# Modeling, Analysis and Control System Development for the Italian Hydrogen House

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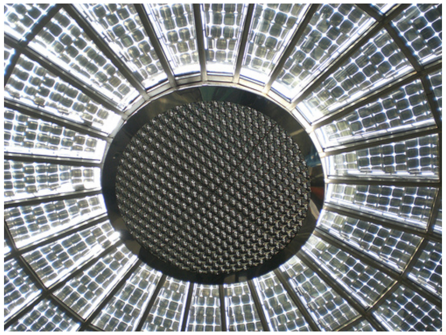
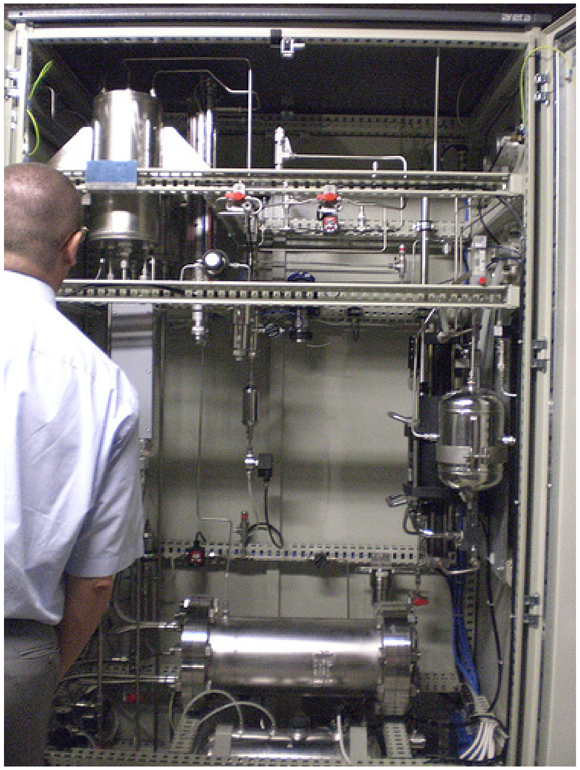
# Overview

- Introduction to the Italian House
- Simulation strategy
- Control system development
- Economic comparison
- Problems and conclusions



# Introduction to the Italian House Demonstration

- Located in Brescia, Italy
- Partially private and public funding
- Analyzed through IEA Task 18
- Main Tasks
  - Control System Development
    - Load Management and Hydrogen Control
    - Event monitoring and control
  - Analysis of system dynamics
  - Analysis of demonstration economics

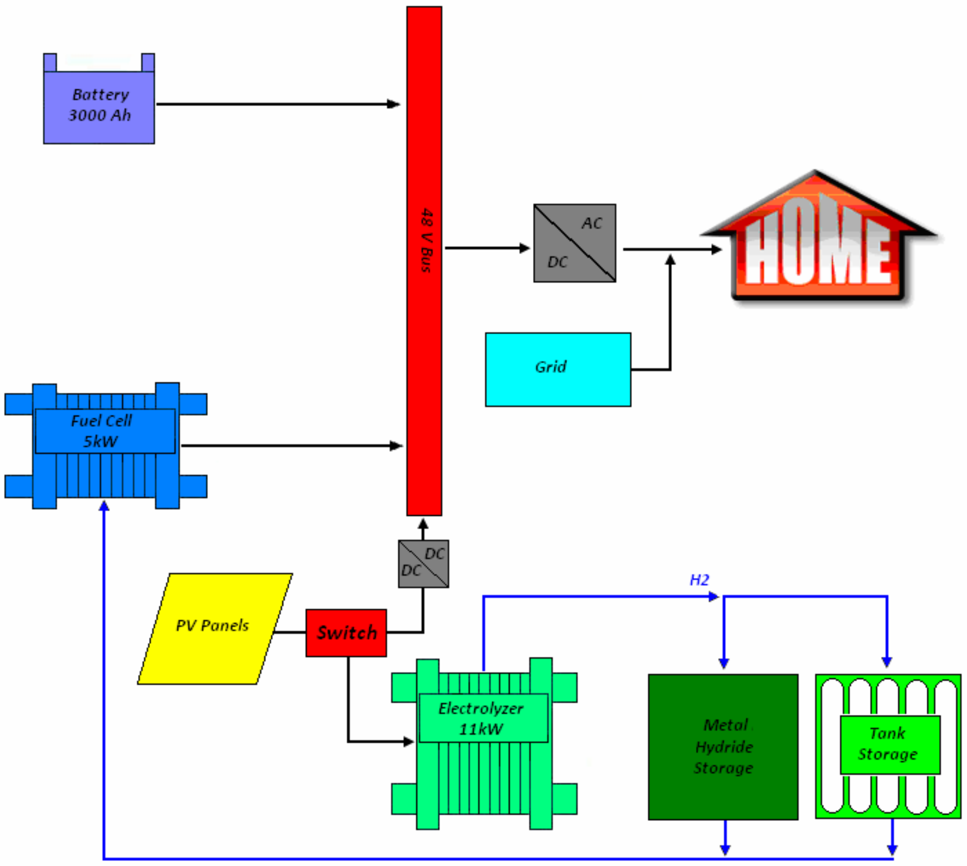


# Sandia's Approach to System Analysis

- Create a library of Simulink modules for H2 specific components
  - Assemble engineering model as system of components
  - Component models based on fundamental physics and chemistry
  - Coupled to Chemkin software for thermodynamic properties
- Economic analysis modules linked to components
  - Compute levelised cost of H2 and electricity over life of system
- Library components can be quickly re-configured for new systems

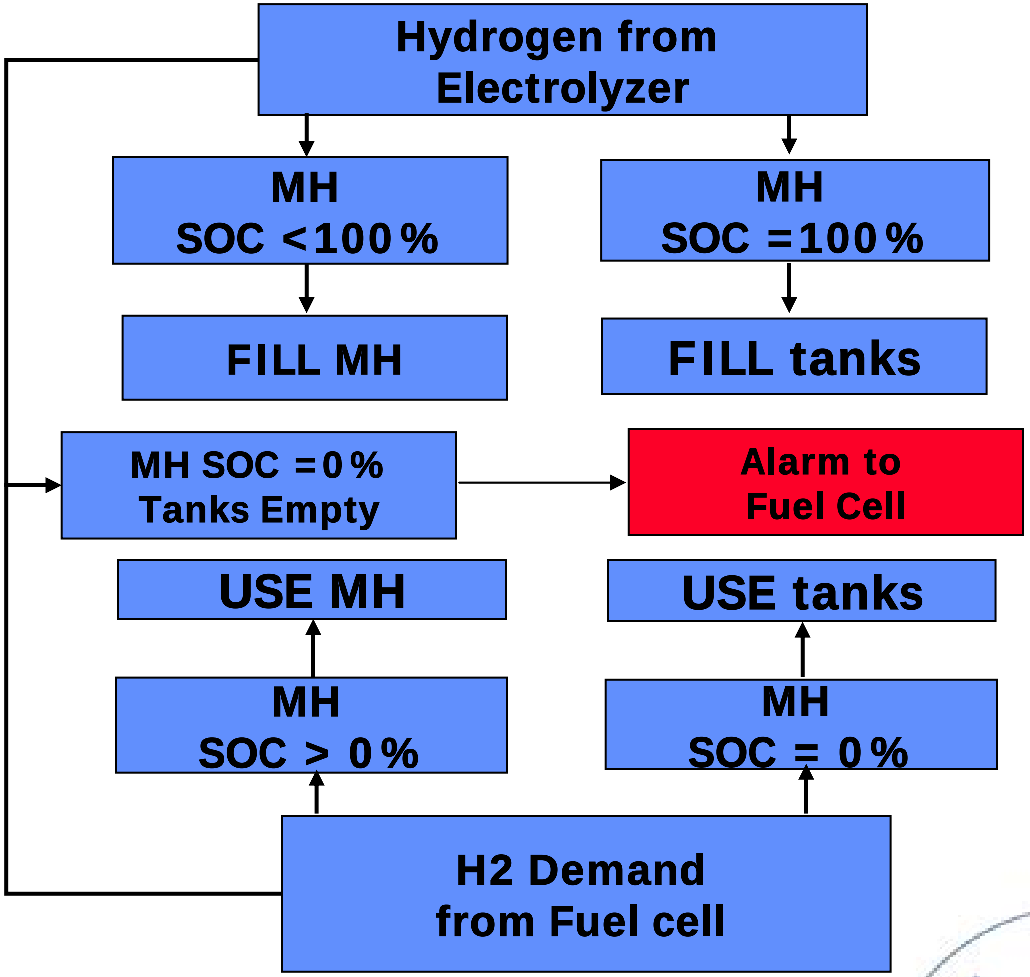
# General Technical Information on the Italian H2 House Design

- High pressure alkaline electrolyzer
  - Produces 1NM$^3$/hr $H_2$ at 200 bar
- 5kW PEM fuel cell
- 3000Ah battery
- 30Nm$^3$ Hydrogen stored in metal hydride
- 120Nm$^3$ Hydrogen in storage cylinders
- 11kW peak power available from photo-voltaic panels
- Performance data adapted from previous verified simulations (DTE, HNEI)



# The hydrogen flow is managed to demonstrate the metal hydride fully

- Hydrogen Flow Control System Methodology
  - Goal of house is to analyze metal hydride (MH) performance and applicability
  - Optimization of this linked strongly to load management and fuel cell operation



Hydrogen from Electrolyzer

MH
SOC <100%

MH
SOC =100%

FILL MH

FILL tanks

MH SOC =0%
Tanks Empty

Alarm to
Fuel Cell

USE MH

USE tanks

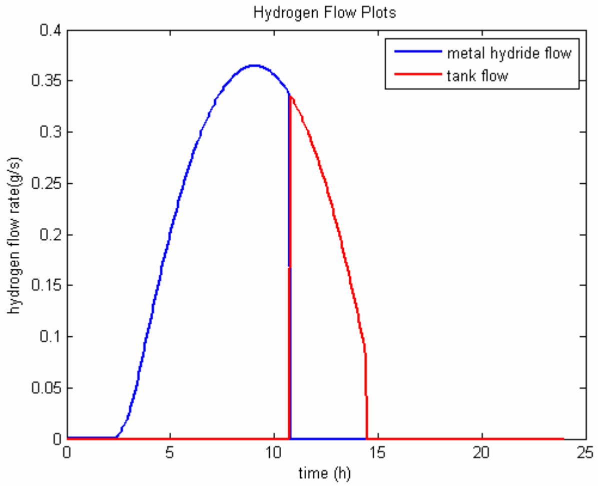
MH
SOC > 0%

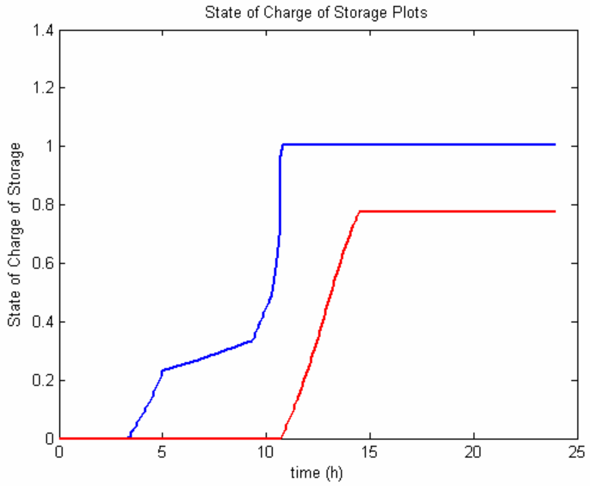
MH
SOC = 0%

H2 Demand
from Fuel cell

# Hydrogen flow control system implementation - the methodology in the model

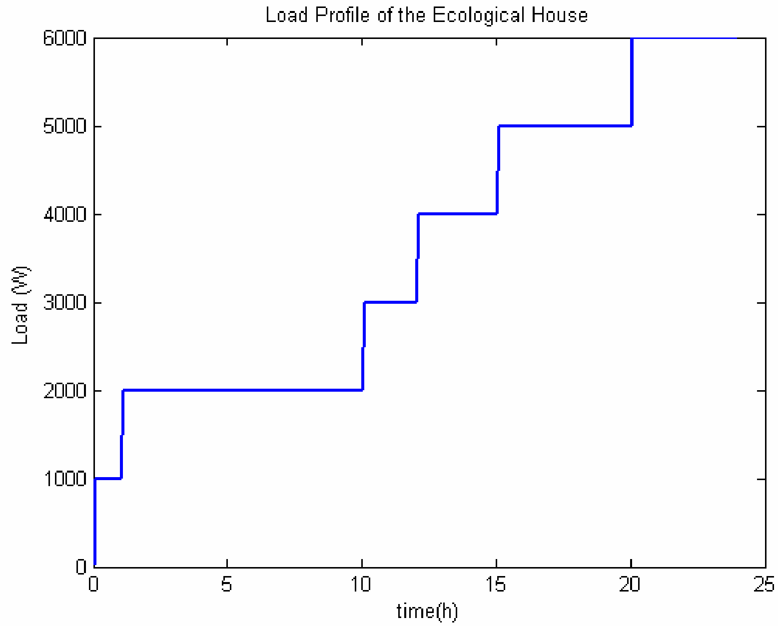
- Switches flow between the metal hydride and the tanks
- Metal hydride is favored for both the first charge and first discharge of $H_2$ from the electrolyzer
- Link to energy flow control to keep fuel cell “out of circuit” if no $H_2$ is available

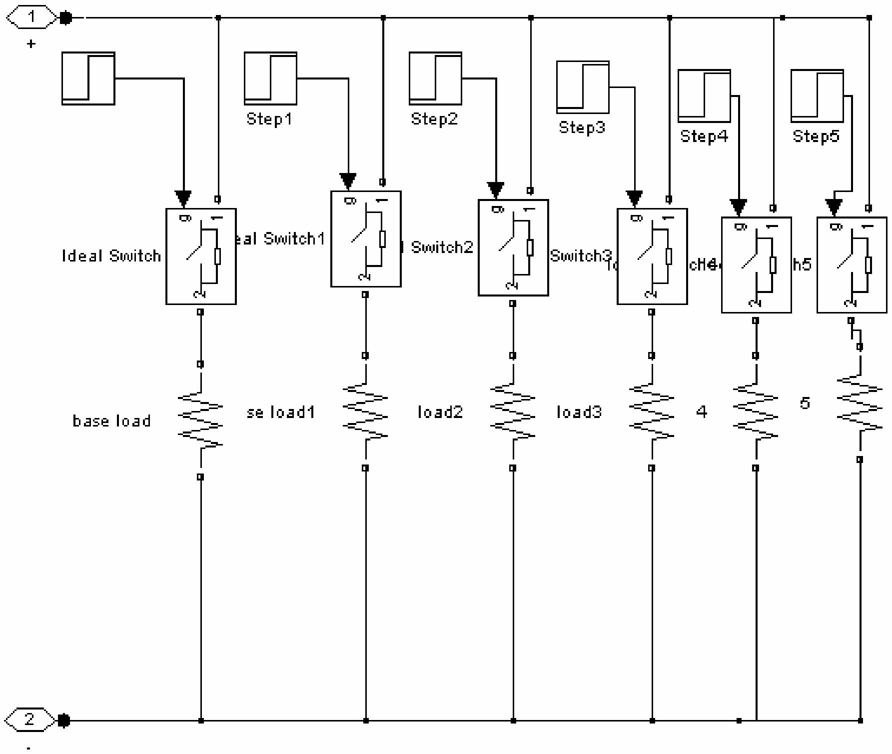




# Load designed as an electrical system using SimPowerSystems - tool box in Simulink

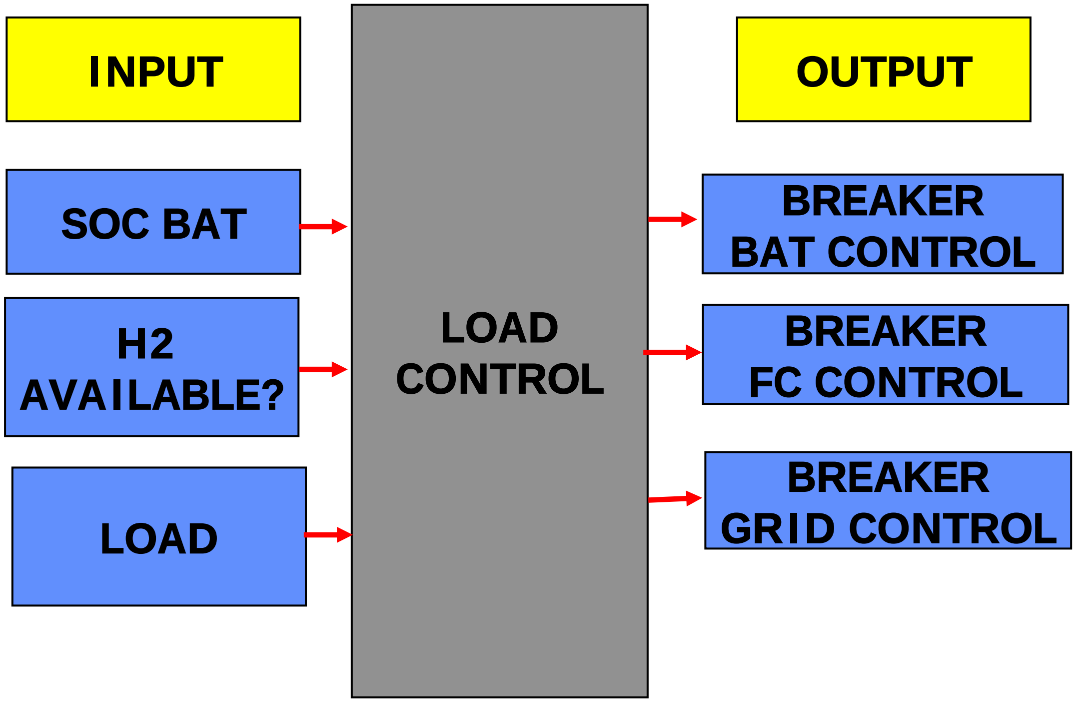
- Circuit breakers step up and down power
- 0 – 6 kW





# Energy flow is managed to fully power the house at all times and prevent component damage

- Energy Flow Control System Methodology
  - Goal of house is to demonstration fuel cell technology effectively and run a grid paralleled system
  - Optimization of this linked strongly the system economics as cost of grid electricity plays a large part in the Cost of Hydrogen (COH)



INPUT

SOC BAT

H2 AVAILABLE?

LOAD

LOAD CONTROL

OUTPUT

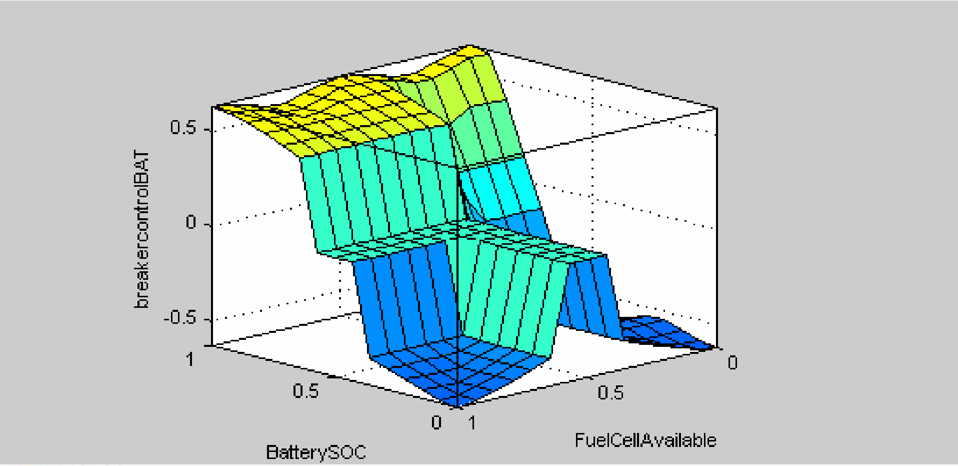
BREAKER BAT CONTROL

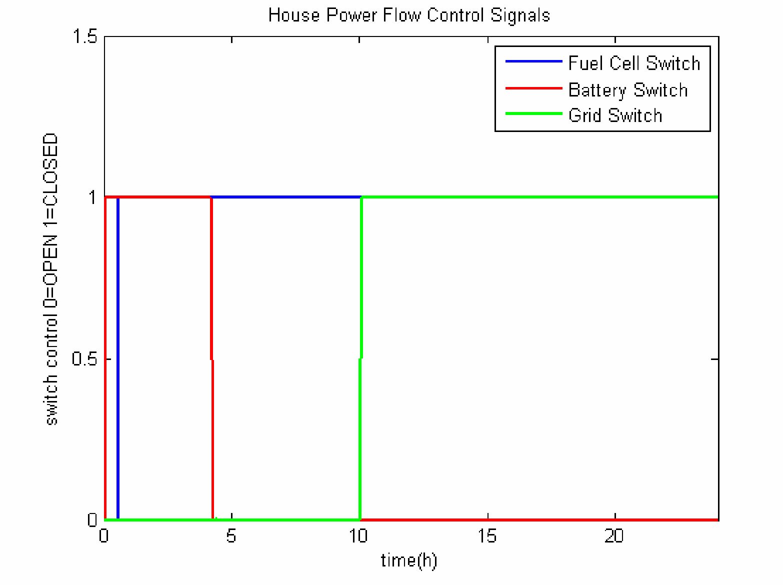
BREAKER FC CONTROL

BREAKER GRID CONTROL

# Load control system implemented using electrical circuit methodology

- Circuit breakers switch in and out the fuel cell, battery and grid connection at the command of the energy flow control system





- Fuzzy logic control system creates smooth transitions

# Economic analysis – cost of H2 and electricity from the Italian demonstration house - Case 1

**Hydrogen Cost:**

- **Electrolyzer capital cost scaled with production rate to 0.6 power**
- **O & M 2% of capital cost**
- **Analysis based on off-peak power rates for Italy (0.05 $/kWh)**

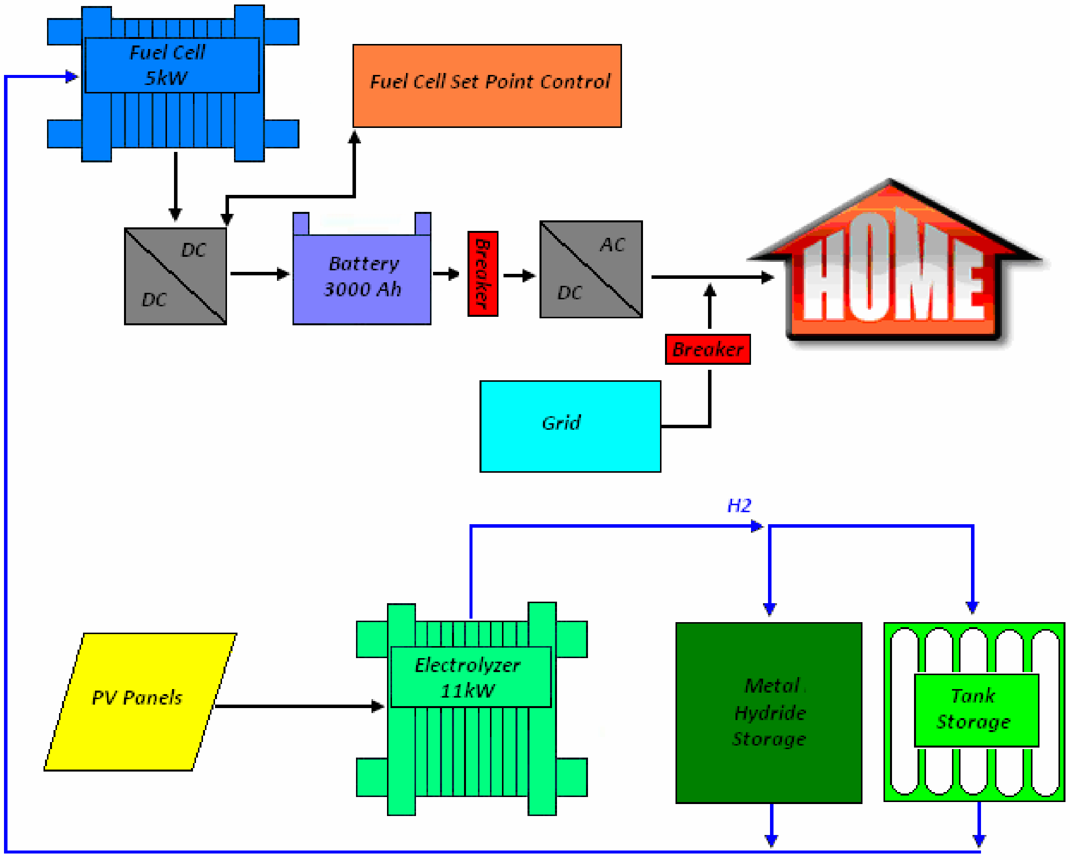
| CONTRIBUTION | COH ($/kg-$H_2$) |
|---|---|
| Capital | 2.37 |
| Feedstock (electricity) | 6.64 |
| O&M | 0.34 |
| **TOTAL** | 9.36 |

**Electricity Cost:**

- **Electricity produced from fuel cell at 0.63 $/kWh**
- **Cost of supplemental grid energy used is $ 7.20 a day (144 kWh/day)**

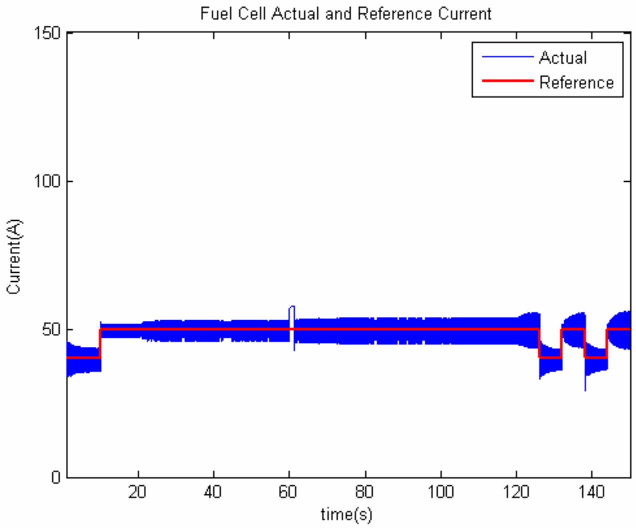
# New Control System provides better load management such that the grid is never used

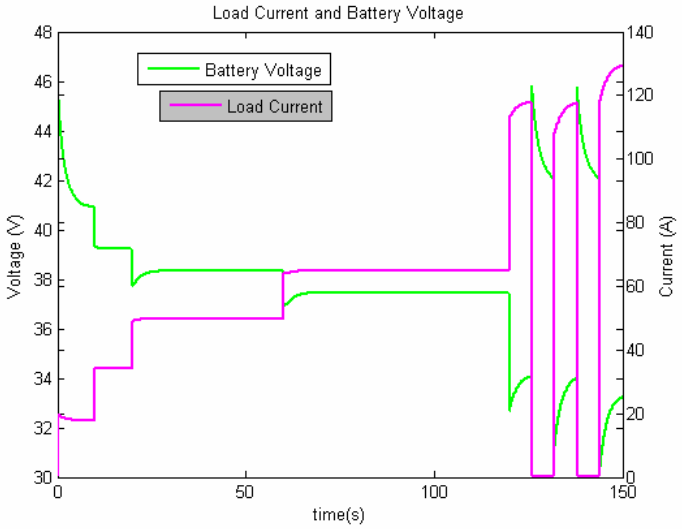
- Removal of 48V bus
- Different operating points for fuel cell
- Minimize use of grid connection



# New control strategy uses active control of DC/DC converters for the fuel cell current

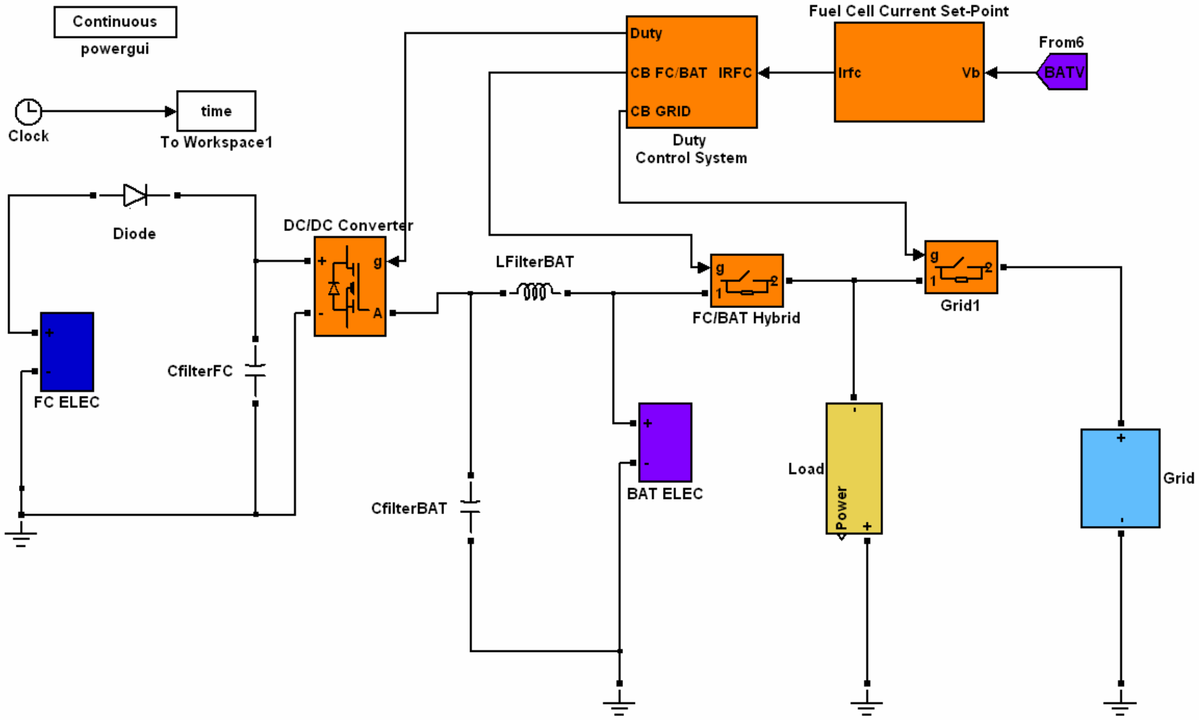
- Design of DC/DC converter strategy
  - Control of duty cycle (determines current drawn from the fuel cell)
- Operation points of fuel cell
  - Maximum efficiency
  - Maximum power
  - Somewhere in-between!
- OR Controls battery current
- OR (in extreme case) disconnects load to control battery voltage if to low and fuel cell not charging





# The DC/DC Converter Model is implemented in Simulink

- Simulink SimPowerSystems Model
- Fuel cell control calculated as a function of the battery voltage
  - increase or decrease current drawn
- Battery can take transient load changes
- Fuel cell charges batteries and supplies load



# Economic analysis – cost of H2 and electricity from the Italian demonstration house using the new control strategy - Case 2

**Hydrogen Cost:**

- **Electrolyzer capital cost scaled with production rate to 0.6 power**
- **O & M 2% of capital cost**
- **Analysis based on off-peak power rates for Italy (0.05 $/kWh)**

| CONTRIBUTION | COH ($/kg-$H_2$) |
|---|---|
| Capital | 2.36 |
| Feedstock (electricity) | 6.61 |
| O&M | 0.34 |
| **TOTAL** | 9.31 |

**Electricity Cost:**

- **Meets a goal of stand-alone operation - removes 7.20 $/day cost of grid electricity**
- ***No grid energy is used to supply the house load***
- **Electricity produced from fuel cell at 0.60 $/kWh**

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# Conclusions

- Fuzzy logic for hydrogen flow control gives a smooth and controlled response
- Active control for fuel cell allows the load to be managed more effectively without a grid connection
- Effect of not using grid connection is a reduction in cost of approximately $7.20 /day (144 kWh)

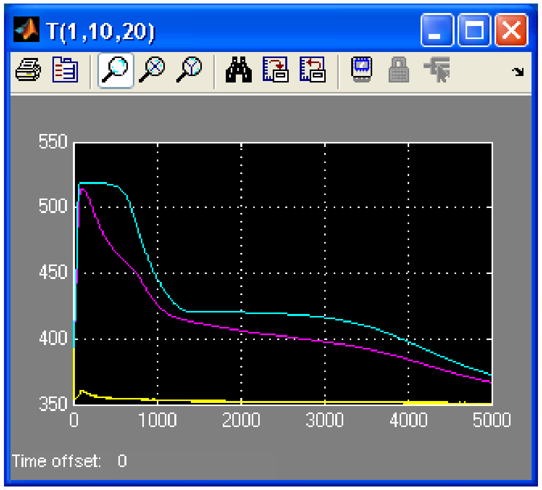
# Future Work

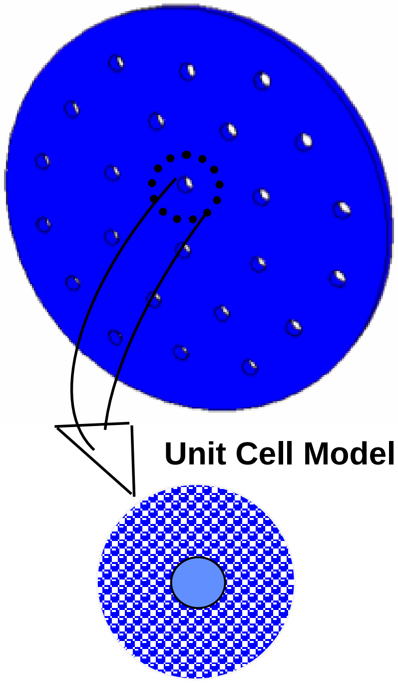
- Control model for management of heat from fuel cell to be used for MH discharge process
- Economic analysis should take into account the sale of electricity back to the utility
- Models to be developed
  - Metal Hydride
  - Battery
- Waiting for operational data to improve assumptions

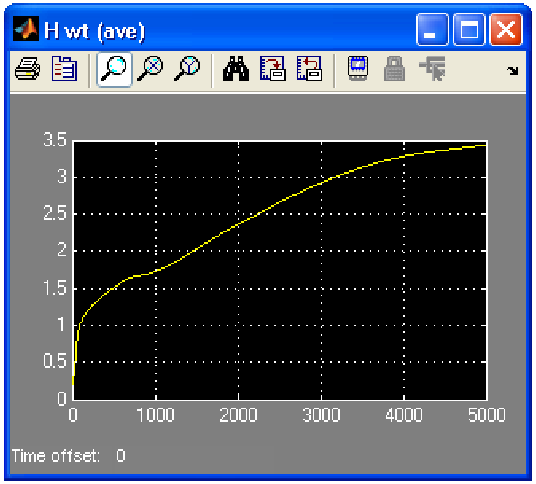
# EXTRAS

# Metal Hydride Model

- Unit-cell: generic 1-D radial geometry represents a region in bed
- Reaction kinetics with heat transfer
  - Variable transport properties
- Dynamic model for charge/discharge







- Energy balance

$$\rho c_v \frac{\partial T}{\partial t} = \nabla \cdot \vec{q} + \dot{q}$$

$$\vec{q} = -k_{cond} \nabla T$$

- Species kinetics

$$\frac{\partial C_i}{\partial t} = K(T) \cdot F(C) \cdot F(P)$$

$$K(T) = K_o \exp(-E/RT)$$

# Battery Model

- Based on Peukerts Equation for State of Charge of a battery
- Assuming battery has Peukerts constant of 1.2  average for a standard battery

$$Cp = I^k t$$

Cp = Battery Capacity (Ah)
I = Discharge Current (A)
k = Peukerts constant
t = Discharge time (h)

- Model will be developed to include electrochemical and thermodynamic effects and also economic analysis including lifetime and capital cost

# PV Model

- **Solar insulation model**
  - Clear-sky algebraic model uses geographic location
  - Adjusted model solar-to-electric efficiency = 9%
  - Correct monthly energy collection for number of cloudy days