Hydrogen Fuel-cell Buses for Megacities of Developing Countries

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Abstract

Diesel buses provide the most important motorised mode of transport in the megacities of developing countries today, but they are also major contributors to local air pollution and the accumulation of carbon dioxide in the atmosphere. Fuel-cell buses (FCBs) – operating on hydrogen fuel – promise to reduce both local transportation-related air pollution and greenhouse gas (GHG) emissions. This article reviews the rationale for FCBs, the status of FCB commercialisation, and the UNDP/GEF FCB commercialisation support programme.

Governments in OECD countries are working with private-sector technology developers to commercialise fuel-cell vehicles. While the largest prospective market for fuel-cell vehicles is that for automobiles, FCBs are likely to be introduced commercially before cars for two reasons. Firstly, they can be centrally refuelled, providing economies of scale in refuelling infrastructure. Secondly, the allowable cost ($/kW) for the power plant on a bus is considerably higher than that for an automobile, providing an easier cost target for fuel-cell engine developers. Developing countries have the largest bus markets in the world and, therefore, FCBs could play a major role in the long-term mitigation of GHG emissions from these countries. To help catalyse the commercialisation of FCB technology for urban areas of developing countries, the United Nations Development Programme (UNDP) and the Global Environment Facility (GEF) have launched a major programme to help these countries set the stage for large-scale commercial deployment of FCBs. The UNDP/GEF programme is supporting commercial demonstrations of FCBs and associated refuelling systems in Beijing, Cairo, Mexico City, New Delhi, Sao Paulo, and Shanghai.

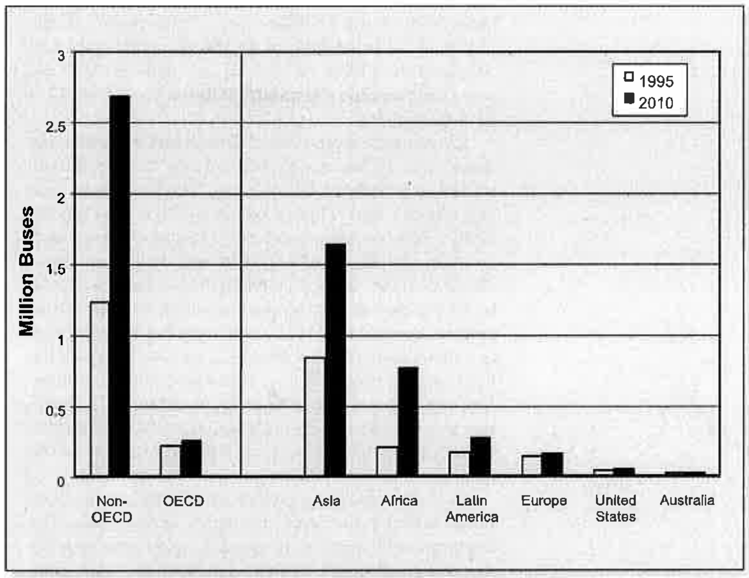

Figure 1
Estimated number of urban transit buses in the world in 1995 and projected for 2010. Based on the projection, 90% of the global market for urban transit buses in 2010 will be in developing countries.
(Source: (Joseph Stauder, Skoda Canada, Richmond, British Columbia, personal communication, April 2000)

WHY FUEL-CELL BUSES?

Fuel-cell vehicles promise zero tailpipe emissions of both criteria pollutants and greenhouse gases (GHG), and have the prospect for very low net lifecycle emissions of these pollutants (including those associated with the production and delivery of fuel to the vehicle). Industry and independent cost projections indicate that fuel-cell vehicles could be cost-competitive by late in this decade, once mass production is established.[1] Governments and the private sector in OECD countries are aggressively pursuing research, development, and demonstration of fuel-cell vehicles in an effort to commercialise this technology. Most of this effort is focused on fuel-cell automobiles, the largest market for vehicles in OECD countries. Complementing efforts in OECD countries to commercialise fuel-cell vehicles, the UNDP is implementing a programme funded by

1. For example, see F.R. Kalhammer, P.R. Prokopius, V.P. Roan, G.E. Voecks, 1998, Status and Prospects of Fuel Cells as Automobile Engines, a report of the Fuel Cell Technical Advisory Panel prepared for the California Air Resources Board, Sacramento, California, July. See also F.D. Lomax, Jr., B.D. James, G.N. Baum, and C.E. Thomas, 1998, Detailed Manufacturing Cost Estimates for Polymer Electrolyte Membrane (PEM) Fuel Cells for Light Duty Vehicles, prepared for the Ford Motor Company under prime contract to the US Dept. of Energy (Office of Transportation Technologies) by Directed Technologies, Inc., Arlington, VA, August.

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the GEF[2] to help catalyse the commercial introduction of FCBs for urban transit applications in the megacities of developing countries.

For such cities, the most important motorised mode of transport in today is the diesel bus. Urban transit buses in developing countries outnumbered those in the OECD countries by a factor of five in 1995, and the gap may grow to a factor of ten by the end of this decade.

Given their abundance, diesel buses contribute significantly to local air pollution in urban areas of developing countries. The cost of this pollution is difficult to quantify, but an order-of-magnitude estimate of pollution cost can be developed for illustrative purposes. Consider the Sao Paulo Metropolitan Region, which has a transit bus fleet numbering over 25,000. If diesel buses account for 10 percent (a guesstimate) of the particulate matter (PM10), SO_x, and NO_x emitted by all diesel vehicles in the Sao Paulo area, then the health costs due to bus emissions of these three pollutants are between \$0.8 and \$4 billion/year, based on an extrapolation of a detailed study of air pollution costs in the Los Angeles basin (Table 1). With an assumed bus life of ten years, this amounts to an air pollution cost of \$0.32 – \$1.6 million/bus.

Replacing the mega-fleets of diesel transit buses in urban areas with FCBs would dramatically reduce diesel-related air pollution while reducing GHG emissions. The only tailpipe emission from a hydrogen FCB is water vapour. GHG emissions will depend on the source of energy used to make the H_2, which in turn will depend on local conditions. For example, if the hydrogen were produced by reforming natural gas, there would be a minimum 30 percent decrease in GHG emissions per bus-km compared to a diesel bus.[3] GHG emissions approximate zero if the hydrogen is made from a renewable energy source. Since the source of hydrogen is important, it is necessary to undertake a system-wide analysis of the local situation to verify that FCBs will result in GHG reductions in a given local situation.

Fuel-cell vehicles have other advantages over conventional vehicles for urban transport applications. The maximum efficiency of a fuel cell roughly approximates that of a diesel engine, but fuel cells reach their maximum efficiencies at low loads in contrast to diesel engines. Therefore, from an energy efficiency standpoint, fuel cells have an advantage over diesel engines in urban transit operations where frequent stops and low travel speeds are common. In addition, fuel-cell engines are much quieter than diesel engines, so that local noise pollution from FCBs is essentially reduced to tyre-noise.

FUEL-CELL BUS TECHNOLOGY AND ITS COMMERCIALISATION

A fuel cell electrochemically combines hydrogen with atmospheric oxygen to produce electricity and water vapour. Fuel-cell vehicles are essentially electric vehicles with the electricity provided by a fuel cell. The fuel cell of choice for vehicular applications is the proton exchange membrane (PEM) fuel cell. With recent developments, PEM fuel cells providing sufficient power to drive a full-size urban transit bus (over 200 kW) can fit in a smaller space than a diesel engine providing similar power.

A fuel cell requires hydrogen (H_2), which can be supplied directly from an on-board H_2 storage system or by converting a hydrocarbon fuel stored onboard into hydrogen. Direct hydrogen vehicles are simpler, more efficient, and less expensive than hydrocarbon-based vehicles,[4] but low energy storage densities of hydrogen limit the range of operation on a single 'tank' of fuel. However, since transit buses are typically centrally refuelled each night and are also able to accommodate larger hydrogen storage volumes, the fuel supply mode of choice for FCBs is direct hydrogen.

Several companies are developing FCBs (Table 2) and demonstration efforts have been launched or are planned in several OECD countries. A consortium led by DaimlerChrysler (a leading FCB developer) and with co-funding from the European Union and local municipalities will be rolling out 30 buses in 2002 and 2003 for demonstration projects in nine major European Cities and Reykjavik, Iceland. These demonstration projects build on the successful four-year trials of an earlier generation of FCBs in Chicago and Vancouver.[5] The California Fuel Cell Partnership has begun FCB demonstrations involving three California transit companies. This partnership[6] will demonstrate 20 FCBs between now and 2003.

THE GEF FUEL-CELL BUS COMMERCIALISATION SUPPORT PROGRAMME

UNDP and GEF have established a programme to support the commercialisation of FCBs for developing countries. The strategic vision for this support is to help reduce GHG emissions from the transport sector long-term in GEF programme countries. The programme involves a partnership between UNDP, GEF, private industry, and local/national governments. Partners are sharing costs and information. UNDP/GEF support for commercialisation of FCBs for developing country markets is consistent with other public sector support for fuel cell technology development, much of which seeks to balance

2 The Global Environment Facility (GEF) was established in the context of the Earth Summit held in Rio de Janeiro in 1992. It funds projects that are based in developing countries (and economies in transition) and that show global environmental benefits. The GEF serves as the operator of the financial mechanism of the UN Framework Convention on Climate Change (UNFCCC), in which context the global benefit is the reduction of present and future emissions of GHG's. UNDP, along with the World Bank and UNEP, are the implementing agencies of the GEF.

3. UNDP, 2000, "Commercialisation of Fuel Cell Buses: Potential Roles For The GEF," proceedings of 27–28 April 2000 Workshop, UNDP; New York, June 6.

4. Ogden, J.M., M. Steinbugler, and T. Kreutz, 1999, "A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles," Journal of Power Sources, 79: 143–168.

5. See "Cleaning Up: Zero-Emission Buses in Real World Use, A report on the XCELLSIS/Ballard Phase 3 Fuel Cell Bus Program," available at http://www.ballard.com/fcb_report.asp.

6. Participants in the California Fuel Cell Partnership include DaimlerChrysler, Ford, General Motors, Honda, Hyundai, Nissan, Toyota, Volkswagen, Ballard Power Systems, International Fuel Cells, XCELLSIS, BP, Shell, ExxonMobil, Texaco, the California Air Resources Board, the California Energy Commission, the South Coast Air Quality Management District, the U.S. Department of Energy, the U.S. Department of Transportation, Air Products and Chemicals, Inc., Praxair, Hydrogen Burner Technology, Pacific Gas & Electric, Proton Energy Systems, Inc., Stuart Energy Systems, Methanex, AC Transit (San Francisco), SunLine Transit Agency (Palm Springs), and Santa Clara Valley Transit Authority (San Jose). See http://www.drivingthefuture.org/ for more information.

the private sector preference to focus commercialisation on the larger and more profitable market for automobiles in industrialised countries. Indeed, as noted above, several public sector programmes in North America and Europe are focusing on public transportation applications.

UNDP/GEF decided to create a FCB commercialisation support programme to help ensure that FCBs become available for developing country markets in the long-term. By supporting commercial demonstration of FCBs in GEF programme countries, UNDP/GEF seeks to focus private sector resources on understanding and meeting the unique demands of these important potential markets for FCBs while helping to prepare the markets in developing countries for the widespread introduction of FCBs. The UNDP/GEF projects will enable these countries to gain experience in operating and maintaining FCBs; to build institutional capacity for managing fuel-cell vehicles and infrastructure; to build public confidence in the technology; and to facilitate international joint ventures for technology transfer. GEF programme countries will also benefit from reduced local air pollution, new export opportunities attributable to local manufacturing, and improved quality of public transit service. Finally, because FCBs are hydrogen fuelled, the UNDP/GEF programme is also assisting developing countries in preparing for a future transition to cleaner fuel-supply systems, especially to ones with lower GHG emissions.

Table 1. Estimated Cost To Health From All Diesel-Vehicle Emissions In Sao Paulo (Assuming Costs Per Kilogram Of Emissions For Los Angeles)

	Health cost of motor vehicle emissions in Los Angeles[a] (1997$/kg)	Sao Paulo Metro area diesel vehicle emissions, 1995[b] (Tonnes/year)	Sao Paulo health costs, assuming Los Angeles costs/kg (Billion $/yr)
CO	0.04 – 0.2	502,970	0.02 – 0.11
NO_x	7.7 – 9.2	367,555	2.8 – 3.4
PM_{10}	69 – 748	22,995	1.6 – 17.2
SO_x	41 – 266	77,015	3.2 – 20.5
HC's	0.6 – 5.1	82,125	0.05 – 0.42

(a) Source: D. McCubbin and M. Delucchi, The Cost of the Health Effects of Air Pollution from Motor Vehicles, Volume 11 (of 21 volumes) of M.A. Delucchi, The Annualised Social Cost of Motor-Vehicle Use in the United States, based on 1990–1991 Data, UCD-ITS-RR-96-3, Institute of Transportation Studies, University of California, Davis, 1998. In this study, the authors related measured pollutant emissions in the Los Angeles basin (kg/year of particulates, CO, NO_x, SO_x, and hydrocarbons) to air quality, air quality to health effects, and health effects to economic welfare. They estimated the economic value of health impacts based on studies of the value of lost workdays, of restricted activity, of tolerating illness symptoms, of life, and other factors. Original costs in 1991$/kg have been converted to 1997$/kg using the U.S. GNP deflator.

(b) Source: Relatorio de Aualidade do Ar no Estado de Sao Paulo, 1995, CETESB (Companhia de Tecnologia de Saneamento Ambiental), State Government of Sao Paulo, Sao Paulo, Brazil, 1996.

Table 2. Fuel-cell Bus Developments (All Buses Are Designed With Compressed H_2 Fuel Carried Onboard)

Company	Bus model	StackMade by	Demo	Notes
Daimler-Chrysler	Citaro	Ballard	2001	250 kW stack, 60 passenger bus by Evobus. Low-volume commercial production starting in 2002 when demonstration fleets will begin to be introduced in 10 cities (3 buses per city): Amsterdam, Barcelona, Hamburg, London, Luxembourg, Perth (Australia), Porto, Reykjavik, Stockholm, and Stuttgart.
Toyota	FCHV-BUS1	Toyota	2001	63-passenger, low-floor bus with regenerative braking. Developed with Hino Motors, Ltd. Tokyo road tests to start 2002.
MAN	NL 263	Siemens	2000	120 kW stack. Road tested in Erlangen, Nuremberg. Funding from state of Bavaria.
Irisbus	12 metre	UTC Fuel Cells	2001	60 kW stack. Road tests to start late 2001 in Torino, Italy. Additional buses to be tested in Madrid and Paris.
Thor	El Dorado 30 foot	UTC Fuel Cells	2001	60 kW stack in mid-size bus with battery supplement, regenerative braking. Trial service with Sunline Transit, California.
Neoplan	N8012	Proton Motor	2000	80 kW total stack capacity. 33-seat bus. Funding from state of Bavaria.
Scania		Nuvera	2001	Product of European Union R&D programme.

Figure 2
Three fuel-cell buses built by a Ballard-led consortium. These buses operated in field trials in Chicago
(photo: http://216.51.18.233/fct/galtrans.html)

Figure 3
Fuel-cell bus (NL263) built by a MAN-led consortium. This bus has been road tested in Germany
(photo: MAN-Nutzfahrzeuge, http://www.fuelcellbus.com)

The UNDP/GEF FCB commercialisation support programme has three stages. Stage I, which is already complete, involved identifying candidate countries and assessing the strength of each local bus market, verifying local and national political and financial support for FCB technology, evaluating the local bus industry's capabilities for new technology development, studying the potential availability of hydrogen supplies, and developing strategic plans for the next Stages. Five of the world's major bus markets emerged as candidates for Stage II projects: Brazil, Egypt, Mexico, India, and China. Stage II – the Demonstration Phase – is focusing on the operational viability of FCBs for urban transit in major cities in each of these countries. This stage will provide significant operational experience with FCBs to allow for informed decisions about the viability of, and interest in, expanded deployment of FCBs.

UNDP and GEF are playing three important roles in Stage II. Firstly, GEF is funding the incremental costs of FCB demonstration projects: since FCBs are not yet commercially competitive with conventional transit buses, GEF's grant resources are helping to 'buy down' the cost of the buses. The total GEF commitment of $60 million corresponds to an annual requirement of $12–$15 million per year spread over the expected four to five year lifetimes of the projects. Table 3 summarises the financial commitments of the partners involved in Stage II activities. This level of spending can be compared against the total GEF spending of between $150 and $200 million per year on all GHG mitigation projects. Secondly, UNDP/GEF is facilitating the process of FCB commercialisation in participating countries by convening stakeholders to discuss, collaborate in, and finance Stage III programmes. Thirdly, UNDP/GEF is facilitating information exchange within and between programme countries, industry,

Table 3. GEF-Approved Financing Arrangements For Stage II FCB Demonstration Projects

(US$ millions)	GEF	Government*	Private	Total
Brazil	12.3	6.3	2.6	21.2
Mexico	12.0	12.2	4.7	28.9
Egypt	11.9	8.6	2.2	22.7
India	11.8	14.2	2.2	28.2
China	11.6	18.1	2.2	31.9
Total	59.6	59.4	13.9	132.9

* Including parallel and in-kind financing, such as import duties

7. See "Demonstration for Fuel-Cell Bus Commercialisation in China" 2001 CPR/01/G31/A/1G/99. Beijing: UNDP and the Government of China. pp. 80.

and other (non-GEF-supported) FCB demonstration projects. UNDP/GEF will organise international workshops, share information and experiences, and host a dedicated website to facilitate information exchange.

Stage III – the Commercialisation Phase – will be the final stage of GEF involvement and is intended to increase the developing country demand for, and production of, FCBs to the point where their costs are competitive with those of conventional diesel buses. Private industry's financial contributions at Stage III are expected to reach at least 50 percent of total project costs. The justification of GEF support for Stage III will depend largely on the nature of the GEF's continuing role in climate change; the degree to which the Stage II demonstrations succeed; and the continued investment and interest in the technology within GEF donor countries. The GEF plans to make an informed decision-most likely in the 2005–2007 time frame-regarding the need for and magnitude of its continued support for Stage III.

A CLOSER LOOK AT A UNDP/GEF FCB PROJECT: CHINA

The Government of China has recently launched major initiatives to address increasingly serious urban air pollution problems. The GEF's FCB Demonstration Programme is one long-term element of these initiatives and is aimed at reducing both GHG emissions and air pollution through eventual widespread commercialisation of FCBs. Beginning in 2002 with the support of the GEF and under the national direction of the Ministry of Science and Technology, two fleets of FCBs (six buses in Beijing and six buses in Shanghai) will run over 1.6 million bus-km in total during a four year period. As a result of a phased FCB commercialisation programme, plans for which include a garage-scale demonstration (100 to 300 buses) following the initial 12-bus project and eventual local manufacturing of FCBs, China envisions mass producing cost-competitive FCBs for widespread introduction in Chinese cities in the 2010–2015 timeframe.

A detailed manufacturing cost analysis carried out by an expert Chinese team during the design of the FCB Demonstration Programme concluded that 12-metre FCBs mass-produced in China will ultimately be cost-competitive on a lifecycle basis with diesel buses in Beijing and Shanghai (Table 4).[7] This analysis assumed a hydrogen cost of $25/GJ, which is a very conservative estimate of the cost for making and delivering hydrogen from coal in a large-scale process that includes capture of the carbon in the coal and sequestering it below ground as CO_2, possibly in conjunction with enhanced oil or coal-bed methane recovery. A preliminary analysis of alternative low-carbon emission options indicated that this would be the lowest-cost and most abundant means for providing hydrogen with low CO_2 emissions to the coastal cities of China in the long term.[7] Natural gas is a potential near-term feedstock for hydrogen production. Even without capturing the CO_2 generated in converting natural gas to hydrogen there would be net reductions in CO_2 emissions to the atmosphere on a lifecycle basis compared to CO_2 emissions from diesel buses. Steam reforming of natural gas will be the hydrogen source for the initial FCB demonstration projects in China.

NEXT STEPS IN THE GEF FCB COMMERCIALISATION SUPPORT PROGRAMME

After a lengthy process of study, consultation, preparation, and approval, the Stage II UNDP/GEF FCB

Table 4. Estimated Lifecycle Costs For 12-Metre Diesel And Fuel-Cell Buses In China (Costs Are Expressed In Constant 1999 US$ Per Bus-Km)

	Diesel, 2010–2015 (a)		Fuel-cell Bus (b)	
	Beijing	Shanghai	Domesticengine (c)	Importedengine (c)
Capital	0.14	0.13	0.25	0.34
Fuel	0.08	0.10	0.37	0.37
O&M	1.07	1.06	0.71	0.71
TOTAL	1.3	1.3	1.3	1.4

(a) These are based on actual average costs for diesel buses operated by the main public bus companies in Beijing and Shanghai in 2000, with diesel fuel at 2.4 RMB/liter for Beijing and 2.5 RMB/liter for Shanghai. O&M costs have been escalated from actual 2000 values to reflect real escalation in labor rates that will occur over time. (8.3 RMB = 1 US$)

(b) The capital charges for the FCB assume a 10% discount rate, a 20-year lifetime, and capital costs as described in note (c). Hydrogen fuel is assumed to cost $25/GJ (2.6 RMB/m³) and to be used at a rate of 1.174 m³/bus-km.

(c) The FCB cost analysis considered two capital cost scenarios. In one scenario the fuel-cell engine is assumed to be imported from an OECD country, while the glider is built and integrated with the engine in China. The second scenario assumed completely indigenous manufacture, including the fuel-cell engine. With the imported engine, the estimated cost for a mass-produced FCB was about US$320,000. With a Chinese engine, the cost was about US$237,000. For comparison, Ballard (of Vancouver, Canada, a leading fuel-cell engine developer) has indicated a cost target for a FCB mass-produced entirely in Canada/USA is under $400,000. Ballard has also indicated that the glider will represent about 70% of this cost. Substantial cost savings in the manufacture of the glider can be expected in China compared to Canada/USA, so the Chinese FCB capital cost estimates appear to be consistent with the Ballard cost projections.

projects are beginning implementation in 2002. The Brazil project is the most advanced, and pre-bidding consultations with all interested participants will likely begin in the first quarter of 2002, followed by solicitation for proposals for the buses. The FCB demonstration fleets in the five countries, are expected to begin actual operation in 2003 and early 2004.

The success of the UNDP/GEF FCB commercialisation support programme will be reflected in the dual benefits of cost reductions associated with commercialisation of the low-GHG emitting FCB technology and the market expansion attributable to early efforts at technology transfer. It is precisely this type of 'technological leapfrogging' that is needed, to achieve sustainable development over the next half century in a climate-constrained world.

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