ENERGY SOURCES FOR HYBRID ELECTRIC VEHICLES: COMPARATIVE EVALUATION OF THE STATE OF THE ART

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ABSTRACT

The choice of a suitable energy storage system (i.e. battery) on board the "all electric combat vehicle" is a key issue in vehicle design. The critical design parameters for this storage system will be dependent on vehicle specifications and on the energy flows within the vehicle, the latter being mainly defined by the drive train topology on one hand and on the power control strategy on the other hand. The primary energy sources on board the vehicles (generator set or fuel cell), and the fact whether or not external electric power input is foreseen, have also to be considered.

The paper gives an analysis of typical drive train topologies and the resultant design constraints which are to be taken into account for selecting the energy storage system. The use of VSP, a proprietary modular simulation tool in analysing and designing vehicle drive trains developed at the Vrije Universiteit Brussel, is illustrated.

The state of the art for storage systems is presented, reflecting the experience developed for various civil applications, such as hybrid buses which are offering unprecedented opportunities for reducing energy consumption and emissions, and which have been surveyed by CITELEC in several European cities.

INTRODUCTION

Electrically driven vehicles present a number of benefits in both civil and defense applications. In urban traffic, due to their beneficial effect on environment, electric vehicles are an important factor for improvement of traffic and more particularly for a healthier living environment. Their limited thermal and noise signatures furthermore offer interesting opportunities for military use.

Hybrid vehicles are particularly promising, since they offer the benefits of electric traction and present unprecedented opportunities for reducing energy consumption and emissions, while being less bothered by range constraints than battery-electric vehicles. Nowadays various hybrid vehicle configurations are being proposed; for the purpose of this paper we will concentrate on heavy-duty vehicles, taking the hybrid city bus as an example. Hybrid city buses are being demonstrated in several European cities with the support of the European Union programs such as "Thermie". The most extensive hybrid bus project in this field is called “Sagittaire”, it aims to introduce hybrid buses in 9 European cities: Luxembourg, Besançon, Alicante, Sintra, Stavanger, Trento, Savona, Athens and Brugge.

HYBRID STRUCTURES

The various possible structures can be differentiated in several categories, according to their structure and to their mode of operation.

According to the **vehicle structure**, one can consider:

Series hybrid vehicles

The series hybrid is a hybridization of energy source.
In the series hybrid, the wheels are exclusively driven by one or more electric traction motors, the electricity being generated by an on-board energy source (diesel generator set, commonly called APU = auxiliary power unit), a traction battery acting as an energy buffer. The series hybrid is considered a most advisable solution for heavy-duty vehicles. The SHEV is an interesting solution for driving in urban areas with passenger cars, light duty vehicles (with e.g. range extender) as well as with heavy-duty vehicles like city buses .

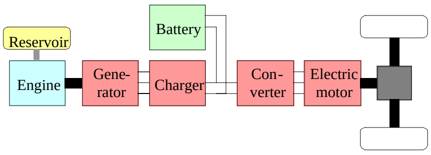


Figure 1: Series hybrid structure

Parallel hybrid vehicles

The parallel hybrid on the other hand, is a hybridization of drive system. The wheels can be driven by either an electric motor or an internal combustion engine. This configuration is considered more adapted for light-duty vehicles. This PHEV benefits makes the PHEV useful for the family or higher class vehicle segment while mainly driving on highway and long distances.

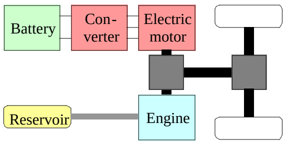


Figure 2: Parallel hybrid structure

Complex hybrids

These structures encompass three or more energy sources and/or drive systems. The possible options are manifold (series-parallel mixed structure, additional energy sources such as flywheels, capacitors,…). The CHEV is an interesting solution for the intermediate car population segment that frequently is used in town but also as a commuter car, with a good road performance and is often the main or only family car. An example of a complex hybrid is the Toyota Prius passenger car.

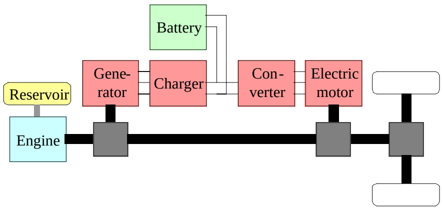


Figure 3: Complex hybrid structure

According to the **mode of operation**, one can consider:

Battery depleting hybrids

In this structure, the state of charge of the traction battery at the end of a service day is lower than at the beginning. The batteries are thus supposed to be recharged from an external source (electric grid).

Non-depleting hybrids

In a non-depleting hybrid, the state of charge of the traction battery at the end of a service day is equal to at the beginning. Only the APU provides energy to the vehicle. (The momentary state of charge of the battery during service will of course be variable).

Hybridisation rate

For use in heavy-duty vehicles such as buses and heavy military vehicles, the series hybrid structure is generally preferred, since it allows benefiting from the optimal traction characteristics of an electric motor on one hand, while optimising the operation of the combustion engine on the other hand. This allows for unprecedented low emissions and energy consumption
Within the series hybrid configuration, different design philosophies are possible according to the relative power output of APU and battery. These move between two “extremes”: on one hand, the pure battery-electric vehicle (without APU); on the other hand, the diesel-electric vehicle (without battery).
This can be described with the aid of a parameter called the “hybridization degree”, also called the Combustion Hybridization Rate, CHR (Van Mierlo, 2000), which represents the ratio between the continuous output power of the APU and the maximal rated power (delivered during a certain period) of the traction motor:

$$\rho_{\mathrm{hyb}} = \frac{P_{\mathrm{APU}}}{P_{\mathrm{mot}}} \qquad (1)$$

It is zero for a battery-electric, and 100 % for a diesel-electric.

For the typical application of an urban bus, the technical preference of discerned vehicle operators clearly goes towards a rather low hybridization degree, preferably lower than 50 %. This represents a “small” engine and generator set, which on itself would not be sufficient to deliver full traction power (e.g. for acceleration or hill climbing) to the motor, this peak power being delivered by the battery. During deceleration or standstill phases, the generator will then recharge the battery.
The advantage of such a low hybridization degree configuration is that the combustion engine can be tuned at an almost constant power level corresponding to its optimal operation point, leading to lower emissions and fuel consumption.

Configurations with large engines, corresponding more to a “diesel-electric” drive train, will inevitably mean variable load conditions for the engine, leading to sub-optimal operation. However, where sustained operation at full power is needed, such as in certain defense applications, the larger hybridization degree may be required

The choice for battery depleting or non-depleting vehicles is dependent on several operational considerations:

- If the vehicle is intended to be operated for a considerable part of its route in a pure electric (zero-emission) mode, battery depletion will be obvious. If a non-depleting vehicle is to be used in this operation mode, the hybridization degree must be high enough to allow a sufficient APU output to recharge the battery.
- Battery depletion means that part of the energy is delivered to the vehicle from the electric grid; this energy source may be preferred because it may be either more economic (for example if overnight recharging is used) or more environmentally friendly than fossil or other fuels fed to the APU.
- Non-depleting operation does not require additional infrastructures, and offers the opportunity of transparent exploitation with traditional diesel vehicles.

CONTEMPORARY HYBRID BUSES AND THEIR BATTERIES

The determination and choice of a suitable traction battery for a hybrid bus remains a very important issue. As one of the functions of the battery is to deliver peak power (during accelerations and hill climbing), the **power density** is a parameter of premier importance.
Energy density however should also be considered, particularly for battery-depleting applications.
Several batteries have been considered by manufacturers today. The following table gives an overview of typical hybrid buses as presented by several leading European bus manufacturers.
All vehicles are series hybrids, and are presented in Table 1 classified by type of battery.

Table 1: Characteristics of hybrid buses

Bus	Length (m)	Tare (kg)	P_{mot} (kW)	P_{APU} (kW)	ρ_{hyb}	Battery Type	Battery (kg)	Battery (Ah)	Battery (V)
#1	12	13150	164	36	22 %	Pb	2250	100	600
#2a	6	2690	32,5	12	37 %	Pb	800	100	192
#2b	6	2490	32,5	12	37 %	NiCd	600	80	192
#2c	6	2340	32,5	12	37 %	Na Ni Cl	450	140	280
#3	10,3	8000	110	60	54 %	VRLA	800	85	324
#4	9	11240	80	105	125 %	VRLA	1470	70	576
#5	12		150	145	97%	VRLA	920	50	612
#6	8	8550	85/118	85	72%	-	-	-	

Let's now consider these vehicles, their batteries and the way the battery option reflects the design philosophy.

#1 and #2: The series hybrid with low hybridization degree

The first two vehicles represent what can be called a "proven design" in hybrid buses, in fact these vehicles (from the same manufacturer) are already being presented on a commercial basis, while all others are still to be considered prototypes.

These vehicles are primarily intended for non-depleting operation, although battery charging through an external source is possible. Their striking feature is the extremely low hybridization degree, or with other words, the low output power of the generator. The engine powering the APU is in fact a 2,5 litre for the 12-m bus and a 1 litre for the 6-m minibus; this size of engine is more readily associated with a passenger car than with a bus! The APU is tuned to work strictly at its constant power output, which allows the bus to move at a constant speed of circa 35 km/h on the level. Extra power for acceleration or hill climbing is taken from the battery. The hybrid-electric drive allows a considerable savings in battery weight compared with a battery-electric type: for the same 6-m vehicle in battery-electric version, the weight of the battery (lead-acid) would be 1375 kg. Tests performed by CITELEC on a 12-m vehicle of this type, albeit one fitted with a natural-gas powered APU of similar power output, (APAS-TAUT 1997) have shown that during a typical city bus exploitation cycle (measured on an actual Brussels city bus route), the battery state-of-charge remains constant from the beginning of the exploitation to the end, highlighting the non-depleting character of operation. The constant power mode of the APU allows for energy-efficient and environmentally friendly operation: the tested vehicle showed emissions, which fell within the standards for passenger cars!

In their current production version, these vehicles come with a conventional flooded lead-acid traction battery, with tubular positive plates. This battery type provides the most economical solution, whilst offering a power density which is sufficient to provide the vehicle with acceptable performance levels (comparable to a conventional diesel bus). Energy density of this battery allows a zero-emission range of at least 20 km. The drawback of the use of these batteries is of course their substantial weight (more than 2 tons of battery for the 12-m vehicle).

For this reason, these vehicles are now being experimented with alternative batteries.

On the 12-m vehicle, advanced lead-acid designs (VRLA) have been experimented. Besides the maintenance-free aspect of these batteries, they offer higher specific power due to the low internal resistance of the advanced design (spiral-wound electrodes). The lower Ah capacity and thus lower energy stored limits the zero-emission capability; on the other hand, a weight saving of 60% compared with the conventional battery is obtained, allowing more payload (i.e. passengers) in the vehicle.

The use of advanced battery types in the 6-m vehicle has been the subject of a specific European demonstration program (Atesina, 2000).

Besides the conventional flooded lead-acid battery, vehicles were fitted with nickel-cadmium batteries and with Zebra sodium-nickel-chloride batteries. Nickel-Cadmium delivers good performance due to their excellent power density; their cost however is substantially higher even if they can be considered established commercial products.

The Zebra battery is mainly characterized by its high energy density, allowing more zero-emission operation. Its high operation temperature and need for additional heating when not used is not such a big issue with an intensively used vehicle such as a city bus.

#3: Design with advanced lead-acid batteries

Vehicle #3 is an innovative lightweight body design, for which a type of advanced lead-acid batteries have been selected.
This maintenance-free battery consists of semi-bipolar plates made of woven lead wires. Although this battery presents very promising values of energy and power density, there are some considerations being brought forward concerning its cycle life, particularly in a demanding application like a city bus.

#4 and #5: High hybridization degree with VRLA batteries

Vehicle #4, a low-floor midibus, presents a high hybridization degree, which exceeds 100% (although one could remark that this is also due to the rather modest motor power in this vehicle, which has in fact been designed for use in a flat country). The APU thus has surplus power. This is the result of a particular design philosophy aimed at a typical mode of exploitation. In fact, during "hybrid" operation, all drive power is provided by the APU and the battery is never drained (although it is recharged during braking and by the APU), making the mode of operation actually diesel-electric. This allows to hold the battery at maximum state of charge for the zero-emission operation in city centres. At the suburban part of the route, the APU's excess power allows to recharge the battery for the next run through the city centre. This allows for extended zero-emission routes while operating in a non-depleting hybrid mode.
The batteries of this vehicle are VRLA with gelled electrolyte, mounted on the roof of the vehicle. These batteries are maintenance-free and available at a reasonable cost; vehicle performance could however benefit if alkaline batteries would be used, the cost of which would be substantially higher however.

Vehicle #5 also presents a high hybridization degree, it is fitted however with advanced lead-acid batteries (spiral electrodes) allowing high power output. The APU power in this vehicle seems too big to really optimize the benefits of hybrid operation; the advanced lead-acid battery allows a (limited) zero-emission operation, with a not too excessive weight penalty.

#6: Diesel-electric vehicle

Vehicle #6 is not fitted with a battery: it is a diesel-electric vehicle, with electric transmission. The absence of a battery as energy buffer will invariably lead to dynamic operation of the diesel engine at different power outputs, leading to a lower energy efficiency and higher emissions compared with a constant-power APU. Notwithstanding the potential merit of diesel-electric drives (which still take advantage of the superior traction characteristics of the electric motor), these vehicles are not to be considered as real "hybrid" vehicles.

BATTERY OVERVIEW AND FUTURE TENDENCIES

As can be seen above, various battery designs are being considered for application in heavy-duty hybrid vehicles. The "definitive" battery can not be defined as such, following considerations can be made however:

- Flooded lead-acid batteries represent a well-known and mature technology which continues to provide an economical solution despite its high weight which limits the zero-emission range

- VRLA designs eliminate maintenance and may offer improved energy and power densities; their reliability and longevity (a premier issue for heavy-duty applications) are however dependent on a strict battery management. Innovative cell designs will have to prove their value in this field. These advanced lead-acid batteries are still advantageous on the price level.
- Alkaline batteries (nickel-cadmium or nickel-metal-hydride) offer excellent performances, particularly in the field of power density, which is very important for a hybrid vehicle. Their cost however is very high
- Advanced batteries represent a very promising solution, combining several characteristics which suit this particular application. The “Zebra” sodium-nickel-chloride battery presents itself as a very interesting option.
- Other advanced batteries, such as lithium-based designs, have not yet reached the market scene, but may become available in the coming years.
- The implementation of a battery management system which monitors individual cells or modules is a necessity for all battery types in order to ensure reliability and long life.

VEHICLE SIMULATION PROGRAM

In order to assess the performances of different vehicle topologies and of different components, simulation techniques are interesting tools. A proprietary simulation program called VSP has been developed at the Vrije Universiteit Brussel (Van Mierlo, 2000). It is a modular user-friendly interactive program that allows simulating the behaviour of electric (battery, hybrid and fuel cell) as well as internal combustion vehicles (petrol, diesel, CNG, etc.). Its modular characteristics make it particularly suitable for the comparative assessment of hybrid drive train structures.

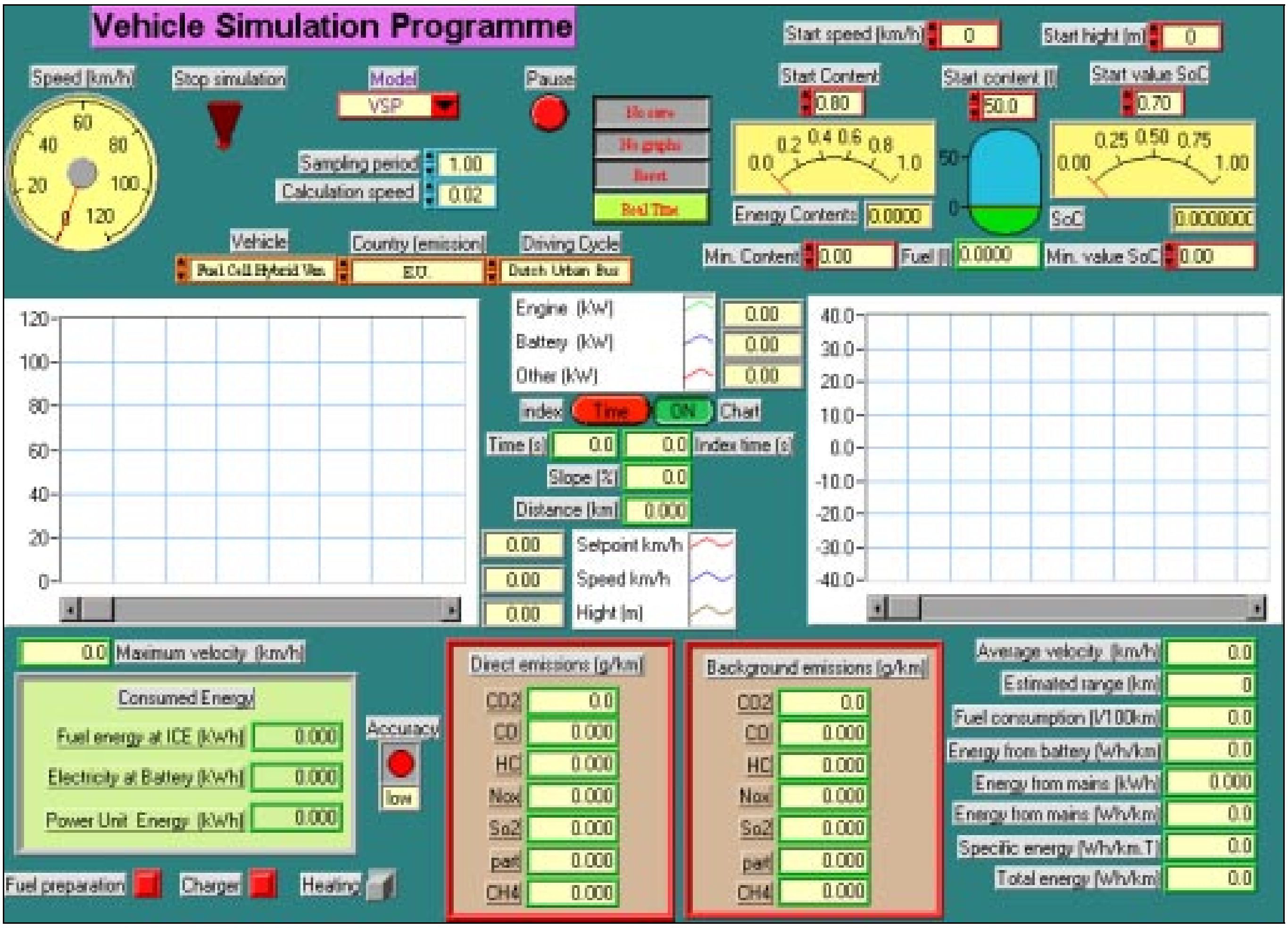
The goal of the simulation program is to study powerflows in drivetrains and corresponding component losses, as well as to compare different drivetrain topologies. This comparison can be realised at the level of consumption (fuel and electricity) and emissions (CO2, HC, NOx, CO, particles, ...) as well as at the level of performances (acceleration, range, maximum slope).

The general aim of the simulation program is to know the energy consumption of a vehicle while driving a certain reference cycle. For thermal vehicle this energy consumption corresponds to fuel consumption and in the case of electric vehicles this is the energy drawn out of the battery. For hybrid electric vehicles fuel consumption as well as energy out of the battery are required. Based on models for battery charging, electricity production and fuel refinery, the primary energy consumption can be simulated. Furthermore VSP has the possibility to be coupled to traffic simulation programs allowing traffic planners to examine congestion and related emission problems (DWTC, 2000).

The program runs in a LabVIEW™ environment. Figure 4 shows the main user interface of VSP.

Figure 5 illustrates the primary energy consumption of the different drivetrains with a total static weight ranging from 1,7 to 2,7 ton (Van Mierlo, 2000).
The simulation results are based on:
- Driving five times the Dutch Urban Bus cycle.
- No component integration work or drivetrain component optimisation.
- End-charge of electric drivetrain is included.

In Figure 5the blue-yellow line represents the Internal Combustion Vehicle (ICV) reference energy consumption. The top of the purple stroke corresponds with the energy consumption of this vehicle with a total weight of 2,7 ton and the bottom with 1,7 ton.



Model: VSP

Sampling period: 1.00

Calculation speed: 0.02

Vehicle: Fuel Cell Hybrid Veh.

Country (emission): EU

Driving Cycle: Dutch Urban Bus

Start speed [km/h]: 0

Start hight [m]: 0

Start Content: 0.80

Start content [l]: 50.0

Start value SoC: 0.70

Energy Contents: 0.0000

SoC: 0.0000000

Min. Content: 0.00

Fuel [l]: 0.0000

Min. value SoC: 0.00

Engine (kW): 0.00

Battery (kW): 0.00

Other (kW): 0.00

Time [s]: 0.0

Index time [s]: 0.0

Slope [%]: 0.0

Distance [km]: 0.000

Setpoint km/h: 0.00

Speed km/h: 0.00

Hight [m]: 0.00

Maximum velocity (km/h): 0.0

Consumed Energy

Fuel energy at ICE (kWh): 0.000

Electricity at Battery (kWh): 0.000

Power Unit Energy (kWh): 0.000

	Direct emissions (g/km)	Background emissions (g/km)
CO2	0.0	0.0
CO	0.000	0.000
HC	0.000	0.000
Nox	0.000	0.000
So2	0.000	0.000
part	0.000	0.000
CH4	0.000	0.000

Average velocity (km/h): 0.0

Estimated range (km): 0

Fuel consumption (l/100km): 0.0

Energy from battery (Wh/km): 0.0

Energy from mains (kWh): 0.000

Energy from mains (Wh/km): 0.0

Specific energy (Wh/km.T): 0.0

Total energy (Wh/km): 0.0

Figure 4: The front panel of the Vehicle Simulation Program

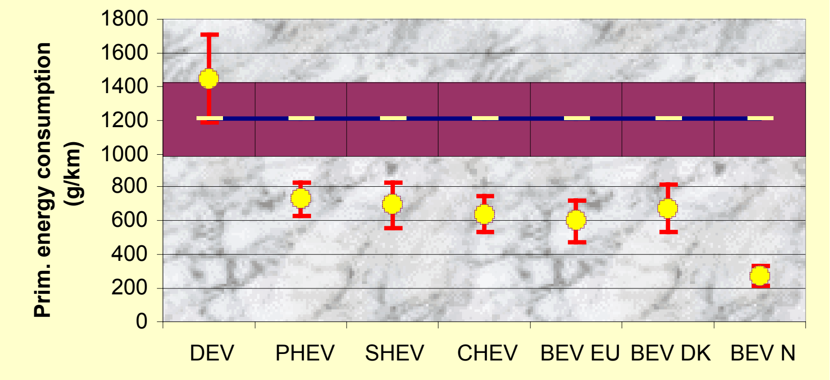


Figure 5:Primary Energy Consumption of Different Types of Drivetrains With a Total Static Weight Ranging from 1,7 to 2,7 Ton

This reference is compared with the Diesel-Electric (DEV), the Parallel Hybrid Electric (PHEV), Series Hybrid Electric (SHEV), Combined Hybrid Electric (CHEV) and Battery Electric Vehicle (BEV). The latter is charged in Europe (EU), Denmark (DK) and Norway (N) (Van Mierlo, 1997)
The results give a confident indication of the potential energy reduction of battery and hybrid electric vehicles.

- In general the case study indicates the possibility to reduce energy consumption, when using hybrid or battery electric vehicles, with more than 40 % in comparison with conventional thermal vehicles.
- The comparison between the hybrid vehicles shows a benefit for the combined hybrid. However the choice of power management strategy is more decisive to the energy consumption than the drivetrain topology itself. This later should be chosen in function of the market segment, cost, etc.
- The battery electric vehicle gives the similar results as the hybrid vehicles. However power generation efficiency influences these results very much.
- At the contrary the diesel-electric drivetrain demonstrates a very bad energy management.

CONCLUSIONS

The hybrid heavy duty vehicle is to be considered one of the most promising fields of application of electric traction in road vehicles today. Whileas the series hybrid structure is almost universally chosen for heavy-duty applications, the choice between battery-depleting or non-depleting hybrids will be primarily depending on exploitation constraints.

The definition of the “ideal” battery for a hybrid vehicle is far from being definitive, as reflected by the wide array of battery types proposed by various manufacturers. For the strenuous operation of a city bus, not only power and energy density of the battery, but also reliability, longevity and cost are premier factors to be considered, offering a major challenge to battery manufacturers.

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