Electric bus

Hydrogen Fuel Cells mini bus for extra-urban application

In extra-urban bus applications, the adoption of powertrains based on full electrochemical energy storage seems not to be a viable solution to achieve a suitable vehicle range. However, hydrogen-powered vehicles (HFCVs) are another technological option trying to overcome BEV limitations still having zero local emissions

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EU's Energy Transition and Sustainable Development policies aimed at mitigating global warming have set the goal of zero greenhouse gas emissions by 2050. The resulting objective for the transport sector is a reduction of Greenhouse Gas (GHG) emissions by 33% (compared to 2005) by 2030 and by 90% (compared to 1990) [1], [2].

One of the main actions in the transport sector of EU strategy aims at reducing CO_2 and other GHG emissions by replacing the conventional Internal Combustion Engine (ICE) based vehicles with electric vehicles (EV) [3], [4]. EVs represent a viable alternative to traditional ICE because of their low emissions, and efficient reduction of CO_2 also achieved by energy recovery during braking operations and zero local emission on the exhaust pipe. [5].

Undoubtedly, the transition to electric mobility represents a fundamental step towards eliminating direct environmental emissions, while indirect emissions depend on the nature of the energy sources used to produce electricity. As for the UE28, forecasts are encouraging, being expected that the EU grid mix will come down from 300 gCO_2 eq/km in 2015 to 200 gCO_2 eq/km in 2030 and 80 gCO_2 eq/km in 2050 [6]. Therefore, EVs powered by renewable energies represent a sustainable solution since they allow for zeroing and/or minimizing both direct and indirect emissions during the entire energy cycle. Moreover, EVs use different alternative vehicle powertrain technologies [7], including hybrid configurations (using a combination of onboard energy sources) and/or alternative fuels, both based on renewable or fossil sources. Indeed, EVs are highly dependent on available energy storage technologies, such as electrochemical battery cells, Fuel Cells (FC), and Ultra Capacitors for power [8]. Each of them is characterized by different values of energy density and power density that, depending on the type of application, must meet the performance requirements of the vehicle. Currently, both hybrid electric vehicles (HEV) and Battery Electric Vehicles (BEV) are based on the use of electrochemical batteries to store electric energy onboard. In the specific calculation of the vehicle GHG emissions, it is also necessary to include the environmental impact associated with the entire life cycle (LCA - "Life Cycle Assessment") of electrochemical storage systems. Recent LCA studies carried out on different types of lithium-ion batteries used in electric vehicles show consistent GHG emission values ranging from 70-175 $kgCO_2$eq per kWh of storable energy. Assuming proper recycling of materials or reuse of the same batteries for other applications, an average emission reduction of 20 $kgCO_2$eq/kWh can be achieved [8].

Nevertheless, in extra-urban bus applications, the adoption of powertrains based on full electrochemical energy storage seems not to be a viable solution to achieve a suitable vehicle range. However, hydrogen-powered (by Fuel cell) vehicles (HFCVs) are another technological option trying to overcome BEV limitations still having zero local emissions. As fuel cells are inadequate to follow highly transient road power demands, for the automotive applications, they are usually hybridized with electrochemical batteries [9–12], and over the last decade, more than 80 hybrid transit buses using hydrogen FC and batteries have been operated on about 8 million kilometers in several European cities, demonstrating the suitability of the technology [13]. Different is the case of

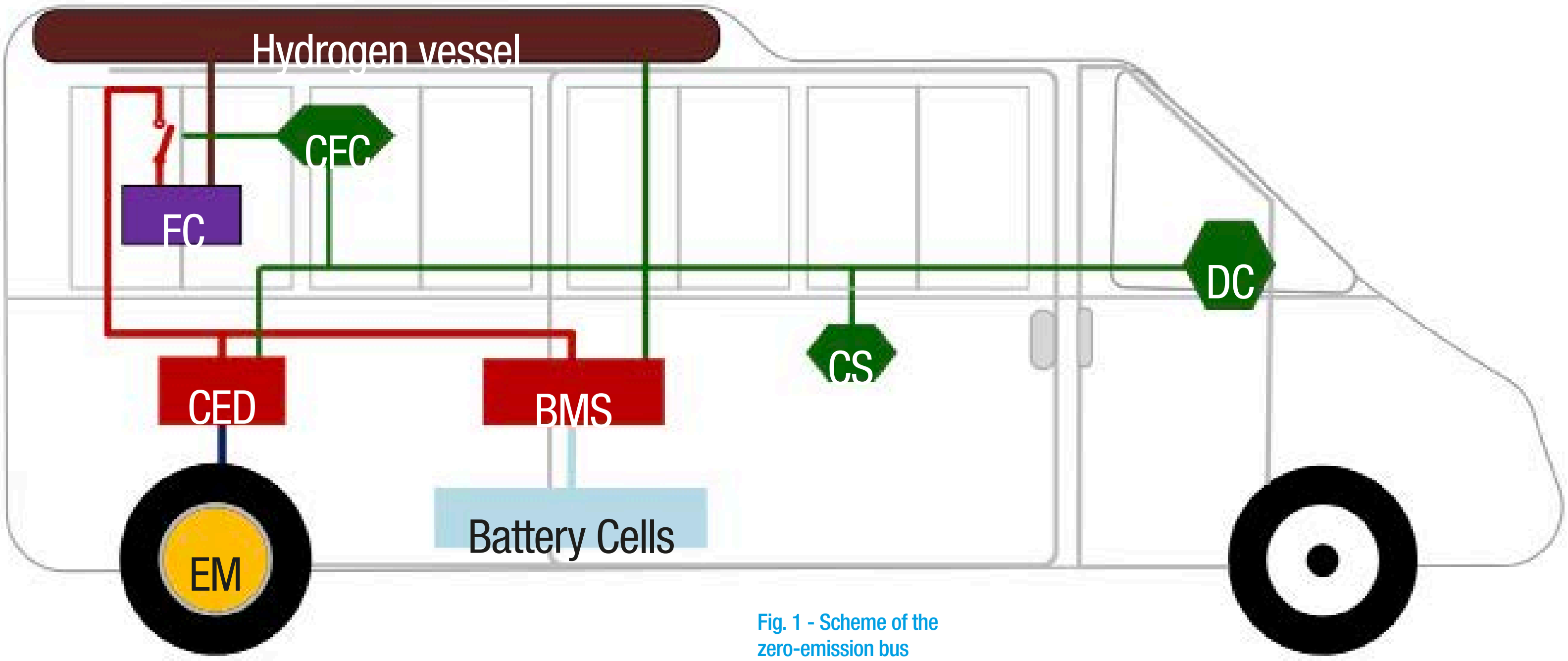

Fig. 1 - Scheme of the zero-emission bus

FC: Fuel Cell
EM: Electrical Motor
CS: Control System
CFC: Control Fuel Cell
DC: Driving Controls
CED: Converter Electric Drivetrain
BMS: Battery Management
DC Power Bus
Communication Bus

extra-urban buses, where the technology is still in demonstration stages, where the available studies tend to confirm that the hybridized configuration featuring FC and batteries is a viable architecture for extra-urban buses to reduce the battery size and to achieve promising vehicle autonomy.

The application

In the extra-urban context, the authors have investigated the adoption of a FC hydrogen mini bus configuration within the Life 3H project which is has been founded by the EU to explore and demonstrate the adoption of Hydrogen-based transportation systems [14]. In detail, the project's overall objective is to set up, demonstrate and exploit 3 Hydrogen Valleys in Italy, starting from the implementation of clean, agile & small H2 buses fueled with surplus H2 coming from local industrial productions thus closing the economical circle locally. H2 by-product will come from two local chemical industries: Terni steel factory and Chimica Bussi chlorine-soda plant. In turn, the project will demonstrate new transport solutions to increase air quality, reducing emissions, facilitating mobility, economic growth, and environmental sustainability while protecting human, building and natural areas. The sites for setting up the Hydrogen Vehicles are: The historical city of Terni (characterized by narrow roads near one of the biggest Italian steel plants), Port of Civitavecchia (with a million of tourists per year and a historical port), the Altopiano delle Rocche (with ski resorts and part of the Regional Park Sirente Velino). In these areas, H2 buses are the envisioned mobility solution to zeroing the emissions and protecting the human, building and natural areas. In particular, the service site – Altopiano delle Rocche is a challenging extra-urban service in terms of altimetric profile since it foresees the connection of cities and villages in a mountain region, covering up to 900 m of difference in altitude. These site characteristics make the demonstration of the H2 bus service challenging, since most of H2 buses available in the market or experimented within research projects are envisioned for urban operation [15].

In this paper, the mentioned FC Hydrogen mini bus configuration has been investigated by simulating the vehicle mission over a driving cycle derived from the standard driving cycle WLTP1, in order to evaluate the vehicle performance and hydrogen consumption.

The architecture and the model of the H2 mini bus

A scheme of the proposed vehicle architecture is shown in Fig. 1. The proposed power plant uses an Electric traction Motor (EM) fed by a hybrid power unit consisting of a hydrogen Fuel Cell (FC) and a battery pack system.

The EM and the FC are connected to the DC power bus (continuous red line) by means of converters, while the high voltage battery is directly connected to the DC power bus and managed by the Battery Management System (BMS). To manage the power flows required, a master control system (CS) communicates with the FC control system (CFC) and the driving control (DC) via a communication bus (green line). The detailed block diagram of the envisioned electric power system is shown in Fig. 2 where the power and control lines are detailed. It is based on an FC stack controlled by its Fuel Cell Controller (CFC) and equipped with a DC/DC converter to ensure the proper energy transfer from the FC to the DC bus. The Energy Storage System (ESS) configured as a Lithium-ion battery is directly connected to the DC bus and managed by the Battery Manager System BMS. The traction electric motor, the vehicle single gear transmission and the related power electronics are referred as the Electric Drivetrain and are managed by the Electric Drivetrain Controller (CED).

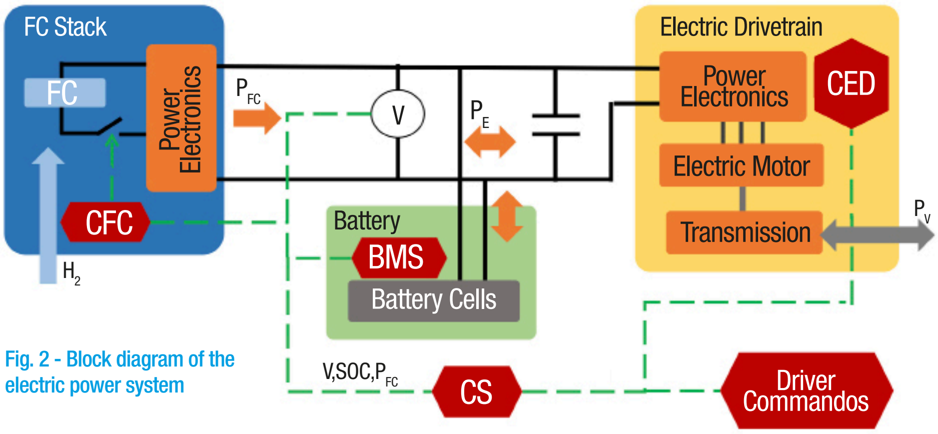

Fig. 2 - Block diagram of the electric power system

> "The transition to electric mobility represents a fundamental step towards eliminating direct environmental emissions, while indirect emissions depend on the nature of the energy sources used to produce electricity"

The Electric Drivetrain is directly connected to the DC bus by mean of a bulk capacitor. wIn terms of power, the proposed configuration requires the battery to be sized to provide the peak power of the Electric Drivetrain, while the FC is envisioned as a range extender, and it is managed to work at a fixed power level where maximum efficiency is achieved. To this extent, the BMS monitors the DC bus voltage and exchanges its level to the other controllers through the communication bus along with the State Of Charge (SOC) of the battery. When the SOC decreases below a proper threshold the main control system (CS) demands the FC to be powered-on and inject power into the DC bus to avoid the battery being fully discharged. Depending on the road grade and on the vehicle dynamics the fuel cell provided energy is used directly by the electric drivetrain or to refill the battery. The dynamic model of the FC bus has been developed for evaluating the performance of the vehicle and its components while moving on the target route. Here, the mathematical model is only briefly described and further details can be found in [14].

Based on the cinematic profile of the mission and vehicle parameters, the traction power requirement has been calculated starting from the differential equation of motion, splitting the external forces in traction thrust T (v(t)), and summation of the resistances to the vehicle motion, ΣR(v(t)). The latter can be expressed as the summation of rolling, R_w, slope, R_s, and air, R_A, resistances.

Thus, the traction thrust is given by:

$$T(v(t)) = m\alpha\frac{dv}{dt} - [R_W(v(t)) + R_s(\beta) + R_A(v(t))]$$

where, m is the gross mass of the vehicle, α is the inertial rotational mass coefficient, v is the vehicle speed, and β is the angle of the road slope.

The electrical traction power, P_{el}, has been calculated considering also the regenerative electrical braking, as:

$$P_{el} = T(v(t))v(t)/(\eta_t\eta_D) \quad for \quad T(v(t))v(t) > 0$$

$$P_{el} = T(v(t))v(t)\eta_t\eta_D \quad for \quad T(v(t))v(t) < 0$$

With η_t and η_D (vT) the transmission and electrical traction drive (namely, converter plus electrical motor) efficiency respectively, the latter is mapped as a function of the vehicle speed and torque. Finally, the model considers that no energy is recovered if the state of charge (SOC) of the battery is full.

The model has been used to develop a simulation software implemented on Matlab-Simulink, whose sketch of the model implementation is shown in Fig. 3. The model calculates the power flows and the energy consumption (traction and auxiliary systems) starting from the definition of the inputs concerning the following three blocks:

1. "Vehicle features" addressing the characteristics of the vehicle (mass, dimensions, mechanics, efficiency, payload, etc.).
2. "Road characteristics" concerning the topography of the path and the road surface features.
3. "Drive cycle" describing the driving profile by specifying the speed versus time.

The "Traction power" block computes the mechanical power needed to drive over the input path with the selected vehicle at the specified speed profile.

From the inputs, the "Electric Drivetrain" block computes the electrical power needed for the traction, accounting for the energy losses of the gear, motor,

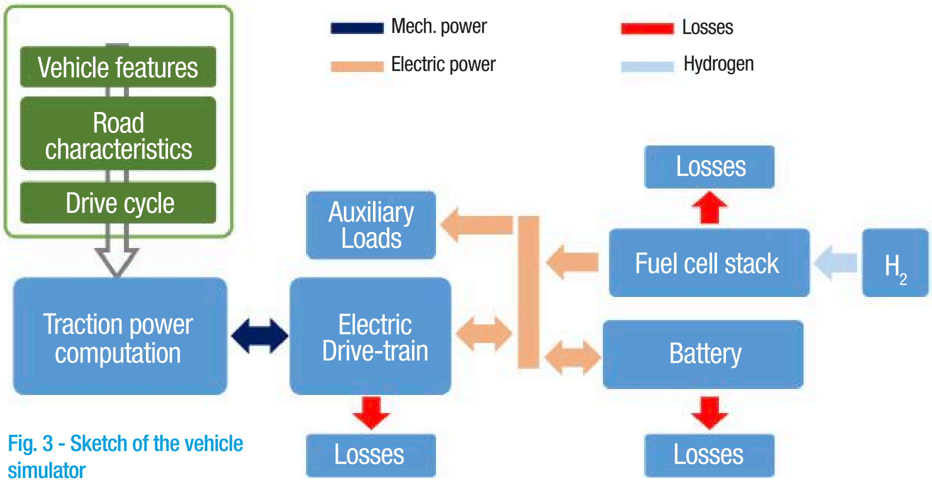

Fig. 3 - Sketch of the vehicle simulator

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ABOUT CITRAMS

CITRAMS is a University of L'Aquila Interdepartmental Center on Transportation and Sustainable Mobility. The Center involves the 7 departments of the university and several national and international experts in the field of transportation. CITRAMS promotes and coordinates interdisciplinary research, technology transfer and dissemination activities in the transportation (passenger and freight) and sustainable mobility sectors, with focus on: planning of transport systems and related socio-economic and management aspects, theoretical analysis and modelling of demand, transport supply and their interaction, advanced transport systems (terrestrial, air, naval, inter-modal and multi-modal) and technological innovation of their components, and interaction between transportation, physical/social environment, education, health, disability and aging.

and power converter. The computation of drivetrain losses is based on look-up tables validated by means of experimental data and by literature. The torque-speed working point of the electric drivetrain is the input of the look-up table; power losses are the output. The losses produced by the fuel cell stack and the battery are evaluated by considering their system efficiency. The model allows computing the total energy required (including auxiliary loads) and the hydrogen consumption in the given track with the envisioned driving cycle.

Estimation of the H2 consumption

The main features of the selected zero-emission hybrid vehicle, with a carrying capacity of 25 passengers, are shown in the Table 1. The selected electric powertrain characteristics suitable for the envisioned vehicle are reported in the following table 2. To preliminary evaluate the vehicle performance in terms of hydrogen consumption, a standard driving cycle has been selected as input of the model. The WLTP1 driving cycle has been recognized as suitable in terms of speed range and vehicle power-to-weight ratio. For a better evaluation of the energy management of the battery and the FC, the WLTP 1 driving cycle is repeated 10 times for a total length of the cycle is about 80 km, the resulting

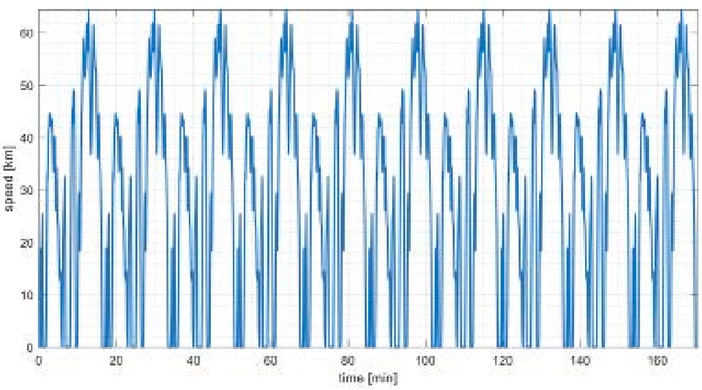

Fig. 4 - Adopted driving cycle derived from the WLTP1 one

Tab. 1 - Main vehicle data used in simulations Main vehicle data used in simulations

Parameter	Symbol	Unit	Value
Length		m	7.76
Width		m	2.4
Height		m	3.05
Passengers seats			25
Full load vehicle mass	m	kg	8700
Frontal section		m_2	7.32
Aerodynamic coefficient	c_x		0.380
Tires type			225/75 R-16

Tab. 2 - Electric powertrain characteristics

Parameter	Symbol	Unit	Value
Electric Drivetrain peak power		kW	200
Electric Drivetrain peak Efficiency		%	95
Battery peak power		kW	200
Fuel Cell Power		kW	50
Battery energy		kWh	50
Auxiliaries peak power		kW	12
DC Bus rated Voltage		V	800

speed profile of the driving cycle is reported in Fig. 4. From the proposed vehicle model, the traction power required to run the vehicle along the driving cycle can be computed and electrical power demanded to the battery and FC can be evaluated. The detail of the traction and electric power assuming 100% braking energy recovery is shown in Fig. 5. The electric power consumption due to auxiliaries must be taken into account to comprehensively compute the energy consumption. Fig. 6 Reports the results of the energy management of the FC and the battery. The control requires the FC to be powered on and off in attempting to maintain the State of Charge (SOC) of the battery close to its reference. The key energy transferred among powertrain components is reported in Fig. 7 where the energy provided by the FC is shown along with the energy required for the traction, the recovered braking energy, the losses in the ESS and the consumption of the auxiliary loads. Hence the H2 consumption can be computed, Fig. 8 reports the H2 consumption of the vehicle on the driving cycle, showing the case where only the traction contribution is considered in the H2 consumption and the case where auxiliary loads are included. Basing on the performance shown on the driving cycle, it can be stated that the vehicle H2 consumption in terms of travel is about 20-30 km/kgH2, taking the lower value as the most representative of the real consumption of the vehicle.

Conclusion

H2 powered vehicles represents an attractive technology for buses application, both in urban and extra-urban applications. The adoption of suitable vehicle models is relevant to early investigate the vehicle consumption, to properly size the vehicle powertrain basing on the vehicle mission profile, and to size and

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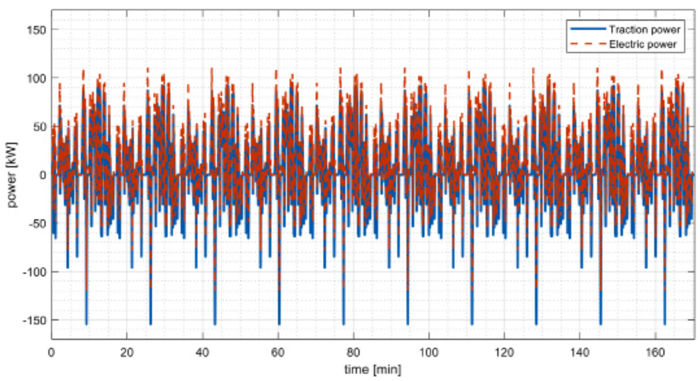

Fig. 5 - Electric power and mechanical power in the driving cycle

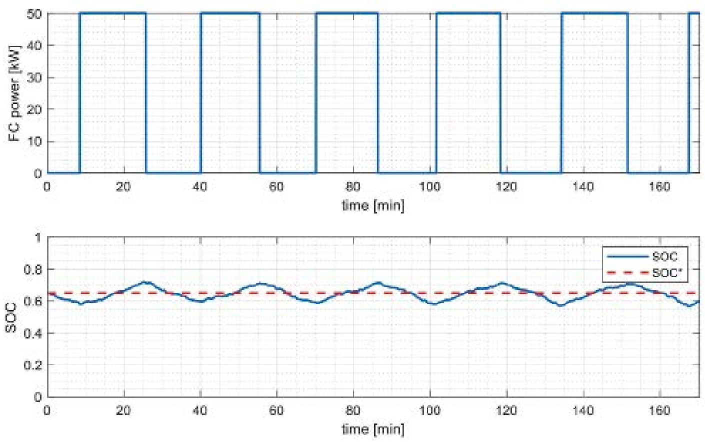

Fig. 6 - State of Charge and FC power over the simulated driving cycle

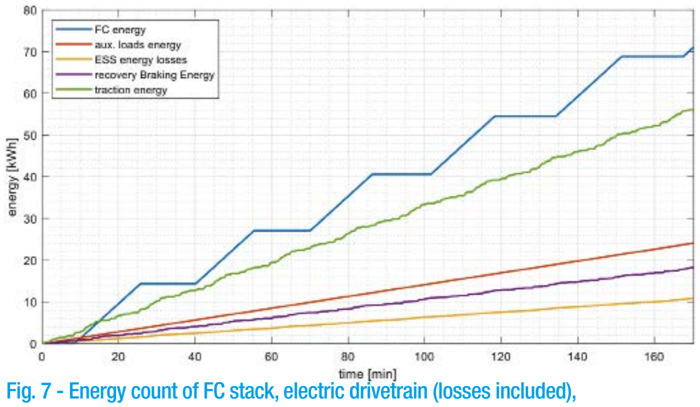

Fig. 7 - Energy count of FC stack, electric drivetrain (losses included), auxiliary loads, and energy losses in the FESS

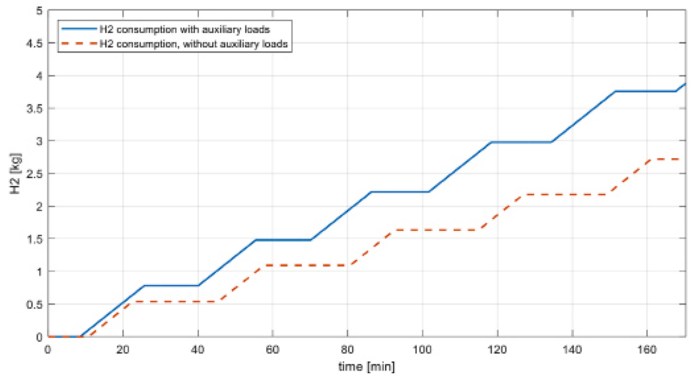

Fig. 8 - H2 consumption to afford the driving cycle, considering auxiliary loads and neglecting auxiliary loads

properly locate the infrastructure for the H2 refueling. Future research within the Life 3H project will focus on the adoption of more realistic driving cycles representing real driving condition and real altitude variation of target service tracks and will aim at the on-site demonstration of a H2 bus.

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