t+k)+$$
$$+\sum_{k=1}^{N_p}\gamma_1(SOC(t+k)-SOC_{ref})^2+\gamma_2(LOH(t+k)-LOH_{ref})^2$$

And operational constraints (power slope)

Implementation

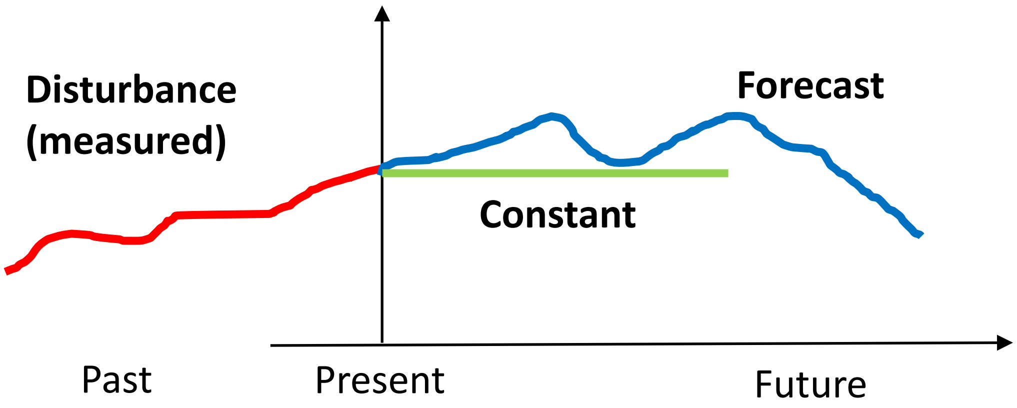
PLC for Real-Time control.
Unity/Vijeo

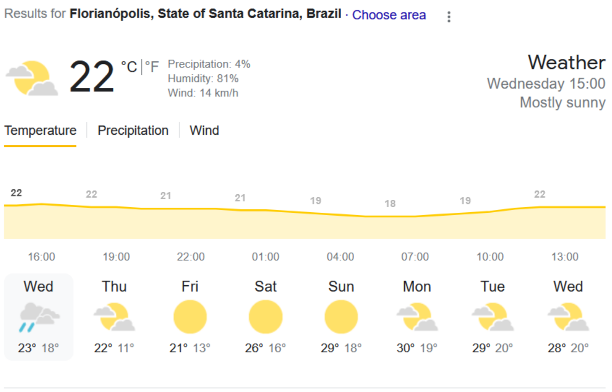
Matlab/Simulink→
Quadratic Programming



Include forecasting

- Make use of the prediction capabilities of MPC
- Include forecasting of renewable **generation** and load **demand**
- Feedback mechanism reduces the effect of disturbances but, besides, MPC can **anticipate** if forecasting is available.

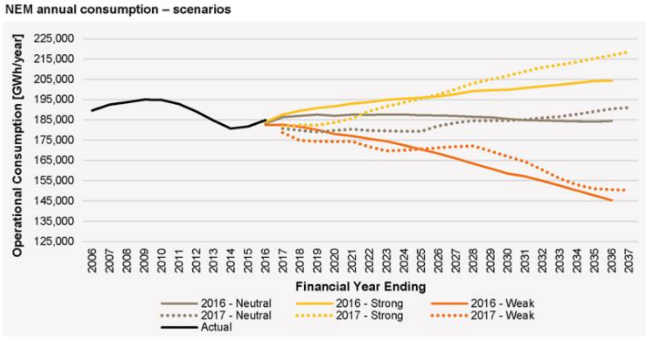




Results for **Florianópolis, State of Santa Catarina, Brazil** · Choose area

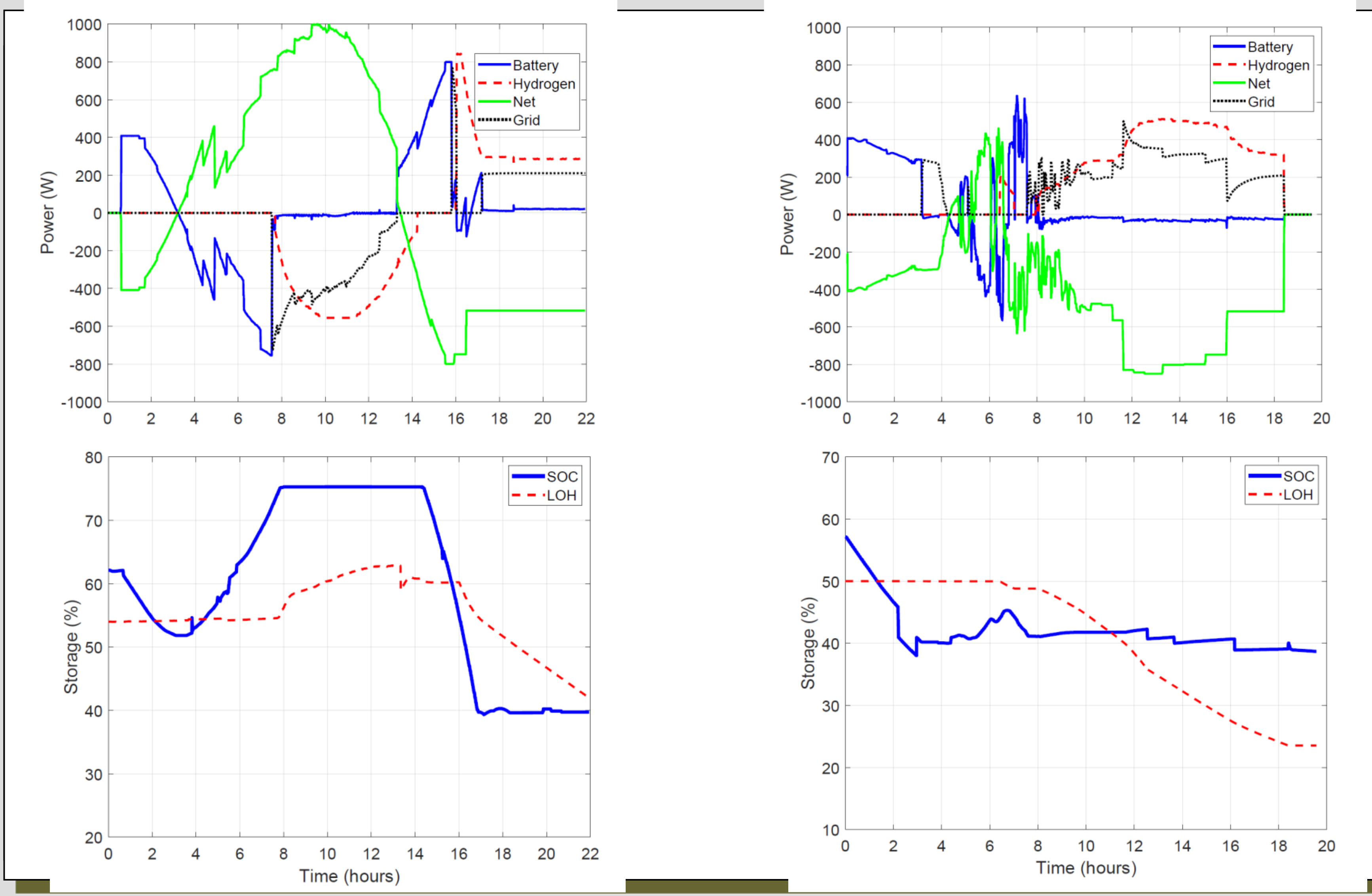
22 °C | °F Precipitation: 4% Humidity: 81% Wind: 14 km/h

Weather
Wednesday 15:00
Mostly sunny



NEM annual consumption – scenarios

Experimental results: Sunny/cloudy day



Extended Control Objectives

- The basic algorithms can be extended: Electrical Tariffs
- Different prices for sale and purchase

$$J_{grid}(t+k|t) = \Big(-\hat{\Gamma}^{DM}_{sale}(t+k|t)\cdot P_{sale}(t+k|t) + \hat{\Gamma}^{DM}_{pur}(t+k|t)\cdot P_{pur}(t+k|t)\Big)\cdot T_s$$

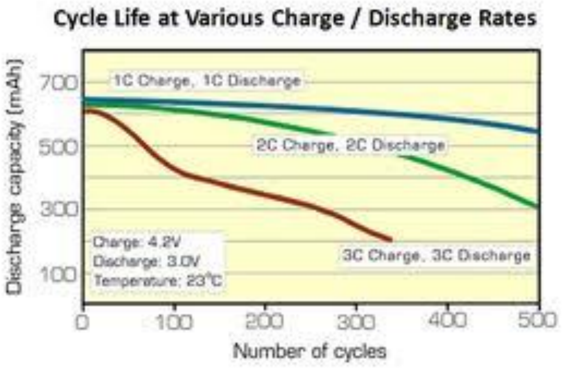
- Implies the consideration of binary (logical) variables: states and transitions

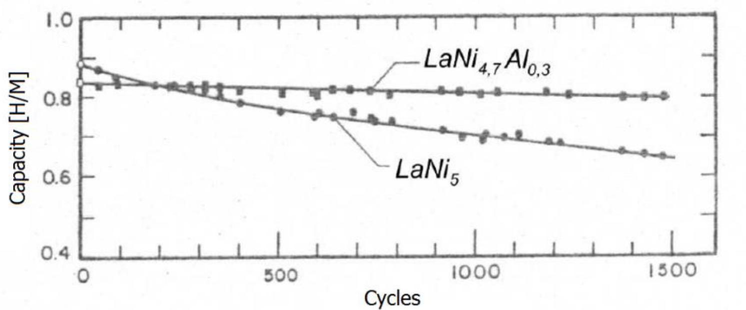
$$P_{grid}(t) \leq 0 \Leftrightarrow \delta_{sale}(t) = 1$$
$$P_{sale}(t) = -P_{grid}(t)\cdot\delta_{sale}(t)$$
$$P_{grid}(t) = P_{pur}(t) - P_{sale}(t)$$
$$\delta_{pur}(t) + \delta_{sale}(t) = 1$$

- Mixed Problem: MIQP using Mixed Logical Dynamic (MLD) framework

Durability and O&M costs

Durability is an important issue in ESS. Manufacturers of batteries/electrolyzers/tanks quantify the life of this ESS as a function of the number of the **charge and discharge cycles**





Metal hydride storage

$$J_{bat} = \sum_{h_i=1}^{24} \left(\frac{CC_{bat}}{2 \cdot Cycles_{bat}} \boxed{P_{bat,ch}(h_i)} \cdot T_s \cdot \eta_{bat,ch} + \mathrm{Cost}_{degr,ch} \cdot P^2_{bat,ch}(h_i) \right.$$

$$\left. + \frac{\mathrm{CC}_{bat}}{2 \cdot \mathrm{Cycles}_{bat}} \frac{P_{bat,dis}(h_i) \cdot T_s}{\eta_{dis,bat}} + \mathrm{Cost}_{degr,dis} \cdot \boxed{P^2_{bat,dis}(h_i)} \right)$$

- Reduce the number of start-ups and shut-downs of ELZ and FC
- Binary variable: transitions → MIQP

Optimal load sharing of hydrogen-based microgrids with hybrid storage using model-predictive control. F Garcia-Torres, L Valverde, C Bordons. IEEE Trans on Industrial Electronics 63 (8), 2016

Conclusions

- Fuel cell systems are considered to be feasible candidates to replace the conventional energy conversion systems for stationary and mobile applications.
- Model Predictive Control can improve the operation of Fuel Cell Systems both for mobility and stationary applications
- MPC shows outstanding features in power management: dynamic performance, smooth operation, lower cost, higher lifetime
- Changes in cost function, tuning parameters and logical constraints can help fulfil different objectives
- Durability and O&M Cost can be included as control objectives
- MPC for FC-based systems is an open field with great potential

Open issues

- Hydrogen for aircraft
- Fault-tolerant control
- Degradation of FC & ELZ
- Demand side management
- Stochastic algorithms
- Blockchain for energy communities
- Digital twins of FC/ELZ and microgrids
- Cybersecurity
- …

Acknowledgements

US: Félix García-Torres, Miguel A. Ridao, Luis Valverde, Pablo Velarde, María del Mar Castilla, Asun Zafra, Sergio Esteban, Alicia Arce, Jorn Gruber, Juanjo Márquez, Guillermo Teno, Pedro Fernández, Carlos Montero, Alejandro Oliva

UFSC: Paulo R.C. Mendes, José Vergara, Marcelo Menezes, Henry López, J.E. Normey

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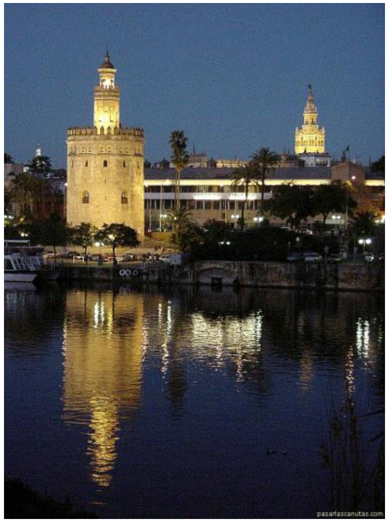

PhD students welcome to Sevilla!

Control of Fuel Cells

Controle de células de combustível

Carlos Bordons

Fuel Cell Control Lab

Systems Engineering and Automation Department / ENGREEN
University of Seville, Spain

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