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Chapter Two

Electric Vehicles

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The purpose of this chapter is to discuss various electric drive and battery possibilities and obtain data for these options. Electric scooters require drive systems (motor, controller, transmission) and power sources (batteries or fuel cells). Since a fuel cell scooter is essentially a battery-powered scooter with battery replaced by fuel cell plus hydrogen storage, the basic electric scooter is described first.

Components are chosen for the electric scooter on the basis of technical qualifications and economic considerations. The resulting electric battery-powered vehicle is used as a base platform to develop the fuel cell scooter design.

The chapter also includes a section on high-power batteries that would supply transient bursts of peaking power for hybrid scooters.

It should be noted that battery-powered scooters are currently commercially available in North America, Asia, and Europe, although they have met with only limited success.

2.1 Drive systems

The speed of a vehicle is determined by the output of its engine. This is more accurately characterized in terms of the motor's torque and angular velocity, but often measured in terms of the product: power.

Torque is measured in lbf-in, ft-lb, or N-m, power in hp or kW, force in lbf or N, and motor speed in rpm or rad/s. Essentially, an internal combustion engine or electric motor generates rotation at a specific speed and torque; this rotation drives a transmission of which changes the speed of the rotation through gearing, and transmits the force to the slower-turning wheel axle.

A transmission decreases engine speed by the same factor it increases engine torque. Its influence is measured by the gear ratio, the ratio of engine revolution speed to driveshaft revolution speed; the slower the output speed, the greater the output torque. Car linear speed v is the wheel circumference ($2\pi r$) times the engine speed ωdivided by the gear ratio u:

$$v = 2\pi\ r\ \omega/u$$

Typical passenger cars use engine speeds between 2000 and 3500 rpm. Transmissions allow the construction of a smaller motor and allow operation closer to the motor's optimum efficiency at all speeds by changing the gear ratio as a function of output desired. As the car accelerates, the maximum desirable engine speed is reached and the gear ratio is reduced to the next level to stay within an efficient zone; engine speed is allowed to drop again, but with the reduction in gear ratio, velocity increases continuously (at the expense of torque). Essentially, torque translates to force at the wheel, and large torques are required for steep hill climbing and fast acceleration.

Scooters are single-wheel drive devices; the engine powers the rear wheel, while the unpowered front wheel is used for steering.

2.1.1 Electric drive systems: introduction

An electric drive system replaces the internal combustion engine and assorted transmission systems with an electric system. The various differences are listed below.

Table 2.1. Comparison of power systems

Internal combustion system	Electric battery system	Electric fuel cell system
• engine including cylinders, air intake • fuel tank, carburetor, air filter • pump for lubricating oil, oil tank • exhaust system • transmission and chain • starter battery	• battery • electric motor(s) • motor controller • transmission and chain	• fuel cell stack • fuel cell subsystems including cooling system, air intake, hydrogen intake, humidification system if any • hydrogen storage device • electric motor(s) • motor controller • transmission and chain • battery for startup

A small internal combustion scooter engine of 50-80 cc weighs about 32 kg and occupies under 50 L of space.[1] Note that current 50 cc scooters require a 12 V starting battery on the order of 1.3 kg and 0.7 L.[2] The cost is on the order of $20 retail. In a fuel cell scooter this extra battery, or something similar, would likely be necessary to start the intake blower, open valves, activate electronic controls, and perhaps even warm up the fuel cell. It would not be necessary at all in a battery-powered scooter.

Three different groupings are defined here for the advanced scooters presented here: “fuel cell stack”, “power system”, and “drive system”. “Fuel cell stack” refers to the series-connected electrochemical cells that make up the core power source of the system, and includes manifolding and a plastic insulating housing around the stack. “Power system” includes not only the stack, but also subsystems like the blower to supply air to the fuel cell, the radiator to cool down the stack, and the coolant pump. The most inclusive term, “drive system,” includes the power system and peaking power battery (if any), hydrogen fuel storage, and the electric motor and controller. For an equivalent battery-powered scooter, “drive system” includes the storage batteries, any peaking power batteries, and the motor and controller pair.

2.1.2 Electric motor theory

Electrical motors operate on the basic principle that a current-carrying wire in a magnetic field will experience a force. The magnetic field can be generated by permanent magnets or by a current in an electromagnet. The *stator* is stationary and produces the magnetic flux, while the rotating armature or *rotor* contains the coils that carry the armature current. In general, motor speed is controlled by increasing the armature voltage, while torque is controlled by increasing the current flowing through the armature.

In a combustion engine, the explosions of the air/fuel mix directly produce rotation with a fixed velocity-torque relation. More flexibility can be achieved in an electric motor, where the ratio between torque and speed can be controlled independently and electronically within the motor/controller. For example, in a pulse-width-modulated system the frequency of rotation of the magnetic field governs the speed output, while the phase difference between the rotor and stator fields determines torque. Transmissions are often not be necessary at all; where used, they offer optimum efficiency (since the output mechanical power can be remapped by the transmission to the higher efficiency portions of the electric motor output) for both driving and regenerative braking.[3] In this study, no transmission was assumed - only a fixed final gearing between the motor output and the wheel.

2.1.2.1. DC motors

DC motors employ a fixed current that causes the rotor to "want" to turn to line up with the poles in the stator. However, the current in the stator is *commutated*, often by a split-ring brush system, so that the direction of the current in the poles switches as the rotor passes by. This ensures that the rotor stays in continual motion. Multiple sets of poles are used to smooth out the rotation. In general, controllers are cheaper than for AC motors; on the other hand, the motors themselves tend to be bulkier and heavier and more expensive.[4]

In the basic *field-wound motor* described above, the stator field is provided by an electromagnet. Speed and torque are controlled by changing the current in the stator field and/or rotor windings.

In a variant, *permanent magnet motors* use permanent magnets rather than electromagnetic windings in the stator. The presence of brushes means relatively high maintenance, but these motors tend to have higher efficiencies than other DC motors due to the lack of stator field windings.[5] They have a narrow peak efficiency, so transmissions are required.

With *brushless DC motors,* it is the rotor that is a permanent magnet. The stator electromagnet current is switched on and off at the correct frequency (instead of commutated to reverse current direction), creating a rotating magnetic field in the stator and causing rotation in the rotor. Changing the speed of the rotating magnetic field effects rotor speed control. Torque is controlled here by varying the magnitude of the magnetic flux of the stator. (The flux, in turn, is controlled by changing stator current). These motors are relatively efficient due to the absence of brushes and can achieve average efficiencies of about 84% for both motor and controller together.[6] Control, however, is more complex.[7]

2.1.2.2 AC motors

Alternating current motors are inexpensive, simple, and reliable. They operate by take advantage of the changing phase of the stator current. AC motor control is expensive, however, and implemented by changing input frequency ("dragging" the actual rotor frequency ahead to match the input frequency) or by changing voltage. Also, an inverter is needed to produce AC from the fuel cell or battery's DC output.

Induction (asynchronous) motors apply alternating current to the stator winding, creating a rotating magnetic field. There is no current in the rotor windings; the stator *induces* a current in the rotor which creates torque. Efficiencies are greater than those of DC motors, on the order of 85%-91%.[8]

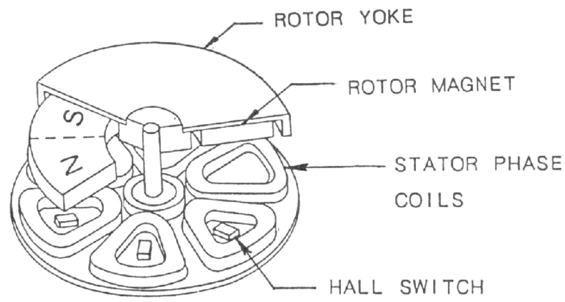
An *AC synchronous motor* is identical to an asynchronous motor, but with a magnet (permanent or electromagnet) in the rotor. In other words, the permanent magnet AC synchronous motor is identical to a brushless DC motor except that the frequency of the supplied alternating current controls the rotation speed of the magnetic field, not the on-off switching of a pulsed DC current.

2.1.2.3 Hub motors

Hub motors, included as a separate section, are an interesting development which could offer benefits for electric vehicles. These motors have stators fixed at the axle, with the permanent magnet rotor embedded in the wheel. By directly driving the wheel, they eliminate the inefficiency of a transmission and chain connecting the motor to the axle. Other advantages include higher efficiencies, less space, and often easier servicing.

The more traditional “exterior rotor” design has the rotor in a hollow cylinder shape and spinning around a stator axle. The rotor consists of permanent magnets, and this is a “radial gap” motor because the air gap between the stator and rotor extends in the radial direction. In a slightly different option known as the pancake or disc-type brushless motor, the rotor is not around the stator, but rather a flat disc of permanent magnets sitting on top of another flat disc which contains the stator coils. These are “axial gap” motors because the space between stator and rotor is in the direction of the axis. The stator can be a Mylar plate, stack of silicon steel plates with wound coils, or even a printed circuit for small, flat applications.

Figure 2.1 Axial-gap pancake motor



Source: Hendershot Jr. and Miller, p. 2-11.[9]

Pulse width modulated (PWM) current is used to supply current to the stator, so in essence the system is a DC brushless motor. Hub motors must run at relatively low speed – equal to the actual rotation of wheel if there is no final gearing stage. The benefit is about a 10% increase in efficiency due to the lack of transmission.

2.1.3 Converters and controllers

The controller connects the power source - fuel cell or battery - to the actual motor. It controls speed and direction, and optimizes energy conversion. While batteries produce fairly constant voltages which decrease as they are used up, the voltage output by fuel cells varies as a function of power. Some controllers require a DC-to-DC converter to step down this changeable voltage to the motor's expected constant operating voltage, but other controllers incorporate a DC-to-DC converter and can accept a varying voltage. In either case, DC-to-DC conversion losses are minimized if the fuel cell output voltage is near the operating voltage. Converter efficiencies are typically greater than 90%.

The controller varies the speed and torque of the motor. Today voltage control is almost always achieved by "chopping" the source current - the voltage is switched on and off, with the ratio of on-to-off determining the *average* voltage. The number of constant-width "on" pulses per unit time can be varied, or the width (duration) of the pulses can be varied. Chopping is performed by power electronics circuitry - diodes and thyristors and silicon control rectifiers (SCRs)

Controllers also effect regenerative braking, which is the process of driving the motor as a generator to recharge the batteries. In practice, about a third of total energy is discarded in ordinary friction braking (the other two-thirds is lost to rolling resistance and drag and auxiliary power). Due to inefficiencies in the regeneration process, only about 70% of this third can be recovered in regenerative braking.[10] (In the Taipei driving cycle studied later, approximately 20% rather than one third of the total mechanical energy output is lost as friction in braking).

2.1.4 Choice

Standard DC electric motors run at 24 or 48 V; The Taiwan scooter industry appears to be moving towards a de facto standard of 48 V and this was the chosen operating point.[11] For the fuel cell design developed for this thesis and described in later sections, voltage varies from 56 V at minimum power to 34 V at maximum power (5.6 kW). Current varies from zero to a maximum of 163 A over this range.

Most electric scooter motors surveyed use DC motors, the majority brushless rather than brushed (see Appendix A). For the reason of good DC efficiency and the lack of need for an AC inverter, this is the type chosen here. Two systems are examined: a New Generation Motors (NGM) hub motor, and a Unique Mobility (UQM) axial gap DC brushless motor.

Table 2.2 Motor specifications: UQM brushless and NGM hub motors

spec	UQM motor	NGM motor
Model	SR121/1.5 L	SC-M150-04
Maximum power output	3.6 kW	2.5 kW
Peak torque (geared)	115 N•m at 2000 rpm	105 N•m at up to 300 rpm
Speed	0-800 rpm	0-1300 rpm
Controller voltage	40-60 VDC	30-68 VDC
Maximum controller current	95 A	260 A
Efficiency	up to 87%	up to 95%
Motor cost	$250 (estimated)	$7,000 (retail)
Motor diameter	20 cm	31.5 cm
Motor volume	5.0 L	unk.
Motor weight	11.4 kg	20 kg
Controller volume	4.1 L	7 L
Controller weight	4.1 kg	5 kg
Controller cost	$300 (projected)	$3,000 (current)

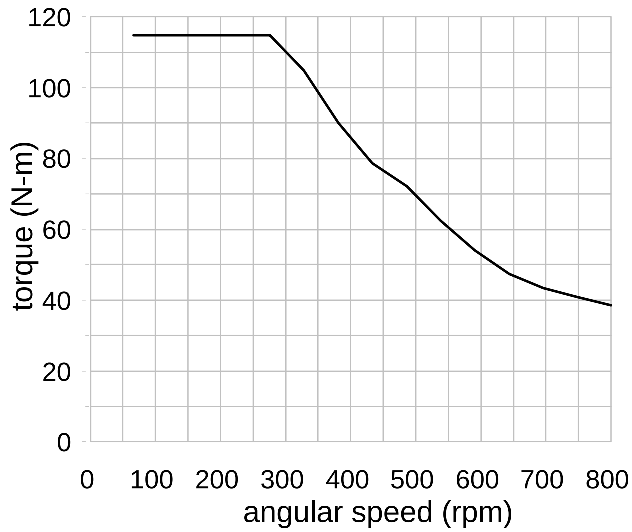
The Unique Mobility SR121/1.5L brushless, permanent magnet design has a maximum output of 3.56 kW. The CD 05-100A controller system includes a battery charger that can rectify AC voltage to battery charging voltage and allows regeneration. A final gearing ratio of 7.24 increases torque and reduces speed.[12] Current prices(May 1999) were estimated by Unique Mobility representatives at $250 for the motor plus $300 for the controller if the motor were to be mass produced immediately.[13] In comparison, a Lynch Motors brushed DC motor with 3 kW continuous output (6 kW peak output), weighing approximately 9 kg, has a retail price of $1,000, suggesting that current prices are higher than Unique Mobility's estimates.

Hub motors offer higher efficiency, but can cost thousands of dollars due almost entirely to their relative newness and lack of development. For example, the New Generation Motors SC-M150-04 motor described above costs almost $7,000, plus $3,000 for the controller, and is used in solar cars - a very small market.[14]

The arrival of cheap electric bicycles run on hub motors and made in the People's Republic of China promise to reduce hub motor prices, though, and the New Generation Motors president stated a high-volume price target of $500 in the future for scooter-sized hub motors.[15] For now, the UQM motor was chosen due to the more established nature of its technology. Hub motors will play a greater role in the future for electric scooters. A 77% efficiency was chosen for the electric drivetrain system, consisting of the DC motor efficiency, fuel cell DC-to-DC conversion, and gear chain / transmission losses. This is at the low end of the motor map, and performance might in reality be slightly greater. The figure was based on previous research in electric vehicles.[16] The variation in efficiency over a DC motor "efficiency map" (plot of iso-efficiency contours on a torque/speed graph) is only 3% so a single value is justified.

The following curve gives an example of how maximum torque decreases as a function of speed; the space of possible torque/speed combinations lies under this curve. For the most part, the curve follows a hyperbola since the product of torque and angular speed is equal to a fixed maximum power. However, the torque is capped at low speeds by the maximum current the electric motor can handle.

Figure 2.2 Typical torque vs. rpm curve for DC motor



The data presented is from a Unique Mobility data sheet for the SR121/1.5 L brushless motor.[17]

2.2. Chemical batteries

Rechargeable chemical batteries are the traditional option for electric vehicles. They tend to be heavy and expensive to replace over their limited lifetimes. In this section, the theory behind battery operation is laid out with some discussion of various battery energy storage options for electric vehicles. A final section deals with the use of specialized high-power batteries to provide surge peaking power during moments of high energy demand, and thereby allow design with a smaller primary power source.

2.2.1. Theory

A battery pairs reduction and oxidation half-reactions to generate electricity. At the anode, one substance is oxidized. The electrons flow through the external circuit (power load) and arrive at the cathode, where a different substance is reduced. Electrochemical equilibrium is maintained by cations in the solution flowing across an ion bridge.

Batteries are divided into primary and secondary cells. Primary cells are those that are used once and cannot be restored by reversing the current flow, because the half-reactions are irreversible. Voltage decreases over time as the reactants are depleted and the concentrations decrease, and eventually the cell becomes useless and must be disposed of, ideally after the chemicals inside are recycled .

Secondary (sometimes termed "storage") batteries can recover the original reactants by reversing the current flow. For example, in the common lead-acid secondary battery, the following half-reactions take place: at the anode, lead metal is oxidized to lead sulfate ($PbSO_4$); at the cathode, lead oxide (PbO_2) is reduced to $PbSO_4$. The electrolyte is a sulfuric acid (H_2SO_4) solution.

$$\text{oxidation: } Pb_{(s)} + SO_4{}^{2-}{}_{(aq)} \rightleftharpoons PbSO_{4\,(s)} + 2\ e^-$$

$$\text{reduction: } PbO_2 + SO_4{}^{2-}{}_{(aq)} + 2\ e^- + 4\ H^+ \rightleftharpoons PbSO_{4\,(s)} + 2\ H_2O$$

The overall reaction is:

$$Pb_{(s)} + PbO_{2(s)} + 4\ H^+{}_{(aq)} + 2\ SO_4{}^{2-}{}_{(aq)} \rightleftharpoons 2\ PbSO_{4(s)} + 2\ H_2O$$

The reversible electrochemical potential E_r^o in this case is approximately 2.04 V, and driving the cell in reverse (i.e. as an electrolytic reaction) regenerates the lead metal and lead oxide. However, there is a ceiling to the number of times any battery can be "cycled" in this way: when recharged the metals tend to precipitate in low-energy configurations like metallic needles or dendrites that eventually grow close to each other, and internal short circuits make the battery useless. After this point, reprocessing is needed if the chemicals inside are to be reused. This accounts for the limited lifetime of rechargeable batteries.

2.2.2. Technology

2.2.2.1 Existing scooter battery systems

As an example of current electric vehicle battery technology, the prototype Taiwan ZES-2000 battery-powered electric scooter developed by ITRI runs on a 24 VDC power system with two configurations: sealed lead-acid batteries, or the more advanced nickel metal-hydride (NiMH) batteries. Each configuration is designed to store the same amount of energy, but the more expensive NiMH batteries do so in about 60% of the lead-acid batteries' weight.

Table 2.3 ZES-2000 electric scooter performance

	sealed lead-acid	**nickel metal-hydride**
Total stored energy (output)	1.34 kWh	1.34 kWh
Total weight	44.0 kg	26.1 kg
Total volume	14.5 L	12.8 L
Specific energy density (Wh/kg)	31	51
Volumetric energy density (Wh/L)	92	105
Range at 30 km/hr	65 km	78 km
Range under ECE 40 driving cycle	35 km	46 km

Data from the ITRI ZES 2000 project[18]

The NiMH batteries a much smaller package but, as discussed in more detail later, are very expensive: $900 or more. Due to the lower weight of the NiMH vehicle, it uses less energy in driving and obtains higher fuel economy. This accounts for the improved range for the same energy storage.

Note that current battery specific energy is very low; to compare, gasoline has an energy density on the order of 920 Wh/L (although conversion to propulsion energy is on the order of 15%, more than five times worse than the round-trip efficiency of battery-powered scooters at about 80%).

2.2.2.2. Technology predictions

The United States Advanced Battery Consortium (USABC) was formed by Chrysler, Ford, and GM in 1991 to accelerate development of electric vehicle batteries. In 1992, goals were set for “mid-term” and “long-term” battery performance. The table of goals is reproduced below.

Table 2.4 Battery goals for various time frames

	1992 lead-acid	Mid-term prediction	Long-term prediction
Specific power (W/kg) 80% DoD, 30 seconds	67-138	150	400
Energy density (Wh/L) C/3 discharge rate	50-82	135	300
Specific energy (Wh/kg) C/3 discharge rate	18-56	80	200
Life (years)	2-3	5	10
Cycle life at 80% DoD	450-1000	600	1000
mass-produced target cost ($/kWh) set by USABC	$70- $100	<$150	<$100

Data is from the *Transportation Energy Data Book: Edition 12* and Hunt (1998).[19,20]

"DoD" stands for depth of discharge, and the nomenclature "C/3" means a discharge rate where the entire battery is expended in three hours. Due to the nonlinear nature of battery capacity, the total energy available is a function of how quickly the battery is discharged; the faster power is drawn, the less total energy is available.

In addition to traditional batteries like lead-acid, nickel metal-hydride and nickel-cadmium (NiCd), there are advanced technologies like lithium-polymer and lithium-ion. Despite the explosion in popularity of notebook computers and their rapid progress from nickel-cadmium batteries to nickel-metal hydride batteries to lithium-ion batteries, electric vehicle battery technology has not kept pace. Most practical electric battery automobiles still use lead-acid batteries, with the more sophisticated using NiMH batteries. The faster adoption of battery technology in notebook computers is due partly to their small size and energy requirements, and the fact that consumers are willing to pay significantly more for improved technology.[21] However, a telling point about how electric vehicle battery technology has not progressed is revealed in USABC's definitions of "mid-term" and "long-term": the mid-term was originally defined as 1994, and the long-term goals had a target date of 1995 [19], but by 1998 the mid-term was redefined as "1995-1998" and the long term goals were not fixed to a date, but rather defined in terms of performance: "competitive with today's internal combustion vehicles"[22].

Some of the different types of chemical battery are listed in the sections below.

2.2.2.3 Lead-acid batteries

Lead-acid batteries have been used for a century due to their high power density, reliability, and ability to satisfy widely varying loads. However, their energy densities are far too poor to act as "storage" batteries for electric vehicles; to store enough energy for decent range requires a massive battery bank. On the other hand, lead-acid batteries specifically designed to provide repeated burst of high power have proven to be useful peaking power devices. Novel spiral-wound designs offer specific powers of over 500 W/kg, at the cost of compromised specific *energy*.[23]

Lead-acid batteries are often classified as either "flooded" or "sealed". In flooded (also "wet") batteries, measuring the density of the liquid offers a method of measuring the state of charge of the battery since as the reaction proceeds, $PbSO_4$ precipitates out and the density of the electrolyte decreases. Note that electrolysis of water can be a side reaction in a lead-acid battery, so hydrogen and oxygen must be vented (electrolysis is favoured when the battery is overcharged). Water vapour also escapes, so that water needs to be occasionally replaced.

Sealed (sometimes called "VRLA", valve-regulated lead-acid) batteries have the electrolyte in a gel rather than liquid form, and valves that release gas only when pressure is too high; otherwise, the battery remains sealed and oxygen is transferred through the gel membrane to the hydrogen side and allowed to recombine with hydrogen into water before levels become high enough to be dangerous.

Lead-acid storage batteries currently cost approximately $60-$80 per kWh retail.[24]

2.2.2.4 NiMH and NiCd batteries

Nickel metal-hydride is currently the advanced technology of choice for electric vehicles, including both automobiles and scooters. Existing Ovonic NiMH batteries for electric vehicles have superior energy and power densities, on the order of 70 Wh/kg, 170 Wh/L, 200 W/kg, and 485 W/L. This is better than USABC's mid-term projections.

However, the predicted "ultimate" commercialized cost is $200-$250/kWh.[25] For 4.1 kWh of storage (the amount of energy needed to drive a 130 kg scooter approximately 200 km at 30 km/h, as discussed later in Chapter 4), this is $820 – $1025 for the batteries alone. This matches the results of a 1998 paper, which estimated that the cost of a NiMH battery for electric scooters "rivals the cost of the entire IC (internal combustion) motorcycle"[26].

NiCd batteries offer fairly high power density for peaking power applications, up to 300 to 660 W/kg possible, but may fall out of favour in the United States due to the toxicity of the cadmium they contain. For peaking power, specially designed lead-acid batteries serve just as well.

2.2.2.5 Lithium variants

Li-ion batteries, like those currently used in notebook computers, transfer Li^{+} ions from the anode to cathode through an electrolyte, with "insertion compounds" accepting the cations without significant structural change. This lengthens overall lifetime.

The more recent Li-polymer batteries use a metallic lithium anode, polymer electrolyte, a cathode, and a current collector in a flat sandwich. Although predicted energy densities are on the order of 200 Wh/kg, and the system is theoretically cheap to manufacture, there are drawbacks: metallic lithium tends to experience dendritic growth that reduces charge transfer, and the battery must operate at 70°C.[27]

The high cost of lithium batteries has prevented their use in electric vehicles. Only the Nissan Altra electric vehicle has demonstrated lithium-ion technology in that application.[28]

2.2.2.6. Zinc-air "regenerative" batteries

The zinc-air battery is an interesting primary battery alternative that offers high energy density - up to 200 Wh/kg, four times the specific energy of lead-acid batteries. The paired reduction and oxidation half-reactions are listed below.

anode reactions:

$$2\ Zn + 8\ OH^{-} \rightarrow 2\ Zn(OH)_4^{2-} + 4\ e^{-}$$

$$2\ Zn(OH)_4^{2-} \rightarrow 2\ ZnO + 4\ OH^{-} + 2\ H_2O$$

net anode half-reaction (oxidation):

$$2\ Zn + 4\ OH^- \rightarrow 2\ ZnO + 2\ H_2O + 4\ e^-$$

cathode half-reaction (reduction)

$$O_2 + 2\ H_2O + 4\ e^- \rightarrow 4\ OH^-$$

The overall reaction is thus the oxidation of zinc metal to zinc oxide:

$$2\ Zn + O_2 \rightarrow 2\ ZnO$$

$$(\Delta G = 318.3\ kJ{\bullet}mol^{-1},\ \Delta H = -348.3\ kJ{\bullet}mol^{-1})$$

The theoretical voltage available from this reaction is $E_r°$ = 1.65 V but in practice, only 1.16 V are available at a C/5 rate (full discharge in five hours) due to kinetics, competing reactions, and other inefficiencies.[29] The quoted figure of 200 Wh/kg includes this inefficiency.

The system has the advantage of using oxygen as one of its reactants. Oxygen can be taken in from the ambient air, so the amount of mass in the battery is lessened and energy and power density are improved. (Of course, as the zinc oxide product accumulates, the total mass increases.) The “air electrode” cathode consists of a polymer-bonded carbon layer, humidified and loaded with electrocatalysts to reduce overpotential and make it easy for the oxygen atoms to adsorb, dissociate, and ionize to O^{2-} anions. In this way, it is much like a fuel cell cathode. It is necessary to keep the oxygen away from the anode to prevent direct oxidation of the zinc.[30] Also, the catalyst on the cathode can be poisoned by other species in the air.

The zinc-air battery is actually a primary battery, since it is not recharged electrically. However, an interesting concept being developed by Electric Fuel, Ltd. of Jerusalem, Israel is that of "regenerative" zinc-air batteries, batteries that are replenished mechanically. These systems run on potassium hydroxide electrolyte, have zinc anodes, and catalyzed oxygen reduction electrodes. Although the specific power is relatively low at less than 90 W/kg, the specific energy of the zinc-air battery is a very good 200 Wh/kg, and the company predicts a price of $80/kWh after full mass production.[31,32] (Zinc recovery and regeneration costs do not appear to be included in this sum.)

The batteries are not recharged by reversing the reaction to restore the initial reactant zinc. Rather, the anode (now mainly converted to zinc oxide) is physically removed and replaced with a fresh zinc anode assembly. The spent anode is returned to a factory for chemical reprocessing – the zinc oxide is reacted with KOH, and the resulting potassium zincate is electrolyzed to restore the original zinc. In some sense these are fuel cells since the system is recharged by replacing reactants, rather than by reversing electric flow. The lifetime of the system is thus not restricted by changes in anode morphology, but by cathode poisoning and contamination. The zinc oxide dissolving process is:

$$ZnO_{(s)} + 2\ KOH_{(aq)} + H_2O_{\ (l)} \rightarrow K_2Zn(OH)_{4\ (aq)}$$

The electrolytic metal recovery process ("electrowinning") for zinc electrode reprocessing follows:

$$K_2Zn(OH)_{4\ (aq)} \rightarrow Zn + 2\ KOH_{(aq)} + H_2O_{\ (l)} + \tfrac{1}{2}\ O_{2\ (g)}$$

The voltage of this reaction is 2.2 V if electrocatalysts are used to reduce oxygen evolution overpotential. Considering only electrowinning losses, the maximum possible round-trip efficiency from power plant electricity to battery output electricity is (1.16 V / 2.2 V) = 52.7%. Additional energy is needed to reprocess the zinc and to complete the potassium zincate process and this could be not only energy-intensive but expensive as well.[31] The technical performance of the battery is good, but the difficulties and costs in exchanging and regenerating the anodes are not well known at this time.[33]

Note that the zinc-air batteries have a self-discharge rate of 1-2% per week.[34]

As alluded to earlier, there is a second replacement cost. Since this is an alkaline electrolyte system, carbon dioxide in the air forms carbonates that accumulates in the potassium hydroxide solution and the air cathode. After 10-30 replacements of the anode (in this application, after about one and a half to four months of travel), the entire battery must be replaced or remanufactured for this reason.[35] On a per-km basis, this could be three times the electricity cost of electrowinning the zinc; as well, beyond the cost of the electricity are the infrastructure costs for stations to process the zinc "fuel" and to remanufacture the batteries.[36]

2.2.2.7 Summary

Ordinary rechargeable batteries are currently a practical technology, and may be adequate for limited-use scooters and "neighbourhood vehicles," but energy densities are far from good enough to compare with current low-end scooters. On the other hand, regenerative zinc-air batteries offer high energy density - six times those of current lead-acid batteries used in the ZES-2000. Power density is not very high, though, and to design a zinc-air battery with the maximum driving cycle *power* as the target would be to create a very heavy battery with an overdesigned range, since power and energy are inextricably bound in a battery-powered system.

One way of decoupling power from energy is to use a hybrid system, with a high-energy battery providing the energy, and a high-power battery supplying extra power for peaking purposes. This is discussed in the next section.

2.2.3 Peaking power and batteries for hybrids

One concept proposed for automobiles is the "hybrid" vehicle. This type of design combines a reduced-size main power source (combustion engine, fuel cell, or even a storage battery) with a peaking power device (flywheel, ultracapacitor, battery). The peaking power device kicks in in moments of high power need to supplement the output of the main power source, and is recharge during periods of low overall power demand.

This allows the main power source to be sized smaller, saving money if it is expensive (fuel cell), saving weight if it is particularly heavy (battery). A hybrid in conjunction with a small combustion engine allows the engine to run at a fixed, well-tuned constant power output for greater efficiency and lower emissions. Transients in all three cases are completely or partially handled by the peaking power device. The important qualities required for the peaking power device: high power density, not necessarily high energy density, and the ability to respond quickly to transients.

A detailed discussion of different hybridization policies, and modeling of various fuel cell hybrid options, is deferred to section 4.7. However, some peaking power options are discussed in this section because the most promising are high-power batteries.

Flywheels offer high power density but low energy density. They have the advantages of long lifetime, linear behaviour, and high round-trip efficiency. On the other hand, they can be perceived as unsafe (although they are not as dangerous as some claim), are expensive, and unless designed carefully produce gyroscopic forces that can be serious in a vehicle as light as a scooter.

High-density capacitors ("ultracapacitors" or "supercapacitors") like those used in the Mazda Demio fuel cell vehicle can supply a great deal of power for many cycles. The energy stored can be measured in a linear fashion, unlike batteries, and power densities can be as high as 4.2 kW/kg for a very brief surge, or 560 W/kg for a six second discharge.[37] Energy densities are low, on the order of 5-10 Wh/kg,[38] but this is not a significant concern for the irregularly peaked scooter driving pattern. They are currently too expensive for practical use, at hundreds to thousands of dollars per kilowatt, but in a few years could offer an ideal alternative to peaking batteries.

A high-power battery like the Bolder Technologies advanced lead-acid offers high power density at relatively low cost. Bolder cells are used in the Chrysler Intrepid ESX series hybrid vehicle. However, with all batteries, chemical changes limit the number of cycles before the battery must be replaced, and current/voltage behaviour is extremely nonlinear, making it difficult to make sure that the battery lifetime is not shortened by overcharging or overdischarging. The power density of this type of high-power lead-acid cell is dependent on discharge rate, and is estimated at about 500-900 W/kg[39]. Cost is much more difficult to estimate, with most data being for storage batteries and not peaking power.

Current PNGV research is focused on batteries, and that group recently dropped research into ultracapacitors and flywheels for reasons of low energy density and safety, respectively.[40]

Thus, a high-power lead-acid battery is selected for the peaking power unit here. The peaking power unit is modeled as a scaled up version of current Bolder "Rebel" thin metal film battery packs, with six cells and a total output of 12 V and capacity of 1 Ah (600 W over 43 seconds). Power density is an impressive 840 W/kg. At an estimated cost of under $100 per pack for volume ordering, this is $167/kW which is halved to $83/kW for pre-installed cost in the scooter.[41]

2.2.3.1. Peaking battery modeling

The Bolder lead-acid battery studied here has the following properties.

Table 2.5 Peaking power battery characteristics

Retail cost based on today's "Rebel" pack	$167/kW
Power density at 43 second discharge	836 W/kg
Energy density by weight	17 Wh/kg
Density	1.02 kg/L
Power density by volume	853 W/L
Energy density by volume	17 Wh/L
Voltage per cell	2.0 V
Capacity per cell	1 Ah
Lifetime for full-discharge and recharge	400 cycles

Data is from a Bolder product sheet for the "Rebel" battery pack

These figures are close to the 1.2 kW/L, 1.2 kW/kg, 59 Wh/kg and 57 Wh/L reported for the 100 kW Bolder peaking power battery used in the Chrysler Intrepid ESX series hybrid (note that the discharge time for the Intrepid performance statistics was not given).[42]

Batteries designed specifically for peaking power (unlike the "Rebel") should sustain many more cycles than the 600 or so for lead acid batteries used for base power, due to the shallower discharge patterns. (Base power batteries are almost fully depleted and recharged to the maximum each cycle). Peaking power batteries might last for 3-5 years, although lifetimes are highly dependent on usage patterns.

The battery is modeled in terms of its state of charge (fraction of total energy capacity), based on an empirical model developed by Tom Kreutz at the Center for Energy and Environmental Studies at Princeton University.[43] Specifically, voltage and internal resistance at any time are a function of the state of charge, while the total cell output is a function of the voltage, internal resistance, and current. The cells in the battery are connected in series. Voltages are in volts and resistances in milliohms.

$$V_{cell} = V_o\,(SOC) + IR\,(SOC)$$

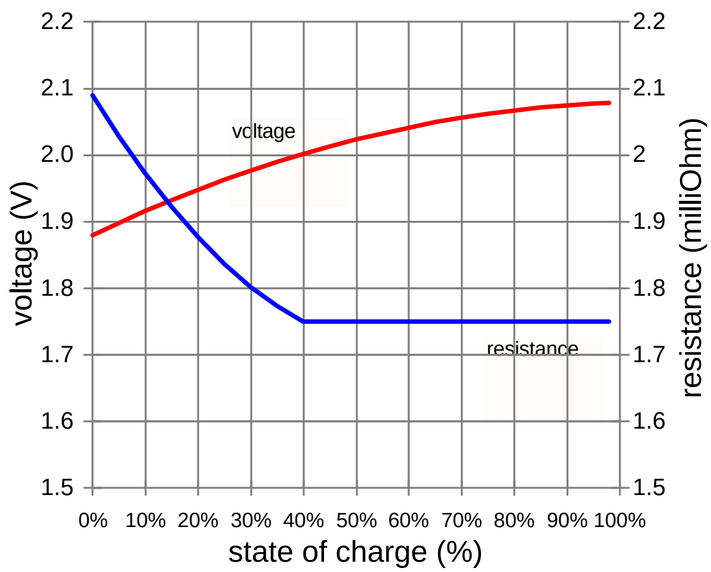
$$V_o(SOC) = 1.88 + 0.375\,SOC - 0.176\,SOC^2$$

$$R(SOC) = 2.09 - 1.28\,SOC + 1.07\,SOC^2 \text{ if } SOC < 0.4$$

$$R(SOC) = 1.75 \text{ if } SOC > 0.4$$

So the voltage output is a function of the state of charge, as is the internal resistance, as illustrated graphically:

Figure 2.3 Voltage and internal resistance of Bolder peaking battery



2.2.3.2. Charge and discharge

Assume that a certain power $P_{kinetic}$ is available to recover from the wheels from a calculation of *mav*. 30% of this energy is simply unavailable, as reported by an NREL paper, due to frictional and other losses.[44] For the generation of electricity from this kinetic energy by driving the electric motor in reverse, a 77% efficiency is assumed - approximately the same as the efficiency of driving the motor in a forward direction.

A final efficiency factor is incurred by the charging of the battery, and is calculated as $(\sqrt{\eta_{coloumbic}})V_o/V_{cell}$. The coulombic efficiency is 95%. The result is an efficiency of 90-95%, comparable to PNGV goals and data for current lithium-ion batteries.[45] So at any point, the power of charging is calculated, and I is solved such that the power into the battery, as given below, is reached

$$P_{charge} = N_{cells} \bullet V_{cell} \bullet I$$

After charging inefficiency, the actual energy entering the battery is $\sqrt{\eta_{coloumbic}} \bullet N \bullet V_o \bullet I$. The battery can only charge at a given maximum rate that is a function of the state of charge; the rate is higher when the battery is near empty. This maximum current limits the amount of energy that can be recovered during periods of heavy braking, and is given by:

$$I_{max} = I_o\,(SOC^{-\alpha} - 1)$$

$I_o = 0.979$ A, and $\alpha = 4.44$, fitting parameters to experimentally-observed curves.[46]. Even if the braking "power" needed is greater than the battery's ability to accept power, braking can still be effected by dissipating the surplus power through resistors (as in dynamic braking for diesel-electric or pure-electric locomotives). An ordinary set of brakes may be used at low speeds where generator-type braking is weak.

The discharge rate for the Bolder cell is 80 A over extended (20-second) periods.[47] With a maximum voltage of approximately 2 V per cell, this is 160 W per cell. Higher powers, up to 1000 A, are possible for short-circuit discharge; in this model, a maximum of 250 W per cell is set.

2.2.3.3 Hybrid battery conclusion

Detailed modeling will describe more precisely how many of the above cells will be needed, and how the power supplied will be divided between the peaking power and base power batteries. The combined fuel cell and hydrogen storage systems, both of which are discussed in the next chapter, have to beat not only four-stroke technology and current batteries, but future hybrid battery systems as well.

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