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## **Hydrogen Fuel Cell Buses for Urban Transportation in Brazil results**

Author1<sup>1</sup>

<sup>1</sup>Author 1 (Monica Saraiva Panik) São Paulo - SP, Brazil, Ohmdenerstrasse 173271 Holzmaden – Germany, monica.saraivapanik@fmpanik.de

Author 2<sup>2</sup>

<sup>2</sup>Author 2 (Prof. Dr. Ferdinand Panik) Berlin, Germany, Ohmdenerstrasse 173271 Holzmaden – Germany, fpanik@t-online.de

Author 3<sup>3</sup>

<sup>3</sup>Author 3 (Prof. Sidney Gonçalves de Oliveira Sobrinho), Rio de Janeiro – RJ, Brazil, Rua Abramo Pezzi 15 – 31ª 95013-020 Caxias do Sul – RS, Brazil sidney@trendtech.com.br

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### **Summary**

The “Hydrogen Fuel Cell Buses for Urban Transportation in Brazil”, was funded by the Global Environment Facility and by the Brazilian Government and implemented by the United Nations Development Programme and a Consortium of Brazilian and International companies. The main objectives were to transfer advanced technologies for pollution free urban transportation to Brazil and to benefit from existing Brazilian industry and country’s renewable energy matrix. The performance of the buses was very positive for passengers and operators. The objective of this presentation is to broaden the basis for scale effects in the early phase of the Fuel Cell Buses commercialization.

*Keywords: bus, fuel cell, hydrogen, market development, public transport*

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### **1.0 Background**

Bus is a major modality in passenger transport in Brazil and the country is one of the biggest bus markets in the world with a production of 30,000 buses per year. The São Paulo Metropolitan Area is the country’s

largest urban concentration and the 6<sup>th</sup> largest in the world, with 21,2 million inhabitants, 39 municipalities and 11,9 million vehicles, among them 43,5 thousand buses. Air quality drops below minimum acceptable standards for more than 140 days a year and motor vehicles are responsible for 90% of toxic pollutants released into the atmosphere. Diesel buses are major contributors to air pollution releasing more than 1.5 million tons of carbon dioxide annually. Brazil has a tradition of developing and using renewable energy sources in large scale, and hydropower and ethanol produced from sugarcane correspond to over 80% of the country energy matrix. The chronology of hydrogen development in Brazil was marked by the UNFCCC (ECO 92) and some initiatives that followed the discussions in Rio de Janeiro.

### **1.1 Historical events**

In November 2000 the GEF (Global Environment Facilities) decided to fund 5 Fuel Cell Bus Demonstration Projects in Developing Countries: Brazil, Mexico, Egypt, India and China. In January 2002, the UNDP (United Nations Development Programme) published a Letter for Expression of Interest, requesting companies to supply fuel cell buses and a hydrogen production and refueling station for Brazil. Ballard Power Systems, Stuart Energy and Marcopolo replied and in November 2004, the UNDP published a tender with the Technical Specification of the Project “Hydrogen Fuel Cell Buses for Urban Transportation in Brazil”.

### **1.2 The Consortium formation strategy**

In 2005, a detailed market research has been performed and the following companies formed a consortium, which signed a contract with the UNDP in May 2006, for the project implementation: AES Eletropaulo (São Paulo – Brazil, only phase II.2), Ballard Power Systems (Vancouver – Canada), BR Petrobras (Rio de Janeiro – Brazil), EPRI International (Palo Alto – USA), Hydrogenics (Mississauga – Canada), Marcopolo (Caxias do Sul – Brazil), Nucellsys (Nabern – Germany, only phase II.2) and Tuttotrasporti (Caxias do Sul – Brazil). The Brazilian governmental partners were the following: Ministry of Mines and Energy (MME), São Paulo Metropolitan Urban Transport Company (EMTU/SP), Financing Agency of Studies and Projects (FINEP) and the Cooperation National Agency (ABC) from the Ministry of External Relations.

### **1.3 Project Budget**

Total - US\$ 15,62 Million; Global Environmental Facilities – US\$ 12,274; Brazilian Federal Government (FINEP) – US\$ 3,346; Co-financing from the consortium members of approx. 10% of the total budget.

### **1.4 Project objectives**

1) To build and demonstrate functionality and reliability of fuel cell buses and of hydrogen infrastructure, under real operating conditions in the São Paulo Metropolitan Area; 2) To accelerate the commercialization of these technologies by involving the local industry; 3) To acquire and disseminate technical knowledge in production, operation and maintenance of fuel cell buses and of the hydrogen infrastructure.

### **1.5 Project strategic concept**

The project combined technology leadership of world class companies in their respective areas with the engineering and large scale capabilities of the Brazilian industry. To integrate an advanced hybrid fuel cell propulsion system in a local bus chassis and body, instead of importing existing fuel cell buses, required extensive engineering, testing and knowledge sharing, but resulted in better performance, stronger commitment and involvement of the local industry and higher public acceptance.

MAIN OBJECTIVES FOR THE BUS: 1) To apply compact and proven automotive fuel cell stacks and systems to reduce weight, volume and costs, and to benefit from the latest international developments and improvements; 2) To employ hybridization by combining fuel cell systems with batteries and energy management systems, allowing higher efficient operation, brake energy recuperation, improving lifetime and reliability; 3) To use proven components to achieve reliability and quality; 4) To integrate local content to fulfil market requirements and reduce costs; 5) To work with experienced companies to reduce risks.

MAIN OBJECTIVES FOR THE HYDROGEN FUELING STATION: 1) To provide a well- to- wheel CO<sub>2</sub>-free hydrogen production and fueling station, and to demonstrate the potential synergy between the Brazilian integrated hydroelectric system and the urban mass transportation; 2) To apply safety standards, codes and protocols; 3) To use the experience of local energy companies for construction, operation and maintenance.

### **1.6 Phased approach for project implementation**

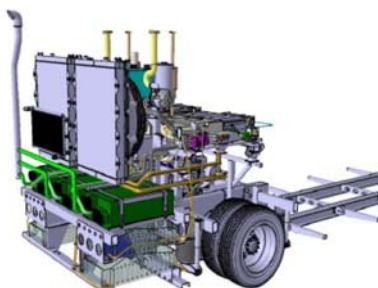
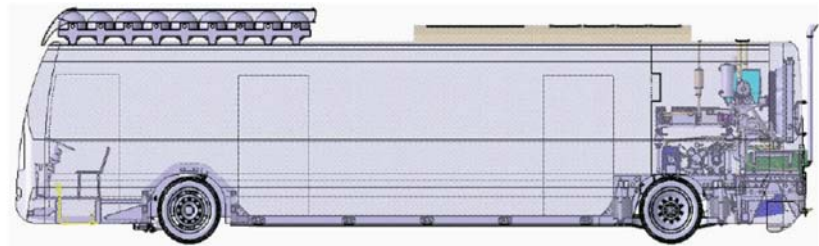
A phased approach was adopted for the project implementation to reduce technological and economic risks:

Phase I: Feasibility study; Phase II: demonstration project – divided in Phase II.2 (build and test a prototype bus and a hydrogen production and refueling station) and in Phase II.3 (build and operate in revenue service 3 new buses and the full use of the hydrogen station); Phase III and IV: scaling up.



## 2.0 Prototype Bus Project Phase II.2 May 2006 to August 2013

In order to reduce the economic and technological risks, the project team has decided to build a first prototype and to test it before building additional buses. The contract with the UNDP for the Phase II.2 has included a milestone for the phase II.3, depending of the success of the functional and verification tests at the EMTU/SP.



## 2.1 Consortium Members and the Prototype Bus Technical Concept

A new fuel cell hybrid bus has been engineered using a local bus chassis, a local bus body and local components. The use of the Brazilian bus industry knowhow and supplying chain played an important role in the mission to reduce costs and to meet the local market demands, by including local content.

### 2.1.1 Ballard Power Systems and the fuel cell stack

Ballard provided 85KW continuous, 300 Amps max and 284 Volts automotive fuel cell stacks: technical specifications; maintenance and service; special tools; and support for vehicle testing and certification, sharing its worldwide experience with the Brazilian engineers.

### 2.1.2 Nucellsys GmbH and the electric fuel cell hybrid system

Nucellsys led the coordination of the drivetrain system; provided two HY80 fuel cell light-duty automotive systems with a capacity of approx.130KW (simultaneously); system engineering of the electric drive, energy and hydrogen systems; some components for the cooling system; technical specifications; maintenance and service; special tools; and support for vehicle testing and certification.

### 2.1.3 Tuttotrasporti and the complete bus integration

With more than 95.000 chassis modified and manufactured, Tuttotrasporti was the bus integrator and chassis manufacturer, including packaging design, vehicle's managing system; software and hardware for the mechanical, pneumatics, hydraulics and electrical subsystems; and communication network's integration. The configuration prioritized the simplicity of the interconnections, safety, easy access for maintenance purposes and weight distribution. Tutto's engineers were trained by Ballard, Nucellsys, Dynetek, Siemens, MES-DEA and Modine, enabling them to take over the leadership of the electric drivetrain system for the 3 new fuel cell hybrid buses of the project phase II.3.

#### **2.1.4 Marcopolo and the bus body**

One of the biggest body builders in the world, with an annual production of 30.000 buses and 20 plants worldwide, Marcopolo was the bus body builder. Their greatest challenge was to combine the low weight requirements and extreme robustness with the comfort and greater capacity. Main specifications of the bus prototype body: Viale H low floor padron, 12,600mm length, 2,500mm width, 3,500mm height, 63 passengers, three urban doors located on the right side, space to wheelchair, hand-operated ramp for wheelchair, driver monitor and air conditioner.

#### **2.1.5 Main Suppliers**

3 ZEBRA Z37 batteries from **MES-DEA** providing 108 kW of peak power installed at the rear underneath the radiators. **Siemens** „ELFA“ systems including two dual inverters, two dual reactors for two traction induction motors combined by a summation gearbox, two auxiliaries induction motors. **Modine** supplied most of the cooling systems' components.

#### **2.1.6 EPRI International and the project management and consortium leadership**

A neutral institution has been chosen for the consortium leadership and project management. EPRI International, a wholly owned, U.S.-based, for-profit subsidiary of the Electric Power Research Institute, promoted the exchange of lessons learned with similar international projects, coordinated testing and an independent evaluation of the final product, and performed simulations to determine an optimum hybrid concept according to the bus corridor drive cycle.

## **2.2 Consortium Members and the Hydrogen Station Technical Concept**

An on-site electrolyser hydrogen production and fueling station has been constructed at the EMTU/SP facilities and Metra's garage in São Bernardo do Campo in the São Paulo State. The first production and refueling station in South America has been integrated by BR Distribuidora, with technical support from Petrobras, Hydrogenics and AES Eletropaulo (only Phase II.2).

#### **2.2.1 Hydrogenics and the hydrogen station equipment**

Hydrogenics supplied a HySTAT-A60 Nm<sup>3</sup>/h (120 kg/d) electrolyser at 10 barg pressure, a 430 barg (6,250 psig) compressor system, 6 high pressure storage vessels of 72 kg and a CaFCP 6.1 Protocol' dispenser; support for site preparation; training; equipment installation, commissioning and maintenance. This fueling station involved a coordinated effort of the Belgium and the Mississauga facilities.

#### **2.2.2 BR Petrobras and the hydrogen station design, operation and maintenance**

Brazil's largest fuel distribution company with more than 7,000 service stations, BR Petrobras (a subsidiary of Petrobras) was the prime integrator of the hydrogen fueling station and responsible for operation, general maintenance and for obtaining the related licenses at the Brazilian local authorities. BR counted with the support of CENPES (Petrobras Research Center), for preparing hazard and safety studies (Hazop).

#### **2.2.3 AES Eletropaulo and the electricity for generating hydrogen by electrolysis**

AES Eletropaulo, an utility company which attends 24 cities in São Paulo Metropolitan Region, was responsible for the specifications, design, and approval of the electric substation; connection of the electric substation with the distribution network; and assuring the energy quality and the availability of the electric substation to the supplying location according to the applicable Brazilian law and standards.

**2.2.4 Perspectives for producing hydrogen by electrolysis in Brazil:** the Brazilian electric system is characterized by long-ranging transmission lines and a hydroelectric producing system. The consumer market is centered on the South and Southeast regions, the more industrialized ones. The North region is intensively addressed by small generating plants, most of them diesel-powered thermoelectric plants. Along the last two decades, the expansion rate of the electric energy consumption was far superior to the GDP, in view of the population growth in the urban zones and the efforts for increasing the energy supply. However, there is always the possibility of hydric reserve surplus (water that should be used to move turbines, and is not, due to lowest demand in that specific moment). The virtual energy available for this application may be estimated, taking as an example the Itaipu's power plant, where about 3,8% of the poured energy not used for consumption corresponded to an average of 4,0 TWh in 2016. If all hydraulic, non-explored potential, were at stream course and had the same utilization level as Itaipu, **more than 28 TWh/year could be used for**

**producing hydrogen.** Another characteristic of the Brazilian electric system is that daily demand is not uniform along the day, and the electric energy produced outside “peak hours”, could be stored in hydrogen.



## 2.3 Main Events and Contract Milestones

The contract has established milestones for bus and infrastructure separated, enabling that the payments for the consortium members were made according to their activities, but at the same time promoting jointly efforts among bus and the hydrogen station stakeholders to reinforce strong commitment and cooperation.

**May 12<sup>th</sup> 2006: Milestone 1 Signature of the contract by all partners.** November 13<sup>th</sup> 2006: Petrobras Technical Event in São Paulo. **January 22<sup>nd</sup>/23<sup>rd</sup> 2007: Milestone 3 Bus “FAT Fuel Cell System”.** **February 1<sup>st</sup> 2007: Milestone 3 Bus “FAT Chassis” & “FAT Body Structure Part1”.** April 17<sup>th</sup> – 20<sup>th</sup> 2007: Safety Workshop to validate 14 generic potential hazards of each safety relevant subsystem of the bus and of the hydrogen station. **May 3<sup>rd</sup> 2007: Milestone 3 Hydrogen Station “Receipt of Main Equipment at the Factory”.** May 5<sup>th</sup> 2007 to May 12<sup>th</sup> 2007 – Visit of the Brazilian license authorities in the hydrogen stations in Hamburg and Amsterdam. The Petrobras Technical Event, the Safety Workshop and the Visit of the Brazilian Certification Authorities to Europe, promoting their early involvement since the early stage of the station design, facilitated the licensing of the hydrogen station. **July 6<sup>th</sup>/August 27<sup>th</sup> 2007: Milestone 4 Hydrogen Station “FAT Main Equipment”.** **October 3<sup>rd</sup> 2007: Milestone 4 Bus “FAT Bus on Battery Mode”.** **Dec 31<sup>st</sup> 2007/Jan 18<sup>th</sup> 2008: Milestone 5 Hydrogen Station “Receipt Main Equipment at EMTU”.** **July 22<sup>nd</sup> 2008: Milestone 5 Bus “Complexion Prototype Hybrid configuration Hydrogen Power”.** **April 28<sup>th</sup> 2009: Milestone 6 Bus “Functional Tests Protocol”.** **April 16<sup>th</sup>-17<sup>th</sup> 2009 and May 20<sup>th</sup>-21<sup>st</sup> 2009** – Training Courses for drivers and maintenance technicians from METRA by Tutto and EPRI Intl. Operation and maintenance manuals in Portuguese language were prepared and distributed, and 21 persons have been trained. **October 2009** – Publishing of the Brazilian Fuel Cell Bus BOOK. **October 11<sup>th</sup> 2010: Milestone 7 Bus “Verification Tests Part 1 Protocol”.** **March 2011** - The Brazilian Fuel Cell Bus voted by a public and a technical jury as one of the 3 finalists in the category of Transportation, of the Green Best, the biggest Brazilian prize for Sustainability. **March 24<sup>th</sup> 2011: Milestone 8 Bus “Verification Tests Part 2 Protocol”.**

## 2.4 Tests and Optimization

### 2.4.1 Functional Tests from November 2008 to April 2009

**Summary results:** a provisory hydrogen station has been built by Air Liquide near Tutto’s manufacturing plant. Carried out in Caxias do Sul on both special and regular roads, the prototype bus has passed with success through all functional tests and has been validated to operate on the EMTU/SP track: 1) **Fuel consumption:** in average 13,30 kg H<sub>2</sub>/ 100 km in bus corridor operation with average speed of 23,6 km/h and max of 60 km/h. 2) **Noise level:** fulfills legal requirements (Conama 272/2000) and meets the CONTRAN resolutions concerning to interior and pass-by-noise. 3) **Acceleration:** meets the basic technical specification 1,10 m/s<sup>2</sup> @ 0% slope, 0,5 m/s<sup>2</sup> @ 10%. Due to route availability the test of 15% hasn’t been done. 4) **Speed**

**recovery:** from 20 to 60 km/h and from 40 to 60 km/h, similar to diesel. 5) **Maximum speed:** non sound alert signal for above 55 km/h. 6) **Startability:** with full load of 18.5 t - 0 to 50 km/h in less than 15 s. 7) **Gradability:** 30 km/h @ 10% slope, 20 km/h @ 15%, start without backward movement up to a 25% slope. 8) **Backward movement:** approved in upward and downward conditions. 9) **Service break:** deceleration and response time better than specified. 10) **Emergency break:** not pushed to braking limit, but deceleration value (2,42 m/ s<sup>2</sup>) was very close to the specification. 11) **Parking break:** remain stationary on a 20% slope at total gross weight condition. 12) **Brake fading:** ABNT NBR 10967 - submitted to a 20 times breaking cycle from 60km/h to 30 km/h. No efficiency loss observed, average deceleration greater then specified.



#### 2.4.2 Verifications Tests Part I from October 30th 2009 to February 28th 2010

EMTU/SP is the transit authority of 5 metropolitan regions of the São Paulo State, formed by 133 municipalities with a population of 29.1 million inhabitants. The fuel cell hybrid buses operated on the segregated bus corridor “São Mateus-Jabaquara (ABD)” along the line 287-P, which has 45 km, 9 metropolitan terminals and 156 bus stops, and which in average transports 300 mil passengers daily, connecting 5 municipalities (São Paulo, Mauá, Santo André, São Bernardo and Diadema). The buses are operated by METRA, a private bus company with 260 buses, among them trolley and hybrid diesel buses, which makes a difference in urban bus transportation offering better service, better products and being environmentally oriented. The average speed at the bus corridor is 21km/h because the buses are running separated from other vehicles avoiding traffic jams. The strategy to introduce clean technology buses in bus corridors in big cities, is based on the fact that they transport more passengers generating higher revenue and therefore enable investments in better services and more expensive equipment.

**Objectives:** To verify 1) the bus performance on the EMTU bus corridors according to customer expectations; 2) the bus acceptance by the bus operator, by the regulation authority, by the drivers and by the general public; 3) the overall bus concept driving on bus corridors, according the operation, maintenance, safety, data collection and fuelling routines at the EMTU/Metra facilities; 4) the bus performance in the different bus corridors and routes comparing with other technologies, such as diesel, ethanol and trolley.

**Summary results:** The verification tests I program was conducted by a Brazilian company (NETZ) and the collected data was used for optimization work, diagnostics and preventive maintenance purposes. The prototype never broke down during operation and always returned to the EMTU/SP-METRA facility. The sub-systems and especially the fuel cell systems and the batteries operated very stable. No degradation could be observed on the fuel cell side but some degradation processes started in two of the three batteries which could be compensated by the battery management system. The failures were mainly caused by corrosion and humidity issues. There were no problems with maintenance, safety and fuelling. The maintenance services were always made jointly with METRA’s teams developing a cooperative and effective team spirit among the partners. Fuel consumption depended on the temperature, mainly due to energy requirements of air conditioning and cooling. Measured values are: 10,5 kg/100 km at 24 °C and 16,1 kg/100 km at 37 °C. In a similar way, the driver performance also influenced the fuel consumption: 10,9 kg/100 km at 26 °C with a moderate driver and 14,1 kg/ 100 km at 26 °C with an “aggressive” driver. The influence of driver behavior on fuel consumption is well known but seems to be even more important in cases of vehicles with brake energy recuperation systems. If the driver is braking aggressively, the charging rate of the battery not always allow a full recovery of the kinetic energy and the efficiency will go down significantly.

### 2.4.3 Verifications Tests Part II from September 2010 to February 2011

**Summary results:** The vehicle has operated 903.7 km in 23 days divided in: 197,7 km without load or passengers and 706 km with passengers. During 18 days operation 1.047 passengers were transported. The average H<sub>2</sub> consumption during this period was 10,4 kg/100 km, which is more than the consumption registered during the Verification Test Part I (9,18 kg/100 km) since the vehicle has operated with passengers. Failures observed in the period: air compressor of the suspension and brake system, sensor of the hydrogen cylinders on the roof, hydrogen sensor at one of the fuel cell systems, BMI of the 3rd traction battery, traction battery “1” and in the measurement equipment which counts the number of passengers in the bus.

### 2.4.4 Conclusion

The first prototype was tested with success operating 2.671,90 km with an average fuel consumption of 9,79 kg/100 km, The vehicle attended all dynamic and safety conditions necessary for the operation in the bus corridor. Further optimization regarding weight reduction, weight balance front/rear, fuel consumption and turning cycle were recommended for the additional 3 buses of the phase II.3. The data collection system helped to detect and to manage problems in a way that the bus never broke down during operation. The drivers, after training, were completely integrated to the driving mode and they liked the easy operation, comfort and ergonomics. The passengers appreciated the low level of noise and vibration. The replacement of parts was an issue due to logistic challenges. The tests showed that when the parts are available, the maintenance services were fast and didn't keep the vehicle out of operation for long period of time. The bus performance was always superior to the diesel buses that are operating in the EMTU/SP corridors. The average hydrogen consumption was very driver dependent but always below 15kg/100km required in the specifications. The testing program included a day-to-day operation in public transportation to prove its functionality and acceptance by the transit authority and the passengers. High temperatures up to 40 °C, strong rain and humidity situations and overloading were special challenges. The failures occurred in some systems due to humidity, dust and weather conditions caused oxidation issues at electronic components. The Verification Tests resulted in an overall approval of the prototype bus and the green light for the implementation of the Project Phase II.3. After the accomplishment of the “Verification Tests Part II”, the bus operated at EMTU/SP's corridor only one time a week with 2 fuel cell systems and one traction battery, due to a failure in 2 Zebra batteries, until a failure in one of the fuel cell systems and the lack of budget for contracting additional maintenance services prevented the further operation.



## 3.0 Project Phase II.3 Implementation from January 2012 until March 2016

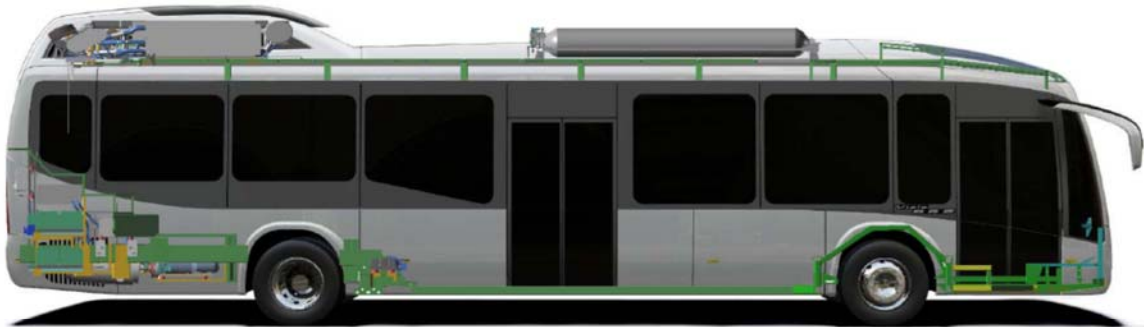
Based on the successful results of functional and verification tests, the UNDP, the Brazilian Government, the Transit Authority EMTU and the Project Consortium jointly decided to enter in the project Phase II.3.. All Consortium Members and main suppliers have agreed to make the necessary and significant cost reductions to enable the phase II.3 within the available budget.

### 3.1 Objectives

Design, production, test and evaluation of three new buses and the full operation, maintenance and evaluation of the hydrogen infrastructure capacity installed in the PHASE II.2..

### 3.2 Overall bus specifications

12,6 m chassis, min. 68 passengers, 10 years lifetime for chassis and body, 12 years or 240.000 km lifetime for the electrical traction system and 6.000 hours or 120.000 km lifetime for the fuel cell system.



### 3.3 Main changes in the technical concept related to the first prototype

1) Fuel cell system HD6 –150kW from Ballard (instead of Nucellsys); 2) One traction electric motor and distributed electric auxiliaries with individual power electronics from WEG (instead of Siemens); 3) Chassis low entry from MAN Brazil (instead of Tutto); 4) New packaging of the hydrogen systems on the roof; 5) Lithium traction batteries from Valence (instead of MS-DEA); 6) Rotrex/WEG fuel cell compressor system (instead of Eaton); 7) Electric vane compressor for chassis' brake & suspension systems (instead of piston compressor); 8) Distributed, flexible and light cooling systems with individual water pumps and automotive radiators and electric fans (instead of radiators with hydraulic fans). These modifications contributed to improve reliability, efficiency, noise, safety, local content and costs reductions, and also facilitated to achieve an overall design concept with two compact packaging areas: one with all hydrogen related components on the roof and another one in the chassis area with all the electric drive train components, leaving the whole length of the bus available for the passenger compartment.

### 3.4 Changes in the consortium

Due to corporative internal changes, two companies withdrew from the consortium without compromising the Phase II.3 implementation: the Nucellsys fuel cell systems have been replaced by Ballard's heavy-duty fuel cell systems and AES Eletropaulo have accomplished its obligations during the Project Phase II.2.

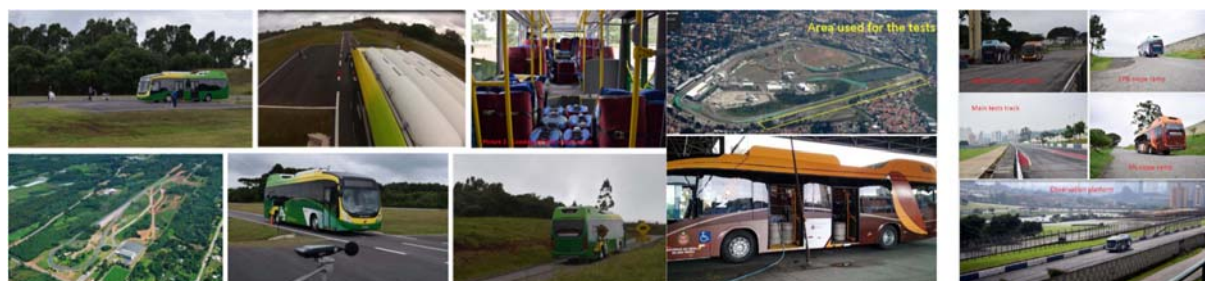


### 3.5 Main Events and Contract Milestones

**December 15th 2011: Milestone 1 “Signature of the UNDP Contract Phase II.3”, December 19th 2011: Milestone 2 Bus “FAT HD6 Systems”. March 30th 2012: Milestone 1 Hydrogen Station “Spare Parts Kit delivered to EMTU/SP”. October 10th 2012: Milestone 3 Bus "Design Freeze HD6 systems/Delivery Technical Specifications". May 23rd 2013: The hydrogen station at the EMTU/SP facilities has been put into operation. July 24th 2013: Milestone 3 Bus "FAT First Chassis + Body Structure. May 27th 2014: Milestone 4 Bus “FAT First Bus in Battery Mode”. October 27th 2014: Milestone 5 Bus “FAT First Bus in Fuel Cell Hybrid Mode”. February 20th 2015: Milestone Bus 7 “Functional Tests Report of the First Bus”. From February 2nd to 12th 2015: Training of the BR Petrobras station operators by Hydrogenics. March 10th 2015: CETESB Operation License for the Hydrogen Station. March 17th 2015: Milestone 2 Hydrogen Station “Maintenance trips 1 & 2”. May 27th 2015: Milestone 6 Bus “FAT Second & Third Buses in Fuel Cell Hybrid Mode Report”. June 15th 2015: Launching of the 3 new buses at EMTU/SP facilities. July 23rd 2015: Milestone 8 Bus “Functional Tests Report of the Second and Third Buses”. From Jul 24th 2015 to Feb 13th 2016: Milestone 6 – II.2. “SAT Station Ready for Bus Operation”. August 3rd and 4th 2015: Additional Training for the team of METRA (10 new drivers trained). From January to March 2016: Milestone 3 Hydrogen Station – Maintenance Trips 3, 4, 5 and Milestone 9 and 10: Verification Tests of the 3 new Buses at the Bus Corridor EMTU/SP.**

### 3.6 Functional Tests of the 3 buses

**3.6.1 Overall results:** The first bus functional tests were performed in Caxias do Sul – RS on the Randon Proving Ground loaded with 95% of the total weight to save free areas for the technicians’ safe circulation. For the second and third buses it was performed at Interlagos’ old racing track in São Paulo and segments of streets used for the circuit services accesses. The main test track is 900 m of a flat (maximum slope of 0.0125% or 0.7°) and straight road as most of the regular bus corridors lines. The same items as for the first prototype have been tested, concerning the accomplishment with norms and standards, especially on brakes, noise, consumption and performance, showing the high level of maturity on the tested topics and also a significant improvement from the first prototype. The measured consumption was about 13,4 kg/100 km with mostly fully loaded bus, enabling 230 km range. The vehicle noise levels are lower than the CONTRAN noise limits for diesel vehicles. The acceleration result meets the basic technical specification defined to the 15% slope, and sustained a constant speed. The vehicle speed is limited to 60 km/h electronically. The alarm is implemented in the VCU software indicating exceeded speed. The regenerative brake system has the performance specified, even tested with 80% of the maximum capacity. Good stability on slalom tests compatible with diesel bus. At 19,5t total gross weight condition, the buses shall be able to maintain a constant and controlled speed running down a hill with 20%. The ‘hill start assistant’ system is an effective hill holder for positive slopes. The overall validation proved that all 3 buses responded positively to all trials carried out, generally reacting far beyond the limits established by norms and by the contract. The driving behavior, up hills, weight distribution, and all others significant items were fulfilled correctly, demonstrating full capability to operate on the EMTU/SP bus corridor.



### 3.7 Verification Tests of the 3 buses

#### 3.7.1 Overall results:

The buses performance have been evaluated in a regular operation of a segregated bus corridor under routes and schedules indicated by EMTU/SP and METRA, according to the following aspects: fueling daily routines, periodic maintenances, drivers fillings compared to diesel and diesel/hybrid vehicles, acceptance

by the regular passengers, reliability of the main systems and energy efficiency. The verification test was initially started with the vehicle unloaded and continually monitored. During the first 700 km, the energy managing system was optimized according to the operation profile on the corridors. The main focus was to balance the use of batteries and fuel cell systems. The next step was to test the vehicle loaded with water gallons, totalizing half load, for tuning the traction systems for comfortable accelerations, torques and regenerative brake. The driver feedbacks were also used as input parameters. The last part of the verification test was executed in regular operation respecting the operator's schedule, including the peak hours in regular service with passengers. The tests were done on three different lines of the ABD corridors but the operation with passengers was on the bus line 287P. Ten new drivers from METRA were trained by Tutto in the basic information about fuel cell and hydrogen technologies and about the bus operation characteristics. Safety and operational information were also included and verified during the practical driving lessons all drivers had the opportunity to drive the bus on the corridor with supervision. The previous experiences of the drivers with electric and hybrid buses, were very helpful and made the training much effective. The average consumption was calculated for the entire period over 3 months, when the operation became more constant after the stabilization of the hydrogen production. Elevated temperatures resulted in higher hydrogen consumption. The operation of the bus with passengers was executed mostly from 5:30h until 12:00h, from Monday to Friday. From 5:30h to 8:30h there was higher occupation, achieving the peak moment around 7:00h with about 75 passengers on board.

### 3.7.2 Results first bus

The accumulated distance during the whole test period was 6019,5 km with 34% of availability measured from October 2015 to March 2016, due to: lack of hydrogen (48%), lack of drivers (11%), bus technical problems (7%). The accumulated distance after fuel station full operation mode was 3.320 km with an availability measured from January 2015 to March 2016 of 68% due to: lack of drivers (23%) and technical problems (cooling system – DI water leak, chassis and body maintenance, ticket system repair, regulatory inspections, side events for bus demonstration, measurement equipment and cooling maintenances - 9%).

### 3.7.3 Results second and third buses

Only the bus 3 was released for regular operation with passengers. The Bus 2 didn't achieve the condition to operate with passengers mainly due to delays caused by problems with a set of electronic cooling fans and with the traction inverter. The solution for these problems were not possible to be implemented due to the non-immediate availability of similar components in the local market and the long time needed for the supplier to repairs the fans. Even though the bus 2 didn't come to regular operation with passengers, 1182 km were executed on tracks defined by METRA, following all routines of regular operations, including 'stops and goes' simulating boarding and landing. Its availability measured from October 2015 to March 2016 was 9,5% due to: lack of hydrogen (45%), lack of drivers (11%), bus technical problems (traction and other parts 25,9%) and its availability measured after full operation of the hydrogen station (517 km) from January 2015 to March 2016 was 10,8% due to: lack of hydrogen (4,2%), lack of drivers (2,5%), bus technical problems (82,5%). The Bus 3 was tested on the corridor and in regular service for passengers' transportation as the Bus 1. The final range achieved by the vehicle was 5044 km. Its availability measured from October 2015 to March 2016 was 38% due to: lack of hydrogen (42%), lack of drivers (16,5%), bus technical problems (fuel cell system, traction and other parts 3,5%) and its availability measured after full operation of the hydrogen station (3.680 km) from January 2015 to March 2016 was 70% due to: lack of hydrogen (1,4%), lack of drivers (9,5%), bus technical problems (traction inverter, chassis, body and suspension maintenance, regulatory inspections, side events for bus demonstration - 19%). The total distance achieved by the two buses accumulates 6224 km, or 50% of the Milestone target. At the end, besides all problems, the new drive train with fuel cell system, hydrogen storage, batteries, and power electronics worked with a high degree of reliability and prove that fuel cell buses have the potential to offer zero emission characteristics with a good efficiency and ranges sufficient for daily operation without intermediate filling or charging processes. In addition, the project proved that it was possible to develop fuel cell busses in Brazil with local electric drive technology and full engineering capability and responsibility for the development of a local energy management and control system as well as the whole bus integration covering all the safety requirements related to the use of high voltage systems and hydrogen as a fuel. Considering the period of regular operations for the three buses, the overall average consumption is 13.9 [kg/100km] which is compatible, and even better than the defined target of 15 [kg/100km]. **The three buses operated a total distance of 12.243 km in a route with 33 km attending 4 municipalities. 18,000 passengers have been transported from January to March 2016 and the hydrogen station proved automatic and continuous operation.**



#### 4. Lessons Learned

1) Regular and continuous operation of bus and hydrogen station avoid technical problems. The automatic operation of the hydrogen station during the “Emergency Plan” showed that this is the ideal operation mode to improve station and bus availability. 2) Vehicle simulations and optimizations in the bus design phase and the hazard and safety analysis, played an important role on achieving a safe operation and reducing technology risks. 3) A centralized communication by the project management with project partners avoided additional issues. 4) Communication among companies and people from different countries, cultures and languages is a challenge. There is a need to translate not only the language, but also the culture and the way of working from one side to the other. 5) A contingency budget has to be included to cover unexpected expenses and assure project continuation. 6) A full time presence of a technician during bus and station operation reduce the downtime period for preventive and corrective maintenance. 7) Foreign companies shall train local companies for maintenance services, in order to extend their technical support’s capabilities and avoid project delays. 8) Local teams need time to assimilate new technologies. 9) Innovative solutions have to be found to overcome challenges and keep the project going, in spite of technical and process problems, corporative changes, political and economic scenarios.

#### 5. Concrete Results of the Project

1) Knowhow and knowledge transfer to the Brazilian industry. 2) Generation of new business and job opportunities 3) Design, production, operation and testing of: 4 fuel cell buses “made in Brazil” and of a hydrogen fueling station well-to-wheel CO<sub>2</sub> – free. 4) Successful international cooperation. 5) Built local man power capability and experts in fuel cell hybrid buses and hydrogen fuelling stations. 6) **REDUCED COSTS OF A FUEL CELL HYBRID BUS:** Thanks to the successful involvement of the Brazilian industry and its large scale production capacity, which enabled the increase of the bus local content from 35% to 65%, the project achieved a bus cost reduction by 3 times. The cost of US\$ 1 035.66 of a Phase II.3 bus, represented at that time, the least expensive fuel cell hybrid bus in the world with this power and specifications.






## 6. Successful Efforts

The Brazilian Fuel Cell Bus Project is a unique initiative that involved teams from private and public institutions from Brazil, USA, Canada, & Europe, each in their own area of expertise. The bus integration process was an example of how true globalization works, as suppliers and integrators from three continents came together to build fuel cell buses. A very important result from these efforts was a demonstration that fuel cell buses attend the specifications for public transportation in the São Paulo Metropolitan Area and could avoid major health problems caused by intense atmospheric pollution. Brazil has historically shown a strong commitment to environmentally friendly technologies for energy production and public transport but unfortunately, financial capabilities from public and private institutions in Brazil and abroad are not in place to enable the continuation of the operation of the products built by this project, and for the scaling up phase. In any case, the project stakeholders and the UNDP&GEF's project external evaluators considered this project successful because it created a sustainable basis for the development, production and operation of fuel cell buses in Brazil and developed a business model and local partnerships that can support the introduction of the technology in commercial scale. The experience of the Brazilian Fuel Cell Bus Project shall be transferred to other developing countries by creating further projects and activities for the dissemination of these important lessons learned.

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## Authors

	<p>Monica Saraiva Panik, 59 years old, graduated in Social Communications Fundação Armando Álvares Penteado, master degree in Marketing Administration Fundação Getúlio Vargas. Worked 18 years for the automotive industry in Brazil and 18 years as project manager for the consortium of the UNDP/GEF 'Hydrogen Fuel Cell Buses for Urban Transport in Brazil'. Winner of the DaimlerChrysler Umweltpreis 2001 with the “Clean Air Initiatives in Developing Countries”. Contributed for: “World Bank Clean Air Initiative in Latin American Cities”, “UNDP Introduction of Fuel Cell Technology in Emerging Megacities” and “EU Controlling Urban Mobility Europe/Latin America” programs. Article writer in the UN Sustainable Development “The Air is Global” in 2000 and in the Book “Ônibus Brasileiro a Hidrogênio” in 2009. Today works for the 22<sup>nd</sup> WHEC in Rio de Janeiro 2018 and contributes for the Brazilian-European Hydrogen Association CTCN project.</p>
	<p>Sidney Gonçalves de Oliveira Sobrinho, 51 years old, graduated in electrical engineering with emphasis in electronics by the Federal Center for technological education of Rio de Janeiro (1991) and specialist in Automotive Engineering and Control Systems by the Federal University of Rio Grande do Sul (2001). Steering Committee member of the consortium for the UNDP/GEF 'Hydrogen Fuel Cell Buses for Urban Transport in Brazil' from 2009 to 2016, as the leader engineer in the integration process, construction and testing of the fuel cell hybrid buses Currently works as a contracted consultant engineer for a manufacturing company of electro-medical equipment in Brazil, head of research and development for technologies such as the High Intensity Focused Ultrasound and radio frequency equipment for medical treatments.</p>
	<p>Prof. Dr. Ferdinand Panik, 75 years old, graduated in Electrical Engineering at the Technical University Berlin and Doctor Degree in Mechanical Engineering. 30 years employee of the Daimler Group: director and head of the Research Group, member of the board and development director for Truck and Bus Mercedes-Benz Brazil, vice-president DaimlerChrysler and head of the strategic Fuel Cell Project. Today professor and member of the Institute of Sustainable Energy and Mobility, University of Applied Science Esslingen. Special Awards: Business Week 50 European Leaders at the “Forefront of Change” in 2001, “Grove- Medal” for Leadership in advancing Fuel Cell Technology by the British Industry in 2002, Society of Automotive Engineers (SAE) as “Exceptional Professional Distinction by reason of outstanding and extraordinary Qualification, Experience and sustained Accomplishment in the Field of Mobility Engineering” in 2010.</p>