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On energy performance of an electrically-driven city-car

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Abstract

Mobility in modern metropolitan cities is plagued by overcrowding producing congestion, low transit speed, fuel consumption, air pollution, parking problems. One of the causes of these phenomena is the growing market-share of vehicles having an excessive size with respect to their more frequent use.

Technological and commercial development of vehicles specifically conceived for urban use, and therefore limited in size, not exuberant in performance, with low fuel consumption and low emissions would be certainly more desirable.

Hybrid and pure electric drive trains are particularly suited to this purpose consuming and polluting very few both on a local and on a global scale.

During last years, ENEA realized a series hybrid prototype, called Urb-E which made available a huge amount of experimental results, based on various control strategies used to optimize ICE utilization.

Basing on those data a modular model of the propulsion system was built and calibrated. Many possible control algorithms, as well as different propulsion schemes, were compared obtaining interest information about the energy fluxes on board and on the possible ways to optimize overall vehicle efficiency.

Keywords: HEV (Hybrid Electric Vehicle), BEV (Battery Electric Vehicle), Energy Consumption, Electric Storage

Introduction

IEA (International Energy Agency) recently distributed a review on the technological maturity of plug-in hybrids (HEV) and pure battery electric vehicles (BEV) [1].

The work makes reference to a now-consolidated scenario, at least at European level, known as ETP (Energy Technology Perspectives) BLUE Map Scenario, which describes the new technologies which have to be introduced in various market sectors to make it possible to reach the CO2 reduction goals: 70% less than 2005 emissions in EU from the transportation sectors within 2050.

The aim will be reached if 50 millions BEV and 50 millions HEV are produced and sold, corresponding to a market share of this vehicles of about 50% in 2050.

This would be possible only with an increase on technological maturity of the main components making the collective costs of the process acceptable for the overall community [2]-[4].

Manufacturers (OEM) production scenarios about HEV and BEV are somehow less optimistic (due to the relevant world-wide economic crisis strongly affecting the automotive sector, and to the correspondent lack in companies liquidity which depress their short and long-term industrial planning capabilities), but still foresee millions of vehicles produced and sold in next decades.

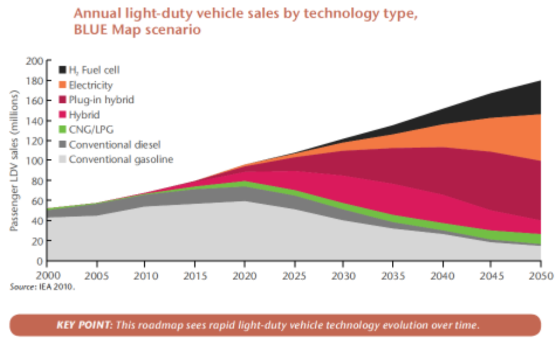

Figure 1 – IEA BLUE MAP Scenario – Technologies Market shares in the automotive sector [1]

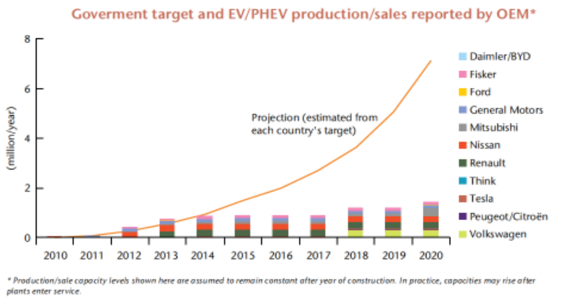

Figure 2 – Majour OEMs production out look [1]

Anyway actual market offer about HEV and BEV is still very limited and too costly to reach a relevant market penetration. It is evident that a deep effort must be taken in product development and standardization and that all the market sub-sectors must be considered.
Our institution (ENEA- Italian National Agency for New Technologies, Energy and Environment), in particular, focused his attention mainly on micro-cars (so-called quadric-cycles in many National normative), a market sector which has been lacking of attention by the OEM during last years, but has a high potentiality in contributing to CO2 emissions, as well as in urban pollutants emissions lowering.
Mobility in modern metropolitan cities is plagued by overcrowding producing congestion, low transit speed, fuel consumption, air pollution, parking problems. One of the causes of these phenomena is the growing market-share of vehicles having an excessive size with respect to their more frequent use. Technological and commercial development of vehicles specifically conceived for urban use, and therefore limited in size, not exuberant in performance, with low fuel consumption and low emissions would be certainly more desirable.
HEV (as well as BEV) are particularly suited to this purpose: properly designed minimal thermal engines can fit for the application, giving an electrical driving option when required, and consuming and polluting very few.
ENEA built a prototype vector, called Urb-E (Urban Easy vehicle) as the leading partner of a team involving various Italian Universities. The vehicle is specifically conceived to be a city car with a series hybrid traction architecture, being a living example of how, by combining appropriate and available technologies, modern components, and careful planning, it is possible to achieve results useful for the user and for the community [5]-[16].

Figure 3 - Urb-E prototype

1 Brief prototype description

A full description of the prototype is reported in previous papers and relations by the same authors [5]. So here only a brief description is given.
The rolling chassis consists of welded steel tubes with an external diameter of 30 mm, thickness 2 mm, for the main structure; 20 mm tubes for stiffening triangles. Overall vehicle dimensions are: 2.70 length and 1.40 m width.
A series-hybrid architecture was chosen, consisting of:

- a motor-generator group (GU, Generator Unit), composed itself by a primary combustion engine (ICE, Internal Combustion Engine) and by an electrical generator (GE) mutually connected through a constant ratio belt drive;
- an energy storage system based on ultra-caps (UC,);
- an electric drive acting on front wheels (TM);
- an electric node permitting mutual energy fluxes;
- three electrical converters;
- a power management system.

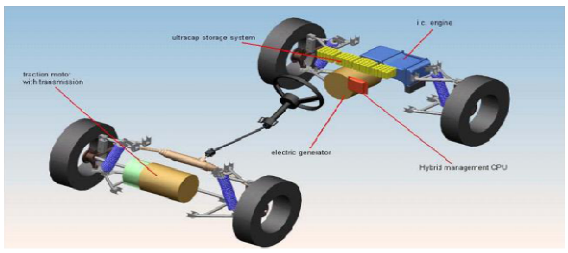

Figure 4 – Traction system layout

As a primary thermal engine, a Piaggio QUASAR 250 cc, which equips Vespa GTV and GTS models as well as Beverly, MP3 and X7, was chosen. It is a modern engine, 4 valves, electronic injection, approved for motorcycles according to Euro 3 standards, whose main technical data are given in the table below.

Internal combustion engine	
Type	Single cylinder 4 stroke
Displacement	244.3 cc
Bore	72 mm
Stroke	60 mm
Cooling	Liquid
Timing	4 valves, single cam
Max power	16.2 kW @ 8250 RPM
Max torque	20.2 Nm @ 6500 RPM
Injection	Electronic
Weight	36 kg
Emissions	EURO 3
Catalytic	3 ways

Tab. 1 – Internal combustion engine

The electric generator is a brushless permanent magnet machine produced by ACM (Varese – Italy) basing on our technical requirements. The main features of the GE are shown in following table.

Electric generator	
Type	Syncr. perm. magnets
Voltage RMS	55 V
Rated power	5 kW
Peak power	8 kW
Rated torque	20 Nm
Rotational speed	5000 RPM
N° poles pairs	3
Magnets	Nd Fe B
Cooling	Liquid
Weight	30 kg

Tab. 2 – Electric generator

The electric generator is driven by the internal combustion engine. To couple the machines, a belt-pulley transmission was chosen, with a constant transmission ratio. The 1:1 ratio was calculated to optimize the efficiency of the motor-generator group.
Also the electric traction motor has been was built on our specifications by ACM, with the same construction technology. The main features of TM are given in the table below. The electric motor is rigidly assembled with a differential gear with final reduction equal to 6.4: 1.

Electric traction motor	
Type	Synchronous with permanent
Voltage RMS	55 V
Rated power	8 kW
Peak power	16 kW along 5 minutes
Rated torque	30 Nm
Max torque	48 Nm
Rotational speed	4600 RPM
N° poles pairs	4
Magnets	Nd Fe B
Cooling	Liquid
Weight	27 kg

Tab. 3 – Electric traction motor

Ultracapacitors were chosen among those sold by Maxwell Technologies: 4 modules at 16 V and 550 F modules were used, connected in series. Each module, even if made itself by 6 elementary capacitors, is rigidly assembled and boxed in an aluminium housing.

Ultracapacitors	
Features of single module	
Producer	Maxwell
Model	BMOD0500 E016
Voltage nominale	16.2 V (6 cells by 2.7 V)
Capacitance	500 F
Spec. energy	3.17 Wh/kg
Spec. power	5.4 kW/kg
Whole system (4 modules in series)	
Voltage nominale	64.8 V
Capacitance	125 F
Energy	73 Wh
Power	124 kW
Size	18.8 litres
Weight	23 kg

Tab. 4 - Ultracapacitors

Each one of three electrical components (alternator, engine, ultracapacitors), is completed by a conversion group consisting of a MOSFET diodes element and a electronic control based on a DSP processor (Digital Signal Processing). The groups are essentially the same, but use different programs to fulfil different tasks.
An High-Level controller was introduced, which is a programmable logical unit Prometheus. It’s a a logical multi-functional component produced by Diamond Systems Corporation.
The communication among components and with the control unit is implemented by a local network that utilizes the 2.0A CAN protocol at a speed of 1Mbit/s.

The management of thermal engine consists of a torque control made by tuning the current supplied by the alternator and a closed loop speed control actuated by the throttle of ICE. Accordingly, its leverage was motorised through a system consisting of a controller, an electronically controlled actuator.

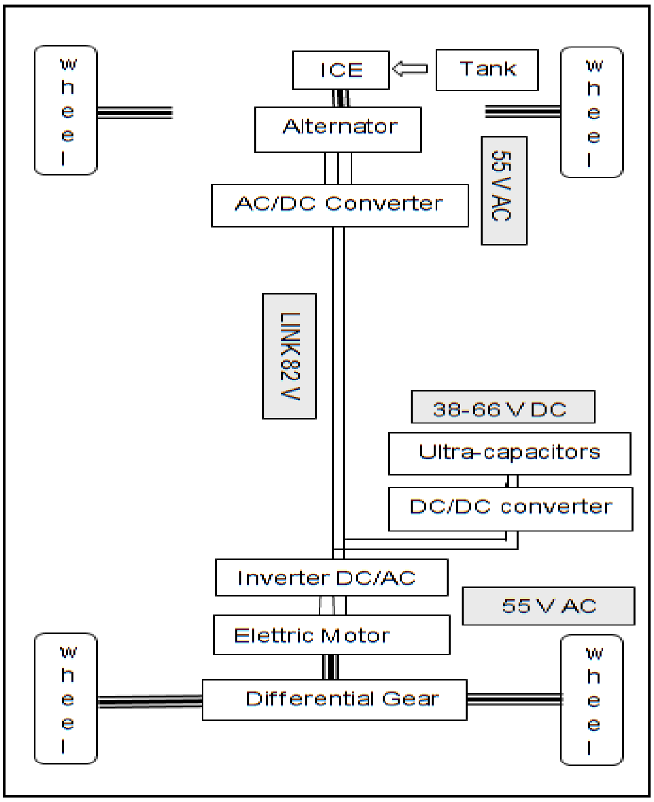

Figure 5 – Main components and energy flows

The management of the hybrid propulsion system is realised by the supervision program installed on the Prometheus processor unit which receives data from all sensors, actuators and devices fitted on the car. The unit has basically the following tasks:

- to manage the generator group, determining, for a given required mission, the power that the GU has to produce;
- to manage the level of state of charge (SOC) of the ultracapacitors, filtering impulsive power requests to have a sufficient energy reserve to cover demand peaks, while maintaining a sufficient capacity to store energy from regenerative braking;
- to identify, for each power request for the GU, its best operative conditions for ICE, basing on its efficiency maps;
- to perform the appropriate filtering of dynamic operations, particularly regarding the power requests to TM and GU;
- to create a virtual dashboard to view main measures, eventually permitting some simple manual actuations;
- to perform safety checks to prevent to exceed electrical and mechanical limit values;
- to perform data acquisition of all measured parameters during the mission.

2 Experimental activity

The utilization of the ENEA dynamometer has been very significant in achieving the goals of stability and performance optimization of the traction system. With this tool it was possible to monitor and then check in real time the evolution of the main electrical parameters, set the desired running conditions.

Here, this experimental activity is only briefly reported because it was detailed in previous papers by the same authors. The attention in this paper will be in fact focused on the utilization of the experimental results to is focused [5]

Figure 6 – Vehicle in test on ENEA rolling test-bench

2.1 GU mapping

A preliminary activity was the obtainment of an efficiency map of the GU: tests were carried out in 45 different points of the engine map. The result of this first set of tests is summarized in the following 4 contour graphs, which are the interpolation of discrete field data collected (denoted by the red dots).

It has so been possible to define for each desired power the corresponding optimal rotational speed of the group (points indicated by green stars). This curve was imposed as optimal reference in terms of torque and rotational speed for control software of the GU. In the graphs:

Measured specific fuel consumption ofGU shows a minimum of 270 g/kWh at 4 kW and 3850 RPM, where output energy in kWh is measured in alternate current out of electric generator.

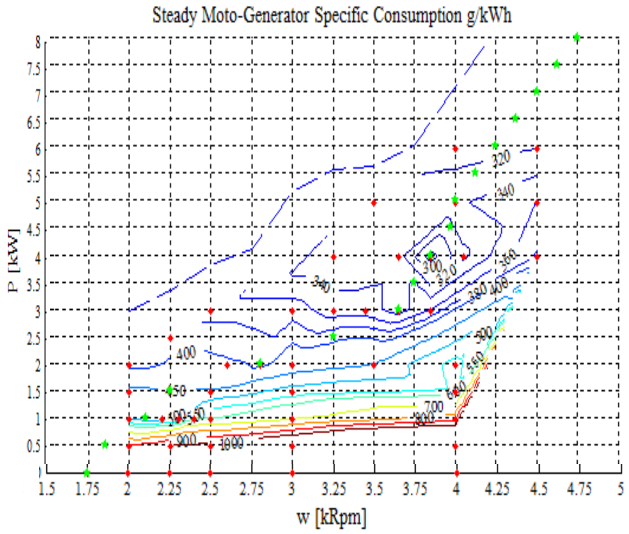

Figure 7 - Specific consumption of the GU

2.2 Tests on urban part of ECE15 cycle

Variable speed tests on the roller test bench were conducted following the urban part of the ECE15 cycle which is characterized by a top speed of 50 km/h. In these first tests GU is never stopped during the mission. GU power therefore "follows" road requirements, properly filtered to limit power gradients for the GU while maintaining a sufficient state of charge for the capacitors. This mode will be hereinafter referred as "load following".

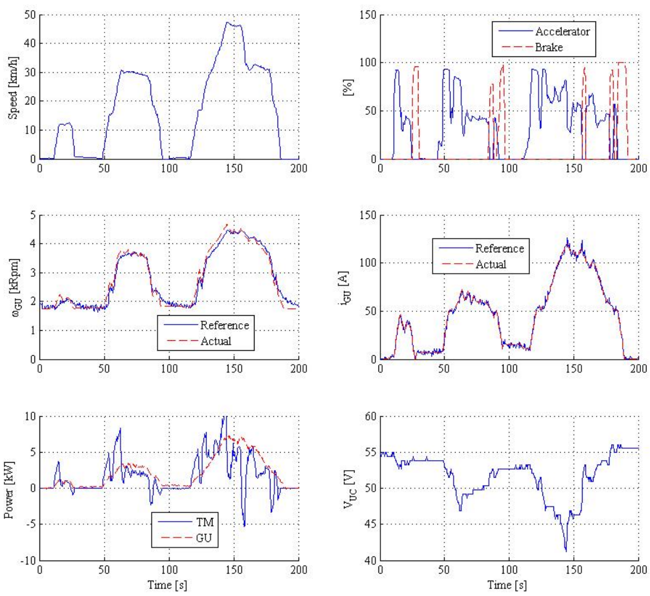

Figure 8 - Urban part of ECE15 with Load following strategy

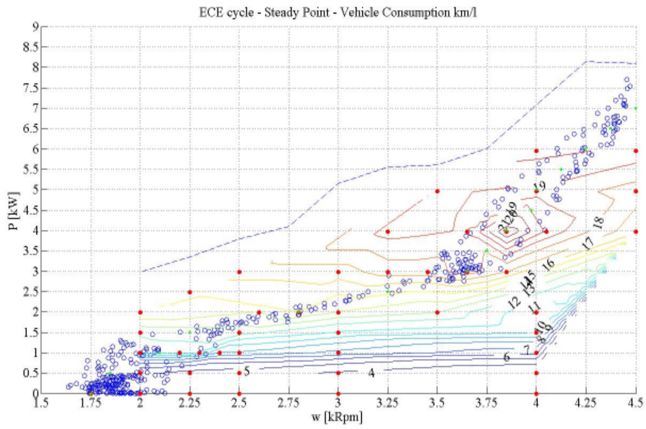

Figure 9 - Urban part of ECE15 with Load following strategy: working points

A second control strategy for the GU was then conceived which compels it to work in the neighbourhood of a power of 4 kW or to remain off. This strategy was called "ON OFF + Load following" since the GU group is either "on" or "off", and when it is "on" is controlled with the same program strategy than Load following.

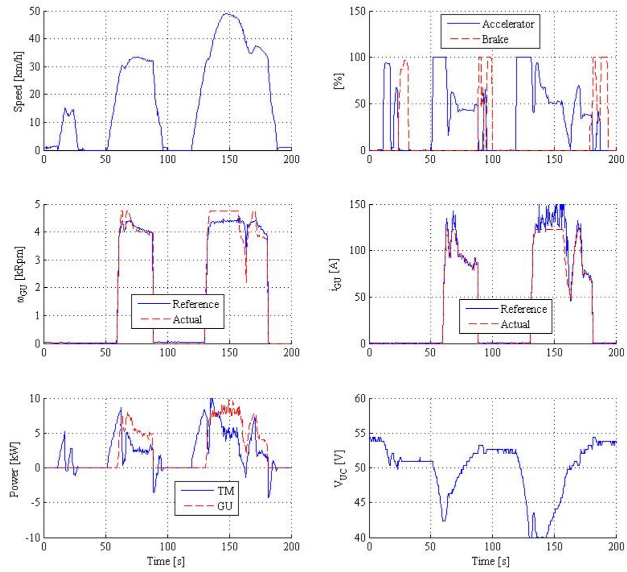

Figure 10 - Urban part of ECE15 cycle with ON OFF + Load following control strategy

It is evident, compared to the previous graphic, the shift of operating points in the lowest fuel consumption zone. The measured range passes from 14.6 km/l with the Load Following strategy to 18.5 km/l with the ON OFF + Load following strategy, with a decrease in consumption of 21%.

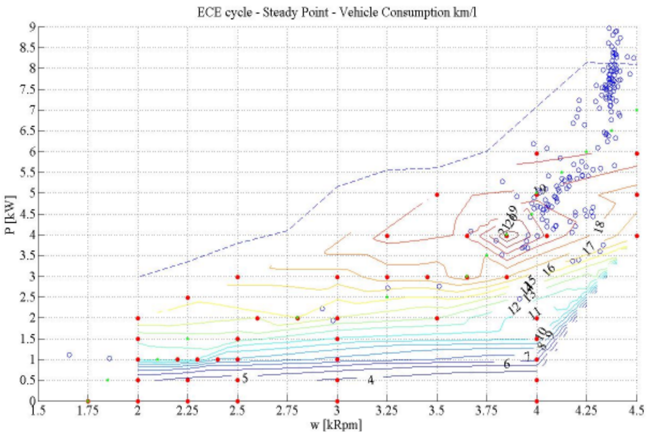

Figure 11 - Urban part of ECE15 cycle with ON OFF + Load following control strategy: working points

The tests were repeated also limiting in slope at 300 W/s the severity of transients for power on and power off. The effect on consumption was indeed light. Additional measurement campaigns are made to assess the effects of these transients on the main vehicle exhaust emissions.
Obtained fuel consumption is not far from the maximum target of about 21 km/l, which would be achieved by turning the heat engine in its best operating point just for the time necessary to produce the electricity required by the mission of the vehicle. This best value, however, does not take into account the constraints imposed by limited energy content of ultracapacitors, which recharge, as evidenced by the results, could require the delivery by the GU group of a power far greater than optimal for maintaining the state of charge sufficiently distant from its minimum limit.
Similar tests were conducted (with similar results, also, as discussed below, in road tests) trying to anchor the ignition and the stop of combustion engine to the achievement of upper and lower limits for the voltage of the UC.
The control strategy “ON OFF + Lf” was tested also driving at constant speed (a test called "Marathon"), providing a greater accuracy and stability of GU operating point.
To confirm data obtained on the dynamometer rolling bench we also carried out a series of road tests, whose results are fully detailed in previous papers, employing the internal streets of ENEA Casaccia Research Center.

3 Modeling activity

As already underlined, the experimental results obtained on the series hybrid prototype were used to calibrate a mathematical model of the vehicle, based on a Simulink platform which was set up with a fully modular approach. This with the aim of evaluating the overall energetic performance of the vehicle and its main parts, as well as comparing the chosen power architecture with various possible different options.
The model used is a lumped parameter one and is fully dynamical in most of its parts.

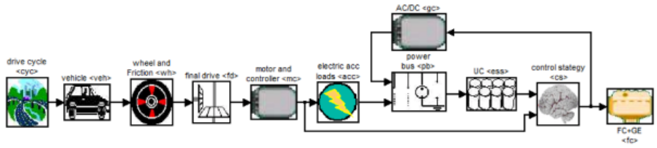

Figure 12 - Skecth of the modular approach of the model

The various propulsion schemes which were compared also included fuel cell simulations, using data coming from a MesDEA 3kW PEM cell.

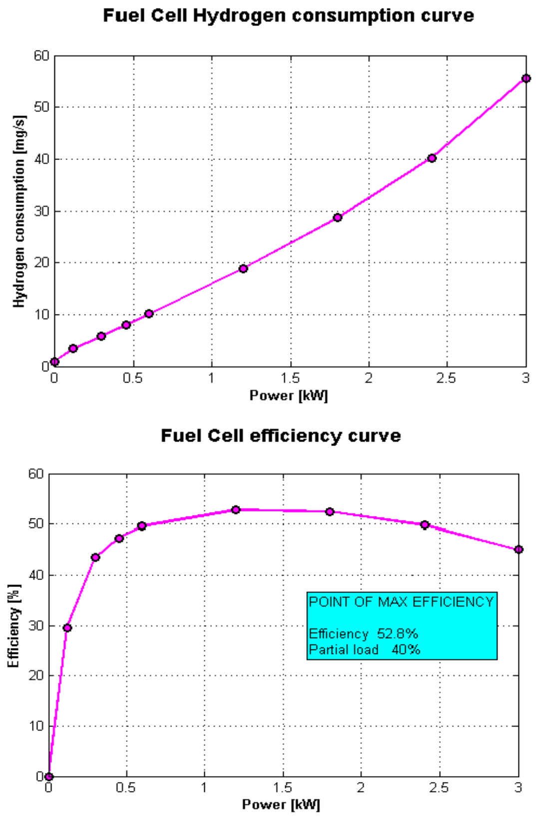

Figure 13 - Characteristic curves of the fuel cell

In the pure electric options, both UC and Bettry driven (BEV) vechicles were simulated. Mixed storage systems with various control approaches are now under simulation and a novel version of the vehicle has been realized equipped with both UC and lead-acid batteries.
Here Lithium batteries (by Kokam and Thundersky) were simulated according which were proposed by our reaserch group and are well consolidated in literature [10].

The experimental data about the batteries were also confirmed by in-house testing of the components.

	Thunder-Sky TS-LFP 60	Kokam SLPB 6046330H
Cells Number	15	15
Type	Li-ion	Li-ion Pol.
Capacity [Ah] – C	60	70
Nominal Voltage [V]	2.5 - 4.25	2.7 - 4.2
Max Discharge I [A]	3 C = 180	5 C = 350
Max Chiarge I[A]	3 C = 180	2 C = 140
Unit Weight [kg]	2.50	1.95
Full Weight [kg]	37.5	29.2

Tab. 4 – Main characteristic data of the battery used

In the following part of the paper the results of the simulations are reported, firstly about the current propulsion schemes, then about some of the possible alternative options.

The first results (Figure 14-17), in particular, show the accuracy of the simulation, when are compared with the experimental outputs.
Max traction power is about 7 kW (on the ECE cycle), while regenerative breaking makes available up to 5 kW mechanical power to be converted by the generator. Mean power values, anyway are much lower, being limited to about 2kW in the various configuration and working cycles (off and on-road).
Comparing red (simulate) and blue (measured) lines, it is possible to evacuate the degree of accuracy obtained by the simulation, witnessing the correct calibration of the model.
In an analogue way all the measured cycles and path performed by the vehicles were simulated and compared with experimental results (data about more than 500 km vehicle running). All the data confirmed the results: those are obviously not showed here for space limitation.

The evaluation of all these power diagrams made it possible to dimension all the other possible propulsion architectures, all basing on an electric traction, but using Batteries, UC, Fuel cells, as well mixed (hybrid) schemes.
Especially in a so-small vehicle the influence of the weight of the power architecture on vehicle overall weight and dynamic behavior is not negligible, so it has to be taken into account by the model.

The second set of results Figures 18-21) is relative to various hybrid configurations obtainable using the Fuel cell (which is dimensioned on mean power requirements) in combination with batteries as well as with UC (of various sizes). A start stop "thermostat" control strategy is used for the FC.

Here only some of the results are reported due to lack of space. Please feel free to contact the authors for a wider report on the modeling activity (which has still not be fully separately published).

The speed and power profile in input and output from the traction motor are similar to the previous ones (being only affected by the overall weight of the vehicle), while the power given by the electric storage varies depending on the state and efficiency of the cell.
In case of a small electric storage (e.g. using UC, Figures 18-19) the ON-OFF storage levels for FC control must be very close to a full charge state. The flexibility of the control strategy is poor in this case: since the path of the vehicle is not assumed to be known, storage state must always be full enough to face a potential high power demand (since FC cannot give more than 3 kW).
Even if these conditions were not happening in the ECE cycle, a so-high mean state of charge of the storage may also lead the impossibility to recover energy during braking phases.

Fuel consumption has been evacuate in this case as "gasoline equivalent" on an energetic basis, on a pure TTW (Tank to wheel) assumption, not considering the Energy requirement for gasoline and hydrogen production distribution and storage.

Further figures are relative to lithium battery storage systems (by Thundersky (Figures 20-21) and by Kokam (Figures 22-23).

Simulation were taken varying many parameters, permitting to choose, for example, the optimal power demand for the FC in its ON state, considering the additional weight to be carried for an over-dimensioned cell (leading to an higher consumption), and the increase in FC efficiency when working at its nominal power (normally 75% of the maximum).

Vehicle mileage was also evaluated, considering the effect of the increased weight, and permitting to highlight the possible negative effect of the demand for an higher mileage on vehicle efficiency and consumption. Mileage was calculated to be (on an ECE cycle basis) 34 km with Thundersky 60 Ah storage, and 38 km for Kokam da 70 Ah.

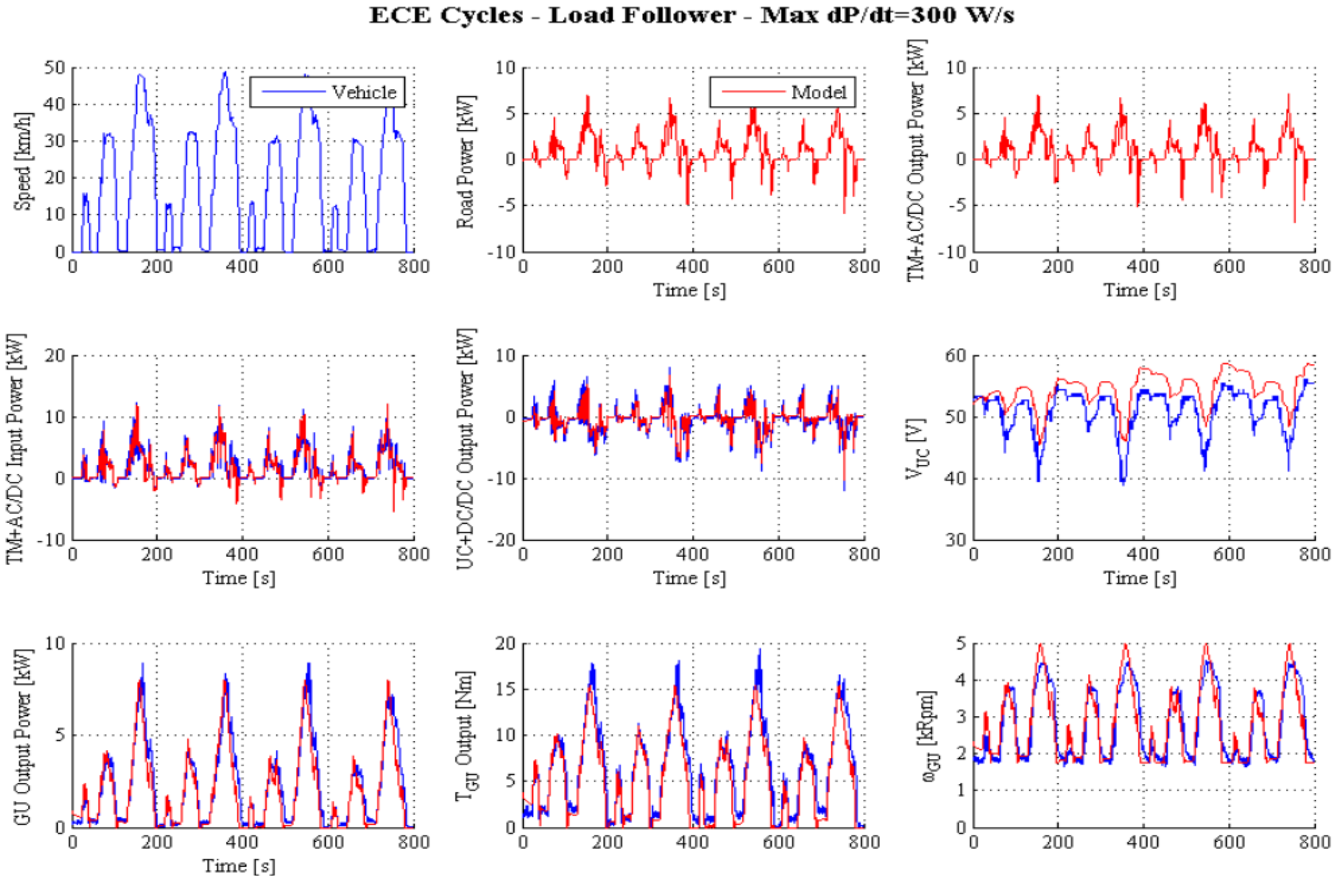

Figure 14 - Series hybrid with ICE: Load folower control strategy. Time-based results

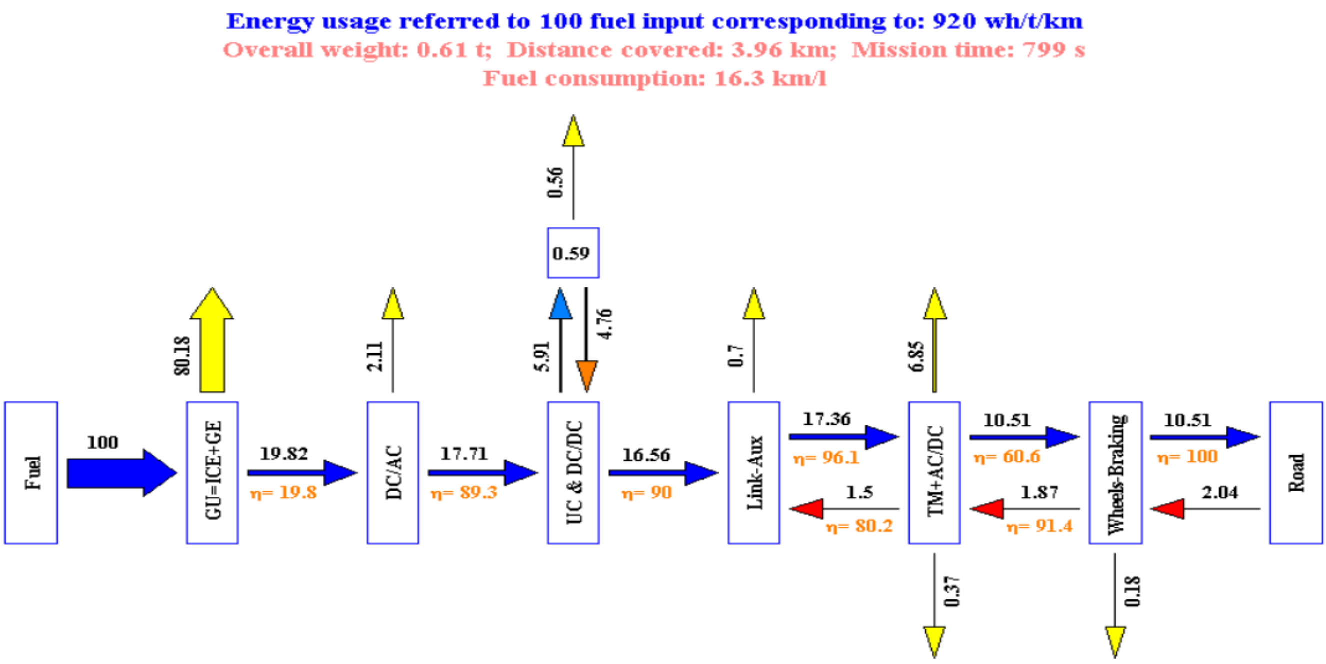

Figure 15 - Series hybrid with ICE: Load follower control strategy. Energetic fluxes

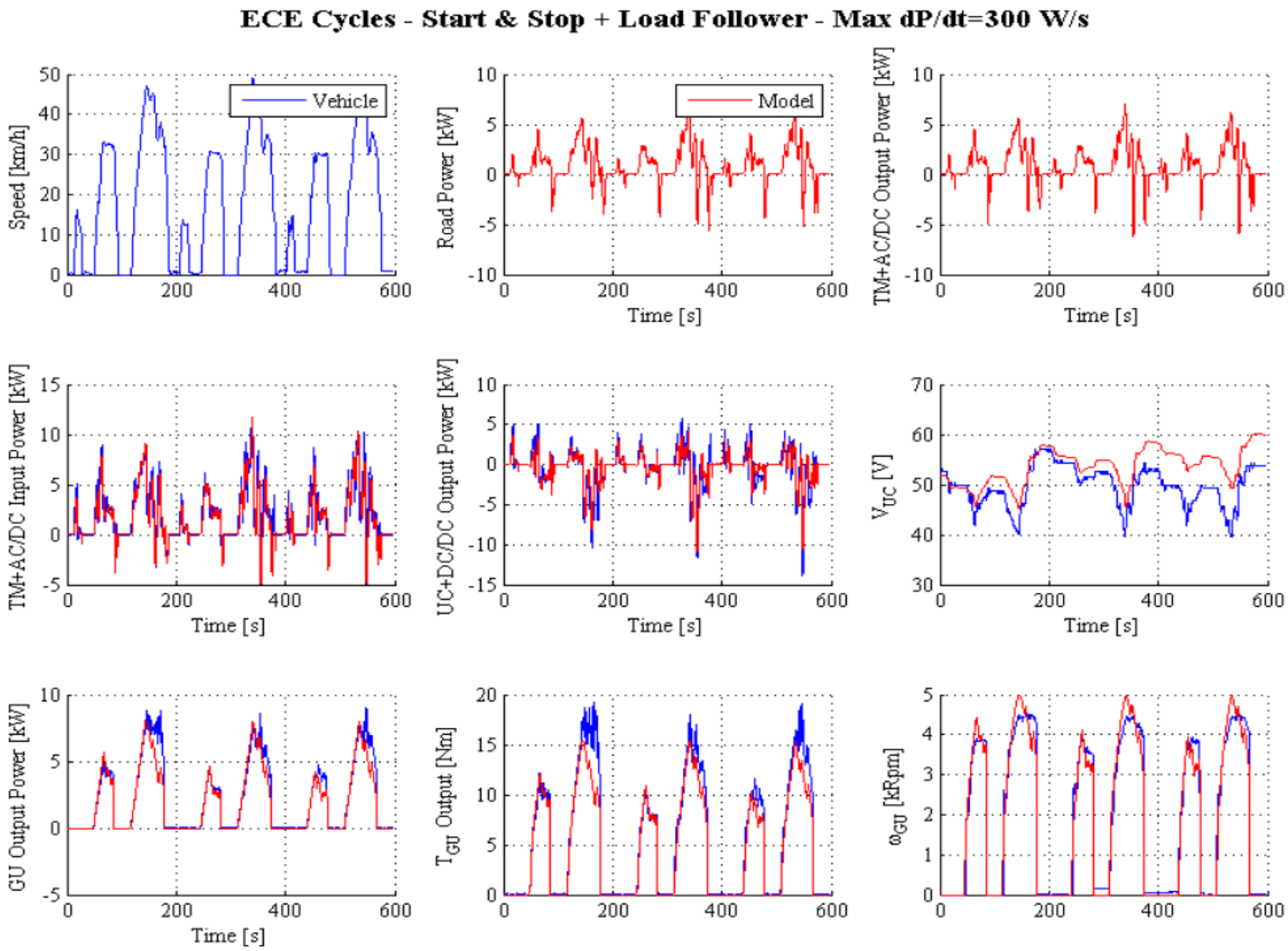

Figure 16 - Series hybrid with ICE: Start and Stop control strategy. Time-based results

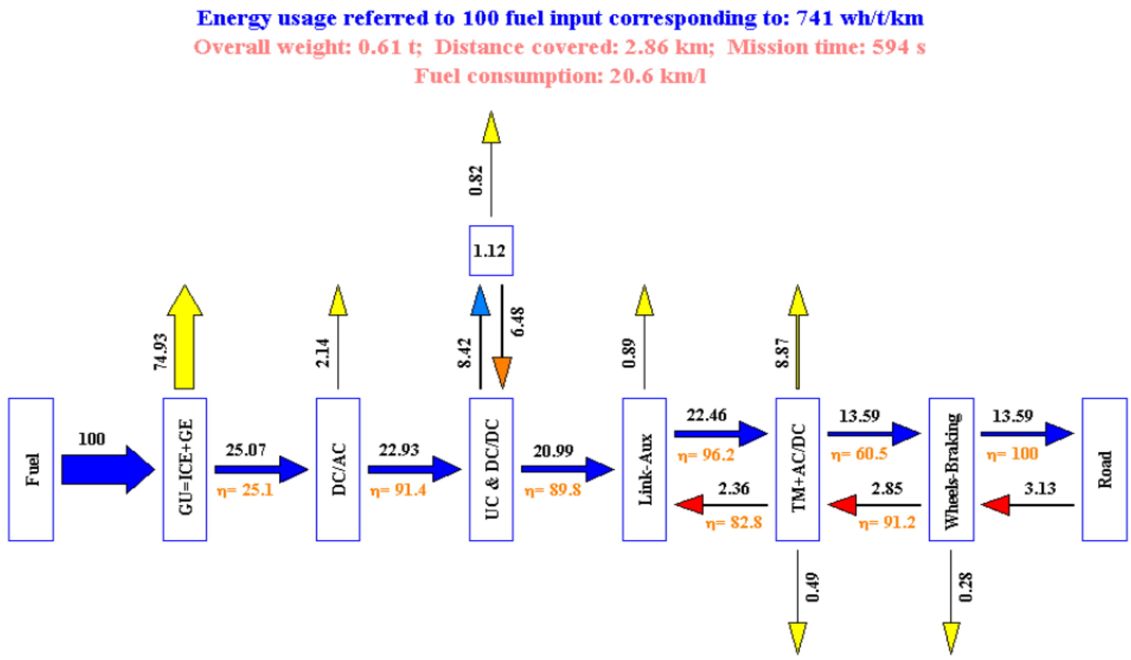

Figure 17 - Series hybrid with ICE: Start and Stop control strategy. Energetic fluxes

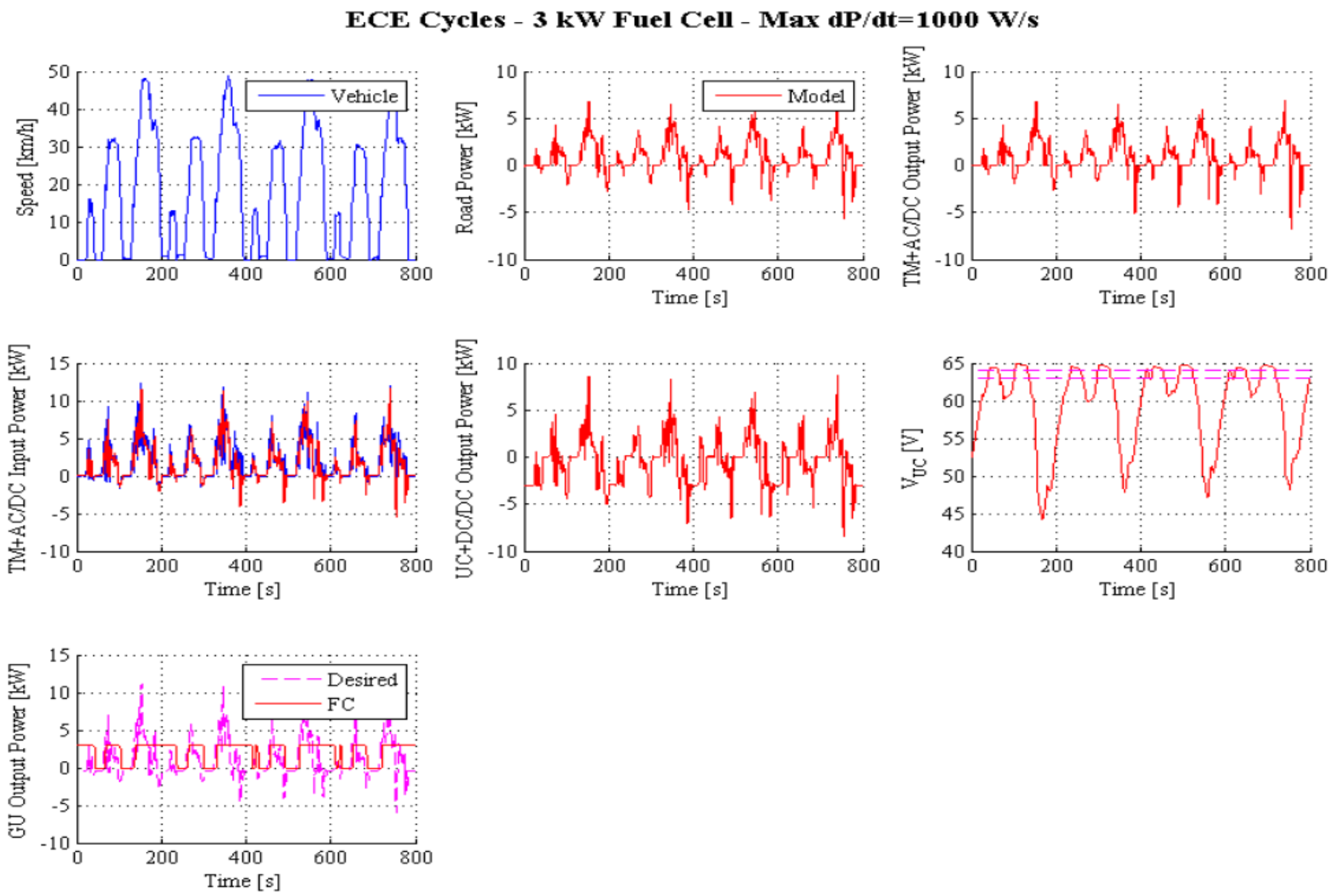

Figure 18 - Series hybrid with MesDea FC and UC: Start and Stop control strategy. Time-based results

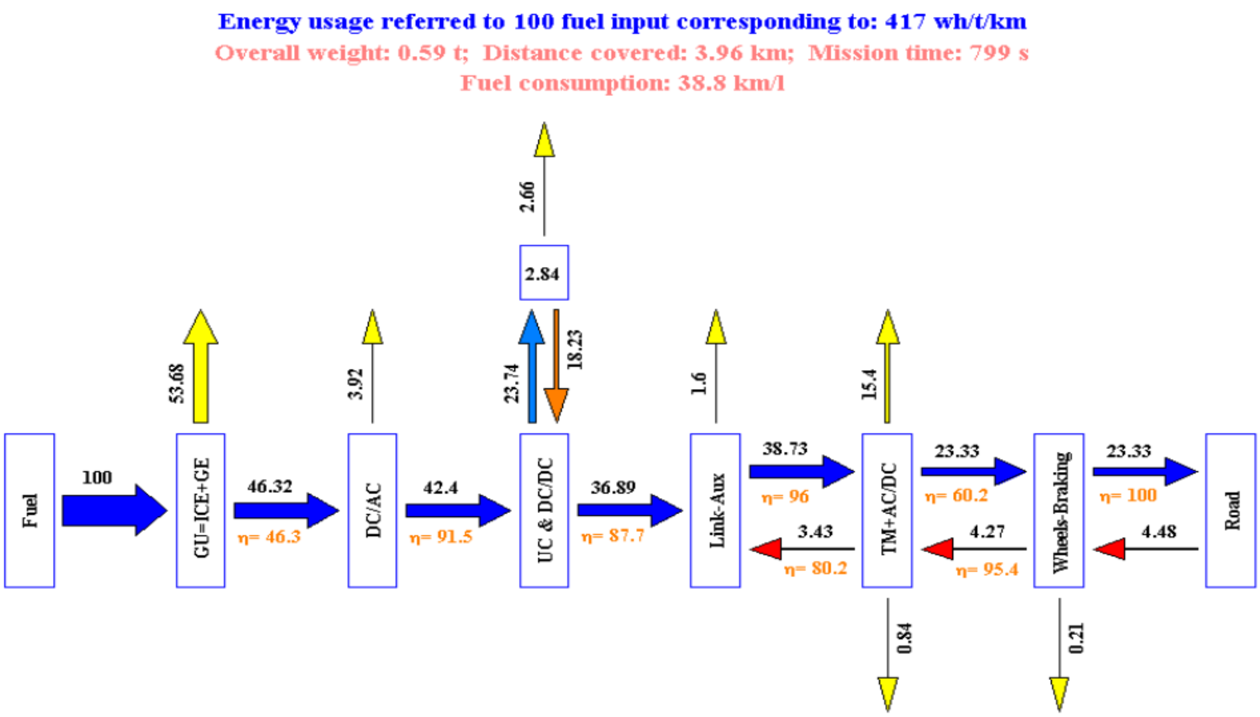

Figure 19 - Series hybrid with MesDea FC and UC: Start and Stop control strategy. Energetic fluxes

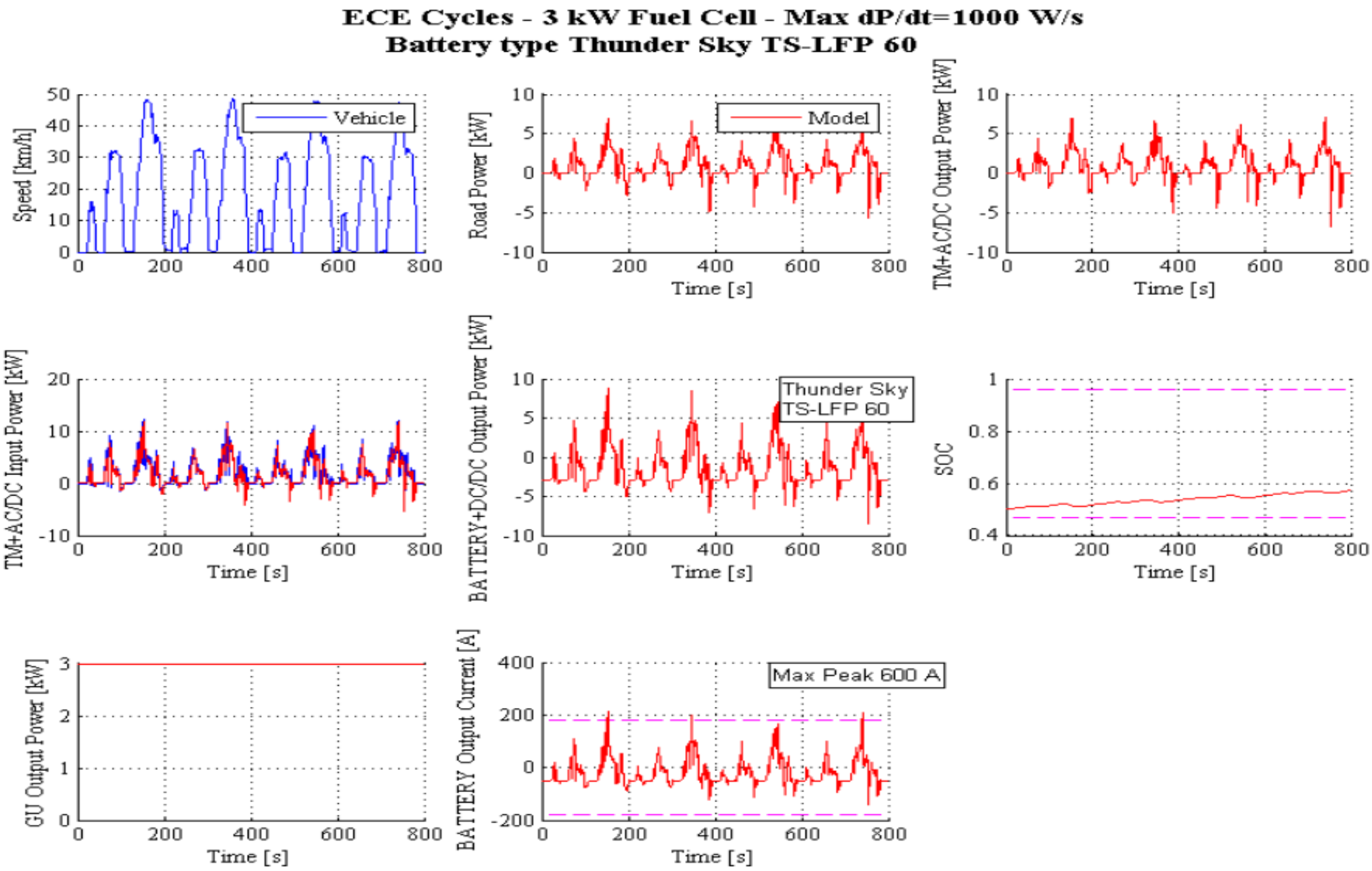

Figure 20 - Series hybrid with MesDea FC and ThunderSky Batteries: Start and Stop control strategy. Time-based results

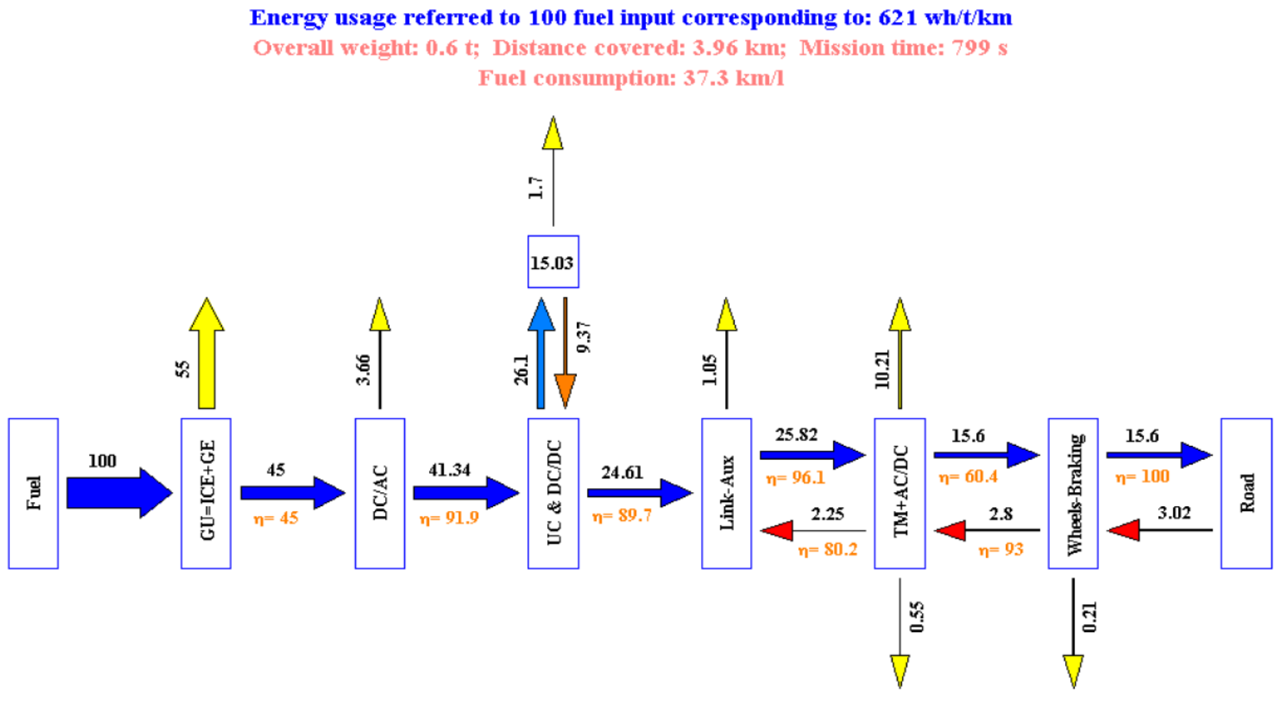

Figure 21 - Series hybrid with MesDea FC and ThunderSky Batteries: Start and Stop control strategy. Energy Fluxes

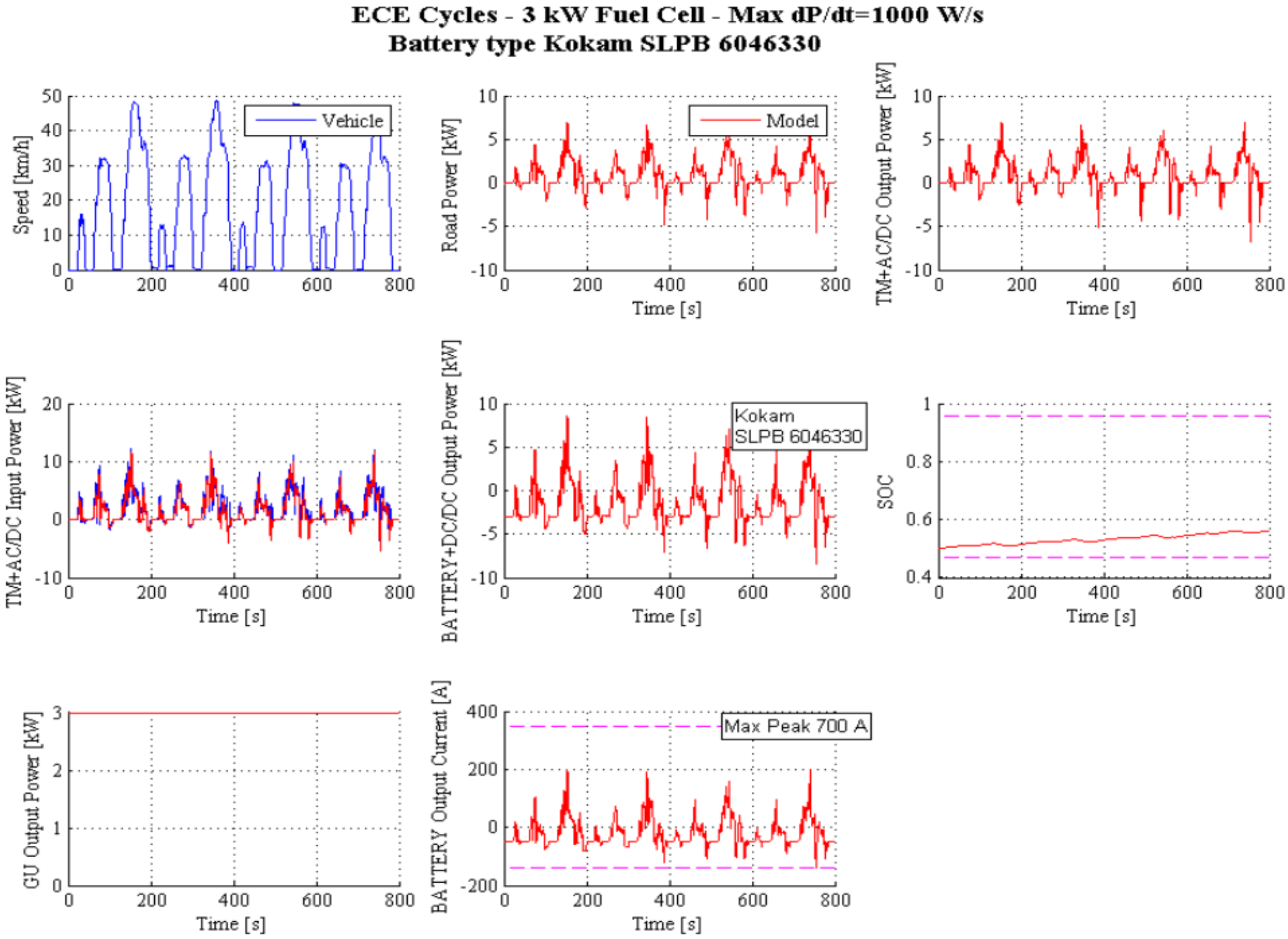

Figure 22 - Series hybrid with MesDea FC and Kokam Batteries: Start and Stop control strategy. Time-based results

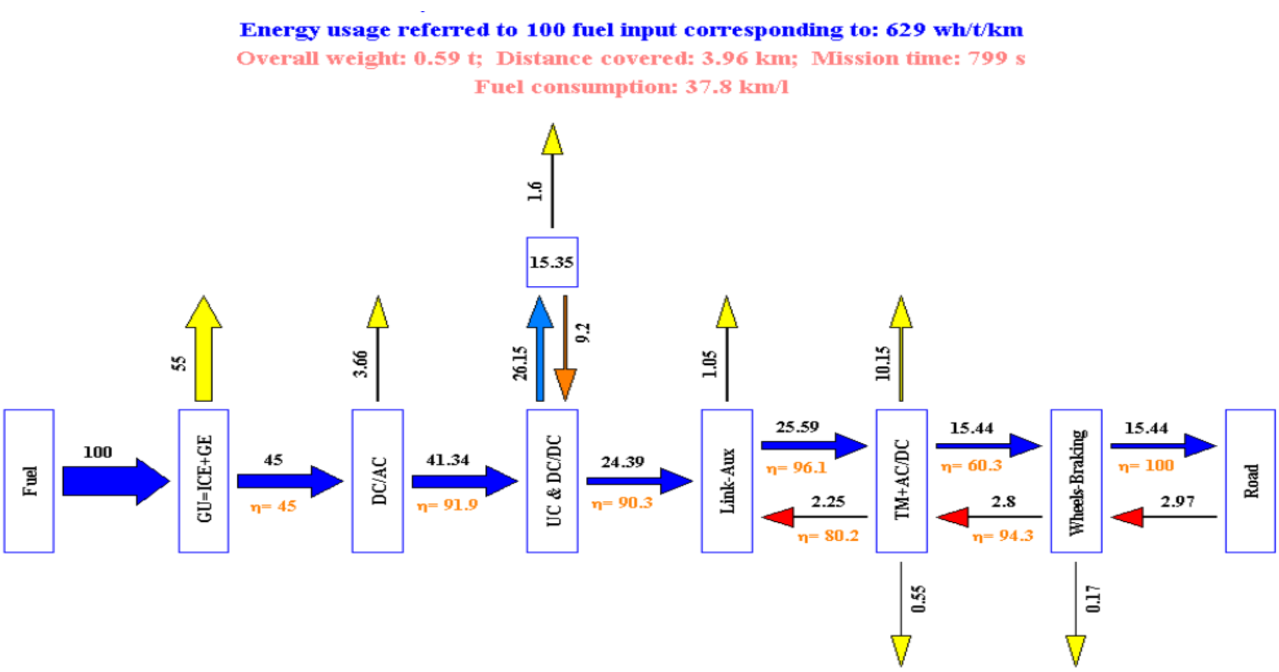

Figure 23 - Series hybrid with MesDea FC and Kokam Batteries: Start and Stop control strategy. Energy fluxes

Conclusions

In this paper some of the result are reported of a multi-annual activity performer by ENEA on a series hybrid prototype for urban transportation purposes (Urb-E).

This paper, in particular, is mainly focusing on the modeling activity which was performer about the vehicle. In fact, taking the lead from the experimental campaign on the prototype, the authors derived and calibrated a mathematical model of Urb-E which was firstly used to obtain a deeper insight about the on-board energy fluxes.

In a subsequent phase the model was used to compare the series hybrid ICE propulsion system equipping Urb-E with the other possible options, also including FC use.

Result shown permit to highlight the Energy losses of the various components in their real usage (which may be very un steady and far from their nominal points.

Time-based results also give interesting information about the depth of discharge of the electric storage systems, and the power demand they have to fulfill on its frequency content (which is strongly affecting storage systems lifetime).

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