# Fuel cell and battery hybrid system

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# Motivation

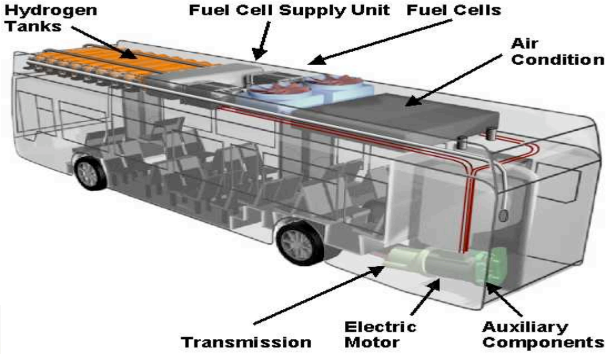
- Human portable applications
  - Light weight, small volume but longer operational life time
    - Low-power consumption
    - More energy density
- Wearable computers
  - 30W+ average and 70W+ peak power
- Fuel cell: next generation power sources
  - High energy density
    - A Li-Ion battery pack (in cellular phones): 250 Wh/L
    - A methanol based fuel cell: 4780 Wh/L
    - A hydrogen based fuel cell (NaBH4): 7314 Wh/L

# Fuel cell basics

- Fuel cell
  - Electrochemical energy conversion device
    - An electrochemical device that directly converts chemical energy in fuels into electrical energy without combustion
    - Uses external supply of fuel and oxygen
    - Produces just a water as a byproduct
- Advantages of Fuel cell
  - High energy density → longer lifetime for same weight/size
  - Instant recharge
  - No performance degradation during discharge
  - Clean, zero emission

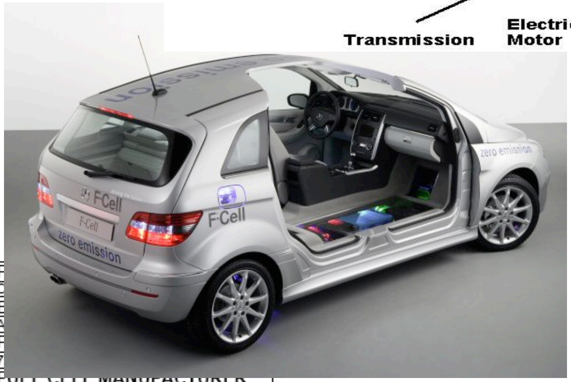
# Fuel cell basics

- Fuel cells in industries
  - Hydrogen fuel cell vehicles (FCVs)
    - Hyundai, GM, BMW, Toyota, etc.






2002
Santa Fe FCHEV



# Fuel cell basics

- Fuel cells in industries
  - Laptops powered by fuel cells
    - Samsung, LG, Toshiba, Motorola, etc.
    - Mostly DMFC
    - Functional demonstration



# Fuel cell basics

- Types of fuel cells

| Fuel Cell Type | Electrolyte | Anode Gas | Cathode Gas | Temperature | Efficiency |
|---|---|---|---|---|---|
| **Proton Exchange Membrane (PEM)** | solid polymer membrane | hydrogen | pure or atmospheric oxygen | 75°C (180°F) | 35–60% |
| **Alkaline (AFC)** | potassium hydroxide | hydrogen | pure oxygen | below 80°C | 50–70% |
| **Direct Methanol (DMFC)** | solid polymer membrane | methanol solution in water | atmospheric oxygen | 75°C (180°F) | 35–40% |
| **Phosphoric Acid (PAFC)** | Phosphorous | hydrogen | atmospheric oxygen | 210°C (400°F) | 35–50% |
| **Molten Carbonate (MCFC)** | Alkali-Carbonates | hydrogen, methane | atmospheric oxygen | 650°C (1200°F) | 40–55% |
| **Solid Oxide (SOFC)** | Ceramic Oxide | hydrogen, methane | atmospheric oxygen | 800–1000°C (1500–1800°F) | 45–60% |

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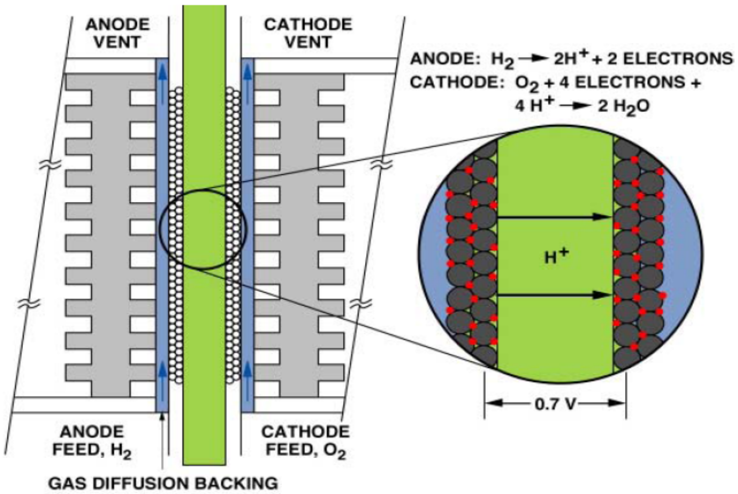
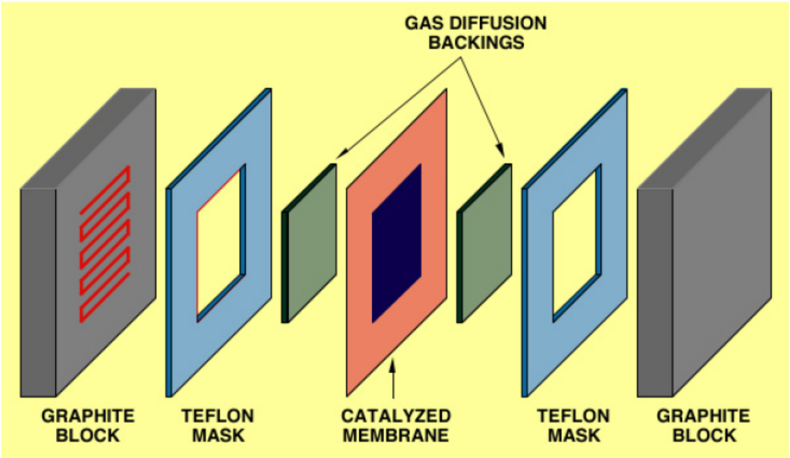
# Fuel cell basics

- Fuel cells for portable systems
  - Both types have their own advantages/disadvantages.
  - PEMFC (Polymer electrolyte membrane fuel cell)
    - Use $H_2$ as a fuel
    - Require fuel processing to generate $H_2$
      - The extraction of H2 from Sodium Borohydride ($NaBH_4$) seems to be a promising solution.
  - DMFC (Direct methanol fuel cell)
    - Use methanol directly as a fuel
    - Relatively low efficiency and shorter membrane lifetime

# Fuel cell basics

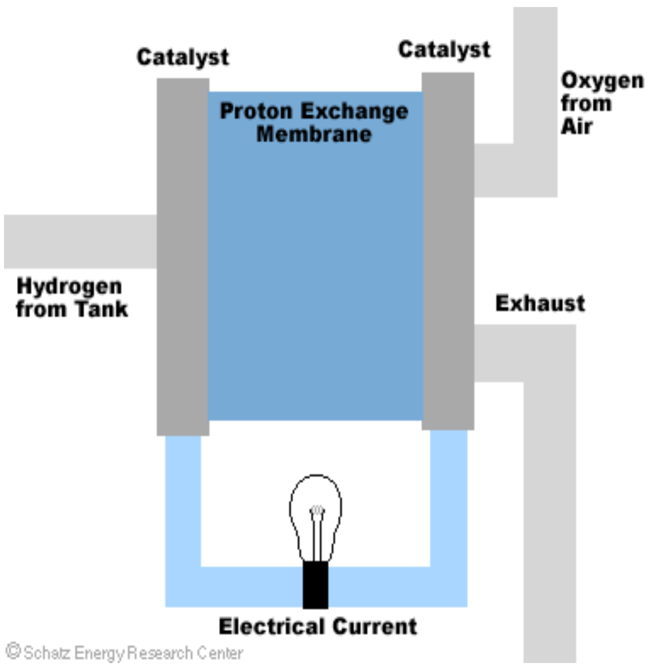
- PEMFC components
  - An ion exchange membrane
  - An electrically conductive porous backing layer
  - An electro-catalyst (the electrodes)
  - Cell interconnects and flowplates

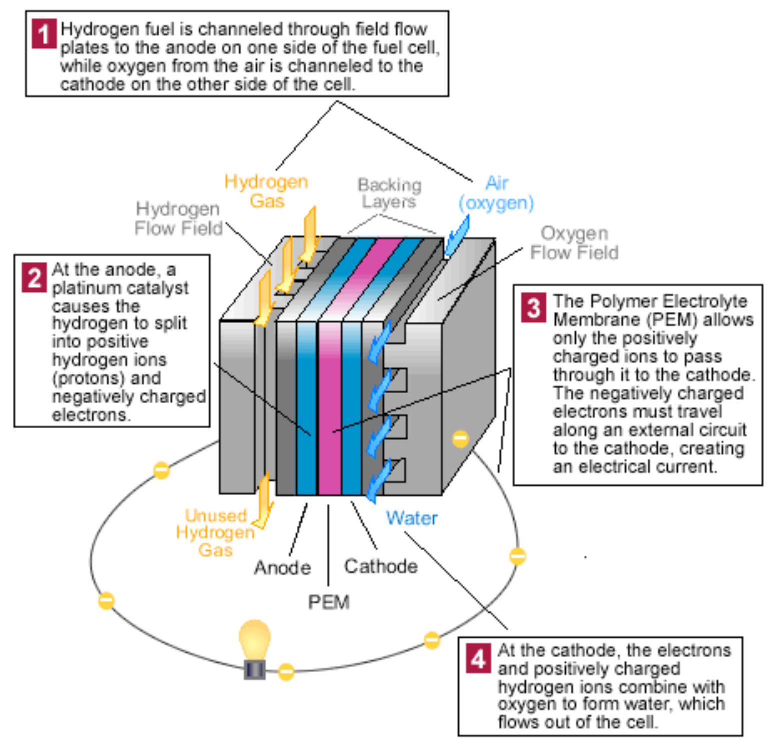


# Fuel cell basics

- PEMFC operation
  - Oxidation at anode: $2H_2 \rightarrow 4H^+ + 4e^-$
  - Reduction at cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$



# Work in progress

- Fuel cell system design issues
  - Stack/cell/membrane
    - Develop more efficient and durable membranes and electrodes
  - Fuel generation/processing
    - Find easier and more convenient ways to obtain $H_2$
  - System control techniques for efficient operation
    - Include battery management, fuel flow control, temperature management, humidity management, and water management
    - Optimize the fuel consumption, the system size, the response time, etc. according to the applications such as vehicles, residence, portable electronics
      ➔ More studies on system control techniques, especially for portable electronics are required

# Work in progress

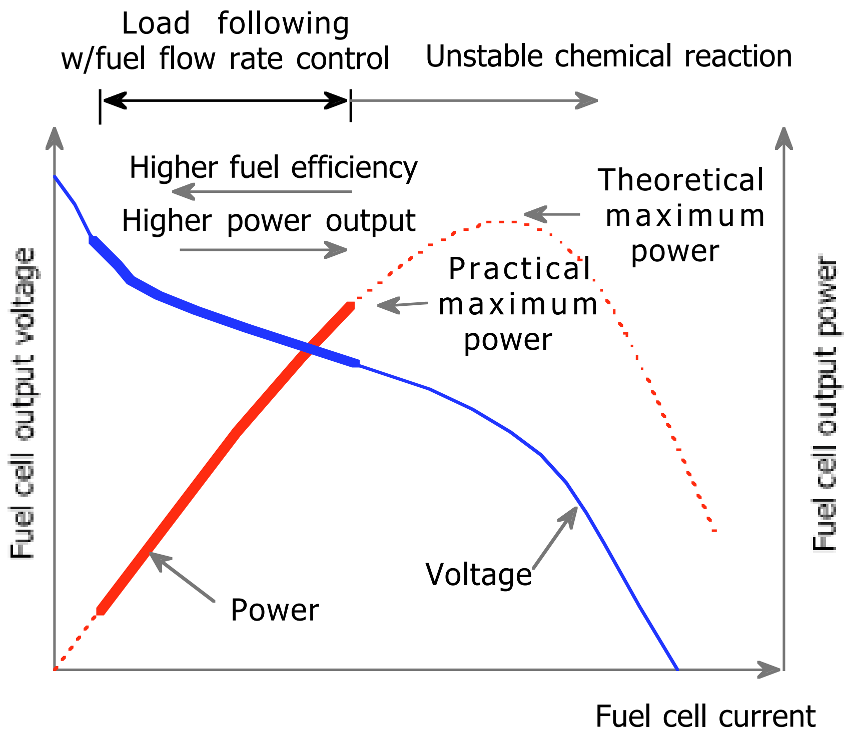
- Most previous work is in the context of hybrid automobiles
- No prior work on system-level optimization of fuel cell powered embedded systems

**Comparison with automobile and embedded applications**

| *Features* | *Automobile applications* | *Embedded applications* |
|---|---|---|
| Primary loads | Traction motor | Processor, memory and peripherals |
| Power generation from the load | > 100 Amps for seconds | No |
| Load dynamics | > 10 miliseconds | 1 miliseconds |
| Fuel flow control by load variation | Moderate | Very difficult |
| Load scheduling | Not applicable | DPM and DVS |
| Load type | Symmetric | Asymmetric |
| Joint fuel cell and load control | Not applicable | Desirable |
| Operating temperature | > 60◦ centigrade | 45◦ to 60◦ centigrade |
| Power requirement | Best effort | Guaranteed |
| Battery cycle life | Important | Critical |

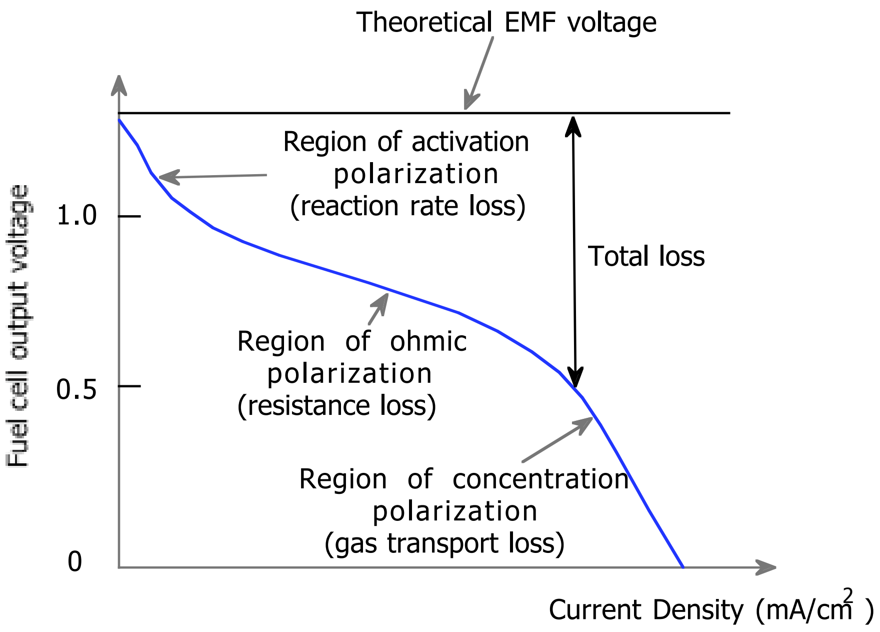
# Fuel cell and battery hybrid

- Fuel cell characteristics
  - The cell output voltage is largely dependent on the load current
  - The cell efficiency is proportional to the cell output voltage
  - Efficiency = (Operating cell voltage)/(Ideal cell voltage (1.23V@PEM))



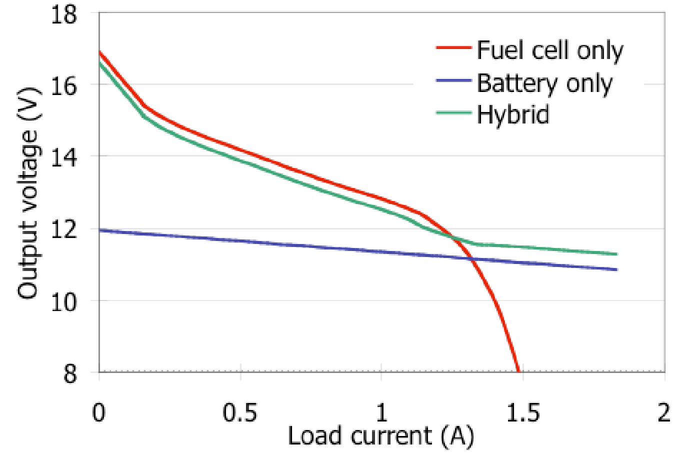
# Fuel cell and battery hybrid

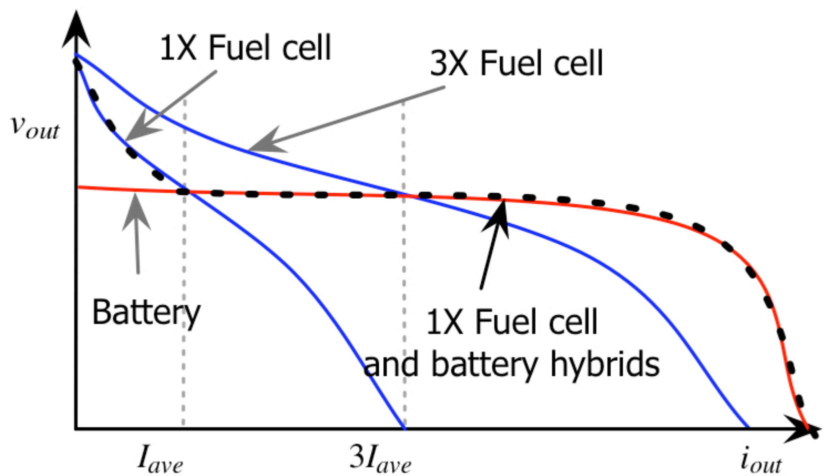
- Fuel cell characteristics
  - Activation-related losses
    - Electrochemical reactions
  - Ohmic losses
  - Mass-transport-related losses
    - Finite mass transport limitations rates of the reactants and depend strongly on the current density, reactant activity, and electrode structure

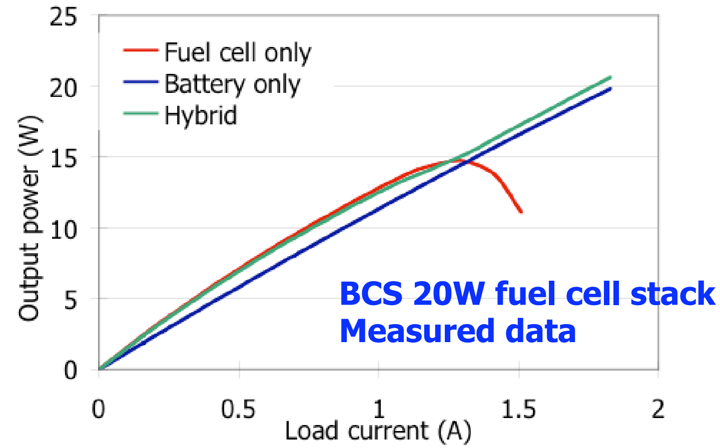


# Fuel cell and battery hybrid

- Motivation of hybrid system
  - Power density vs. energy density
    - Fuel cells: low power density, but high energy density
    - Batteries: high power density, but low energy density



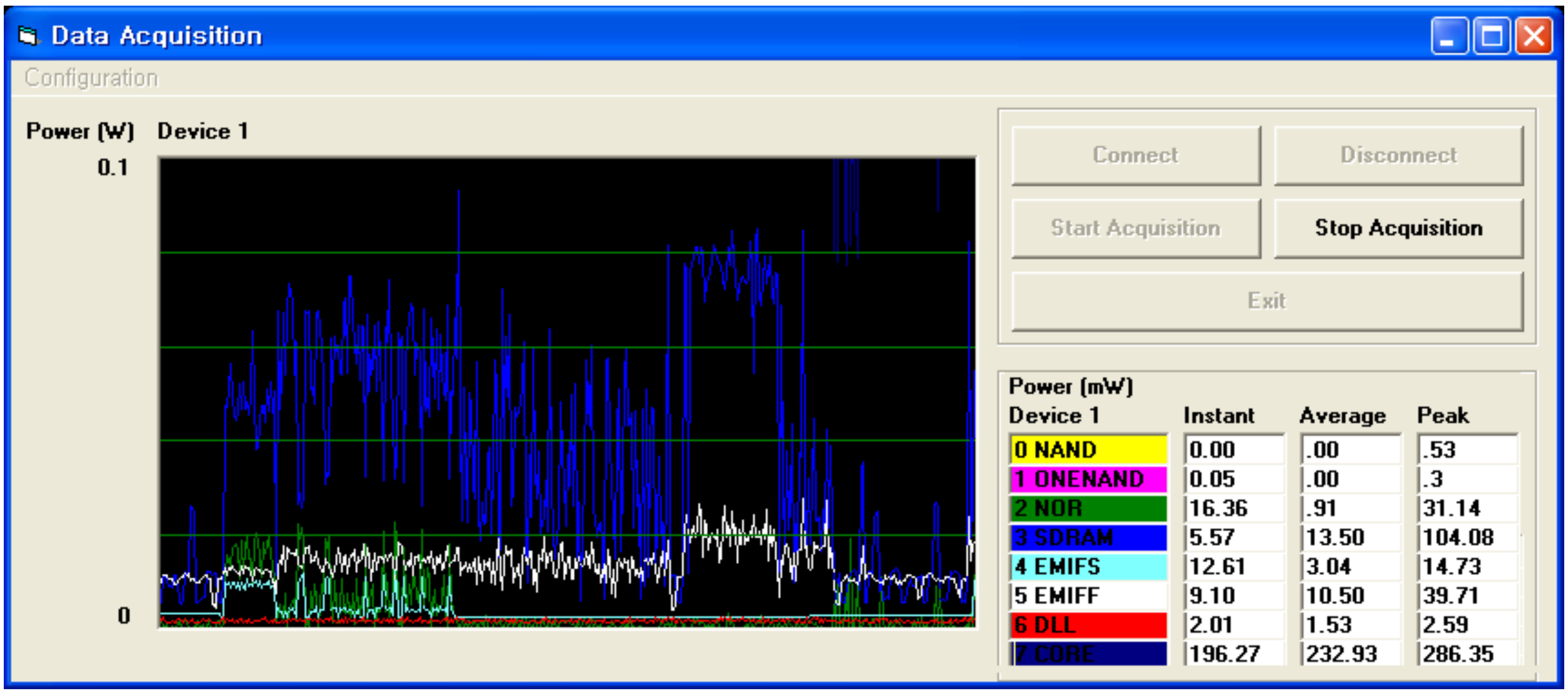



# Fuel cell and battery hybrid

- FC and battery hybrid systems for portable electronics applications
  - Power range
    - A few dozens of milli-Watts to hundreds of Watts
  - Very low supply voltage ranges
    - 3.3 V @ 350 nm, 2.5 V @ 250 nm, 1.8 V @ 180 nm, 1.2 V @ 130 nm, and 1.1 V @ 90 nm semiconductor technologies
  - Current range is a few dozens mili-Ampere to hundreds of Amperes when VDD < 5 V
    - Requires extremely low ESR and ESL
    - Need to avoid diode drops
  - System dynamics of digital systems are extremely fast
    - Program phases and I/O device access patterns
  - Load variation is very high
    - Modern dynamic power management makes larger variation

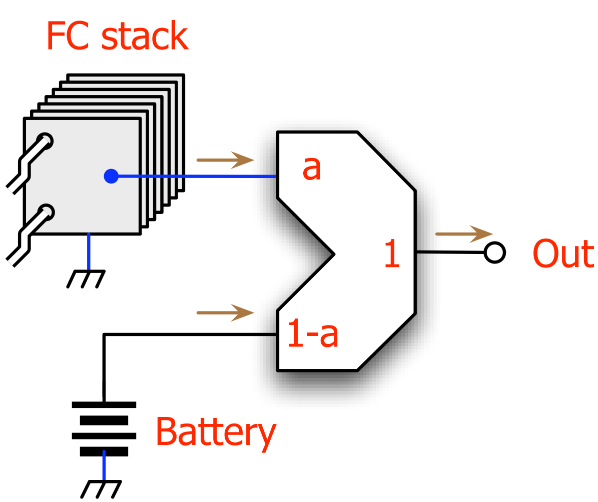
# Fuel cell and battery hybrid

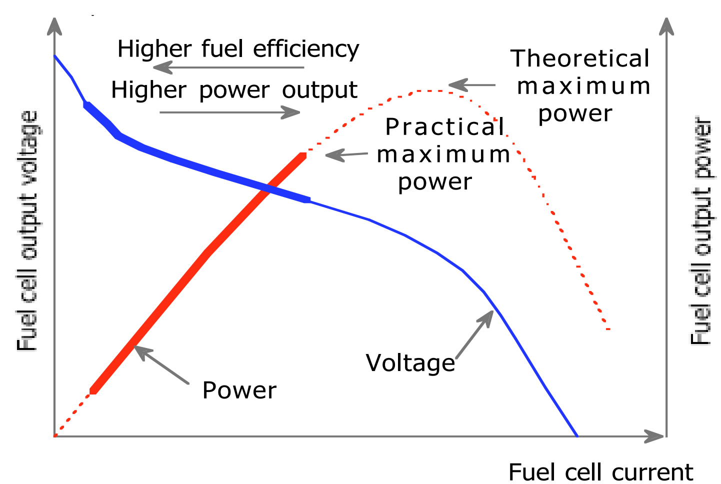
- Power variation of a portable electronics system
  - Up to 8X difference between the peak and average power in SDRAM



# Fuel cell and battery hybrid

- Why dynamic current sharing?
  - Optimal determination of the FC and battery current
    - $I_{Load} = I_{FC} + I_{Battery}$
    - Fuel cell efficiency is not constant
    - Large $I_{FC}$ implies low efficiency
      - Smaller $I_{FC}$ operation is desirable whenever possible
    - Should be jointly optimized with the dynamic power management of the electronics system
  - Arbitrary proportion of the current sharing is required



# Objective

- Purpose of FC and battery hybrid systems for portable electronics applications
  - Achieve the least possible fuel consumption
  - Achieve stable operation under range of operating conditions
  - Increase the power capacity
  - Reduce the battery size
  - Extend the battery life cycle
  - Reduce the form factor
  - Provide data acquisition and analysis capability
  - Achieve FC control and BOP interface
    - Demonstration of portable applications

# Objective

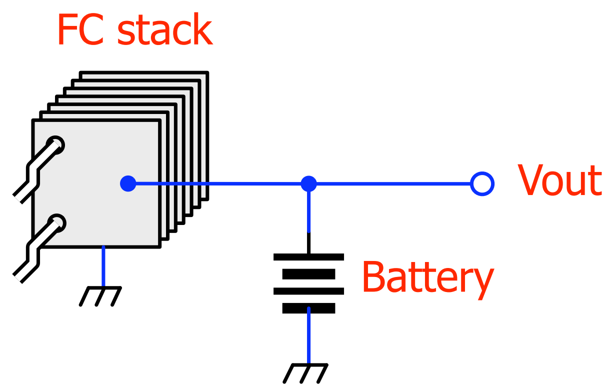
- Design consideration
  - Dynamic active current sharing between the FC and battery
    - Arbitrary current proportion of the FC and battery
    - High-efficiency architecture
  - Precise battery charge management
    - Scheduled constant-current and constant-voltage charging
    - Determination and control of the battery charging current
    - Dual battery support
  - Self-start capability
  - 32-bit RISC microprocessor-based FC control and BOP interface
  - Graphic LCD user interface
  - Communication port with a computer (load)
  - Joint FC control and dynamic power management of the electronics systems

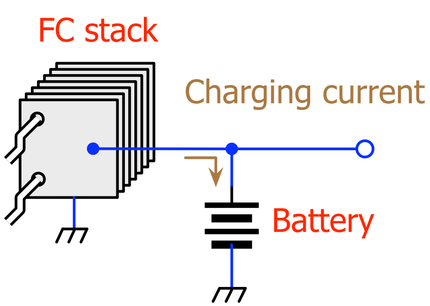
# Architecture of Hybrid Setups

- Passive hybrid setups
  - The proportion of the FC current and the battery current is not controllable, but determined by the device characteristics
    - Parallel connection
    - Two-diode connection
    - MOSFET Diode-OR (enhanced two-diode connection)
- Active hybrid setups
  - The proportion of the FC current and the battery current is controllable
    - Static selection
    - Parallel connection with a DC-DC converter
    - Two-diode with a DC-DC converter
    - Multiple-input bidirectional DC-DC converters
    - Multiple-input bidirectional choppers
    - Multiple-input active current sharing DC-DC converters

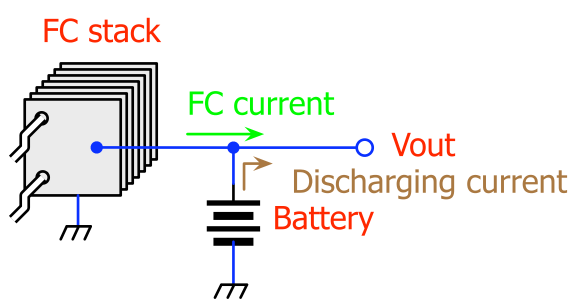
# Architecture of Hybrid Setups

- Passive hybrid setups
  - Parallel connection
    - A fuel cell and a battery are connected together
    - The simplest setup
    - Disadvantages
      - Constant voltage charging
      - Deep-cycle operation is not feasible
      - Decrease safety
      - Charging and discharging control is passive

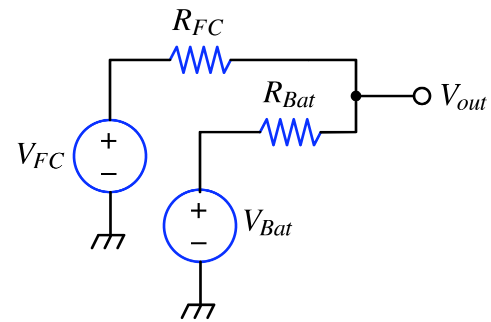



Constant voltage charging

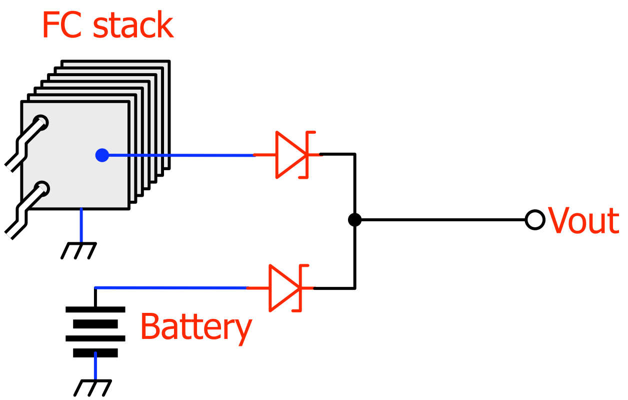


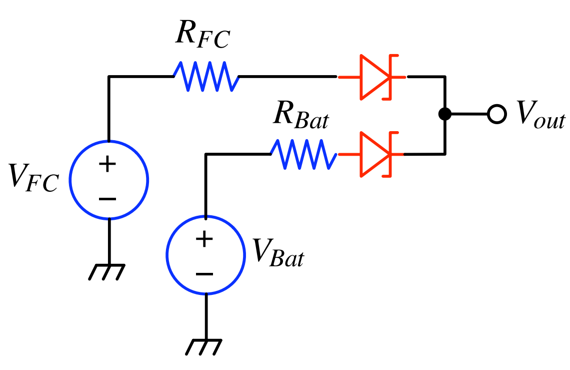

Constant voltage charging

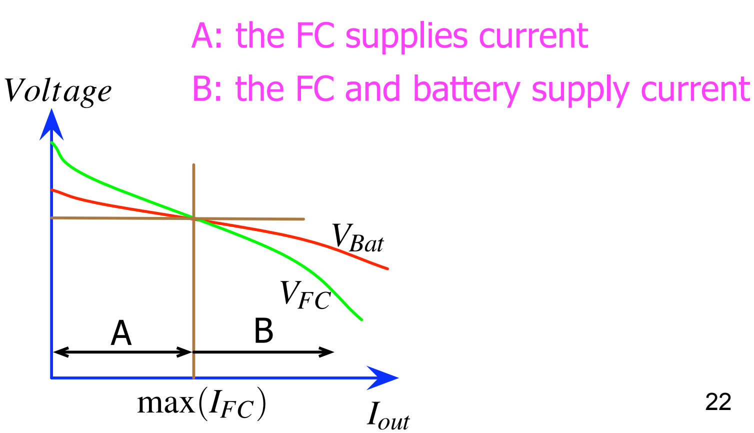


# Architecture of Hybrid Setups

- Passive hybrid setups
  - Two-diode connection
    - The FC and battery outputs are tied together after diodes
    - In general, $R_{FC} >> R_{Bat}$
      - $V_{FC}$ is clamped to $V_{Bat}$
      - FC stack current is bounded to $\max(I_{FC})$
      - Simple but guaranteed operation
    - Disadvantages
      - Battery voltage and stack voltage should match with each other
      - Subject to diode loss

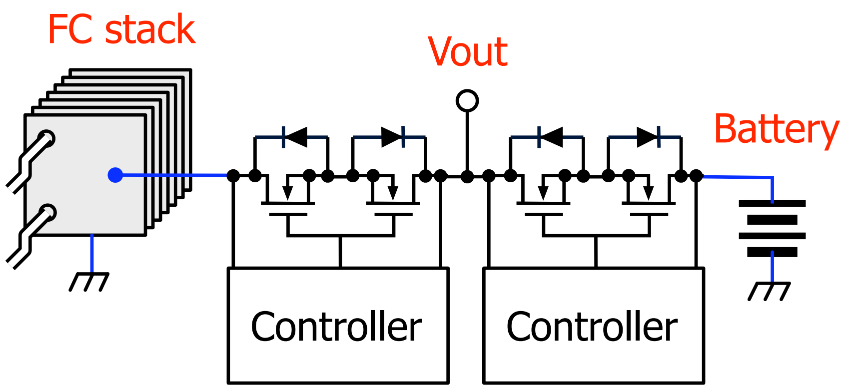


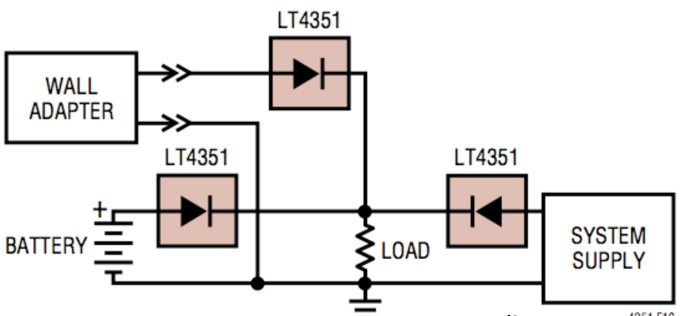



# Architecture of Hybrid Setups

- Passive hybrid setups
  - MOSFET Diode-OR (enhanced two-diode connection)
    - Two-diode setup results in diode loss
    - To overcome the diode loss, voltage-sensitive MOSFET switches are used
      - Feasible with a commercial controller: LT4351
    - Advanced passive hybrid setup

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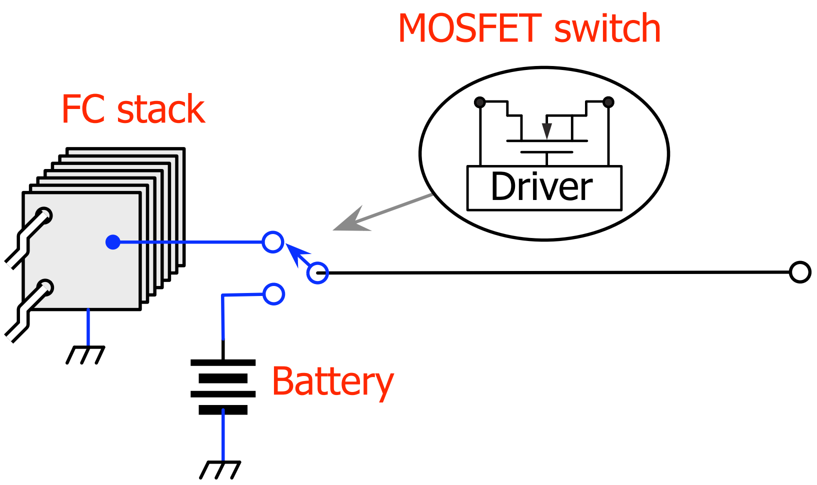
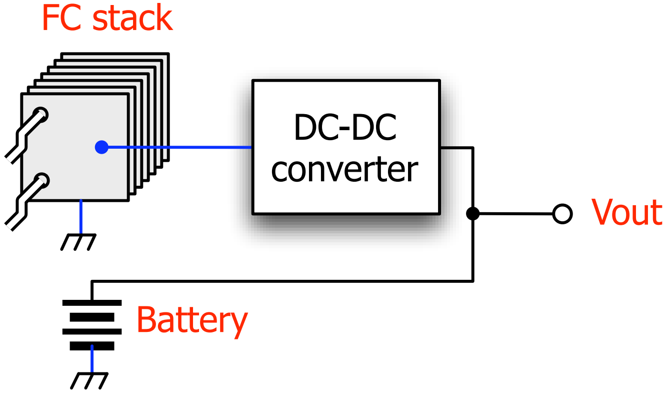
# Architecture of Hybrid Setups

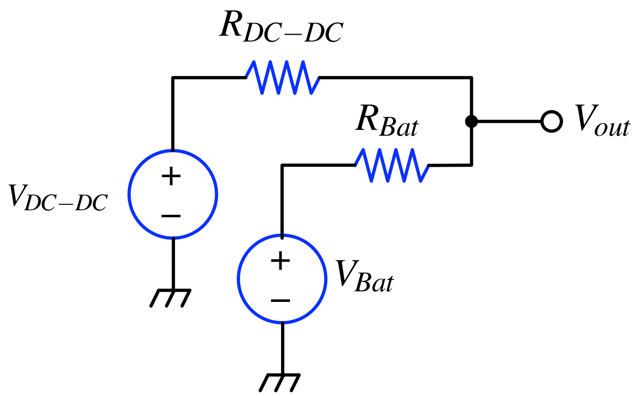
- Active hybrid setups
  - Static selection
    - Switch between the FC and battery
      - When the load current is smaller the than the FC current limit, the switch selects the FC
      - When the load current exceeds the FC current limit, the switch selects the battery
    - Very simple structure
    - Disadvantage
      - Very frequently repeated charge/discharge of the battery
      - The maximum hybrid system capacity is the battery capacity



# Architecture of Hybrid Setups

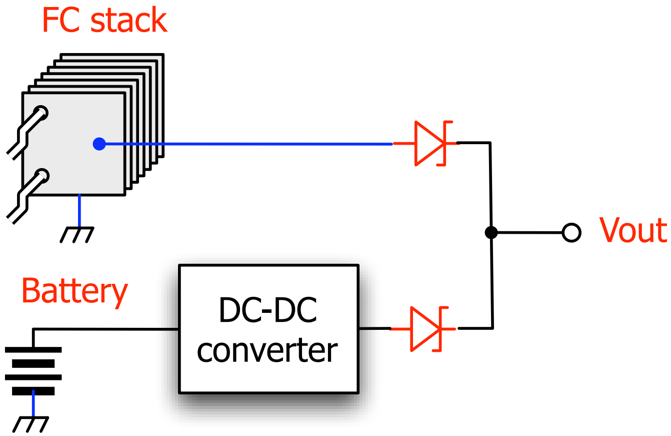
- Active hybrid setups
  - Parallel connection with a DC-DC converter
    - FC stack voltage is stepped up/down by a DC-DC converter
      - Battery voltage need not match with the FC stack voltage
    - Disadvantages
      - Constant voltage battery charging
      - Precise current sharing is tricky to control because $R_{DC\text{-}DC} \approx R_{Bat}$
      - Cascaded DC-DC converter loss
      - Needs a dynamically adjustable DC-DC converter for dynamic sharing

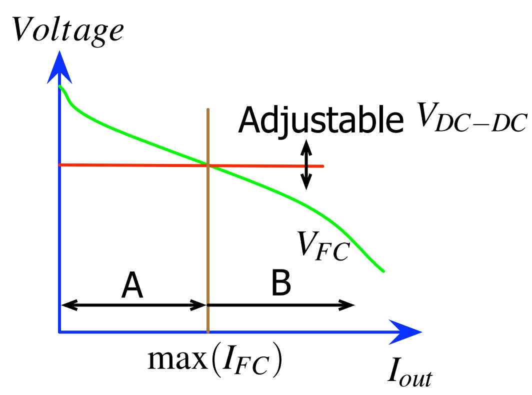


# Architecture of Hybrid Setups

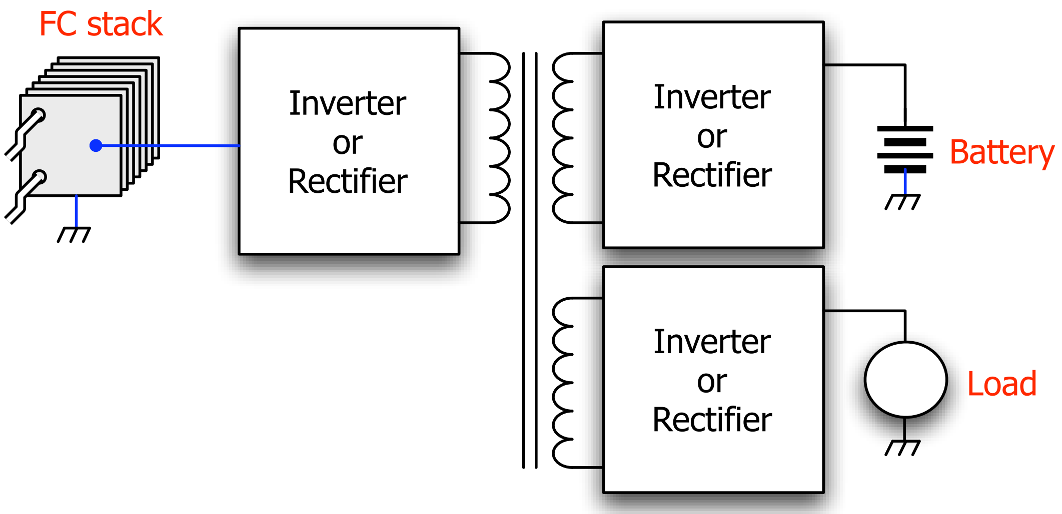
- Active hybrid setups
  - Two-diode with a DC-DC converter
    - Battery voltage is stepped up/down by a DC-DC converter
      - Battery voltage need not match with the FC stack voltage
    - The proportion of the FC and battery current can be actively controlled by the DC-DC converter voltage
    - Disadvantages
      - Cascaded DC-DC converter loss plus diode loss
      - Needs a dynamically adjustable DC-DC converter
    - Diode-OR can be replaced with a MOSFET diode-OR to avoid diode loss



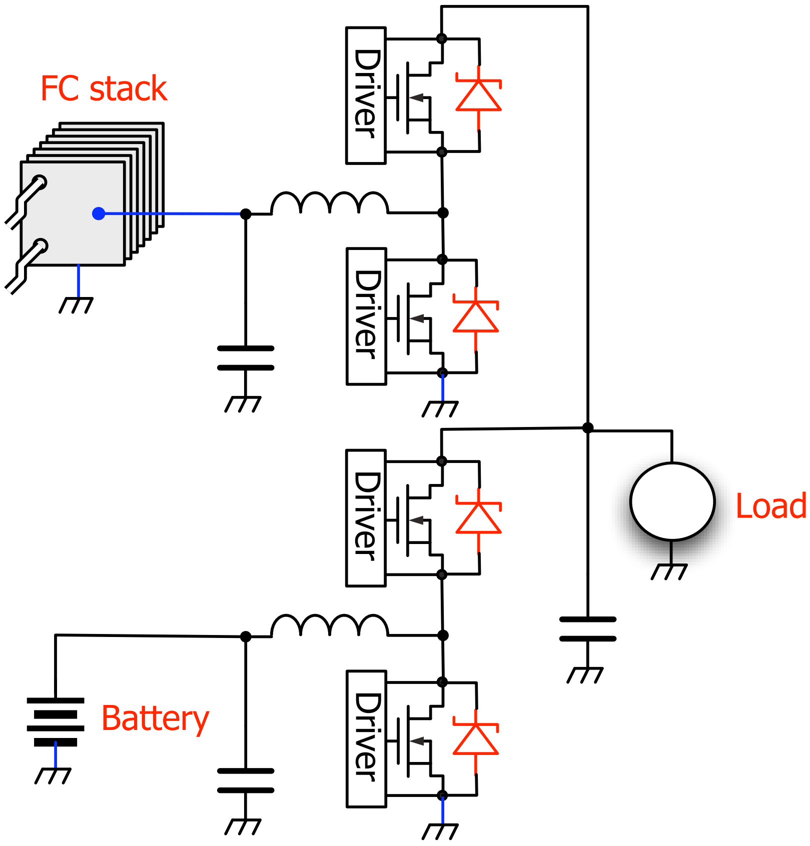
# Architecture of Hybrid Setups

- Active hybrid setups
  - Multiple-input bidirectional DC-DC converters
    - Flyback DC-DC converter with rectifiers
    - Easy to control the current sharing
      - No phase synchronization of inverters
    - Disadvantages
      - Diode loss for low-voltage applications
      - Complicated flyback DC-DC converter



# Architecture of Hybrid Setups

- Active hybrid setups
  - Multiple-input Bidirectional choppers
    - Standard buck- and boost- operations
    - Advantage
      - Easy to control
      - Fast response time
    - Disadvantages
      - Less efficient than synchronous converters
      - Significant loss for low-voltage operations

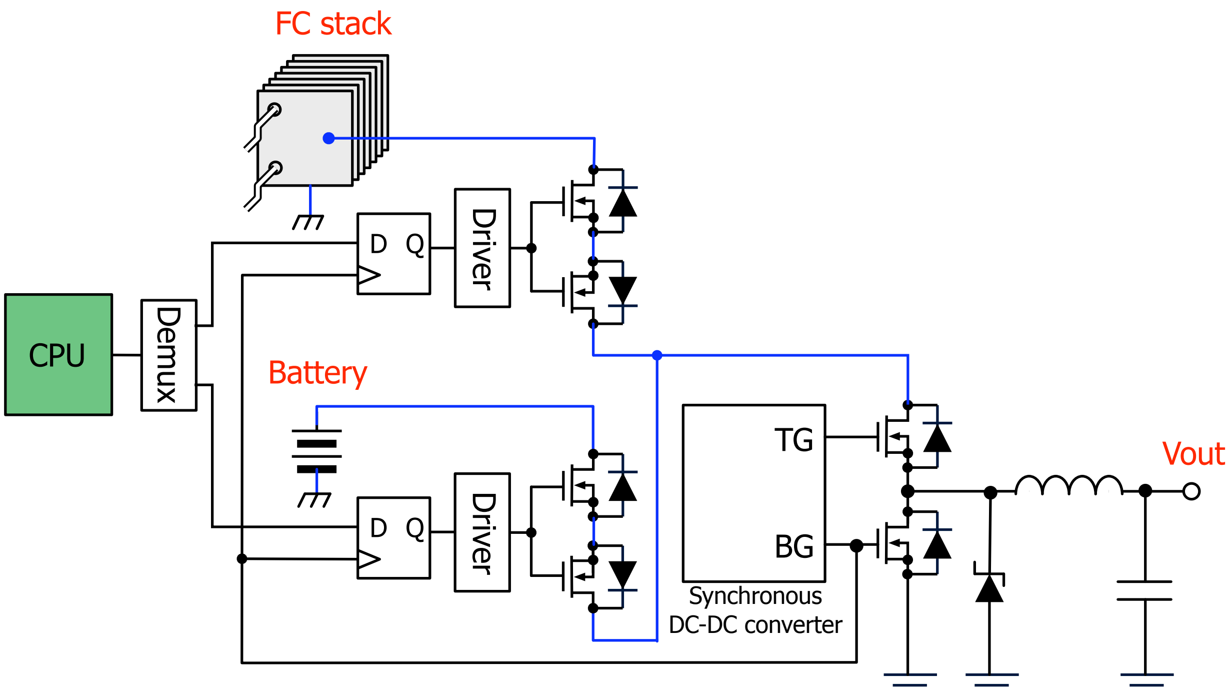


# Architecture of Hybrid Setups

- Hybrid setups for portable electronics applications
  - Low diode loss
    - Avoid using
      - Multiple-input flyback DC-DC converters
      - Bidirectional choppers
      - Two diodes
  - Active current sharing and charge current setting
    - No passive current sharing is desirable
    - True active current sharing is more desirable
      - Avoid using parallel connection with a DC-DC converter
  - Less DC-DC converter loss
    - No cascaded DC-DC converter is desirable
      - Avoid using two diodes with a DC-DC converter
    - Synchronous DC-DC converter is desirable
      - Avoid using a bidirectional chopper

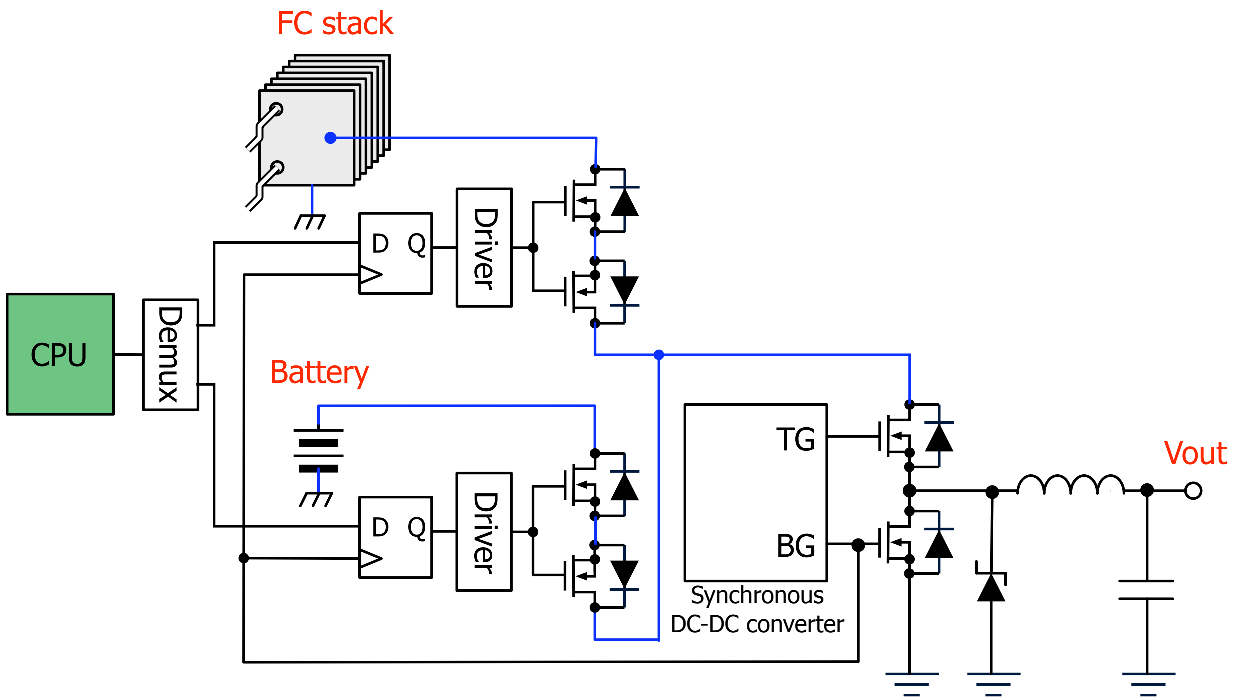
# Architecture of Hybrid Setups

- Proposed hybrid setup
  - DTC (Dynamic Input Duty Ratio Control)
    - True active current sharing
    - Synchronous duty ratio controlled multiple-input DC-DC converter
    - Synchronous buck converter-based
    - No diode loss



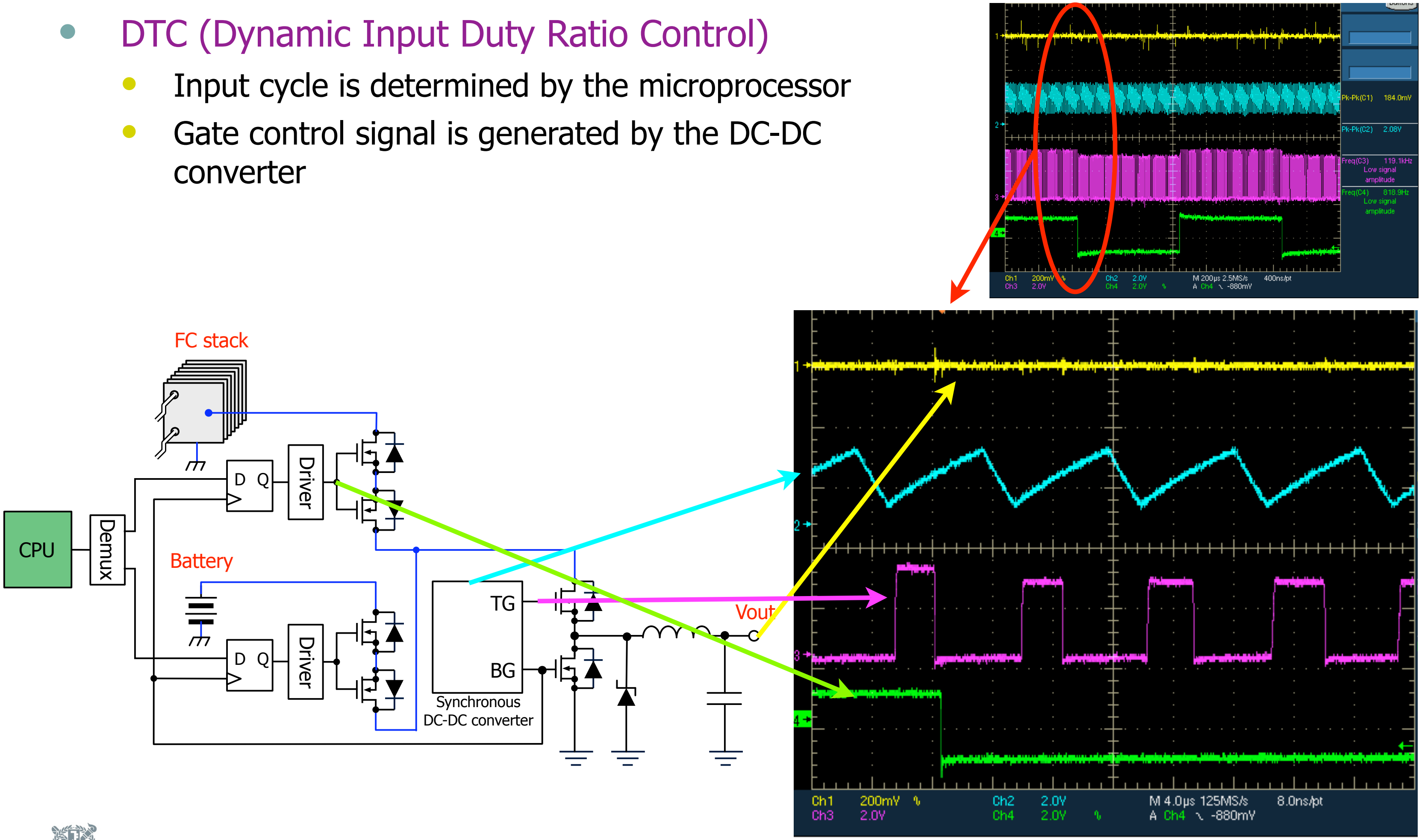
# Architecture of Hybrid Setups

- Proposed hybrid setup
  - DTC (Dynamic Input Duty Ratio Control)
    - Active proportion control regardless of the fuel cell or battery voltage
    - Microprocessor controlled
      - Open-loop control for rough operation
      - Feedback control for nonlinearity compensation



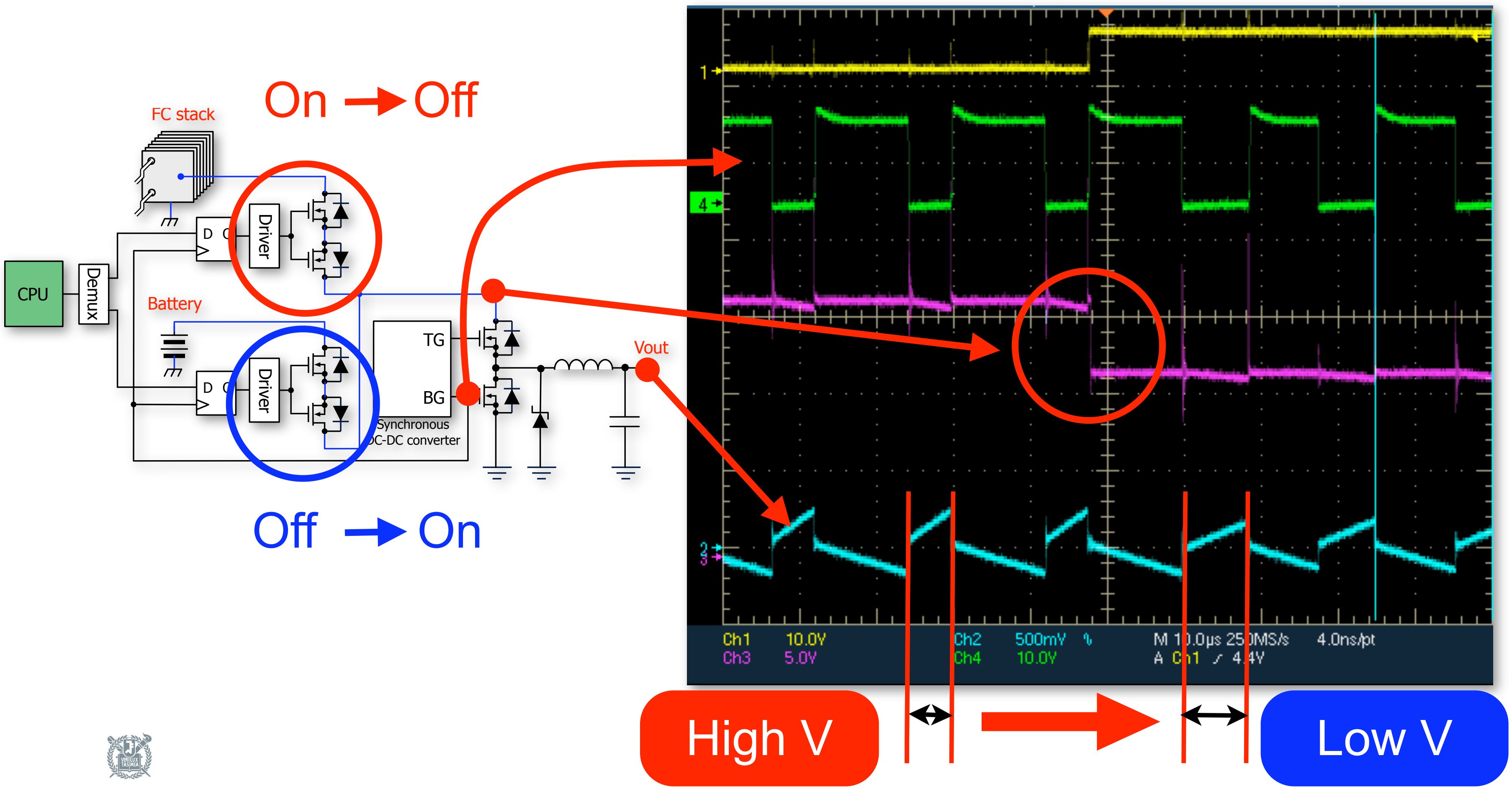
# Architecture of Hybrid Setups

- Proposed hybrid setup
  - DTC (Dynamic Input Duty Ratio Control)
    - Input cycle is determined by the microprocessor
    - Gate control signal is generated by the DC-DC converter



# DTC operation

- Power source switching



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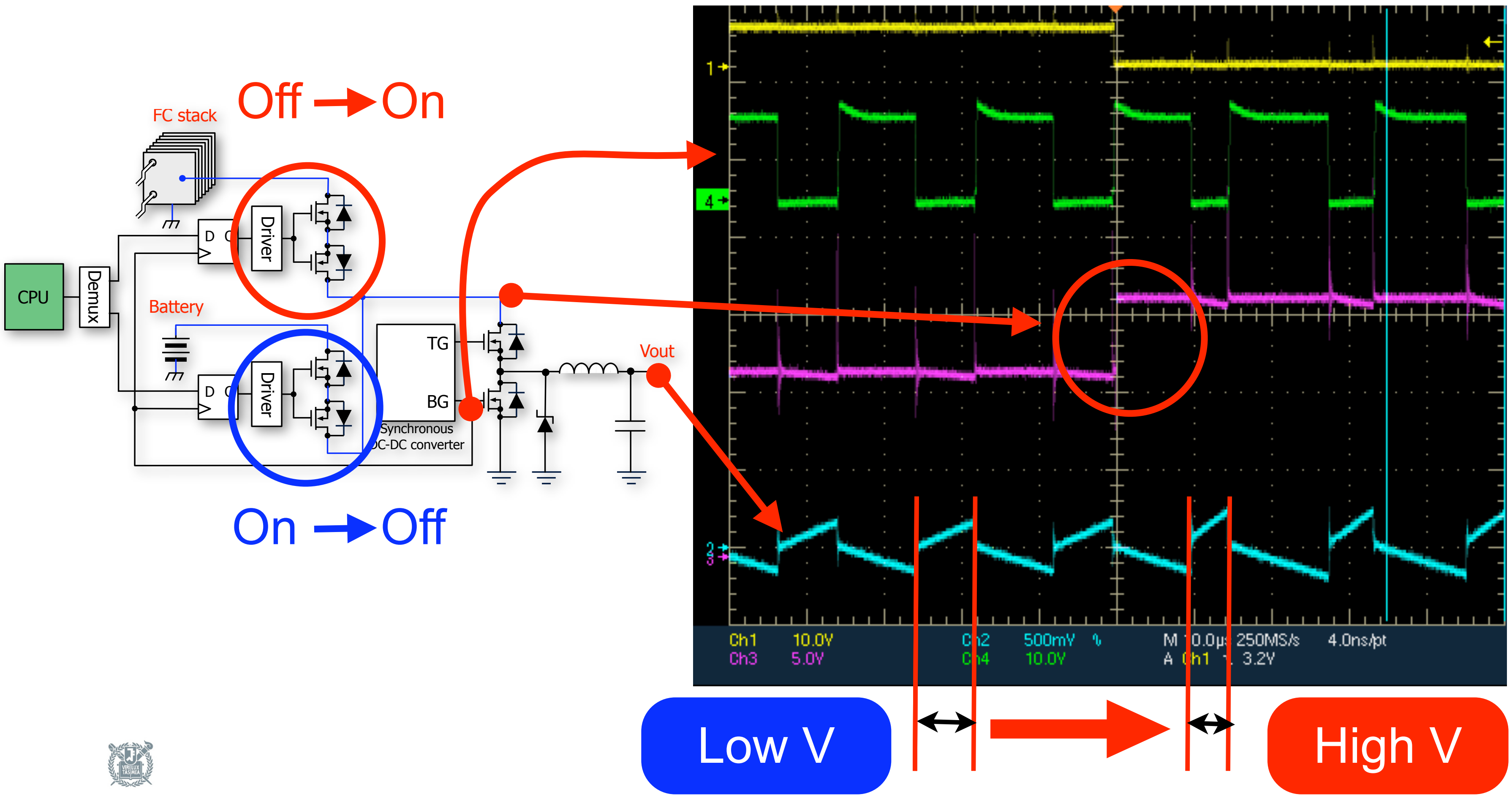
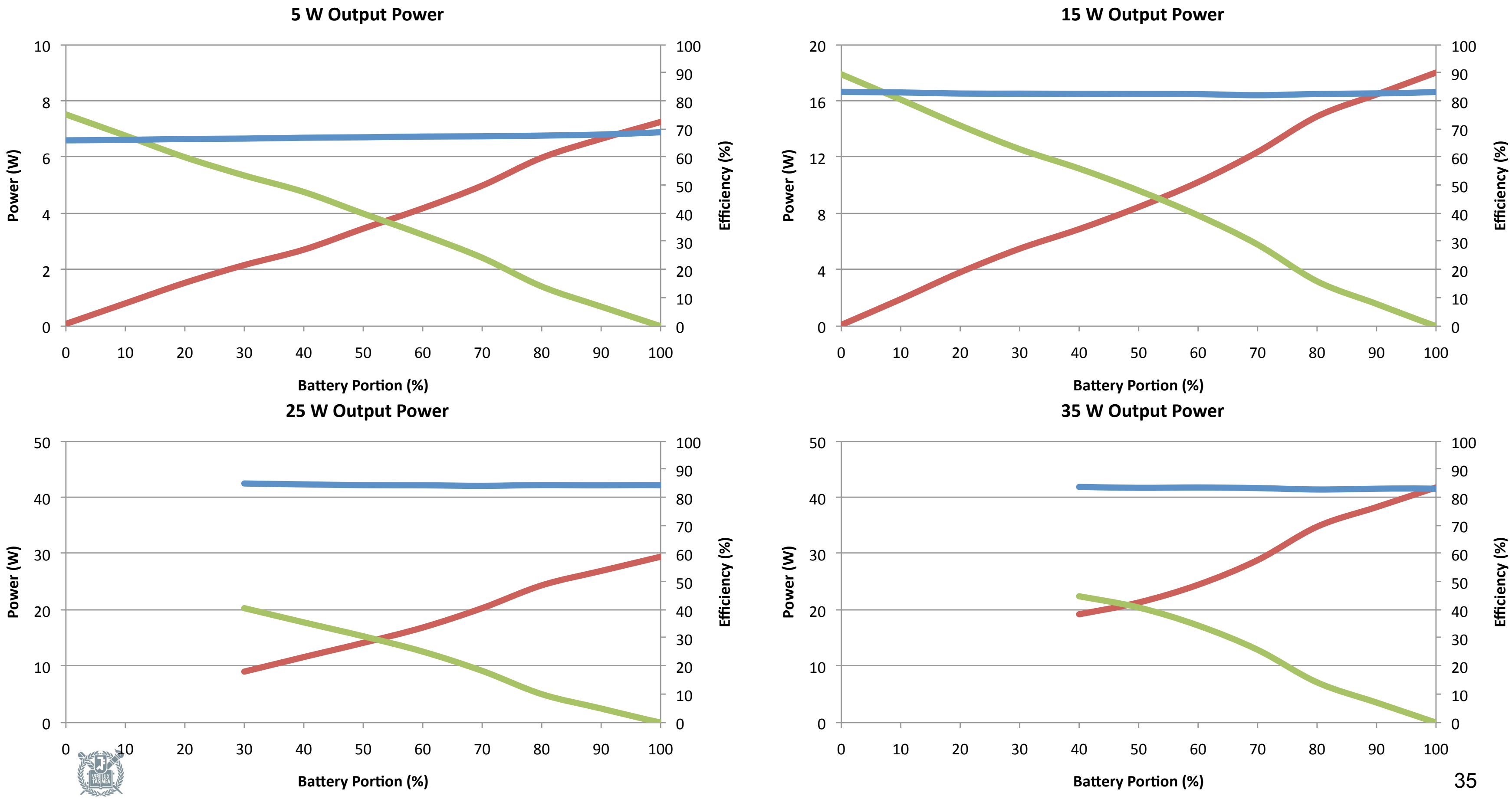


# Architecture of Hybrid Setups

- Measured system efficiency of the proposed hybrid setup
  - Including the control circuits and BOP power consumption



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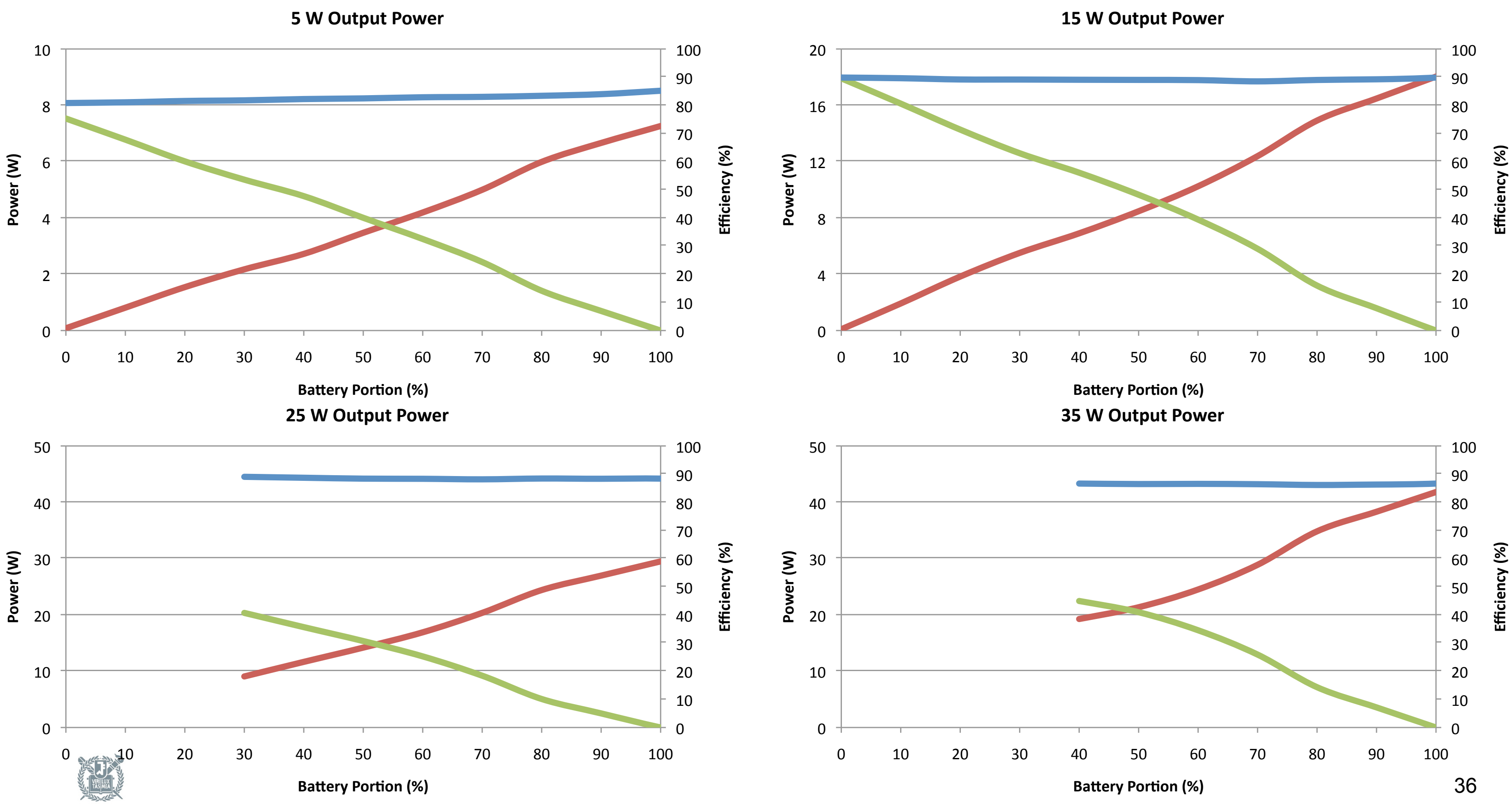

# Architecture of Hybrid Setups

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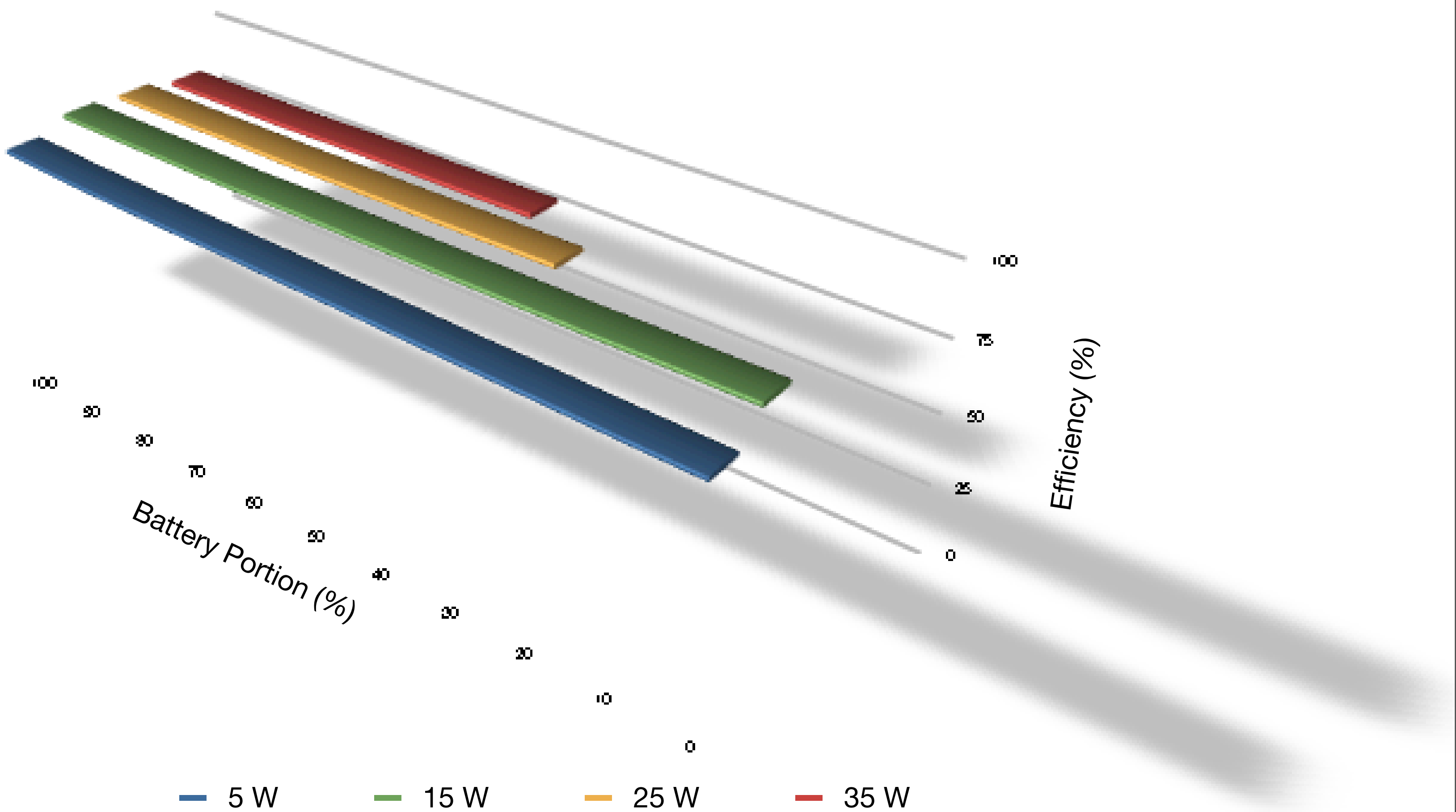
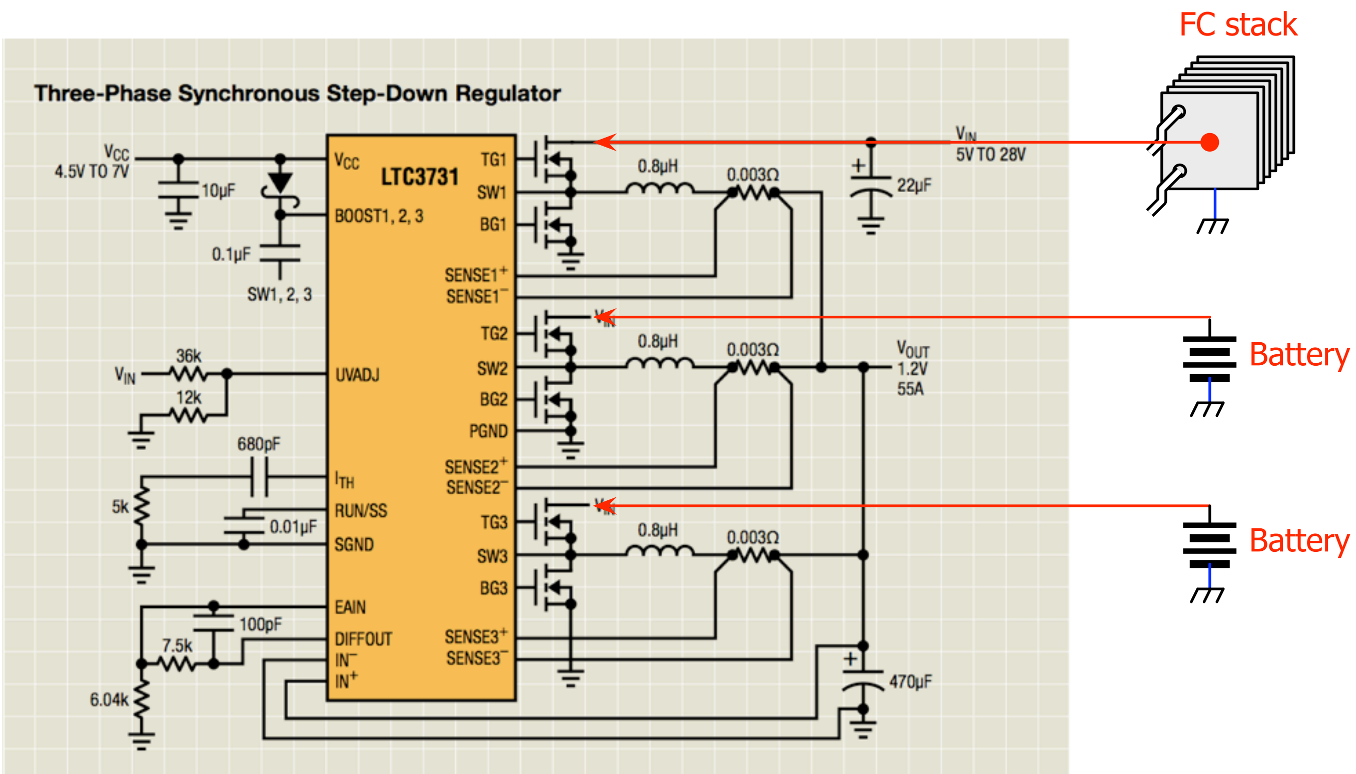
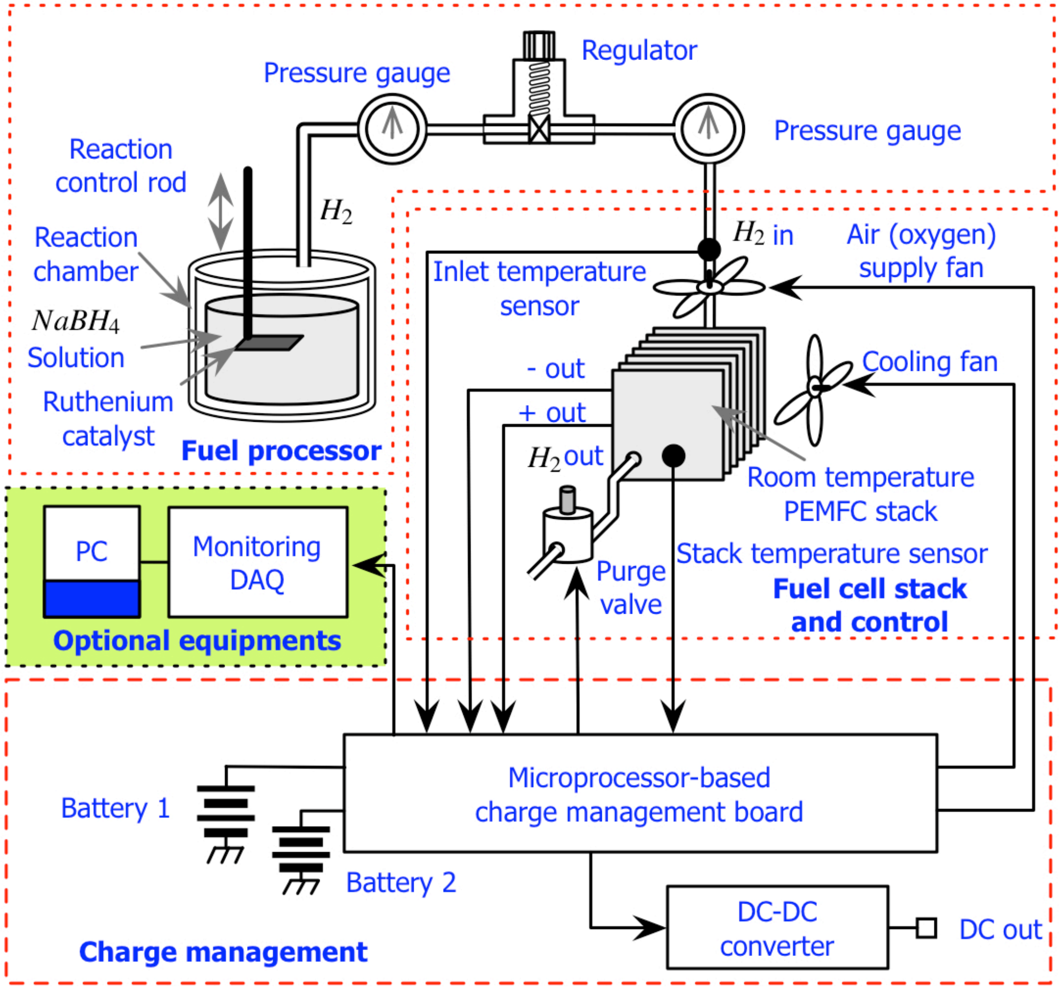


# Architecture of Hybrid Setups

- Additional consideration
  - PolyPhase DC-DC converters
    - For high-capacity, low-ripple DC-DC converters
    - Currently realizes equal current sharing



# Hybrid platform



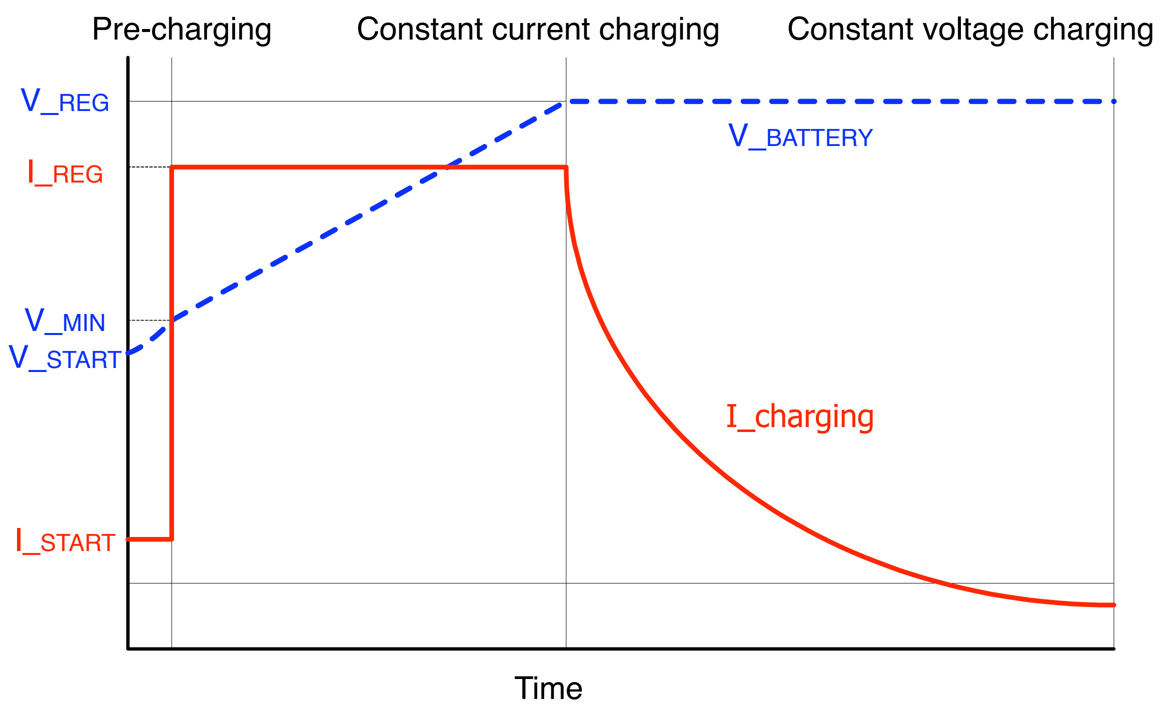

- A fuel cell system
  - Fuel cell stack
  - $H_2$ generator
  - Cooling system
  - Purging system
  - Humidifier

# Battery Management

- The standard charge algorithm for Li-ion batteries
  - Apply a 1C charging current to the battery until the voltage limit is approached
    - E.g., 1C discharging means to discharge 1 Ah battery in an hour
  - After the battery terminal voltage reaches to the limit, constant voltage charging is continued
- Quick charge methods for Li-ion batteries
  - 1.5C charging current is permitted by a few cell manufactures
    - E.g., 1.5C charging means to charge 1.5 Ah battery in an hour
  - 2.0C is generally not allowed by the manufactures
  - Affect the safety and life cycle of the battery

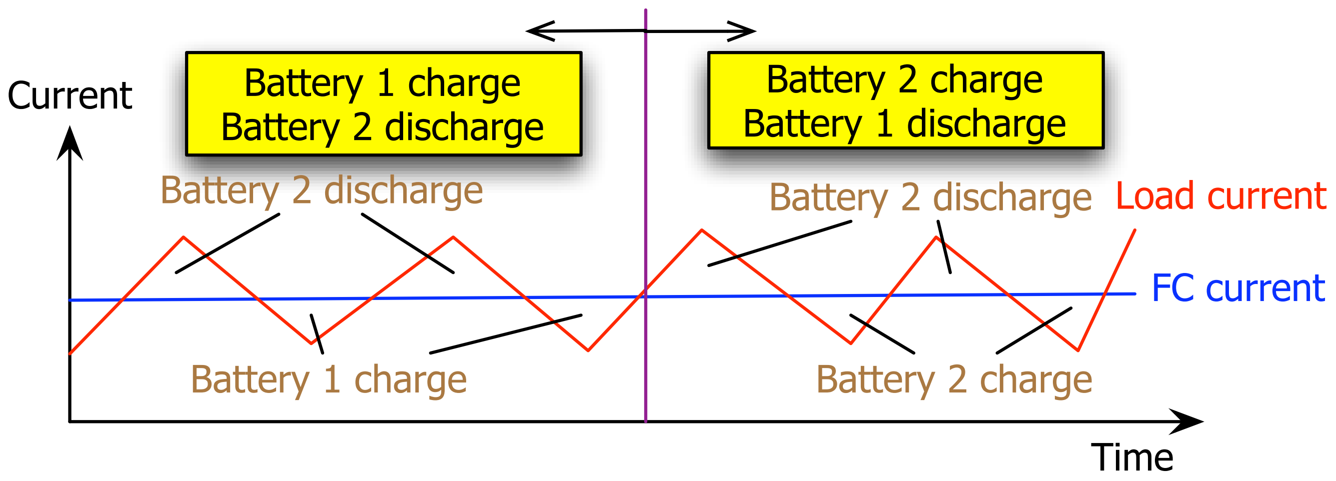
# Battery Management

- Three charging phases
  - Pre-charging: for empty battery
  - Constant current charging
  - Constant voltage charging



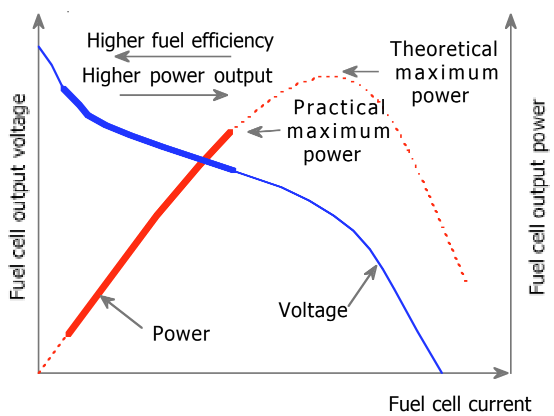
# Battery Management

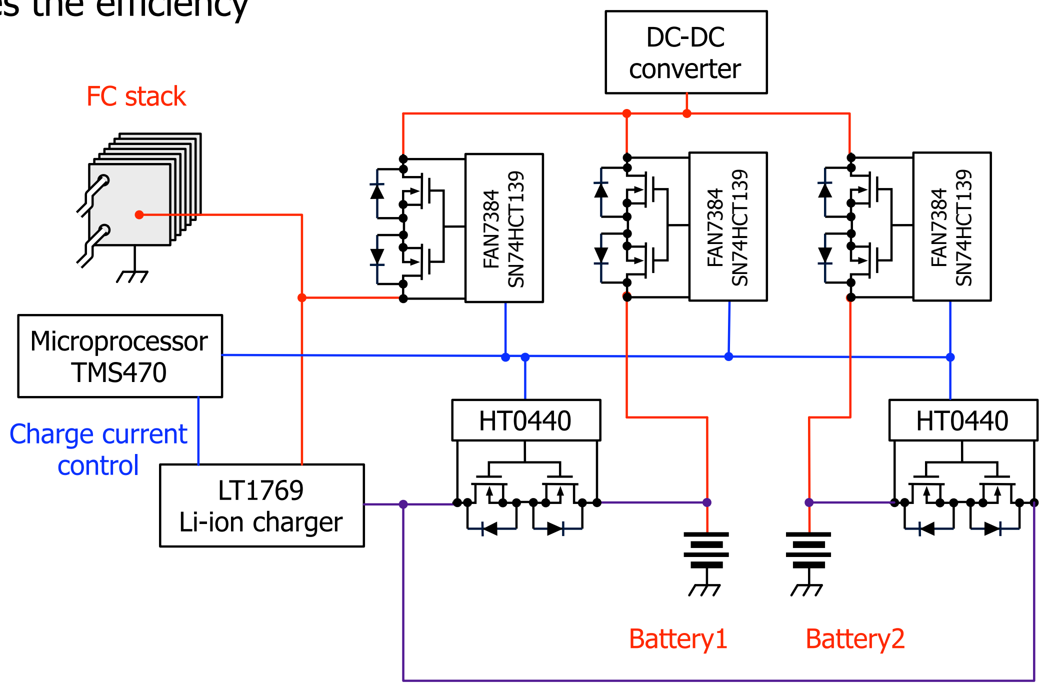
- Two Li-ion batteries
  - Allows 2-cell and 3-cell battery packs
- Mode change policy
  - Each battery has charge and discharge modes
    - One battery is in charge mode, the other is in discharge mode
    - Once a battery is in discharge mode, it keeps discharging until the mode is changed to prevents from frequent charge/discharge mode changes



# Battery Management

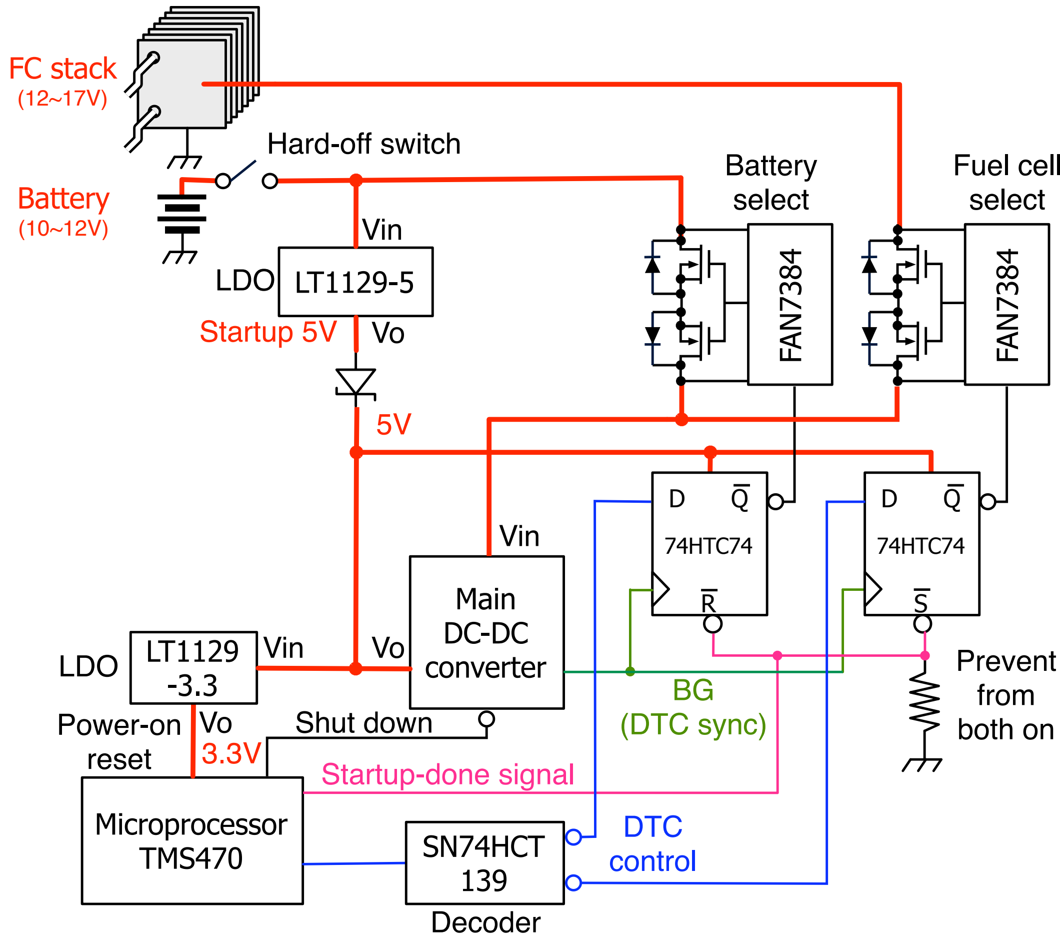
- Determination of the charging current
  - Within the range of the charge current limit, the charing current is determined by the FC current
    - For a given load current, $I_{Load}$, determine the FC current $I_{FC}$
      - $I_{Charge} = I_{FC} - I_{Load}$
      - FC current determines the efficiency



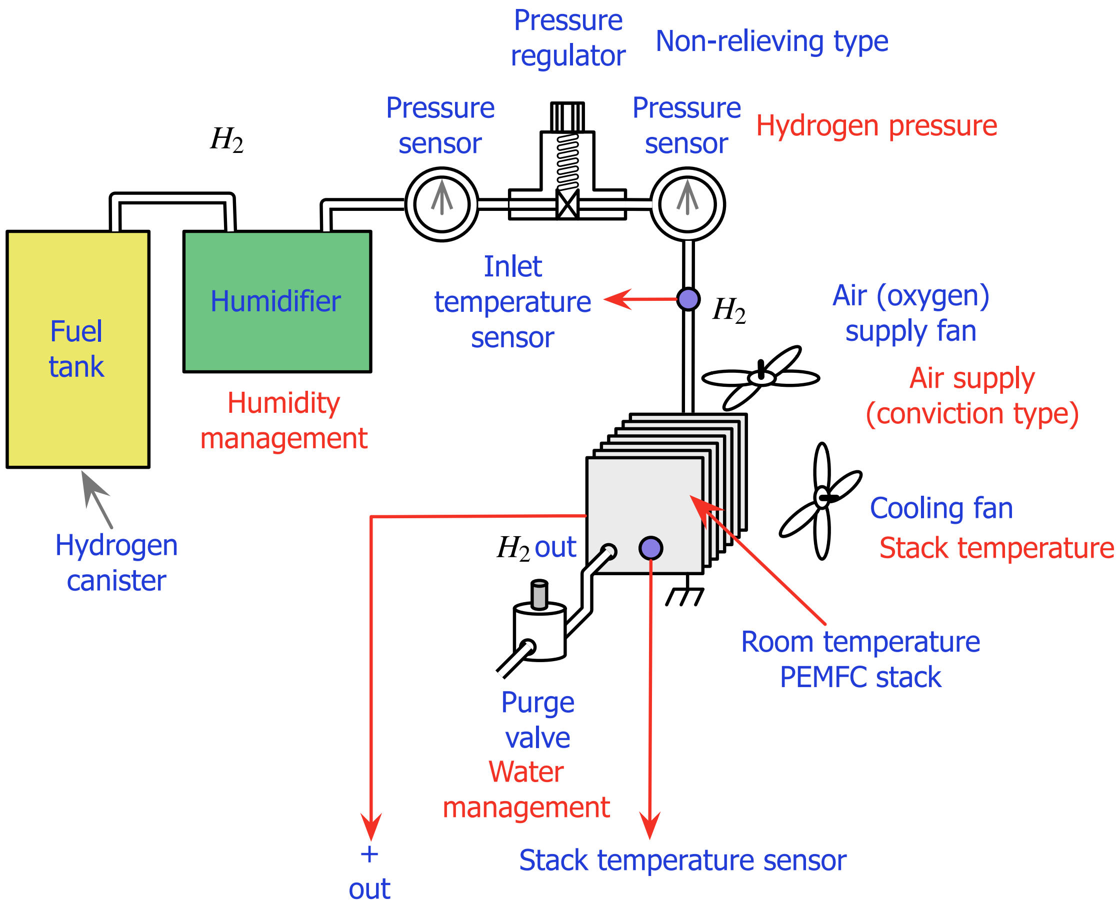
# Self-Start

- The hybrid system must be able to start with the battery
  - Startup power is supplied by the battery
  - LDO regulates the battery voltage
  - Diode stops the startup power after the main DC-DC converter wakes up
  - Flip flop is reset during the startup sequence until the FC is ready



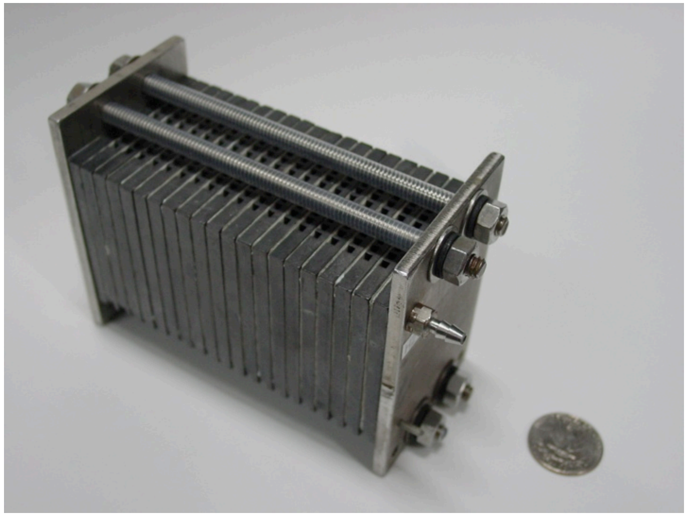
# Stack and BOP

- FC stack operation
  - Hydrogen pressure
  - Hydrogen humidity
  - Stack temperature
  - Air pressure
  - Water management



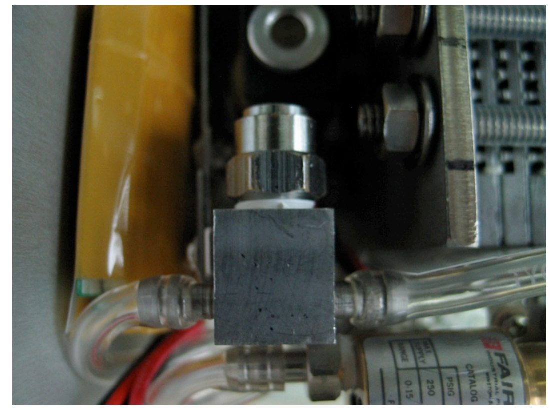
# Stack and BOP

- FC stack
  - BCS 20 W PEMFC stack
  - 20 W with 20 stacks
  - Conviction type
    - The next generation will use a pressured air PEM fuel cell for better efficiency
  - Self humidification
    - Use external humidifier for better efficiency

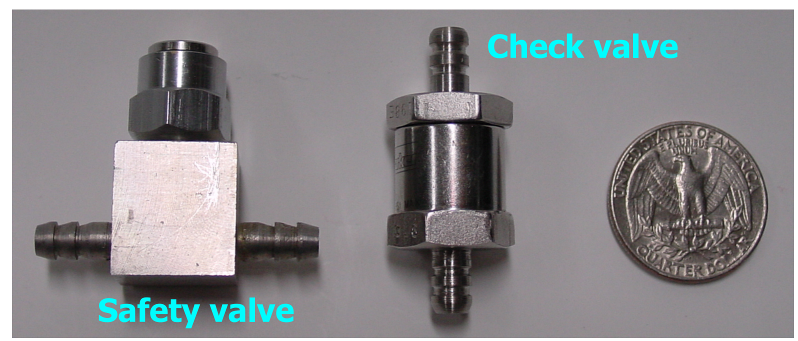


# Stack and BOP

- Safety valve
  - Opens at 8 psig
  - Protect the PEM fuel cell stack in case of emergency (controller failure)

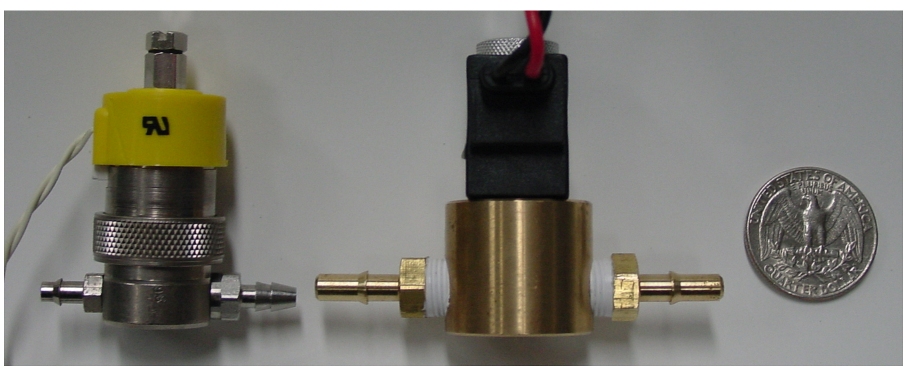


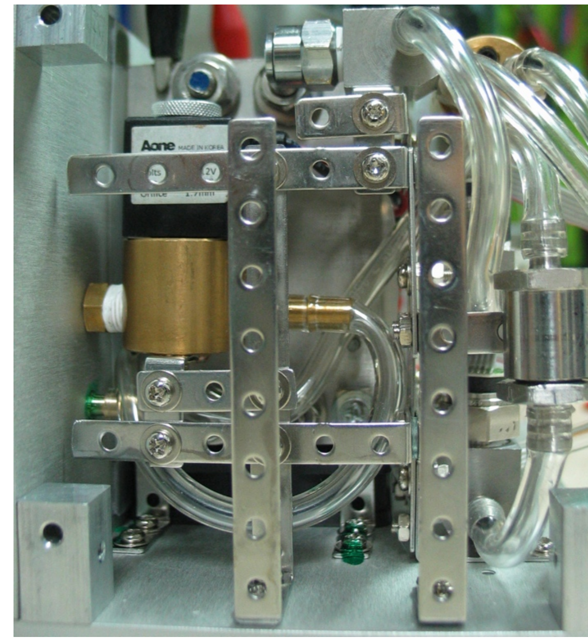
- Check valve
  - Prevent from negative pressure and thus reverse flow
  - Opens at 2 psig



# Stack and BOP

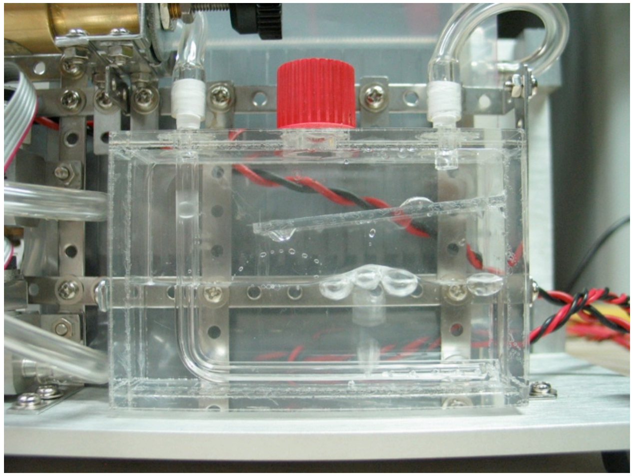
- Purge valve
  - Drain accumulated water at the hydrogen anode
  - Solenoid valve
  - Periodically opened by the microprocessor
  - Emergency open when the hydrogen inlet pressure exceeds the limit



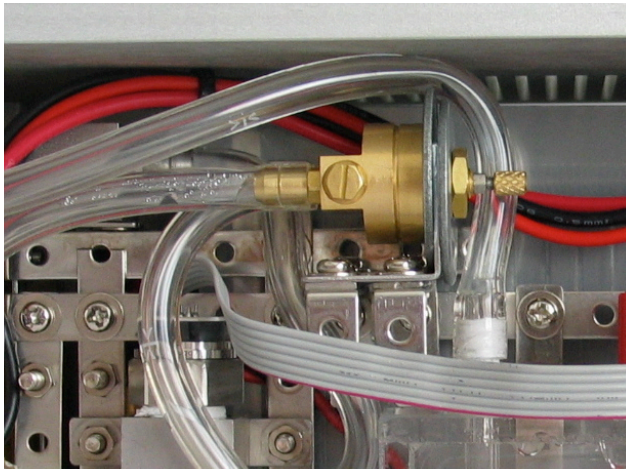


# Stack and BOP

- Humidifier
  - Generates wet hydrogen
  - Needs upgrade for portable applications

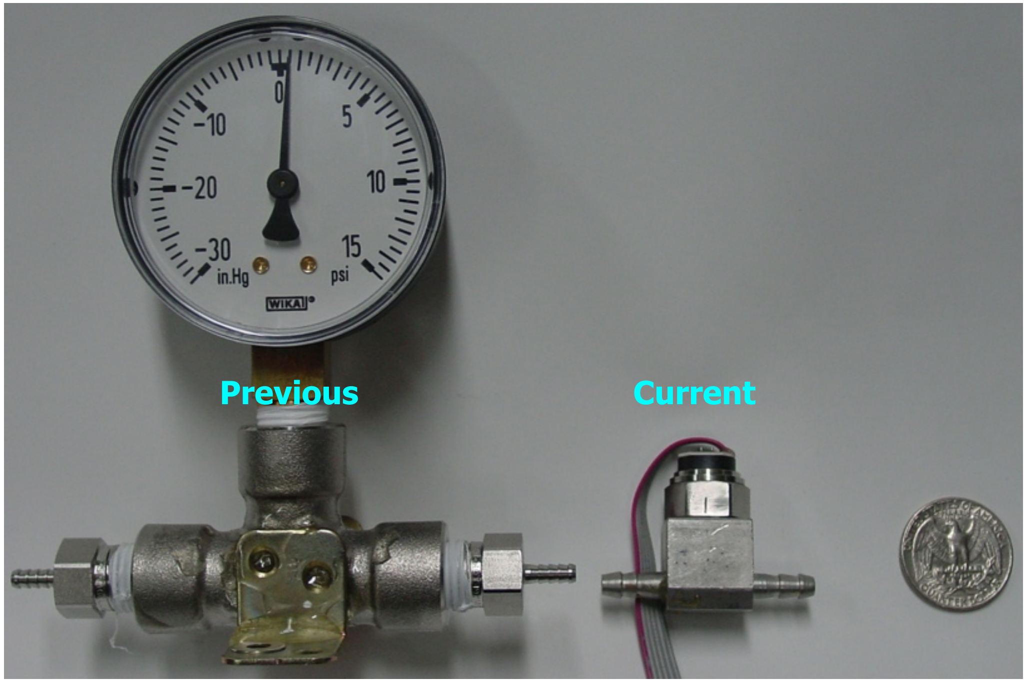


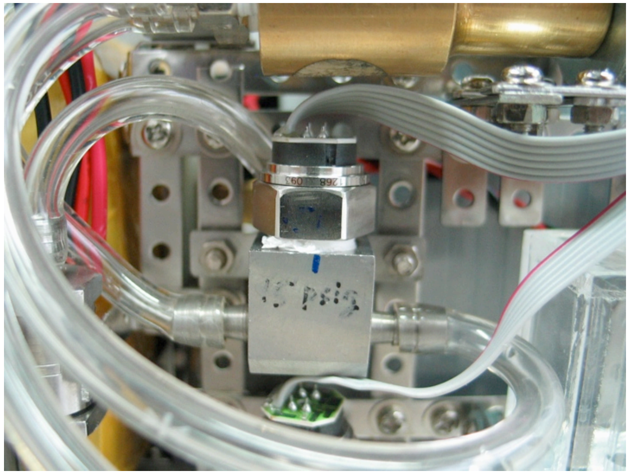
- Pressure regulator
  - Generate 2 to 4 psig hydrogen pressure
  - Non-relieving type for hydrogen
  - Need to tolerate wide input pressure range for various types of hydrogen generators



# Stack and BOP

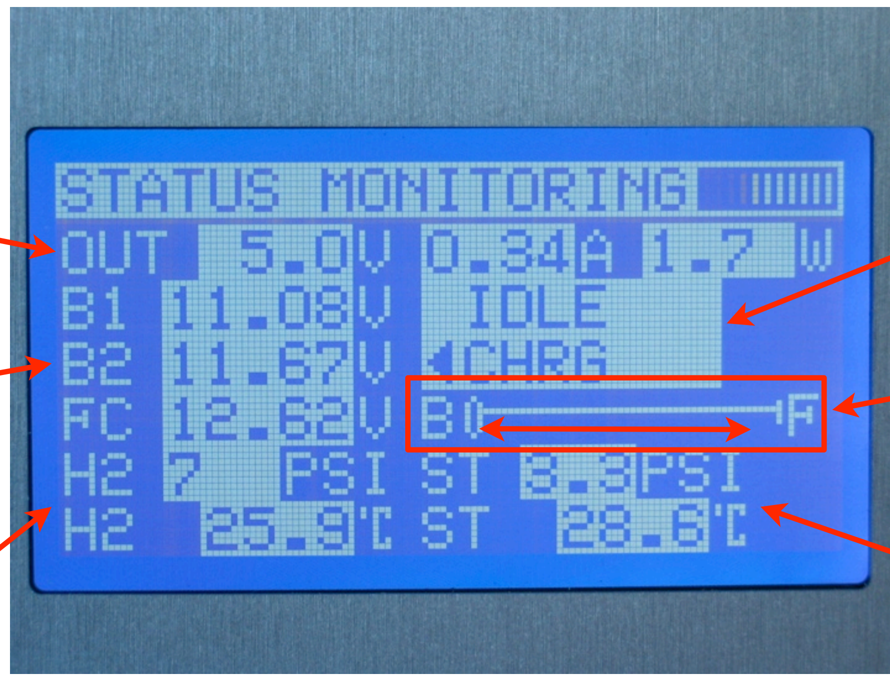
- Pressure sensor
  - 0 to 15 psi and 0 to 100 psi
  - Differential voltage output
  - Signal conditioning with an instrument amplifier



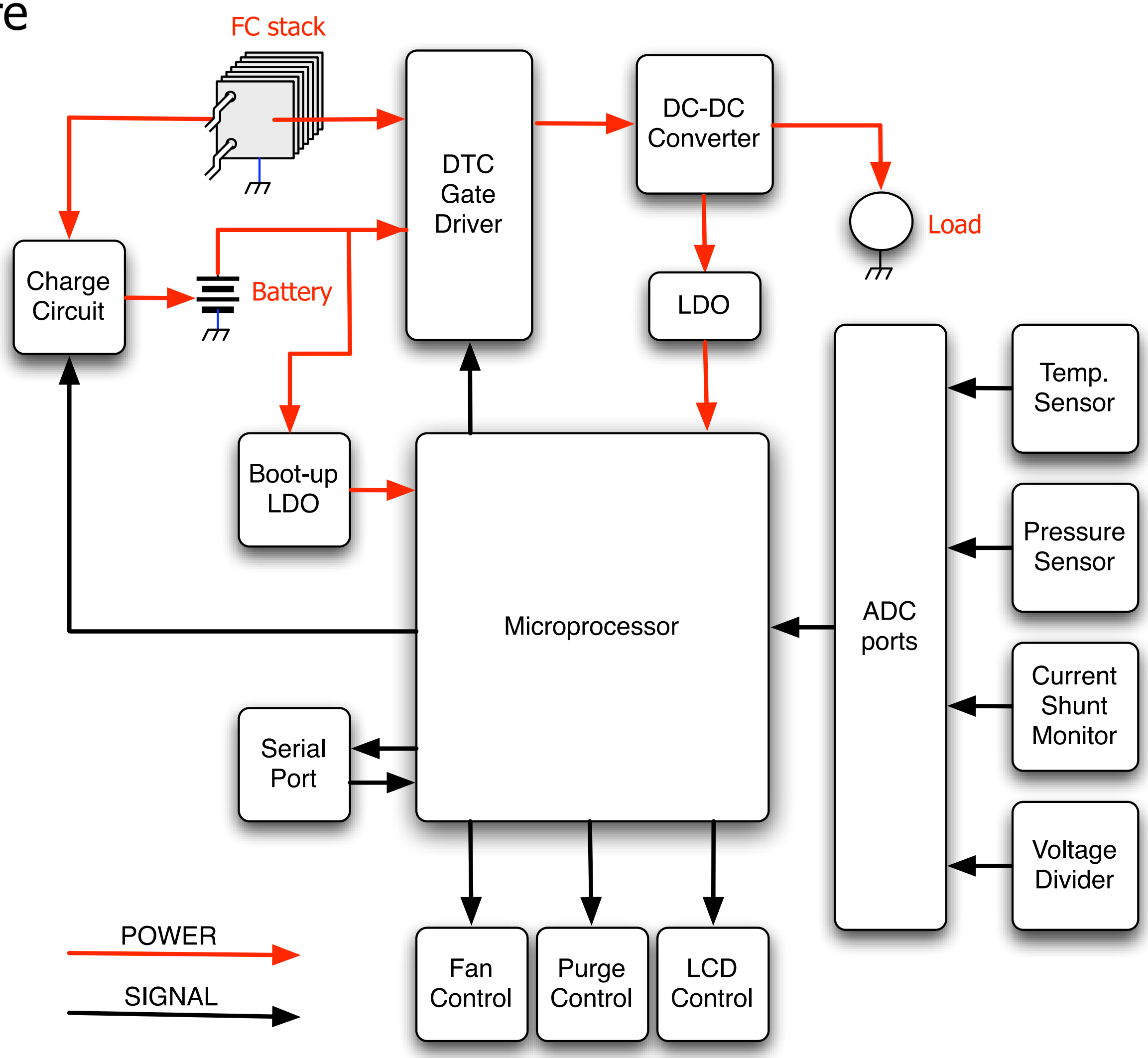
# Monitoring and User Interface

- Control and monitoring software
  - Current, voltage, pressure and temperature monitoring
  - DTC status monitoring
  - Battery status monitoring



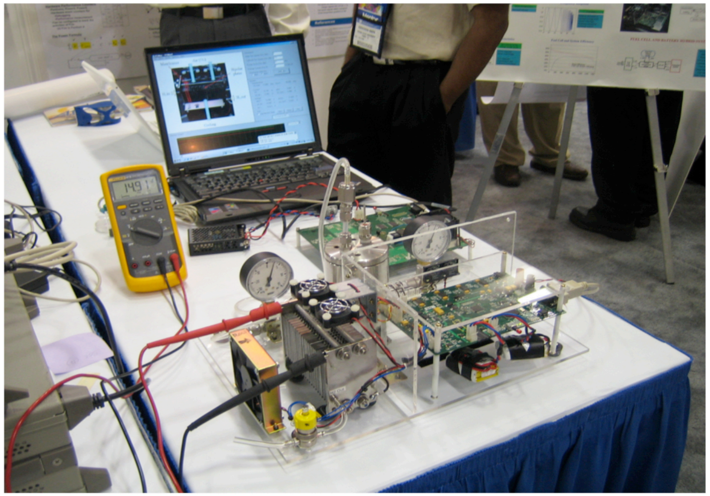
# Implementation

- Architecture

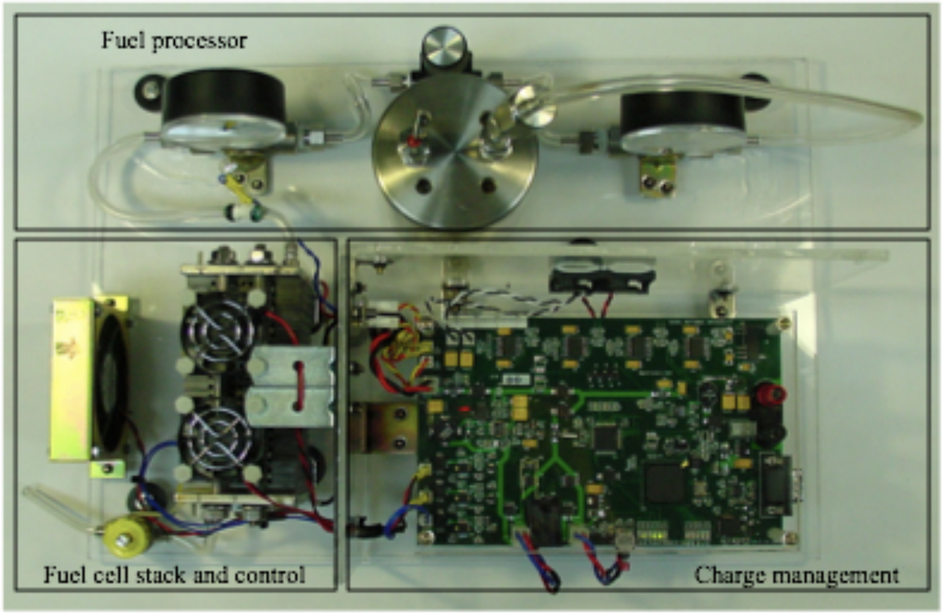


# Implementation

- A proof-of-concept prototype
  - No miniature BOP components
  - Basic hybrid operation

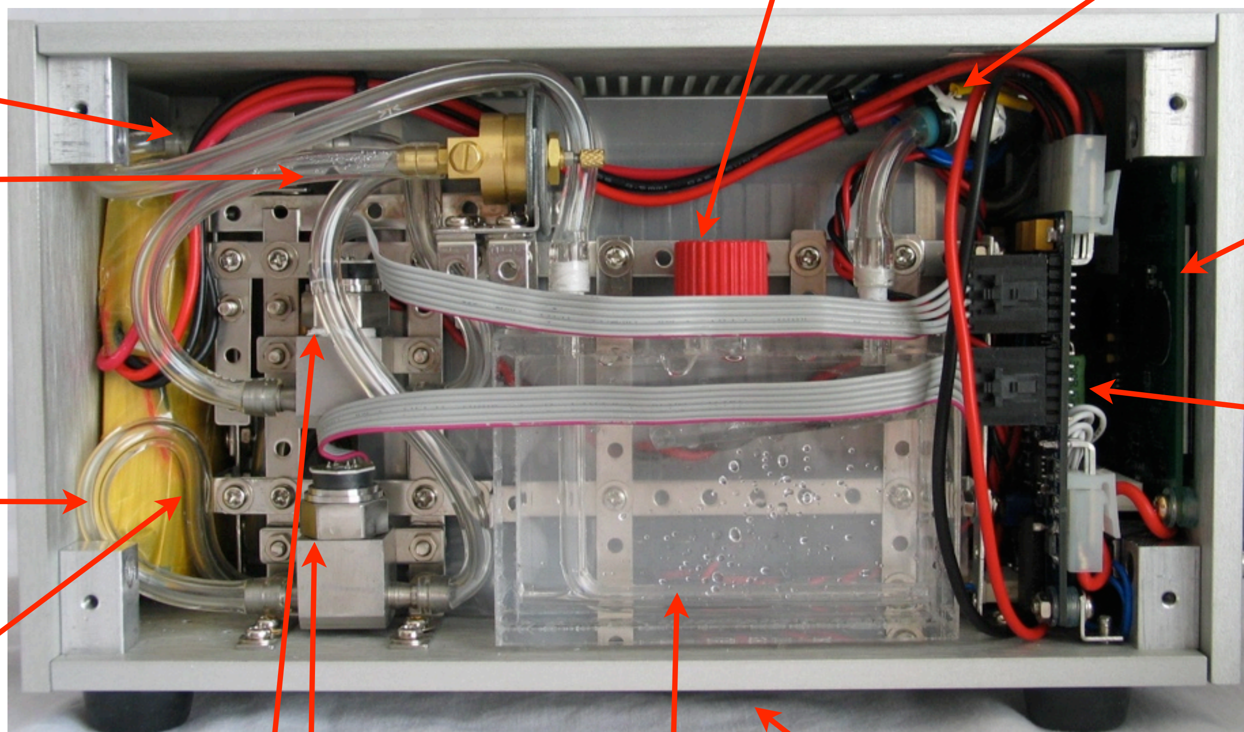


ACM SIGDA University Booth 2006



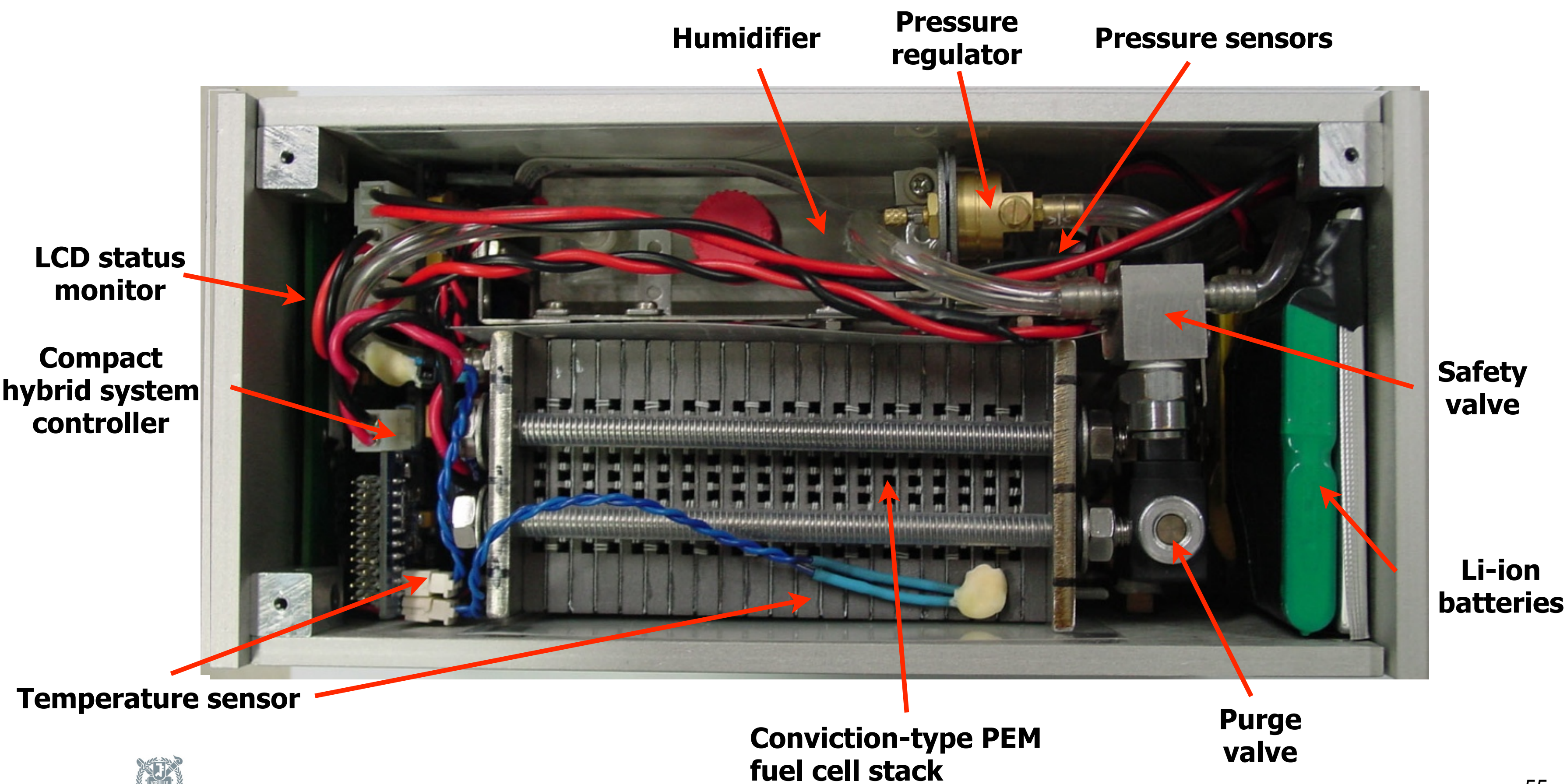
# Implementation

- Revision 2.0 Prototype
  - Side view



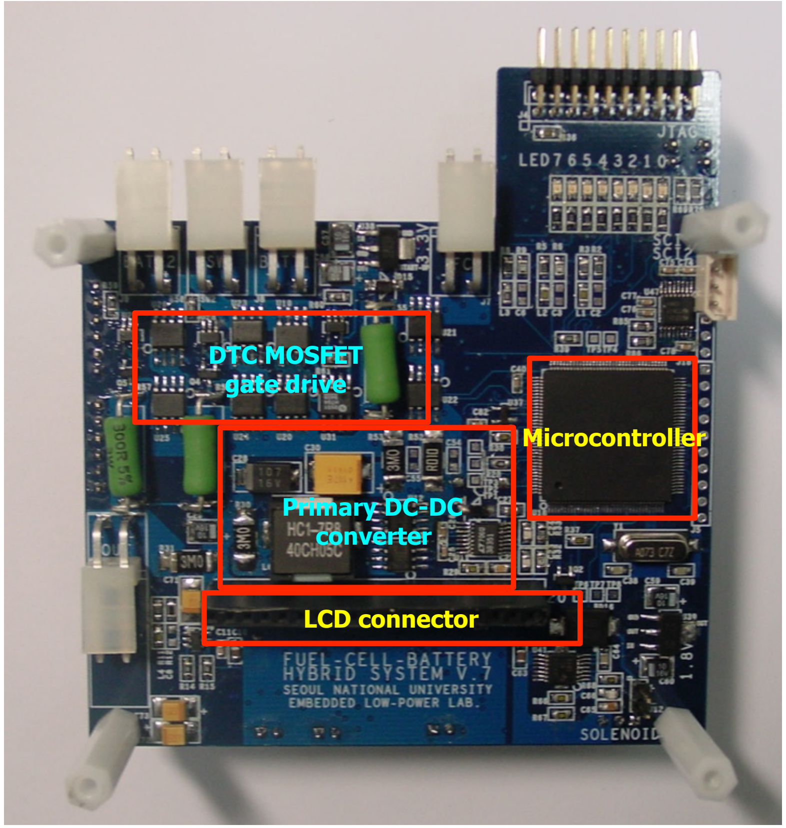
# Implementation

- Revision 2.0 Prototype
  - Top view

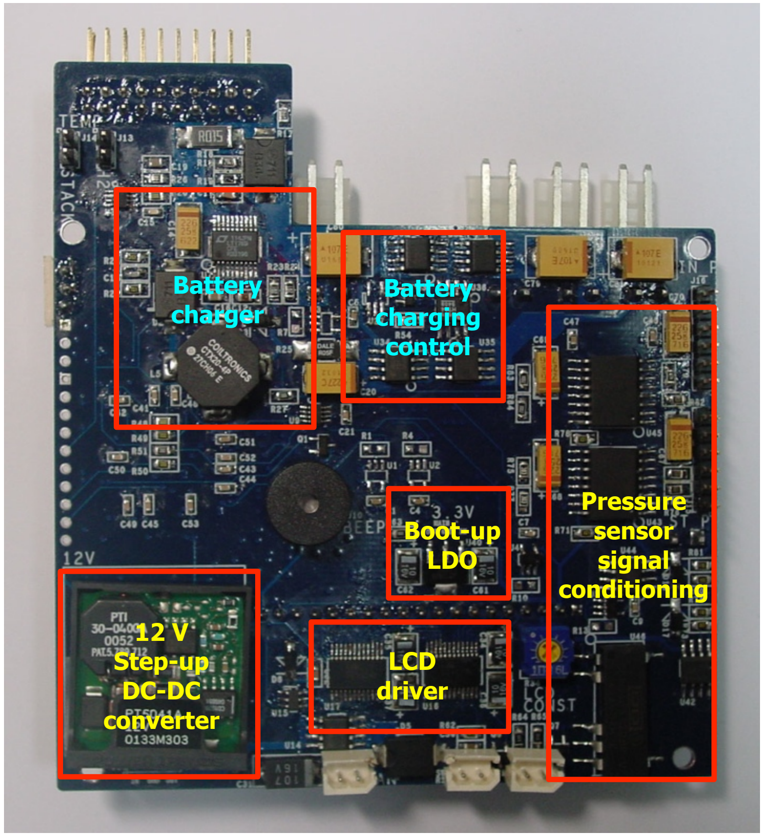


# Implementation

- Hybrid system controller




Top view



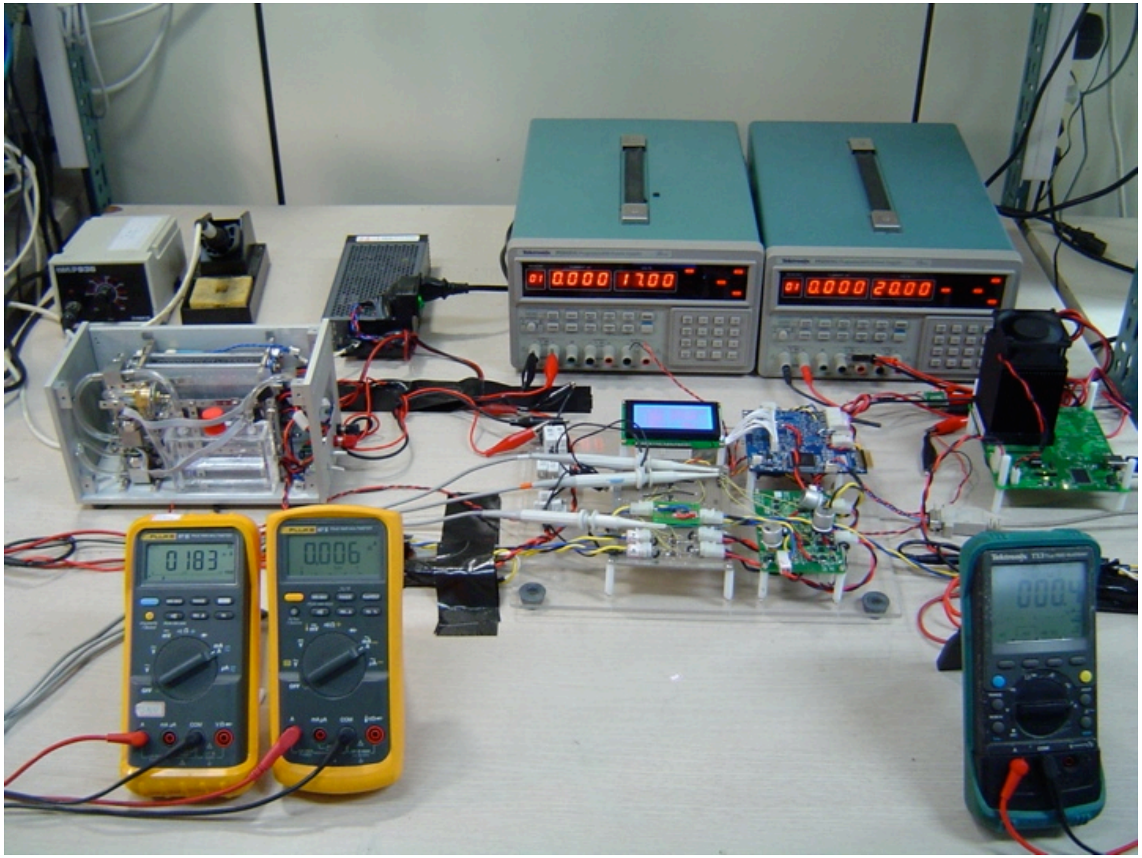

Bottom view

# Implementation

- ISLPED '07 Design Contest Award
  - Operation of a PMP

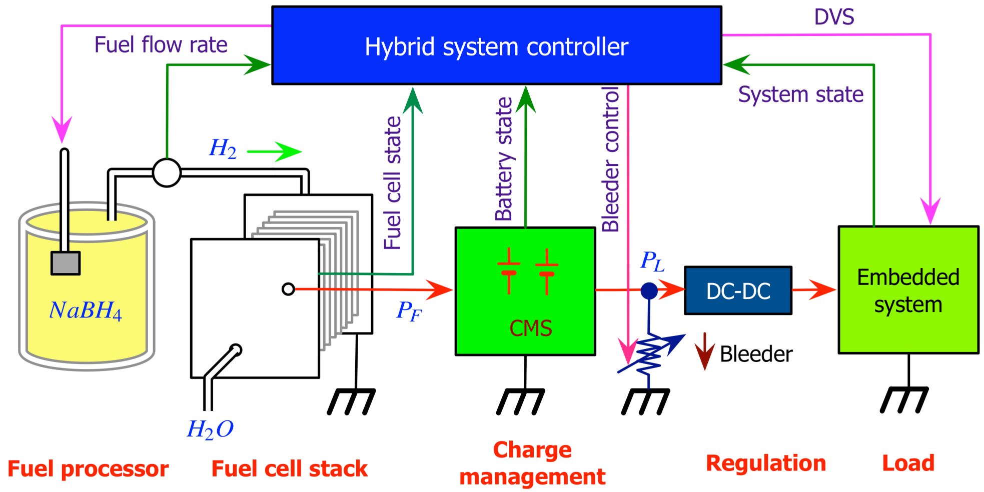
# Implementation

- Experimental environment



# Objectives: efficiency

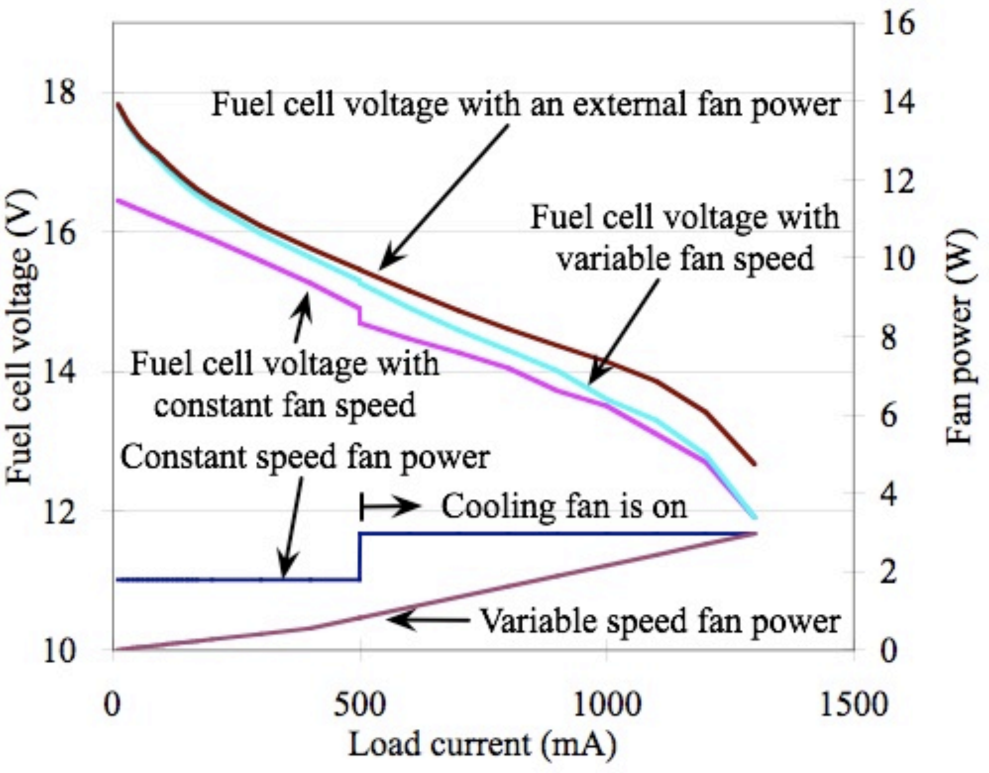
- Hybrid system optimization




- Maximize the lifetime of the fuel cell
  - Fuel cell lifetime is determined by the fuel consumption
  - Fuel consumption rate is proportional to the current value
  - Total fuel consumption is proportional to the total charge consumption
- Maximizing the lifetime → minimizing the charge consumption
- Other objectives → minimizing the form factors (battery size, etc.)

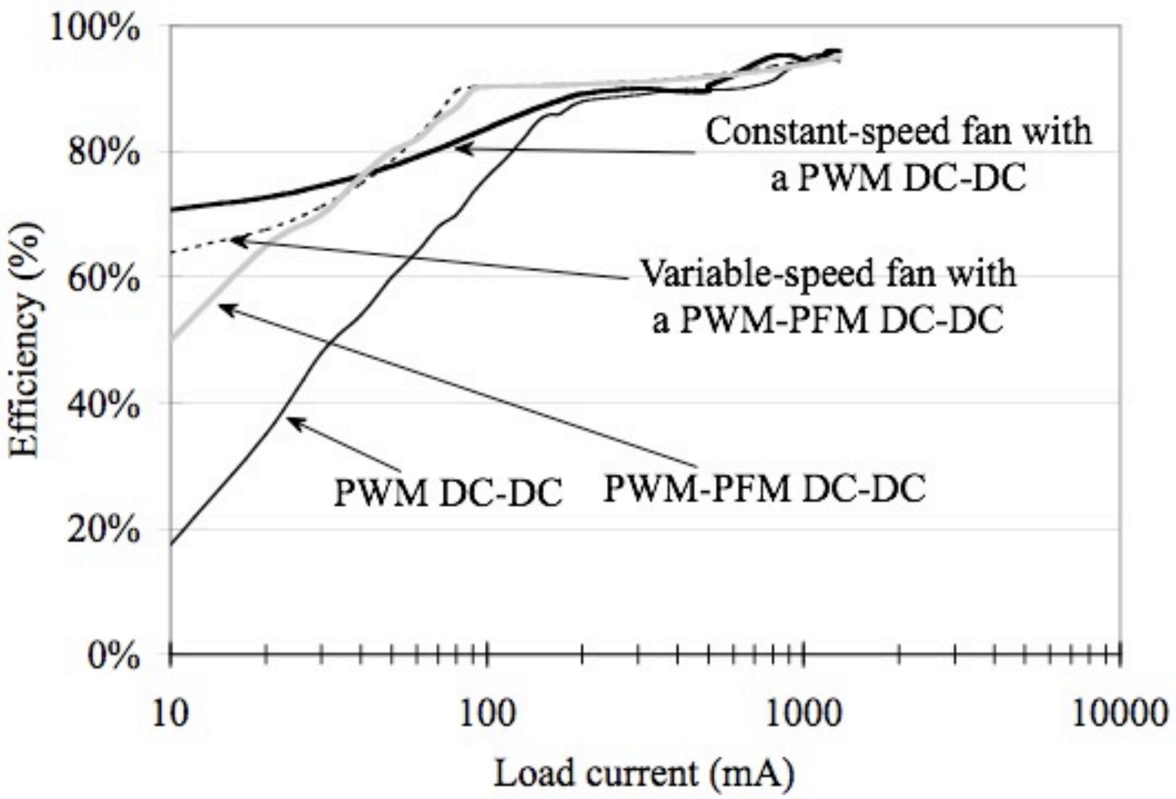
# Fuel cell system efficiency

- Fuel cell output voltage considering the controller power consumption



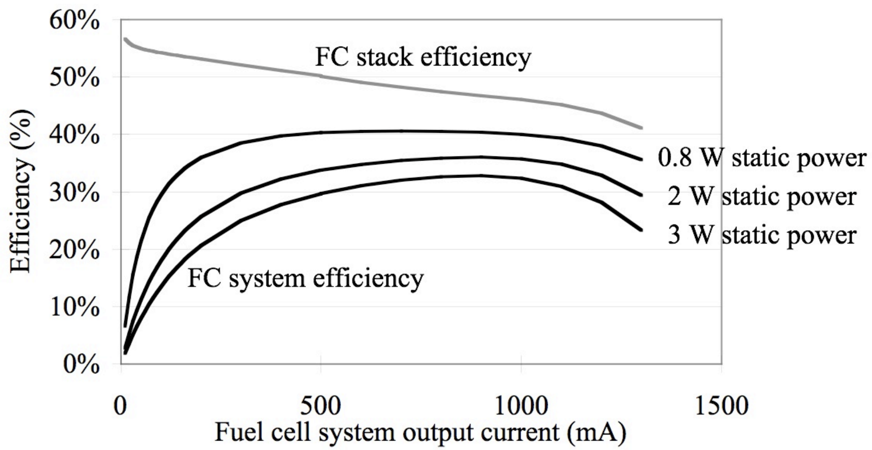
# Fuel cell system efficiency

- DC-DC converter efficiency

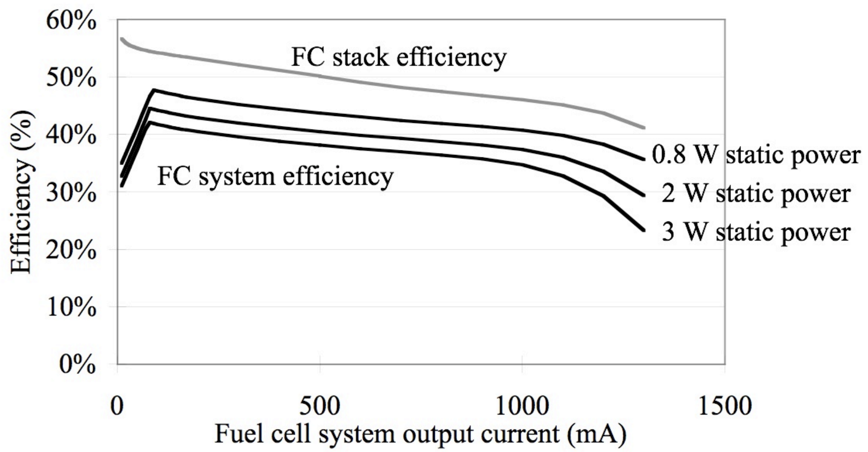


# Fuel cell system efficiency

- System efficiency




(a) Constant-speed cathode and cooling fans




(b) Variable-speed cathode and cooling fans

# Challenges

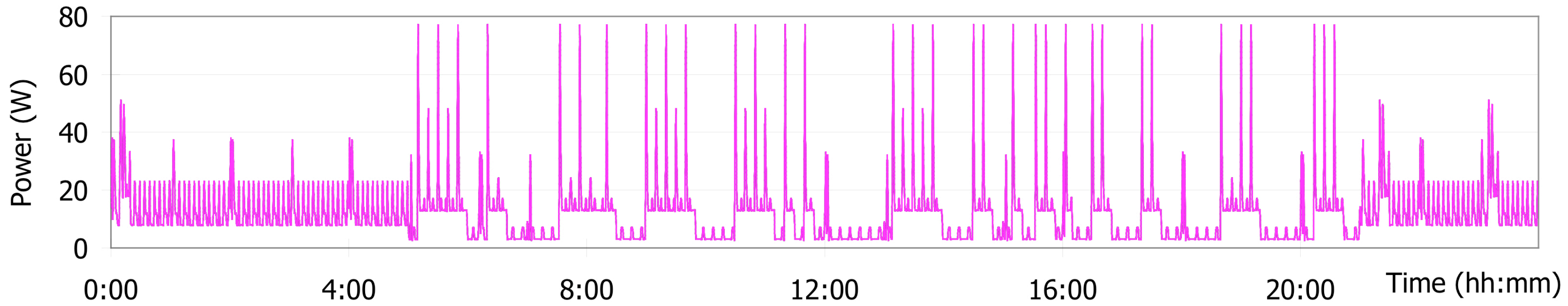
- Fuel flow control
  - Various hydrogen supply
  - Slow dynamics
- Efficiency analysis
  - Various control schemes and design specifications
- Joint power management
  - How to utilize the efficiency characteristics
  - Energy aware versus FC aware
- Implementation issues

# Example 1: wearable computer application

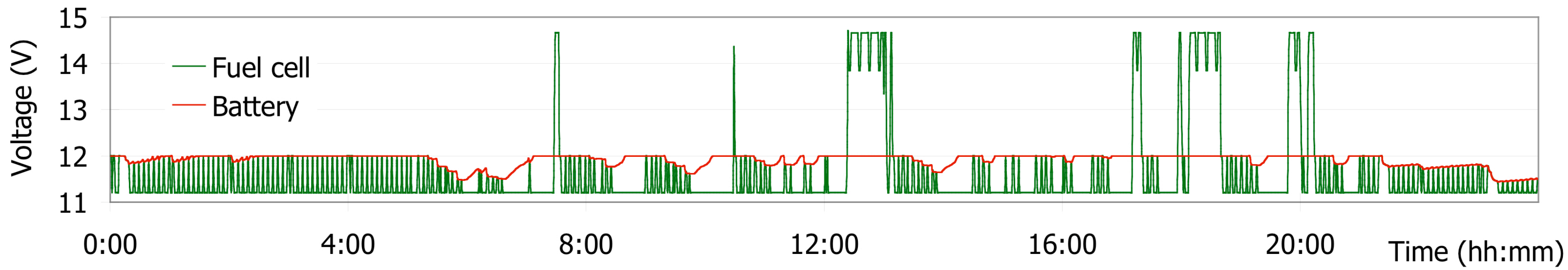
- Load characteristics
  - Navigation: 5W
  - Night vision: 20W
  - CCD video camera with an MPEG2 encoder: 5W
  - Laser scope for distance measurement: 5W
  - Laptop: 30W in active mode and 1W in sleep mode
  - GPS:1W
  - Communication: 5W during transmission and 1W during receiving
  - Head mount display: 4W
  - Audio cue: 1W in active mode
  - Satellite communication: 30W during transmission and 2W during receiving

# Example 1: wearable computer application

- Synthetic one-day outdoor wearable computer application scenario



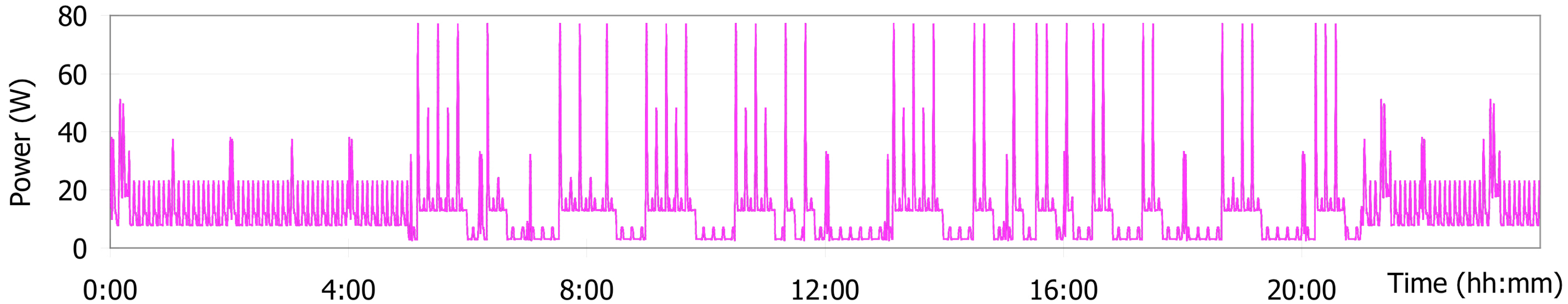

Load profile



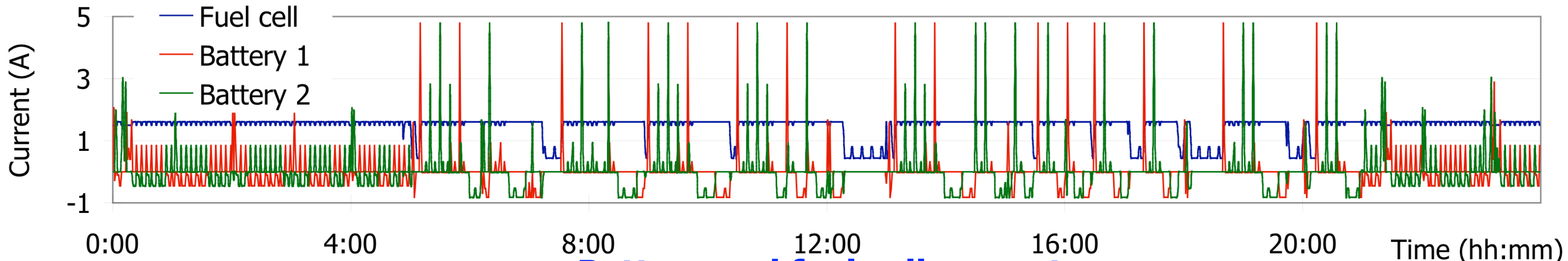

Battery and fuel cell voltage

# Example 1: wearable computer application

- Synthetic one-day outdoor wearable computer application scenario




**Load profile**

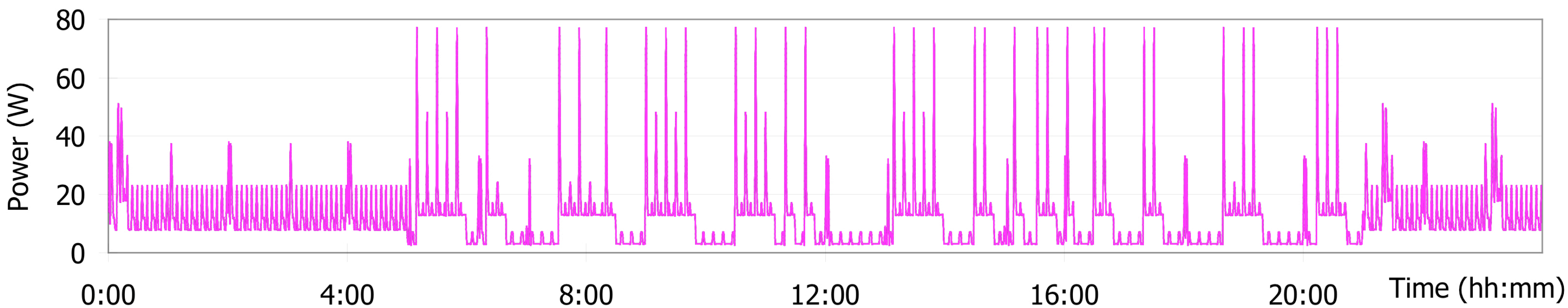



**Battery and fuel cell current**

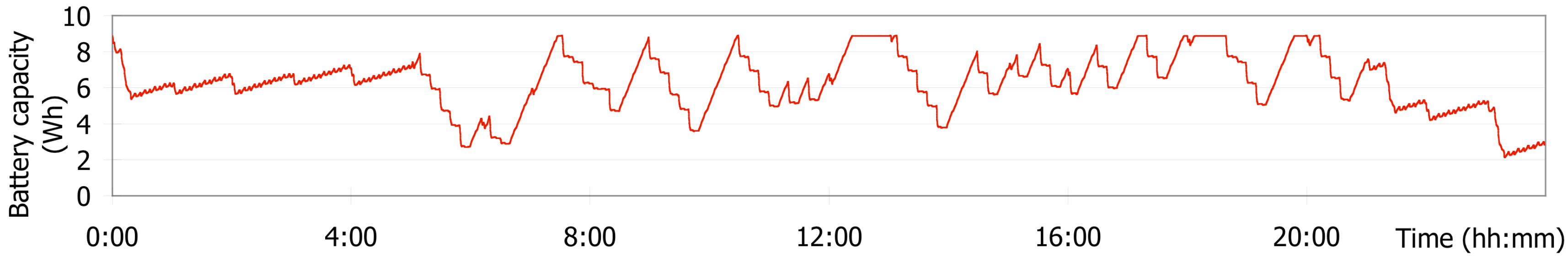
# Example 1: wearable computer application



- Synthetic one-day outdoor wearable computer application scenario




**Load profile**

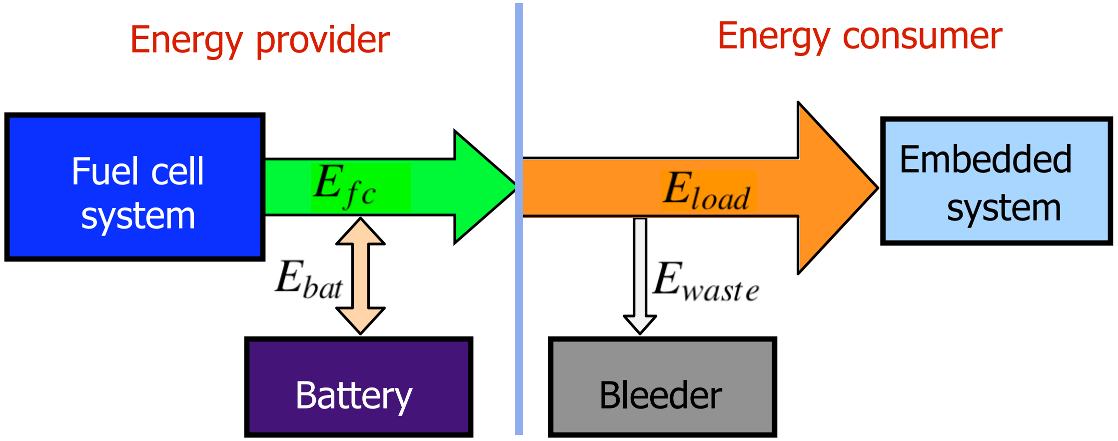



**Battery state of charge**

# Example 2: Fuel cell DVS

Minimize $E_{load} + E_{waste}$

$$E_{fc} + E_{bat} = E_{load} + E_{waste}$$




- When fuel cell power is less than load power
  - Battery provides extra power to support the system
- When fuel cell power is larger than load power
  - Battery stores the excess power
  - If battery is fully charged, then $E_{waste} > 0$

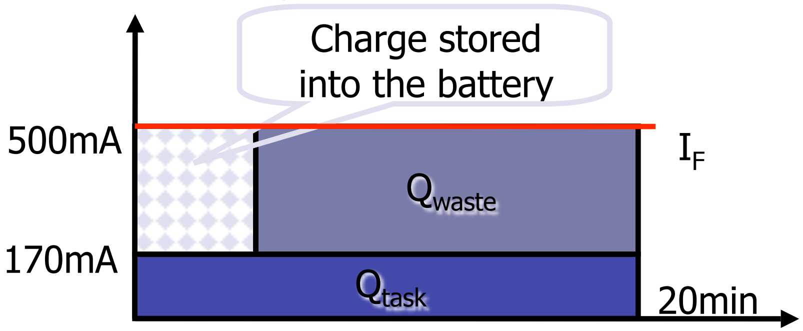
# Example 2: Fuel cell DVS

- Fuel cell-aware DVS with fixed fuel cell current (DAC06)

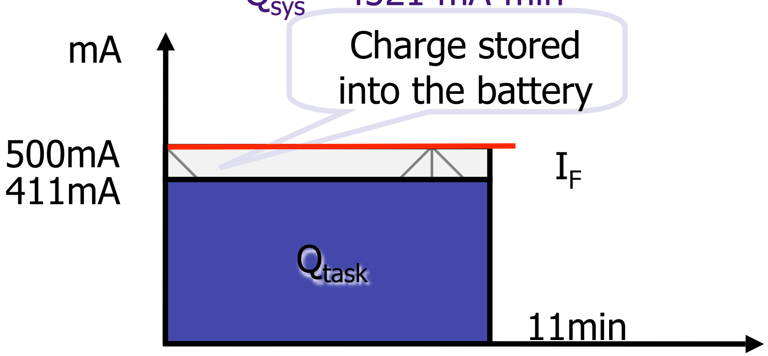
$I_F$ = 500mA, $B^{max}$ = 2000 mA-min, $B_k^{ini}$=1000mA-min,
Task $T_k$ has execution time 10min. $i_k(1)$=500mA
DVS scales from 1 to 2.5 with steps of 0.1, $\alpha_1 : \alpha_2 = 4 : 1$

Case I: energy efficient scaling
$s_k$ = 2, $i_k$=170mA
$Q_{task}$ = 3400 mA-min
$Q_{waste}$= 5600 mA-min
$Q_{sys}$= 9000 mA-min

Case II: fuelcell efficient scaling
$s_k$ = 1.1, $i_k$ = 411mA
$Q_{task}$ = 4521 mA-min
$Q_{waste}$= 0
$Q_{sys}$= 4521 mA-min




Case I: Energy efficient scaling

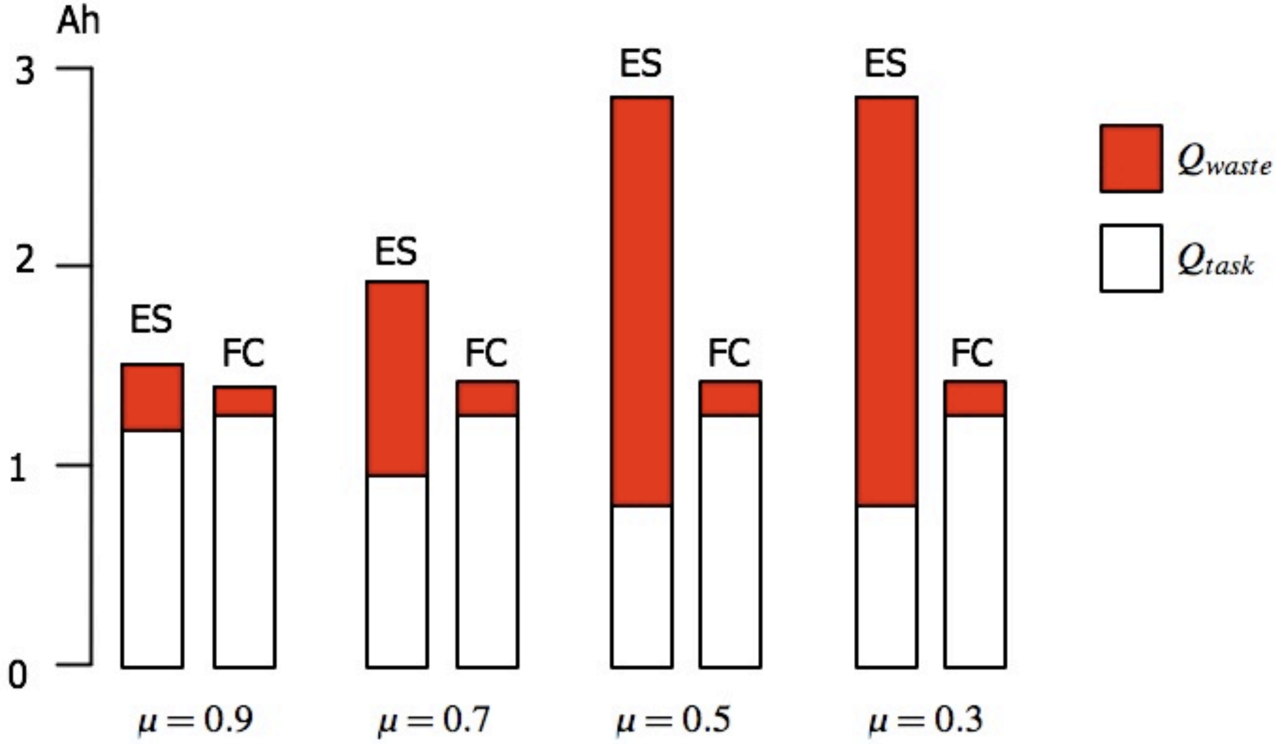



Case II: Fuel cell efficient scaling

# Example 2: Fuel cell DVS

- Fuel cell-aware DVS with fixed fuel cell current (DAC06)

  Power source setting: $I_F$ = 800mA, $B^{max}$ =250mA-hr
  (load current is 700mA on highest frequency)

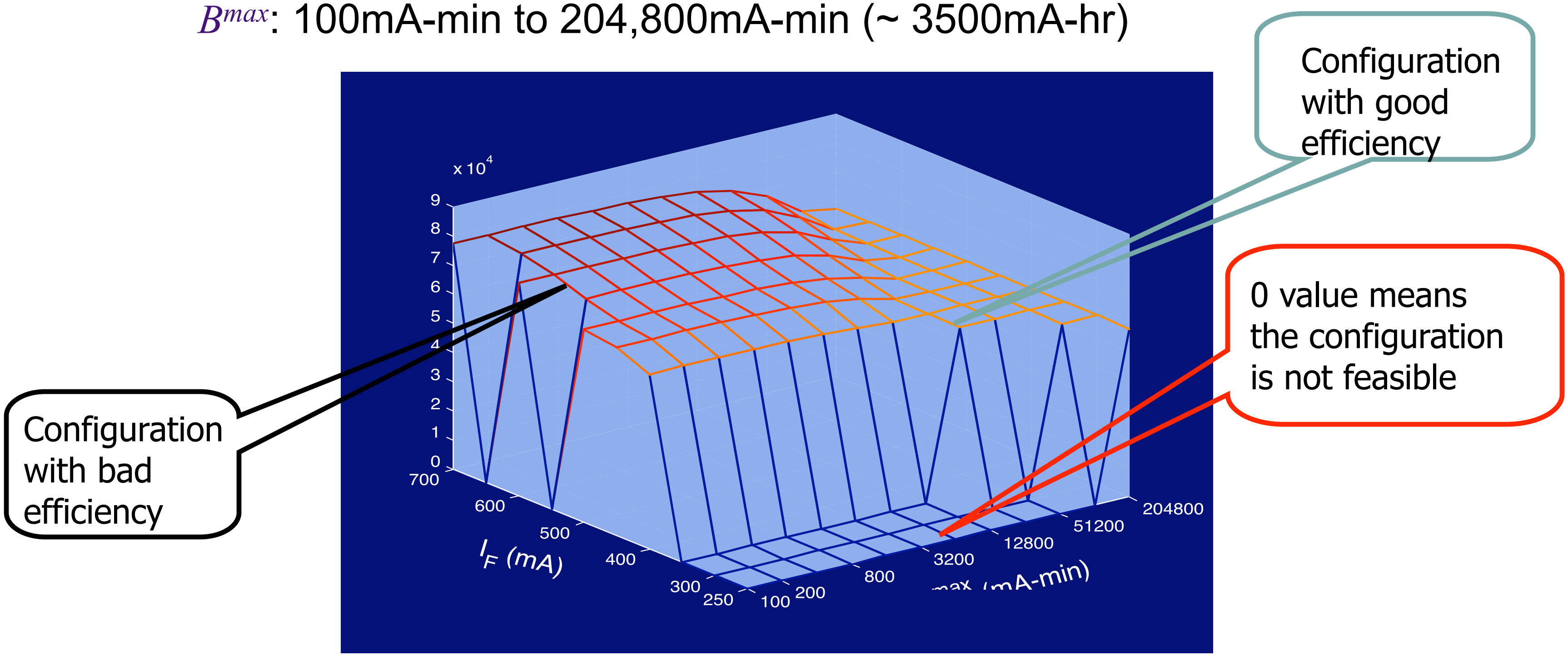


# Example 2: Fuel cell DVS

- Fuel cell-aware DVS with fixed fuel cell current (DAC06)
  - Now we vary both fuel cell current and battery capacity

    $I_F$: 250mA – 700mA with steps of 50mA

    $B^{max}$: 100mA-min to 204,800mA-min (~ 3500mA-hr)



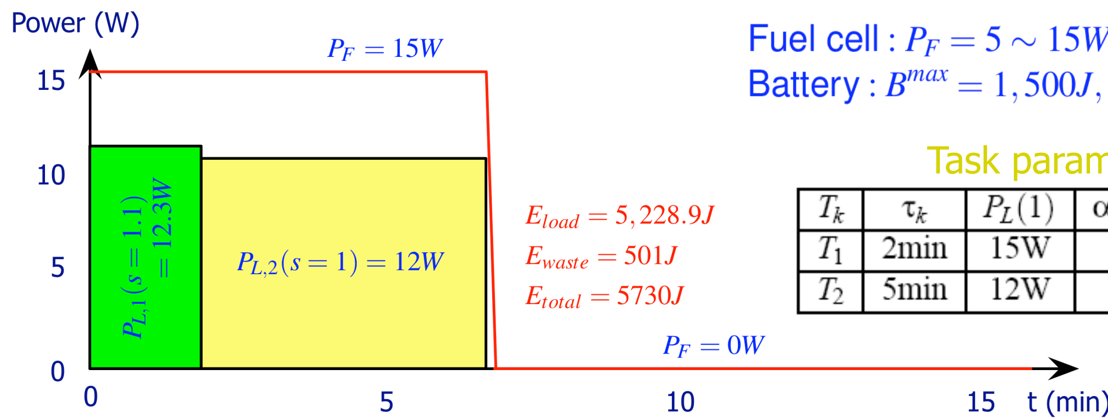
# Example 2: Fuel cell DVS

- Fuel cell-aware DVS with fuel flow rate control (ISLPED06)

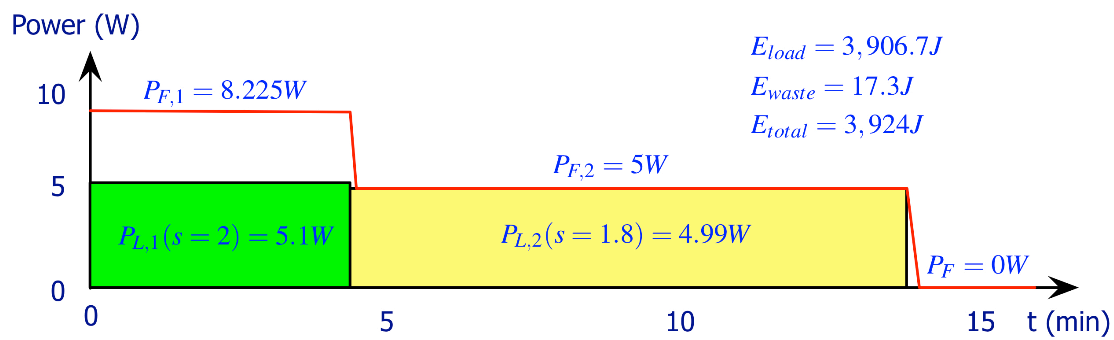
Fuel cell : $P_F = 5 \sim 15W$
Battery : $B^{max} = 1,500J,\ B_k^{ini} = 0.5 \times B^{max}$

Task parameters

| $T_k$ | $\tau_k$ | $P_L(1)$ | $\alpha_1 : \alpha_2$ | $D$ |
|---|---|---|---|---|
| $T_1$ | 2min | 15W | 4:1 | 15min |
| $T_2$ | 5min | 12W | 3:1 | 15min |




**Without the load following algorithm: fc_scale (DAC 2006)**




**With the load following algorithm: fc_scale_ctrl**

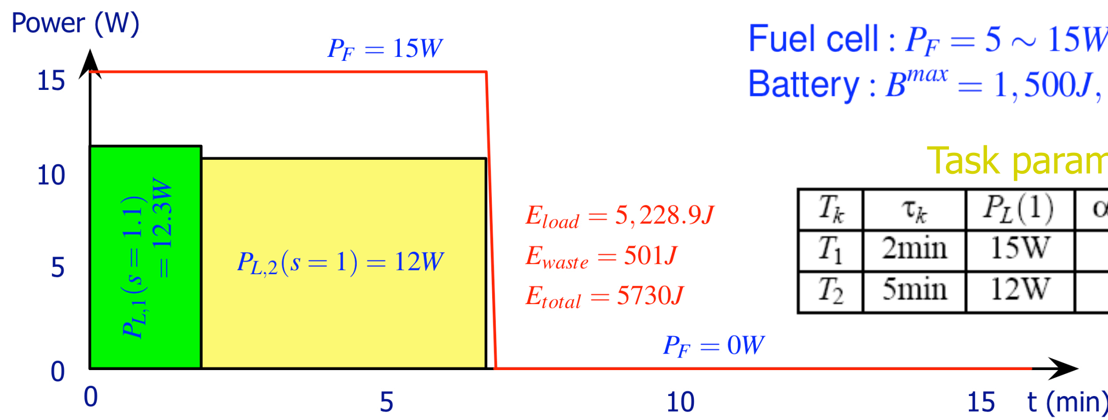
# Example 2: Fuel cell DVS

- Fuel cell-aware DVS with fuel flow rate control (ISLPED06)

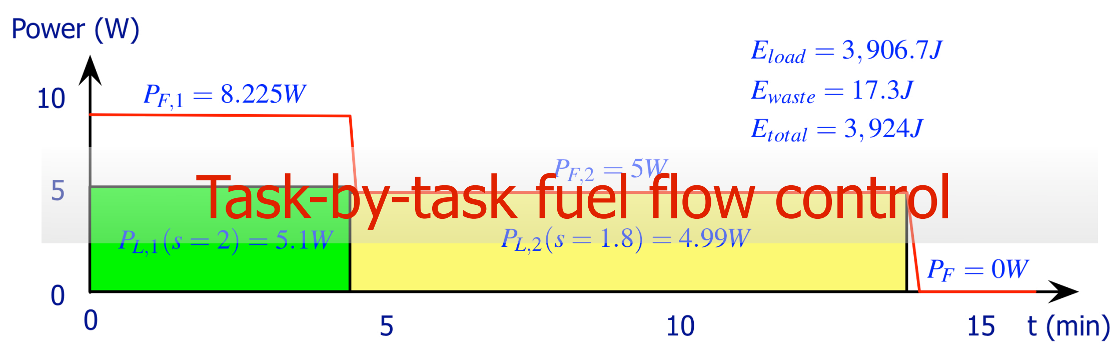
Fuel cell : $P_F = 5 \sim 15W$
Battery : $B^{max} = 1,500J,\ B_k^{ini} = 0.5 \times B^{max}$

Task parameters

| $T_k$ | $\tau_k$ | $P_L(1)$ | $\alpha_1 : \alpha_2$ | $D$ |
|---|---|---|---|---|
| $T_1$ | 2min | 15W | 4:1 | 15min |
| $T_2$ | 5min | 12W | 3:1 | 15min |




**Without the load following algorithm: fc_scale (DAC 2006)**



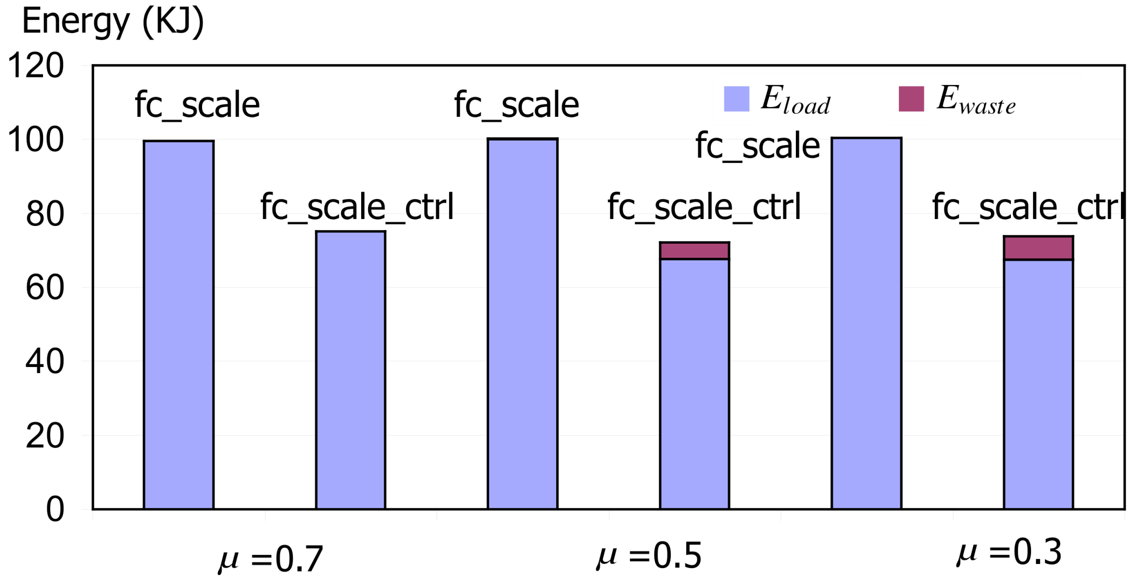

**With the load following algorithm: fc_scale_ctrl**

# Example 2: Fuel cell DVS

- Fuel cell-aware DVS with fuel flow rate control (ISLPED06)

$P_{L,k}(1) = 15W$ for all tasks

$\alpha_1 : \alpha_2$ is randomly chosen from 3 to 7, for each task



# Conclusions

- Fuel cell
  - Convert chemical energy into electrical energy
  - Clean and efficient power source
- Fuel cell and battery hybrid system
  - Provide both high energy density and high power density
  - A promising solution for portable electronics as well as vehicles
- Most fuel cell researchers focus on the stack/cell/membrane
  - Need contributions for the hybrid systems and controllers
  - Suitable for CSE people
- Hybrid system optimization for portable electronics
  - Optimize fuel consumption, size, power/energy density, etc.
  - Must consider the characteristics of the application, the fuel cell efficiency, the battery charging/discharging efficiency and the wasted charge

# Acknowledgment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  - Kyungsoo Lee (SNU), Youngjin Cho (SNU), Donghwa Shin (SNU), Jaehyun Park (SNU), Younghyun Kim (SNU), and Jihun Kim (SNU)
- Fuel cell operation support
  - Dr. Dominic Gervasio (ASU) and Sonja Tasic (ASU)
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  - Dr. Ken Han (KITECH)
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