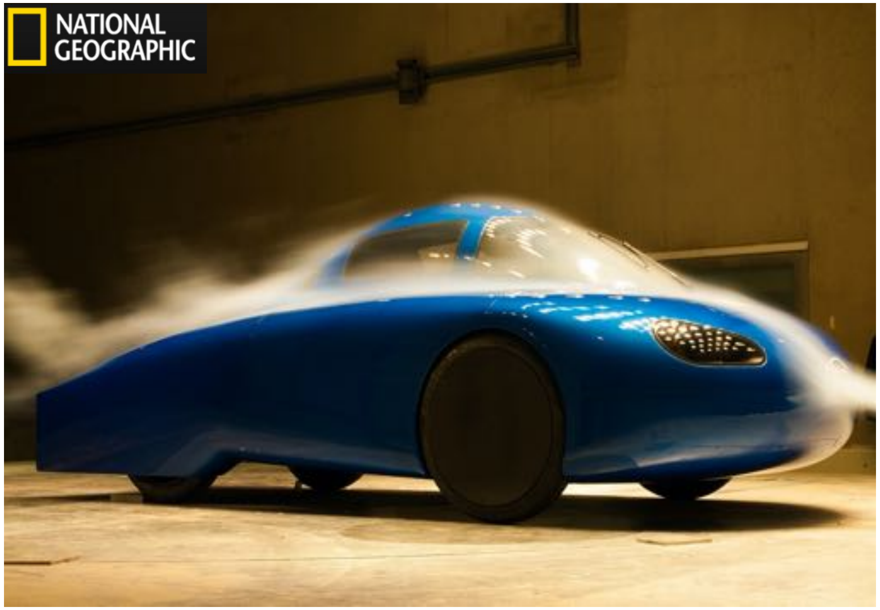
Nantes Université

IREENA
Institut de Recherche en Energie Electrique de Nantes Atlantique - UR 4642

Fuel Cell Electrical Vehicle : Design and optimization



Prof. TRICHET Didier

Head of IREENA Lab
University of Nantes
Polytech'Nantes
Graduate School of Electrical Engineering
France

didier.trichet@univ-nantes.fr
www.univ-nantes.fr

Objectives

- Main objective :
  - Achieve the most energy efficient Hybrid **Fuel Cell** Electrical Vehicle (HFCEV)

    => participation to Shell Eco Marathon race (https://www.makethefuture.shell)

- Actions :
  - Mechanical : Build a car with very low mass and very low frictions (aero. drag and rolling resistance)
  - Electrical / thermal / electrochemical :
    - Design of a fuel cell stack with high efficiency (>60 % with accessories)
    - Optimize the energy conversion / consumption / structure
  - Control : Optimize driving strategy

- Presented work :
  - General information about Fuel Cell and benefits of hybrid structures for electrical powertrain
  - A Tank-to-wheel energetic model of the vehicle : Mechanical, Electrical and Thermal models and Optimization of the driving strategy to minimize the fuel consumption

Fuel Cell

- Comparison between Internal combustion Engine vehicle (ICEV), Fuel Cell Electrical vehicle (FCEV) , Battery Electrical vehicle (BEV). Stage of maturity ?

Characteristics	ICEV	FCEV	BEV
Reference vehicle	Volkswagen Golf VI	Honda FCX Clarity	Nissan Leaf
Fuel weight (kg)	40.8	4.1	171
Storage capacity (kWh)	500	137	24
Specific energy – fuel (Wh primary/kg)	12,264	33,320	140
Storage system weight (kg)	48	93	300
Specific energy – fuel + storage (Wh primary/kg)	10,408	1469	80
Net power (kW)	90	100	80
Power plant and auxiliary weight (kg)	233	222	100
Specific energy – total equipment (Wh primary/kg)	1782	315	60
Average conversion efficiency	21%	60%	92%
Effective storage capacity (kWh usable)	105.0	82.0	22.1
Specific usable energy – total equipement (Wh usable/kg)	374	260	55

H2 best energy mass density (Wh/Kg)

Weight limitation of BEV / FCEV

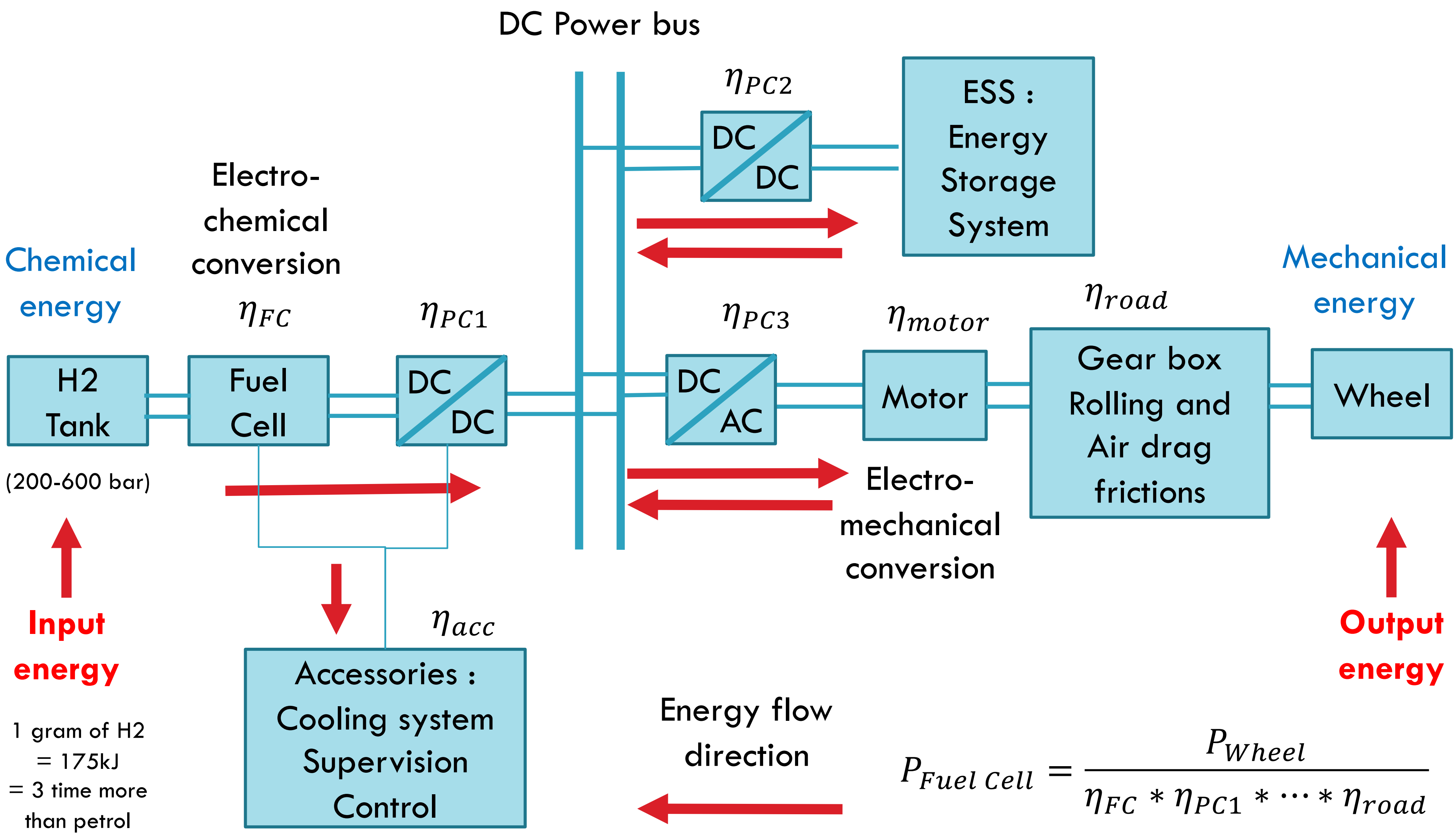
Higher efficiency FCEV / ICEV

Range extension with FCEV / BEV (200km vs 550km)

=> FCEV a promising solution for long range vehicle and lower impact on environment (drawback : production of dihydrogen must be improved probably with renewable energies)

(*)Intelligent Hydrogen Fuel Cell Range Extender for Battery Electric Vehicles, May 2019, World Electric Vehicle Journal

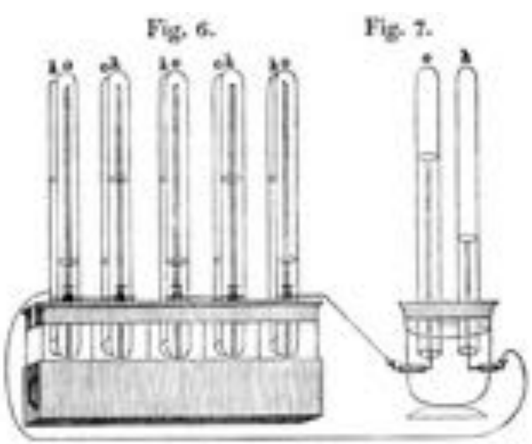
Global structure of FCEV

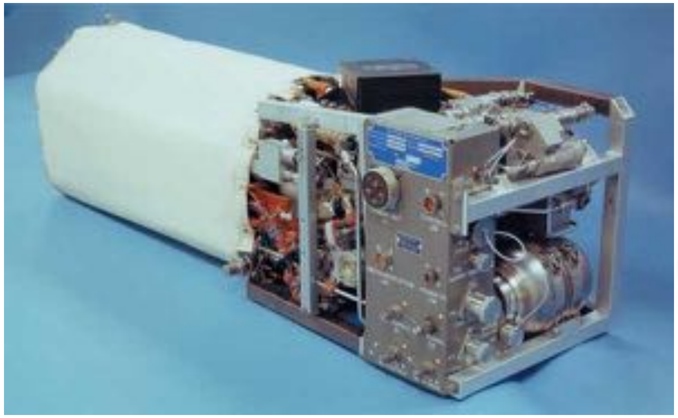


$$P_{Fuel\ Cell} = \frac{P_{Wheel}}{\eta_{FC} * \eta_{PC1} * \cdots * \eta_{road}}$$

Fuel Cell

- Some history
  - 1839 - William GROVE discover the principle of Fuel Cell
  - 1960 – Space travels revive fuel cell developments
    - Chemical storage
    - No emission of toxic gas
    - Very long energy life
  - Today – Production of renewable energy





Fuel Cell

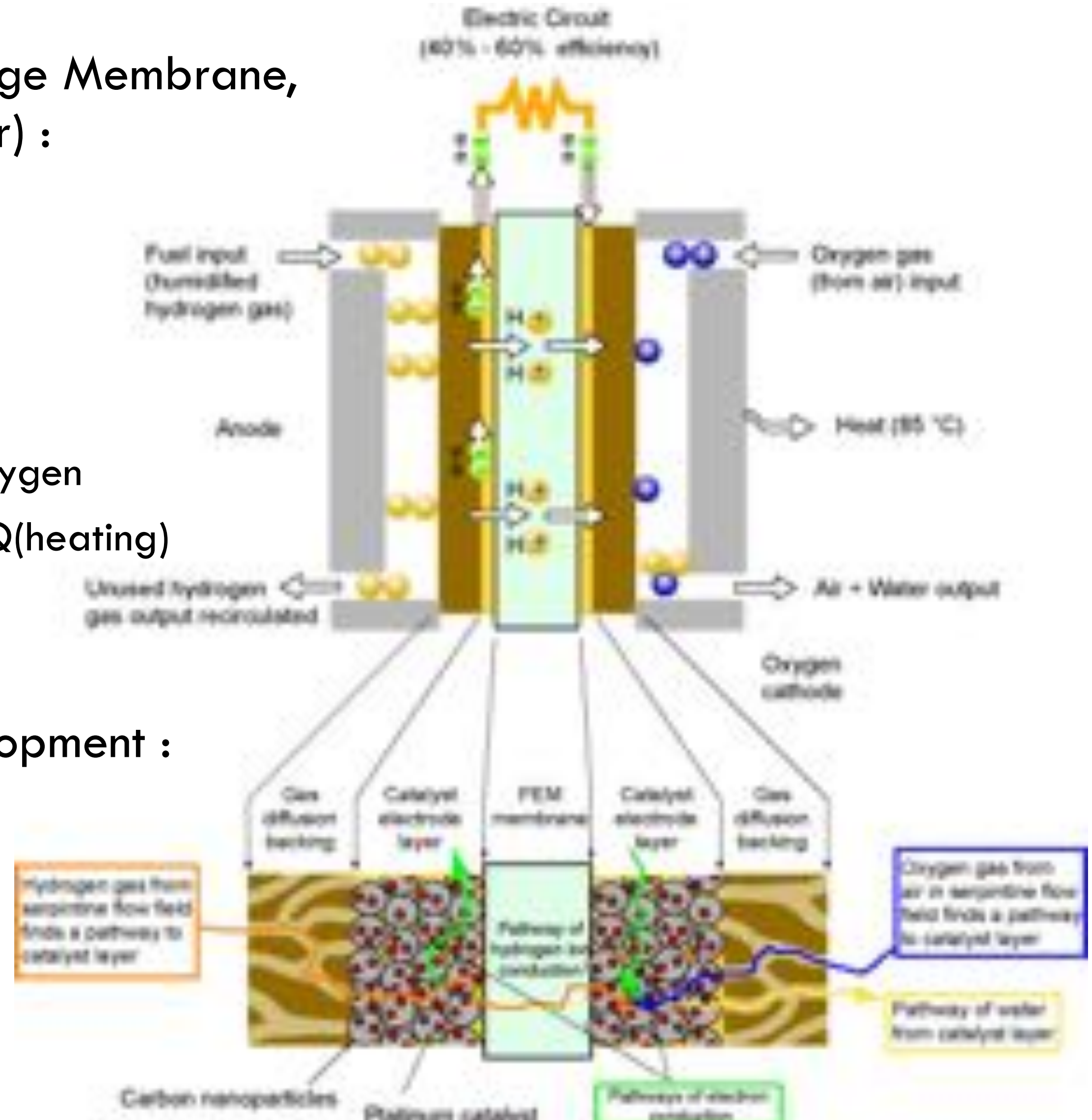
- Fuel cell principle (Proton Exchange Membrane, PEMFC, electrochemical converter) :
  - Anode : Separation of dihydrogen

    $2H_2 \rightarrow 4H^+ + 4e^-$

  - Cathode : Recombination with dioxygen

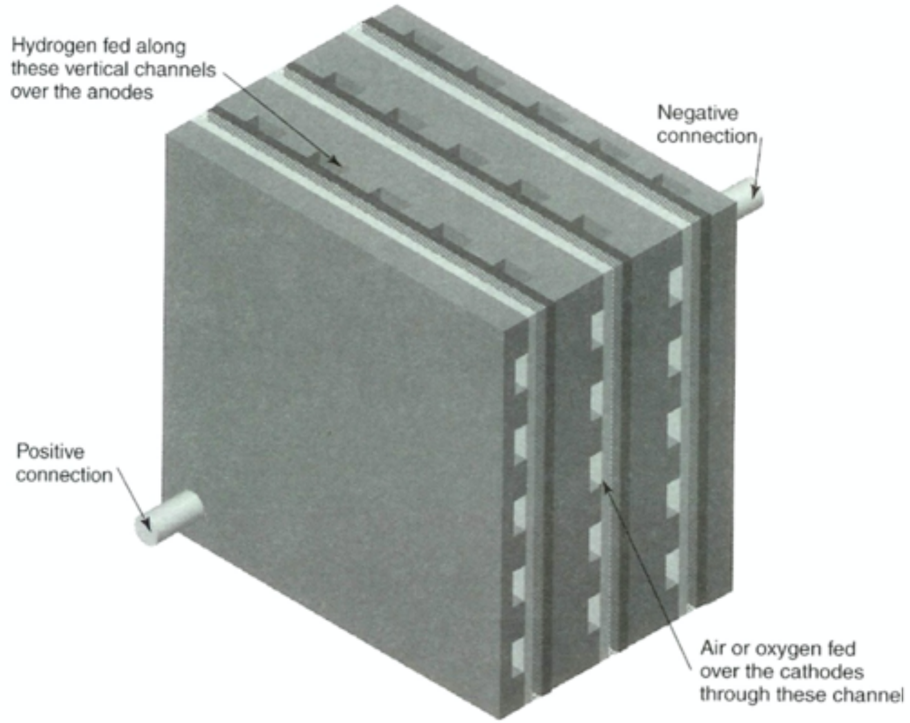
    $4H^+ + 4e^- + O_2 \rightarrow 2H_2O + \Delta Q$(heating)

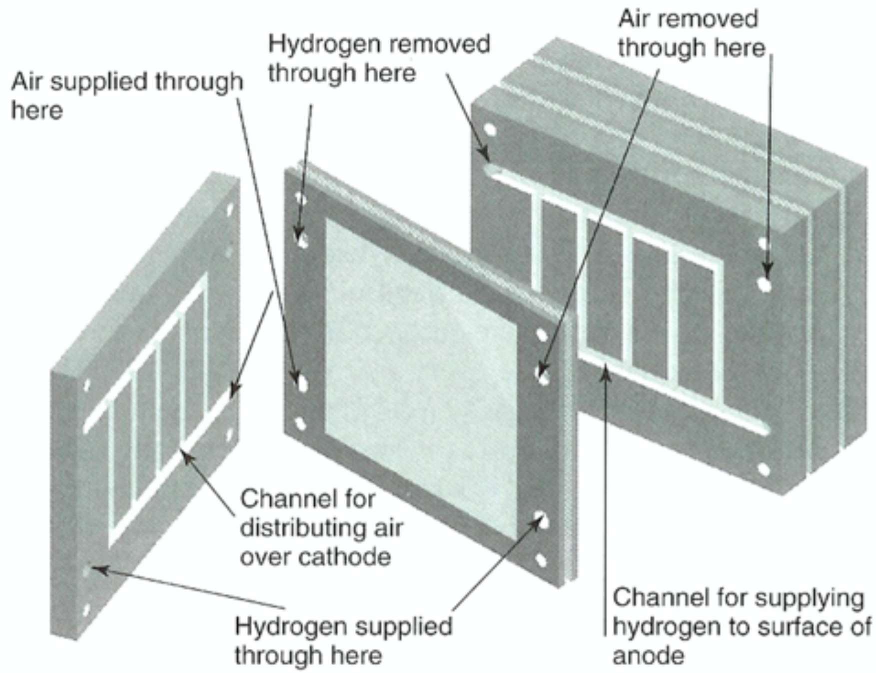
- Main issues for large scale development :
  - lifetime
  - Price
  - Flooding
  - H2 storage and production



Fuel Cell

- Fuel cell principle (Proton Exchange Membrane, PEMFC) :





Example of stack of three cells showing how a bipolar plate connects the anode of one cell to the cathode of the next cell

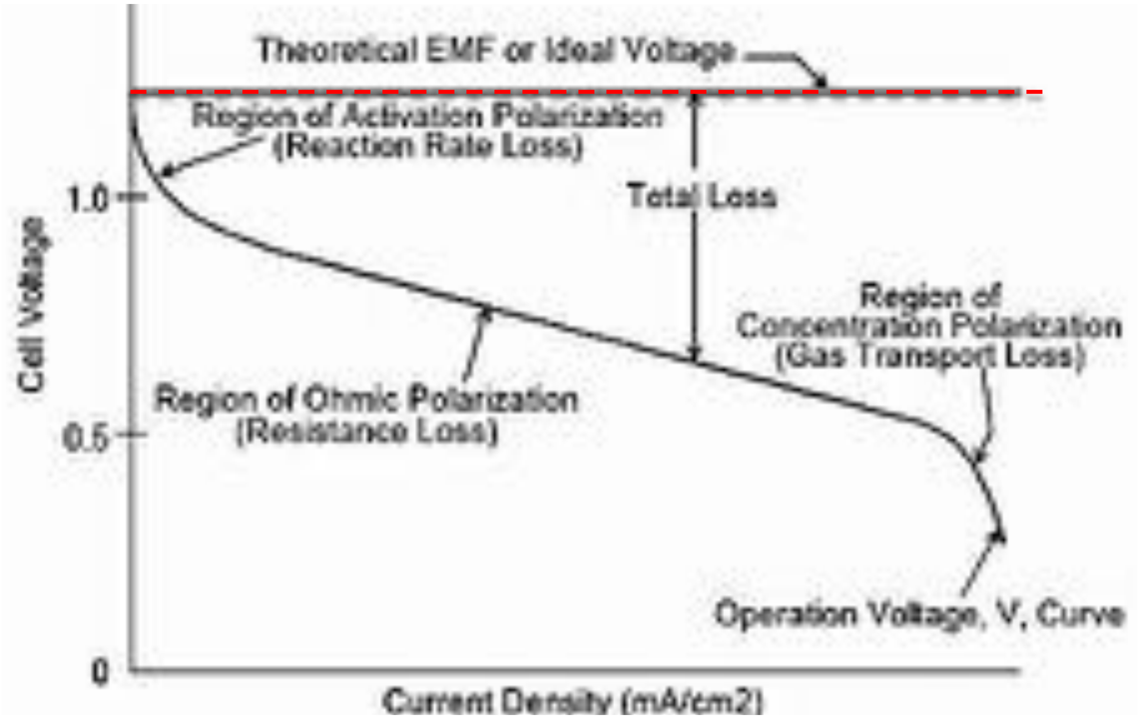
Fuel Cell

- Efficiency calculation of a Fuel Cell
  - Efficiency evaluation :
    - Entrance ➔ Chemical energy (di-hydrogen)
    - Output ➔ Electrical energy
  - 3 different working zone ➔ 3 type of losses

$$EMF = V_0 - \frac{RT}{2\alpha F}\ln\left(\frac{i}{i_0}\right)$$

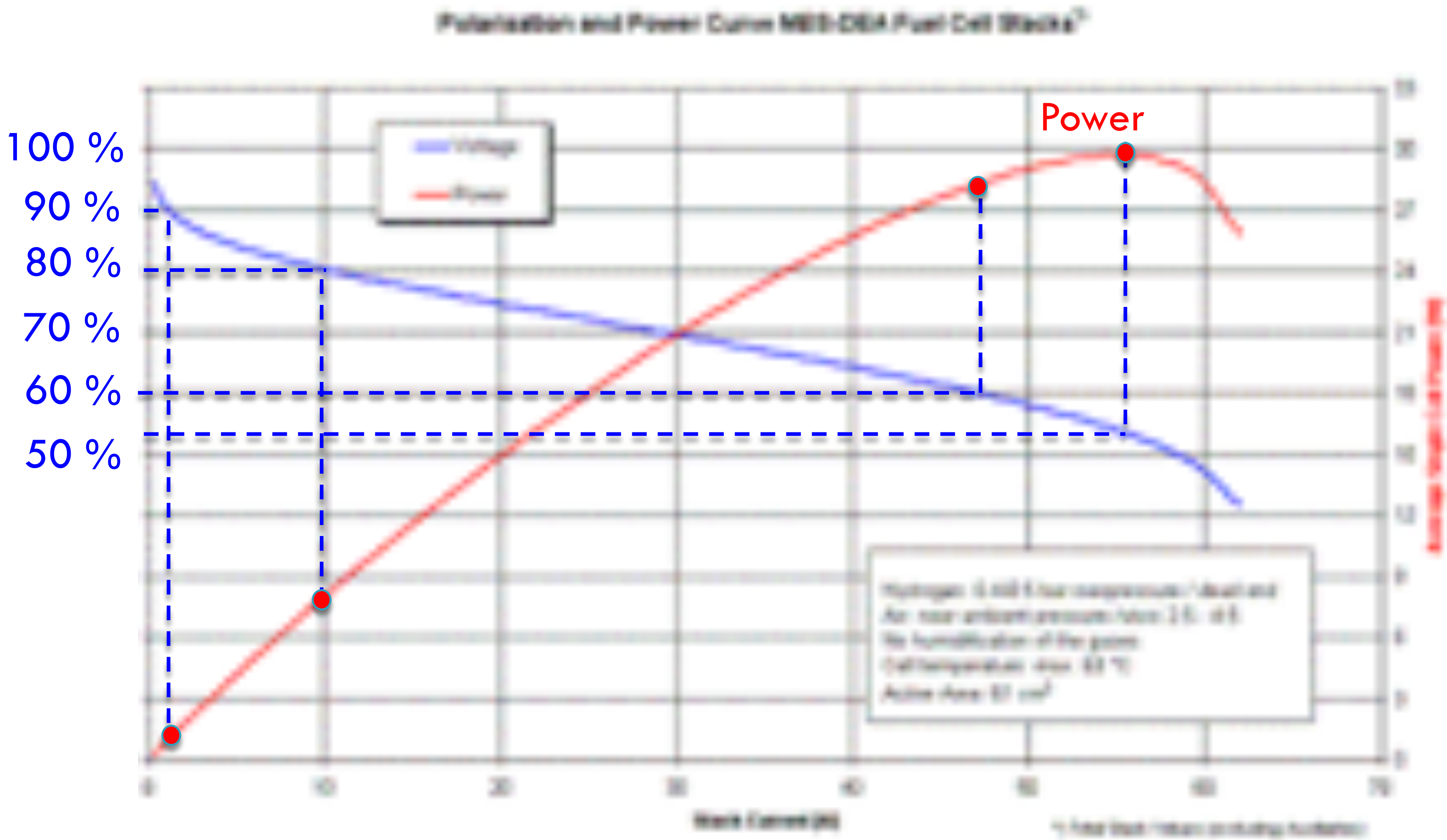
$$V_{ohm} = \mathrm{R}_{eq}\, i$$

$$V_{conc} = m.\exp(n.i)$$



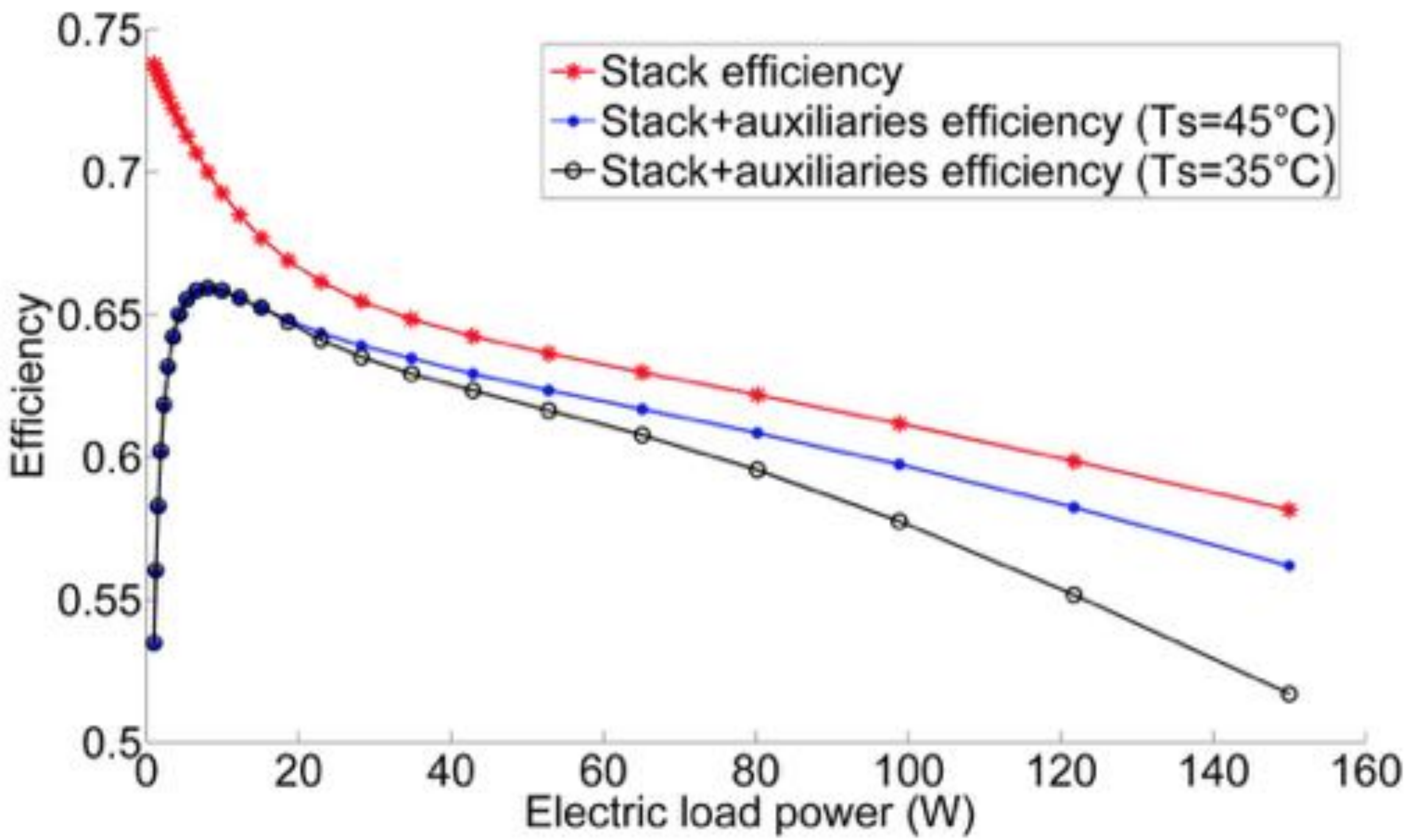
Fuel Cell

- Efficiency is directly connected to the output voltage
- Balance between power and efficiency



Fuel Cell

- Efficiency with or without accessories and according to temperature



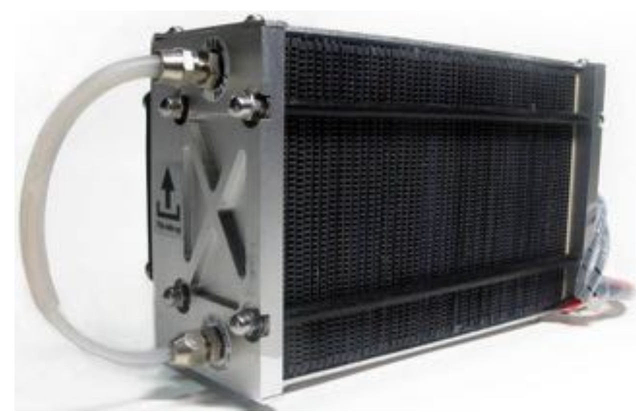
Fuel Cell

- Different technologies

Description	Anode gas/liquid	Cathode gas	Power range	Temperature	Efficiency	Maturity	Applications
AFC –Alcaline stack	H_2	**O_2**	<100 kW	**60-200 °C**	**60 %**	**Market ready**	**Transportation**
PEMFC	H_2	**O_2-Air**	<500 kW	**60 – 200 °C**	**50 %**	**Market ready**	**Transportation,** Stationary
SOFC – Solid Oxyde	**H_2, Methane, Gas synth.**	**O_2-Air**	**<100 MW**	**800 °C**	**60 %**	development	Stationary


SOFC


AFC

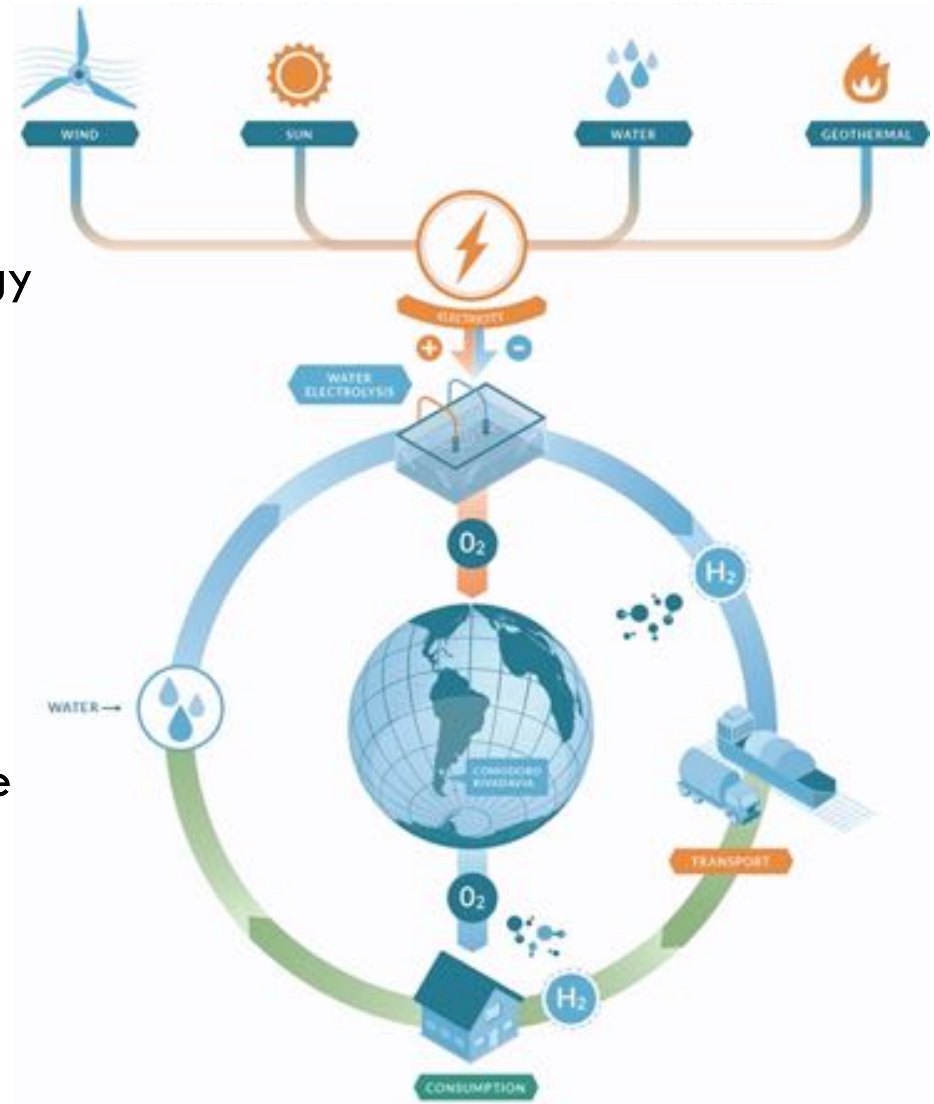

PEMFC

Fuel Cell

H2 Sectors

- Electricity produce by renewable energy
  - Solar
  - Wind energy
  - Tidal energy
  - Biomass
  - Biofuels

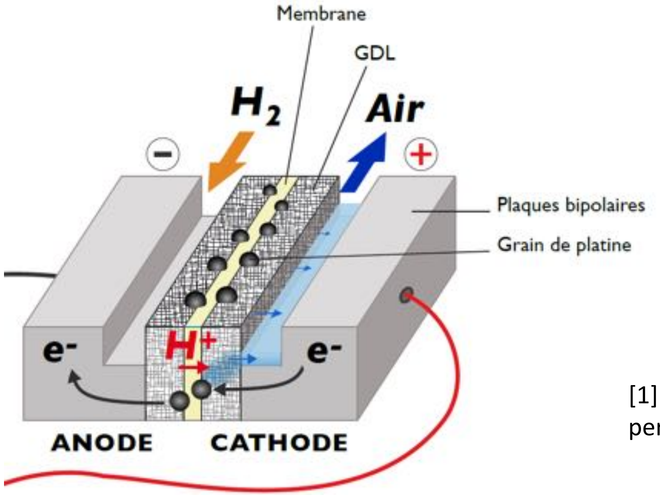
- Production of di-hydrogen by hydrolyse
  - Smoothing of energy production for network
  - Storage for transportation

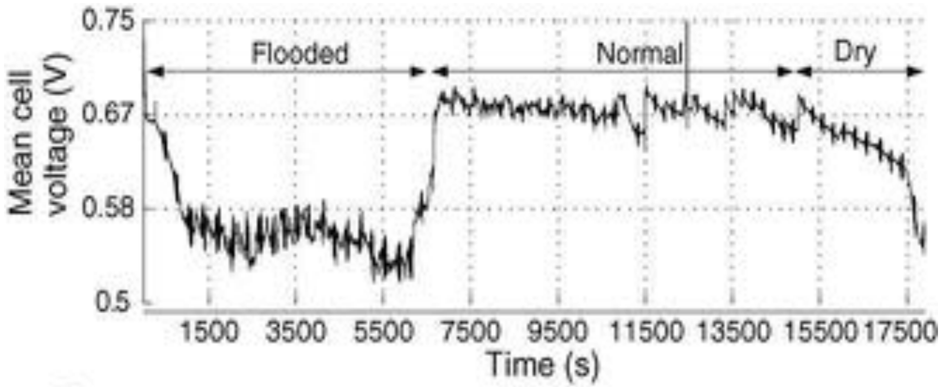


http://www.hychico.com/hydrogen-and-renewable-energy-sources.php

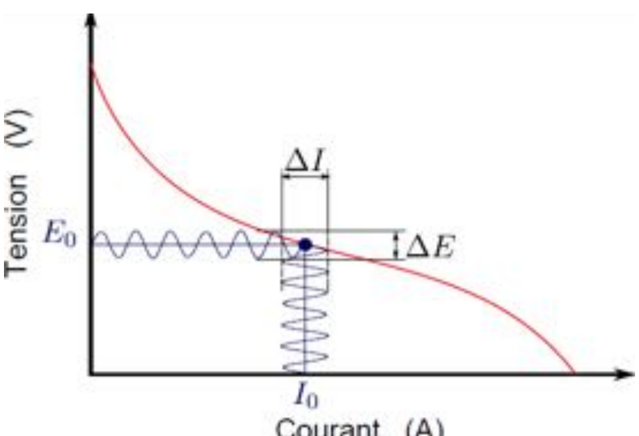
Fuel Cell

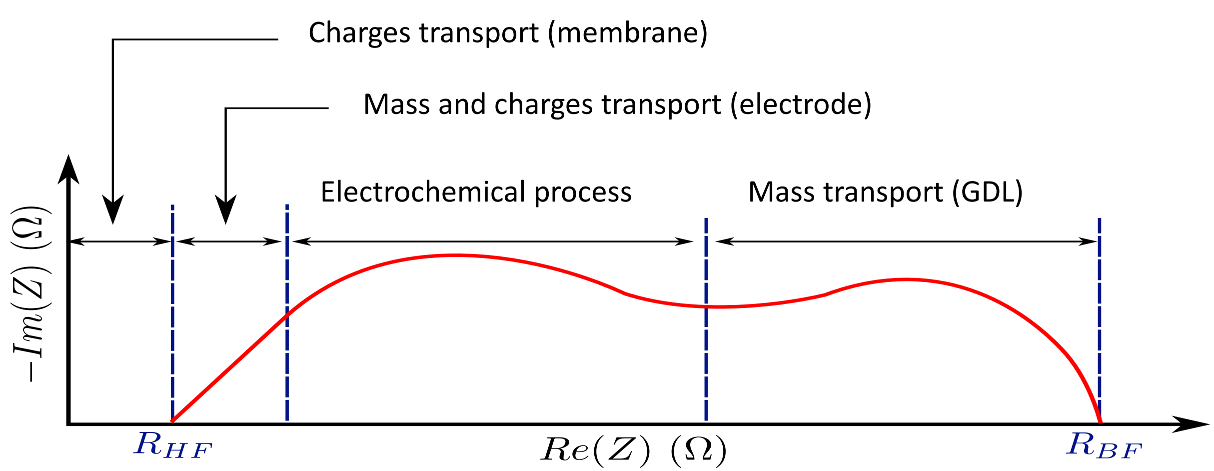
- Electrochemical Impedance Spectroscopy (EIS) is one of the best technique to do diagnosis of FC (drying, flooding, platinum degradation)





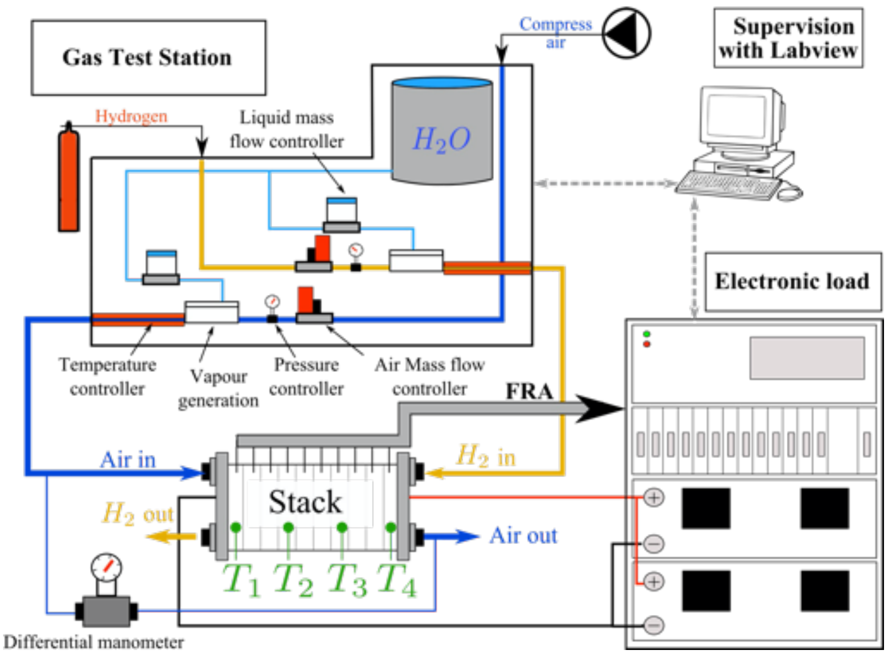
[1] Schmittinger, W., & Vahidi, A. (2008). A review of the main parameters influencing long-term performance and durability of PEM fuel cells. *Journal of Power Sources*

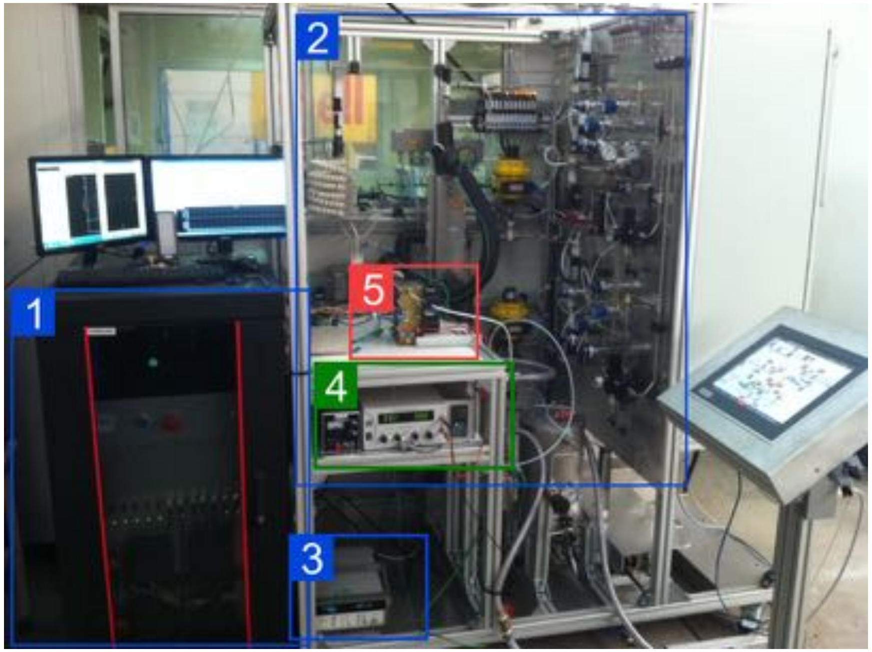


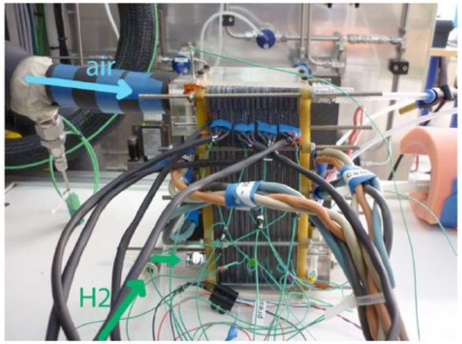


Fuel Cell

- Fuel cell test bench



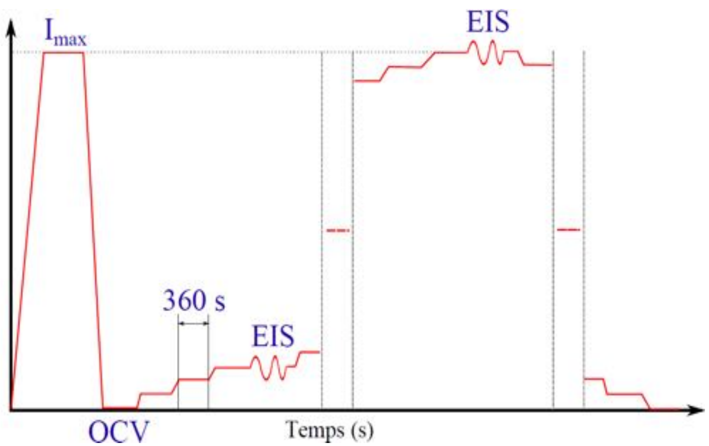




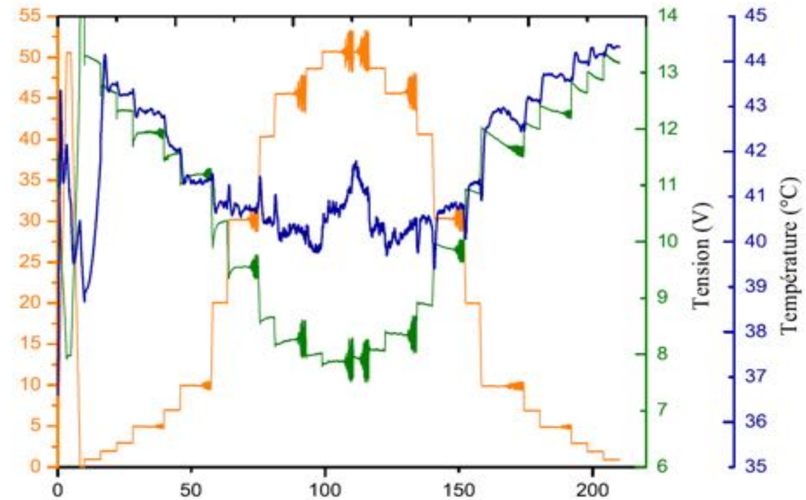
① 2 Electronic Load (2*1.2kW), E.I.S. measurements (52 channels)
② Gas conditioning (temperature, humidity, pressure, stoichiometry …)
③ Temperature acquisition (16 channels)
④ Regulation of stack temperature
⑤ Fuel Cell stack to be tested (up to 2kW)

Fuel Cell

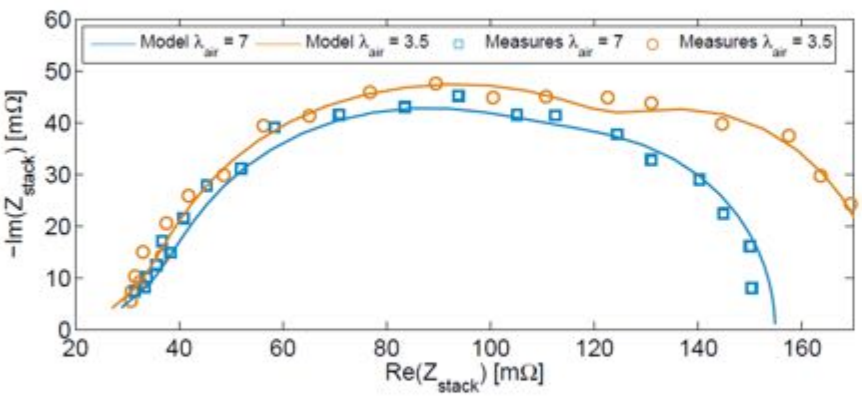
- Some results



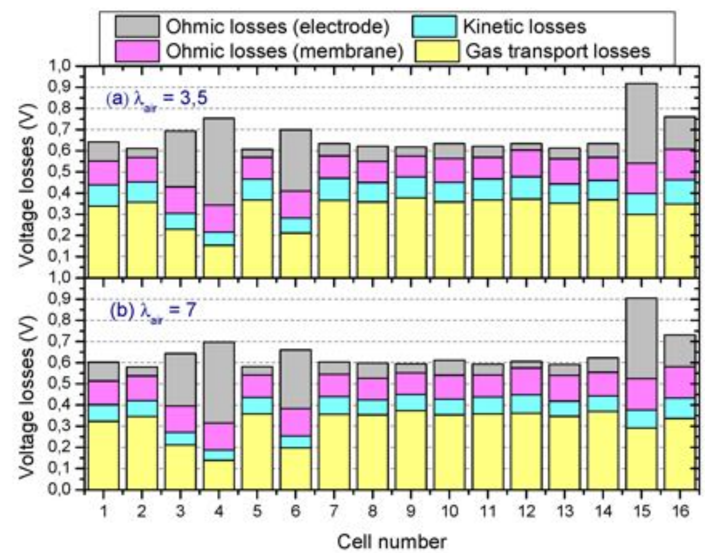
Constant air&H2 stoichiometry/hygrometry, 24 currents levels (12 up and 12 down), 10 EIS measures in 3h40.



Real time monitoring



Simplex optimization algorithm is used to compare EIS measurements and model.



Potential losses for different stoichiometry for each cell

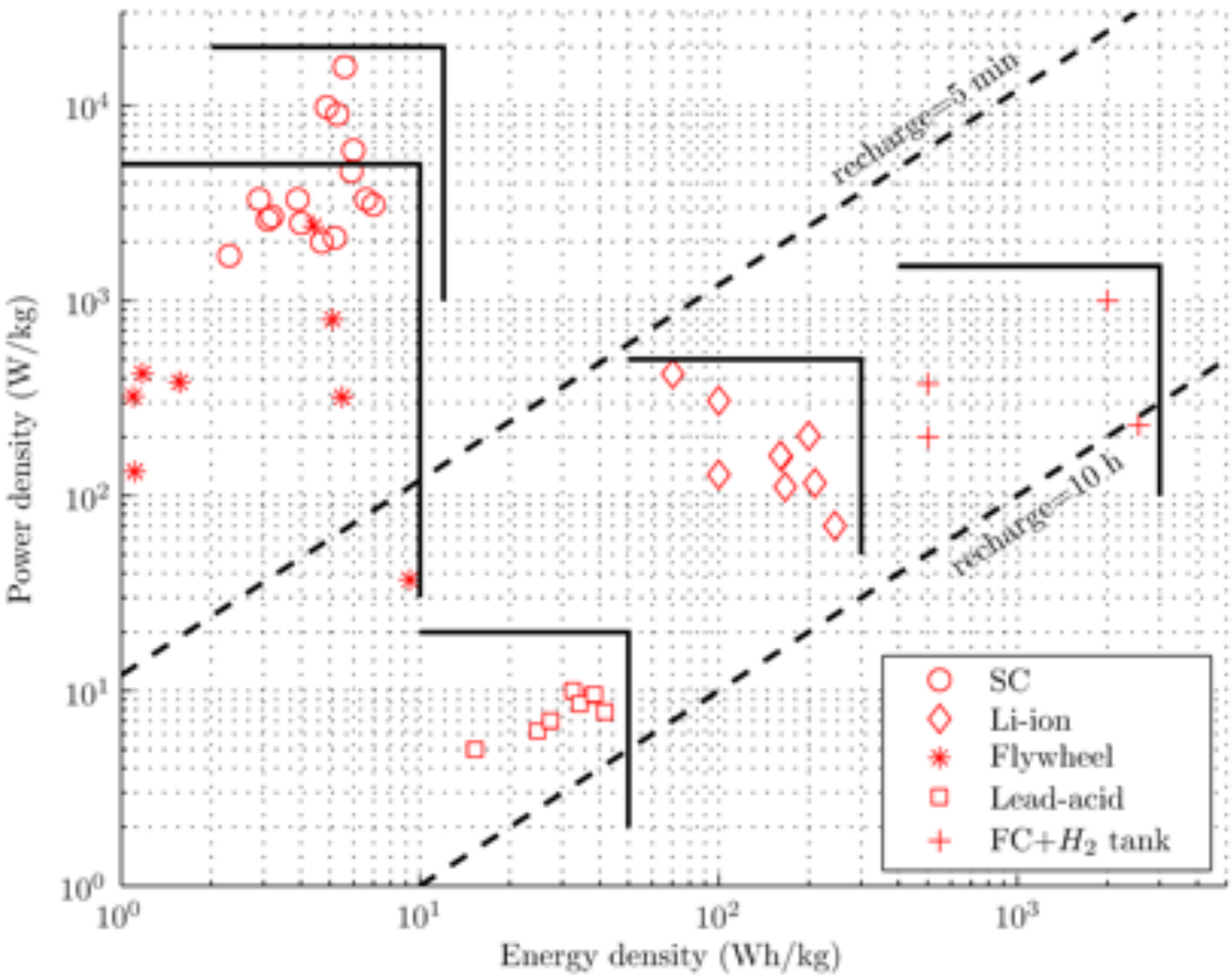
Fuel Cell

- Advantage of hydrogen as an energy vector
  - Mass energy density very high
  - Combustion without polluting exhaust
  - Renewable energy available in large quantities
  - Different way to be used (combustion, low or high temperature Fuel Cell)
  - Very good efficiency (between 50 et 70 %)

- Some drawbacks
  - Low volumic density → High pressure storage, liquid or solid
  - Explosive gaz → Security problems
  - Cost of nowadays converters for production of H2 (Electrolysor, Fuel cell, reforming, …)

Fuel Cell

- Comparison of producing and storage systems



Fuel Cell

Some economic comparison for a 50kW car (today)

- Classical diesel ICE (lifetime: 4000 h) (Internal Combustion Engine)
  - ICE : 3000 € - 110 kg
  - Starter/generator: 300 € - 10 kg
  - Accessories (catalytic converter, filters, …): 1000 € - 50 kg
  - tank : 100 € - 50 kg
    - TOTAL: 4400 € - 220 kg

- Fuel Cell car (lifetime: 2000 h)
  - Fuel Cell(~ 2000 €/kW) : 100 k€ - 100 kg
  - Electric drive (~ 20 €/kW): 1000 € - 100 kg
  - Power converter r (~50 €/kW): 2500 € - 50 kg
  - tank (~500 €/kgH2): 2000 € - 70 kg
    - TOTAL: 105 500 € - 320 kg

Fuel Cell

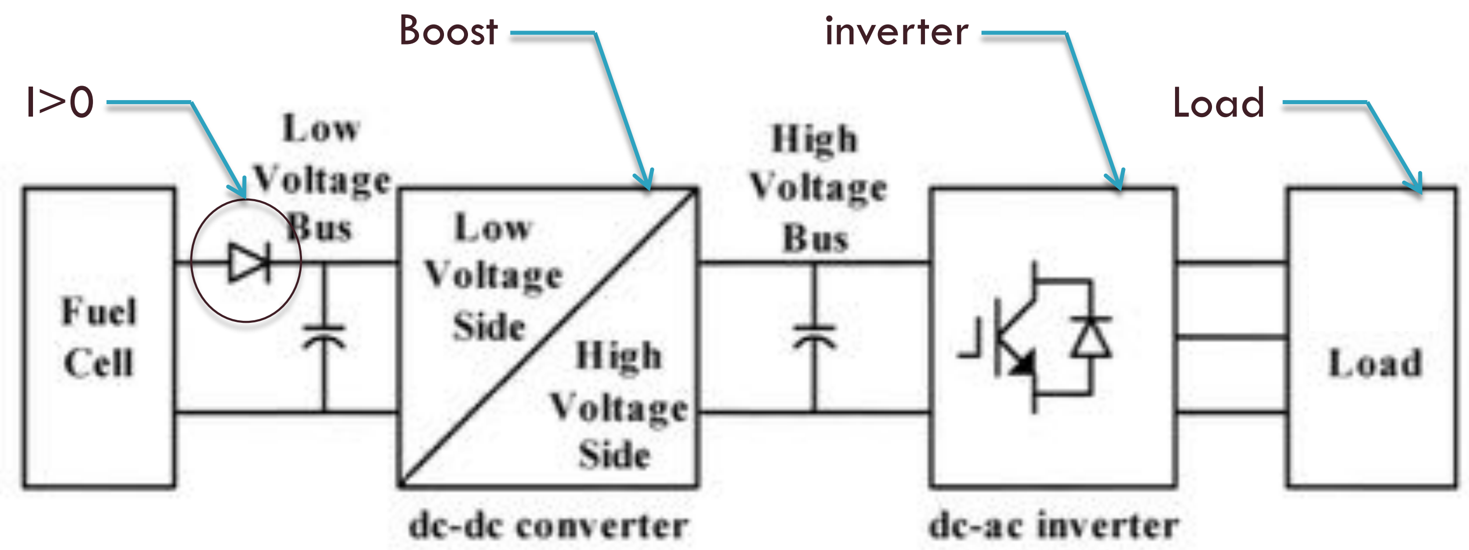
Some economic comparison for a 50kW car (reasonable perspective)

- Classical diesel ICE (lifetime: 4000 h)
  - ICE : 3000 € - 110 kg
  - Starter/generator: 300 € - 10 kg
  - Accessories (catalytic coverter, filters, …): 1000 € - 50 kg
  - tank : 100 € - 50 kg
    - TOTAL: 4400 € - 220 kg

- Fuel Cell car (lifetime: ~~2000 h~~ 4000 h)
  - Fuel Cell(~~≃ 2000 €/kW~~, 50 €/kW) : 2500€ - 100 kg
  - Electric drive (~~≃ 20 €/kW~~, 10 €/kW): 500 € - 100 kg
  - Power converter r (~~≃50 €/kW~~, 20 €/kW): 1000 € - 50 kg
  - tank (~500 €/kgH2): 2000 € - 70 kg
    - TOTAL: ~~105 500 €~~ 6000€ - 320 kg

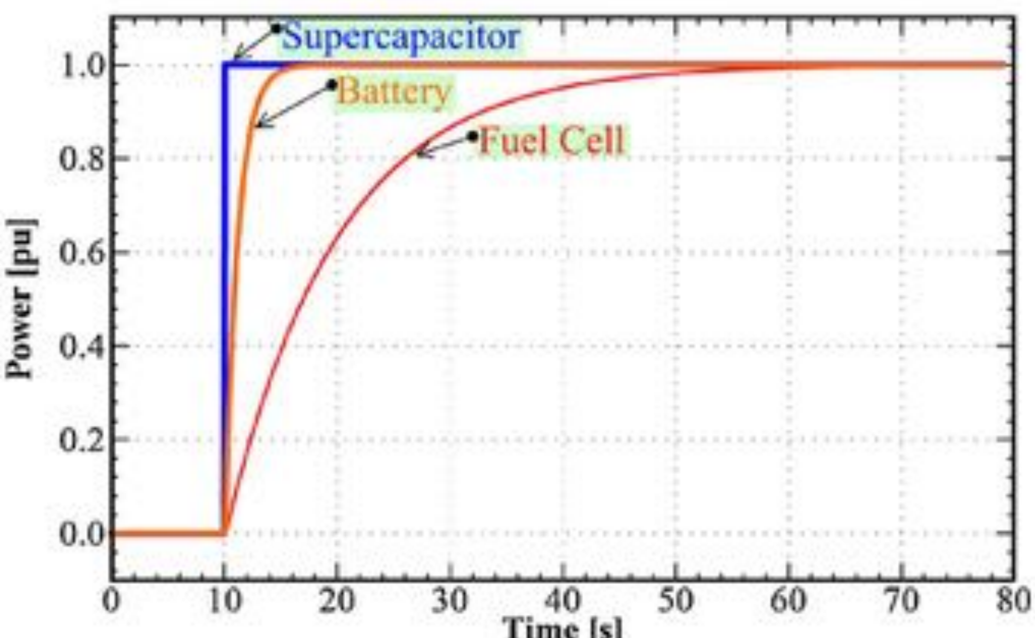
Benefits of hybrid structure

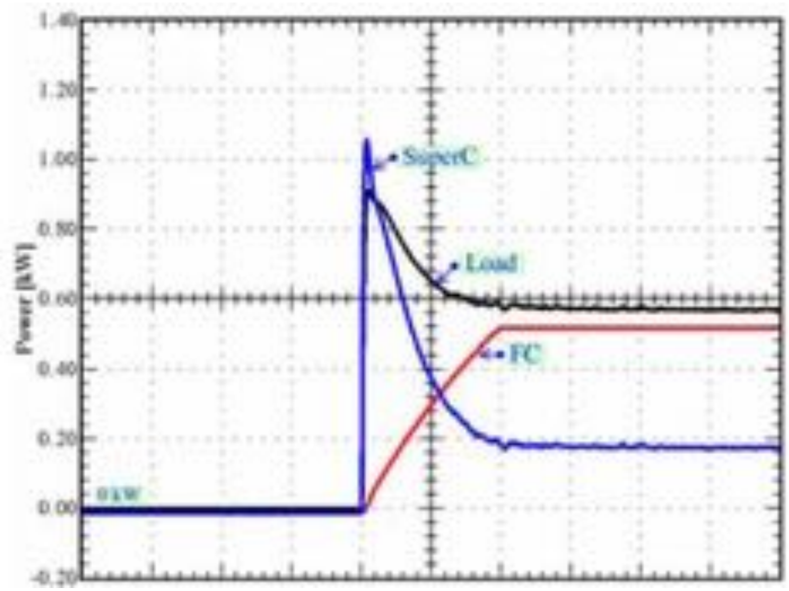
- Classical power conversion structure (FCEV)
  - Fuel Cell : Non perfect voltage generator ➔ Current regulation
  - Number of cell in series limited (thermal and leakage problems), voltage of one cell between 0.5 and 0.7 V (1-1.5A/cm^2; 0.5-1W/cm^2)➔ Boost voltage
  - AC loads ➔ Using of an inverter
  - Reversible system ➔Hydrogen production !!! ➔ Must be non reversible



Benefits of hybrid structure

- Benefits of hybrid structures
  - Stationary working of the fuel Cell (furniture of mean value of power)
  - Adding of one or more storage system for transient power demand
  - Reducing cost and weight of global system
  - Reducing warm up time
- Disadvantages
  - Greater complexity of vehicle and control system

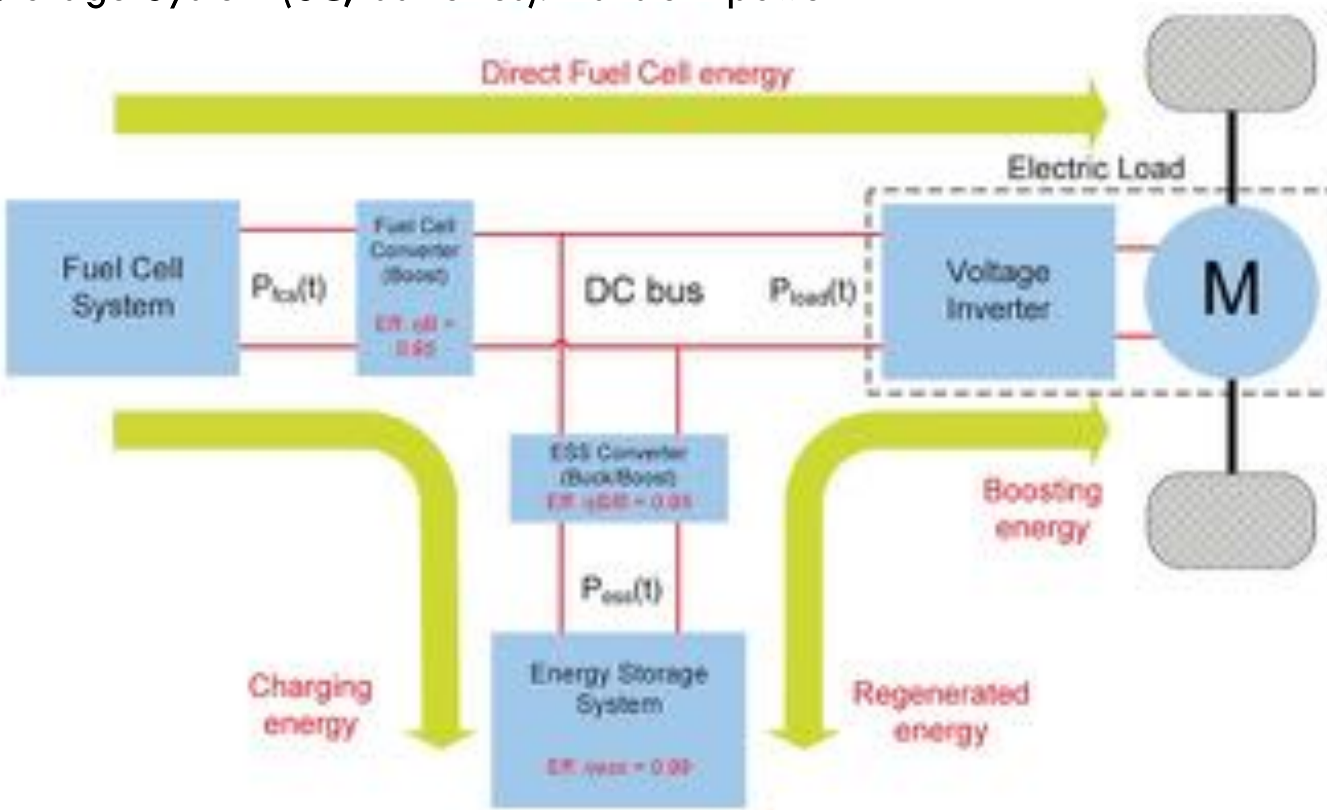




Separation of roles (FC : mean value, Storage : fast variations)

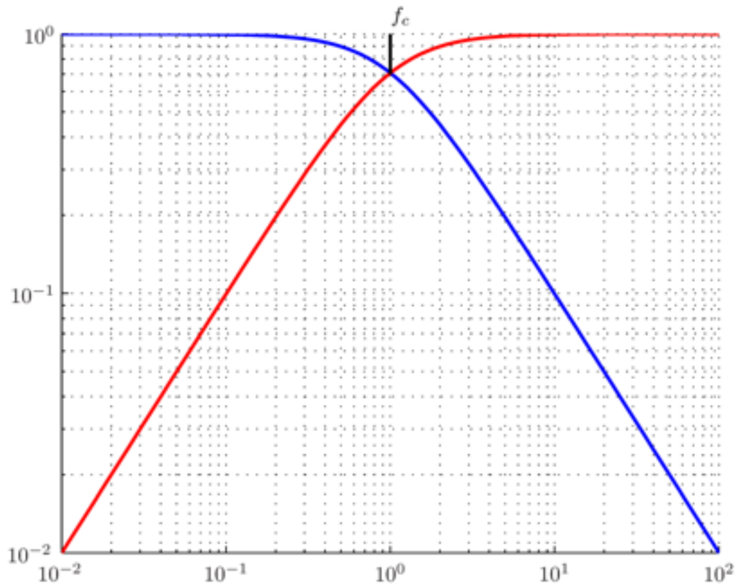
Benefits of hybrid structure

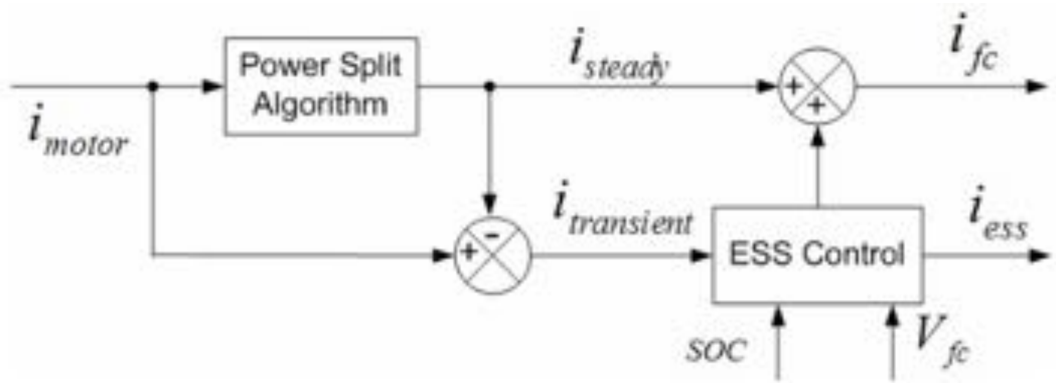
- Hybrid Fuel Cell Electric Vehicle structure with separation of roles
  - Fuel Cell : Furniture of average power
  - Energy Storage System (SC, batteries): transient power



Diego Feroldi, Maria Serra, and Jordi Riera. **Design and Analysis of Fuel-Cell Hybrid Systems Oriented to Automotive Applications**, IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, VOL. 58, NO. 9, NOVEMBER 2009

Benefits of hybrid structure





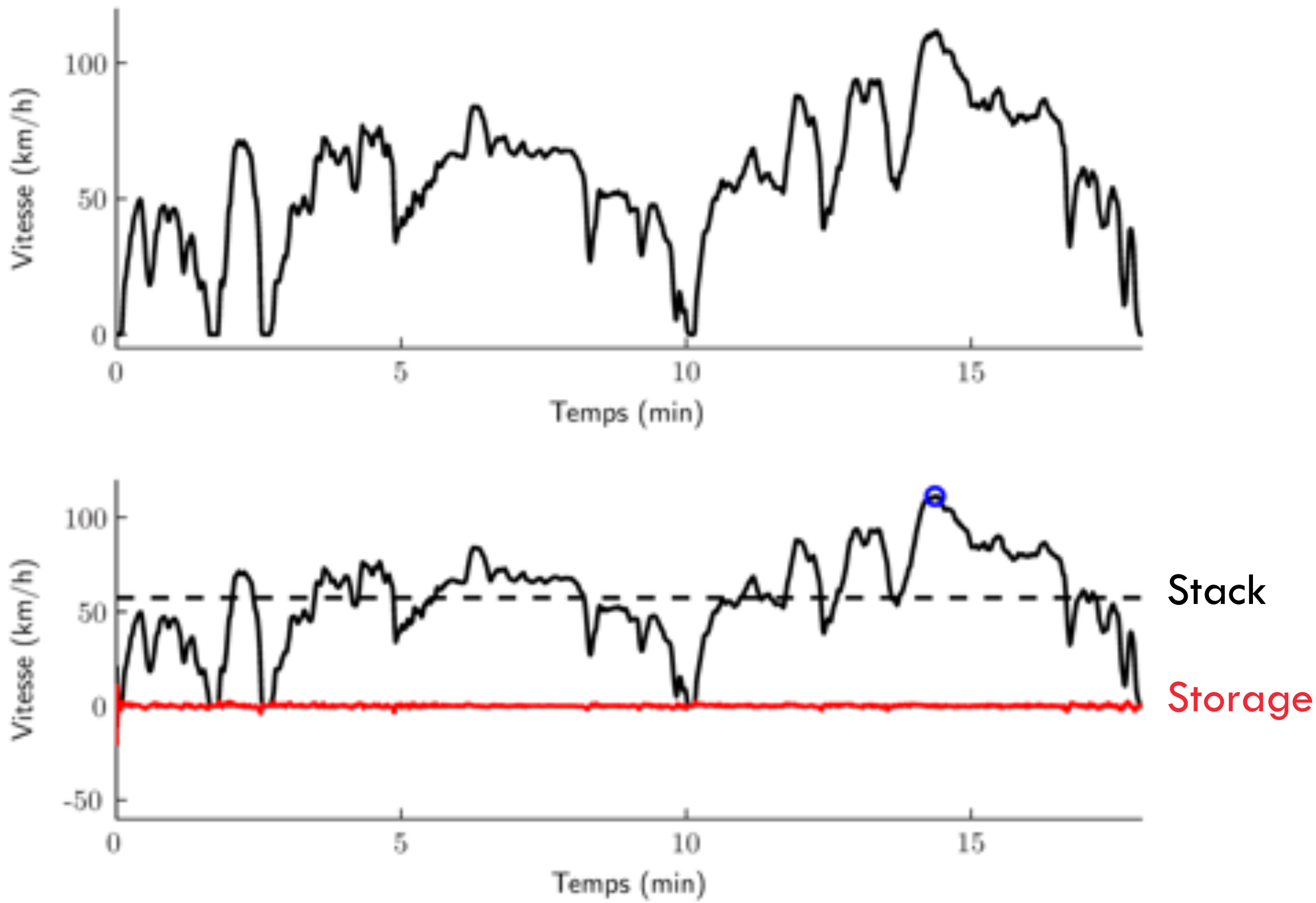
Separation of roles (FC : mean value,
Storage : fast variations)

Diego Feroldi, Maria Serra, and Jordi Riera. **Design and Analysis of Fuel-Cell Hybrid Systems Oriented to Automotive Applications**, IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, VOL. 58, NO. 9, NOVEMBER 2009

Benefits of hybrid structure

- Benefits of hybrid structures
  - Dynamic repartition between the different sources

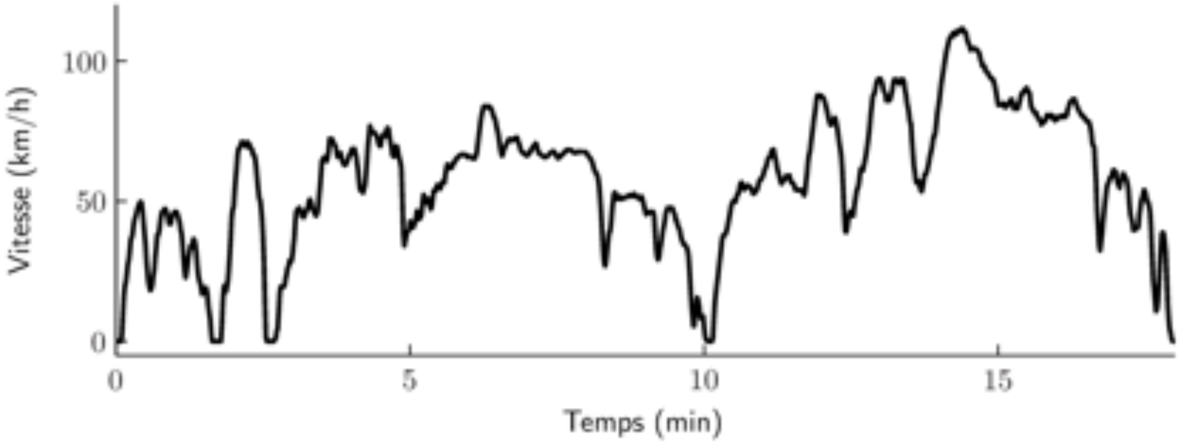
$t_c = 2$ sec

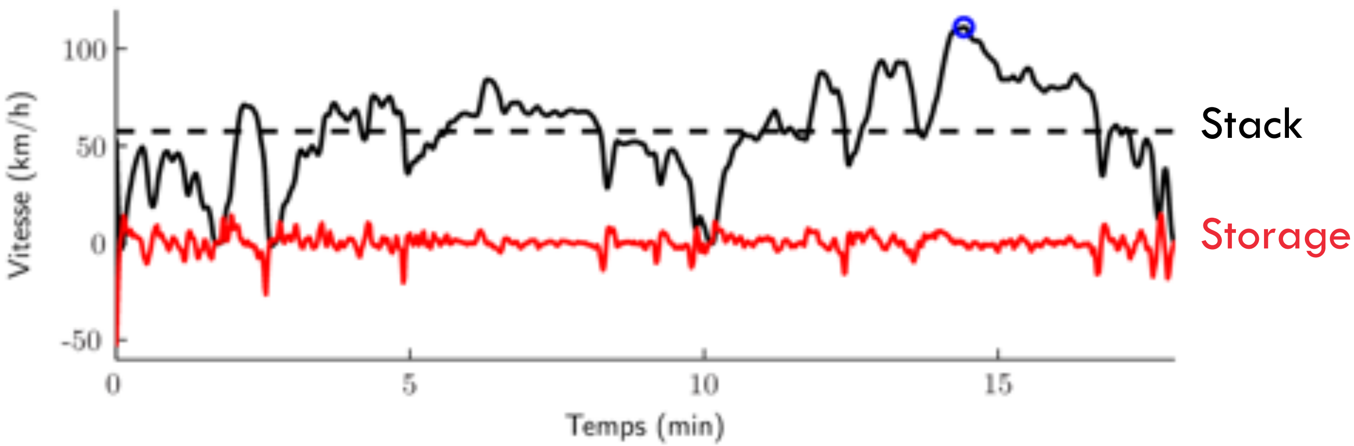


Benefits of hybrid structure

- Benefits of hybrid structures
  - Dynamic repartition between the different sources

$t_c = 5$ sec

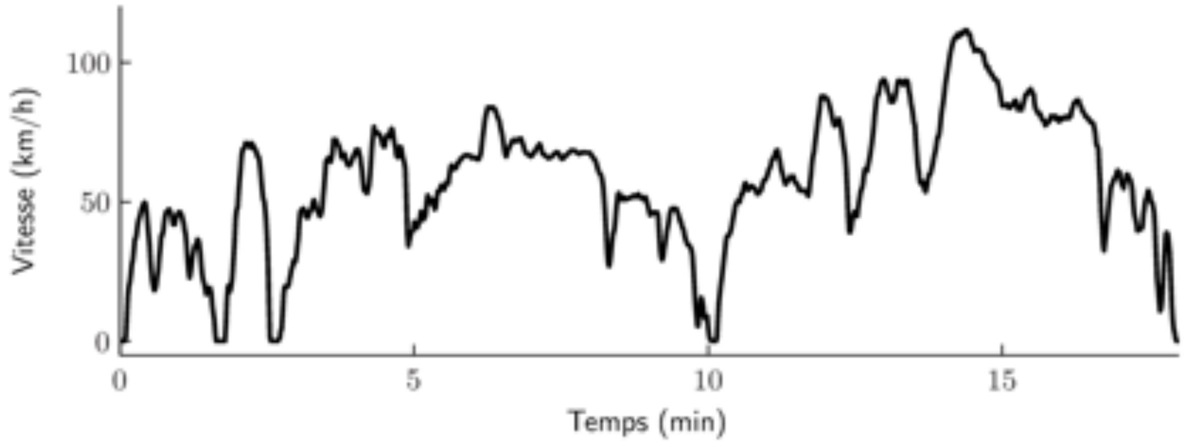


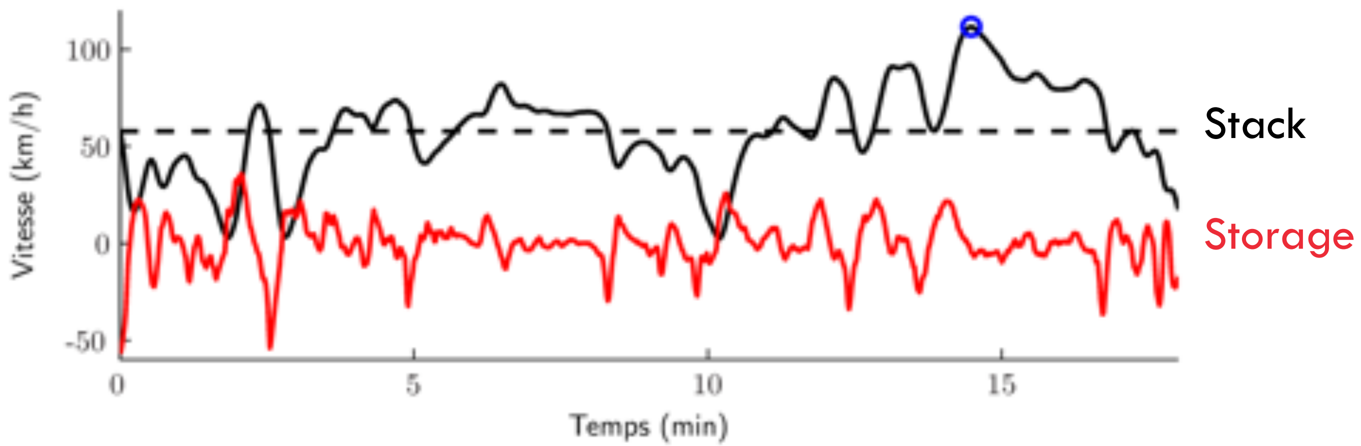


Benefits of hybrid structure

- Benefits of hybrid structures
  - Dynamic repartition between the different sources

t_c = 20 sec

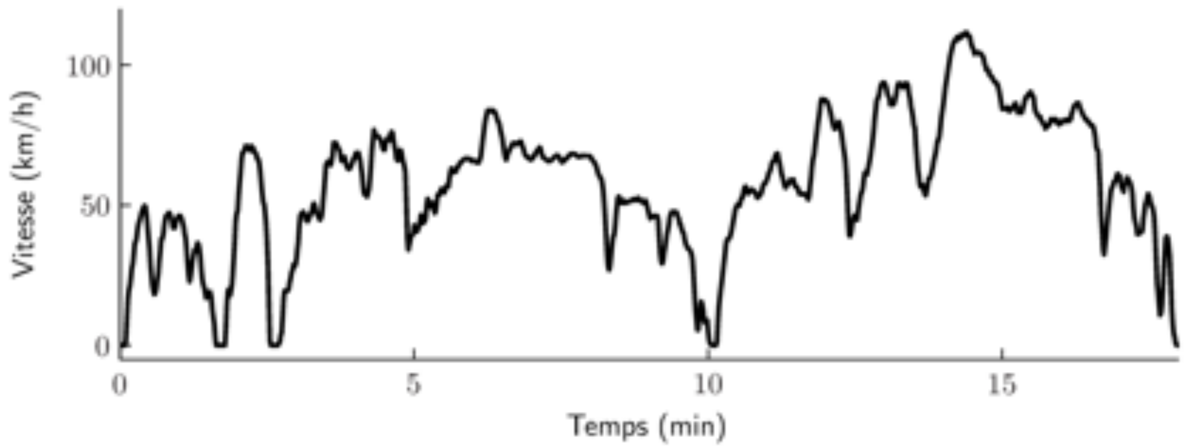


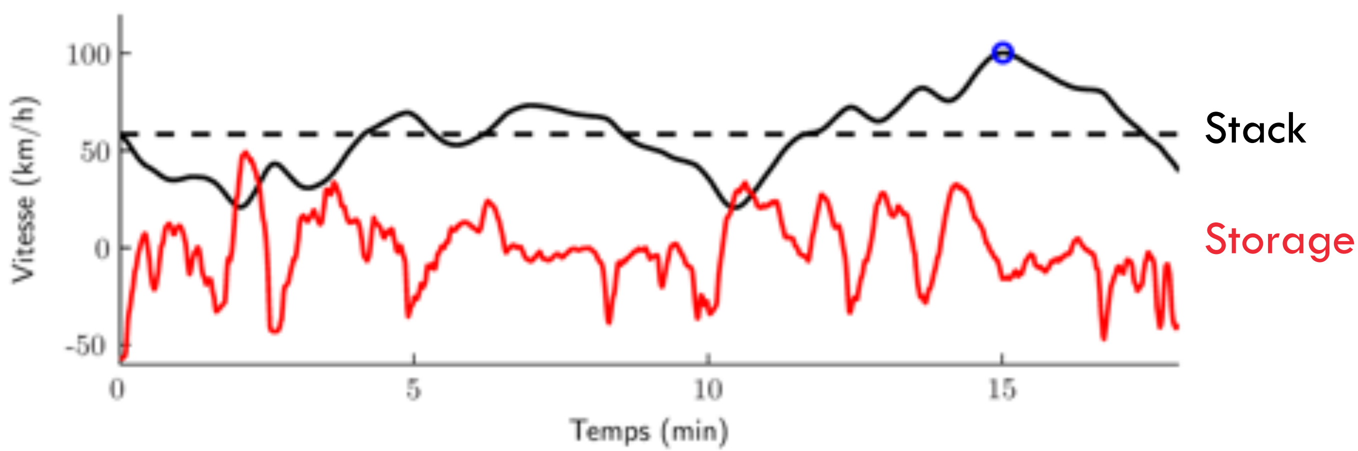


Benefits of hybrid structure

- Benefits of hybrid structures
  - Dynamic repartition between the different sources

$t_c = 1$ min

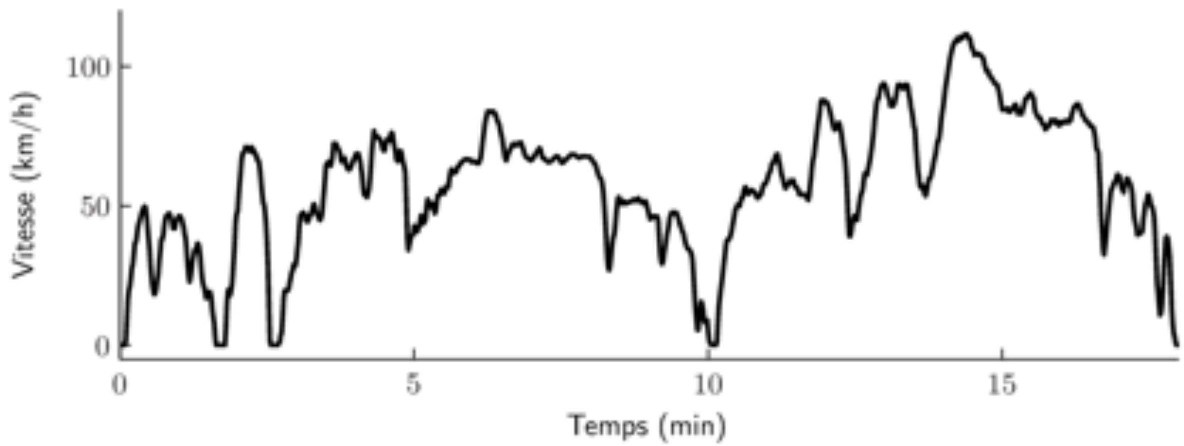


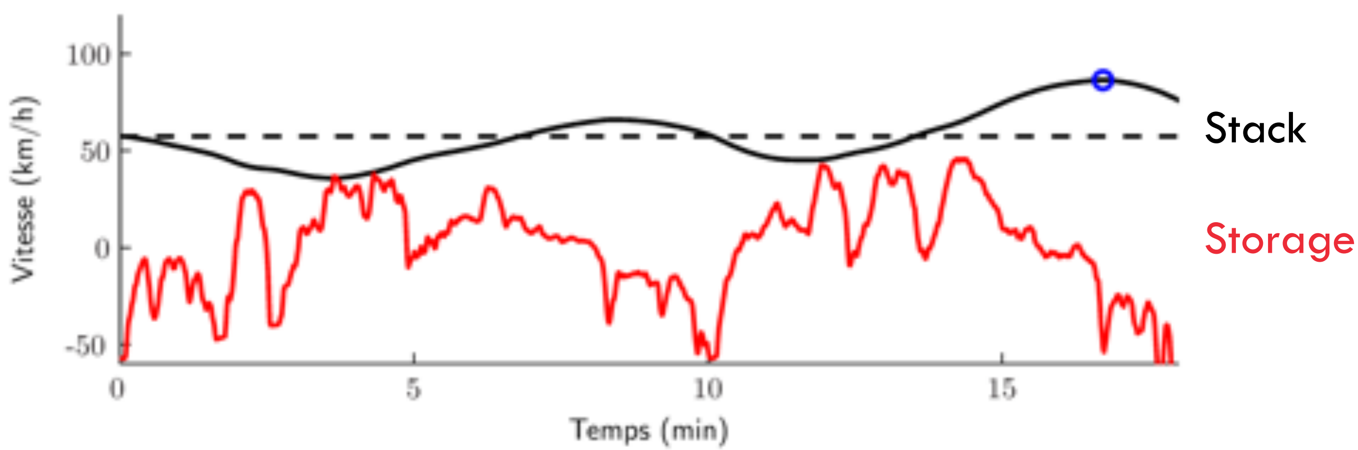


Benefits of hybrid structure

- Benefits of hybrid structures
  - Dynamic repartition between the different sources

$t_c = 5$ min

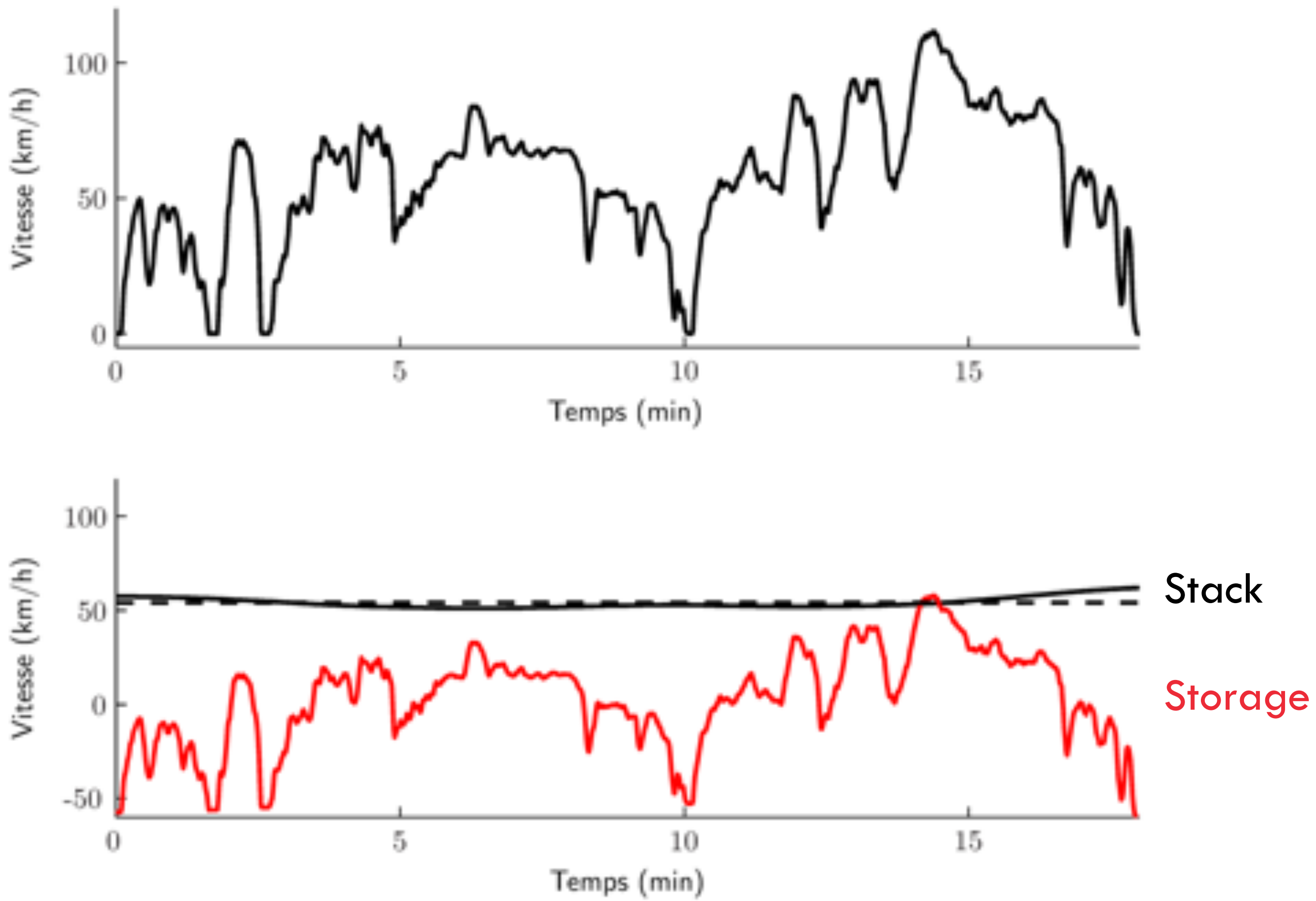




Benefits of hybrid structure

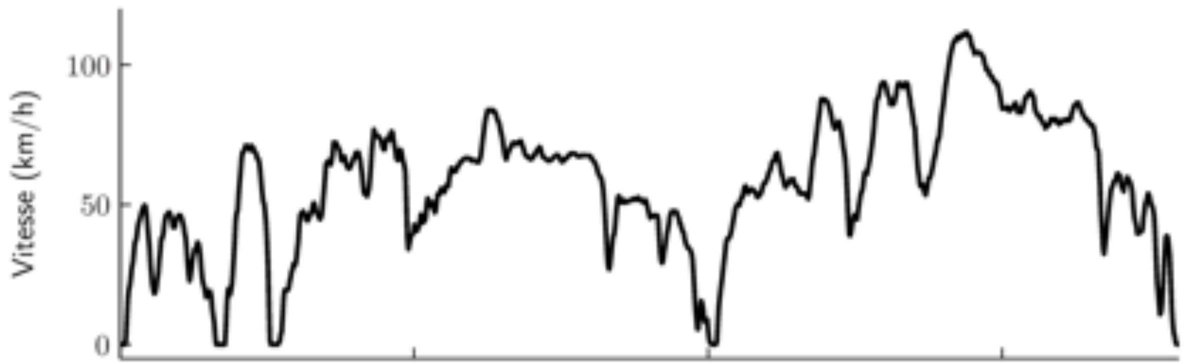
- Benefits of hybrid structures
  - Dynamic repartition between the different sources

$t_c = 15$ min

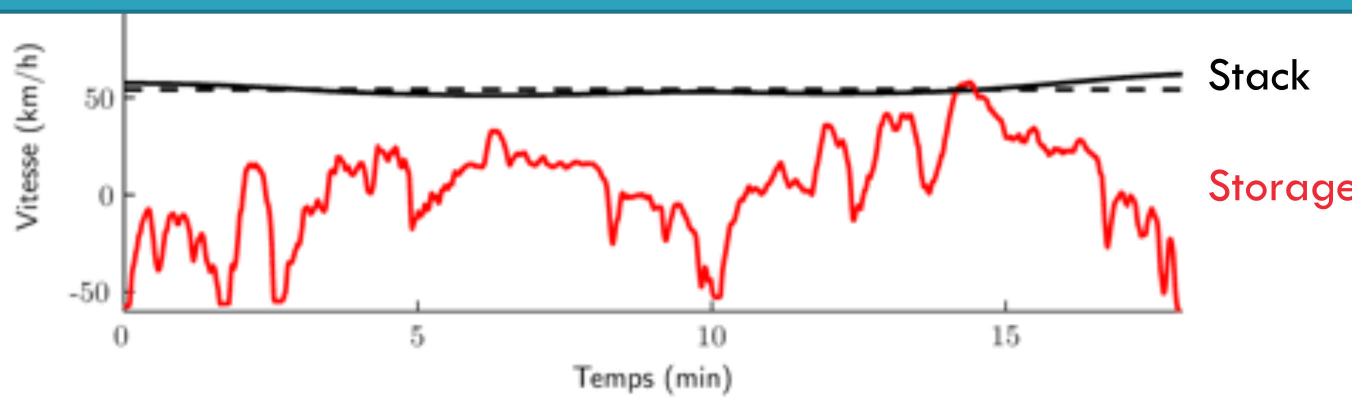


Benefits of hybrid structure

- Benefits of hybrid structures
  - Dynamic repartition between the different sources

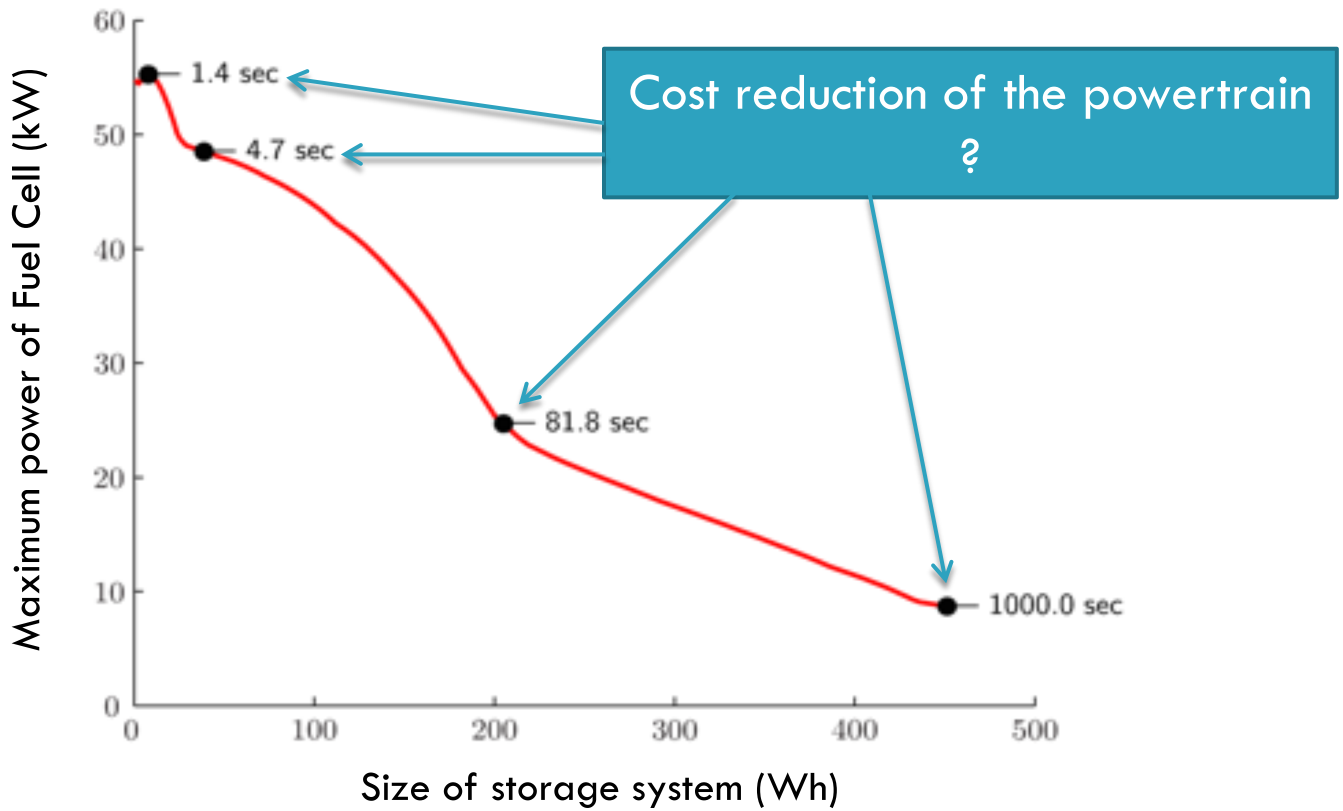


Balance between maximum power of the fuel cell and size of the storage system



Benefits of hybrid structure

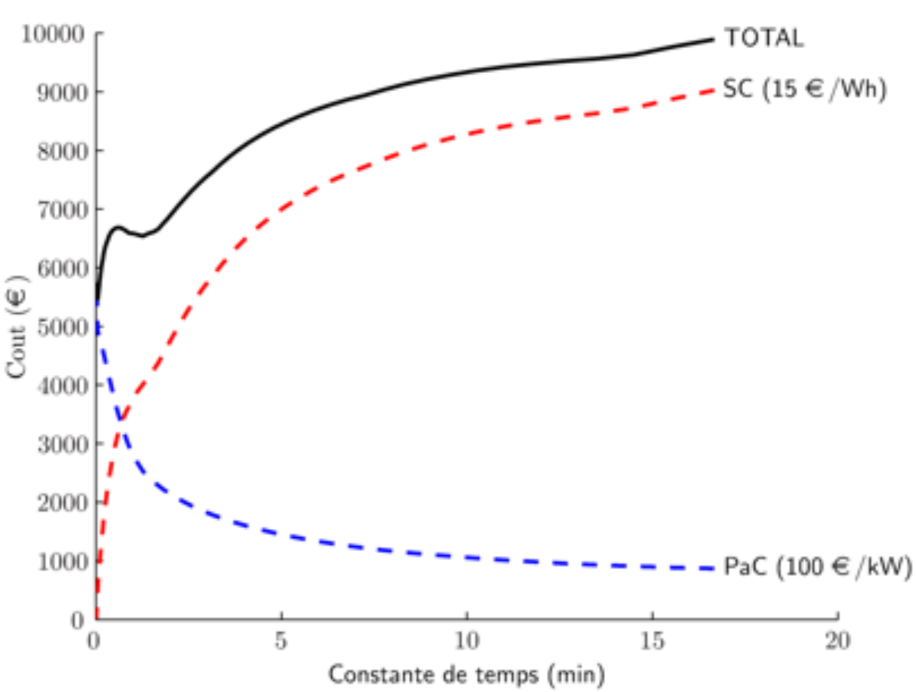
- Benefits of hybrid structures
  - Dynamic repartition between the different sources.
    - **Choice of constant time.**



Benefits of hybrid structure

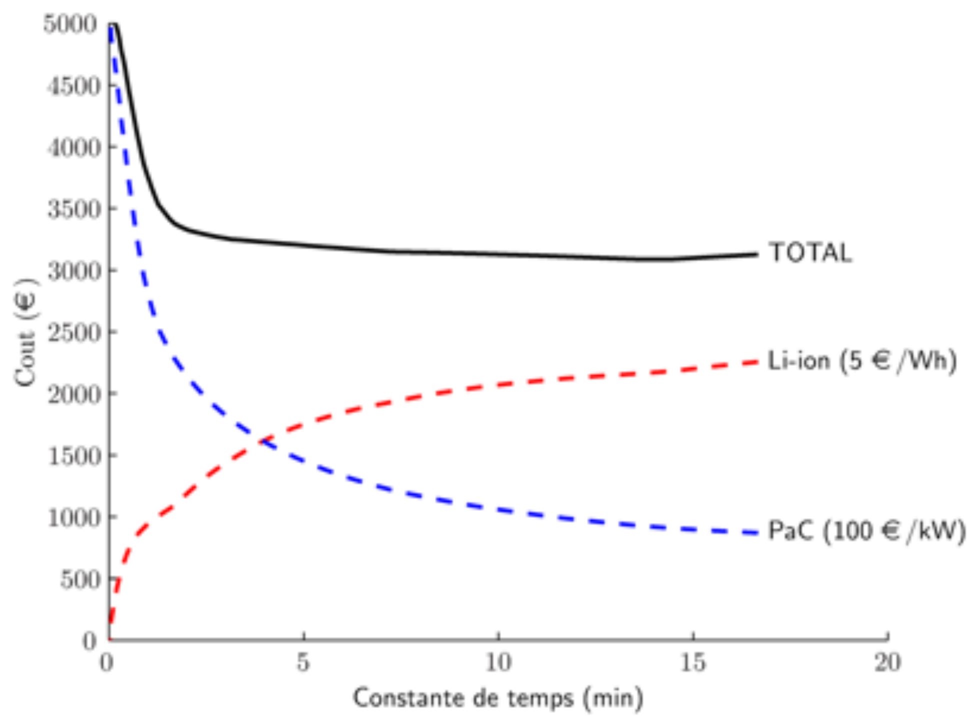
Supercapacitor / FC :

No constraint on life duration, cost always higher



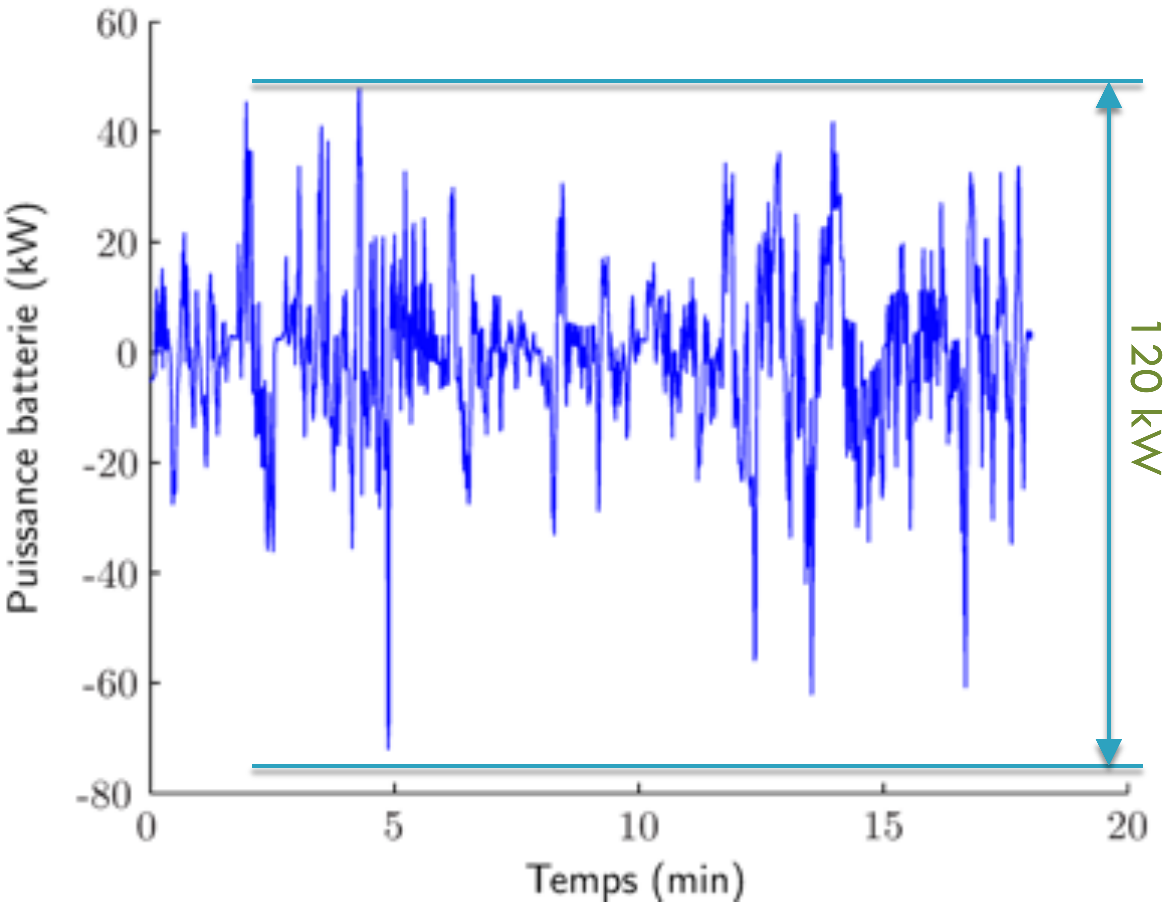
Battery Li-ion / FC :

No constraint on life duration, cost always smaller → Benefit of hybrid structure for urban cycle



Benefits of hybrid structure

Battery Li-ion / Super capacitor :

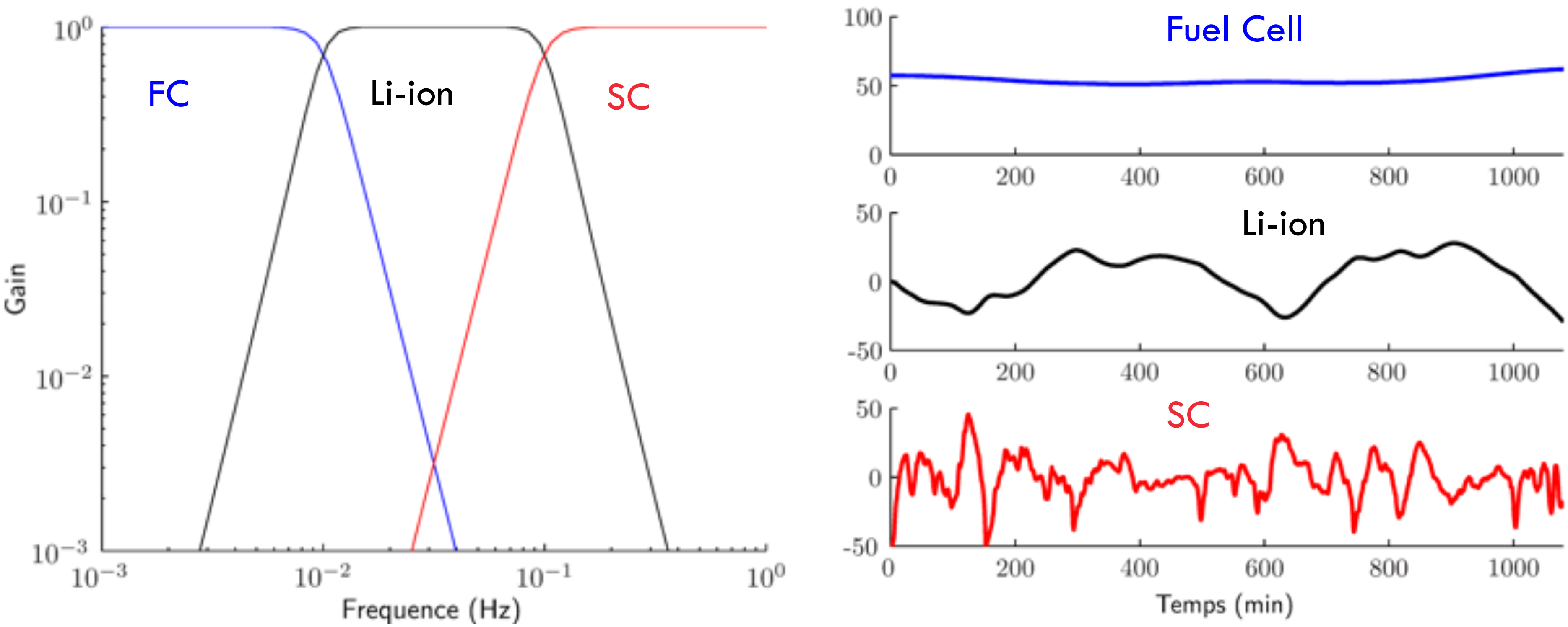


Battery Li-ion
200 €/kW → 24 k€

Supercapacitor
75 €/kW → 9 k€

Benefits of hybrid structure

- Hybrid strategy could be generalized to several storage systems
- Dynamic according to the nature of the system



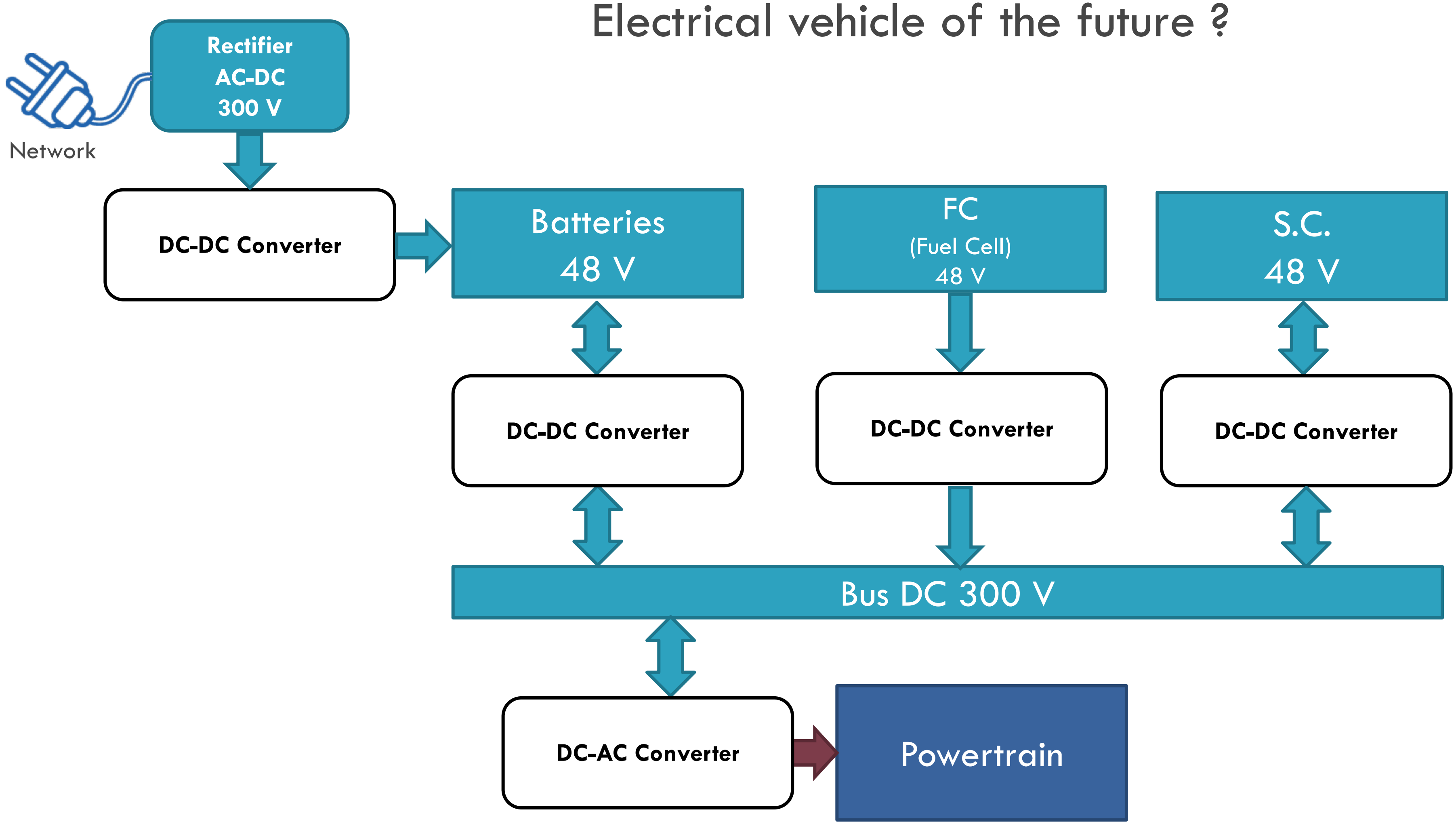
Benefits of hybrid structure

- Example of hybrid vehicle

	Fuel Cell only	Fuel Cell + supercapacitors	Fuel Cell + SC + batteries
Fuel Cell mass	111.4 kg	34.3 kg	21.2 kg
SC mass	-	43.3 kg	43.3 kg
Battery mass	-	-	4.6 kg
Total mass	111.4 kg	77.6 kg	69 kg
Cost	6000 €	5500 €	5000 €

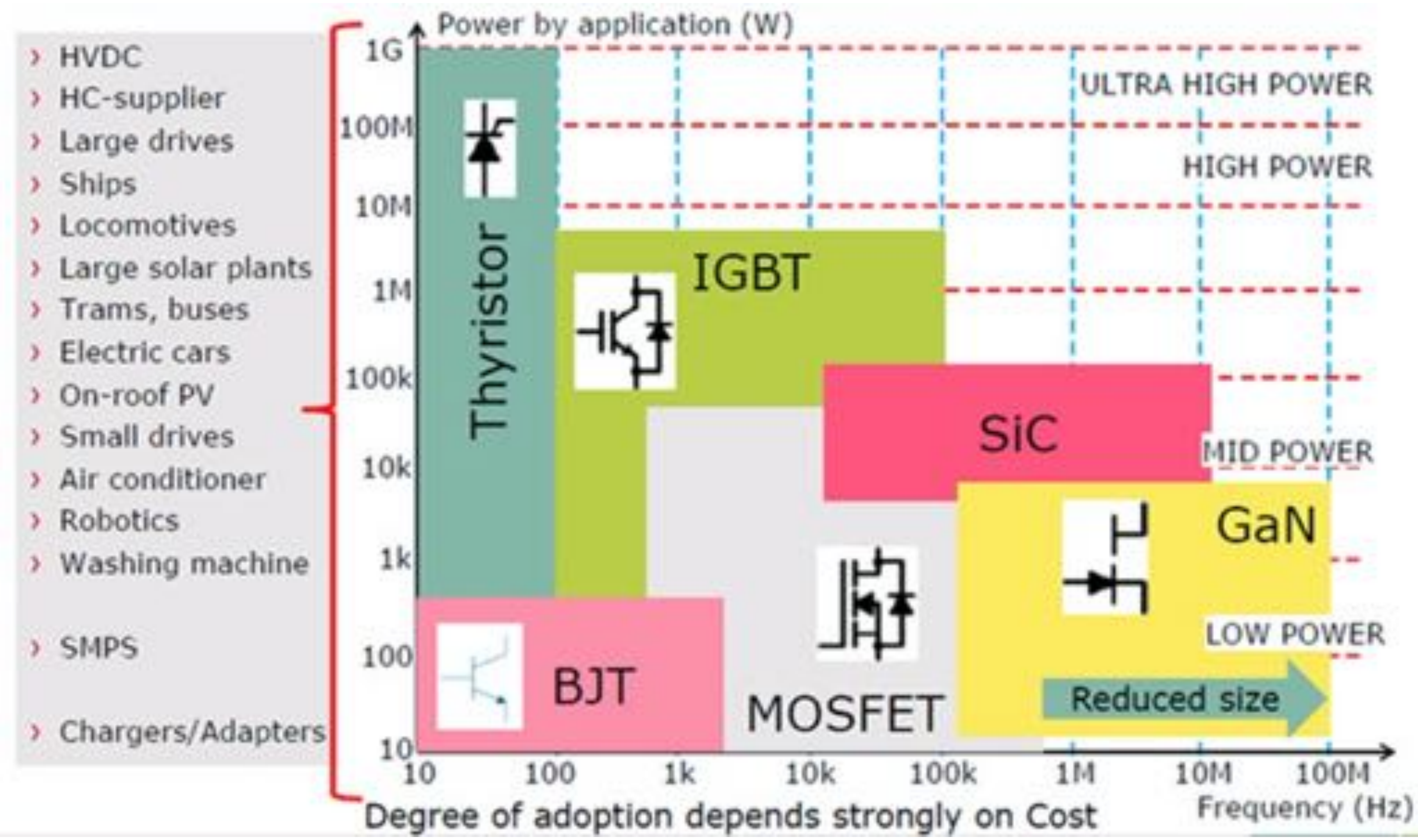
Benefits of hybrid structure

Electrical vehicle of the future ?



Power converter

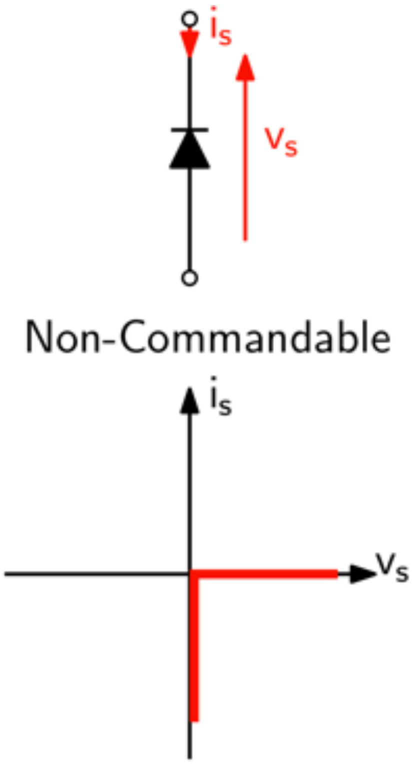
- Performance diagram :

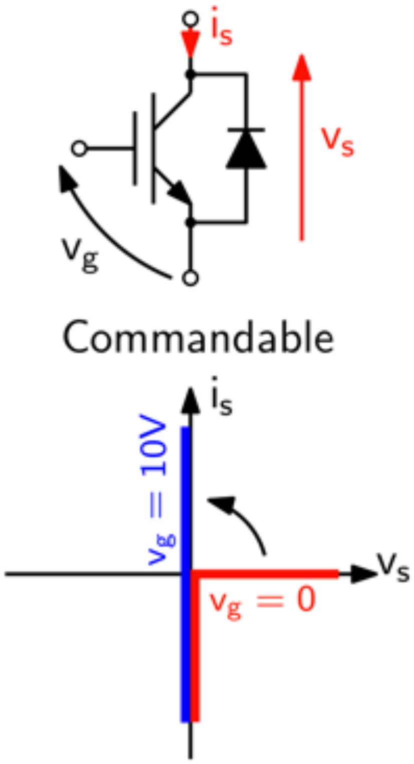


- Choice is a balance between :
  - Voltage / Current
  - Power / frequency
- Repartition :
  - High power : GTO / Thyristor
  - Medium power : IGBT / SIC
  - Low power : MOSFET /GAN

Power converter

- Application for electrical car (or renewable energy) :
  - Medium power from some kW to some MW,
  - Diode and transistor (IGBT or MOSFET or GAN)

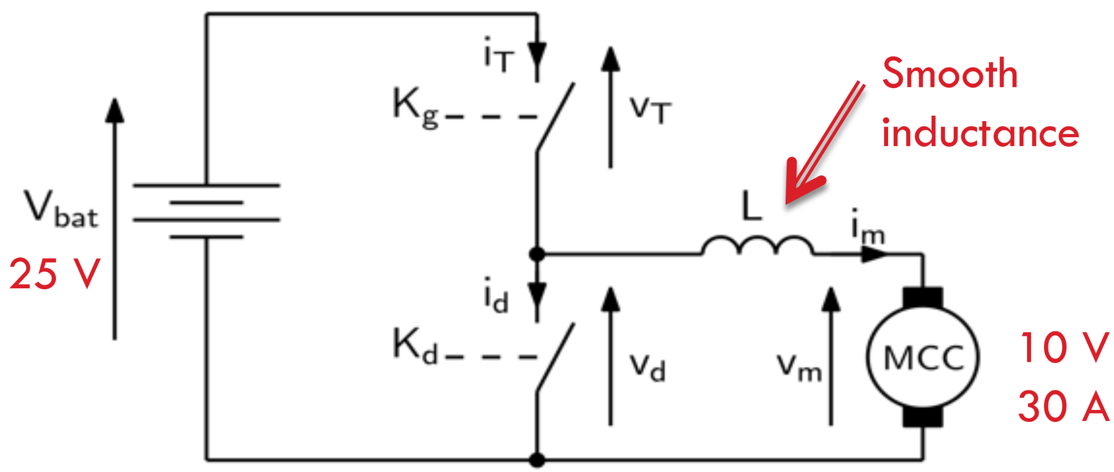




Power converter

Study of a structure

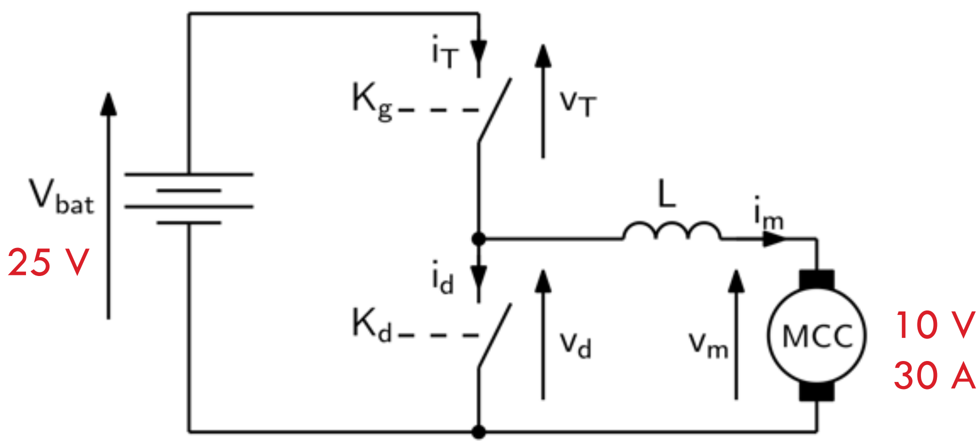
- DC/DC conversion
  - Source : Fuel cell (battery)
  - Load : DC motor
- Objective
  - Reduce voltage from 25V to 10V
  - Minimum losses

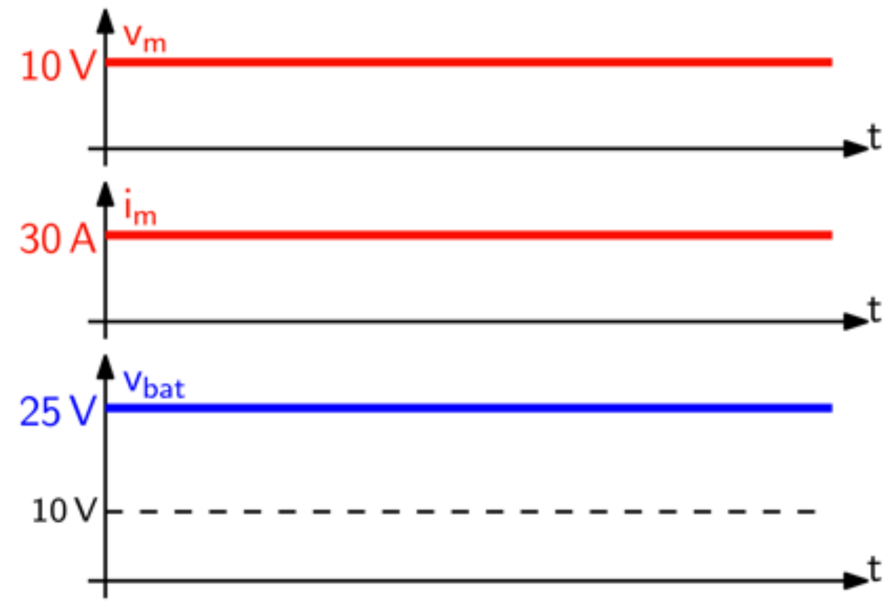


Power converter

Study of a structure

- Signals analysis

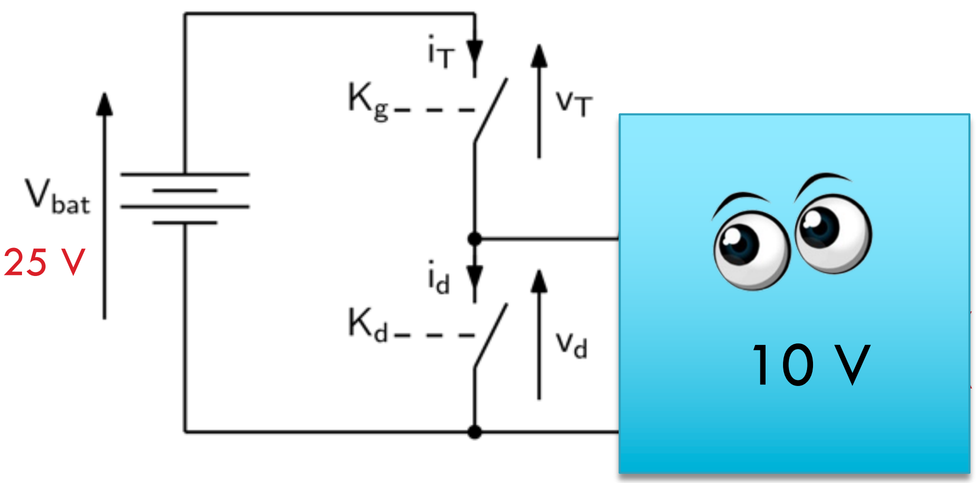


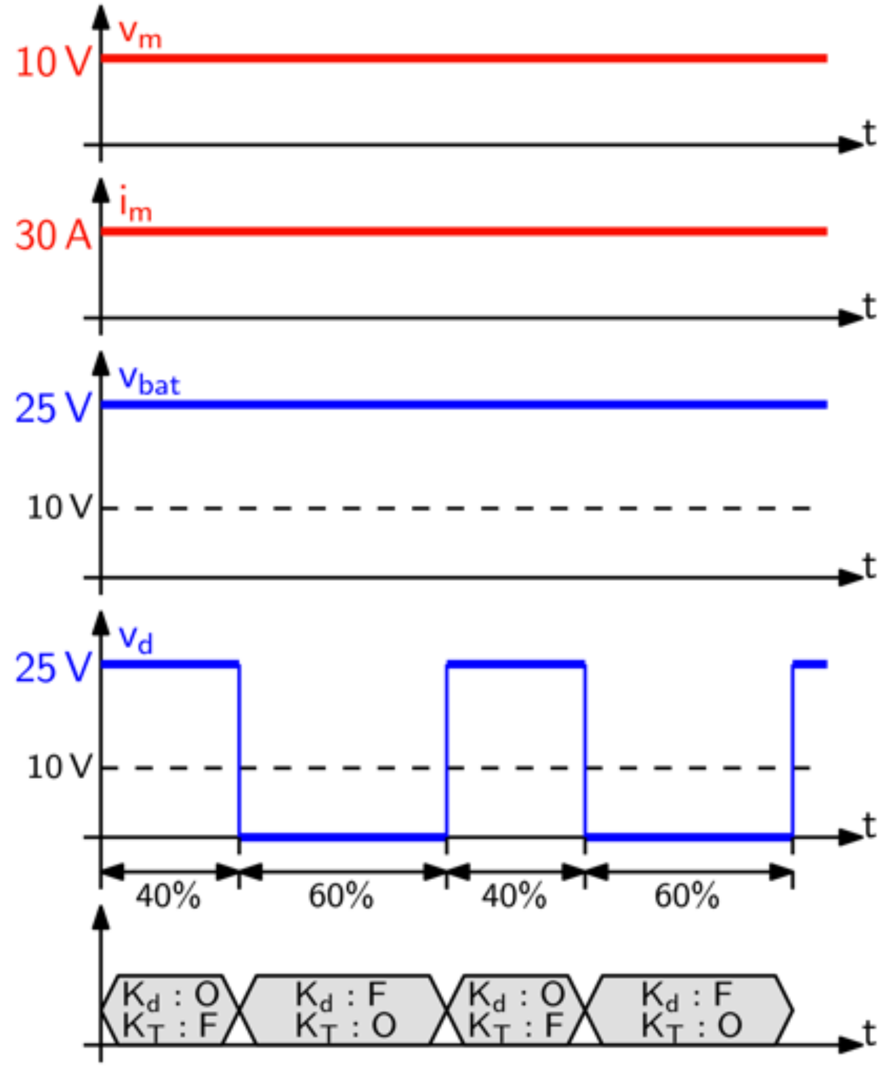


Power converter

Study of a structure

- Signals analysis :



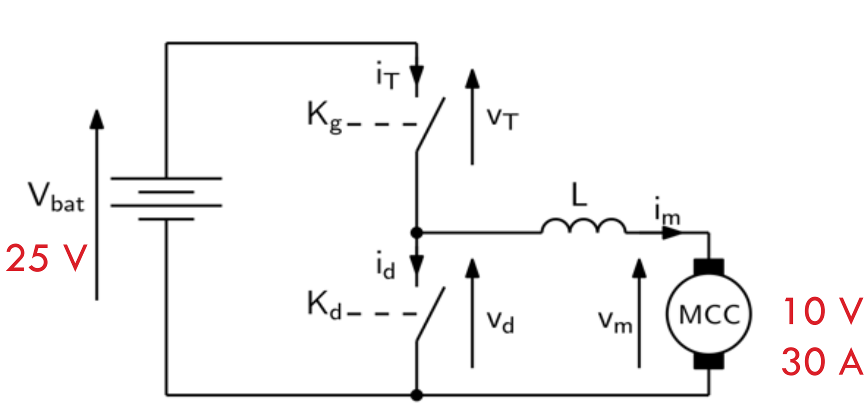


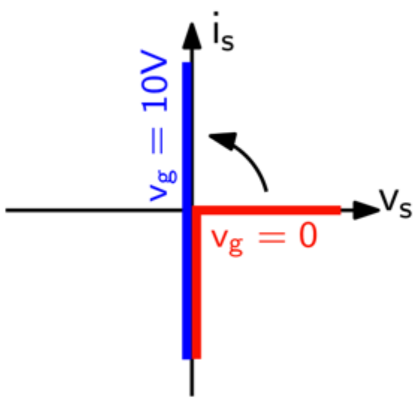
Control duty cycle

Power converter

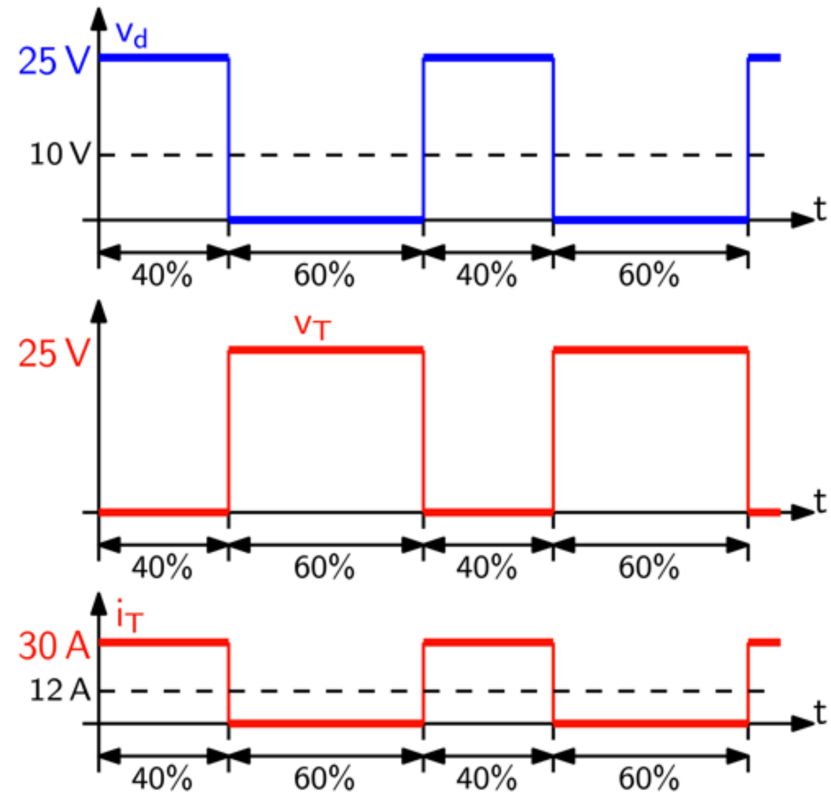
Study of a structure

- Signals analysis :





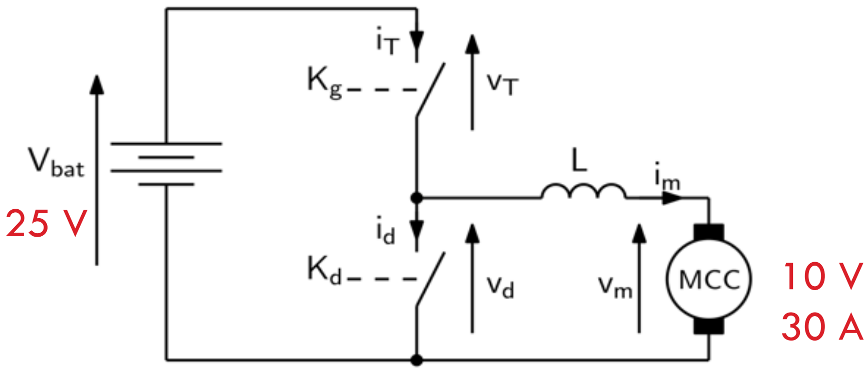
- Switch Kg :
  - Move from [0A, 25V] to [30 A, 0V]
  - Controlled switch

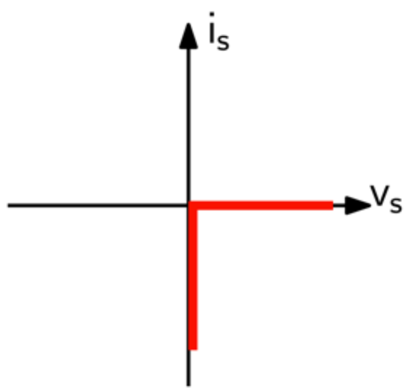


Power converter

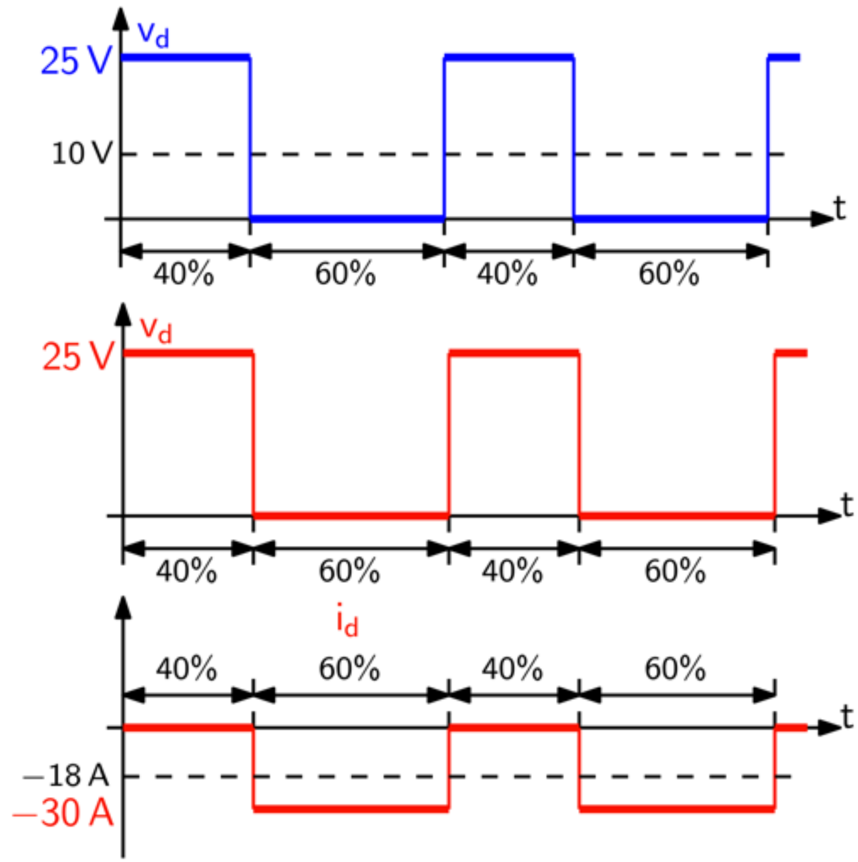
Study of a structure

- Signals analysis :





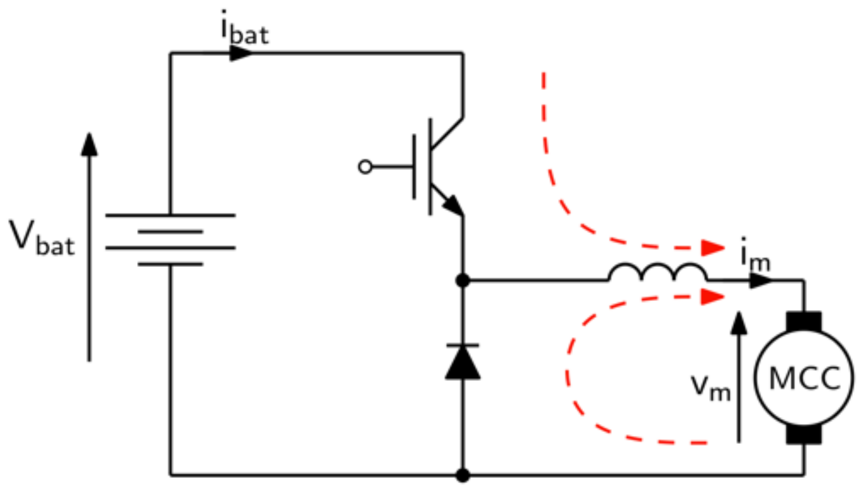
- Switch Kd :
  - Move from [0A, 25V] to [-30A, 0V]
  - Controlled switch



Power converter

Study of a structure

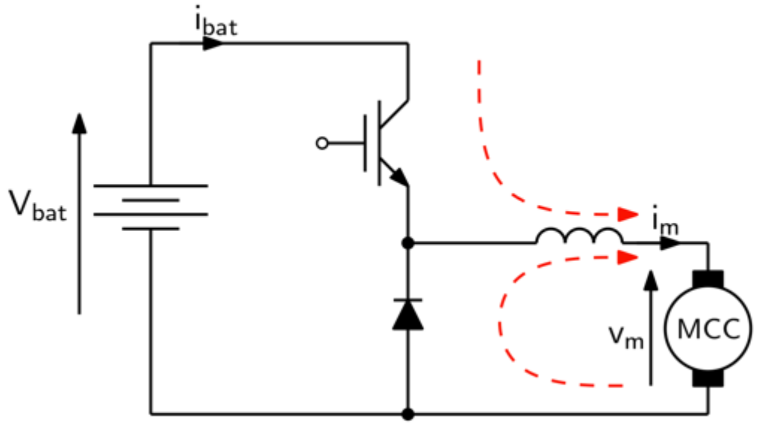
- Converter DC/DC : voltage reduction (BUCK)
- Flux of power : from Fuel Cell (battery) to motor



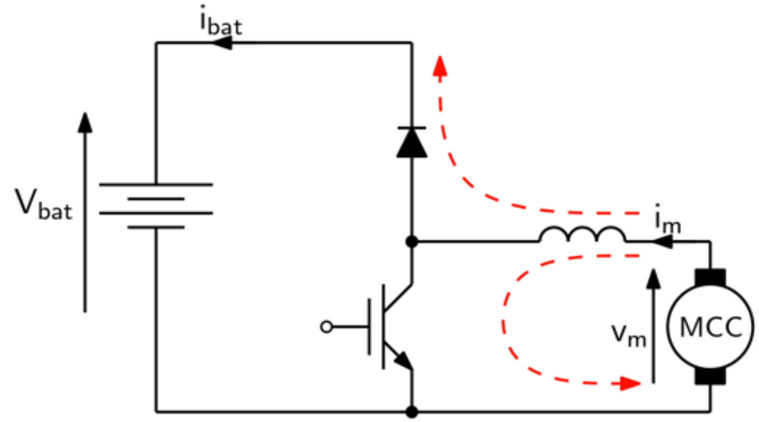
What about energy recovery during braking phases ?

Power converter

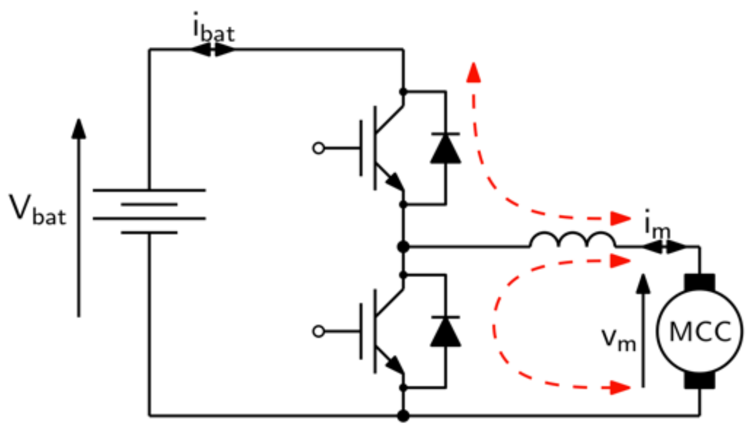
Possible structure :



Source to motor : voltage drop (BUCK)



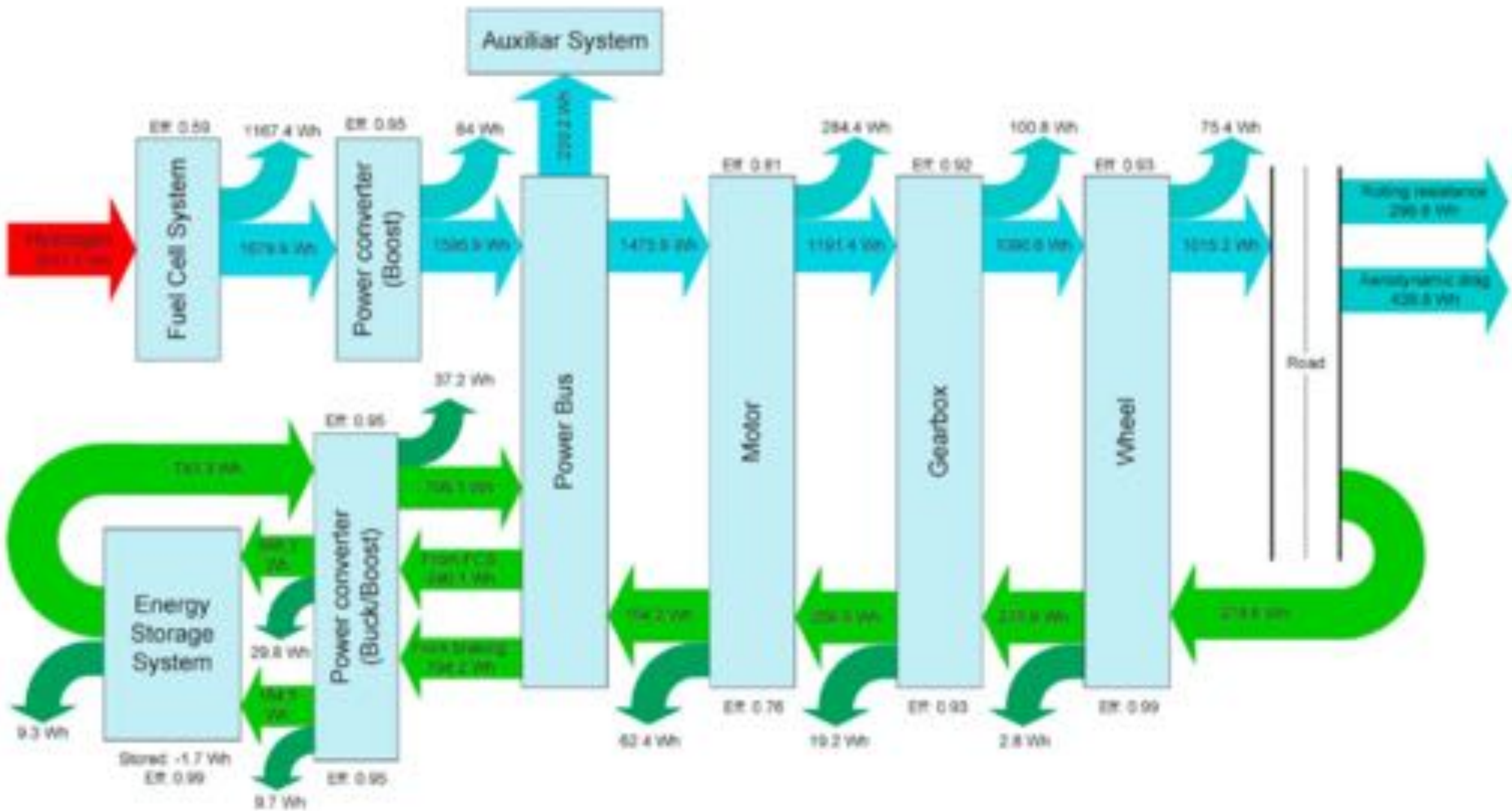
Motor to source : voltage BOOST



Bi-directional : BUCK-BOOT

Benefits of hybrid structure

To optimize, a global energetic model is needed…



« Design and Analysis of Fuel-Cell Hybrid Systems Oriented to Automotive Applications », Diego Feroldi, Maria Serra, and Jordi Riera, IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, VOL. 58, NO. 9, NOVEMBER 2009

Objectives

- Shell Eco Marathon (www.shell.com) :
  - « To design, build and drive energy efficient vehicles. The winners are the teams that go the farthest distance using the least amount of energy »

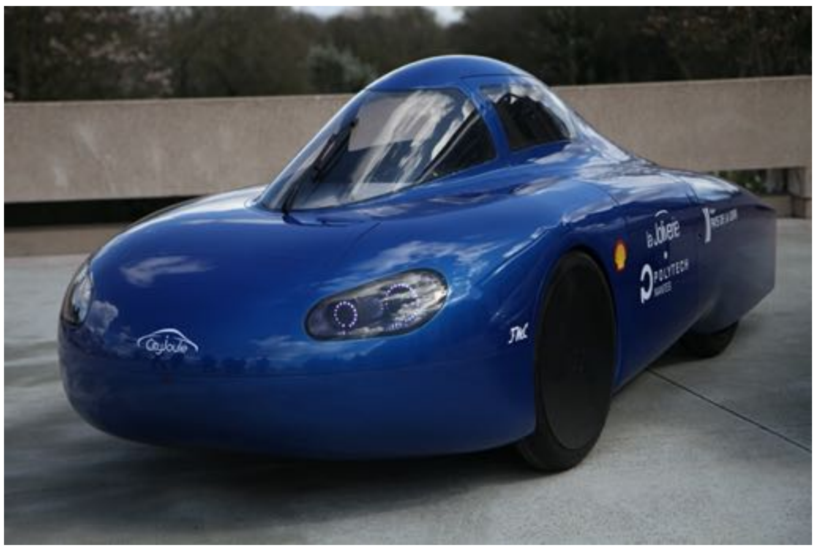
- European edition :
  - 240 teams, 30 countries
  - 2 categories : Prototype, Urban-Concept
  - Distance : 16.3 km (10 rounds in city)
  - Speed > 25km/h (average)

- Energies :
  - ICE : Gasoline, diesel, ethanol, CNG
  - Electric mobility : H2, solar, batteries

Fig1 : Cityjoule at London track 2018

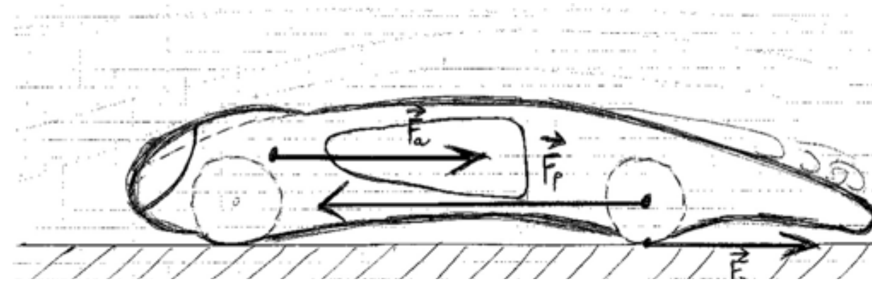
Global energetic model

- Before model optimization of vehicle is required :
  - High performances electric car



Urban-Concept « Cityjoule »

Need to reduce : mass, drag coefficient, tires friction, …



$$m\frac{d\,v(t)}{dt} = F_w - F_{rr} - F_{slope} - F_{aero} - F_{brake}$$

$$F_w = \eta_g \frac{r_{gear}}{R} \Gamma_m$$

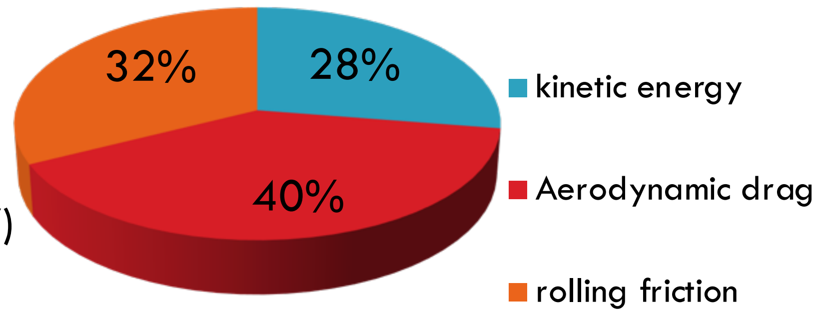
$$F_{rr} = m\,g\,f_r\,\cos\left(\arctan\left(r_{slope}\right)\right)$$

$$F_{slope} = m\,g\,\sin\left(\arctan\left(r_{slope}\right)\right)$$

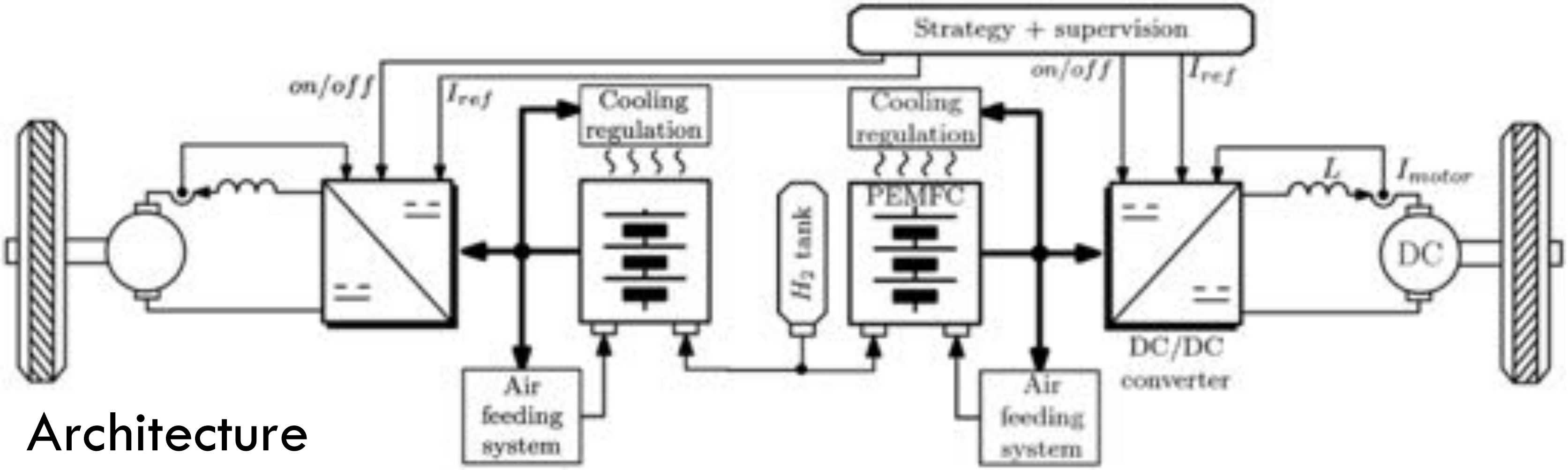
$$F_{aero} = \frac{1}{2}\rho_{air} S\, C_x \left(v(t) + v_{wind}\right)^2$$

Global energetic model

- Mechanical part
  - Weight : 100 kg + Pilot (70 kg)
  - Drag coefficient (Cx) : 0.09 (0.3 Tesla EV)
  - Frontal area : 0.88 m2
  - Tires friction coefficient : 0.0035 (0.2 Tesla EV)
  - Wheel diameter = 0.535 m
  - Max. speed : 100 km/h



Global energetic model



- Architecture
  - Power train:
    - Simplest structure, without auxiliary energy storage
    - DC/DC power converter (Buck)
    - High efficiency DC ironless motor
  - Supervision/Security:
    - H2 detector
    - Controller for speed/torque/fan control and for power saving management (unused systems can be turned off)
    - Real-time Data acquisition Workstation (UEI) for post-processing data

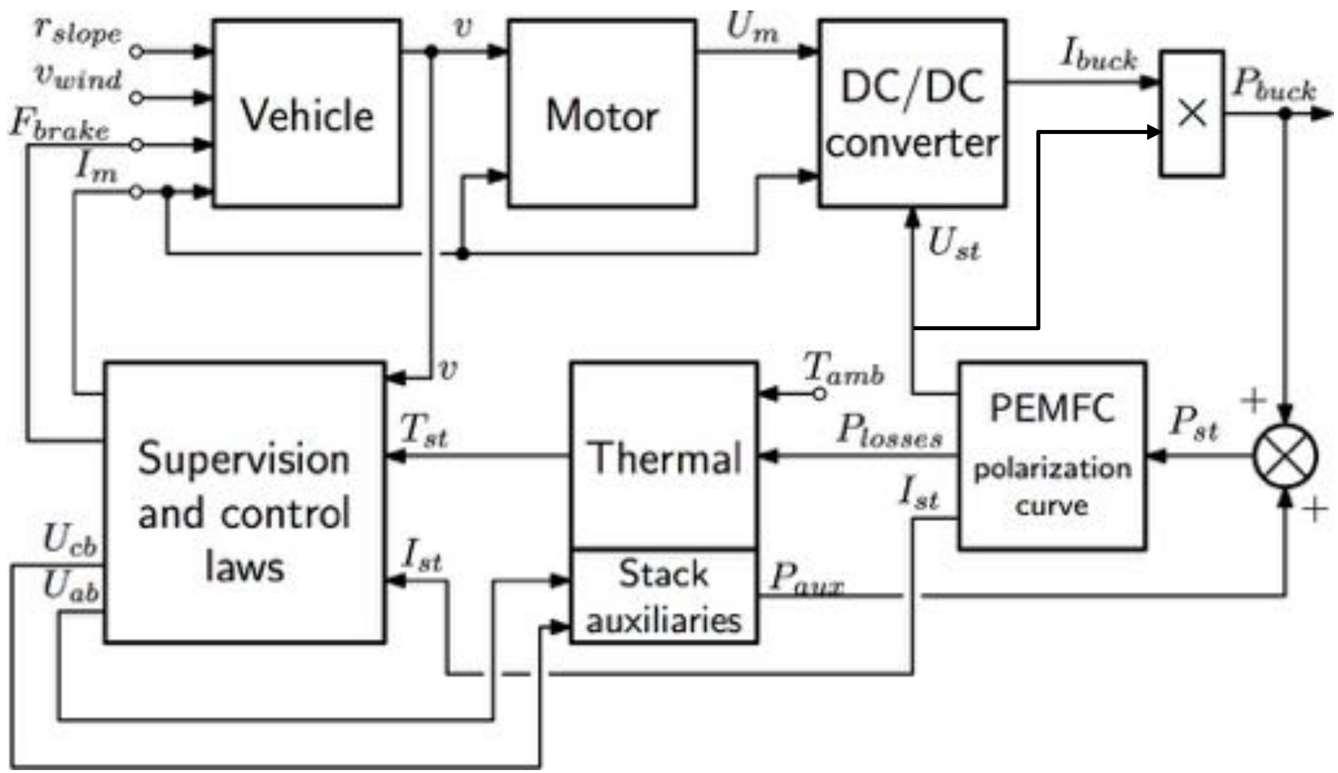
Global energetic model

- Tank-to-wheel
  - Inputs :
    - Motor current (for torque control, acceleration)
    - Velocity cycle (Min/Max speeds)
    - External constraints (Wind, slop of the track, ambient temperature, …)
  - Outputs :
    - Power/energy consumption and efficiency, for each stage
    - Thermal behavior of Fuel Cell
    - Global Efficiency of the vehicle, from the tank to the wheel

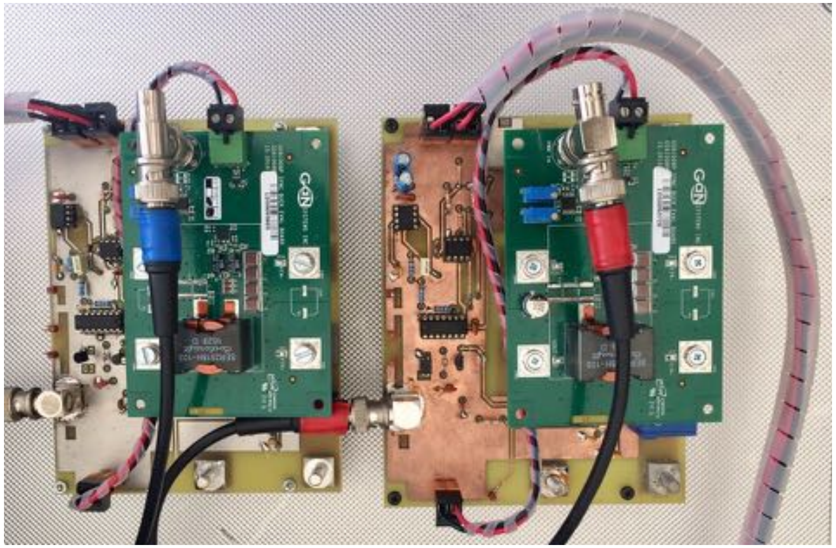
- Model to be implemented
  - PEMFC : Electrical + thermal +auxiliaries consumption
  - Powertrain : electrical losses + consumption of electronic devices
  - Mechanical : mechanical losses + dynamic behavior

Global energetic model

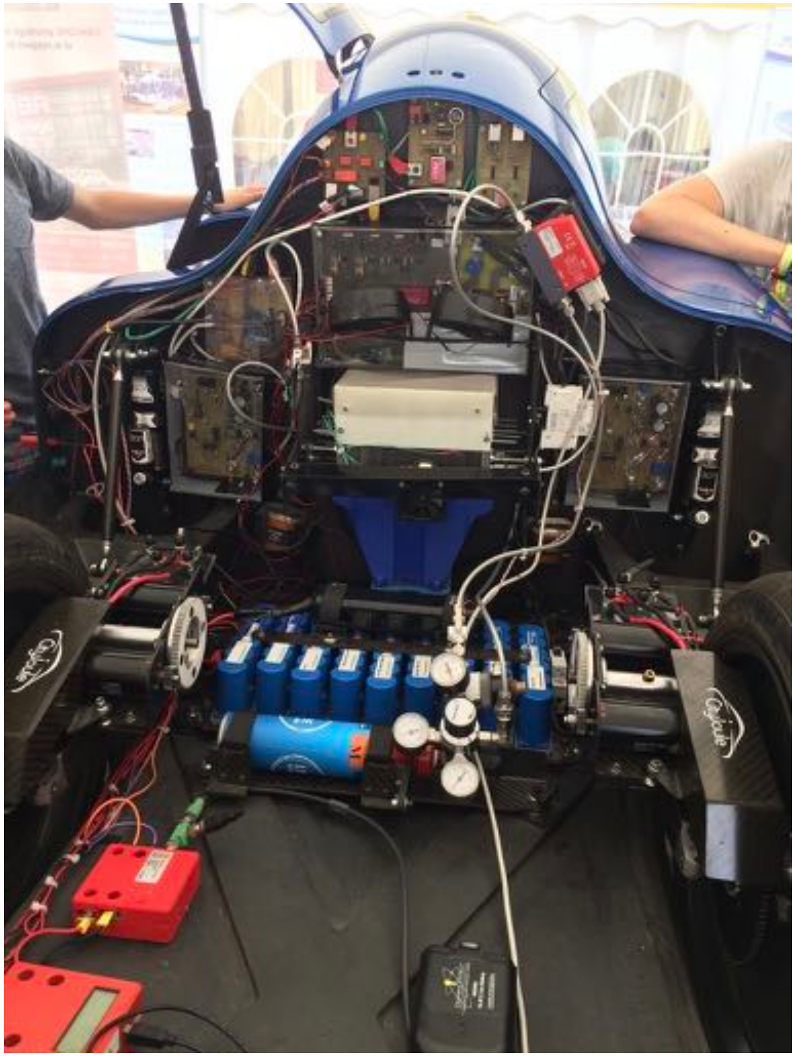
- Multi-physics tank to wheel model



Global energetic model



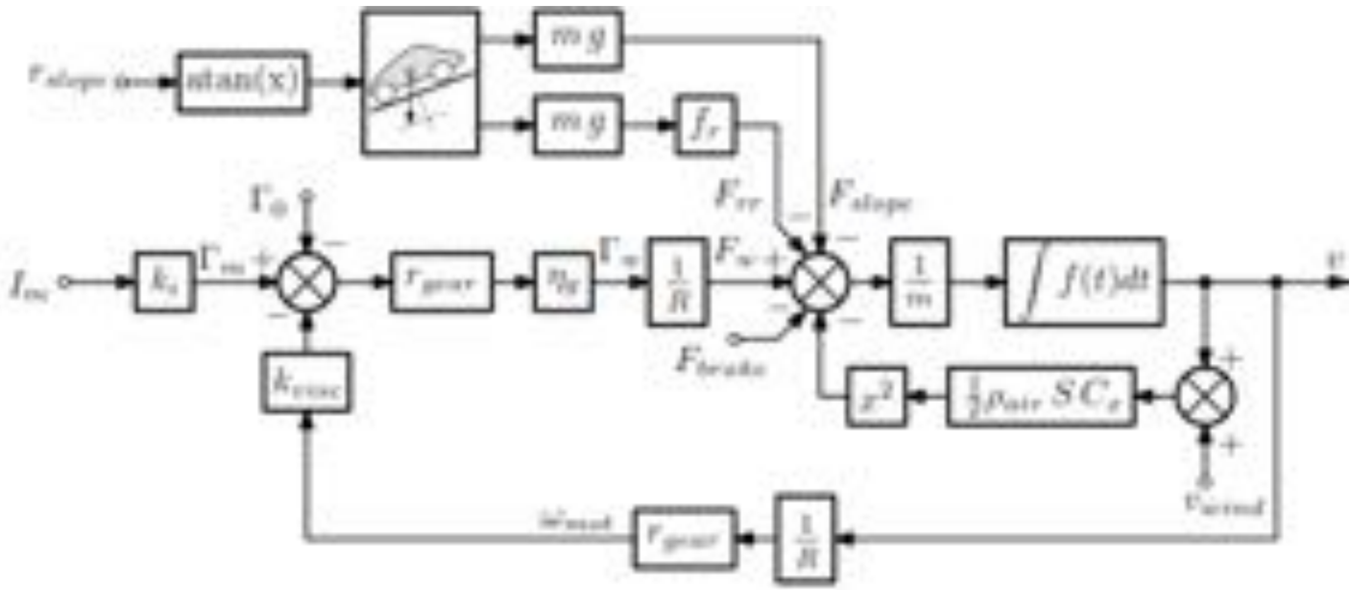
GaN components to increase global efficiency and remove smooth inductances

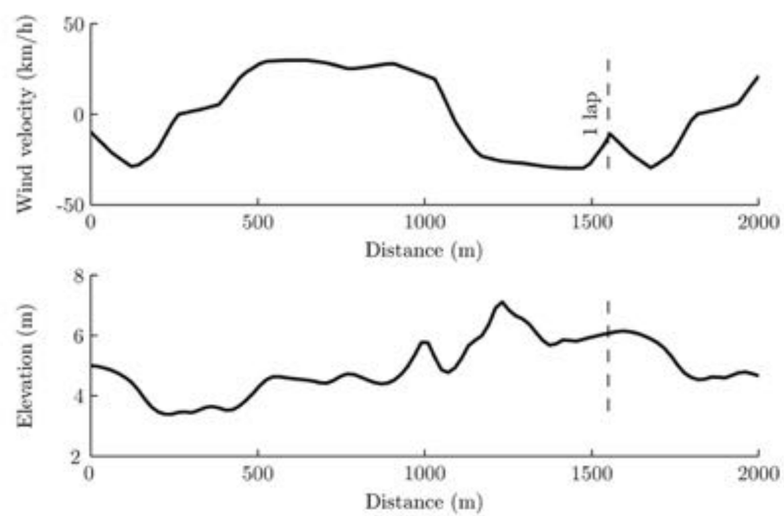


Rear side of vehicle

Global energetic model

- Mechanical model
  - Input : Motor current
  - Output : Speed and Torque profiles
  - Parameters : Slope and Wind in any position on the track, gear ratio



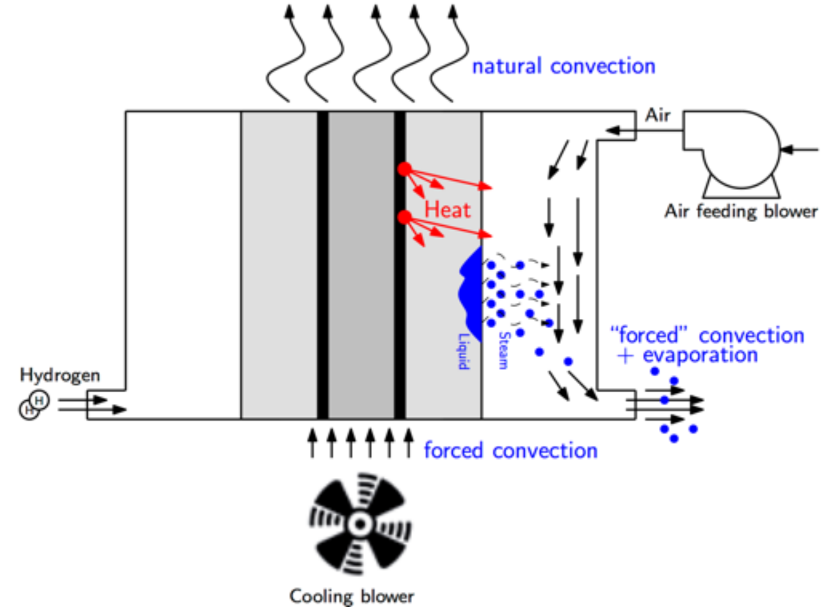


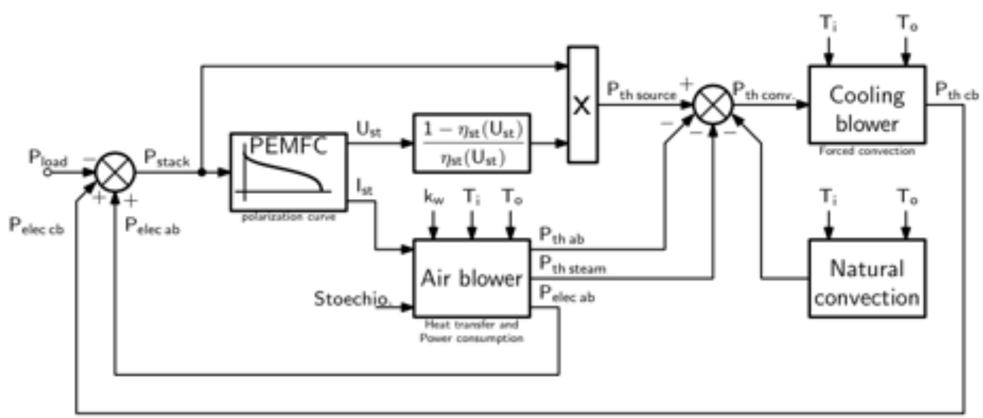
Global energetic model

- Thermal model of the PEMFC
  - 1st order model: Homogeneous temperature

$$mC_p \frac{dT}{dt} = P_{th\ src} - P_{th\ ab} - P_{th\ evap} - P_{th\ nat} - P_{th\ cb}$$

  - Thermal power source
    - Given according polarization curve
  - Thermal power evacuated by evaporation
    - Water produced during reaction in liquid form
    - Water completely drained in vapor form
  - Thermal power evacuated by air blower
    - Forced convection by air flow in air channel
  - Thermal power evacuated by cooling blower
    - Forced convection by air flow
    - Perfect exchange with fuel cell
  - Thermal power evacuated by natural convection



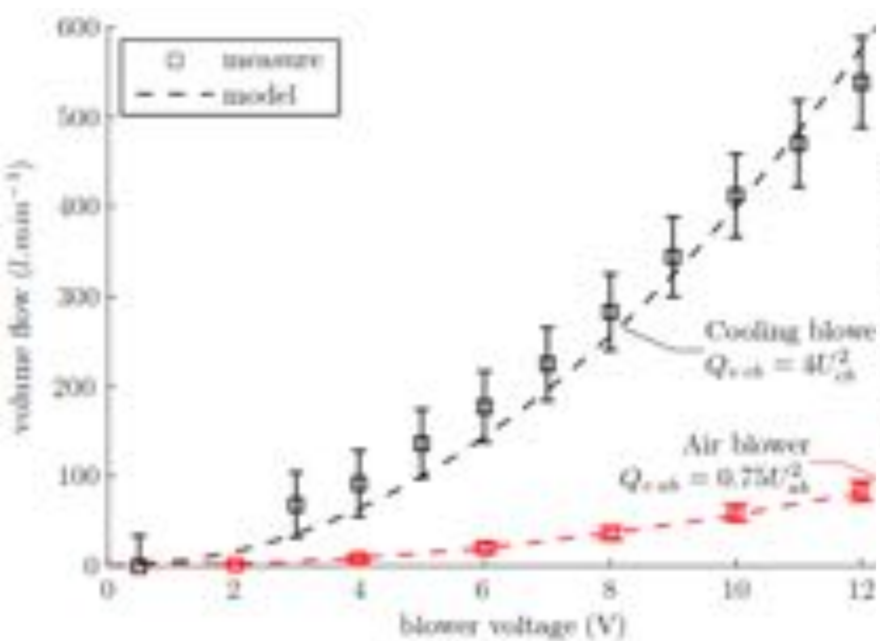


Multi-physics model

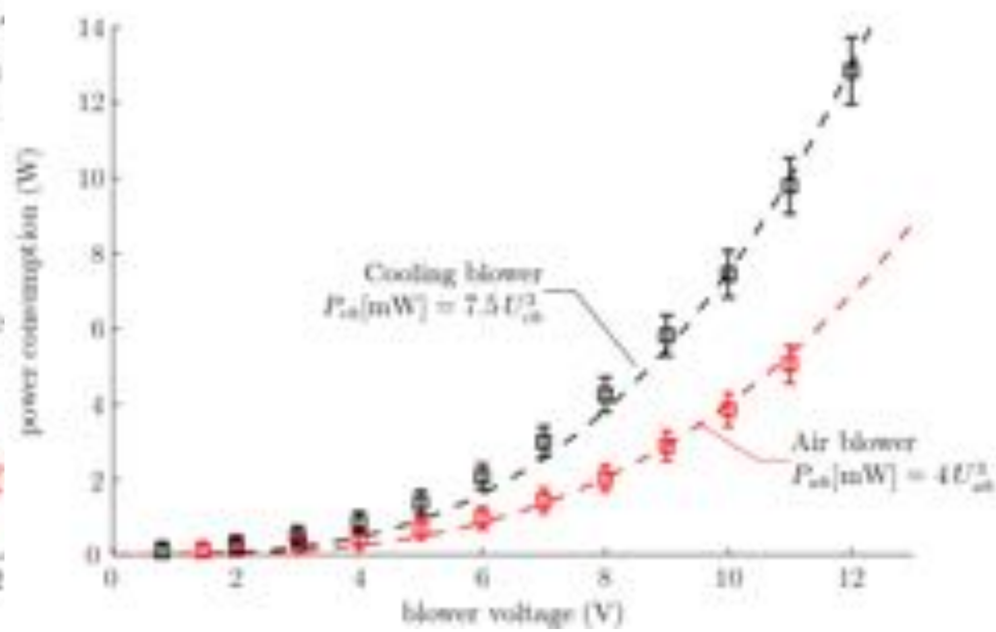
- Auxiliaries control laws and electrical consumptions
  - Air flow controlled through the blower voltage, depending on the stack's current and Air stoichiometric ratio Sc:

$$Q_{v\,ab} = 60000\,\frac{5\,R_c\,(273,15 + T_{st})}{4\,P_a\,F}\,I_{st}\,n_{cells}\,S_c$$

  - Cooling blower: Air flow drive by cooling regulation (Hysteresis controller)



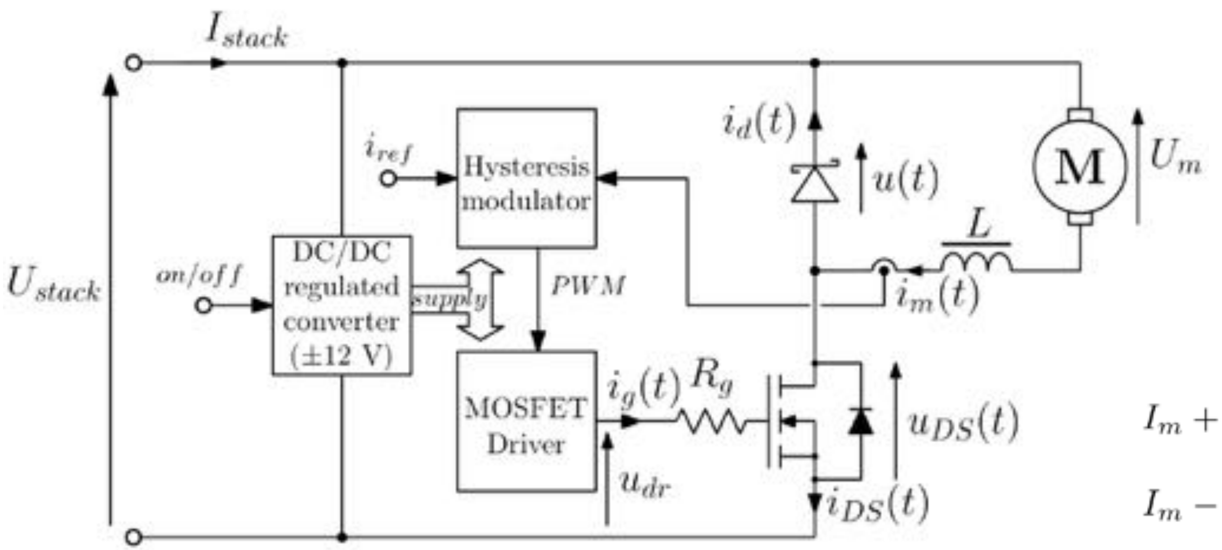
AIR FLOW FOR EACH BLOWER

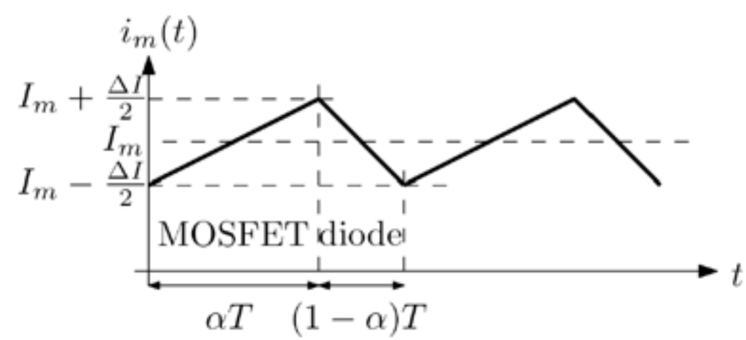


ELECTRICAL POWER CONSUMPTION

Global energetic model

- Studied power converter

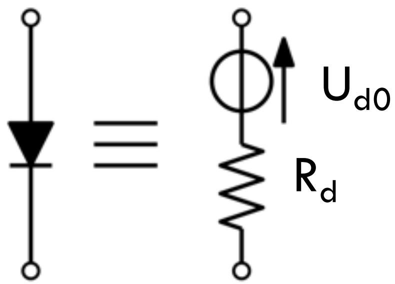




- Losses in power converter :
  - Diode + MOSFET : commutation (transient behavior), conduction, open)
  - Smoothing inductance
  - Command (sensor, regulator, wiring, drivers, electronics, …)
  - Wiring + contact

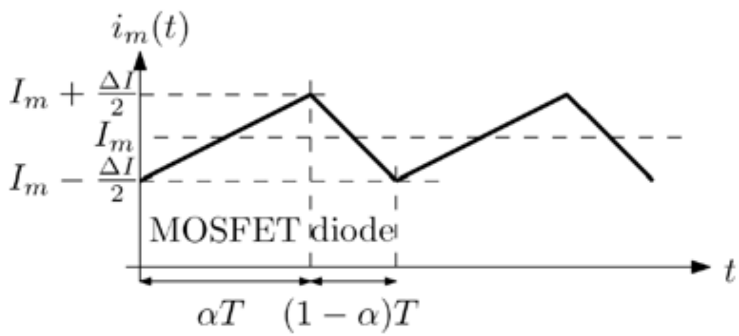
Global energetic model

- Diode model during conduction

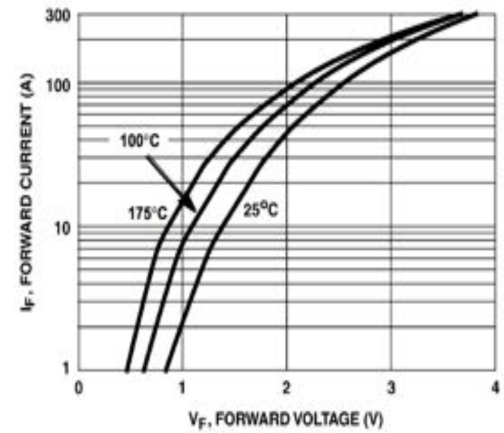


$$U_d(I) = U_{d0} + R_d I$$

Constant threshold voltage in series with resistance



Motor current with ripple



RHRP3060

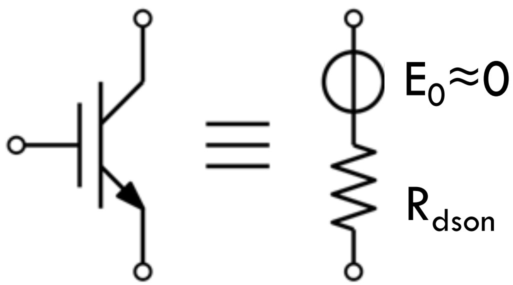
30A, 600V Hyperfast diode

- Losses by conduction

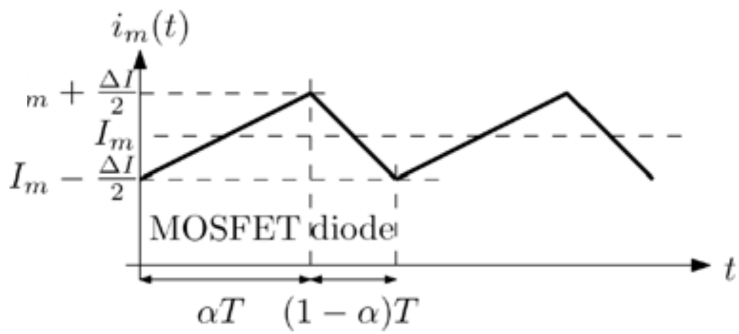
$$P_{c\ diode} = \frac{1}{T}\int_0^{(1-\alpha)T} \left(U_{d0} + R_d i_m(t)\right) i_m(t)\, dt = (1-\alpha)\left(\frac{\Delta I^2}{12} + R_d I^2 + U_{d0} I\right)$$

Global energetic model

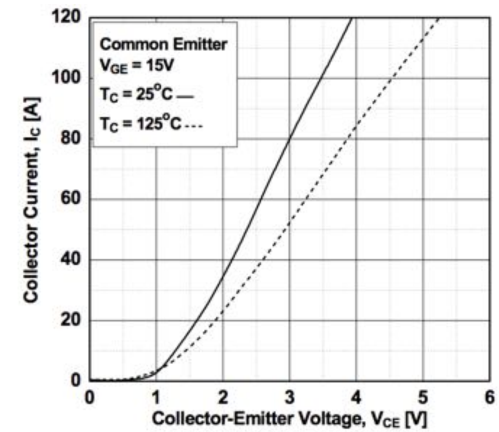
- MOSFET model



Constant threshold voltage in series with resistance



Approximation of motor current with ripple

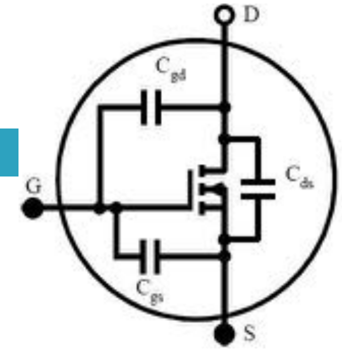


FGA20N120FTD
1200V, 20A Trench IGBT

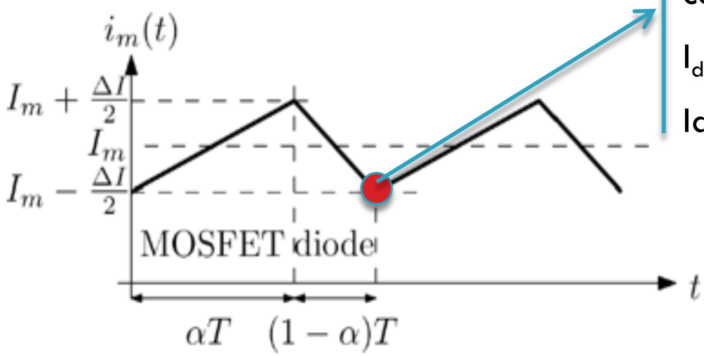
  - Losses by conduction

$$P_{c\ mosfet} = \frac{1}{T}\int_0^{\alpha T} R_{ds(on)} i_m(t)^2\, dt = R_{ds(on)}\alpha\left(\frac{\Delta I^2}{12} + I^2\right)$$

Global energetic model



- Commutation losses for MOSFET and Schottky diode



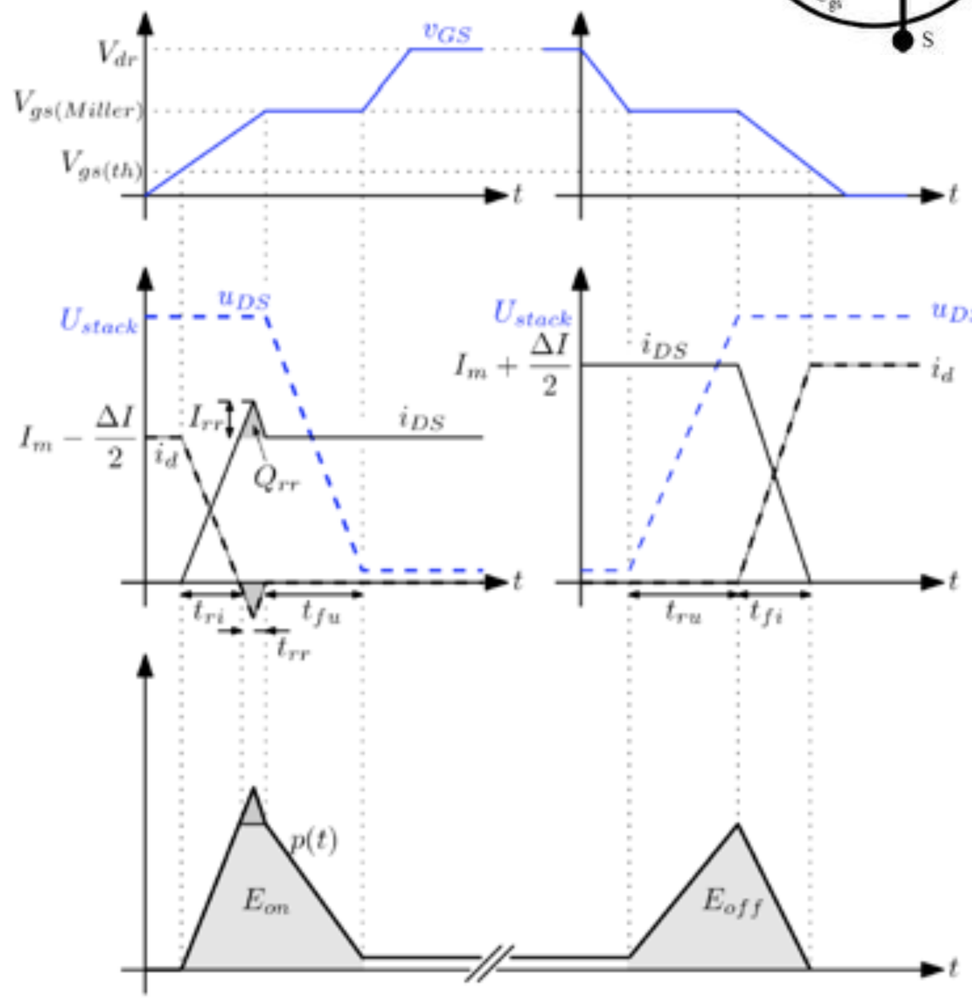
Before commutation :

$I_d = I_m - \Delta I/2$

Ids=0

- Transient divided in three steps :
  - Vgs>Vgs(th) :

    Start of current I_{DS} rising
  - Reverse-recovery current has to be absorbed by the MOSFET (extra losses)
  - When the diode is switched off, The voltage of the MOSFET can reach the supply voltage



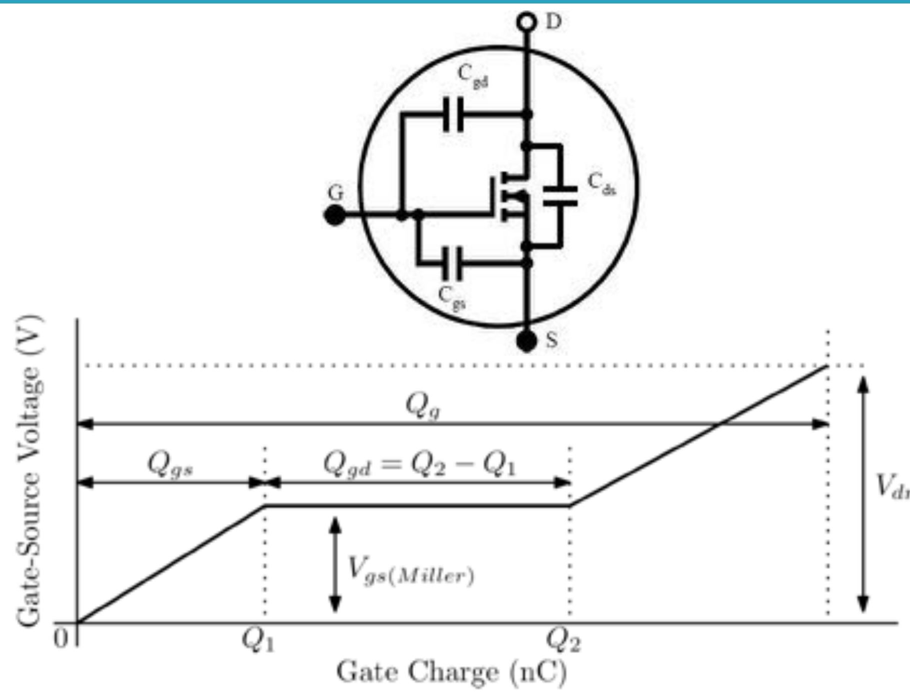
Global energetic model

- Commutation power evaluation

V_{gs} and I_g can be easily calculated:

$$V_{gs(Miller)} = V_{gs(th)} + \frac{I_D}{g_{fs}}$$

$$I_{g(Miller)} = \frac{V_{dr} - V_{gs(Miller)}}{R_g}$$



Rise and fall time can be deduced and power calculated :

$$t_{fu} = \frac{Q_{gd}}{I_{g(Miller)}} = \frac{g_{fs} Q_{gd} R_g}{g_{fs}\left(V_{dr} - V_{gs(th)}\right) - I_D} \qquad t_{ru} = \frac{g_{fs} Q_{gd} R_g}{g_{fs} V_{gs(th)} - I_D}$$

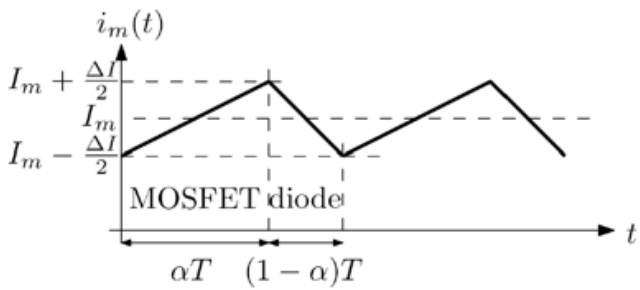
$$E_{on} = (I_m + \Delta I) U_{stack} \frac{t_{fu} + t_{ri}}{2} + Q_{rr} U_{stack} \qquad E_{off} = (I_m - \Delta I) U_{stack} \frac{t_{ru} + t_{fi}}{2} \qquad P_{sw} = \left(E_{on} + E_{off}\right) f_s$$

Global energetic model

- Losses in the smoothing inductance
  - Geometric and physical description (1mHenry/20A)

Parameter		Value
effective volume	V_e	71 890 mm^3
effective length	L_e	172 mm
effective area	A_e	418 mm^2
air gap	e	0.5 mm
relative permeability	μ_r	10 000
number of turns	n	44

  - Wiring Joule's losses



$$P_{c\ ind} = \frac{1}{T}\int_T R_L\, i_m^2(t)dt = R_L\left(\frac{\Delta I^2}{12} + I_m^2\right)$$

Approximation of motor current with ripple

Global energetic model

- Core losses (hysteresis and eddy current losses)

Typically Steinmetz formula used :

$$P_{mag} = k\, f^{\alpha_m}\, \Delta B^{\beta}$$

Where ΔB is peak induction, f frequency in kHz,

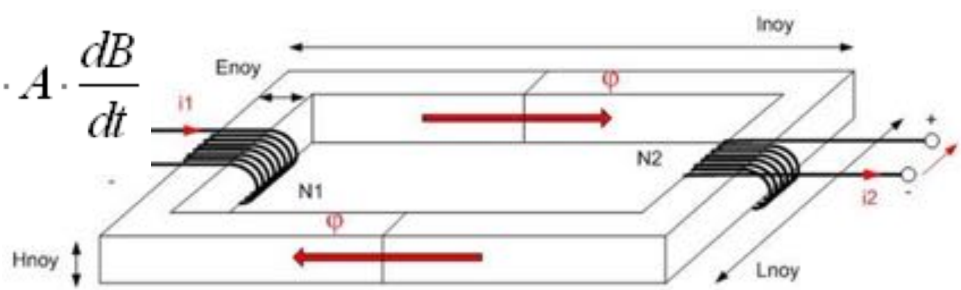
P_{mag} magnetic loss density (mW/cm^3).

Experiment rather than Epstein test bench

$$E_{lossV} = \int_{-B}^{+B_{max}} H \cdot dB \; ; \; V_2(t) = N_2 \cdot \frac{d\varphi}{dt} = N_2 \cdot A \cdot \frac{dB}{dt}$$

$$H(t) = \frac{N_1 \cdot i_1(t)}{l_m}$$

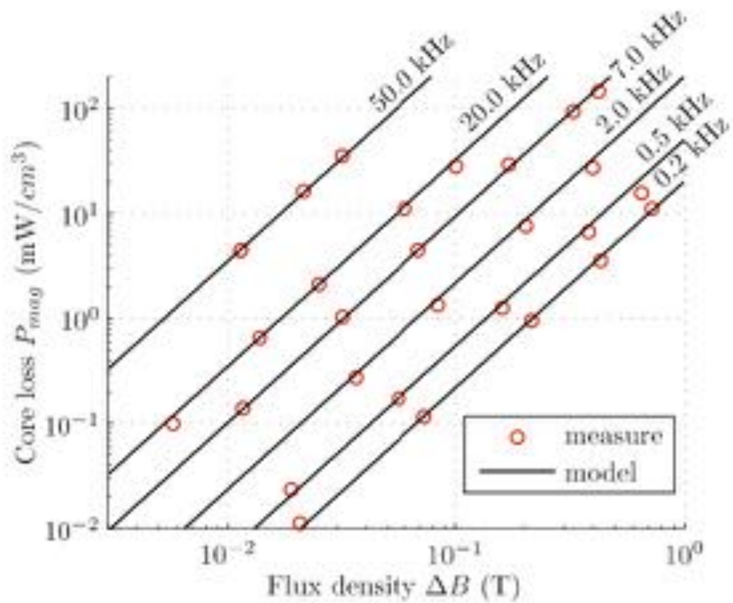
$$p_{v\ mag} = \frac{1}{V_{core} T} \int_T i_m(t) \frac{n}{n_2} u_2(t)\, dt$$



Principle of core losses measurement

Global energetic model

- Comparison between measure and model



Comparison measure/Steinmetz formula with k=100.05, β=1.96 and $\alpha_m = 1.0 + f\ 9.10^{-6}$

- Expression of peak induction according to current ripple

To be included in the model, must be expressed in term of current ripple

$$\Delta B = \Delta I \frac{\mu_0 n}{\frac{L_e}{\mu_r} + e}$$

then

$$P_{mag} = p_{v\ mag} V_{core}$$

Global energetic model

- Losses involved by command

!!!! Due to the very high efficiency, the small signal electronic has to be taken into account !!!

- Power to stabilize fuel cell voltage

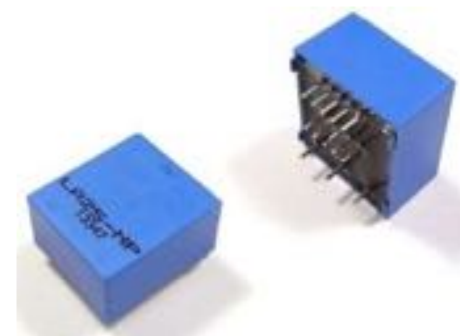
$$P_{supply} = P_{eon}\left(\frac{1}{\eta_n} - 1\right) + I_0 U_{stack}$$

Where I_0 no load consumption, P_{eon} the total consumption of small signal electronics and η_n the efficiency of source stabilization

TMR 3-2423WI from TRACOPOWER®

- Current probe

$$P_{LEM} = \frac{|I_m|}{1000} V_{dd} + I_{LEM0}\left(V_{dd} - V_{ss}\right)$$



LA25 from LEM®

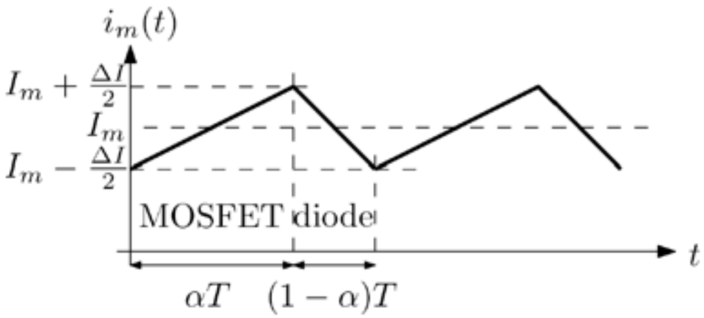
- Final consumption (with small electronics)

$$P_{supply} = \left(\frac{|I_m|}{1000} V_{dd} + I_{LEM0}\left(V_{dd} - V_{ss}\right) + P_{ctrl}\right)\left(\frac{1}{\eta_n} - 1\right) + I_0 U_{stack}$$

Global energetic model

- Losses wiring and contacts

Connecting cables between the electronic board, the smoothing inductor and the propulsion motor



Approximation of motor current with ripple

$$P_{c\ ind} = \frac{1}{T}\int_T R_L\, i_m^2(t)dt = R_L\left(\frac{\Delta I^2}{12} + I_m^2\right)$$

$$P_{wiring} = R_c\left(\frac{\Delta I^2}{12} + I_m^2\right)$$

!!! Evaluation of contact resistance remains a big issue !!!

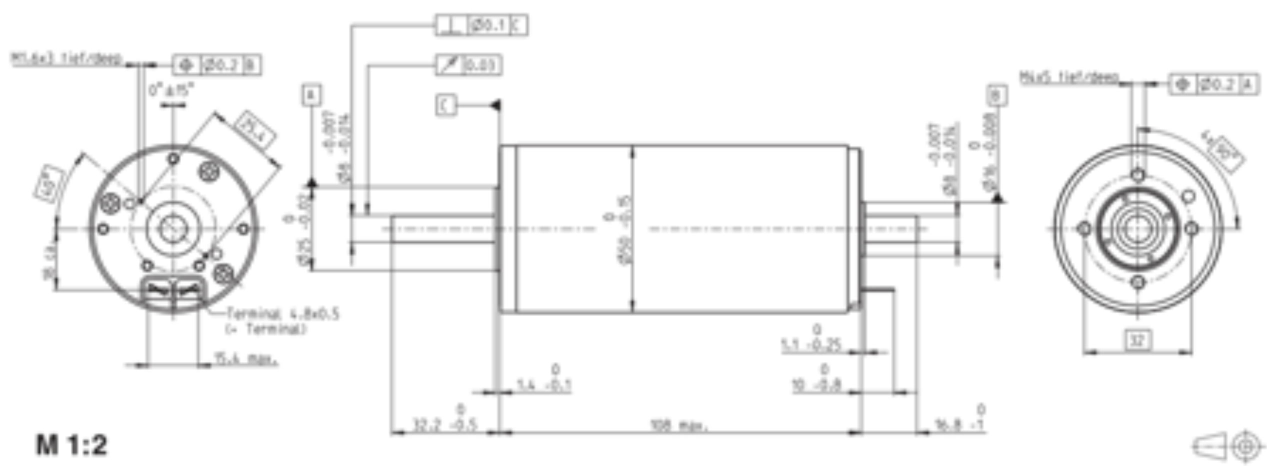
!!! Temperature evolution not taken into account !!!

Global energetic model

- MAXON RE50 Ironless DC motor

標準在庫製品		注文番号			
標準製品					
特別仕様製品（受注生産）					
		370354	370355	370356	370357
インダストリアル・バージョン IP54*		389089	389090	389091	389092
モータ・データ					
公称電圧時のデータ					
1 公称電圧	V	24	36	48	70
2 無負荷回転数	rpm	5950	5680	4900	2760
3 無負荷電流	mA	236	147	88.4	27.4
4 最大連続トルク時の回転数	rpm	5680	5420	4620	2470
5 最大連続トルク	mNm	405	418	420	452
6 最大連続電流	A	10.8	7.07	4.58	1.89
7 停動トルク	mNm	8920	8920	7370	4340
8 起動電流	A	232	148	78.9	17.9
9 最大効率	%	94	94	94	92
モータ固有値					
10 端子間抵抗	Ω	0.103	0.244	0.608	3.9
11 端子間インダクタンス	mH	0.072	0.177	0.423	2.83
12 トルク定数	mNm/A	38.5	60.4	93.4	242
13 回転数定数	rpm/V	248	158	102	39.5
14 回転数／トルク勾配	rpm/mNm	0.668	0.638	0.666	0.638
15 機械的時定数	ms	3.75	3.74	3.78	3.74
16 ロータ慣性モーメント	gcm²	536	560	542	560

RE 50 ∅50 mm, グラファイトブラシ, 200 Watt



Global energetic model

- Motor losses
  - Brush losses

$$p_{balai} = E_b.I$$

  - Windings losses (Joule's losses)

$$p_{Joule} = r.I^2$$

  - Dry and viscous friction losses

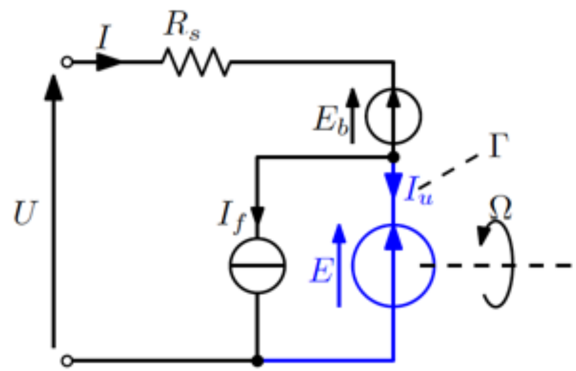
$$I_f = k_v.\Omega + k_s$$

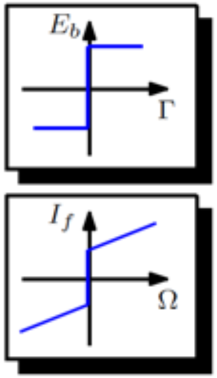
  - Efficiency calculation connected to circuit equation

$$E = U - rI - E_b$$

$$I_u = I - I_f$$

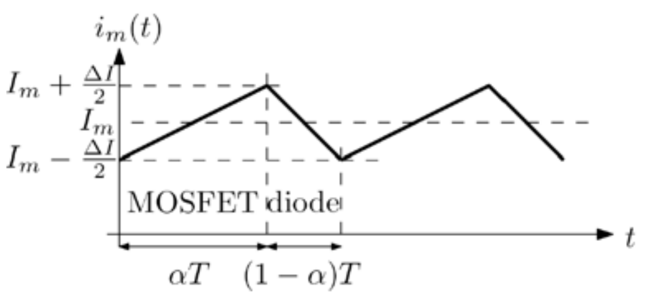
$$\eta = \frac{k_\phi \Omega (I - (k_v \Omega + k_s))}{k_\phi \Omega I + rI^2 + E_b I}$$





Voltage threshold in brush

Dry and viscous friction



Approximation of motor current with ripple

Losses in DC motor

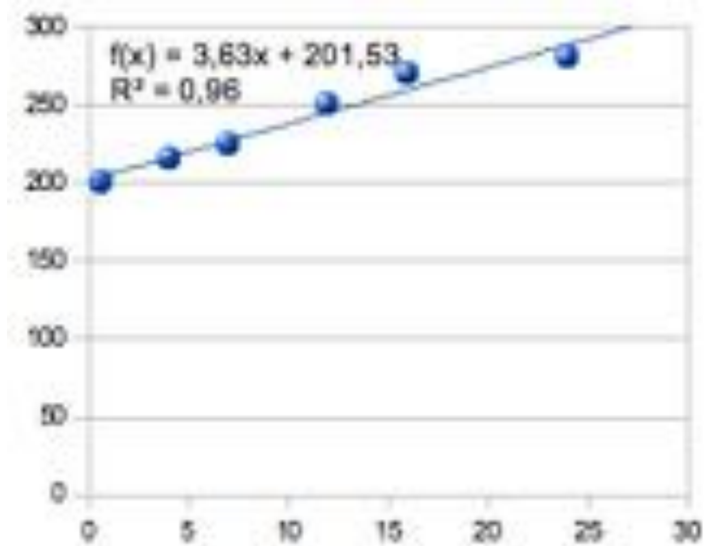
- Identification of parameters
  - Friction parameter with no load test

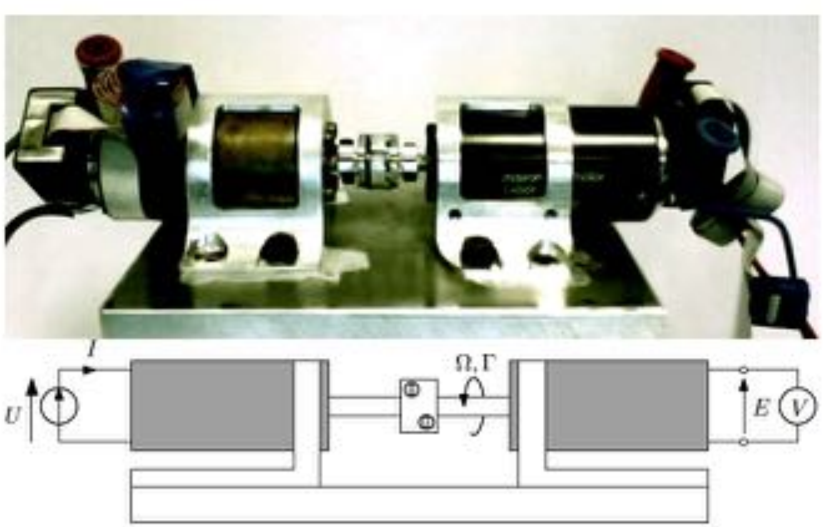
$$I_f(E) = Y_v E + I_0$$

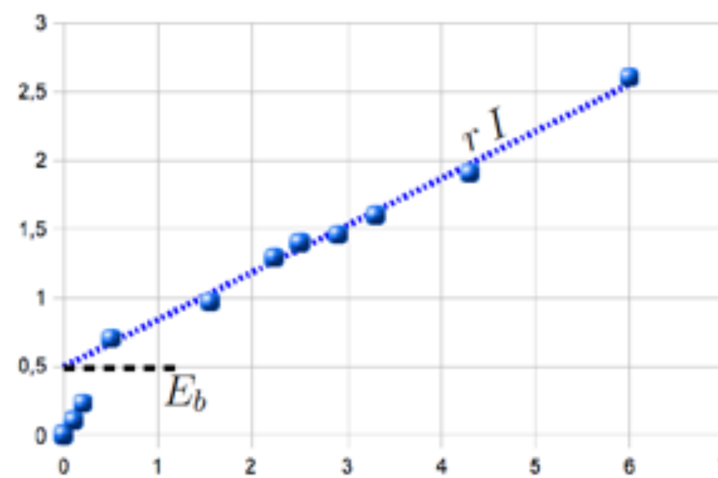
With E no load voltage, I_f current source and I_0 starting current

  - Brush voltage drop and windings losses with Ω=0

$$U(I) = r\,I + E_b$$

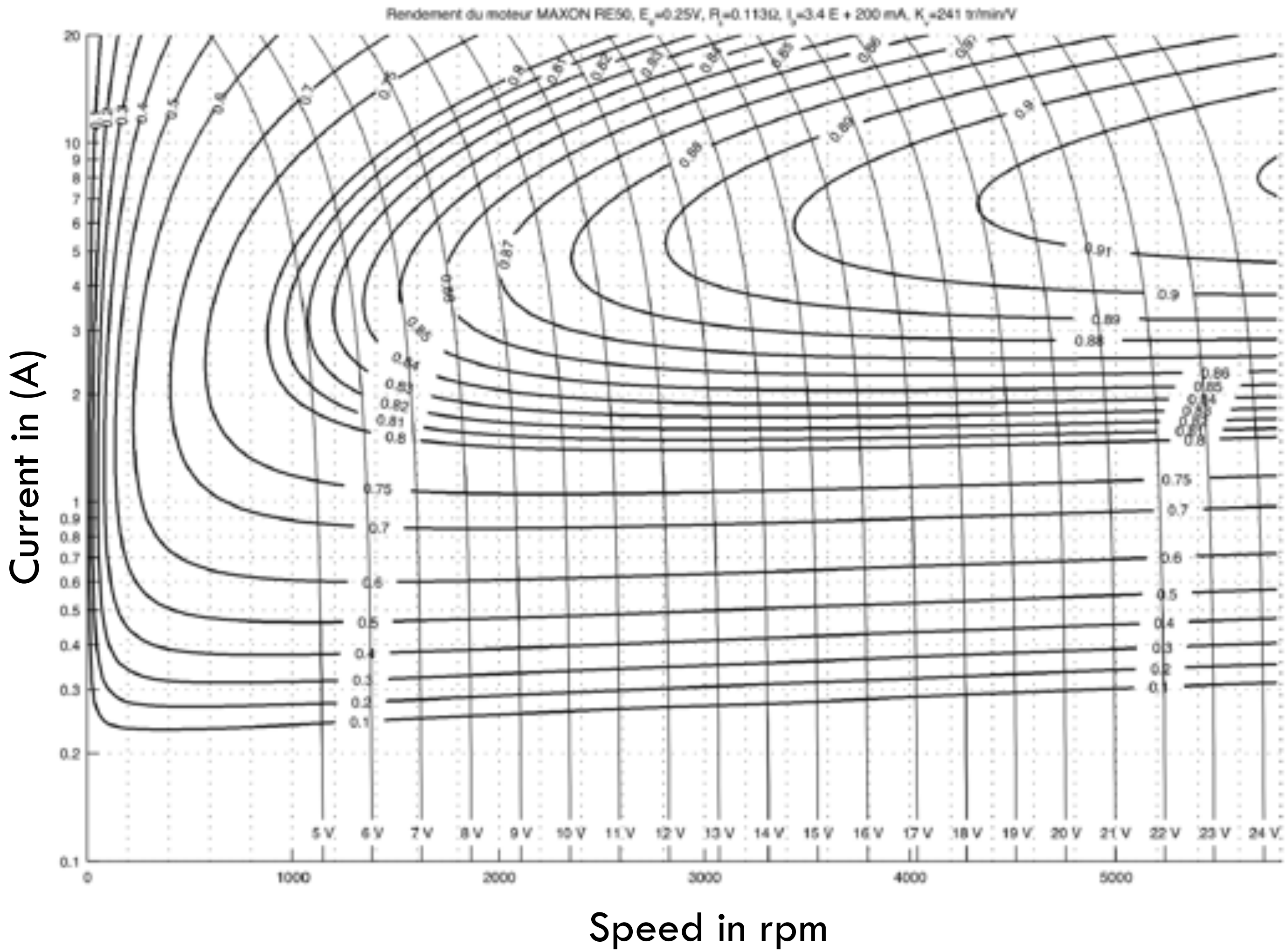






Losses in DC motor

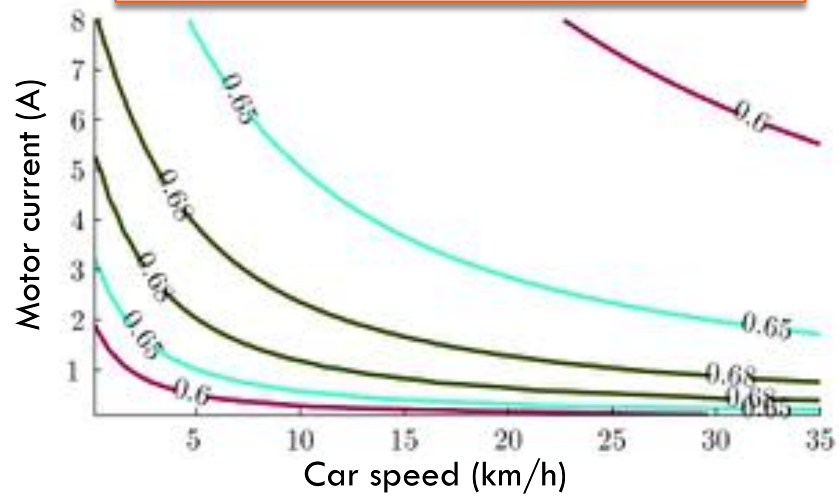
- Example of cartography working point and efficiency for RE50 motor



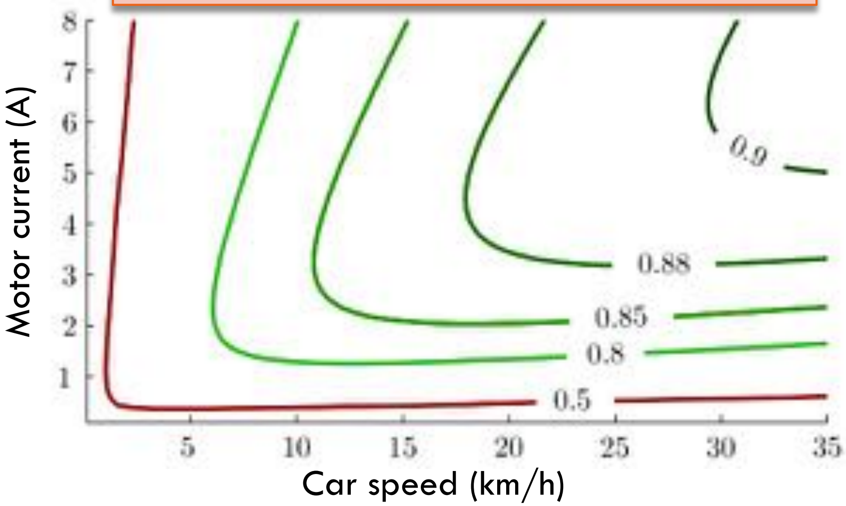
Global energetic model

- Result
  - Each sub-system is described according to efficiency, speed of car and
  - The tank to wheel efficiency is the superposition of all curves

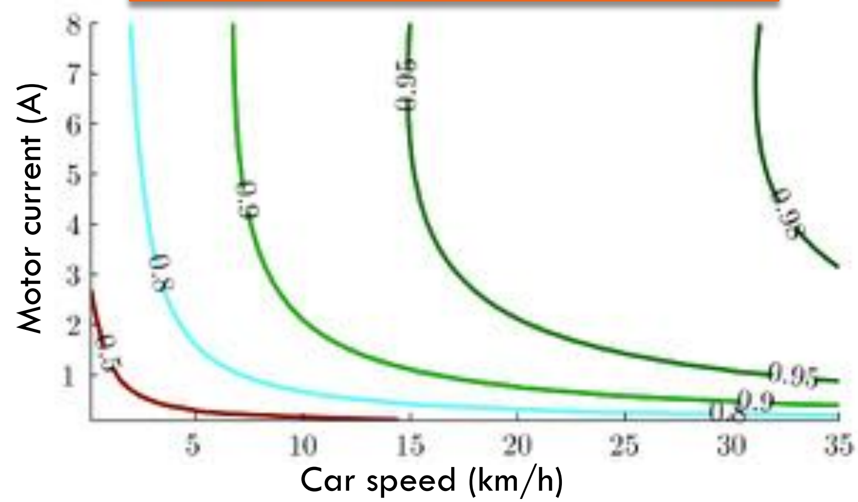
Stack + accessories



Motor drive

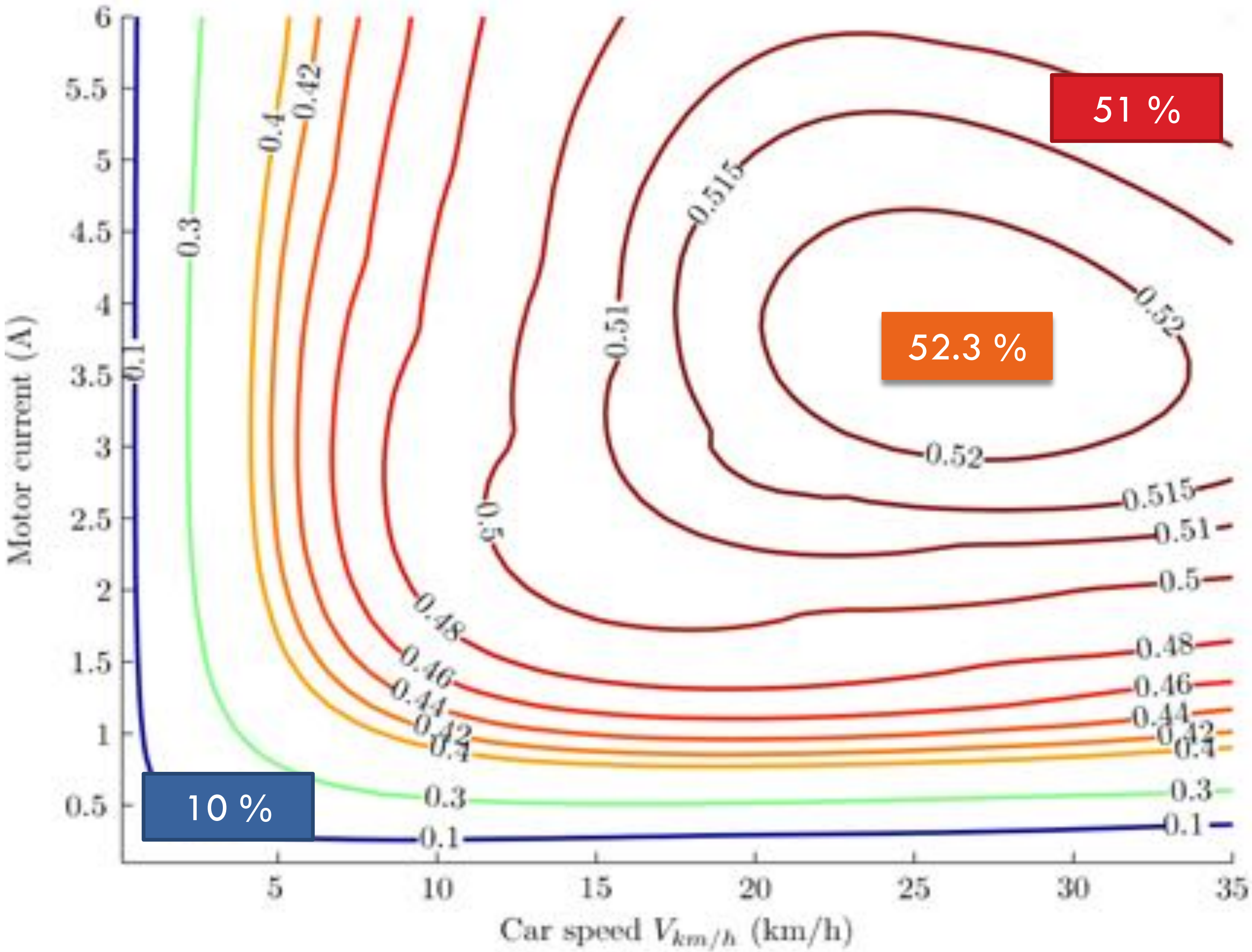


DC/DC converter



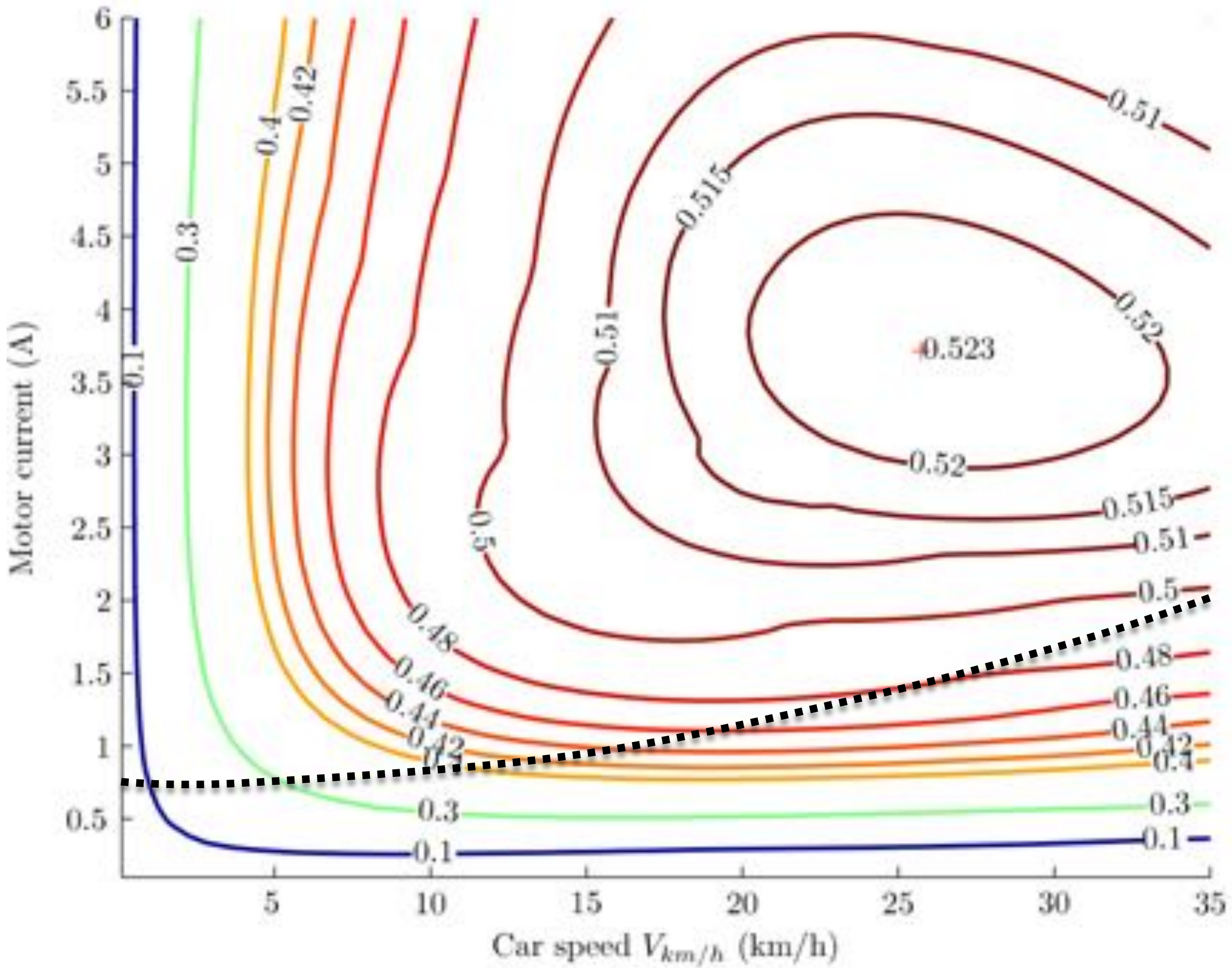
Global energetic model

- Tank to Wheel efficiency



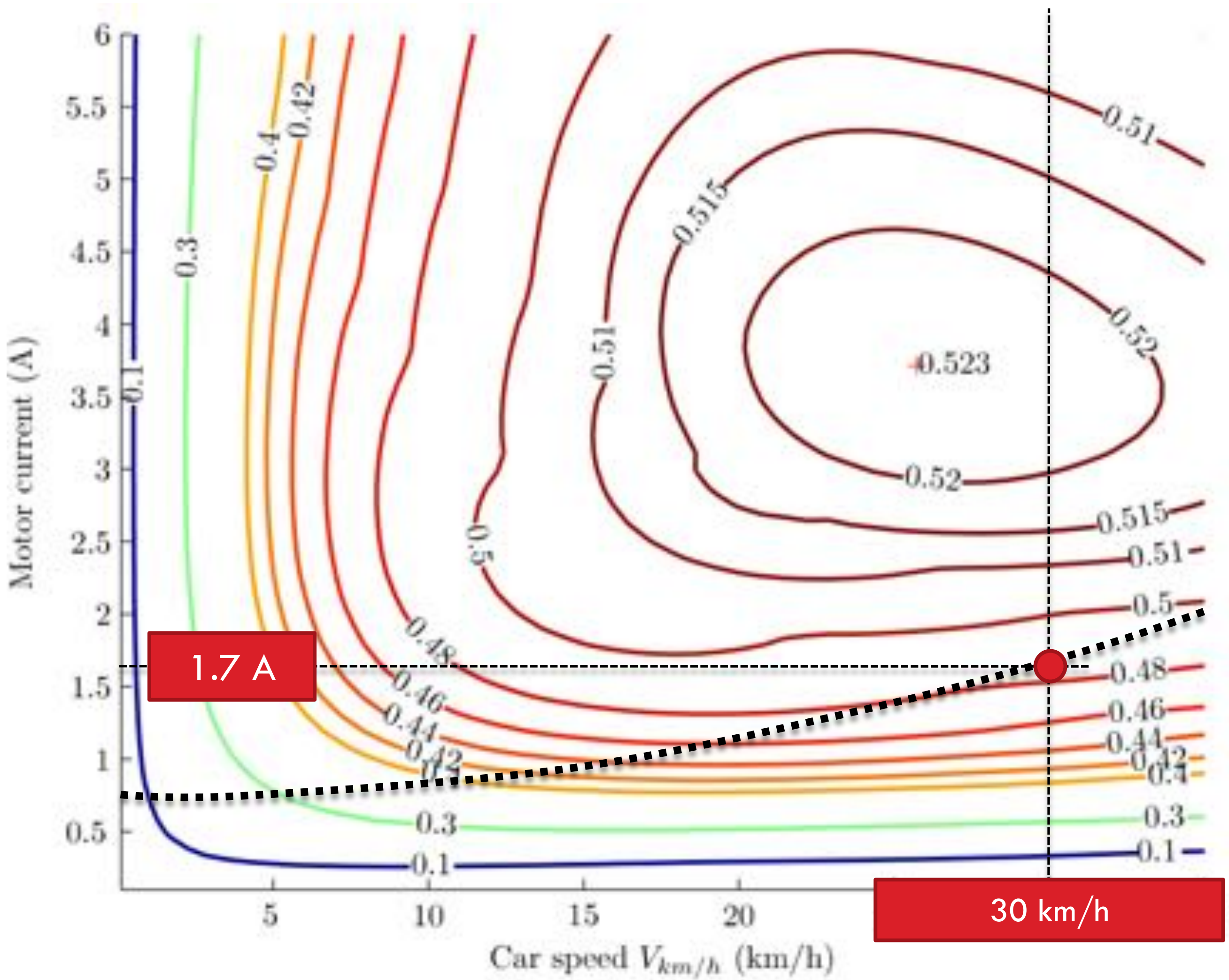
Global energetic model

- Working point of car with no wind and no slope



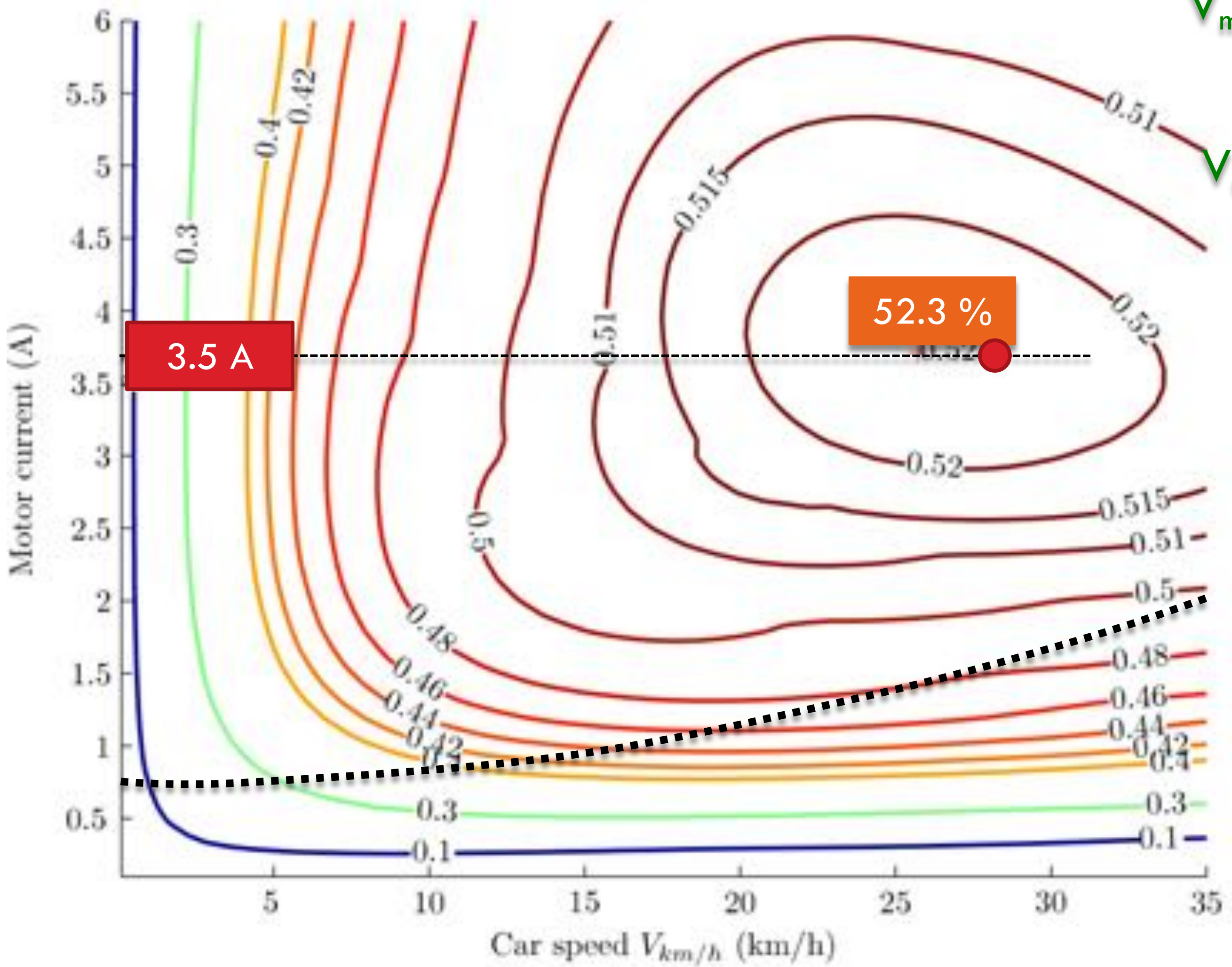
Global energetic model

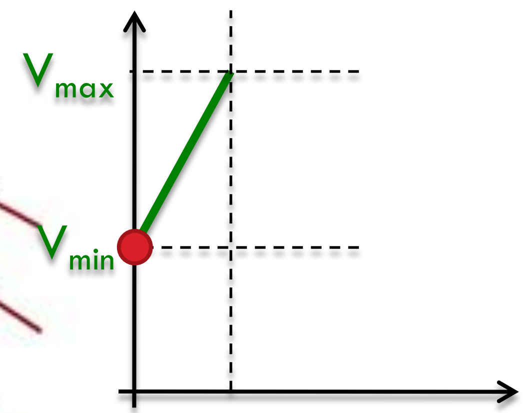
- To have a speed of 30km/h, 1.7A is required (49% efficiency which is not the best)



Global energetic model

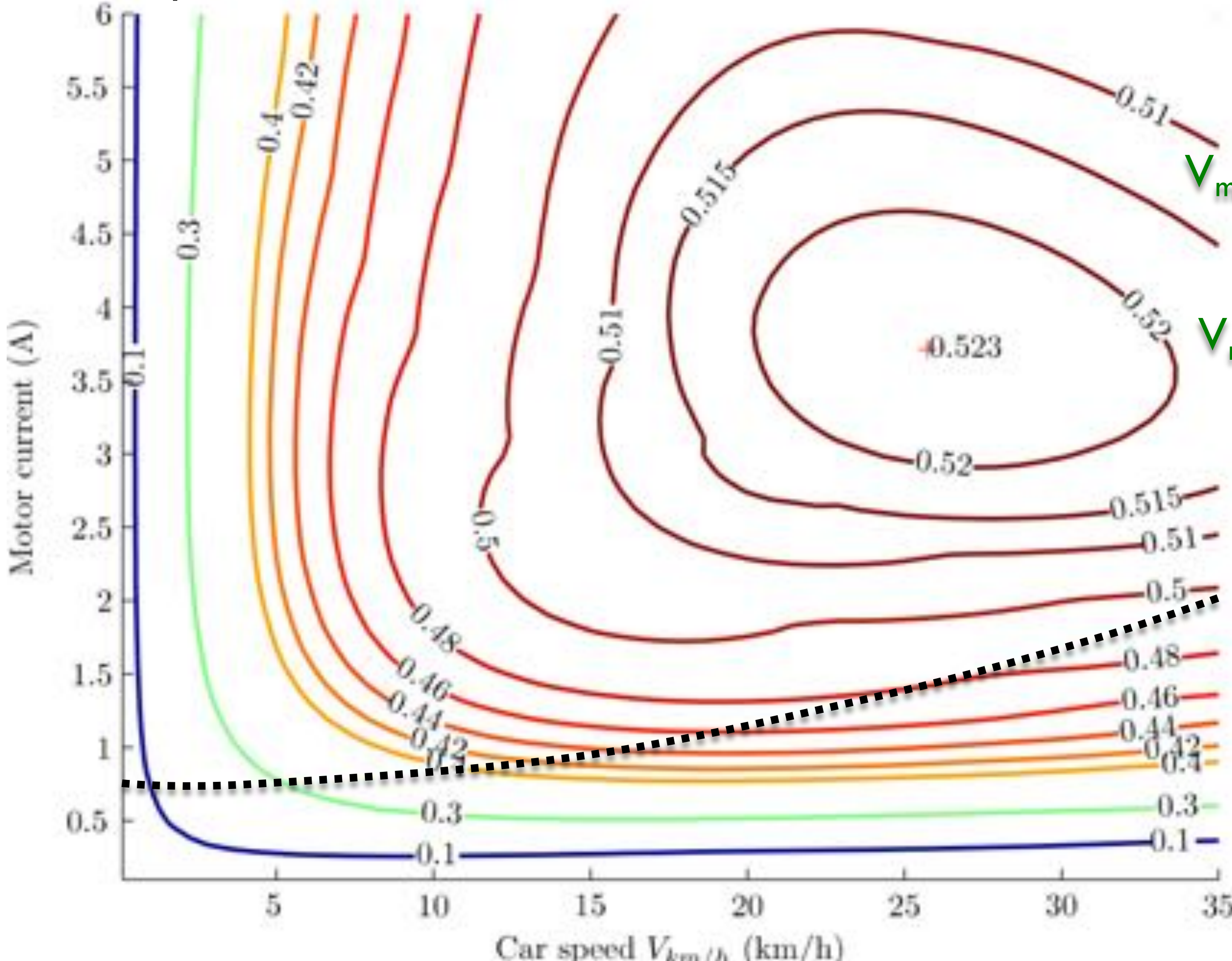
- Evolution of driving strategy to improve efficiency to 52.3%

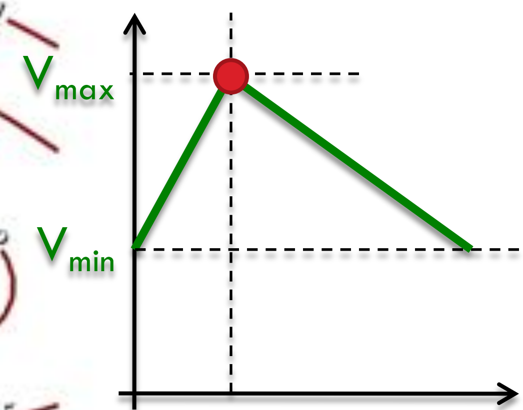




Global energetic model

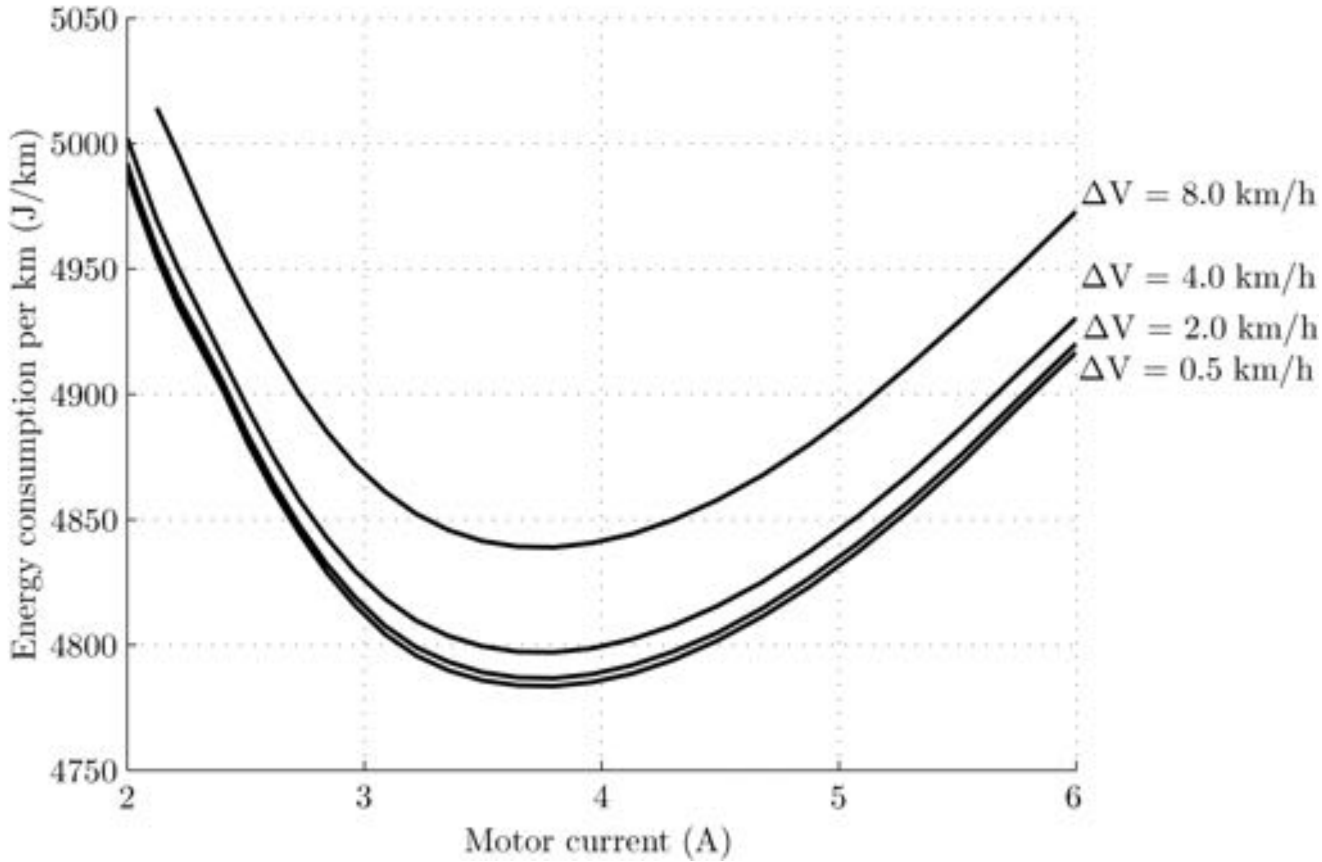
- Acceleration (52.3% efficiency), then deceleration with motor off (efficiency=0%) but consumption =0.8W





Results and exploitation

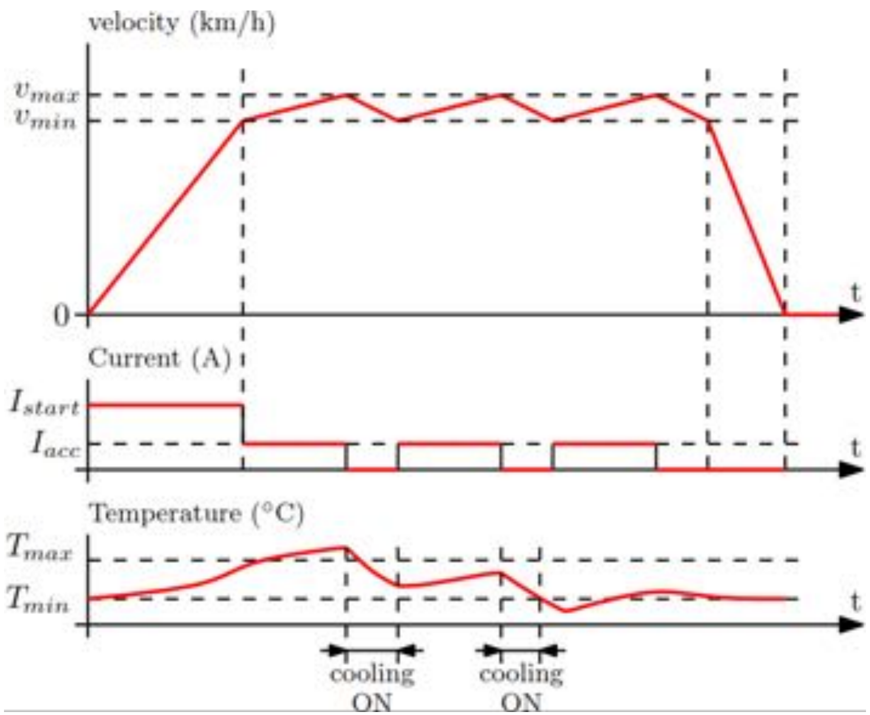
- Using of multi-physics model to optimize V_{min}, V_{max}

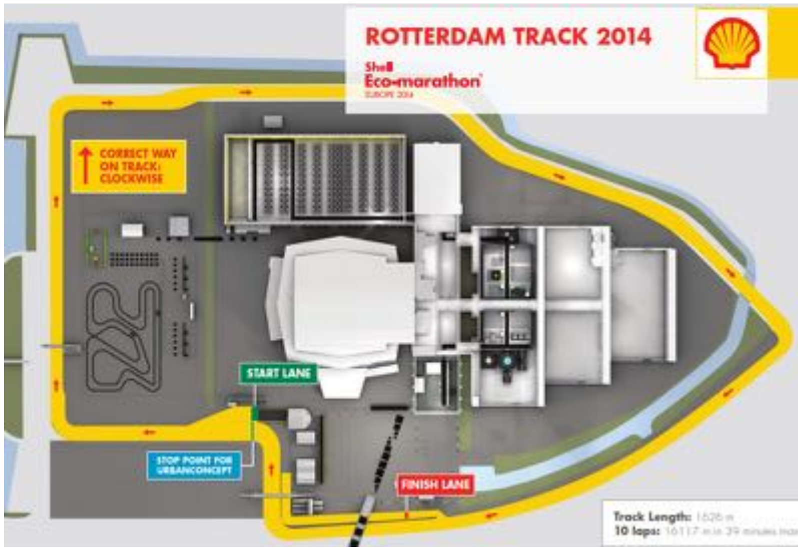


Efficiency is reduced for ΔV=2km/h => optimization required

Optimization

- Driving strategy
  - 3 phases per lap :
  - Phase 1: Acceleration from 0 to Vmin
  - Phase 2: “Constant” speed (series of acceleration and free wheel)
  - Phase 3: Braking (energy recovery in 2016)





- Control strategy
  - Torque/Current control with velocity thresholds
  - Hysteresis law for stack temperature regulation
  - Stack cooling during freewheel phases

Optimization

- Problem formulation
  - Objective function: The minimization of the fuel consumption on a full race (10 laps), under constraint of a minimum average speed of 25 km/h
  - Tank-to-Wheel 4th order Runge-Kutta ODE model implemented in Matlab:

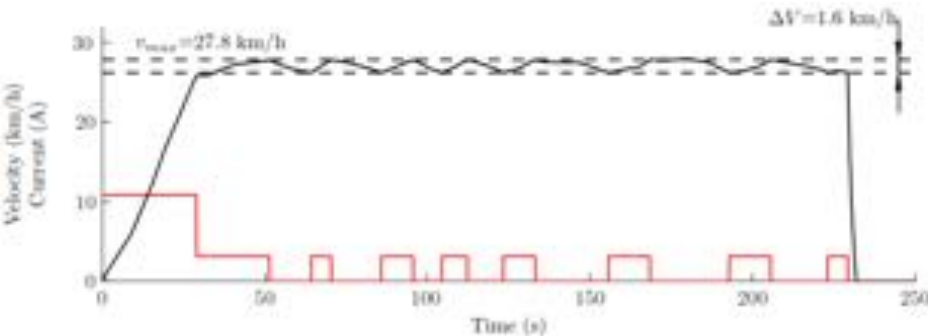
$$\frac{dx}{dt} = f(t,x),\ x = \left[T_{st}(t), v(t), X(t)\right]^T$$

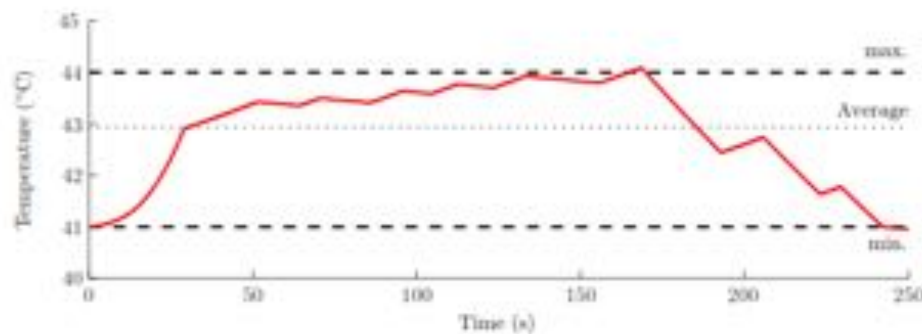
  - Simulation over one lap, in steady state for the Temperature Tend=T0
  - Particle Swarm Optimization: 50 particles and 200 maximum iterations
  - Input parameters: Istart, Iacc, Vmax, Vmin and gear ratio
  - Constraints: Average speed >25km/h

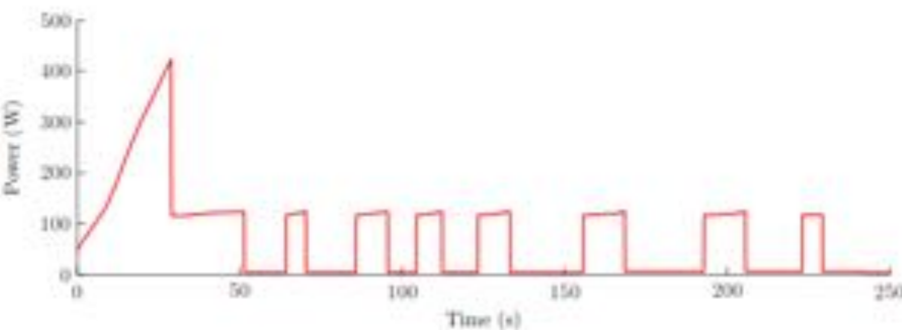
Optimization

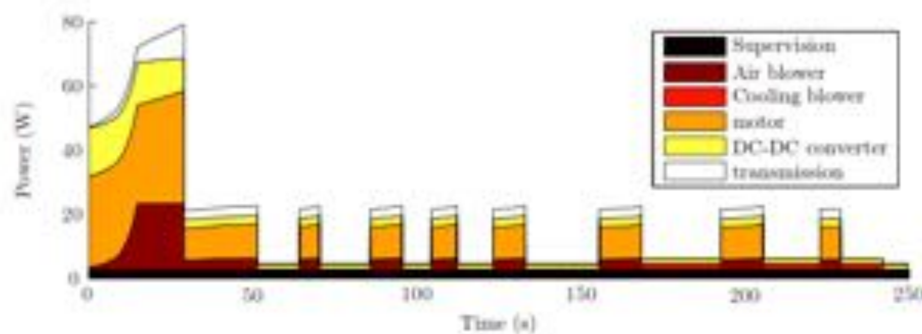
- Optimization result

Istart	Iacc	Vmax	Vmin	Gear ratio	Avg speed
10.8A	3.1A	27.8km/h	26.2km/h	200/14	25.0km/h



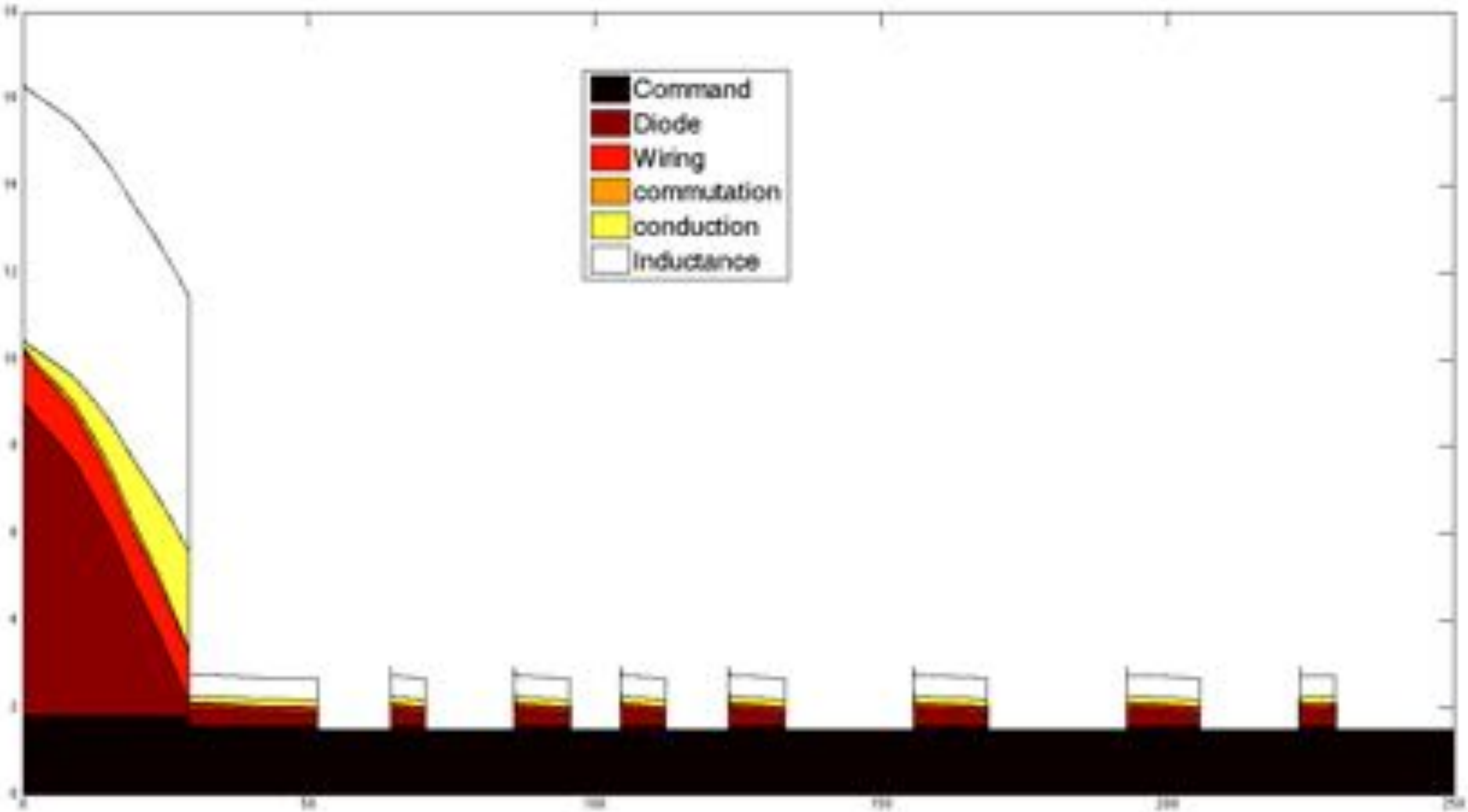






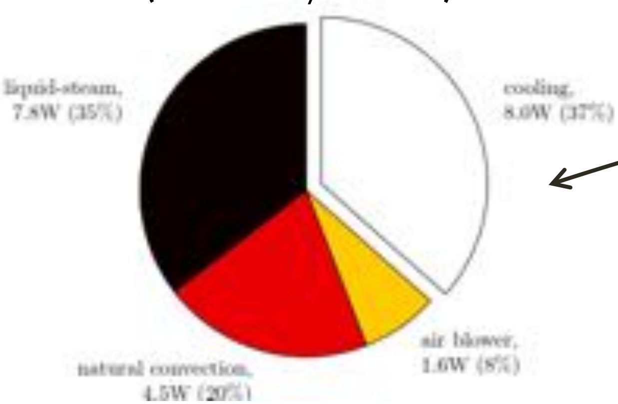
Optimization

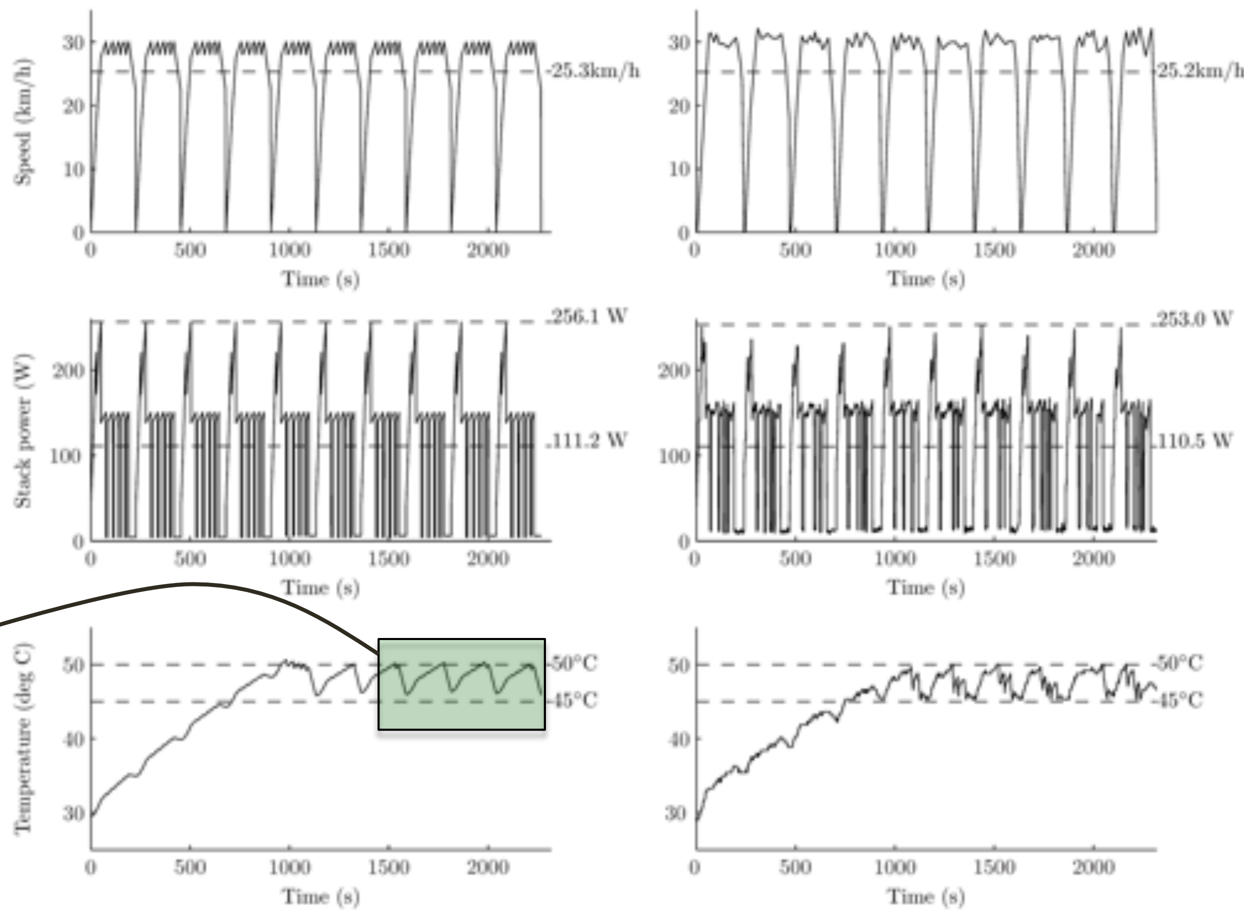
- Optimization result for power converter



Optimization

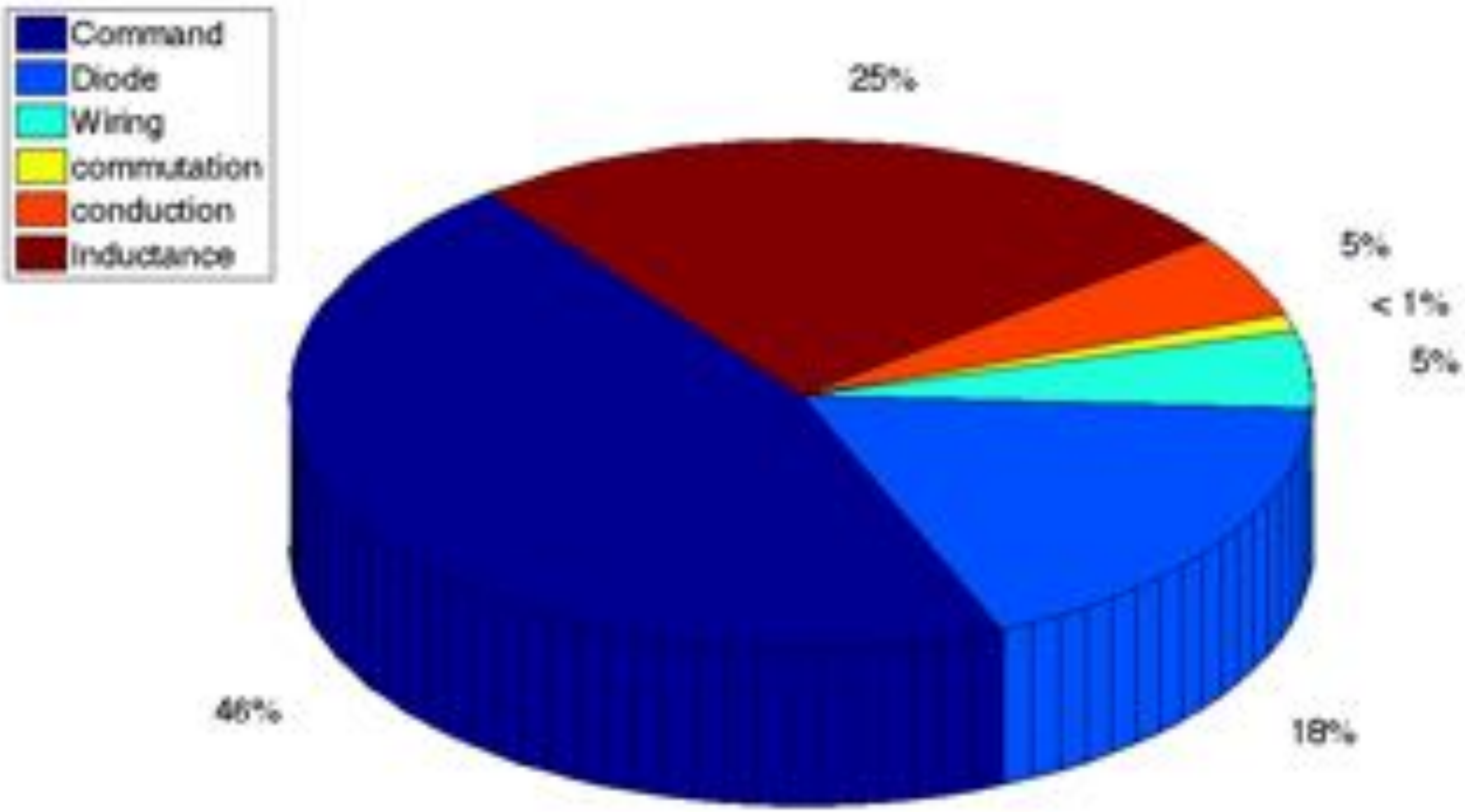
- Measures-Model for one race
  - May 2015, Rotterdam, Netherlands
  - 10 laps
  - Ambient temperature: 27°C
  - Max. wind: 30km/h
- Performance:
  - 800Wh/100km (1114km/LSP95)





Result and exploitation

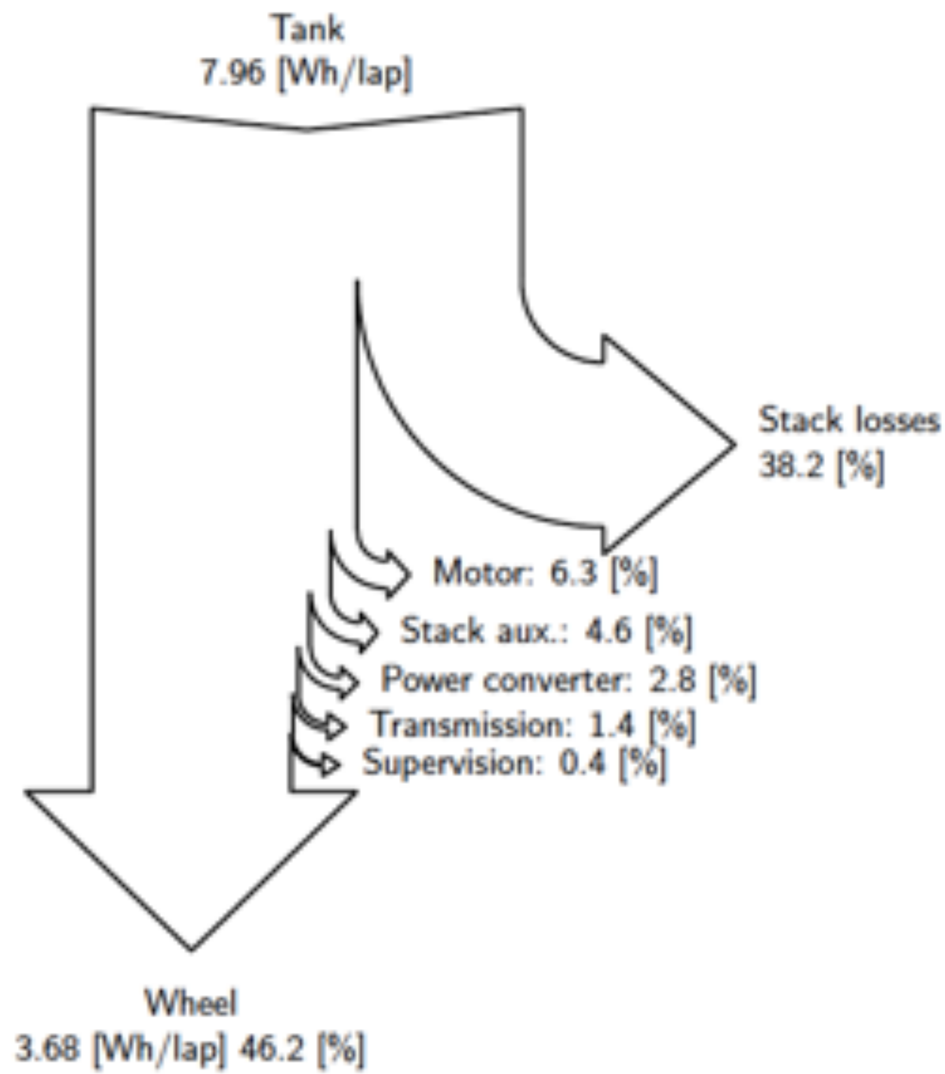
- Optimization result



Result and exploitation

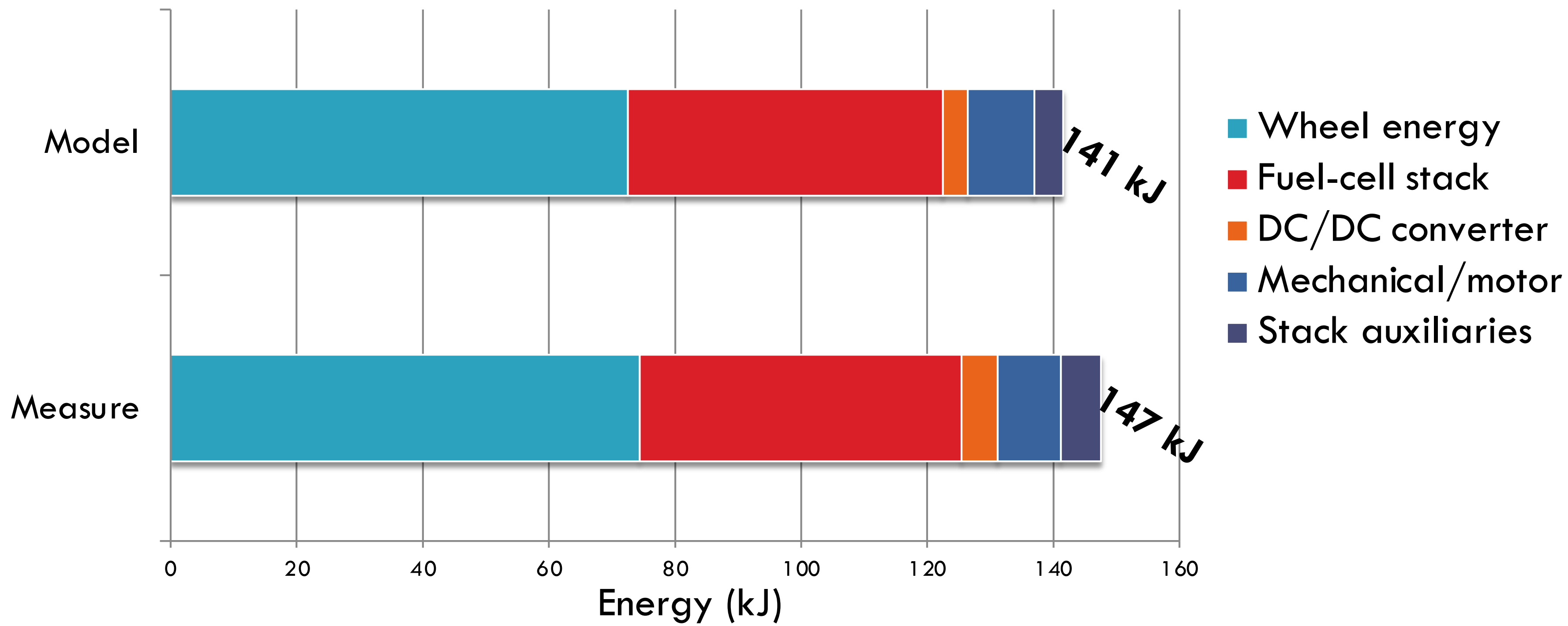
- Optimization result

Parameter	Value
I_{start}	10.8 A
I_{acc}	3.1 A
v_{max}	27.8 km/h
v_{min}	26.2 km/h
r_{gear}	200/14
Average velocity	25.0 km/h
Fuel cell losses	3.04 Wh/lap
Motor losses	0.39 Wh/lap
DC-DC converter losses	0.23 Wh/lap
Mechanical transmission losses	0.11 Wh/lap
Supervision system consumption	0.37 Wh/lap
Mechanical energy	3.7 Wh/lap
Hydrogen consumption	7.96 Wh/lap
Tank-to-wheel efficiency	46.20 %
Performance	4.94 Wh/km
	1855.75 km/L_{SP95}



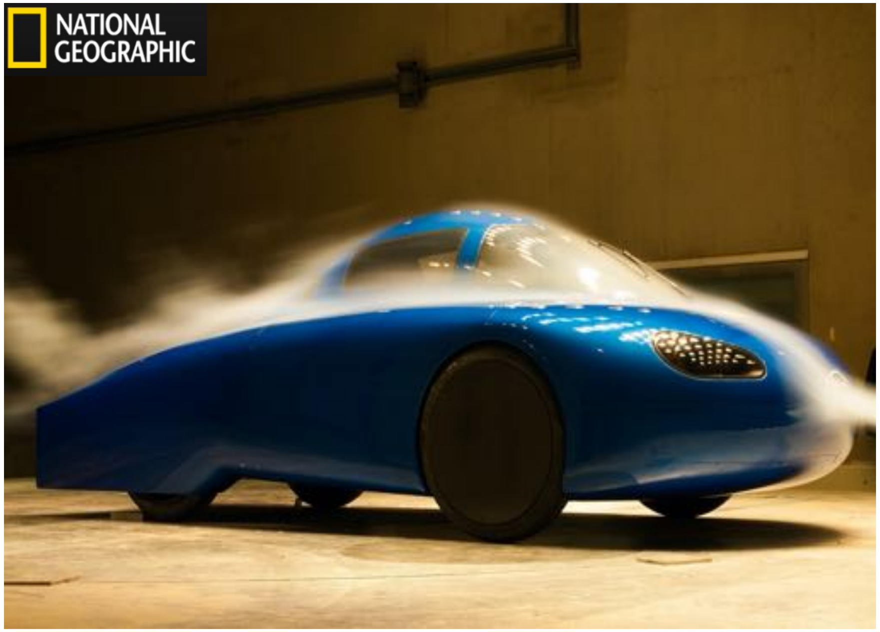
Results and exploitation

- Validation of the proposed approach



Error less than 4%

Thank you for kind attention



Prof. TRICHET Didier

Chair of IREENA Lab
Graduate School of Electrical Engineering
University of Nantes
France

didier.trichet@univ-nantes.fr
www.univ-nantes.fr