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Hydrogen-based hybrid power unit for light vehicles: Assessment of energy performance and radiated electromagnetic emissions

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Summary. — Electrification of transport (electro-mobility) is considered an essential strategy to meet Europe's climate and energy challenges. Nonetheless, within the future perspective of living in smart cities, the interaction between electro-mobility devices and the surrounding environment, including humans, needs to be further investigated. In this study, a new hybrid power unit is developed and equipped on a commercial electric bike. The energy performance of this prototype are analyzed together with its contribution to radiated electromagnetic emissions. The former analysis demonstrated the remarkable fuel efficiency shown by the new power unit, *i.e.*, a 140 km long distance can be covered at mean power, while the latter tests, undertaken within the reverberating chamber of the Università degli Studi di Napoli "Parthenope", demonstrated that the hydrogen bike prototype is compliant with the actual European Union regulations in terms of electromagnetic radiations, and that long-term effects of its radiations on humans are negligible.

1. – Introduction

The urbanization of the last decades has left many cities with strong congestion and unhealthy air pollution. In fact, increasing population density led to several critical issues in current urban mobility architectures, making necessary a radical paradigm shift in order to mitigate negative effects on health, economy and transport systems effective functioning. Hopefully, conversion to smart cites, already in place in a growing number of communities across the globe, will improve the efficiency of future mobility architectures by developing proper information and communication technology infrastructures. In this context, transition to electro-mobility becomes crucial, causing a wide range of positive effects across several sectors. In fact, shifting vehicle design away from the use of fossil fuels will also help reduce CO_2 emissions from cars by 88% by 2050 and in parallel

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help cut air pollution from causing 467000 premature deaths in Europe every year. The transition to electro-mobility would also allow the EU to cut its spending on oil imports by 49 billions in 2030 [1].

Within the electro-mobility framework electric bikes (e-bikes) are of great importance. In fact, e-bikes allow for longer distances to be cycled with respect to conventional bikes, make it easier to overcome natural obstacles such as hills and open up cycling for groups that have not cycled previously due to their physical condition. In 2023, global sales of e-bikes are forecast to reach approximately 40 million units, especially in China, leading with 34.3 predicted sales [2].

To improve the efficiency of battery-powered vehicles such as e-bikes, a hybrid configuration in which the electric motor uses both energy stored in a battery and energy produced in a fuel cell stack can be adopted.

In this study, a hybrid power unit based on a fuel cell stack fed by hydrogen is proposed and implemented on board of a commercial electric bike. The energy performances of this hybrid prototype are assessed as well as its radiated electromagnetic emissions by means of standard electromagnetic compatibility facilities.

The remainder of the paper is organized as follows: in sect. **2** the prototype is pre-

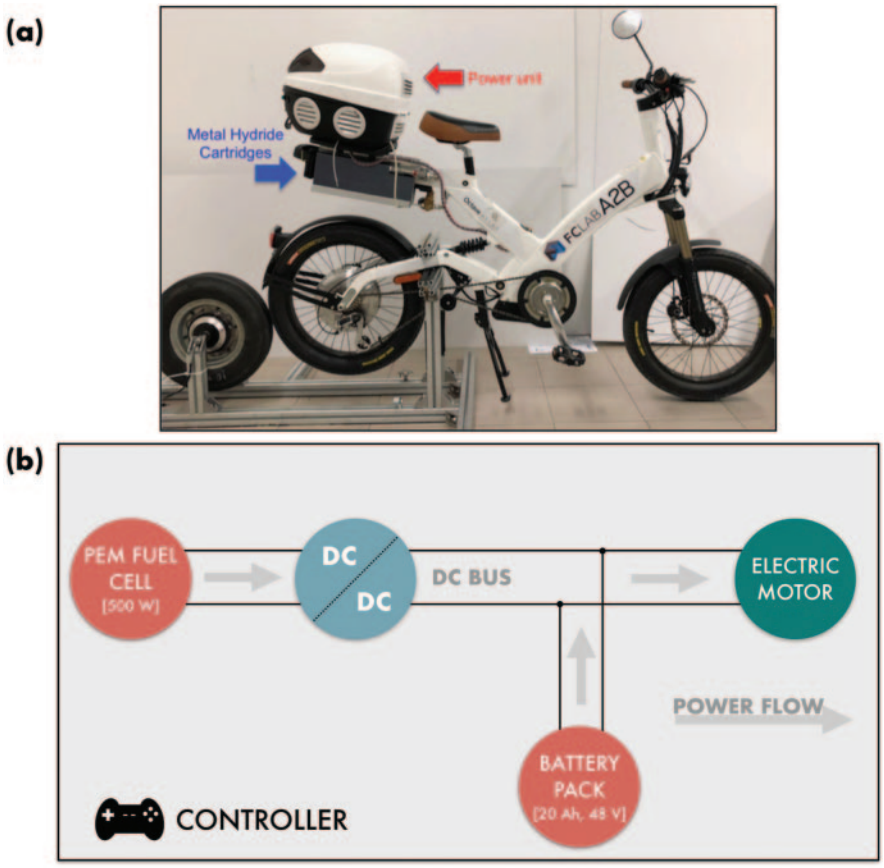

Fig. 1. – The proposed prototype: (a) hybrid 24 model produced by A2B; (b) sketch of the hybrid power unit.

sented focusing on its hybrid power unit; in sect. **3** the measurement setup adopted for evaluating the radiated emissions is described as well as the experimental results are interpreted in terms of standard regulations on electromagnetic emissions and their long-term effects on humans' health; conclusions are drawn in sect. **4**.

2. – The Hy-bike

The hydrogen bike (Hy-bike) is an electric-assisted bicycle powered by a combination of human effort and electric engine (500 W DC brushless motor). This Hy-bike has been realized by modifying an existing battery-based electric bicycle produced by A2B (Octave model, see fig. 1(a)). The new bike configuration proposed in this study is equipped with a hybrid power unit consisting of a fuel cell stack and a lithium ion battery. A PEM fuel cell stack, fed by hydrogen, supplies the required electric power so that the pedal-drive system reduces the rider's energy consumption during the cycling activities [3]. A sketch of the hybrid power unit is depicted in fig. 1(b).

The fuel cell is a PEM stack fed by hydrogen stored by means of metal hydride cartridges installed on board the vehicle beneath the rear rack. The stack consists of 24 cells with nominal and peak power of 500 W and 550 W, respectively. The battery is a 12 Ah $LiFePO_4$ rechargeable battery pack. The fuel cell stack is designed to operate at 65 °C and its performance, in terms of hydrogen consumption *vs.* power production, is illustrated in fig. 2. Details on the Hy-bike configuration are listed in table I.

Furthermore, an on-board control system allows to manage the power sources; in particular, if the battery state of charge is higher than a high threshold value, the fuel cell stack is off, and the battery provides all the energy needed by the motor, while when the battery state of charge drops below the high SOC (state of charge) threshold value, the fuel cell turns on and operates either in load balancing mode producing constant power with the maximum efficiency or in load following mode, charging the battery (when it is possible) and producing all the power needed by the electric motor until its

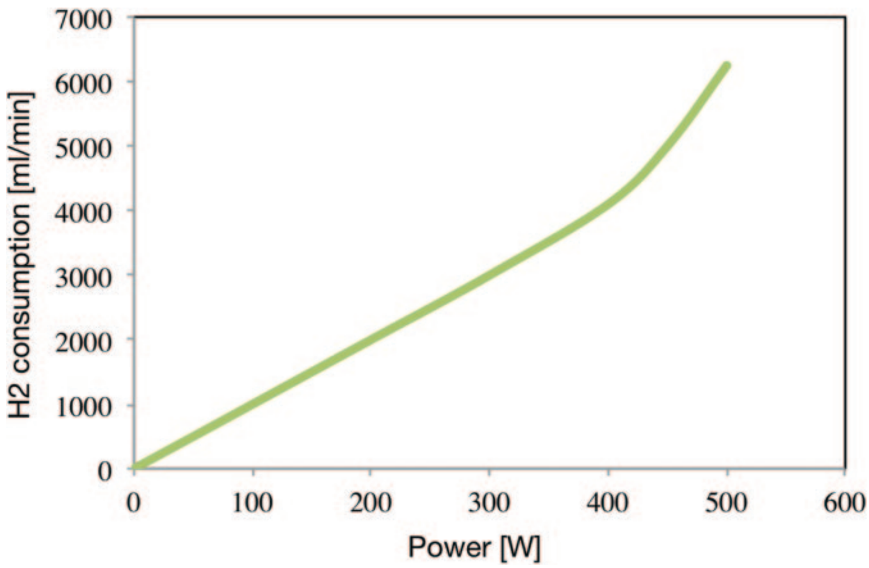

Fig. 2. – Fuel cell hydrogen consumption *vs.* power production.

rated power is reached.

Thus, the proposed prototype combines the advantages of electrically assisted battery-based bicycles with the high performance of the fuel cells technology by obtaining a significant improvement with respect to the original electric bike, *i.e.*, the distance covered at maximum power —500 W— is approximately doubled if compared to the Octave model. In addition, a 140 km long distance can by covered by the Hy-bike at mean power (250 W). The energy performance of the Hy-bike are summarized in table I.

In addition, since in the context of a large-scale transition from fossil-fuels–based

TABLE I. – *Hy-bike specifications.*

Bike	
Model	A2B OCTAVE
Frame	Aluminium 6061
Brakes	Tektro Auriga E-Comp, Hydraulic Disc Brake
Electric engine type	Brushless DC hub monitor
Electric engine power	500 W
Maximum speed	25 km/h
Distance at max power (500 W)	50 km
Distance at mean power (250 W)	140 km

Hybrid power unit	
Fuel Cell	
Type	PEM FC
Humidification	Self-humidified
Reactants	Hydrogen and air
Dimensions (cm)	$13 \times 26.8 \times 12.25$
Rated power (W)	500
Rated voltage (V)	14.4 (at 35 A)
Maximum stack temperature (°C)	65
H_2 Pressure (bar)	0.45–0.55
H_2 Purity (%)	99.995
Efficiency (%)	40 (at 14.4 V)
Battery	
Type	LiFePO4
Voltage (V)	36
Current (Ah)	12

Hydrogen storage unit	
Type	Metal hydrides tank (AB2 type)
Weight (kg)	3.6
Dimensions (cm)	$32.5 \times 12 \times 3$
Cartridge internal volume (l)	0.48
Maximum operating pressure (bar)	20
Maximum H_2 charging pressure (bar)	30
Minimum temperature charging cooling (°C)	3
Maximum operating temperature (°C)	65
Filling capacity (g)	32

vehicles to electro-mobility the economic issue plays a key role, a first attempt of a large-scale production cost-analysis was undertaken. The latter pointed out how the proposed Hy-bike could be an affordable e-device considering that the cost of the prototype is ≈€6000,00 —which may be reduced up to less than €4000,00.

3. – Evaluation of radiated emissions

In order to evaluate the effects on the environment and the humans' health, several tests on the electromagnetic emissions radiated by the Hy-bike have been accomplished using the facilities of the Università degli Studi di Napoli "Parthenope". They include a reverberating chamber, electric and magnetic field probes and spectrum/network analyzers.

The emission measurements are undertaken, in the frequency range 250 MHz–1 GHz, by placing the Hy-bike in a reverberating chamber whose sizes are 5 m × 6 m × 4 m, see fig. 3(a). It is a standard test facility widely used for several applications that include emission and immunity tests, microwave absorbing, shielding effectiveness, emulation of propagation channels and scattering measurement of test targets [4-6]. The reverberating chamber is all made of aluminium and the stirring is achieved by two volume and three plane stirrers. The measurements are accomplished under a continuous-mode stirring, where volume (plane) stirrers rotate at a speed of 10 (30) rpm in order to randomize

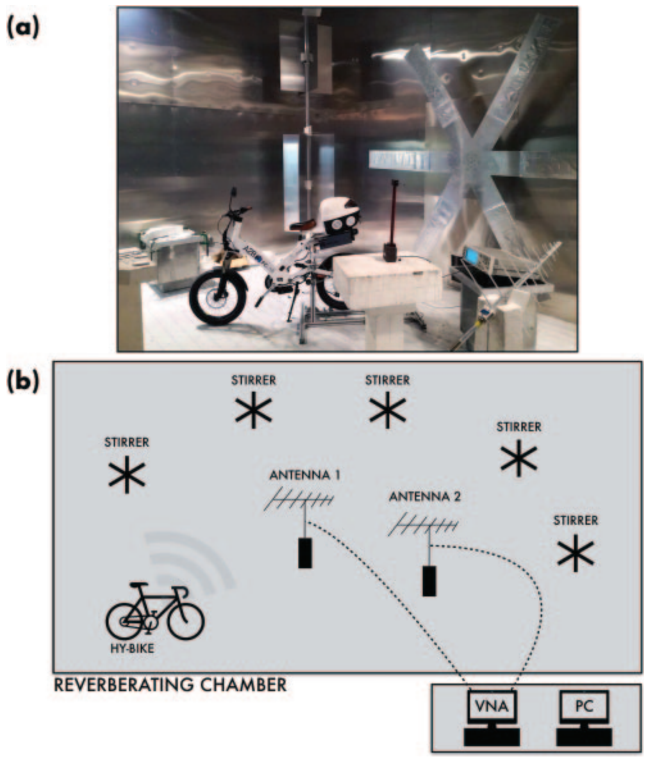

Fig. 3. – Emission measurements setup: (a) Hy-bike prototype within the reverberating chamber of the Università degli Studi di Napoli "Parthenope"; (b) sketch of the experimental configuration.

Table II. – *Measurement facilities for electromagnetic compatibility tests.*

Reverberating chamber	
Dimensions (m)	4
Plane (Volume) stirrers	3 (2)
Stirring mode	Continuous
Plane stirrers speed (rpm)	30
Volume stirrers speed (rpm)	10

Measurement equipments	
Network analyzer	Agilent E8363B
Spectrum analyzer	Rohde & Schwarz FSP
SA frequency range	9 kHz–40 GHz
Detector mode	Quasi-peak

the field within the chamber. The "calibration" of the reverberating chamber is made by measuring the insertion loss through an Agilent E8363B network analyzer using an horizontally polarized antenna, while the radiated power measurements are undertaken by means of two linearly polarized, with orthogonal polarizations, antennas and a Rohde&Schwarz FSP spectrum analyzer. Further details on the measurement setup and instrumentation, whose sketch is shown in fig. 3(b), are listed in table II.

High performance is achieved by the reverberating chamber that experienced a noise floor below −100 dB over the considered frequency range (250 MHz–1 Ghz). Once the power radiated by the Hy-bike in the reverberating is measured, emissions of the electric field can be evaluated.

Radiated electric emission tests are undertaken according to the regulation standard

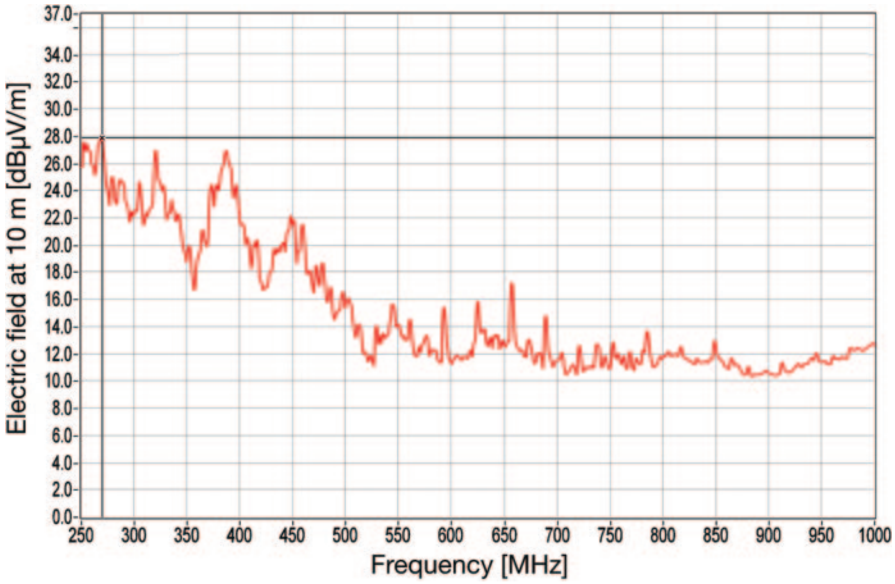

Fig. 4. – Electric field radiated by the Hy-bike at an equivalent distance of 10 m (averaged over all the polatizations).

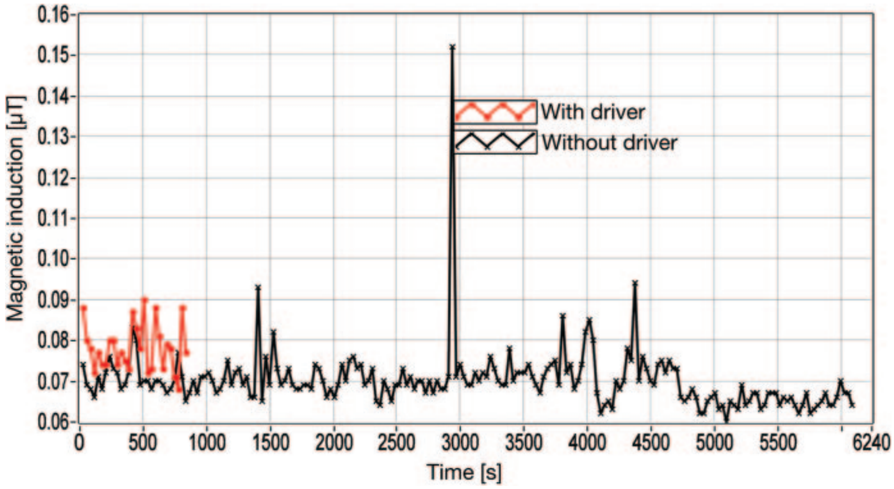

Fig. 5. – Hy-bike radiated magnetic field: magnetic induction measured in the frequency range 5 Hz–100 kHz.

for private devices *CISPR 16-2-3:2016* [7] and *IEC 61000-4-21* [8], that establish the limit and attention values. Figure 4(a) shows the electric field radiated by the running Hy-bike under a constant load, measured at an equivalent distance of 10 m and averaged over the two main antenna polarizations. It can be noted how the electric field is well below the limit value of 37 dBμV/m over the whole considered frequency range (250 MHz–1 GHz).

Radiated magnetic emission tests, in turn, are undertaken according to the legislative decree n. 81 (9 April 2008) [9], which provides the attention values for long-term exposition of humans to radiations. Figure 5(b) shows the magnetic induction produced by the Hy-bike and measured with and without the driver during about 10 minutes in the frequency range (5 Hz–100 kHz), which is recognized as the most critical one in terms of biological effects for humans. It can be observed how the magnetic induction is significantly below the lowest (at 100 kHz) attention value of 20 μT in all cases.

4. – Conclusions

This study demonstrates the effectiveness and the high performance of the proposed prototype, *i.e.*, the Hy-bike. The latter represents a new concept of electro-mobility with negligible electro-smog contribution with respect to the actual regulations in terms of short- and long-term impact on the environment and humans' health, respectively.

In detail, remarkable energy performances are achieved by the Hy-bike —about 140 km can be covered at the mean power of 250 W, while electromagnetic emissions lie well below the actual limit and attention values imposed by standard regulations, *i.e.*, less than 28 dBμV/m and 0.16 μT for the radiated electric field and magnetic induction, respectively.

From a commercial viewpoint, it must be pointed out that the individual prototype proposed in this study globally costs ≈ €6000,00, which may be reduced up to less than €4000,00 in a large-scale production perspective.

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REFERENCES

[1] ECF, *Fuelling Europe's Future*, `https://europeanclimate.org/fuelling-europes-future/`.
[2] Statista.com, *Worldwide sales of electric bicycles*, `https://www.statista.com/statistics/255653/worldwide-sales-of-electric-bicycles/`.
[3] Mellino Salvatore, Petrillo Antonella, Cigolotti Viviana, Autorino Claudio, Jannelli Elio and Ulgiati Sergio, *Int. J. Hydrogen Energy*, **42** (2017) 1830.
[4] Sorrentino A., Ferrara G., Migliaccio M. and Cappa S., *Appl. Comput. Electromagn. News.*, **33** (2018) 91.
[5] Migliaccio M., Gil J. J., Sorrentino A., Nunziata F. and Ferrara G., *IEEE Trans. Electromagn. Compat.*, **58** (2016) 694.
[6] Gifuni A., Ferrara G., Sorrentino A. and Migliaccio M., *IEEE Trans. Electromagn. Compat.*, **57** (2015) 1.
[7] IEC, *CISPR 16-2-3:2016*, `https://webstore.iec.ch/publication/25877`.
[8] IEC, *IEC 61000-4-21: Testing and measurement techniques - Reverberation chamber test methods*, *Electromagnetic Compatibility*, Part 4-21 (2011).
[9] DECRETO LEGISLATIVO 9 aprile 2008, n. 81, *Gazzetta Ufficiale della Repubblica Italiana* (2008), `http://www.gazzettaufficiale.it/eli/id/2008/04/30/008G0104/sg`.