Journal of Power Sources 186 (2009) 464–477

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Energy analysis of electric vehicles using batteries or fuel cells through well-to-wheel driving cycle simulations

Stefano Campanari *, Giampaolo Manzolini, Fernando Garcia de la Iglesia

Politecnico di Milano, Department of Energy, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

ARTICLE INFO

Article history:
Received 1 August 2008
Received in revised form
24 September 2008
Accepted 28 September 2008
Available online 17 October 2008

Keywords:
Well-to-wheel analysis
Battery electric vehicle
Fuel cell vehicle
Hydrogen
CO_2 emissions

ABSTRACT

This work presents a study of the energy and environmental balances for electric vehicles using batteries or fuel cells, through the methodology of the well to wheel (WTW) analysis, applied to ECE-EUDC driving cycle simulations.

Well to wheel balances are carried out considering different scenarios for the primary energy supply. The fuel cell electric vehicles (FCEV) are based on the polymer electrolyte membrane (PEM) technology, and it is discussed the possibility to feed the fuel cell with (i) hydrogen directly stored onboard and generated separately by water hydrolysis (using renewable energy sources) or by conversion processes using coal or natural gas as primary energy source (through gasification or reforming), (ii) hydrogen generated onboard with a fuel processor fed by natural gas, ethanol, methanol or gasoline. The battery electric vehicles (BEV) are based on Li-ion batteries charged with electricity generated by central power stations, either based on renewable energy, coal, natural gas or reflecting the average EU power generation feedstock. A further alternative is considered: the integration of a small battery to FCEV, exploiting a hybrid solution that allows recovering energy during decelerations and substantially improves the system energy efficiency.

After a preliminary WTW analysis carried out under nominal operating conditions, the work discusses the simulation of the vehicles energy consumption when following standardized ECE-EUDC driving cycle. The analysis is carried out considering different hypothesis about the vehicle driving range, the maximum speed requirements and the possibility to sustain more aggressive driving cycles. The analysis shows interesting conclusions, with best results achieved by BEVs only for very limited driving range requirements, while the fuel cell solutions yield best performances for more extended driving ranges where the battery weight becomes too high. Results are finally compared to those of conventional internal combustion engine vehicles, showing the potential advantages of the different solutions considered in the paper and indicating the possibility to reach the target of zero-emission vehicles (ZEV).

1. Introduction

The environmental impact of energy production, conversion and final use is more and more influencing our life, and the consensus about the necessity to limit carbon dioxide emissions is widely increasing. Moreover, energy is becoming an increasingly expensive commodity, and even in absence of climate change issues, all the energy intensive processes need to explore new technologies able to reduce their consumptions. One of the sectors featuring the most energy-burning processes is transportation, typically covering 30–35% [1] of the primary energy needs of most industrialized countries, with a large majority of consumption related to road transportation: as a matter of fact the average power consumption of transportation is typically comparable to the maximum electricity power demand of a national power grid.[1]

For this reason, road transportation of passengers through vehicles is one of the sectors where R&D activities are more important, generally aiming to reduce the pollutant emissions and the energy consumptions of cars. It is well known that the current widespread technology is based on reciprocating internal combustion engines (ICE), directly driving the vehicle wheels through a gearbox, but

Abbreviations: AC, alternating current; BEV, battery electric vehicle; CGH_2, compressed gaseous hydrogen; DC, direct current; FCEV, fuel cell powered electric vehicle; ICE, internal combustion engine; HEV, hybrid vehicles; LH_2, liquid hydrogen; P, power; PEM, polymer electrolyte membrane fuel cell; TTW, tank-to-wheel; W, weight; WTW, well-to-wheel; WTT, well-to-tank.

* Corresponding author. Tel.: +39 02 2399 3862; fax: +39 02 2399 3863.
E-mail address: stefano.campanari@polimi.it (S. Campanari).

[1] In Italy, there is an average annual power consumption related to transportation of about 55 GW (or 480.000 GWh year^{-1}), approximately equal to the maximum electricity power demand on the national grid.

0378-7753/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2008.09.115

the majority of car manufactures are developing a number of new solutions which make use of electric drives experimented through prototypes intended for medium or long term applications and in some cases already on the market. The proposed solutions typically cover three general categories:

- pure battery electric vehicles (BEV), where a battery stores energy previously taken from the electric grid, and the battery powers an electric drivetrain, which includes an electric motor driving the car wheels;
- fuel cell powered electric vehicles (FCEV), where a fuel cell generates onboard the electricity needed to power an electric drive; the fuel cell is fed with hydrogen, either coming from a tank (filled with hydrogen produced elsewhere), or produced onboard through a dedicated fuel processor, using gasoline, bio-ethanol or other liquid fuels;
- hybrid electric vehicles (HEV), integrating in several possible ways the use of ICE, batteries and/or fuel cells, which together generate the electricity required to power an electric drive.[2]

This paper explores the energy saving potentials of two of these technologies, BEV and FCEV, aiming to assess the advantages given by their possible future introduction on the market, where they could integrate or substitute the current dominating ICE technology.

After a preliminary survey of available battery and fuel cell technologies [2], it is proposed a comparison of two technologies based respectively on the use of state-of-the-art Li-ion batteries and Polymer Membrane Electrolyte fuel cells (PEM).

Both BEV and FCEV are often regarded as the only long term complete solution to the problem of pollution in urban areas, as well as to the problem of CO_2 emissions, thanks to the use of clean energy vectors like electricity and hydrogen: in principle, the electricity used by BEVs or the hydrogen used by FCEVs (at least in the option where it is not produced onboard) could be generated by clean and CO_2-free processes, using renewable sources or nuclear energy or fossil energy with CO_2 capture and storage techniques.

Several examples of vehicles corresponding to the three categories have been demonstrated or put into the market in recent years. Among many available examples, we may recall here:

- BEV intended for urban mobility, like the Think project recently endorsed by GE, featuring the use of Li-ion or sodium batteries in a 250 kg pack, powering a 30 kW drivetrain to a top speed of 100 km h^{-1} and 200 km driving range [3];
- BEV sport vehicles intended for high performances, like the Tesla roadster, a two seat car featuring a 185 kW electric drivetrain powered by 150 Ah Li-ion battery, with a top speed of 200 km h^{-1} and a driving range of about 300 km, with regular production scheduled for starting in late 2008 [4];
- FCEV running with hydrogen stored onboard, like the Class B Mercedes Benz prototypes, which after several previous versions (starting from the NECAR projects in the late 90 s with Ballard PEM fuel cells) have reached a 400 km driving range with gaseous hydrogen stored at 700 bar and a 100 kW PEM drivetrain, and expect production in 2010 [5]; or the Honda FCX, already marketed in small fleets in California, featuring 300 km driving range with a 150 litres compressed hydrogen tank, top speed of 150 km h^{-1} and a 78 kW fuel cell drivetrain [6]; or the recent FCHV-adv of Toyota which can travel up to 830 km on a single hydrogen fuelling thanks also to an optimized use of onboard batteries and regenerative braking [7].
- FCEV systems running with liquid fuels like gasoline, ethanol, methanol or natural gas through an onboard fuel processor, like the Star™ project, developed by Nuvera fuel cells with Renault and other automakers, featuring up to 200 kWth (LHV) and 80% energy efficiency [8].
- HEV with conventional gasoline ICE, like the well known Toyota models which are established on the market since several years (the Prius, and Lexus high performance models) [9]; or recent projects like the GM Chevrolet Volt, where the driving range in all-electric mode is extended up to 60 km through a 16 kW h^{-1} Li-ion battery pack and a 120 kW electric drivetrain [10].

The approach followed by the work is twofold.

(1) Initially, for both technologies it is assessed a number of energy pathways where primary energy sources are converted into electricity (for the BEV) or hydrogen (for the FCEV), calculating their efficiency in terms of well-to-tank (WTT), tank-to-wheel (TTW) and ultimately well-to-wheel (WTW) energy balances. The analysis yields the primary energy consumption for each kWh of energy given at the vehicle wheels.

The pathway study compares different possible feedstocks, choosing the most plausible possibilities and analyzing the associated efficiencies. Feedstocks considered are, for BEV: coal, natural gas, renewable energy and the average mix of the Italian electric park. Regarding hydrogen for FCEV, coal, natural gas and renewables are taken into account. Finally, for FCEV, other considered on-board fuels are gasoline, natural gas, methanol and ethanol (biofuel).

This approach is often referenced in literature [11,12] and offers an immediate comparison among different solutions, although results are affected by numerous assumptions regarding the energy conversion chain that have to be evaluated carefully. However, such analysis gives an idea of the energy performances only at "nominal" operating conditions of the drivetrain, i.e. does not take into account the effects of a real use, featuring variable loads and the necessity to sustain a rather long (up to several hundreds km) driving range.

(2) The second approach used in this work considers the necessity to sustain a realistic driving cycle and range. In this case, the vehicle and drivetrain specifications change, heavily influencing both the vehicle weight (for instance, the weight of the batteries required by a BEV varies, and the power and weight of the fuel cell system also varies) and the energetic performances of the well-to-tank comparison. These effects are taken into account by simulating the vehicle power and energy demand under standardized driving cycles, for a variable driving range, with homogeneous specifications for the vehicle performances.

Within these hypothesis, it is possible to recalculate the WTT balances and evidence realistic efficiency scenarios for each technological solution. The analysis is based on the simulation of ECE-EUDC standardized driving cycles, which constitutes a widely used reference and are normally used to qualify vehicle consumptions and emissions in the European Union.

Moreover, aiming to reproduce the power features of current average market cars, it is also assumed that the power capacity of all vehicles must be able to sustain a standard "high performance" driving cycle, for which we have assumed the US06 cycle, normally used to test vehicles under aggressive driving conditions.

The simulation of driving cycles points out that one of the advantages, which can be achieved by adding a significant bat-

[2] Further category distinctions are possible according to the possibility of recharging batteries also by a grid connection, beside using the onboard ICE or fuel cell generator, with the so-called "plug-in" hybrid solutions.

tery electricity storage onboard a vehicle, is the possibility to recover energy during vehicle deceleration, and to give it back during acceleration (except for the losses related to the charge/discharge cycle). For this reason, in the FCEV case it is also discussed the possibility to add a significant battery storage to the vehicle powertrain.

The conclusions of the work offer an interesting and original insight on the comparison between the BEV and FCEV technologies, through a realistic simulation of primary energy consumptions and CO_2 emissions under reference driving cycles.

The comparison shows equilibrium as well as advantage or disadvantage areas depending on the vehicle driving range, and indicates the possibility to reach CO_2 emissions well below those of current vehicles and ultimately to fit the perspective of clean or zero-emission vehicles (ZEV).

2. Well-to-wheel analysis on different energy pathways

The well-to-wheel (WTW) analysis evaluates the total primary energy consumption yielded by the vehicle for each kWh of energy given at the vehicle wheels, comprising all the steps covered by the well-to-tank (WTT) conversion path and subsequently by the tank-to-wheel (TTW) onboard energy conversion. The analysis depends on the considered energy pathway, and results are influenced by the numerous assumptions made to evaluate the efficiency of each passage in the energy conversion chain. Aiming to establish a sound and coherent set of assumptions, we have carried out a detailed preliminary analysis, integrating recent results of simulation work performed by the group of energy conversion systems at Politecnico di Milano and reported in literature.

Below we briefly discuss the definition of all the requested assumptions, regarding:

- Electricity generation to feed the BEV.
- Hydrogen generation to feed the FCEV.
- Battery technology onboard the BEV.
- Fuel cell technology onboard the FCEV.
- Electric drivetrain required onboard both by BEV and FCEV.

2.1. Electricity generation

A detailed WTW analysis requires the definition of production and transport efficiency for the electricity required in BEV.

Regarding electricity production, two different scenarios have been considered: the first where electricity is produced by single primary sources (with three different possible types), the second where electricity is produced from a mixture of feedstocks and technologies representative of an average national energy balance.

In the first option, three possible primary sources are considered:

(i) Renewable energy (as sun, wind or hydraulic energy), resulting in zero consumptions of primary fuels.[3]

(ii) Natural gas. In this case, the state-of-the-art power plant for electricity production is a combined cycle (NGCC), with net electric efficiency at the power station approaching 58–60% under nominal ISO conditions. The average yearly efficiency, considering ambient condition influences and real plant operation, is assumed at 52.5% according to recent EU Directives on the calculation of energy savings [13]. In addition to the power station efficiency, 90% efficiency for NG extraction, compression and transport (ext./tra.) to power plant sites is considered [11,12].

(iii) Coal. In this case, the state-of-the-art power plant for electricity production is a supercritical steam cycle (USC). Referring to EU directives, as for the previous point, the average annual efficiency for this kind of plant is 44.2% [13]. In addition, the efficiency for coal extraction and transportation is equal to 98% [11,12].

In the second option, for simplicity we have made reference to the real situation of the Italian electricity balance, where in 2006 the average electricity production efficiency is 42.7%. The average efficiency for fuel extraction and transport is assumed equal to 95%[14].

Finally, electricity transport losses do not depend on the production technology; making reference to the latest European Directive on cogeneration for low voltage users, total losses can be calculated through an 86% average grid efficiency [13].

2.2. Hydrogen generation, transport and storage

This section can be divided into two main parts describing the technologies for (i) production and (ii) transport.

As far as the first point is concerned, hydrogen can be produced using an external energy source by means of several well-known and industrialized processes, the main of which are divided here according to three primary energy sources:

- *Renewable energy*: Hydrogen is produced through water electrolysis where the electricity required is generated through renewable energy, that is considered free. Commercial electrolyzers, based on alkaline electrolytes, have a wide range of performances (usually between 60% and 90%) depending on size and working condition. A conservative average efficiency of 72% is assumed in this work.
- *Natural gas*: Steam reforming of natural gas is the most common process to satisfy current total annual worldwide hydrogen consumption, generating about 50% of the overall 600 billion Nm^3 consumed yearly [15]. If a good thermal integration is carried out, production efficiencies can achieve 85%; in this work it is assumed a conservative efficiency of 80%. The efficiency related to NG extraction and transport to the reforming plant is assumed equal to 90% as for electricity production.
- *Coal*: Hydrogen can be produced from coal through gasification leading to a wide range of efficiencies depending on gasification technology adopted (i.e. dry feed gasifiers vs. syngas cooling gasifier arrangements). We will refer to an efficiency of 60% as reported in specialized literature [16], keeping the 98% efficiency for coal extraction and transportation already assumed for electricity generation.

In all cases the gaseous hydrogen generation efficiency includes pressurization at 60 bar, which is performed either directly within the generation process (for instance by the PSA purifier of the coal gasification plant, or by a high pressure electrolyzer) or by a subsequent compression.

The issue of transport is by far less consolidated, because of the absence of any widespread structure for hydrogen distribution, except for limited purposes related to the chemical industry. We make here reference to the outcome of a recent study [17,18].

After production, hydrogen can be transported as a liquid or as a pressurized gas.

[3] The situation is different for biomass, whose production, transport and use brings about a significant consumption of primary fuels, as considered for the cases related to hydrogen generation.

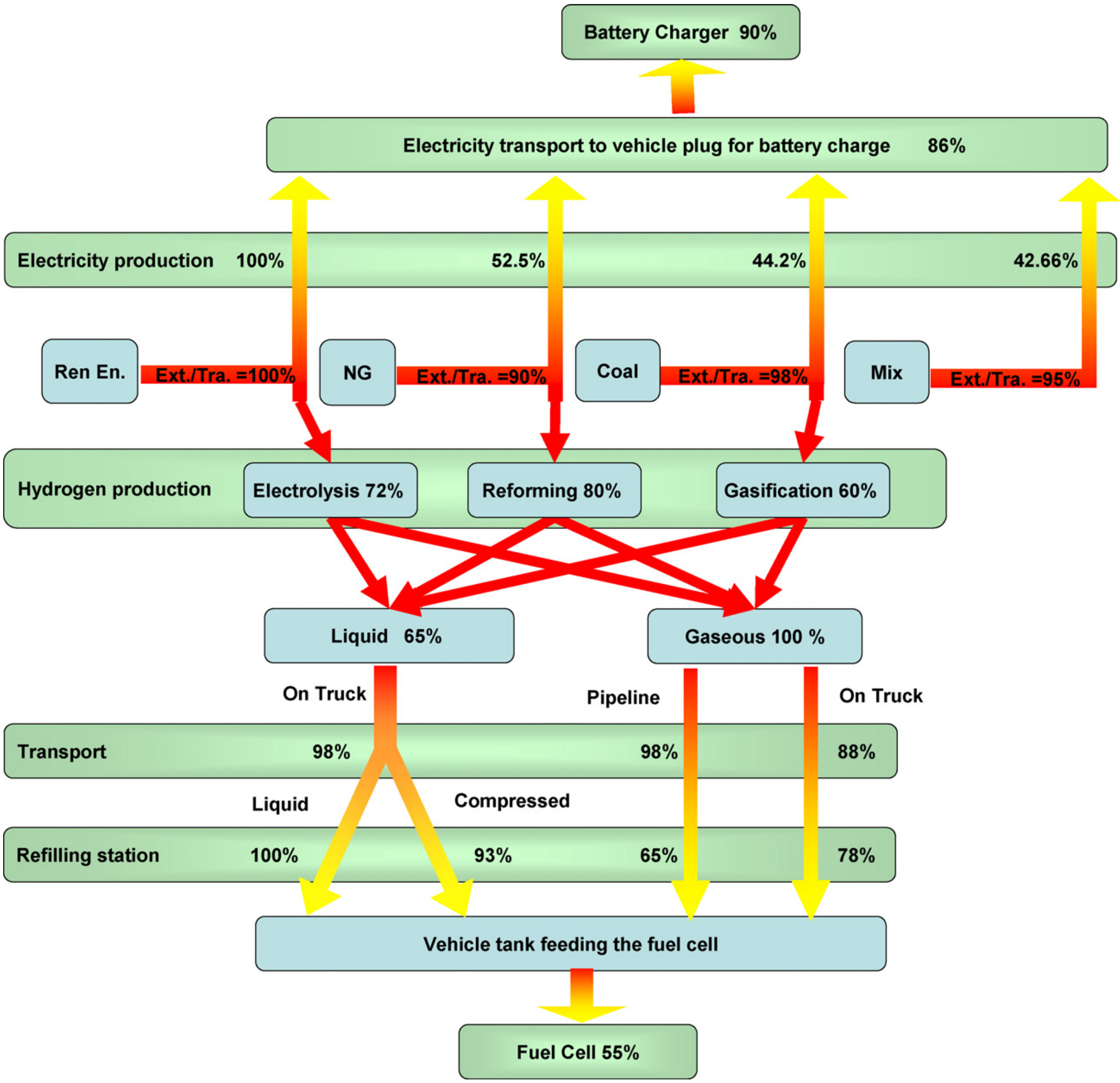

Fig. 1. Conversion chain from primary sources to the vehicle (well-to-tank pathways) and related efficiencies. Gaseous hydrogen is generated and compressed at 60 bar (see text). Ext./tra. stands for extraction and transportation.

Efficiency of liquefaction process is presently limited to about 65%, but it allows to increase the energy density (kWh m^{-3}) of hydrogen leading to lower distribution losses during transport to the final users (efficiency of 98%). At the refilling station, liquid hydrogen can be supplied “as it is” with practically no losses (in this case the vehicle must have a cryogenic tank), or pumped and re-boiled to a high pressure gas for storage into the vehicle with a 93% efficiency.

Otherwise transportation of gaseous hydrogen can be done through pipelines (@60 bar), with small consumptions and a 98% efficiency,[4] or in pressurized bottles (@200 bar) by means of trucks with higher losses and a 88% efficiency.

Considering the two different levels of pressure resulting by the two gaseous transport options, the energy consumptions at the refilling station to compress hydrogen at tank pressure (700 bar) will be different: the conversion efficiency is 65% for hydrogen taken from pipeline and 78% for hydrogen transported by trucks.

All the considered processes and the related efficiencies are shown in Fig. 1.

The type of hydrogen storage adopted influences the conversion chain efficiency, but also the car weight: compressed hydrogen at 700 bar requires heavier tanks than liquid hydrogen. Weight figures assumed in this work for hydrogen tanks are shown in Table 1.

Table 1
Tank weight for liquid and gaseous hydrogen storage.

Fuel	PCI (MJ kg^{-1})	kg_{tank}/kg_{fuel}
LH_2	120.0	13.50
CGH_2 @ 700 bar	120.0	17.54

[4] The efficiency penalty during pipeline transportation is about double than in the case of natural gas. Calculation is based on an optimization analysis for minimizing transportation costs in 24″–56″ pipelines [17].

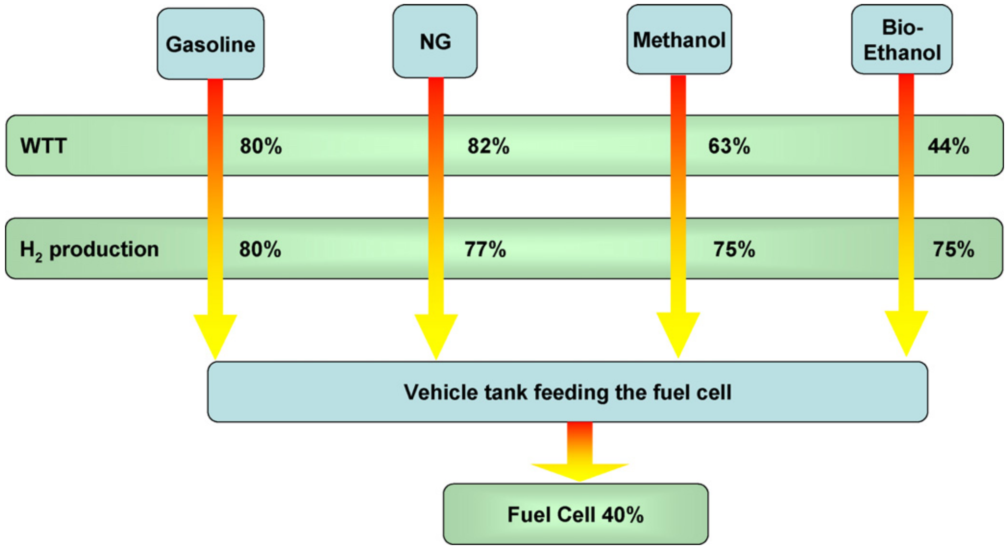

Fig. 2. Conversion chain for different fuels used for vehicles with onboard hydrogen generation.

Table 2
Tank weight for different kind of fuels.

Fuel	LHV (MJ kg^{-1})	kg_{tank}/kg_{fuel}
CNG @ 250 bar	48.0	1.75
Gasoline	44.0	0.10
Ethanol	26.8	0.10
Methanol	19.7	0.10

2.3. Fuel processors for onboard hydrogen generation

Hydrogen can also be produced directly onboard through a small fuel processor.

The WTW analysis of this solution depends on the primary fuels and different fuel processing techniques. As far as the primary fuels and related well-to-tank conversion is concerned, we refer to the results of recent extensive studies carried out by the USA administrations and by primary car manufacturers[5] [11,12].

Auto Thermal Reforming (ATR) is selected as the most favourable fuel processor option because of its compactness and fast start-up. Fuel processing is composed also by two water gas shift reactors and a preferential oxidizer in order to increase hydrogen partial pressure and to limit CO content below 10 ppm as required by PEM. Hydrogen production efficiency depends on the kind of fuel used, and is in the range 75–80% for the most advanced manufacturers [19,20]. These values are close to those of commercial large scale chemical plants for hydrogen production, because no hydrogen separation and compression are required.

The final reformate stream feeding the FC consists of about 40% hydrogen and the remaining components are water and inerts: dilution of hydrogen significantly affects PEM performance, increasing activation and diffusion losses and limiting maximum hydrogen conversion (fuel utilization) to about 80%. The resulting net FC electrical efficiency considered in this case is 40% (see Section 2.5 for further information). The considered scenarios are summarized in Fig. 2.

Fuel processors power density has been assumed equal to 800 W kg^{-1} [20], while tank weight for different fuels are reported in Table 2.

Table 3
Energy features assumed for Li-ion batteries.

Power density (W kg^{-1})	400
Energy density (Wh kg^{-1})	130
Efficiency (%)	92

Differences of tank weight per kg of fuel can be neglected among liquid fuels, while the CNG case requires a much heavier high pressure tank. The weight is however lower than in the case of compressed hydrogen due to the lower stipulated pressure and to the lower volume required per kg of fuel.

2.4. Battery technology

The main properties required to a battery are high flexibility and energy density. Among several types of commercial batteries, Li-ion has been selected as the most favourable technology because it well matches the required characteristics (see Fig. 3).

Power density and energy density of the assumed Li-ion battery are shown in Table 3 according to literature reports [21,22], coherently with specific battery studies [23–25] and recent developments (i.e. Tesla Roadster battery features 125 Wh kg^{-1} and 444 W kg^{-1}; Kokam High Energy/High Power models feature 110/100 Wh kg^{-1} and 490/940 W kg^{-1}, respectively [26]).

The battery efficiency during discharge and charge periods, that is affected by losses due to internal resistances, has been calculated with a simplified model assuming the discharge efficiency dependent on the current intensity (I):

$$\eta_{discharge} = \frac{E - RI}{E} = 1 - \frac{R}{E} \cdot I \qquad (1)$$

where the resistance R (Ω) and the open circuit voltage E (V) generally depend on the battery state of charge (SOC) as well as on the battery size and cell array configuration.

A preliminary simulation of the instant efficiency for ECE-EUDC and US06 high-performance cycles allowed to estimate an average discharge efficiency $\eta_{average\text{-}discharge}$ = 96%.[6] The same value has

[5] Even if the WTT analysis is dependent on the geographic location, we apply here in all cases the results of studies related to North America, neglecting possible differences regarding for instance the case of European countries.

[6] Size and configuration considered for calculation refers to a Li-ion "Thunder sky" battery, with 60 cells rated 3.95 V each for a 50 Ah capacity, 0.2 Ohm average resistance and 90 kg overall weight [27,28].

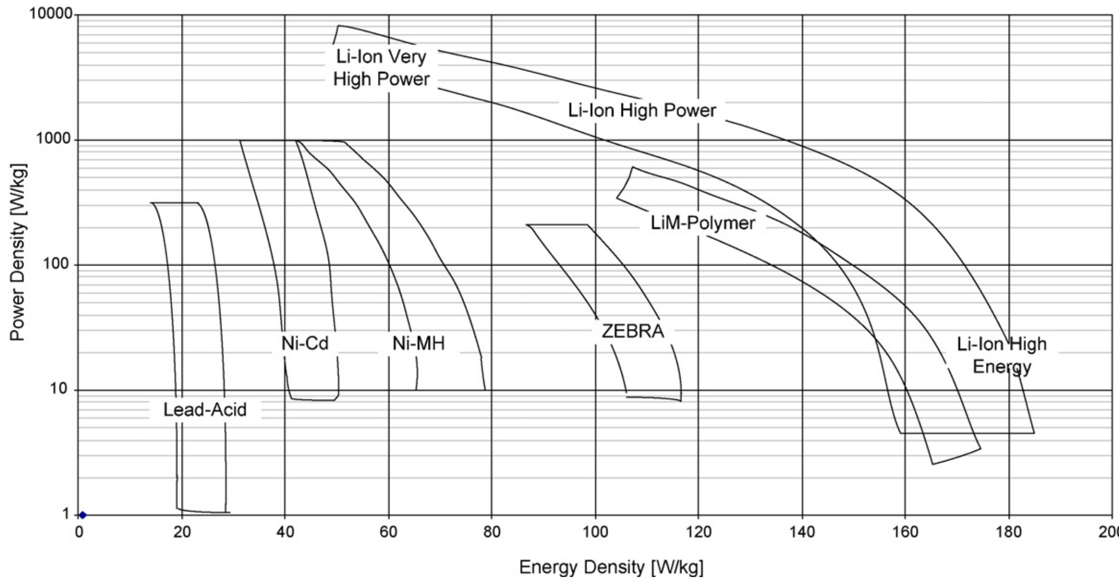

Fig. 3. Power density vs. energy density for most common batteries (adapted from [11]).

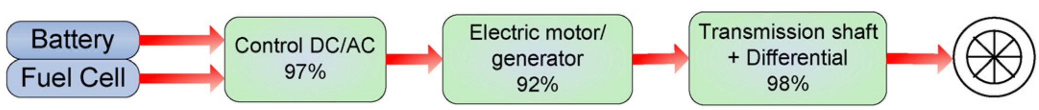

Fig. 4. Electric drivetrain from electric power to wheels.

been assumed for the charge process, resulting in an overall efficiency for a charge–discharge process of 92%, kept constant for all simulations (Table 3).

2.5. Fuel cell technology

A fuel cell is defined as an electrochemical device where the chemical energy stored in a fuel is converted directly into electricity. Avoiding the heat-to-mechanical energy conversion typical of heat engines, fuel cells can achieve higher efficiencies than conventional ICE with the further advantage of avoiding combustion processes and related pollutant emissions; moreover, as opposed to reciprocating engines, at partial load FC efficiency tends to increase.

Among the various FC technologies (SOFC, MCFC, PAFC and PEM), this work focuses on the PEM type. This choice is driven by several considerations, that make the PEM the preferred choice of FC car manufacturers: (i) high power density, (ii) low operating temperature, (iii) fast start-up capability and (iv) the use of low cost materials,[7] with the potential for mass produced units of achieving relatively low capital cost and high reliability.

Example of PEM manufacturers for transportation are Ballard [29] and Nuvera [19].

Hydrogen conversion efficiency in the FC is largely affected by the current density in the cell as well as by the composition of the stream at the anode inlet.

Increasing the current density allows to decrease the stack dimension and weight, but also yields a lower cell voltage and efficiency. In automotive applications, where the weight is at least as important as the efficiency, working conditions are usually selected close to the maximum power density of the FC, in order to have the lightest and smallest stack. Thus, the current density is usually close to 800 mA cm^{-2} [30] leading to a cell voltage of about 0.68 V when the anode stream is pure or humidified hydrogen.

The cell voltage depends also on the fuel composition at the anode inlet: feeding the anode with hydrocarbon (e.g. methanol, ethanol) reformate fuels increases activation and diffusion losses [31,32] with consequent 4–8% cell voltage decay with respect to the case of pure hydrogen feeding. Moreover, if hydrogen is diluted only a limited part of it (usually 80–85%) can be converted without incurring in heavy voltage losses.

The final fuel-to-electricity conversion efficiency of the FC is about 55% for pure hydrogen and 40% for diluted reformate fuels, respectively. The first assumption is coherent with available specifications of commercial PEM products for UPS stationary applications as well as with Nuvera specifications for automotive application systems [19].

For simplicity, fuel cell power density assumed in this work is equal to 500 W kg^{-1} for both pure hydrogen and reformate feeding, according to recent reports [26].

2.6. Electric drivetrain

The electric drivetrain includes all energy conversion from the electricity produced by battery or fuel cell to the wheels. As shown in Fig. 4, it consists of a DC/AC controller, an electric motor/generator and a mechanical powertrain.

The electric motor is assumed to be a triphase induction type, as proposed by the majority of manufacturers, with a nominal efficiency of 92% [33–35].

Regarding the DC/AC control, an average efficiency of 97% has been estimated according to several product specifications [33,34,36–38], while mechanical losses are assumed equal to 2% [39,35].

[7] With the exception of platinum used as electrode catalyst. The platinum load has been steadily reduced in the most recent PEM FC generations.

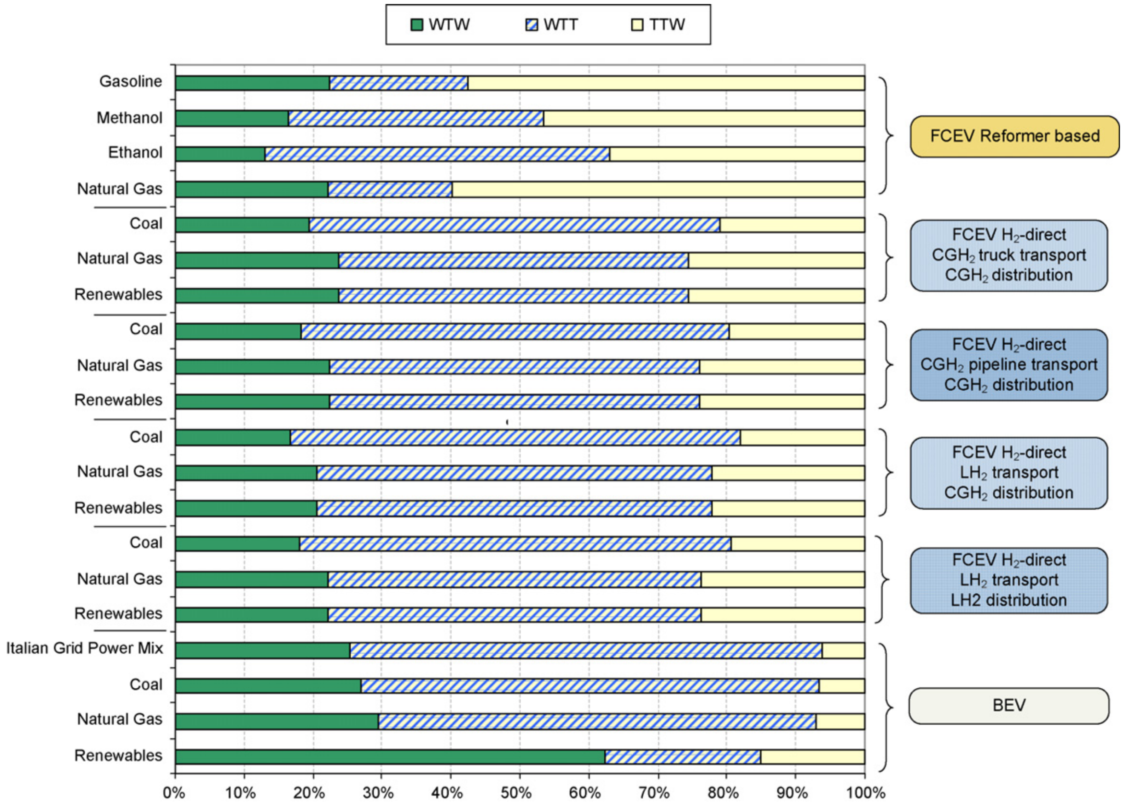

Fig. 5. Well-to-wheel (WTW) efficiency, Well-to-tank (WTT) and Tank-to-wheel (TTW) losses for the considered energy pathways.

Therefore the total drivetrain energy efficiency is 87.5%, coherently also with assumptions used in similar studies [40].

2.7. Results of the well-to-wheel analysis on different energy pathways

The combination of all processes related to the energy chain from each primary sources to vehicle wheels allows to estimate the total primary energy consumption yielded by the vehicle for each kWh of energy delivered to the wheels.

Results of all the considered pathways are shown in Fig. 5. Starting from a 100% primary energy consumption, some energy is lost in the well-to-tank path (WTT) and then in the tank-to-wheel path (TTW), leading to a final well-to-tank efficiency (WTW).

The lowest consumption is achieved by the BEV pathway with renewable energy as primary source, where the short conversion chain allows a WTW efficiency above 60%. The solution is clearly the best in terms of efficiency and primary fuel consumption, limited by the feasibility and cost-competitiveness issues which currently negatively affect the exploitation of renewable sources.

In case of conventional fossil fuel feeding, results are of course worse and rather similar in all options: best efficiency for FCEVs (about 22%) is reached by the hydrogen-direct option where

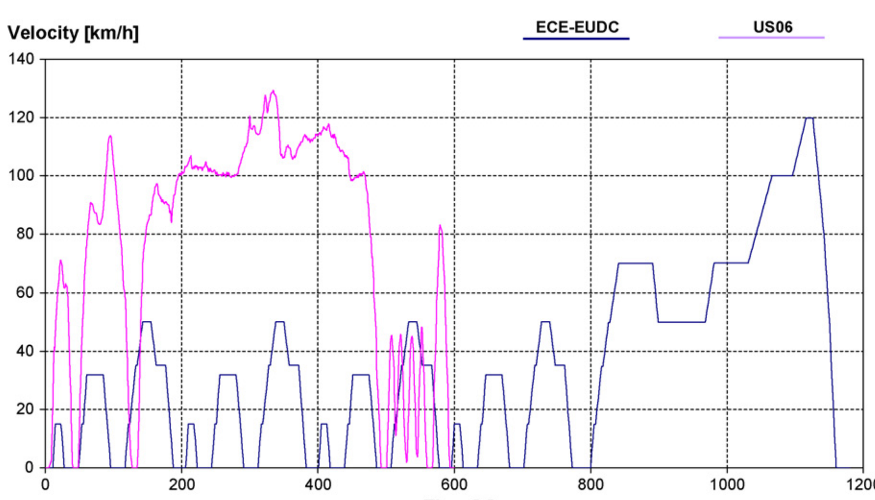

Fig. 6. Test cycle ECE-EUDC and US06 [42,43].

Table 4
Main features of the driving cycles.

	ECE	EUDC	ECE + EUDC	US06
Average speed ($km\,h^{-1}$)	18.7	62.6	33.6	77.9
Time (s)	195 × 4	400	1,180	596
Total distance (m)	1013 × 4	6955	11,007	12,897
Maximum speed ($km\,h^{-1}$)	50	120	120	129.2
Maximum acceleration ($m\,s^{-2}$)	1.04	0.83	1.04	3.76

hydrogen comes from natural gas reforming or electrolysis from renewable energy, which have identical energy efficiency (see pathways in Fig. 1); the BEV holds anyway an advantage, reaching 25–28% in the coal or natural gas pathways, respectively.

Among the different possibilities for hydrogen distribution, the compressed solution with truck transport shows some advantage towards the pipeline and liquid cases. However, large scale distribution of compressed hydrogen by means of high pressure bottles is not feasible due to the high consequent number of required transports, so that the "liquid" solution is considered the best choice in terms of feasibility on a large scale [17].

As regards the FCEV Reformer-based systems (with onboard fuel processor), the overall WTT efficiency seems to be similar to that of some H_2 pathways, except for the ethanol and methanol, which are definitely lower.

The results of Fig. 5 are globally coherent with those proposed by other authors [11,12,40,41], and in principle suggest the partially misleading conclusion that BEV are always the best solution [40,41]. But in order to give a realistic outlook of WTW energy consumption, these results must be integrated in a simulation of driving cycles, as presented in Section 3.

3. Driving cycle simulation

The simulation of the driving cycle is carried out with reference to standardized cycles, namely the ECE-15 (part one, urban) and EUDC (part two: "extra-urban driving cycle") used by European legislation to assess car consumptions and emissions [42].

Because of low acceleration and rather low maximum speed, the peak power demand generated by ECE-EUDC cycles is low and does not correctly reproduce the features of current average market cars. For this reason, it is also assumed that:

(1) all vehicles must achieve a maximum speed of at least 150 $km\,h^{-1}$ (about 93 Mph) on an horizontal path, and 90 $km\,h^{-1}$ (about 56 Mph) with a 5% slope;
(2) the power capacity of all vehicles must also allow to perform a standard "high performance" driving cycle, as US06 cycle, which is frequently considered as a supplemental test procedure to address the shortcomings of basic driving cycles (like FTP-75 and ECE-EUDC cycles) under aggressive and high speed driving [42].

The second assumption is generally prevailing, i.e. a vehicle able to follow the US06 cycle has a power capacity which also satisfies the first condition.

Speed profiles and main parameters for ECE-EUDC and US06 are summarized in Fig. 6 and in Table 4.

3.1. Simulation model

The simulation model calculates the vehicle weight and consequently the energy demand through the ECE-EUDC driving cycle.

The conceptual scheme of the iterative process adopted for calculating the energy consumption during a driving cycle (expressed in ($Wh\,km^{-1}$)) is shown in Fig. 7.

Because the vehicle weight depends on the drivetrain maximum power, which results from conditions 1 and 2 above, as well as by the vehicle driving range through the fuel and tank, or the battery weight, an iterative process on the car weight must be adopted. As first approach, the basic vehicle weight ($W_{vehicle}$) has been assumed equal to 1100 kg [44]. This value includes all the car components

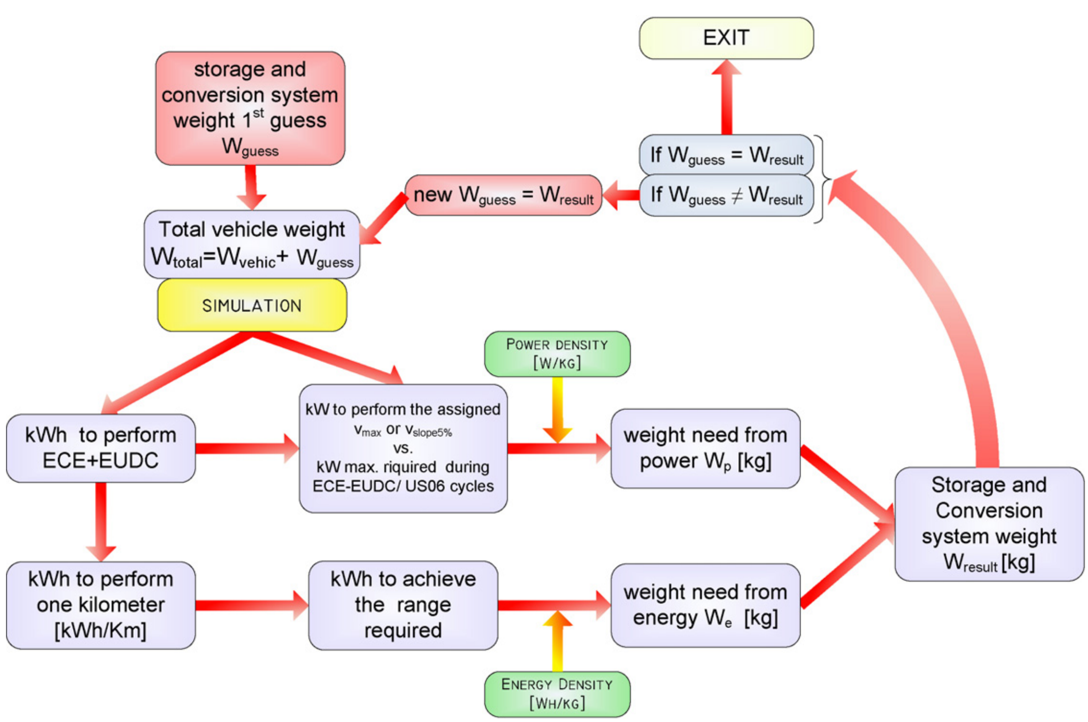

Fig. 7. Conceptual scheme of the iterative calculation procedure adopted for the simulation.

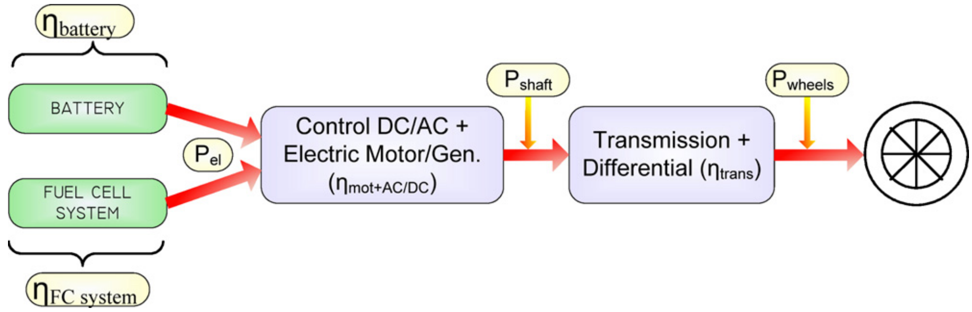

Fig. 8. Scheme of the main elements and power flow inside a vehicle.

with the exception of the energy storage (tank or battery) and fuel conversion system (fuel cell and fuel processor).

The weight of the onboard energy storage and processing system W_{guess} is then added to the basic vehicle weight to obtain the total weight W_{total}.

Then, it is possible to go through the calculation and obtain the vehicle consumption along the cycles, which allows to set the energy storage weight depending on the desired driving range, at least within the simplified hypothesis that the vehicle will always drive with a speed sequence reproduced by the ECE-EUDC cycle.

In order to take into account that the car structure (body, shock-absorbers, etc.) is designed on the vehicle load, it is also assumed here that the basic vehicle weight of 1100 kg holds only for W_{guess} below 200 kg, while above it is added a conservative overweight equal to $0.15 \times W_{guess}$ depending on the storage and fuel conversion system weight.

Globally, the meaning of the parameters W_{guess}, W_p, W_e and W_{result} shown in Fig. 7 differs from the BEV to the FCEV case:

3.2. BEV case

Calculation proceeds with the following steps: $W_{guess} = W_{battery}$; $W_{result} = W_{battery} = \text{Max} \times (W_p, W_e)$. Power and energy density are given by the battery peak power density (W kg^{-1}) and the battery energy density (Wh kg^{-1}), respectively.

3.3. FCEV case[8,9]

Calculation proceeds with the following steps: $Wguess = W_{FC} + (W_{Fuel\ Processor}) + W_{Fuel\ Tank} + W_{Fuel}$; $W_p = W_{FC} + (W_{Fuel\ Processor})$; $W_e = W_{Fuel\ Tank} + W_{Fuel}$; $W_{result} = W_p + W_e$. Weight need for power W_p is given by the fuel cell power density (case of hydrogen feeding) or FC + Fuel Processor peak power density; weight need for energy W_e is calculated based on the fuel content, the fuel heating value (LHV) and on the tank weight.

Along the driving cycles, the vehicle power must balance resistance forces that depend on the instant speed conditions. Neglecting gravity effect (the driving cycles assume horizontal paths), the forces are given by aerodynamic resistance, friction between wheels and the road and acceleration.

The power required at the wheels P_{wheel} is then:

$$P_{wheel} = F_{res} \times \text{v} = (\frac{1}{2}\rho \text{v}^2 \text{S} C_x + k_1 \text{ mg} + k_2 v^2 \text{ mg} + ma) \times v \qquad (2)$$

where m: vehicle mass (kg), v: instant speed (m s^{-1}), a: instant acceleration (m s^{-2}), S: area of the vehicle front surface (m^2), ρ: air density (kg m^3), k_1: roll resistance coefficient, k_2: speed dependent roll resistance coefficient, C_x: aerodynamic penetration coefficient.

Considering drivetrain and electric efficiencies (Fig. 4), the power supplied by the battery (BEV case) or the fuel cell (FCEV case) to the electric motor P_{el} is given by:

$$P_{el} = \frac{P_{shaft}}{\eta_{elec+AC/DC}} + P_{aux} = \frac{P_{wheels}}{(\eta_{trans} \cdot \eta_{elec+AC/DC})} + P_{aux} \qquad (3)$$

where P_{aux} is the electric auxiliary equipment power and $\eta_{elec+DC/AC}$ the energy efficiency that considers the electric motor as well as the DC/AC control losses. The power flow scheme is shown in Fig. 8.

The battery, which can be also integrated in FCEV, can be recharged during deceleration. The power recovered $P_{el,rec}$ is given by:

$$P_{el,rec} = P_{shaft} \cdot \eta_{elec+AC/DC} - P_{aux} = P_{wheels} \cdot (\eta_{trans} \cdot \eta_{elec+AC/DC}) - P_{aux} \text{ if } P_{wheel} < 0 \qquad (4)$$

Calculation proceeds with a time-step of 1 s. The resistant force F_{res} is calculated using the average speed between the beginning and the end of each time step; this method is called *semi-implicit*, and differs from the *explicit* approach which assumes the step initial velocity v_i leading to a lower accuracy. The resulting formula for the calculation of F_{res} becomes

$$F_{res\ i} = \frac{1}{2}\rho\left(\frac{v_i + v_{i+1}}{2}\right)^2 \text{S}C_x + k \text{ mg} + k_2 \text{ mg}\left(\frac{v_i + v_{i+1}}{2}\right)^2 + ma_i \qquad (5)$$

where $a_i = (v_{i+1} - v_i/\Delta t)$.

Finally, the energy calculation along the cycle is calculated by

$$E_{el} = \sum_{\text{cicle}} P_{el,i} \cdot \Delta t \qquad (6)$$

4. Simulation results

4.1. Effect of a regenerative braking

As already mentioned, one of the most interesting ways to improve the vehicle efficiency under real driving cycles is the introduction of a battery able to store energy during braking, recovering part of the vehicle kinetic energy. This option can be easily adopted in a BEV, where the vehicle is equipped with a battery, while in the case of a FCEV the installation of a dedicated battery pack is required. In this case, the battery size has been calculated after an optimization process in order to minimize the vehicle consumption as a function of the onboard battery weight. The results are shown in Fig. 9 for the case of LH2 vehicles, but they can be extended also to the other cases.

Based on results presented in Fig. 9, a battery pack weight of 15 kg has been selected because it minimizes the consumption on

[8] The Fuel Processor weight is added only for the Reformer based cases. If there is a FC + Fuel Processor system, the overall power density is considered.

[9] CO_2 emissions for natural gas combustion are assumed equal to 202 g_{CO2} kWh^{-1}.

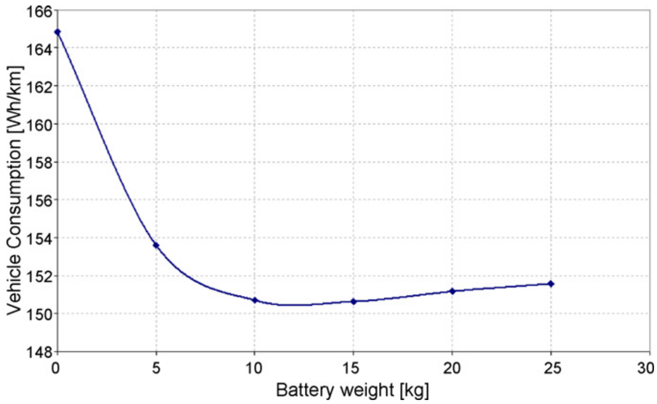

Fig. 9. Vehicle consumption (Wh km^{-1}) vs. weight of regenerative braking battery for a LH_2 FCEV, ECE-EUDC cycle.

a ECE-EUDC cycle. It is worth noting that the battery weight used in current ICE HEVs is higher (i.e. about 35–50 kg [6,9]), but is optimized for a different drivetrain and it relies on Nickel batteries, featuring a lower power density.

A comparison of BEV and FCEV tank-to-wheel consumptions with or without regenerative braking are shown in Fig. 10.

It is shown that the average energy saving with regenerative braking is about 8,6%, which is consistent with previous studies [41] reporting an energy saving of about 10%.

Fig. 10 outlines a different behaviour of BEV and FCEV systems: energy required per km is strongly dependent on range for BEV, while FCEV has only a slight dependency.

Battery weight largely affects total BEV weight, and increasing the range implies to significantly increase car weight and, consequently, the amount of energy required per km. Oppositely FCEV, thanks to the much higher energy density and the moderate H_2 tank weight, feature a car weight lightly affected by the range, resulting in a low slope trend of the energy required per km.

Hydrogen vehicles are in both cases (with and without regenerative braking) more interesting than FCEV reformer-based for low ranges, since the fuel processor unit affects more the car weight than the H_2 storage. As the driving range increases, their energy demand per km becomes more similar to that of the other FCEV mainly due to the tank weight.

4.2. Simulations for a ECE-EUDC cycle

The simulation results of the entire energy chain from well to wheel (WTW efficiency), as a function of the driving range for ECE-EUDC cycles are shown in Fig. 11.

As previously said, BEV cases show a higher energy increase than other cases, so the use of BEVs (with current Li-ion technology) seems feasible only for medium-low range purposes, i.e. hardly above 400–500 km driving range (a term of comparison can be given by the two-seater – thus rather light – Tesla roadster BEV, featuring a 365 km driving range on EPA combined cycle [4]). Above 500 km, considering a realistic case where battery is recharged through the national power grid (BEV-Mix), the resulting energy required is the second highest.

Of course this behaviour is less problematic for the BEV when energy is produced by renewable sources, which stands on the lowest consumption values in all the driving range extensions considered.

FCEV with H_2 tank using renewable sources or natural gas pathway have an identical WTW balance, consequence of identical WTW efficiency (see Figs. 1 and 5). With the liquid hydrogen storage (FCEV-LH2), these solutions have the second best pathway for driving ranges above 250 km, while the BEV-natural gas case reaches slightly better results for lower driving ranges.

The cases with onboard fuel processor (FCEV reformer based) show similar but slightly worse results for gasoline and natural gas, which are the most advantageous fuels because of low pathway energy losses. On the contrary, ethanol and methanol have a low WTT efficiency leading to high energy consumption per km.

A result comparison for each primary energy feed shows that for coal, the best option for a range up to 400–450 km is BEV, while above that range the FCEV-LH_2 becomes more advantageous. For the NG, instead, the FCEV-LH_2 becomes more interesting than BEV after only 250–300 km.

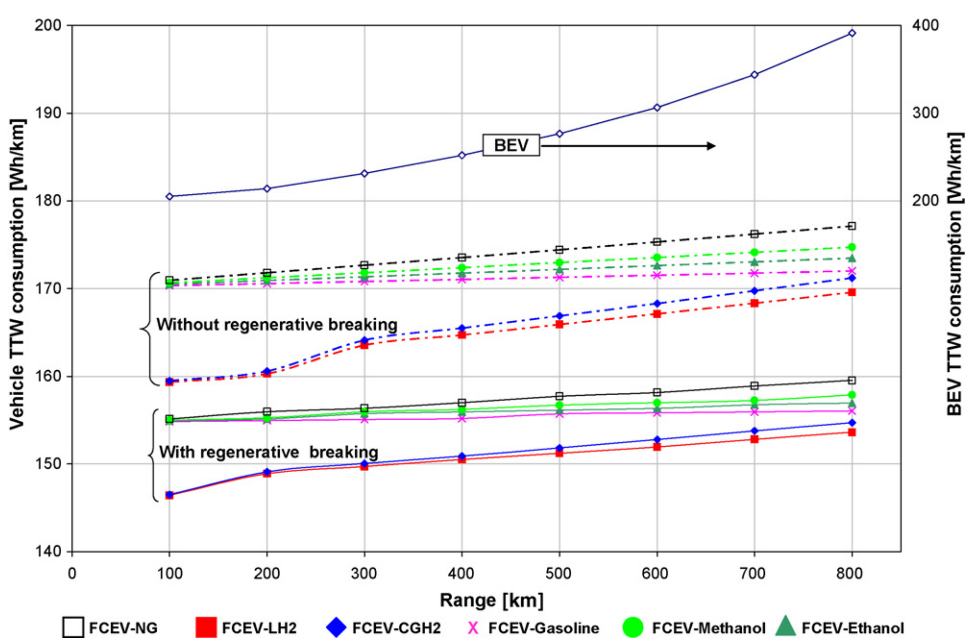

Fig. 10. Vehicle tank-to-wheel energy consumption (Wh km^{-1}) for each pathway, with regenerative braking (dashed lines) or without (continuous line), as a function of the vehicle range.

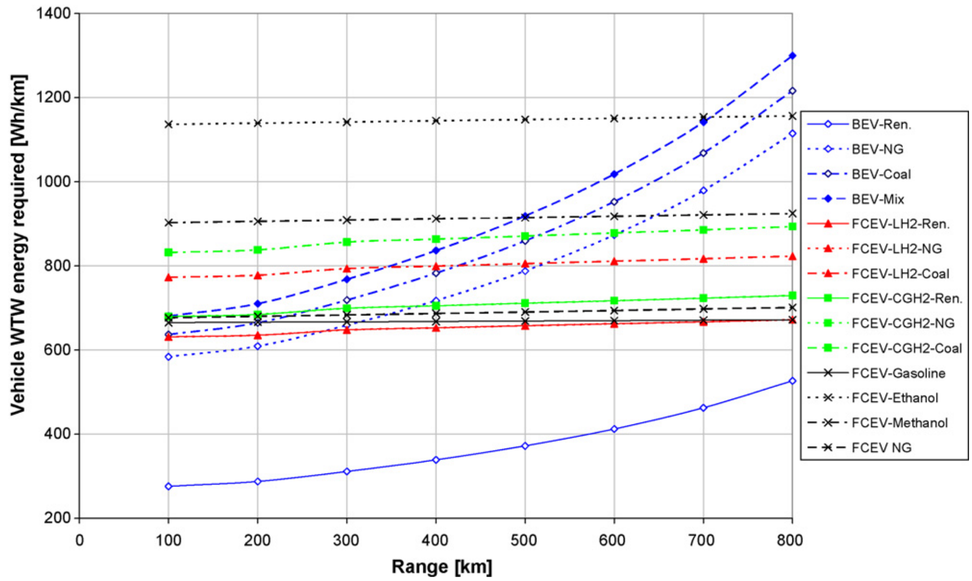

Fig. 11. Total energy required for each pathway (WTW balance) applied to ECE-EUDC cycle as a function of the driving range.

The worst pathway for almost all ranges is the case FCEV-ethanol, where the fuel production requires a lot of energy.

Results for each case including regenerative braking are shown in Fig. 12.

Regenerative braking improves FCEV performance of about 9% (as anticipated also in Fig. 9), decreasing the trade-off range between BEV and FCEV pathways (see Fig. 11):

- BEV technology seems competitive only below a maximum of 300–400 km, instead of 400–500;
- BEV with electricity coming from the "electric grid mix" shows energy expenses which are higher than any other possibility above 400 km range;
- the second best option is always FCEV-LH_2, with hydrogen generated through natural gas or by renewable sources pathway (these two pathways are still identical). Cases with onboard fuel processor fed with gasoline or natural gas still reach similar, but slightly worse results.
- the coal pathway shows BEV as the best option only until 300 km vs. 400–450 of previous case, while above FCEV-LH_2 becomes more interesting.

The effect of a different driving cycles combination in the composition of a driving range has been evaluated mixing one ECE cycle with 4 EUDC cycles, featuring a driving range with majority of extra-urban operation. Results are shown in Fig. 13.

Although the general behaviour shown in Fig. 13 is the same discussed above, the main difference is that the energy demand is reduced in all cases thanks to the higher influence of the extra-urban cycle, that requires less energy and features a higher impact of regenerative braking. In this way, the BEV high-range energy demand significantly decreases, improving the performance when compared to the FCEV vehicles at high ranges.

However, it is questionable that this result is a real-life indicator, since real extra-urban driving does not always include the long braking distances assumed here.

4.3. CO_2 emissions

The analysis carried out above allows to express the energy consumption results also in terms of CO_2 emissions. For simplicity we consider here only the case of liquid hydrogen transportation, which is regarded as the most promising for a possible large scale use with respect to gaseous hydrogen transport [17].

CO_2 emissions are calculated as emissions related to fuel or electricity production (value that coincides with WTT process) plus the carbon content in the fuel only for cases with onboard reforming.

CO_2 emissions for BEV and FECV H_2-direct cases are summarized in Table 5 and expressed in grams per kWh. In order to calculate the total emissions per km, this value has to be multiplied by the total amount of energy required for each km, presented in the previous section.

Production of electricity and hydrogen from renewable energy has zero CO_2 emission because it is assumed, for simplicity, to neglect emissions during plant construction and decommissioning.

Onboard reformer has emissions for fuel production as well as for fuel conversion into hydrogen. Values are assumed in Table 6a according to previous studies and literature reports [12,45].

Table 5
Carbon dioxide emissions for each pathway.

	Emissions (g_{CO_2} kW h^{-1})		
	BEV	FCEV LH_2	FCEV CGH_2
Renewable	–	–	–
Natural Gas	600	801	861
Coal	1109	1660	1785
Electric grid mix	683	–	–
Coal with 95% CO_2 capture	–	89	–

Combustion of Illinois#6 coal produces 340 g_{CO_2} kw h^{-1} while a South African coal about 344 g_{CO_2} kw h^{-1}. An average value of 342 g_{CO_2} kW h^{-1} has been assumed in this study.

Table 6a
Carbon dioxide emissions for each fuel considered in cases with onboard reforming.

	Emissions (g_{CO_2} kW h^{-1})		
	Fuel production	Fuel carbon content	Total
Methane	20.85	72.49	93.34
Gasoline	21.33	57.05	78.37
Methanol	24.64	69.20	93.84
Ethanol	−21.67	72.24	50.57

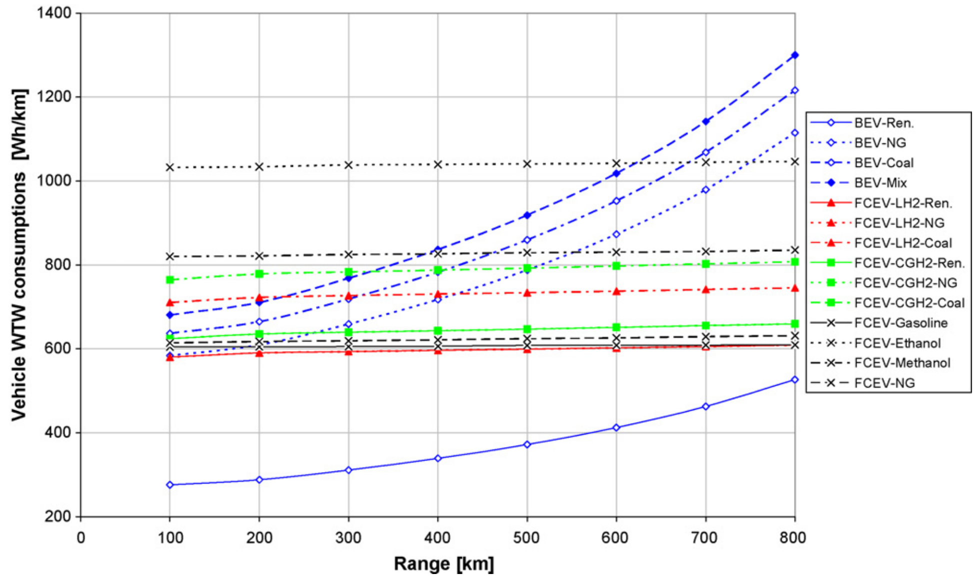

Fig. 12. Total energy required for each pathway (WTW balance) applied to ECE-EUDC cycle with regenerative braking as a function of the driving range.

Emissions of ethanol are lower than other cases because it is produced from biomass (so that in the production phase it captures CO_2 from the environment). The energy content of ethanol mainly comes from solar power with minor contribution from fossil fuel feedstock during farming, distillation and transport [45].

The results of emissions related to TTW balance are shown in Fig. 14 for the case of ECE-EUDC cycles with regenerative braking.

As for the energy analysis, the BEV is interesting only for low ranges, while FCEV has almost constant emissions. BEV-Mix case, that is the most realistic case, is competitive only below a range of 400 km, while afterwards it produces less emissions only than coal cases.

Among NG cases, FCEV-LH_2 is always the best option, followed by the Reformer-based FCEV for ranges above 350 km.

The coal options, due to highest carbon content in the fuel, have the highest CO_2 emissions. Despite that, if carbon capture technology is applied for co-production of hydrogen and electricity, CO_2 emissions can be the lowest, except for the case of renewables, where they are zero. Ethanol represents an average case, being a biofuel, leading to about 30% lower emissions compared to conventional fossil fuels [45].

The results presented above can be finally compared with conventional ICE vehicles and current hybrid vehicles CO_2 emissions, which are certified and published with reference to the same standard driving cycles based on a TTW energy balance. In order to carry out a coherent comparison on a WTW basis, it is necessary to take into account the energy consumption yielded by the well-to-tank pathway for conventional fuels, which is shown in Table 6b according to [12].

The results are shown in Fig. 15 for a number of representative vehicles.

It can be seen that, for ranges yielded by today's most common commercial vehicles (>700–800 km), only FCEV are competitive, since BEV show rather high emissions not too far from those of

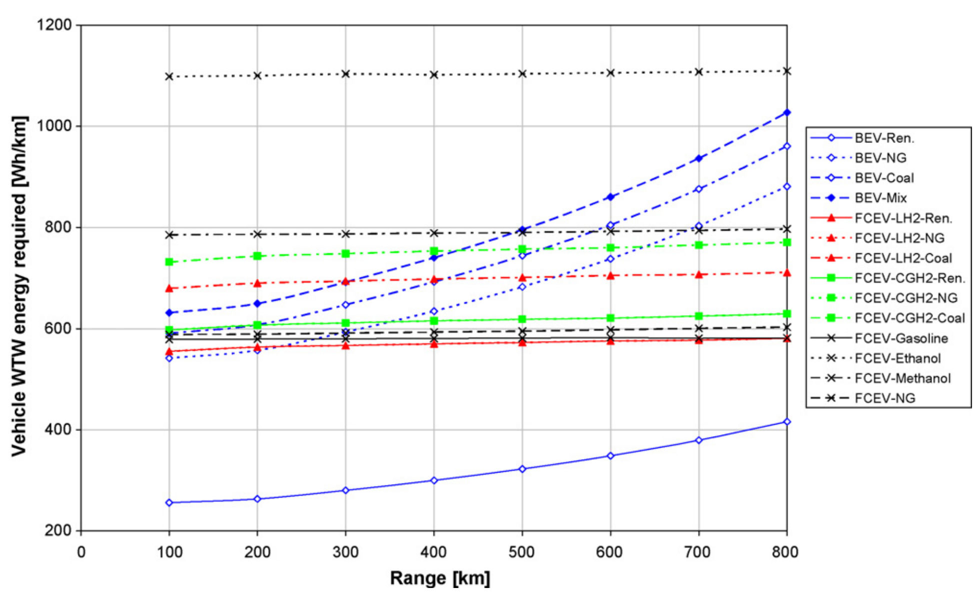

Fig. 13. Total energy required for each pathway applied to ECE-EUDC4 cycle with regenerative braking and for different range.

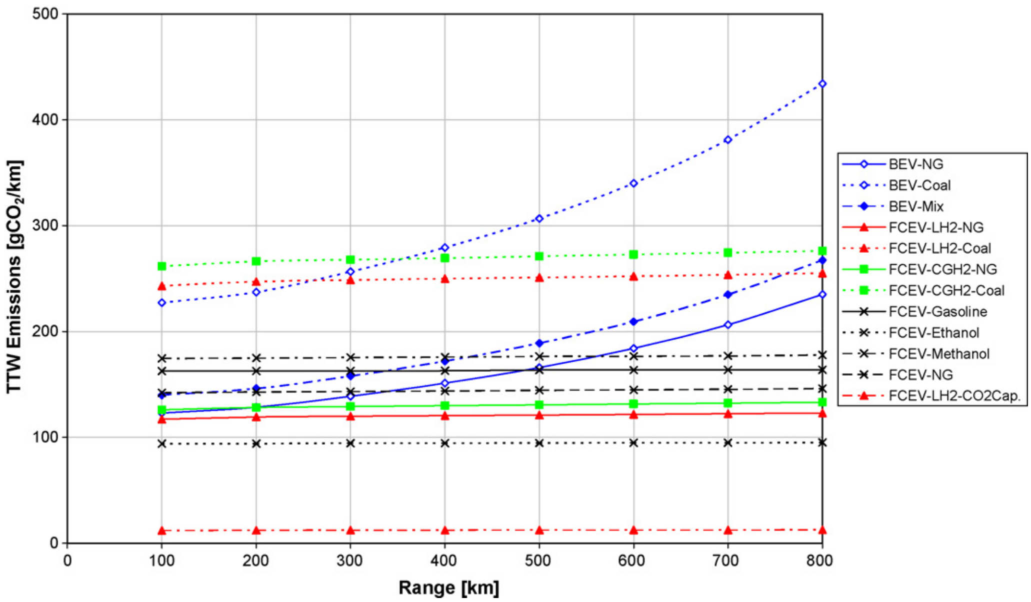

Fig. 14. CO_2 emission related to TTW balance for each pathway applied to ECE-EUDC cycle including regenerative braking as a function of the driving range.

Table 6b
Well-to-tank emissions for conventional fuels.

	WTT CO_2 emissions ($gCO_2\ MJ^{-1}$)	Fuel energy density ($MJ\ l^{-1}$)	WTT CO_2 emissions ($gCO_2\ l^{-1}$)
Gasoline	20.85	57.36	683.56
Diesel	16.11	36.16	582.60

high performance vehicles (such as Ferrari F430) or large SUV (i.e. Hummer H2 or Audi Q7). It can also be noted that global emission of FCEV are not dissimilar from those of hybrid or Diesel top-ranked low-consumption vehicles, which have already reached extremely low values.

These results indicate that some commercial vehicles are already close or better than several BEV or FCEV solutions from the CO_2 emissions point of view. However, the emission comparison neglects here for simplicity other pollutants as CO, HC, NO_x and particulate matter, which are produced by commercial vehicle and are typically harmful for the human health more than for the environment.

Under this point of view BEV and FECV-H2 do not produce any of these pollutants onboard, and only a small amount is generated in the FCEV with onboard fuel processor (reformer based). A smaller fraction of such pollutants is conversely emitted by central power station as long as they use fossil fuels.

Only cases with carbon capture or with biofuel as ethanol, achieve much lower CO_2 emissions, while, obviously, the case of BEV with renewable energy feeding has no CO_2 emission (nor any other gaseous emission).

It is important to recall that the same emission results of the BEV with renewable energy feeding would be reached also by nuclear power feeding, i.e. another all-electric pathway with no gaseous emissions; however this option does not exploit a free energy source and the power station efficiency would have to be taken into

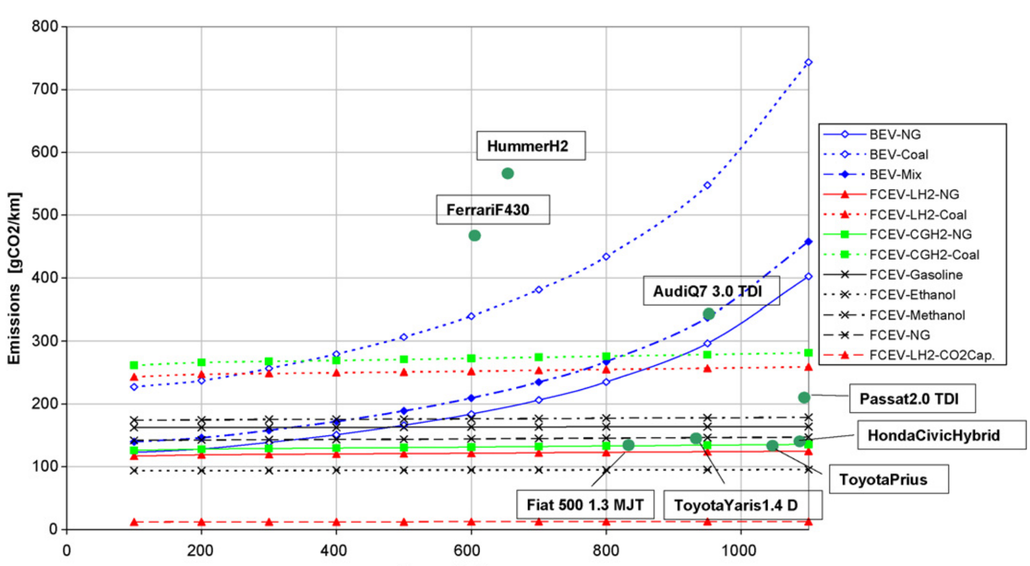

Fig. 15. CO_2 emission of the entire WTW balance, for each pathway applied to ECE-EUDC cycle with regenerative braking and compared to commercial vehicles.

account, so that the disadvantage of a high energy consumption for long driving ranges would hold relevant importance.

5. Conclusions

This work discusses the energy and environmental balances for electric vehicles using state-of-the-art Li-ion batteries (BEV) or PEM fuel cells (FCEV), through the methodology of the well to wheel (WTW) analysis, applied to ECE-EUDC driving cycle simulations. Well to wheel balances are carried out considering different scenarios for the primary energy feedstock (renewable energy, coal, natural gas) and for the energy conversion chain, which in the case of FCEV may rely on gaseous or liquid hydrogen generated in central power stations and later stored onboard, or make use of onboard fuel processors fed with gasoline, natural gas or liquid biofuels.

After a preliminary discussion of all the technological assumptions required and after a WTW analysis carried out under nominal operating conditions, the work shows the energy balances resulting from a simulation of the vehicles energy consumption when following standardized ECE-EUDC driving cycles. Calculation is a function of the required vehicle driving range, which influences the vehicle weight through the onboard energy storage capacity and the powertrain size, taking into account maximum speed requirements and the possibility to sustain more aggressive driving cycles. The results are significantly different from those of a simpler "nominal load" WTW calculation. The analysis shows that (i) when using 100% renewable energy sources to generate electricity, the BEV is the most efficient option, obviously also featuring zero emissions; (ii) when using an average primary source mix in electricity generation, or a 100% coal or natural gas feeding, the BEV performances are much lower, and the FCEV solutions become much more favourable both by the point of view of efficiency and CO_2 emissions, especially if the driving range requirement becomes significant (e.g. several hundred km) due to the progressive increase in the battery weight; (iii) among FCEV options, FCEV-LH2, with liquid hydrogen generated through the natural gas pathway or by renewable sources, is the most efficient and low CO_2 emission solution.

The ranking of results does not change when altering the driving cycle composition, although absolute values change.

The cases with gaseous hydrogen generated with the same primary sources or the cases with onboard fuel processor fed with gasoline or natural gas reach similar, but slightly worse results. The cases with onboard fuel processor fed with biofuels are significantly less efficient on the overall WTW analysis, although they hold lower CO_2 emissions.

The analysis shows that pure BEV vehicles should hardly compete with FCEV in presence of medium-to-long driving range requirements. Of course intermediate solutions (like plug-in FCEV hybrids with relevant battery storage) could combine the strength of the two technologies, although adding complexity to the vehicle.

Results are finally compared to those of conventional internal combustion engine vehicles, showing the potential advantages of the different solutions considered in the paper.

References

[1] Eurostat website: http://epp.eurostat.ec.europa.eu, 2008.
[2] F. Garcia de la Iglesia, Energy and environmental analysis of electric and Fuel cell vehicle through Well-to-Wheel driving cycle simulations, Master thesis, Politecnico di Milano, 2007.
[3] Think website: http://en.think.no/think/content/view/full/384, 2008.
[4] Tesla motors website: http://www.teslamotors.com/performance/tech_specs.php, 2008.
[5] Daimler HTR report 2/07 and website: http://www.daimler.com/dccom, 2008.
[6] Honda FCX website: http://world.honda.com/news/2007/4071114All-New-FCX/, 2008-04-07.
[7] Toyota FCHV-adv website: http://www.toyota.co.jp/en/news/08/0606_2.html, 2008-06-06.
[8] Nuvera website: http://www.nuvera.com/products/star.php, 2008.
[9] Toyota website for Prius http://www.toyota.com/prius-hybrid/index.html, 2008.
[10] Chevrolet Volt: http://www.chevrolet.com/electriccar/, 2008.
[11] TIAX LLC for the California Energy Commission, Full fuel cycle assessment, Well to Tank energy inputs, emissions and water impacts, California, February 2007.
[12] Argonne National Laboratory for General Motors Corporation, Well-to-Tank Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems-North American Analysis, June 2001.
[13] European Commission DG TREN, Analysis and Guidelines for implementation of the CHP Directive 2004/8/EC. Reference Values – Matrix, January 2006.
[14] Terna website "Statistical data on electricity", http://www.terna.it, 2008.
[15] A. Midilli, M. Ay, I. Dincer, M.A. Rosen, Renew. Sust. Energy Rev. 9 (3) (2005) 255–271.
[16] P. Chiesa, S. Consonni, T. Kreutz, R. Williams, Int. J. Hydrogen Energy 30 (2005) 747–767.
[17] E. Macchi, From oil to hydrogen economy, Politecnico di Milano, 2003 (in Italian).
[18] G. Valenti, E. Macchi, Int. J. Hydrogen Energy 33 (2008) 3116–3121.
[19] Nuvera website: www.nuvera.com, 2008.
[20] B.J. Bowersa, et al., Int. J. Hydrogen Energy 32 (2007) 1437–1442.
[21] M.H. Westbrook, The Electric Car. Development and Future of Battery, Hybrid and Fuel Cell Cars, Institution of Electrical Engineers, London, 2001.
[22] A.N. Brooks, Perspectives of Fuel Cell and Battery Electric Vehicles. Presented at the CARB ZEV Workshop, December 5, 2002.
[23] K.N. Han, H.M. Seo, J.K. Kim, Y.S. Kim, D.Y. Shin, B.H. Jung, H.S. Lim, S.W. Eom, S.I. Moon, J. Power Sources 101 (2001) 196–200.
[24] J. Van Mierlo, Subat: Sustainable Batteries. Final Public Report, Work Package 5, Vrije Universiteit Brussel –ETEC, 2005.
[25] D.A.J. Rand, R. Woods, R.M. Dell, Batteries for Electric Vehicles, Research Studies Press Ltd., Taunton, UK, 1998.
[26] F.R. Kalhammer, B.M. Kopf, D.H. Swan, V.P. Roan, M.P.Walsh, Status and Prospects for Zero Emissions Vehicle Technology, Report of the ARB Independent Expert Panel 2007, Sacramento, California, April 13, 2007.
[27] http://www.thunder-sky.com, document 2007127142910.pdf, 2007.
[28] Personal communications with F. Mapelli, Department of Mechanical Engineering, Politecnico di Milano, 2007.
[29] Ballard website: www.ballard.com, 2008.
[30] Gore website: http://www.gore.com, product section on fuel cells, 2008.
[31] S. Campanari, E. Macchi, G. Manzolini, Int. J. of Hydrogen Energy 33 (2008) 1361–1373.
[32] Personal communications with Nuvera, May 2006.
[33] Azure Dynamics Corporation website: http://www.azuredynamics.com, 2008.
[34] BRUSA Elektronik AG website: http://www.brusa.biz/products/g_products.htm, 2008.
[35] Mes-Dea website: www.mes-dea.ch, 2008.
[36] Electro Automotive website: http://www.electroauto.com/, 2008.
[37] Metric Mind Engineering website: http://www.metricmind.com/, 2008.
[38] Solectria Renewables website: http://www.solren.com/products/pwreleccomp.html, 2008.
[39] M. Gentilini, Study and LCA analysis of electric vehicles, Master Thesis, Politecnico di Milano, 2005.
[40] S. Eaves, J. Eaves, A cost comparison of fuel-cell and battery electric vehicles, J. Power Sources 130 (2004) 208–212.
[41] U. Bossel, Efficiency of Hydrogen Fuel Cell, Diesel-SOFC-Hybrid and Battery Electric Vehicles, European Fuel Cell Forum, October 2003.
[42] Council Directive 70/220/EEC of 20 March 1970 on the approximation of the laws of the Member States relating to measures to be taken against air pollution by gases from positive-ignition engines of motor vehicles, 1970.
[43] U.S. Environmental Protection Agency siteweb: http://www.epa.gov.
[44] G. Konrad, M. Sommer, B. Loschko, A. Schell, A. Docter, System Design for Vehicle Applications: Daimler Chrysler, Chapter 58, vol. 3: Fuel Cell Technology and Applications. Handbook of Fuel Cells – Fundamentals, Technology and Applications, John Wiley & Sons, Ltd., 2003.
[45] G. Manzolini, S. Tosti, Hydrogen production from ethanol steam reforming: energy efficiency analysis of traditional and membrane processes, Int. J. Hydrogen Energ. 33 (2008) 5571–5582.