Energy Management of Fuel Cells/Electrolyser Systems

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Lead academic partners

Overview:

- Electrolyser Operation Challenges
- Green hydrogen from renewables
- Renewable energy fluctuation
- Water electrolyser integration/control approaches
- Hydrogen compression energy
- Novel energy system control
- Fuel cells hybrid systems
- Why hybridizing?
- MPC control of FCHEV
- Energy management of Plug-in FCHEV

Green Hydrogen Production Challenges

- Maximize safety of plant and personnel
- Migrate, integrate and scale up
- Reduce production costs
- Ensure gas purity and precise metering
- Balance capital and operational spend
- Standardize automation and control systems across their product fleet
- Meet market standards
- Ensure user plant integration
- Lack of long-term operation and lifecycle management experience
- Lack of experience integrating the latest automation and control systems
- Delivered on-time, on-budget with low complexity
- Exploit economies of scale

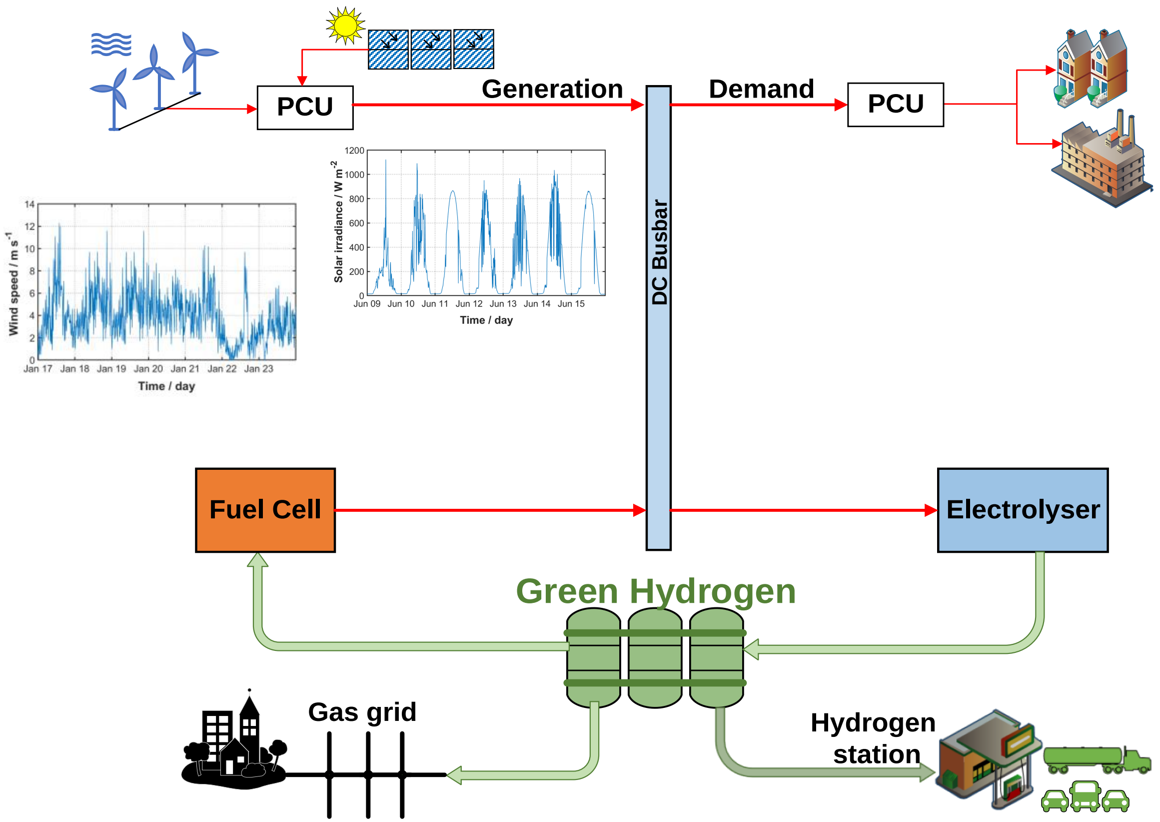
Ref: EMERSON_ Accelerating the Transition to Hydrogen Fuel

The impact of implementing the latest automation solutions:

- Increased scale to drive unit costs
- Appropriate levels of process control redundancy and safety
- Compliance with latest regulations, protocols and norms
- Increased electrolyzer system efficiency and lifespan
- Increased adaptability to fluctuating power supplies
- Greater power density and stack size
- Lower material costs and increase flexibility

Ref: EMERSON_ Accelerating the Transition to Hydrogen Fuel

Green hydrogen from renewables



- ➢ Convert surplus power into hydrogen
- ➢ Renewable energy variability
  - ➢ Deterministic component
  - ➢ Stochastic component
- ➢ Demand variability

Wind power variability

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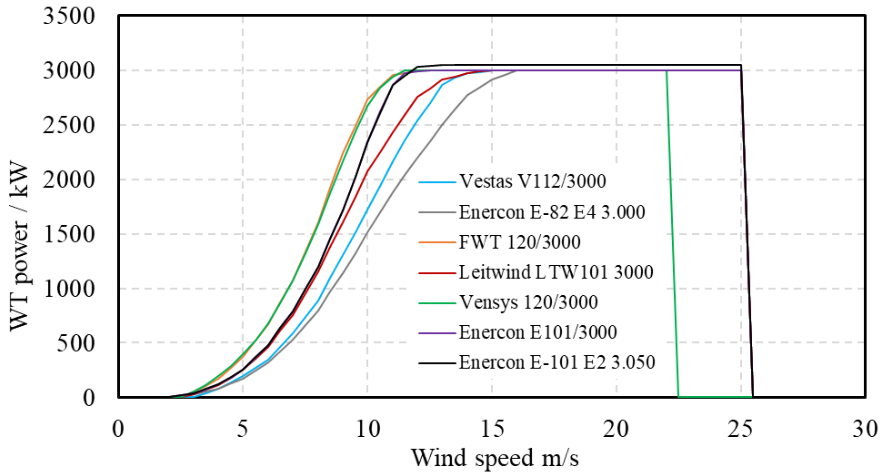
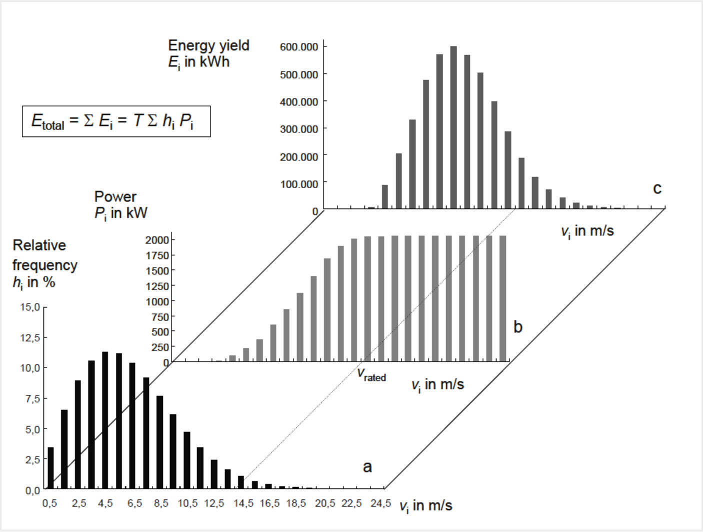
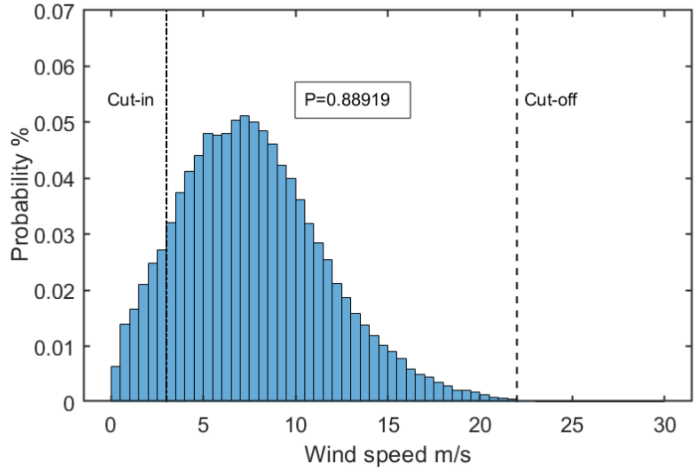
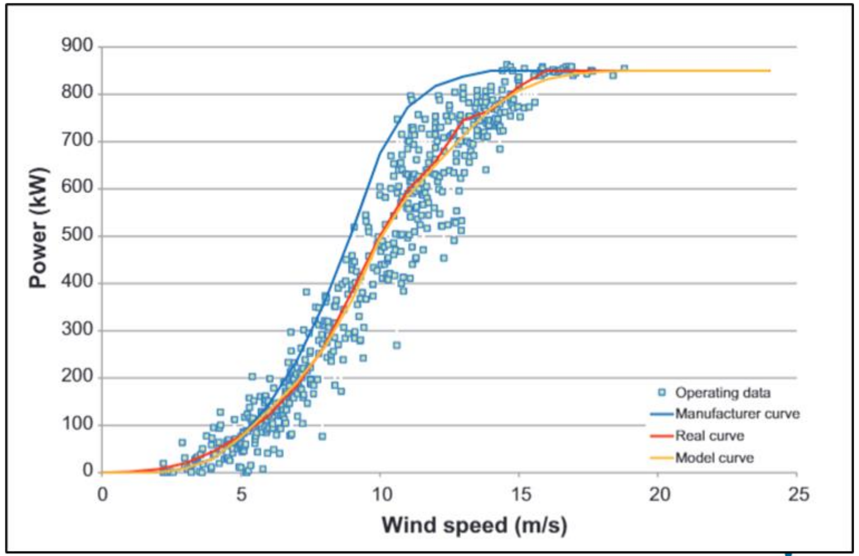


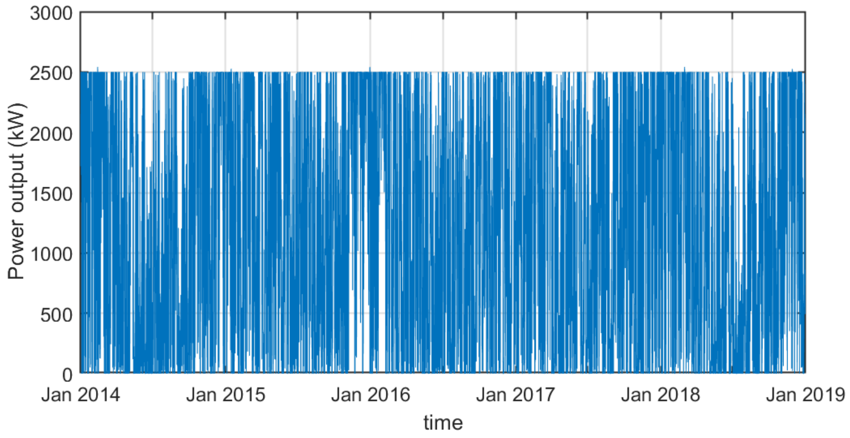


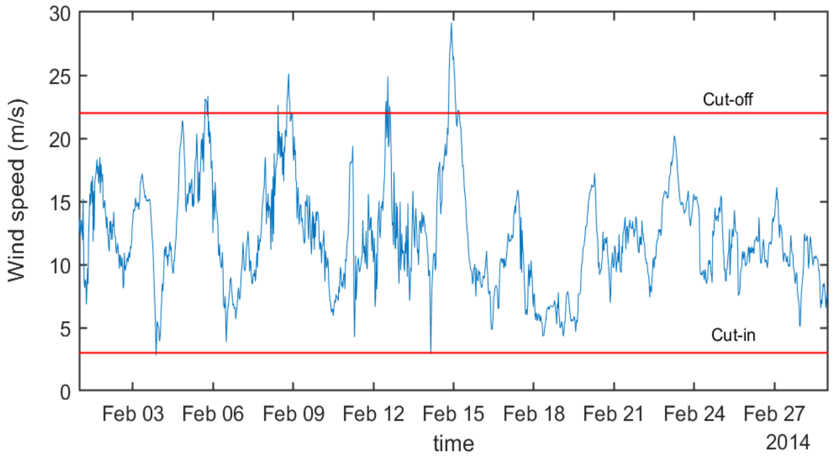


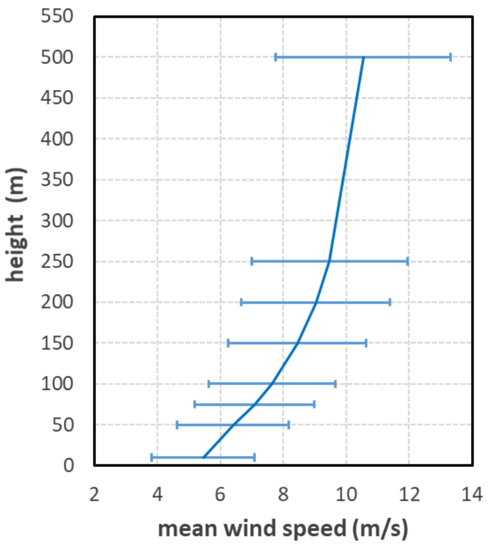


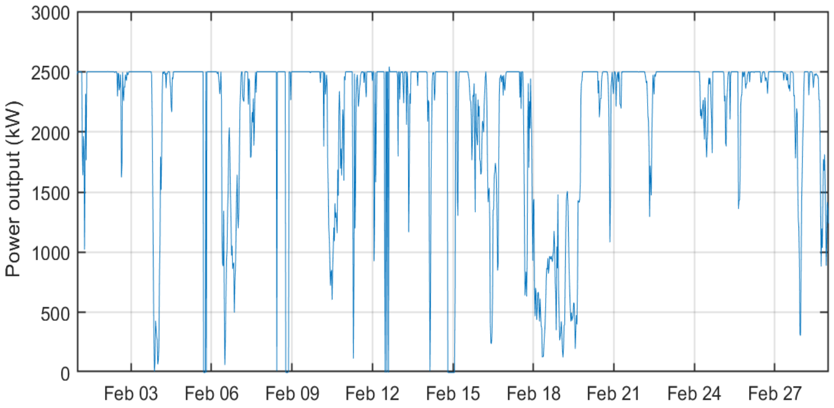
Comparison of WT manufacturer power curve, real data power curve and mathematic model curve

Wind energy variability





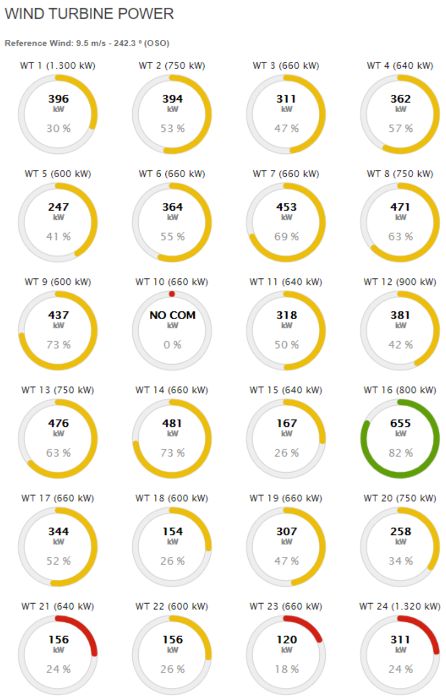




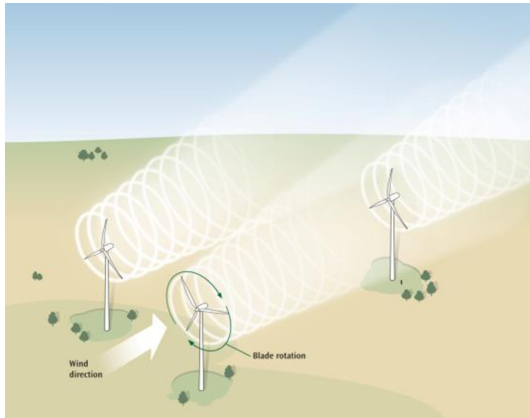
Wind energy variability

Example: Sotavento wind farm (Spain) 24 WT units

http://www.sotaventogalicia.com/en/real-time-data/instantaneous-wind-turbines

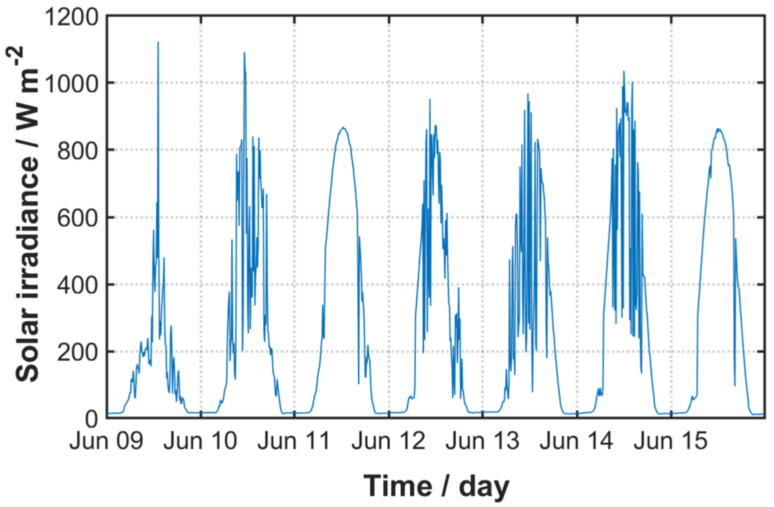


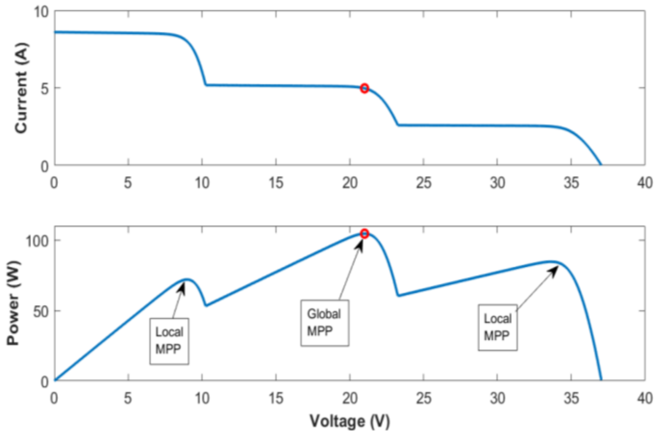
Windfarms: Wake



- Deterministic component
  - ✓ Seasonal wind speed & wind direction profile
- Stochastic component
  - ✓ Wind speed & direction variations
  - ✓ Windfarms wake
  - ✓ System components degradation

Solar energy variability





- Deterministic component
  - ✓ Daily profile
  - ✓ Seasonal profile
- Stochastic component
  - ✓ Partial shading (cloud index)
  - ✓ System components degradation

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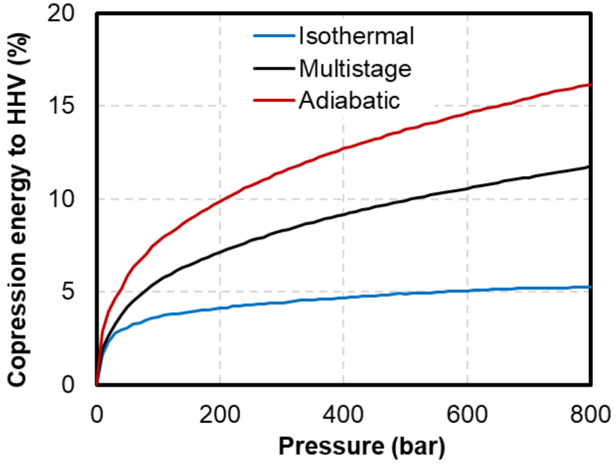
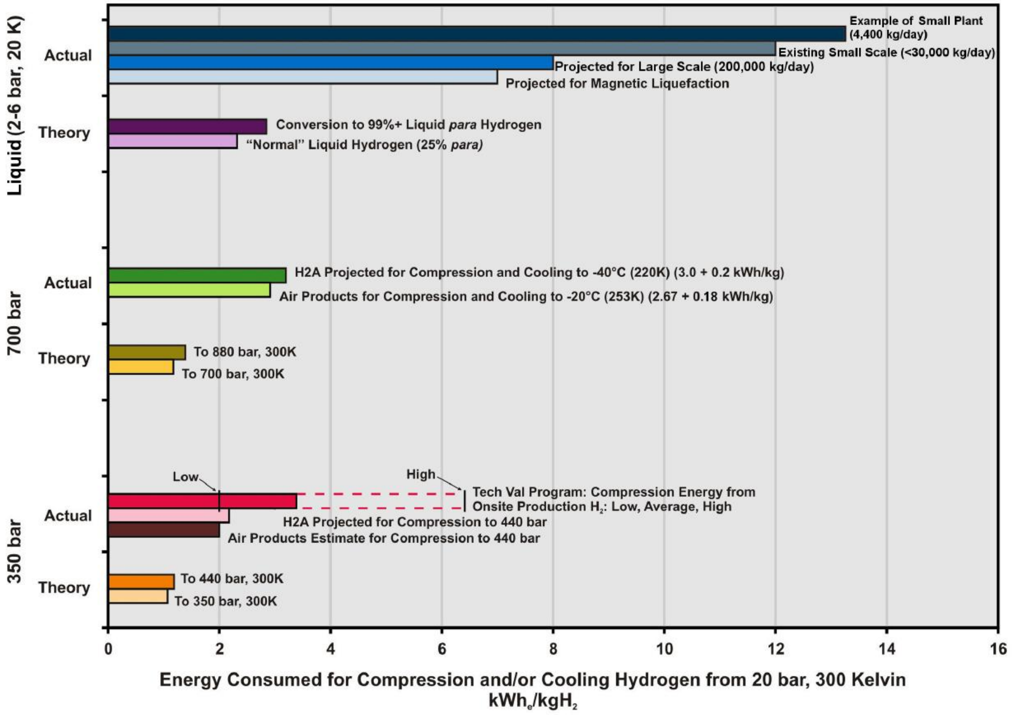
Hydrogen compression energy



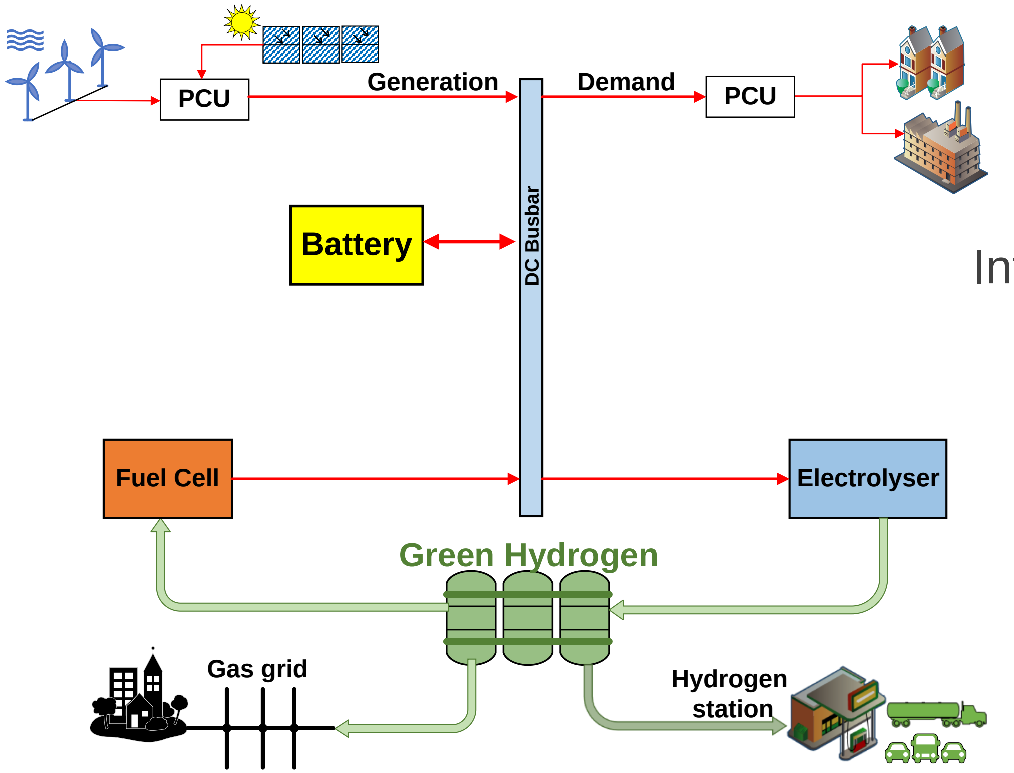
Energy required for the compression of hydrogen compared to its HHV (39.7 kWh/kg H2)

- @ 700 bar
- $\frac{\text{Compression energy}}{\text{H2 HHV}} = \sim 8\%$
- $\frac{\text{Compression energy}}{\text{Electrolyser energy}} = \sim 5.6\%$

DOE Hydrogen and Fuel Cells Program



H2 energy storage integration/control

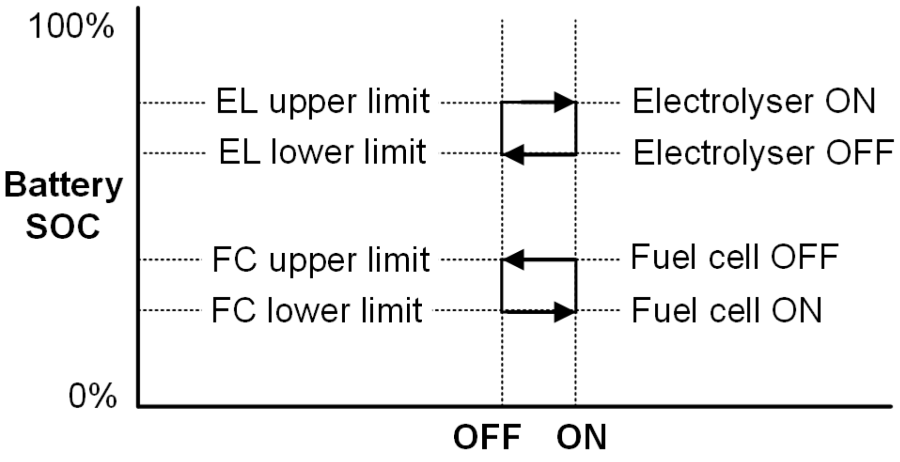


Integration/Control approaches:

- Battery hysteresis cycle
- Model-based scheduling
- Frequency Response

(i) Battery Hysteresis Cycle

Disadvantages / limitations



- On/Off control only
- Operate at fixed efficiency
- Huge battery size required
- Large-scale integration might not be feasible
- The battery is subject to intensive energy cycling (degradation)
- SoC is model-based → uncertainty (Battery technology dependant)

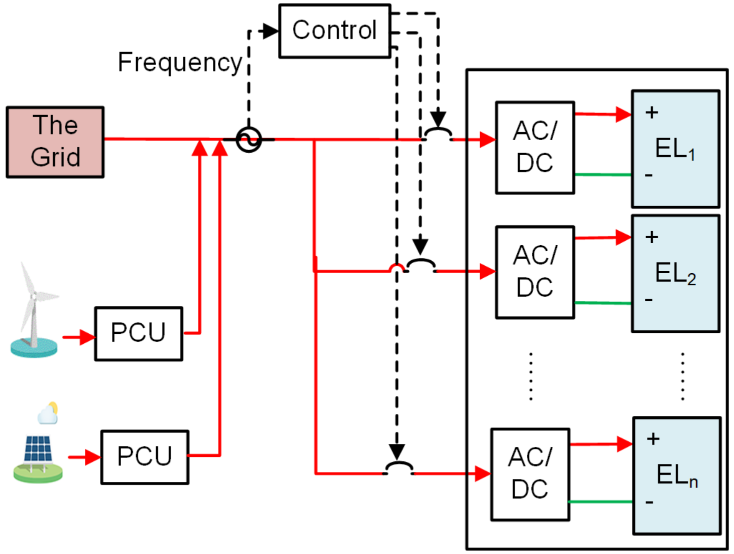
(ii) Model-based Scheduling

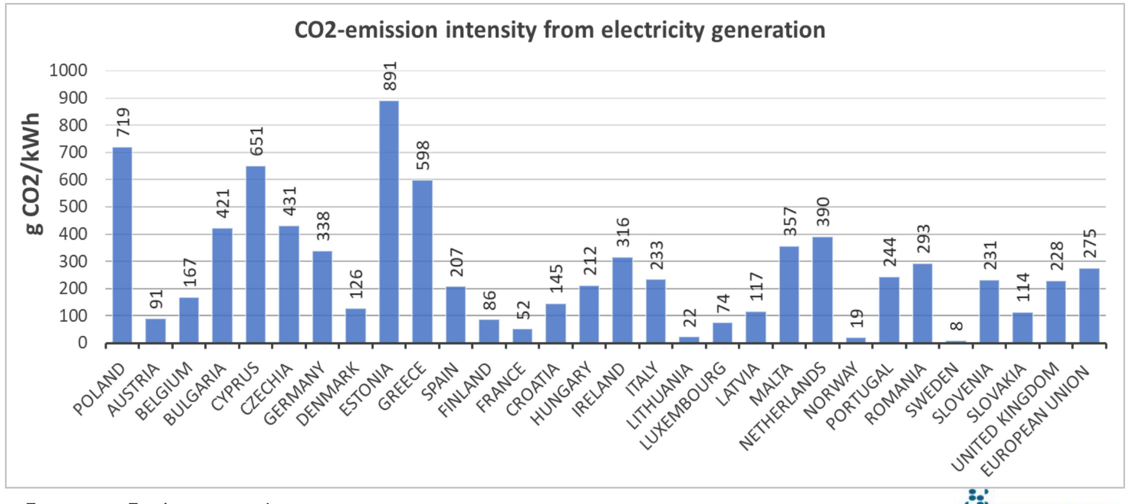
- Renewable generation prediction models (Feedforward)
  - Deterministic model only (Complicated models for stochastic component)
- Open loop control / No feedback
  - (or much delayed feedback based on battery SOC)
- Forecast for a day/week a head
- Forecast over large time intervals (30-60 min)
- Off-line control (pre-determined schedule)
- Battery as an energy buffer to mitigate forecast error
- Large battery size is still required (due to off-line energy balancing)
- Advanced forecast methods are required (to reduce uncertainty)
- Stochastic component of RE generation is still an issue
  - partial shading / PV panel degradation
  - Random wind gusts / turbine degradation / WT wake

$$\min J = \sum_{k=0}^{N} \alpha_1 \cdot {P_{fc}}_k^{\,2} + \alpha_2 \cdot {P_{ez}}_k^{\,2} + \alpha_3 \cdot {P_{grid}}_k^{\,2} + \alpha_4 \cdot {P_{net}}_k^{\,2} + \beta_1 \cdot \Delta {P_{fc}}_k^{\,2} + \beta_2 \cdot \Delta {P_{ez}}_k^{\,2} + \beta_3 \cdot \Delta {P_{grid}}_k^{\,2} + \beta_4 \cdot \Delta {P_{net}}_k^{\,2} + \gamma_1 \left(SOC_k - SOC_{ref}\right)^2 + \gamma_2 \left(MHL_k - MHL_{ref}\right)^2$$

(iii) Frequency Response

- Use the grid electricity
- Monitoring grid frequency
- Carbon footprint per kWh of grid electricity
  - EU grid 275 g CO2/kWh in 2019
- Non-green source (using electricity mix)
- No battery (advantage)
- ON/OFF control
- Fixed EL efficiency
- Freq. regulators on the grid
  - Fast EL response (PEM)

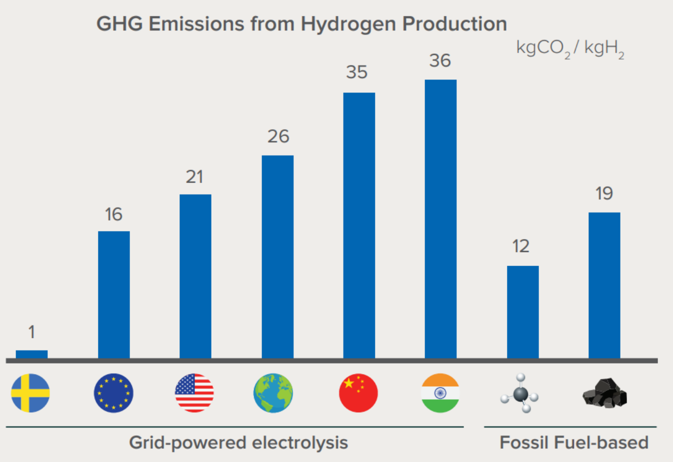




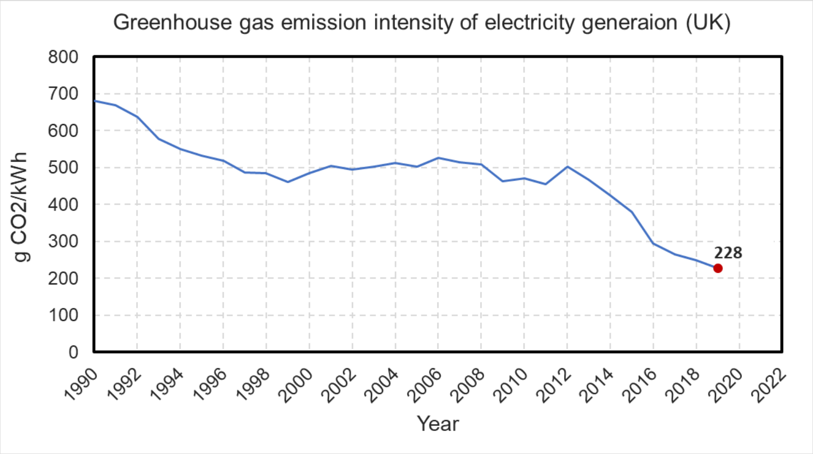
European Environment Agency

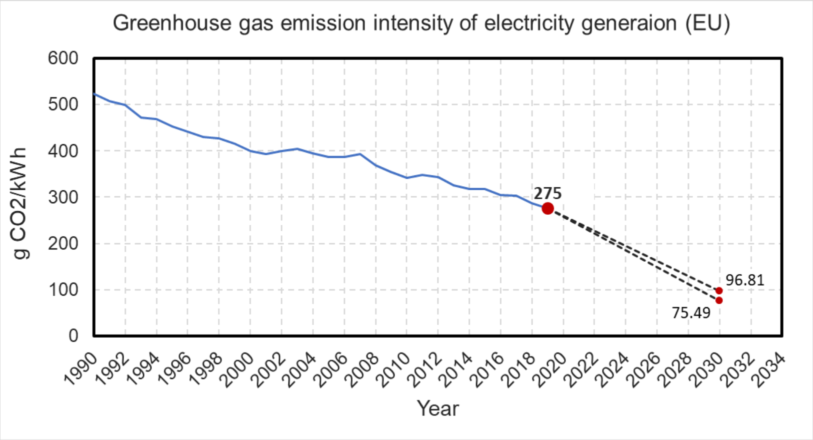
Carbon footprint per kWh

- Compare to Steam Methane Reforming (SMR)
  - SMR: 8-12 kg CO2/ kg of H2
- Electrolysis: 39.4 kWh/kg HHV with 70% eff.
  - ~ 56 kWh/kg H2
- EU grid (average): ~15.4 kg CO2/ kg of H2
- UK grid: 12.8 kg CO2/ kg of H2



Hydrogen's Decarbonization Impact for Industry





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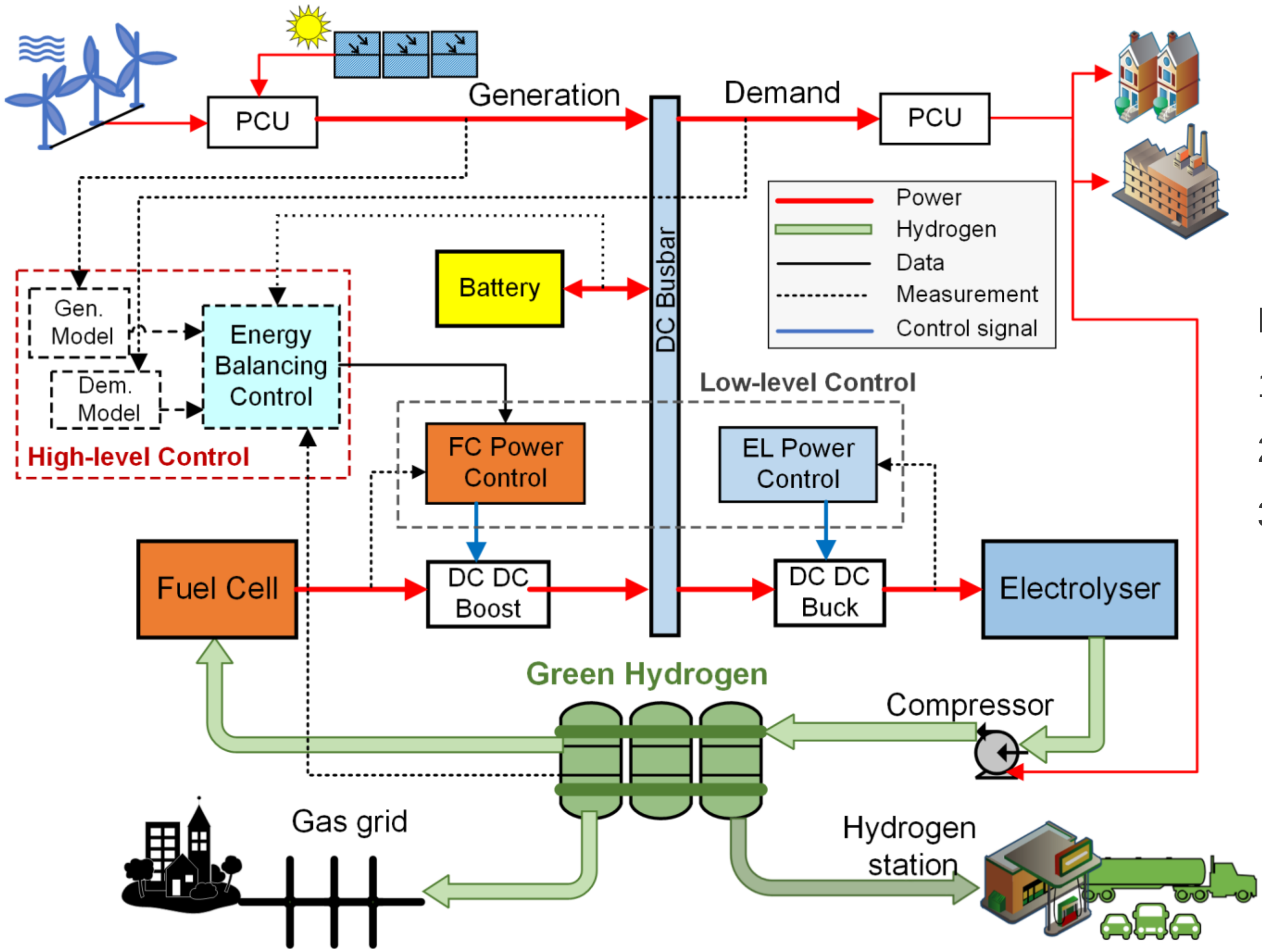
Novel energy system control (UoB)



Battery key functions:

1. Energy buffer
2. Sensor for prediction error
3. Feedback to compensate for model uncertainty

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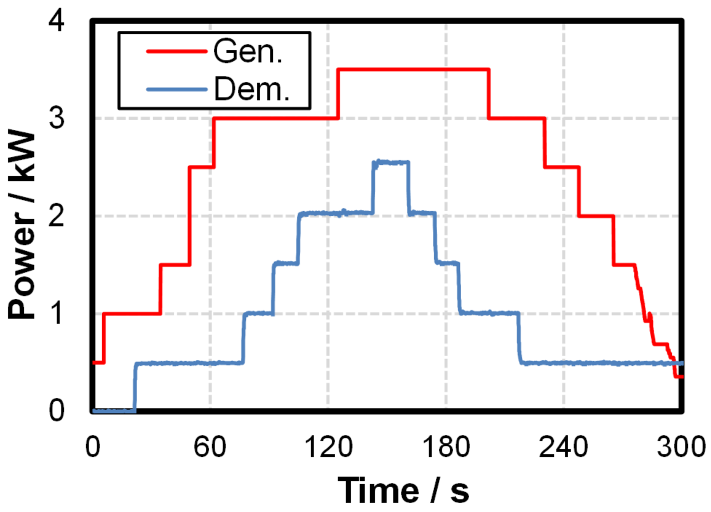
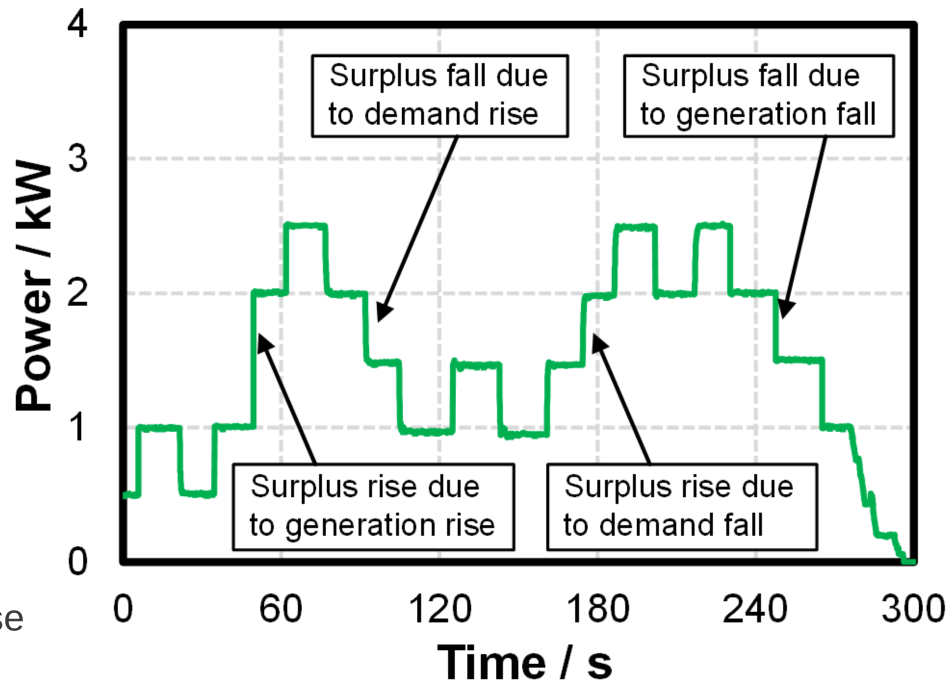
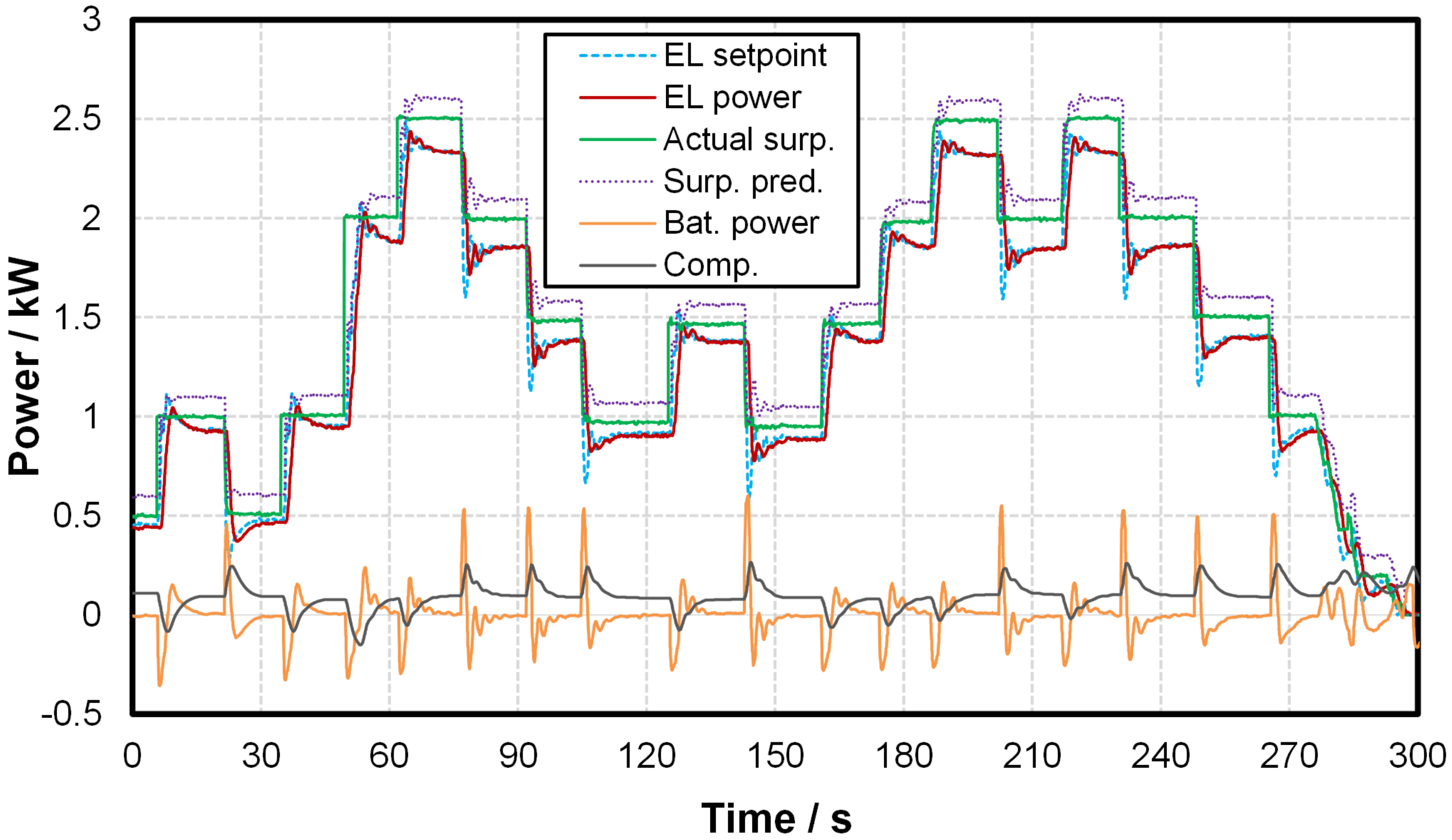
Energy balance performance



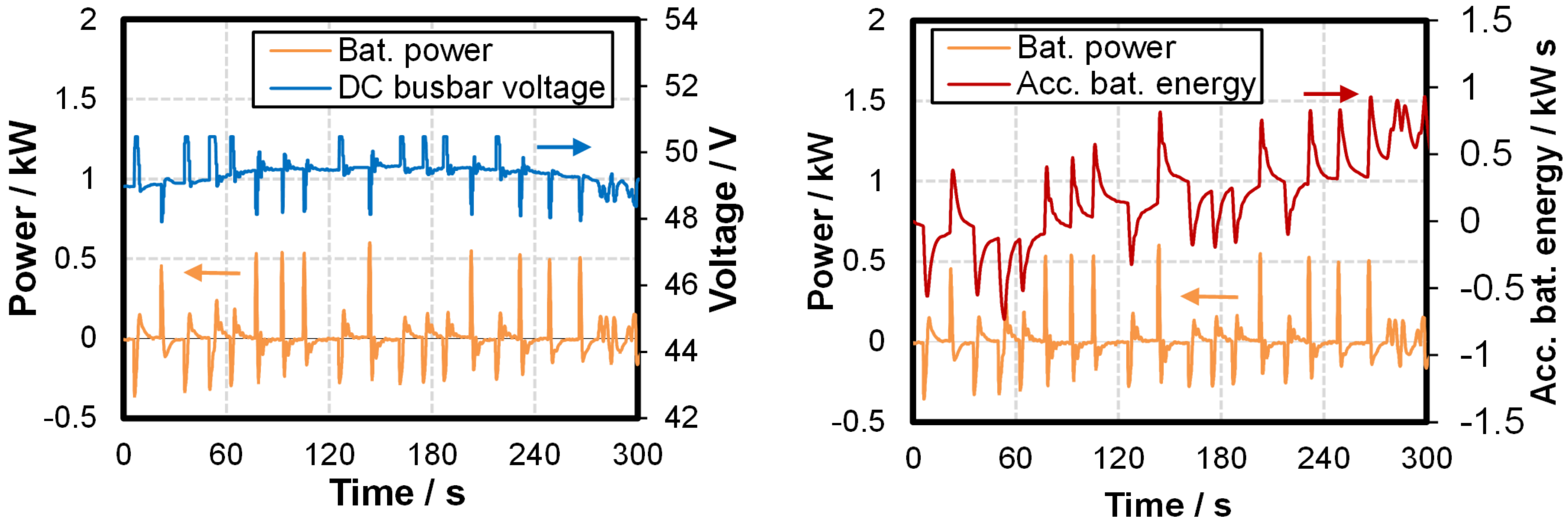


- **All possible scenarios**
  - I. A surplus rise due to a generation rise
  - II. A surplus fall due to a demand rise
  - III. A surplus rise due to a demand fall
  - IV. A surplus fall due to a generation fall

Energy balance performance



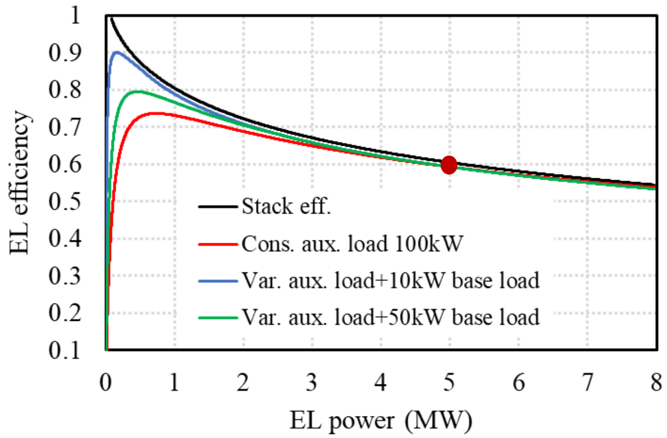
Energy balance performance

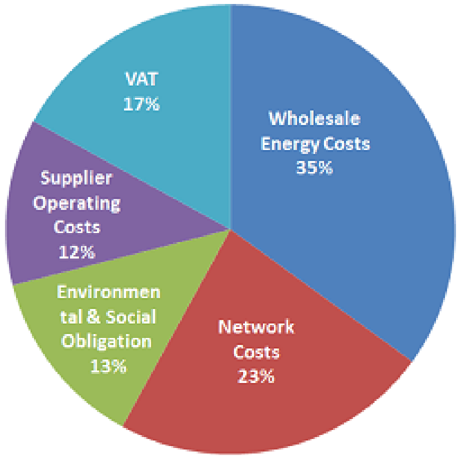


- Minimal battery energy required to recover the energy balance
- Battery voltage remains almost constancy (SOC constant)
- Maintaining high SOC of the battery (to act as energy buffer when required)
- Battery size can be estimated as maximum battery power spike over the transient time while recovering the energy balance

Specs of Energy Control System

- Variable electrolyser load
- Higher EL operating efficiency
- Higher H2 yield
- Real-time energy balance
- Surplus power always quantified & converted into hydrogen
- Simplified prediction models (generation & demand)
- Largely reduced battery size requirement
- No intensive battery energy cycling
- Grid scale integration is viable
- Extended battery life
- Fully automated control system
- Reduced CAPX and OPEX
- Lower cost of H_2 production
- Applicable to any RE mix

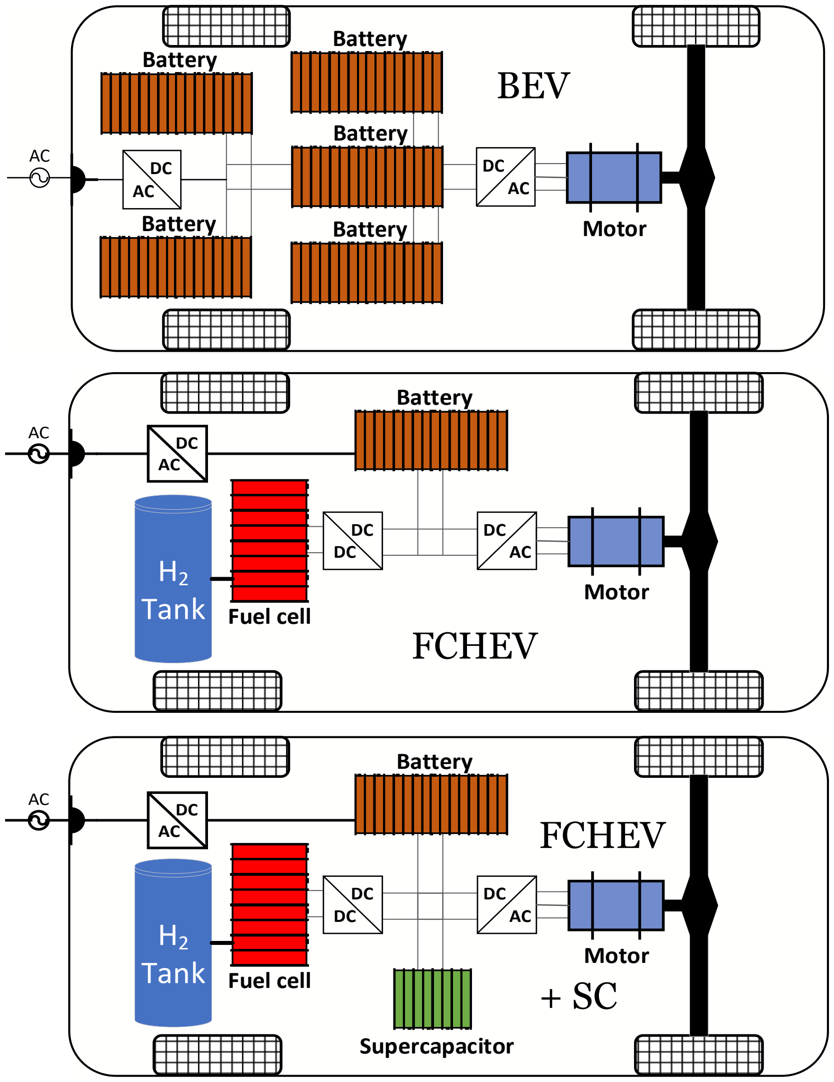


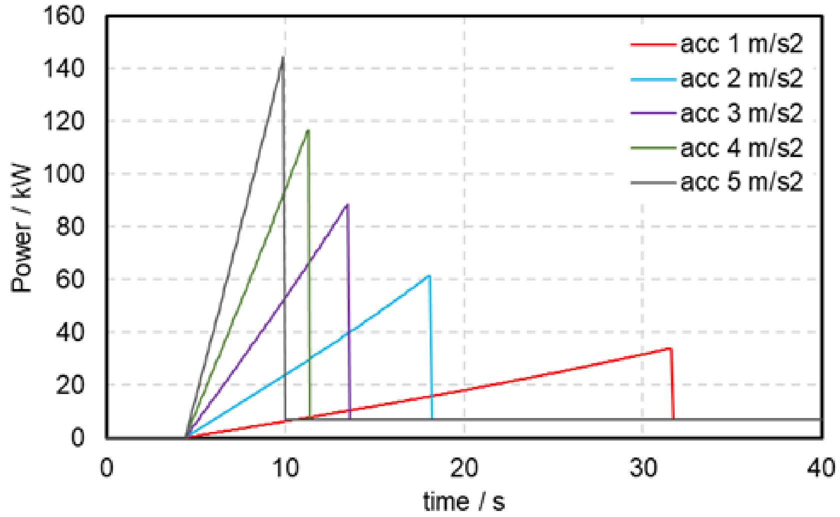


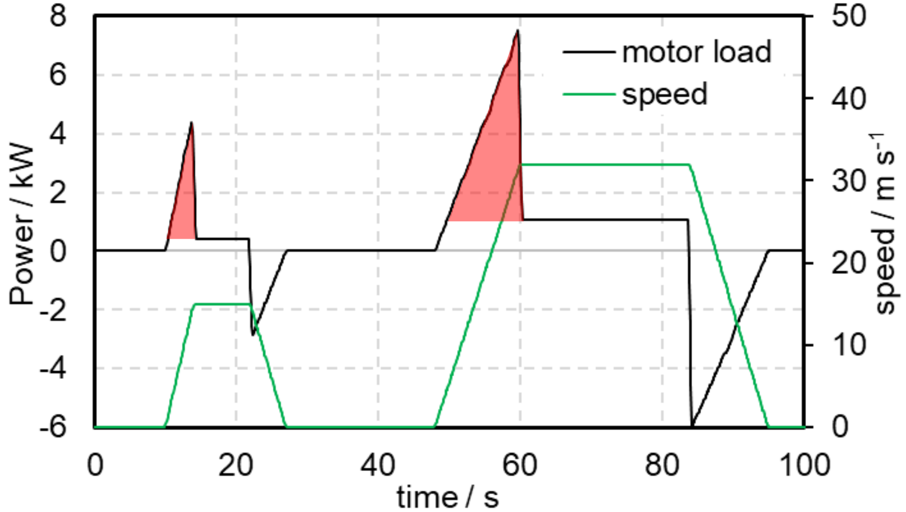
https://www.businessjuice.co.uk/energy-guides/what-makes-up-your-electricity-price/

Fuel Cells Hybrid Systems

Do we need Hybridisation?

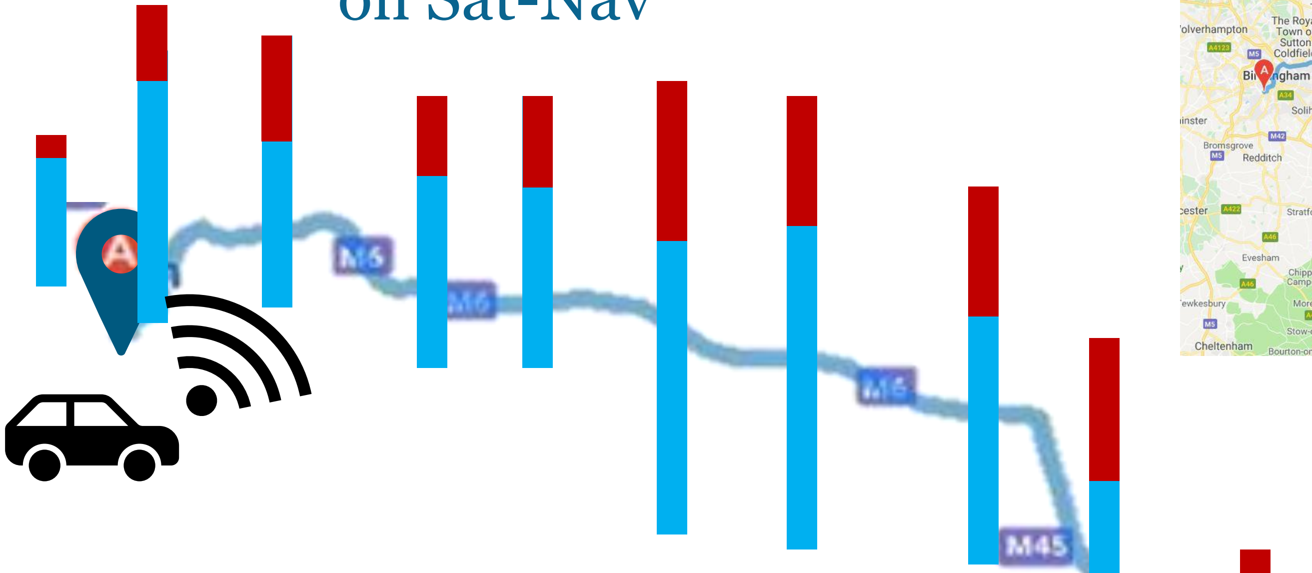


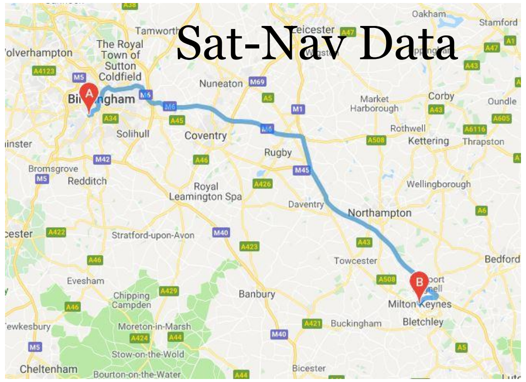




Multi power sources require energy and power management

Energy management with MPC based on Sat-Nav





FC power

Bat. power

- Model-based power prediction
- Updating prediction (unexpected traffic)
- Curtailed horizon (receding horizon in classical MPC)
- Implementing the current load measurement (load following concept)

Model Predictive Control

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Prediction models

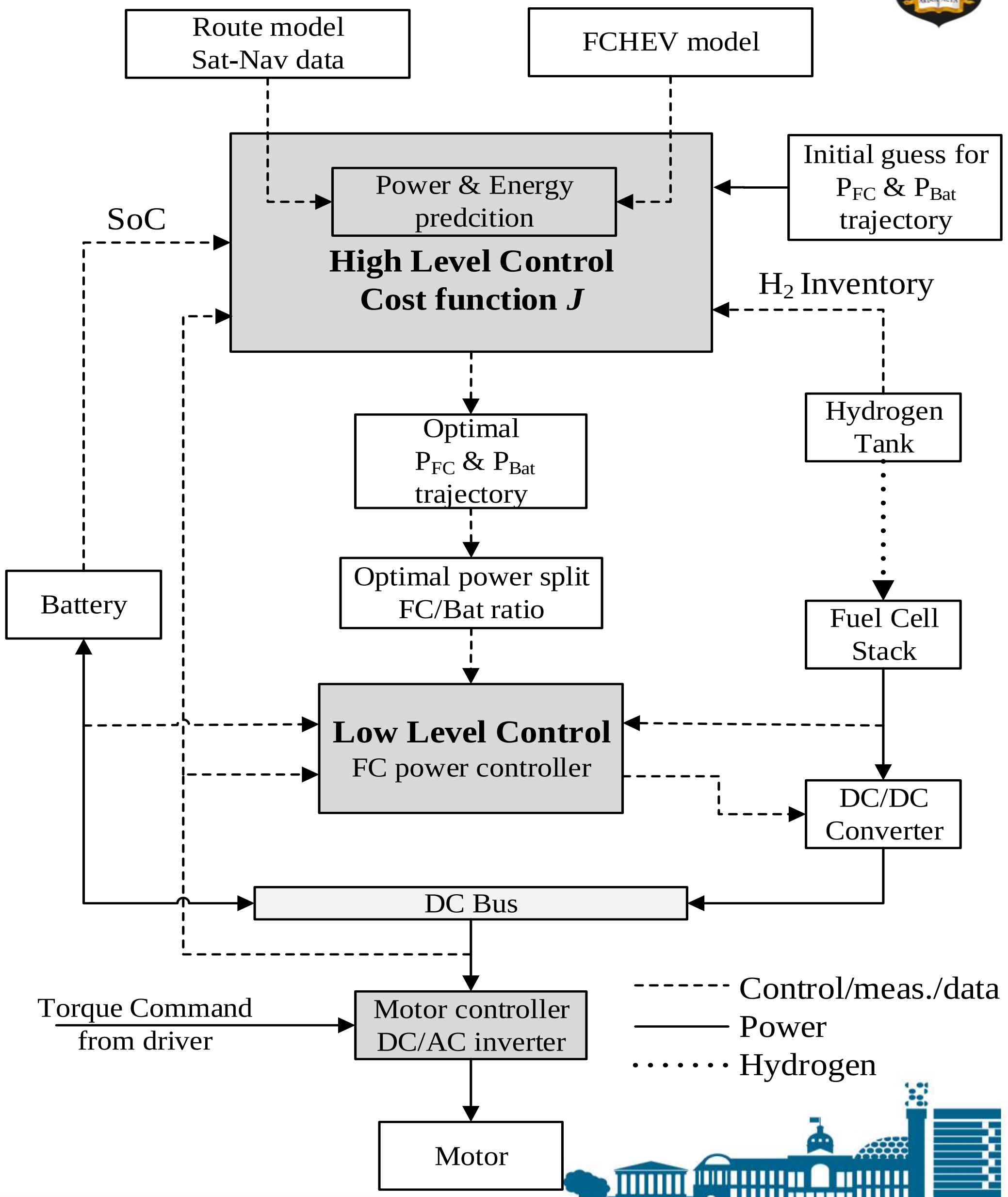
- EV power model

$$P_v(t) = \left(F_{aero} + F_{grade} + F_{rr} + F_i\right) v(t) \quad \begin{cases} F_{aero} = 0.5\,\rho C_d A_f v^2(t) \\ F_{grade} = mgsin(\theta) \\ F_{rr} = mgC_{rr} \\ F_i = ma \end{cases}$$

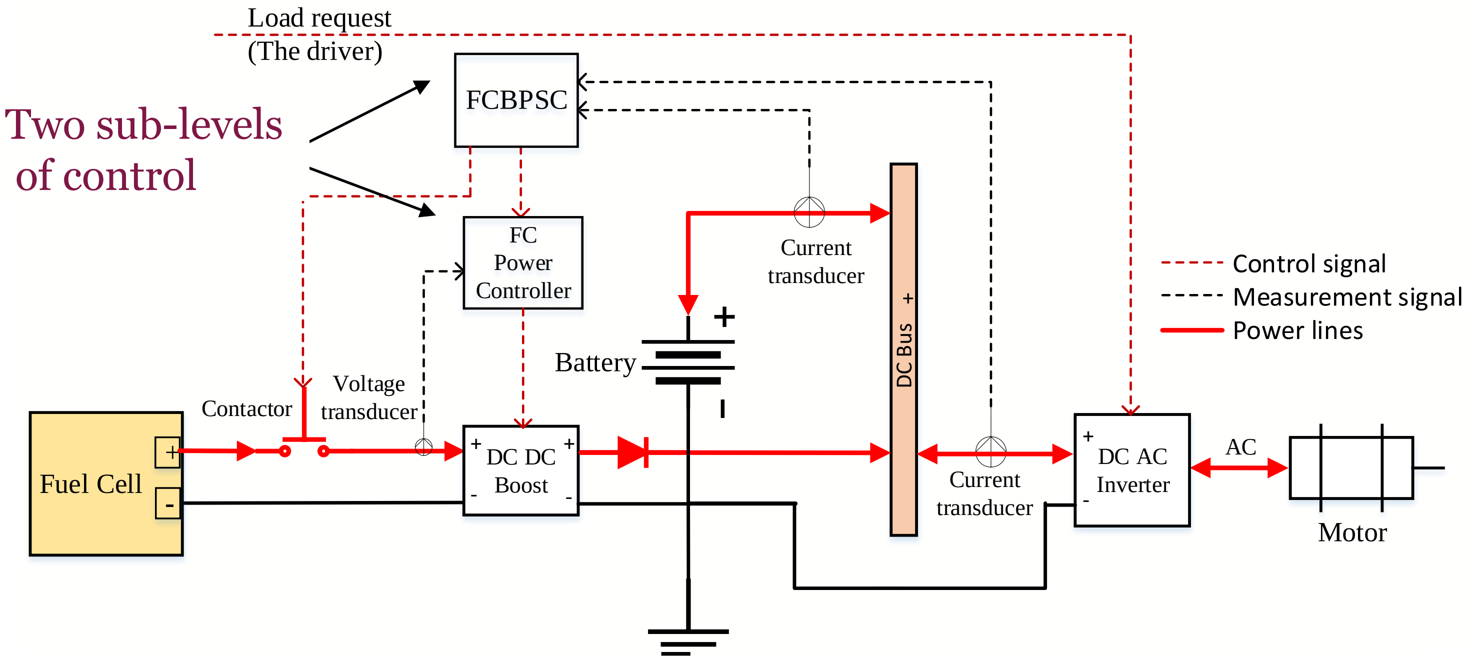
- Route model (Sat-Nav model)
  - Road segments
  - Segments length
  - Estimated speed → Estimated time (each segment)
  - Road angle

Model Predictive Control

- High-Level energy management control
- Low-level power split control
- Master/Slave control configuration
- SoC & H2 inventory updated in real-time
- Control-loop time is limited by optimisation solver
- More detailed model → higher computation burden → lower sampling rate
- Route model uncertainty is compensated for by passing FC/Bat power ratio to LLC



Low-level power split controller

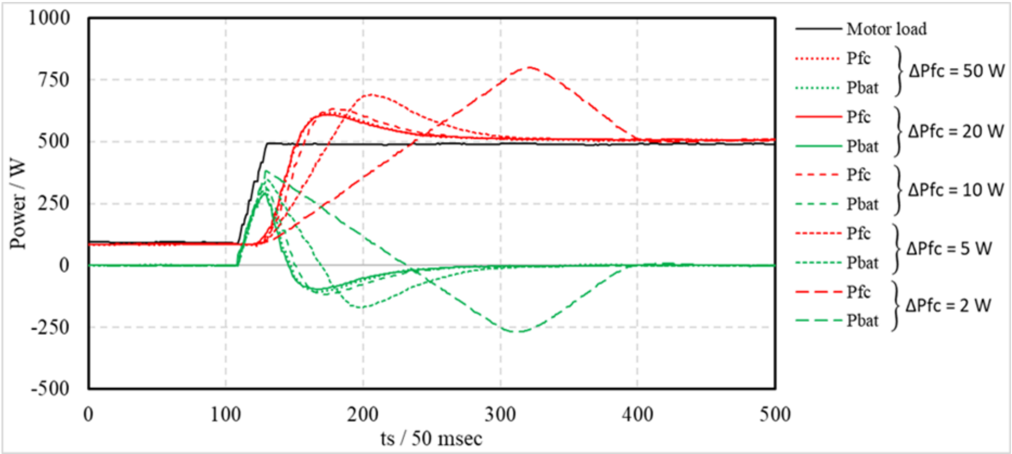


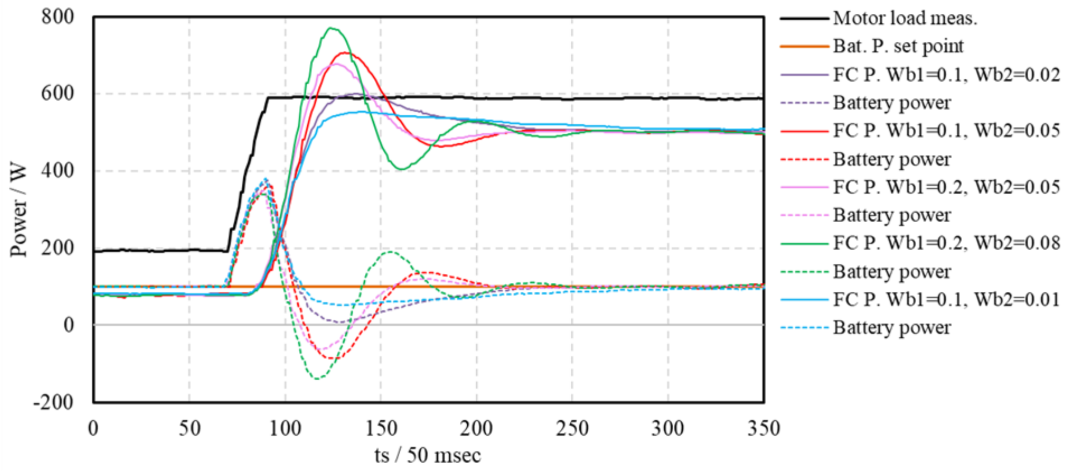
- FC & Bat. Share the same DC-bus
- Simultaneously supply motor load
- Load following model applied
- LLC is a slave controller to implement the optimal control orders of HLC.
- LLC consists of two sub-levels of control

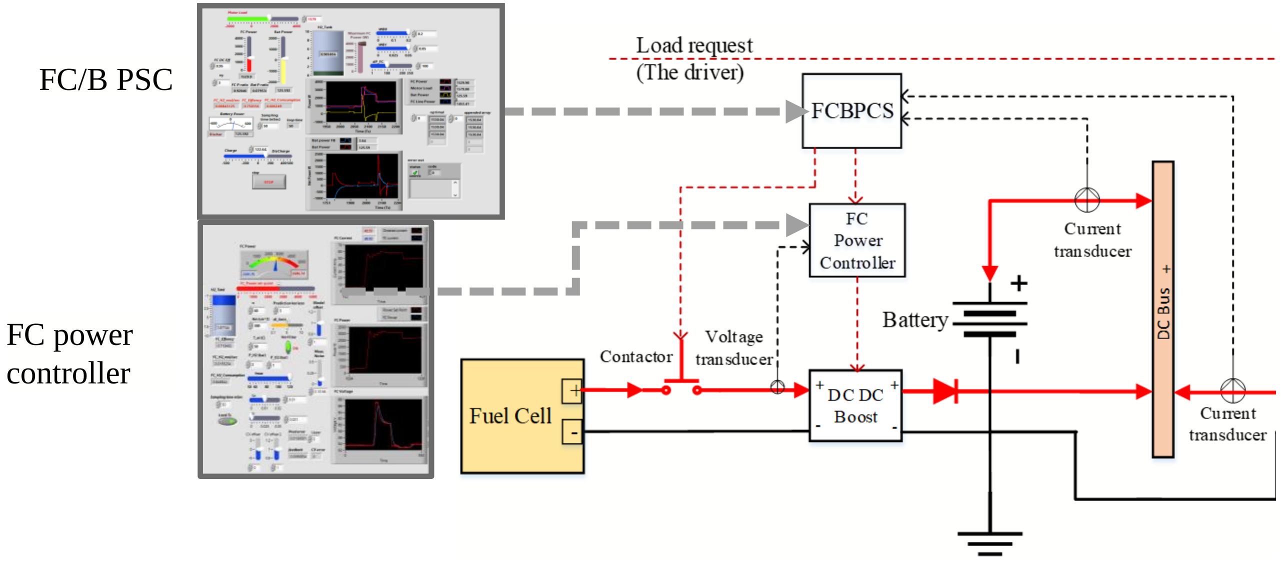
(i) FC/Bat power ratio control (ii) FC power control

Power Split Control NI Platform (Prototype)

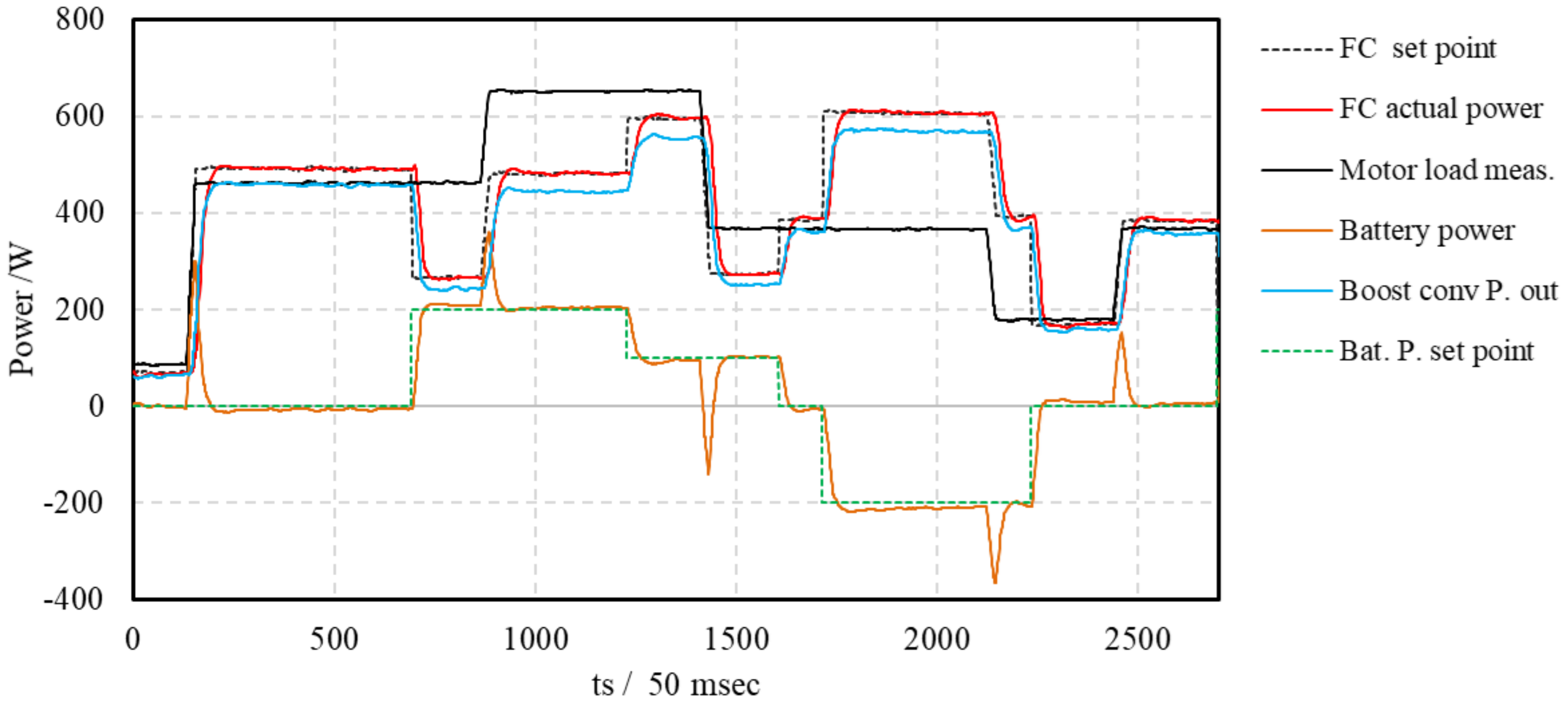
FC/B PSC tuning







FC/B PSC performance

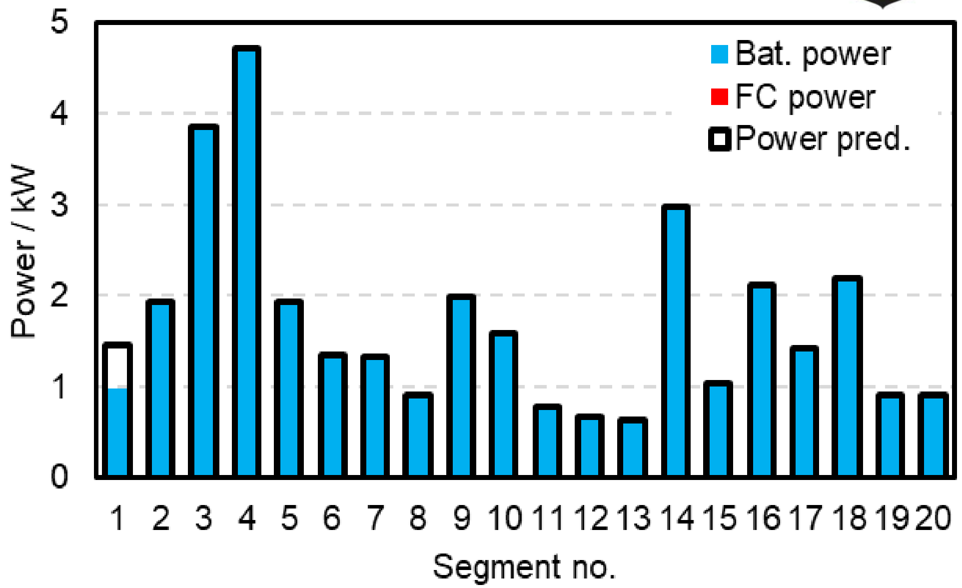


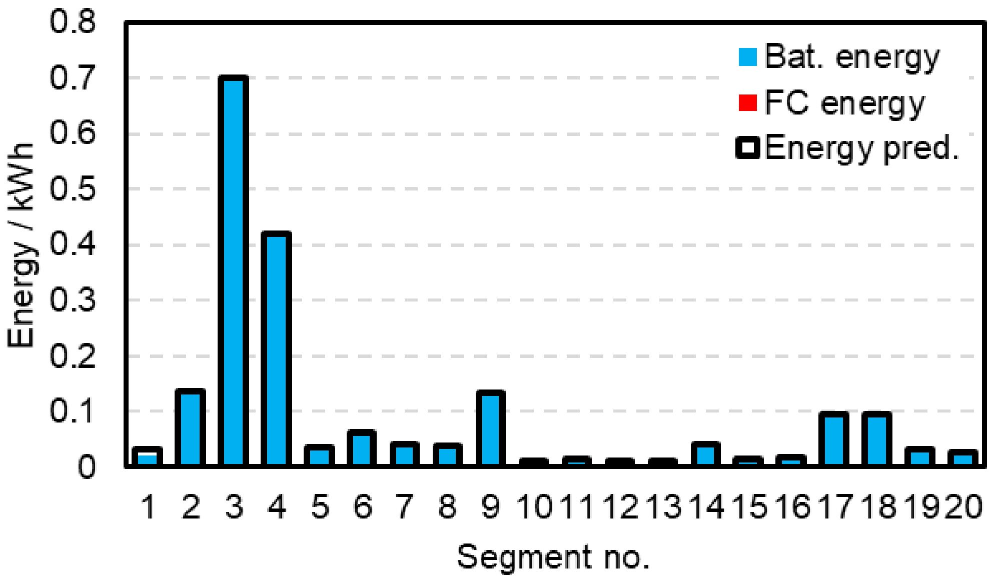
- Two power set points for the FC & the battery
- Zero battery power can be maintained although of motor load changes
- Non-zero (∓) battery power can be tracked and maintained
- Rise time and settling time can be tuned locally (independent from HLC)
- Solely one control element (FC DC-DC converter in current-control mode)

Energy management

Example 3: Short trip

- 20 segments (~20km)
- Initial and final SoC are enough to supply energy
- Only one power source is used
- Battery power is more cost effective
- FC is not used during this trip

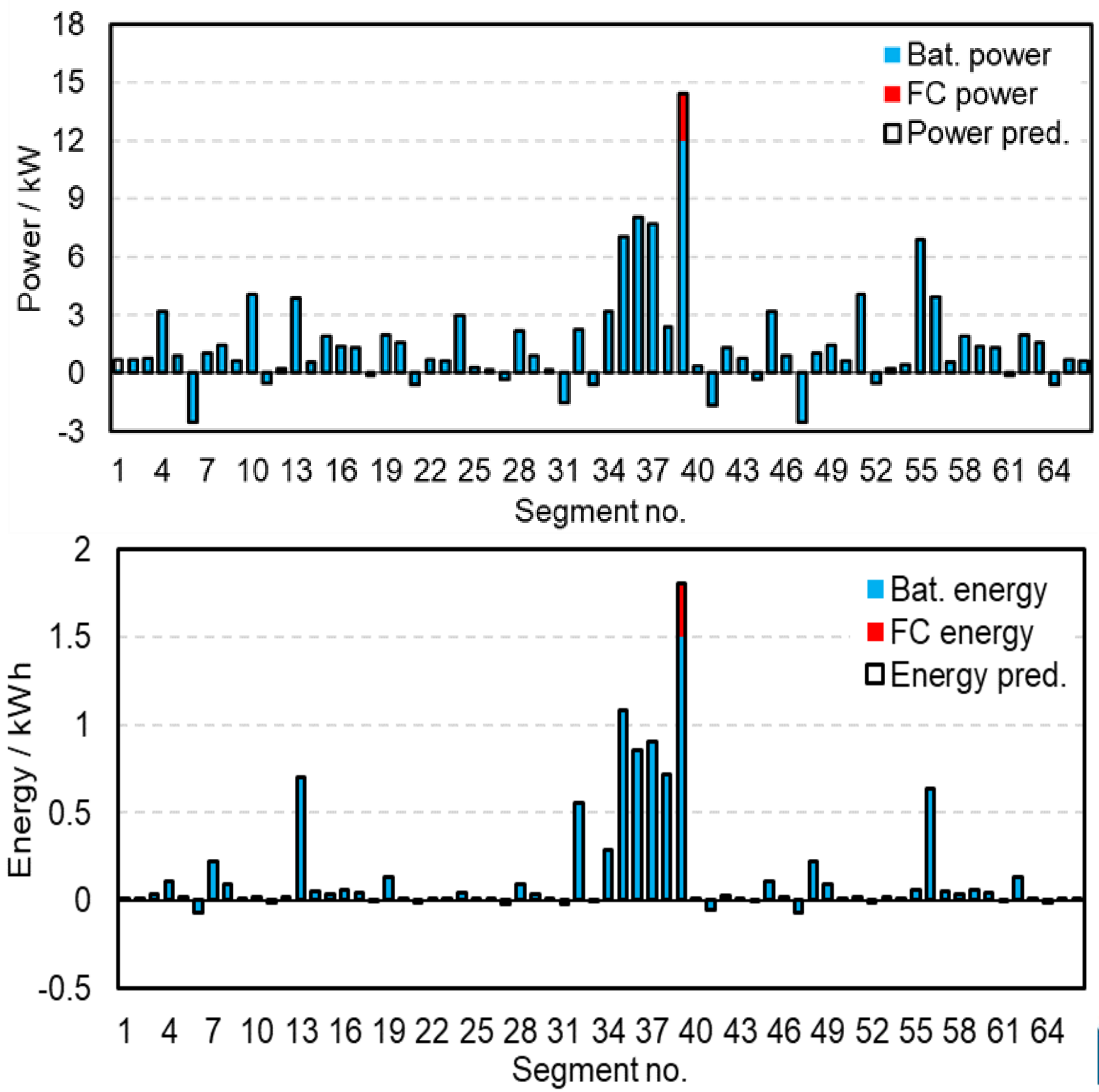




Energy management

Example 4: Long trip

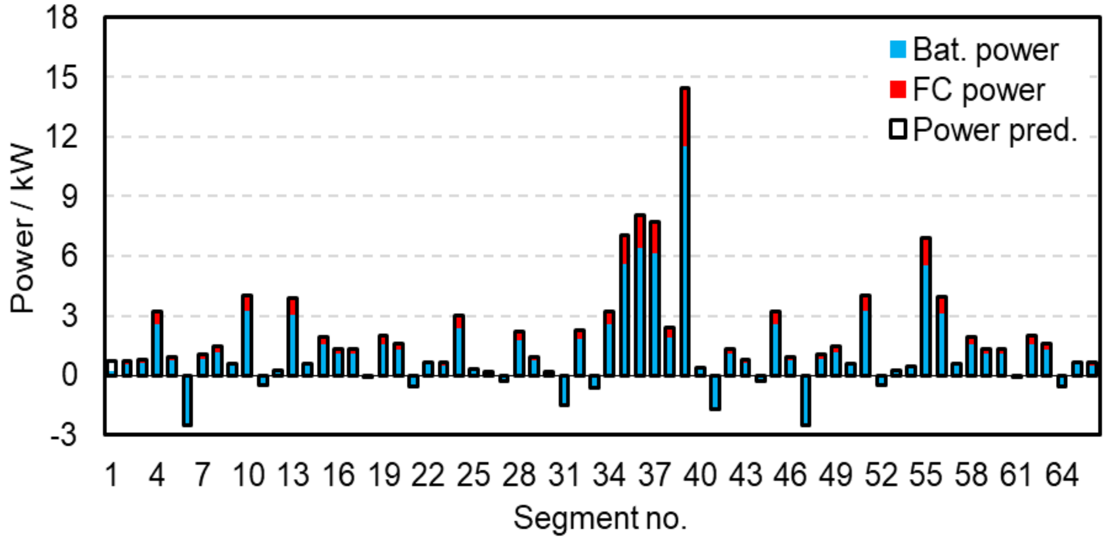
- 66 segments (~100km)
- Final SoC limit is **20%**
- Mostly enough SoC
- Mainly one power source is used
- FC power only dispatched to respect max battery power constraint
- Power management is applied together with energy management

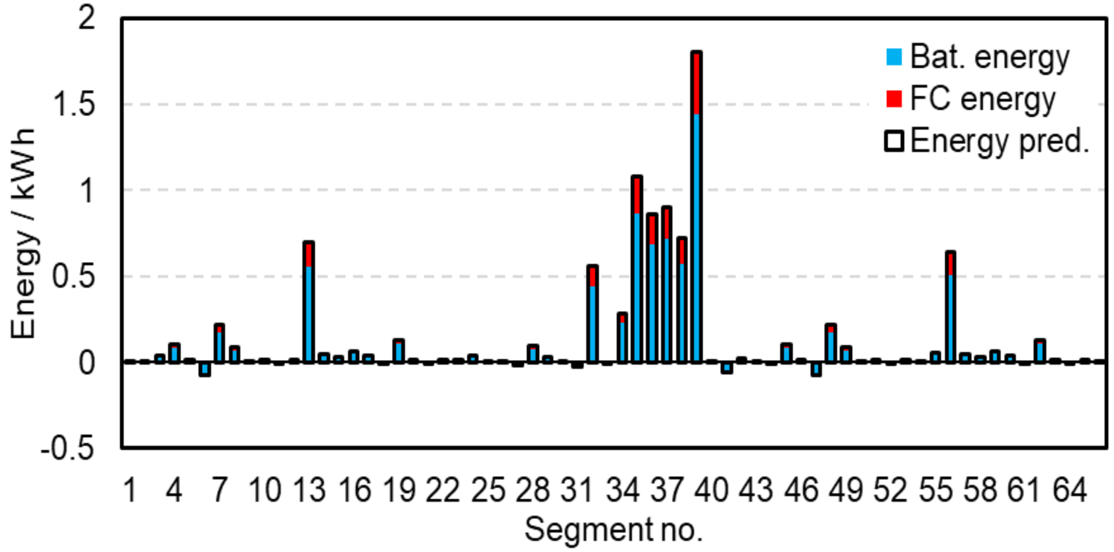


Energy management

Example 5: Long trip

- 66 segments (~100km)
- Final SoC limit is **40%**
- More use of FC power to verify final SoC limit
- FC/Bat PSR 1:6
- Power management is applied together with energy management





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Summary:

- Battery size (power and energy) can be reduced with hybridisation
- The need for energy & power management
- MPC algorithm applied based on vehicle and route models
- Multi-level control hierarchy
- Energy management through model-based constraints
- Power management through soft constraints of power limits

Future Work:

- Route model improvement
  - Sat-Nav data vs computational burden
- Controller implementation to real FCHEV powertrain
  - Cost effective micro-controllers vs optimisation capability
- Simplify the MPC algorithm (one-level control)
- Supercapacitor involvement (additional control objectives)
- Adapt to non-linear control when necessary
- Control objectives for non-plug-in configuration

Thanks for your attention
Questions?

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