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# Chapter Five

# Implementation and Conclusions

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The main purpose of the thesis is to analyze the technical merits of the proposed fuel cell scooter. However, the scooter will never be practical unless it can be affordable as well. This chapter attempts to assess various issues contributing to the eventual adoption of commercial fuel cell scooters: price of the scooter itself; operating costs, in terms of fuel; and a brief survey of infrastructure and hydrogen distribution. The results of this chapter and the previous chapters is summarized in the final section.

## 5.1 Scooter cost

This first section of this chapter estimates costs of the fuel cell scooter after commercialization and mass production. This identifies the long term prospects of the hydrogen scooter, which are fair.

Three different types of prices must be defined. The cost-to-manufacture is the cost most often quoted by developers of new technology like zinc-air batteries. Estimated at double this manufacturing cost is the cost of the component as part of the vehicle – this is defined as the sale or retail vehicle price.[1] Finally, after-market replacement automotive components or those developed for separate purposes (like industrial blowers or radiators) are four times the manufacturing cost. Note that, depending on the part in question and the particulars of manufacturing and marketing and distribution, this factor of four may be quite different, so the cost totals should be taken with a grain of salt.

The method used here is to take existing scooter prices, remove the cost of the power system, and add back the new hydrogen fuel cell power system.

### 5.1.1 Base cost by subtraction

Current 50 cc two-stroke scooters retail for approximately $1,000 in Taiwan (1999), while the ZES-2000 has a target sale price of $1,850.[2] Costs for the major power system components are shown below and used to estimate a “base” cost for the vehicle body (with wheels and frame and controls and electronics) plus assembly.

***Table 5.1 Internal combustion engine scooter parts***

| Part | Description | Cost |
|---|---|---|
| 50 cc two-stroke engine | includes carburetor, transmission | $300 |
| Exhaust system | Muffler, exhaust pipe | $60 |
| Fuel tank | 5 L of fuel | $40 |
| Starting battery | Yuasa-Exide | $10 |
|  | TOTAL | $410 |

Prices are retail prices listed by an American parts dealer[3], and thus divided by two for cost as part of the complete vehicle sale price. The sole exception is the engine cost, which is based on a $150 manufacturing cost and a factor of two multiplier for the price it would cost as part of a vehicle’s total sale price.[4]

Subtracting the total from a two-stroke’s $1,000 sale price leaves a $590 base cost for the vehicle shell, assembly, internal electronics, controls, and assorted other ancillaries.

To verify this result by comparing with the cost of existing electric scooters, the most important electric scooter components – battery, motor, and controller – are added. With lead-acid batteries currently costing about $80/kWh retail, and a typical electric scooter having a stored energy of 1.2 kWh for 50 km of range at 30 km/h, a total battery cost of $96 is obtained. As previously quoted, Unique Mobility predicts motor and controller prices of $250 and $300 respectively for mass production today, although this is expected to decrease over time.[5] This is assumed to be in-vehicle retail cost.

***Table 5.2 Battery-powered electric scooter parts***

| **Part** | **Description** | **Cost** |
|---|---|---|
| DC motor | UQM brushless SR121/1.5 L | $250 |
| Controller | UQM CD05-100A | $300 |
| lead-acid batteries | 1.2 kWh | $100 |
| "base" cost | retail | $590 |
| | TOTAL | $1,240 |

This electric scooter retail total is close to cost of the cheapest electric scooters, which now retail for about $1,500, and is lower than the $1,850 previously quoted for the ZES-2000. The difference is likely due to the current cost of electric motors.

### 5.1.2 Cost of hydrogen storage system

Metal hydride hydrogen systems are based on the calculations of Chapter 3. The long-term cost projection for the FeTi metal hydride was based on an $8.80/kg materials price, and an extra factor of 50% for systems and packaging.[6] This resulted in a storage cost of $0.75 per gram of hydrogen stored. The quantity of hydrogen, as previously discussed, was set to allow 200 km of travel at 30 km/h.

***Table 5.3 Metal hydride storage costs***

| | **5.9 kW** | **3.2 kW** | **1.1 kW** |
|---|---|---|---|
| Hydrogen stored | 248 g | 266 g | 285 g |
| Manufacturing cost of hydride | $187 | $201 | $215 |

### 5.1.3 Fuel cell system cost based on parts predictions

The cost estimate of Appendix B, first described in section 3.1.3, was repeated for the two other hybrid alternatives. For each of the three fuel cell options and the hybrid battery, a long term price prediction is made based on mass production of all parts – especially the fuel cell and metal hydride storage system. These cost predictions are difficult to make, given the uncertainty involved with this emerging technology and the several years before the mass produced prices can be realized, so should be treated as a rough estimate only.

Retail prices for industrial parts like blowers, radiators, starting batteries, and coolant pumps are divided by a factor of four to include them in the sum below. Other costs, like the fuel cell, zinc-air battery, and metal hydride, are already given as cost-to-manufacture. Peaking battery costs are assumed to decrease to 75 \$/kW.

The fuel cell stack costs are for the ultimate long-term prices predicted by an automobile analysis done by Directed Technologies, Inc. These estimates are valid for the larger membrane sizes of 170 $cm^2$ and 100 $cm^2$ for the 5.9 kW and 3.2 kW stacks, but the 1.2 kW stack has membranes only 34 $cm^2$ in area, less than the minimum of 116 $cm^2$ employed in the DTI study, so the cost estimates are much less certain for this size. More details are in Appendix B. In contrast, the zinc-air battery cost was based on an 80 \$/kWh projection for "large-scale production" made by Electric Fuel.[7]

The component parts are added to the base vehicle cost of \$590 retail (or \$295 to manufacture) in the chart below.

***Table 5.4 Long-term scooter cost to manufacture***

| **Part** | **Description** | **pure FC (5.9 kW)** | **hybrid (3.2 kW)** | **hybrid (1.2 kW)** | **zinc-air hybrid** |
|---|---|---|---|---|---|
| FC stack | DTI model; long-term cost | $220 | $165 | $135 | |
| Starter battery | Yuasa-Exide | $10 | | | |
| Hydrogen storage | DTI metal hydride model; long-term cost | $190 | $200 | $215 | |
| Storage batteries | Zn-air, 4.1 kWh | | | | $330 |
| Heat exchanger | Lytron M10-080 | | | $30 | |
| | Lytron M14-120 | $60 | $60 | | |
| Coolant pump | generic | $10 | $10 | $10 | |
| Blower for 1-2 psi | Ametek 116628-E | $110 | $110 | $110 | |
| Plumbing | Water, air pipes | $50 | $50 | $50 | |
| DC brushless motor | UQM SR121/1.5L | $125 | $125 | $125 | $125 |
| Controller | UQM CD05-100A | $150 | $150 | $150 | $150 |
| Peaking battery | Bolder lead-acid | – | $195 | $340 | $285 |
| Vehicle shell | body and misc. parts | $295 | $295 | $295 | $295 |
| | TOTAL | $1,220 | $1,360 | $1,455 | $1,185 |

The hybrid battery appears to be a very competitive option in terms of capital cost, if Electric Fuel's predictions of long-term zinc-air battery cost are correct. Due to the low fuel cell prices predicted for the long run, the (relatively) high expense of peaking power batteries eradicate the benefit of smaller fuel cells. Right now this is certainly not the case, as peaking power batteries currently sell for approximately $166 per kW, while fuel cells are as high as $3000 per kW.

The greatest uncertainties in these cost estimates are in the most important components: the fuel cell stack itself, the metal hydride storage unit, and in the case of the electric hybrid, the zinc-air battery. The peaking power lead-acid battery is also relatively novel technology, although it has been demonstrated in prototype vehicles. The other components are all "off-the-shelf" industrial parts and are not expected to decrease dramatically due to advancing technology. On the other hand, better engineering integration and design specific to the scooter application might reduce costs.

Doubling the costs gives a rough estimate of retail cost - the price for the consumer.

***Table 5.5 Summary of cost estimates***

| **type** | **price** |
|---:|---|
| pure FC (5.9 kW) | $2,440 |
| hybrid (3.2 kW) | $2,720 |
| hybrid (1.1 kW) | $2,910 |
| hybrid battery | $2,370 |

There is some room for cost reductions in the motor and controller prices of $250 and $300, respectively. The peaking power battery price may also drop further, while there is great uncertainty in the zinc-air battery price. However, the fuel cell cost is quite low and it is unlikely that it could go much lower. In addition, the fuel cell stack itself makes up a relatively small portion of the total cost.

The results suggest that margins will be very low since the manufacturing cost is very close to the current prices for small scooters. The scooter as designed, with 5.9 kW of output, might be better targeted against the low end of the 125 cc scooter range, rather than the 50 cc two-stroke scooter. This would give more freedom in terms of higher sale price and larger size to store the various subcomponents. By the same token, resizing for smaller-power and lower-performance scooters (say 3 kW) would bring a fair cost reductions – a simple calculation shows that the 3.2 kW hybrid scooter stripped of its peaking power batteries would cost $1160 to make. While it would be able to perform the basic performance criteria of acceleration and hill climbing, it would not be as quick to accelerate as comparable two-strokes.

### *5.1.3.1 The short term*

In the short term, hybridization with peaking power batteries drastically reduces the price of the scooter. In the long run when fuel cells are less expensive, the added complexity of batteries (and their lack of performance advantage over comparably-sized fuel cells) make them unnecessary. However, there is an intermediate stage as the price of the fuel cell drops to meet the cost of the peaking power batteries, where at a rough estimate, fuel cells will cost about $500/kW and batteries are $100/kW. The hydrogen storage and Zn-air batteries might be twice as much as the ultimate costs.

***Table 5.6 Short term bridging to the future***

| **Part** | **Description** | **pure FC (5.9 kW)** | **hybrid (3.2 kW)** | **hybrid (1.1 kW)** | **zinc-air hybrid** |
|---|---|---|---|---|---|
| FC stack | DTI model; long-term cost | $2950 | $1600 | $600 | |
| Hydrogen storage | DTI metal hydride model; long-term cost | $380 | $400 | $430 | |
| Storage batteries | Zn-air, 4.1 kWh | | | | $660 |
| Peaking battery | Bolder lead-acid | | $260 | $460 | $380 |
| | Rest of system | $810 | $800 | $770 | $570 |
| | TOTAL | $4140 | $3060 | $2260 | $1610 |

The ordering of the costs is reversed for the fuel cell hybrids here, and illustrates how hybrids might be required for the next several years in order to bridge the gap to inexpensive fuel cells. Once again, hybrid batteries prove to be an able competitor, although it should be recalled that neither the 1.1 kW hybrid nor the zinc-air hybrid can sustain the original hill climbing requirements. Whether the zinc-air hybrid scooter's lower capital cost is mirrored by lower operating costs is a subject for the next two sections, which deal with overall efficiency and fuel costs.

## 5.2 Wells-to-wheels efficiency

The on-vehicle fuel economy does not account for the entire story. To obtain complete cycle efficiencies, the inefficiencies in producing hydrogen or electricity, and in distributing the "fuel," must be considered. To be consistent with previous results and with the standard for large power plants in the United States, the higher heating value efficiency is considered here.

Steam reforming of natural gas in large plants is 84% efficient, with another 87% efficiency for distribution of hydrogen (including losses due to hydrogen compression). With a driving cycle fuel cell net conversion efficiency of 47.7% and 77% drivetrain efficiency, the final result is 27% from natural gas to road work.[8,9]

This should be compared to a scooter engine with gasoline distribution from the refinery to the filling station at 95% efficiency, a thermal efficiency of at most 20%, and transmission efficiency of 77%, for a total of 15%.[10]

In the case of the electric scooter, a factor of 40% is used to account for electricity production: the product of 90% electricity distribution efficiency and 45% electricity generation efficiency from a very good combined-cycle coal plant. The efficiency involved in electrowinning zinc from solution and then discharging it again in the battery is the ratio of the electrowinning voltage (2.2 V) to the output voltage (1.16 V), or 52.7%. On the vehicle there is a 77% drivetrain efficiency, for a total efficiency of 16% from coal to road work.

(Admittedly, these three efficiencies of 27%, 15%, and 16% technically do not start from the same starting point. Hydrogen will almost certainly be produced from natural gas, scooter combustion engines will run on gasoline, and coal is the major source of electricity in Taiwan and would be used (indirectly) for battery powered scooters.)

The internal combustion engine performs its most wasteful conversion step onboard, and cannot take advantage of economies of scale to produce high efficiencies. On the other hand, the zinc-air battery converts coal to electricity at a large power plant and loses (relatively) little there, but the electrowinning process is energy-hungry. So the hydrogen fuel cell system is actually the most efficient in terms of converting chemical energy to road work. However, even if it is the most efficient, it may not be the cheapest.

## 5.3 Fuel cost and infrastructure

In addition to the cost of the scooter itself, the fuel cost must also be accounted for. This is the electricity in the case of the battery-powered scooter, the hydrogen for the fuel cell scooter, and the gasoline in the standard internal combustion engine scooter.

Energy prices for Taiwan and the United States (4th quarter1997) are compared below. Note that there is regional variation in American prices which is not reflected here.

***Table 5.7 Taiwan vs. USA energy prices, 1997 USD***

| | **Taiwan** | **U.S.A.** |
|---|---|---|
| **Unleaded premium gasoline** | 65.1 ¢/liter | 36.9 ¢/liter |
| **Natural gas (industrial price)** | 7.71 $/GJ GCV | 3.53 $/GJ GCV |
| **Natural gas (household price)** | 10.81 $/GJ GCV | 6.26 $/GJ GCV |
| **Coal (steam coal)** | 83.97 $/tonne | 36.03 $/tonne |
| **Electricity (industrial price)** | 6.69 ¢/kWh | 4.07 ¢/kWh |
| **Electricity (household price)** | 10.02 ¢/kWh | 8.31 ¢/kWh |

Data is from the International Energy Agency.[11] GCV stands for Gross Calorific Value, which is the same as higher heating value ("Net Calorific Value" is equivalent to lower heating value).

When converted to common units of GJ of thermal energy (higher heating value), this is:

***Table 5.8 Fuel costs for Taiwan in $/GJ HHV***

| | **Taiwan** | **U.S.A.** |
|---|---|---|
| **Gasoline (premium, at the pump)** | 16.7 $/GJ | 9.5 $/GJ |
| **Natural gas (industrial price)** | 7.7 $/GJ | 3.5 $/GJ |
| **Coal (industrial price)** | 2.6 $/GJ | 1.1 $/GJ |
| **Electricity (industrial price)** | 18.6 $/$GJ_{elec}$ | 11.3 $/$GJ_{elec}$ |

This calculation assumes that the coal energy content is 14,000 BTU/lb (HHV, and average for an American coal), gasoline is an average 140,000 BTU/gallon, and that the quoted price is industrial pricing.[12,13] The gasoline price "at the pump" includes a markup for retail which was not listed in the source data. All energy values are higher heating value.

Taiwan prices are about twice as high as American prices, due to the island's lack of natural resource. Also, the higher gasoline price may be due to a different taxation policy.

### 5.3.1 Zinc-air battery “fuel” costs

Traditional storage batteries are punished for their short lifetimes (on the order of 600 cycles, or approximately 2 years at the present); the need to purchase replacement batteries adds to the lifetime cost. The zinc-air case is different, though, since it is not electrically recharged. Instead, after the zinc anode is oxidized into ZnO, it is switched for a fresh zinc anode. The depleted anode is sent back to a factory where it is electrolyzed an converted back into zinc.

Electric Fuel’s proposed zinc air infrastructure involves refilling stations (gas stations equivalents) where depleted anodes are exchanged for fresh zinc anodes, and “regeneration centers” which are centralized factories where the anodes are regenerated. The refilling stations essentially act as distributors and installers for the regeneration centers. The refilling stations could use automated machinery to switch the anodes in a short time (comparable to gasoline refilling) although capital costs might be high.

The regeneration centers are more complex. The “used up” zinc oxide is removed from the current collector plates, and dissolved in an alkaline (potassium hydroxide) solution. The solution is then electrolyzed (“electrowinning”) to restore the original zinc, which collects on the cathode and is scraped off and allowed to sink to the bottom of the electrolyte solution. The resulting zinc and potassium hydroxide slurry is periodically drained off, strained, and pressed against a current collector frame to produce a new anode assembly.

First, the theoretical minimum cost from the energy required is calculated. The maximum efficiency of the process is 52.7%, based on the ratio between the 1.16 V discharge voltage and the 2.2 V for electrowinning. So a 4.1 kWh output from the batteries is equal to 7.8 kWh at the electrowinning plant, and the electricity cost of 6.7 ¢/kWh gives a price of 52¢ for a single recharge. During daily driving, the Taipei Motorcycle Driving Cycle gives a fuel economy of 36.2 km/kWh. At 40 km/day (two hours of driving at TMDC speeds), and 300 days of travel per year, this is a total annual mileage of 12,000 km. The annual driving cost, taken from the 52¢ per recharge cost given previously for just the electricity needed to recreate the zinc anodes, is $42 per year. This is a net *electricity* cost of just 0.35 ¢/km.

A CSC (China Steel Corporation) study of costs for zinc-air battery replacement, however, calculated a total zinc-air driving cost over ten times higher, 4.3 ¢/km.[14] The assumptions are slightly different, with 4,300 km a year driving and a fuel economy of 40.3 km/kWh of output rather than 12,000 a year and 43.5 km/kWh:

***Table 5.9 Comparison of assumptions for zinc-air electrowinning costs***

| | **CSC study** | **this study** |
|---|---|---|
| **zinc-air battery size (output)** | 3.6 kWh | 4.1 kWh |
| **energy to recharge battery** | 4.9 kWh | 7.8 kWh |
| **single-charge mileage** | 145 km | 200 km (at 30 km/h) |
| **fuel economy (km/kWh-recharged)** | 29.6 km/kWh | 25.7 km/kWh (at 30 km/h) |
| **electricity cost** | 4.7 ¢/kWh | 6.7 ¢/kWh |
| **electricity cost per km** | 0.16 ¢/km | 0.35 ¢/km |

The electricity cost assumption is lower, but the energy price does not tell the whole story. The CSC study goes on to calculate costs for the complete refueling infrastructure: labour, periodic electrode and electrolyte replacement materials costs, spare batteries kept at the service station for exchange purposes, and land and building fees. Each station supplies approximately 2,400 scooters a day. This more comprehensive study results in annual fuel costs of $185 per year at 4,300 km per year, or $516 per year at the 12,000 km per year assumed here – for a total “fuel” cost of 4.3 ¢/km. This is extremely high but it is possible that costs may come down with time.

(Note that the electricity cost is insignificant, only 3.6% of the total cost of refueling the vehicle.)

When converted to a cost per kWh for comparison to the hydrogen and gasoline cases, this is $2.1 per kWh of output. In other words, a full recharge of the 4.1 kWh battery costs $8.60. By taking the cost as a function of energy recovered, this allows the original assumptions about annual driving and fuel economy to be used.

Pilot regeneration plants currently exist in Italy and Israel to service fleets of zinc-air demonstration vehicles, but one major drawback for zinc-air scooters is that car makers are not considering this technology and that eliminates one of the major players in technology advancement and cost reduction. This is different from PEMFCs, which are seeing broad development for not only vehicles but also portable power and stationary generation.

### 5.3.2 Hydrogen costs and infrastructure

In comparison, the 5.9 kW pure fuel cell system with 250 g of storage has a fuel economy of 0.527 km per gram of hydrogen (344 mpge) under TMDC driving. Hydrogen in Taiwan would likely be produced by imported natural gas converted at local hydrogen filling stations using steam reformers.

A study by Ogden *et al.* calculated that hydrogen produced by on-site conventional steam reformers would cost 12-40 $/GJ based on a Los Angeles-area natural gas price of 2.8 $/GJ.[15] The range of costs is a function of how large each reforming station is; a large reformer capable of producing 2 million standard cubic feet of hydrogen per day could handle 13,000 automobiles at a cost of 11.5 $/GJ, while a small 100,000 SCF/day station would handle 650 cars at 40 $/GJ. (Note that these calculations assume the existence of a natural gas distribution network, which may not be the case in Taipei.)

The same driving pattern that was calculated for the zinc-air version is assumed here: 45 km of travel per day. Taiwan prices for natural gas are 7.7 $/GJ, so prices for hydrogen increase by 5 $/GJ to 17-45 $/GJ. At the smallest station size (100,000 SCF/day), an area of 4,050 scooters running at 12,000 km per year could be serviced at a cost of 45 $/GJ. The fuel cost of operating a scooter turns out to be $145 a year or 1.21 ¢/km.[16] If a larger plant capable of servicing an area of 72,000 scooters was built, costs would drop to 17 $/GJ for a cost per vehicle per year of $55 and a driving cost of 0.46 ¢/km.

More advanced reformers would reduce the cost to 29 $/GJ for a 100,000 SCF/day 4,050-scooter plant, but larger stations would not be much cheaper. $29 $/GJ is the cost assumed here. Note that the raw natural gas cost is only 27% of the total delivered hydrogen cost; the rest is for labor, reformer construction, electricity, hydrogen storage and compressor.

While direct hydrogen is not currently being considered for first-generation fuel cell automobiles, buses are being demonstrated that store hydrogen in large compressed gas cylinders, and scooters could “piggyback” on a hydrogen distribution infrastructure for public transportation. In this case, there would not have to be 72,000 scooters within the operating area of a single refueling station plant.

Refueling metal hydrides essentially is a matter of filling at pressures of about 10 atm; the rate of adsorption is dependent on how quickly the excess heat of adsorption can be removed, and liquid coolants in the nozzle design can be used to effect this. The process could be done in just 5-15 minutes.[17]

### 5.3.3 Combustion scooter gasoline costs

The 100 mpg fuel economy of the gasoline-powered scooter is scaled down to 65 mpg for driving cycle performance (the same ratio as for the hydrogen powered scooter; note that actual performance will be different because of the efficiency-versus-power characteristics of the combustion engine).

Assuming the same travel distance of 12,000 km a year, and 65.1 ¢/liter for gasoline yields an annual fuel cost of $105, or 1.5¢ per kilometer.

### 5.3.4 Fuel cost summary

The advanced reformer for small service areas, at 24 $/GJ, was used for the hydrogen case; the China Steel Corporation cost analysis was used for the zinc-air battery to obtain a per-kWh price of $2.1, which was applied to driving 12,000 km per year under the lower mileage of the TMDC.

*Table 5.10 Fuel cost summary*

| | zinc-air hybrid | gasoline | 5.9 kW pure FC | 3.2 kW hybrid | 1.1 kW hybrid |
|---|---|---|---|---|---|
| **refueling cost** | 583 $/GJ$_{elec}$<br>(2.1 $/kWh) | 16.7 $/GJ$_{HHV}$<br>(65.1 ¢/L) | 24 $/GJ$_{HHV}$<br>(0.34 ¢/g) | 24 $/GJ$_{HHV}$<br>(0.34 ¢/g) | 24 $/GJ$_{HHV}$<br>(0.34 ¢/g) |
| **TMDC mileage** | 36.2 km/kWh | 65 mpg | 0.527 km/g | 0.484 km/g | 0.525 km/g |
| **on-vehicle mileage** | 780 mpge | 65 mpg | 344 mpge | 320 mpge | 363 mpge |
| **cost per distance under TMDC** | 5.8 ¢/km | 1.5 ¢/km | 0.65 ¢/km | 0.70 ¢/km | 0.65 ¢/km |
| **annual cost** | $696 | $184 | $78 | $84 | $78 |
| **present value of fuel over 10-year lifetime** | $4,275 | $1130 | $480 | $515 | $480 |

Present value costs were calculated over a ten-year scooter lifetime, with a 10% discount rate (meaning future fuel costs are discounted heavily compared to the up-front capital cost)

The zinc-air battery's energy cost is actually very low, but infrastructure costs, spare battery expense, and depreciation of the stock of batteries all add up to a very expensive per-km cost. Over time, infrastructure costs must reduce drastically if zinc-air batteries are to be competitive.

The gasoline-powered scooter reflects current efficiencies, and improvements in air pollution technology like fuel injection will likely improve fuel economy by a small amount and reduce driving costs.

Hydrogen production at the infrastructure levels assumed here results in hydrogen costs that are less than half the price of gasoline, due to the high efficiency of the fuel cell scooter. Even with the extremely small-scale hydrogen reforming station assumed here, the cost is low enough to make hydrogen fuel cell scooters a cheaper option to drive than gasoline-powered scooters.

Under these assumptions, the fuel cost is roughly on the order of the vehicle cost for the gasoline vehicle, much more expensive for the zinc-air hybrid due to its low cost, and significantly cheaper for the hydrogen powered scooter due to its high efficiency. However, the comparison is uncertain due to the great uncertainties in the fuel cell and zinc-air technology costs. Also, maintenance and repair costs are not yet quantified for the advanced technologies. These two reasons explain why the capital and present value of fuel were not directly summed.

## 5.4 Final Conclusions

Advanced fuel cell powered scooters could produce more than three times the 100 mpg of current gasoline-powered scooters, with zero tailpipe pollution. In the long run, a rough cost estimate predicates that they would cost about $1,200 – $1,300 to produce, although prices for the consumer would be as much as twice this amount. In comparison, more advanced combustion-powered scooters (like four-stroke scooters) could offer pollution reduction of about 75% of hydrocarbons and 50% of carbon monoxide for an additional cost over two-stroke scooters of under $200. However, one methodology shows that there is significant health benefit to even removing that last stage of emissions, so if the proper dollar value were assigned to the air pollution reductions, a value of several hundred dollars would apply to the zero-emission scooters.

This study arrived at this conclusion through an analysis of current scooter performances and pollution trends, a general examination of the health benefits of zero-pollution scooters over four-stroke scooters, a discussion of electric vehicle technology including battery, fuel cell, and hydrogen storage options, and detailed modeling of scooter driving and fuel cell performance that had not been done before for this type of vehicle.

A fuel cell design was presented for the scooter that focused on simplicity on all fronts: pure hydrogen operation, low temperature. In addition, hybrid designs were examined in an effort to accelerate fuel cell scooter adoption by reducing the size of the fuel cell stack needed. Hybrids reduce price in the short term, but in the long run fuel cells should come down in price by enough to make peaking power batteries unnecessary.

Finally, another option, the zinc-air battery, was examined. This technology showed good technical performance, and a zinc-air drive system would be half the weight of a fuel cell system. Questions remain about the expense of developing an infrastructure for zinc anode regeneration and electrolyte / cathode replacement, which currently are projected to be very expensive. So low capital cost is traded for high fuel costs

The original work done and results obtained are summarized below.

### 5.4.1 Background

The focus was placed on Taiwan because of its extremely high vehicle density, the large number of scooters, and its pre-eminence as a scooter manufacturing center. High pollution levels, especially in cities, are a concern among the populace and government and one of the primary motivators for cleaning up cheap two-stroke scooters. Four-stroke scooters will likely expand to fill the role of these two-stroke scooters, and provide significant reductions in emissions.

A sketch of cost and benefits shows that hundreds to thousands of dollars of health benefit per vehicle could be realized by switching from four-stroke engines to zero-emission vehicles. The government’s chosen solution, the battery powered scooter, currently lacks adequate range.

Proton exchange membrane fuel cell systems offer greater range, with the same zero tailpipe emissions since they produce electricity electrochemically, with water as the only exhaust. As is the case with battery-powered scooters, pollution emissions would be shifted to central (in this case, hydrogen-generating) plants.

Hydrogen storage is best supplied with hydrogen stored onboard in cylinders or in the form of metal hydrides. The latter offers excellent synergy with the cooling system due to its endothermic hydrogen release, and greater safety due to the far lower pressures (1-10 atm), and is recommended here.

### 5.4.2 Modeling results

Modeling shows that maximum power required is just under 6 kW for performance comparable to combustion two-stroke scooters. Average power demands are a tenth, at 670 W for urban driving. The following performance specifications were required:

***Table 5.11 Fuel cell scooter performance requirements***

| Specification | Fuel cell scooter |
|---:|:---:|
| **max motor power output** | 4-6 kW |
| **range before refueling at 30 km/h cruising speed** | 200 km |
| **fuel efficiency** | > 100 mpge |
| **acceleration** | 0-30 m in less than 5 seconds |
| **sustained speed on 15° slope** | 10 km/h |
| **sustained speed on 12° slope** | 18 km/h |
| **maximum speed** | 60 km/h |

### 5.4.3 Design

This thesis presents a fuel cell design for a scooter of approximately 5 or 6 kW, a niche that was previously unexplored. Size, weight, and cost restrictions force the design to be simple and to remove any unnecessary systems. Where data were not well known and assumptions were necessary, performances were assumed to be worse than expected to ensure a feasible design.

A compressor/expander system to provide 3 atm pressurized air at the cathode was rejected as the benefit did not outweigh the parasitic power losses and additional complexity, weight, and expense. The advantages of high pressure for water removal were not considered.

Cooling of the fuel cell system proved to be a significant problem. A radiator was chosen that could handle the maximum continuous cooling load (produced by slope climbing requiring 3020 W of power for an indefinite period). Benefits in cooling derived from “ram effect” air flowing over the radiator were not included so the system was somewhat overdesigned. Integration of a metal hydride hydrogen storage system provided a useful method of extracting 17% to 30% of surplus heat. The thermal mass of the system and the low *average* heat production meant that over the TMDC, cooling is not a problem

The complete drive system configuration (fuel cell, battery, motor, controller, hydrogen storage in DTI-modeled metal hydride) is summarized below.

*Table 5.12 System design results*

| | today's ZES-2000 | pure FC (5.9 kW) | hybrid (3.2 kW) | hybrid (1.1 kW) | zinc-air battery |
|---|---|---|---|---|---|
| **Sustained net power** | ~ 3 kW | 5.6 kW | 3.0 kW | 1.0 kW | 1.8 kW |
| **Range (30 km/h)** | 65 km | 200 km | 200 km | 200 km | 200 km |
| **Range (TMDC)** | < 35 km | 131 km | 129 km | 149 km | 148 km |
| **Drive system (size)** | 24 L | 43 L | 43 L | 30 L | 41 L |
| **Drive system (weight)** | 60 kg | 61 kg | 63 kg | 60 kg | 45 kg |

The fuel cell auxiliary systems make the drive system heavy, even though the weight of the fuel cell itself is relatively low. To go from today's ZES-2000 to a 1.1 kW hybrid requires 6 L of additional space which is easily found in the current body frame, but the other systems will require a redesign of the body (although this is not be a "show-stopping" requirement).

The relatively poor energy density of the hybrid zinc-air battery causes the high volume requirements of that design, whereas the 5.9 kW and 3.2 kW fuel cells feature very large radiators that account for the high volume.

Hybrid power systems with a combined peaking power battery and hydrogen prime energy source offer significant reductions in cost because fuel cells are so expensive right now, although in the long run this situation is expected to reverse in favour of pure fuel cell scooters. The costs are detailed in the next section.

### 5.4.4 Costs and infrastructure

The following costs-to-manufacture are listed below for various cases.

*Table 5.13 Long-term cost of hybrid fuel cell scooters*

| **pure FC (5.9 kW)** | **hybrid (3.2 kW)** | **hybrid (1.1 kW)** | **hybrid battery** |
|---|---|---|---|
| $1,220 | $1,360 | $1,455 | $1,185 |

The sale cost may be as much as double this price, which would be significantly more than today's two-stroke internal combustion scooters at $1,000 and electric battery-powered scooters (albeit with only one third the range) at $1,500.

Assuming hydrogen costs of 24 $/GJ from small reforming stations running on pipelined natural gas obtains the following comparison:

*Table 5.14 Fuel cost summary*

| | **zinc-air hybrid** | **gasoline** | **5.9 kW pure FC** | **3.2 kW hybrid** | **1.1 kW hybrid** |
|---|---|---|---|---|---|
| **on-vehicle mileage** | 780 mpge | 65 mpg | 344 mpge | 320 mpge | 363 mpge |
| **cost per distance under TMDC** | 5.8 ¢/km | 1.5 ¢/km | 0.65 ¢/km | 0.70 ¢/km | 0.65 ¢/km |
| **annual cost** | $696 | $184 | $78 | $84 | $78 |
| **present value of fuel over 10-year lifetime** | $4,275 | $1,130 | $480 | $515 | $480 |

Fuel prices for the zinc-air hybrid battery scooter are incredibly high according to the one study cited in this study. Hydrogen fuel cell scooters have very good range and mileage, and can operate cheaply even if hydrogen is produced at the relatively small scales assumed here. It is not only the pollution benefits that make hydrogen scooters better than current gasoline-powered scooters; the fuel savings are also significant.

### 5.4.5 Parting words

Fuel cell scooters face many of the same problems as fuel cell automobiles: the technology is new, and thus expensive, and distribution infrastructure does not exist for hydrogen delivered to the end user. On the other hand, the Taiwan situation features somewhat high fuel prices, relatively high income levels, and extremely poor air quality, two drivers for more efficient and cleaner vehicles. The situation in China, Japan, and other Asian countries is similar, with varying degrees of pollution and wealth. Some European countries have high numbers of scooters as well and could be markets for this technology.

In the long run, the hydrogen fuel cell scooters could cost approximately $1,200 to manufacture. This is dependent upon significant reductions in metal hydride and fuel cell costs, and these reductions would occur most quickly if they piggybacked off other markets that called for large numbers of these two core components.

Ordinary electric battery scooters are not projected to have the energy densities required, and a recharging infrastructure is a problem in Taiwan where indoor vehicle storage off the street is not always guaranteed. Zinc-air scooters are likely to cost less than fuel cell scooters, but are projected to have, at least in the short term, extremely expensive refueling costs based on more complex battery exchanging stations. Hydrogen scooters would be cheaper to drive than combustion scooters.

Future work on this topic would move the conceptual design and feasibility test presented here to more applied design work and prototype construction. The performance presented here is unlikely to be far from actual results, and assumptions made here have always erred on the side of more waste and worse performance. So building a prototype fuel cell scooter – or even only the fuel cell power system – and obtaining more detailed data on the parasitic power would be an excellent way to measure real-world performance, which for the reasons outlined above is expected to be higher than the conservative estimate here. System integration of the various heat flows and physical assembly of the variously-shaped parts also needs to be demonstrated.

Also, “smart” hybrid power management algorithms should be designed to optimize hybrid scooters that may be used in the next several years while fuel cells are still too expensive to be the sole power source for vehicles. Detailed research specific to Taiwan and other Asian locations is needed on the subject of hydrogen distribution. Finally, as reformer and direct methanol fuel cell technology advance, they may become feasible for this application and this must be kept in mind.

Recommendations: in the short run, getting rid of two-strokes and speeding a transition to four-stroke engines is an inexpensive path to deep reductions in emissions. The Taiwan government is following the right track in legislating emissions performance requirements rather than enforcing technology. A hydrogen fuel cell scooter offers additional air pollution reduction benefits over four-strokes that could justify its increased costs, however, and is worth investment in research and development. Peaking power batteries for upcoming scooters are highly recommended to allow the use of smaller and less expensive fuel cells without the performance compromises that would cause public rejection of advanced scooters, and metal hydride technology is the best fuel storage strategy.

FIN

# References for Chapter 5

1. Mark DeLuchi. Institute of Transportation Studies, University of California, Davis. *Hydrogen Fuel-Cell Vehicles.* Research Report UCD-ITS-RR-92-14 September 1, 1992. p. 147

2. Jet P. H. Shu, Wei-Li Chiang, Bing-Ming Lin, Ming-Chou Cheng. Mechanical Industry Research Laboratories, Industrial Technology Research Institute. "The Development of the Electric Propulsion System for the ZES2000 in Taiwan" Internal paper, date unknown (October 1997 or later)

3. Randy Knudson, Scooter Therapy. Personal communication May 21, 1999

4. $150 estimate of cost from Dr. Philip G. Felton, Princeton University Department of Mechanical and Aerospace Engineering, personal communication July 26 1999

5. Jeffrey Ho. Deputy Director, Taiwan UQM. Personal communication May 24, 1999.

6. Brian D. James, George N. Baum, Franklin D. Lomax, Jr., C. E. (Sandy) Thomas, Ira F. Kuhn, Jr. Directed Technologies, Inc. "Comparison of Onboard Hydrogen Storage for Fuel Cell Vehicles" Task 4.2 Final Report. Prepared for Ford Motor Company under Prime Contract DE-AC02-94CE50389 "Direct Hydrogen Proton-Exchange-Membrane (PEM) Fuel Cell System for Transportation Applications" to the U. S. Department of Energy, pp. 4-56, 4-63, 4-52

7. Jonathan Goldstein, Ian Brown, Binyamin Koretz. "New developments in the Electric Fuel Ltd. zinc / air system" *Journal of Power Sources* **80** (1999) pp. 171-179

8. Joan M. Ogden, Margaret M. Steinbugler, Thomas G. Kreutz. "A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles: implications for vehicle design and infrastructure development" *Journal of Power Sources* **79** (Elsevier: 1999), pp. 143-168

9. Note that the overall conversion efficiency is actually 55.7% from hydrogen heating value to electricity. However, about 10% of that electricity is needed for parasitic purposes and is wasted in terms of useful output like road motion or auxiliary power. The efficiency net of parasitics is 46.7%

10. Matthew Brekken and Enoch Durbin. "An Analysis of the True Efficiency of Alternative Vehicle Powerplants and Alternative Fuels." Society of Automotive Engineers 981399, 1997.

11. International Energy Agency. "Key World Energy Statistics" http://www.iea.org/stats/files/keystats/stats_98.htm. Accessed May 8, 1999

12. World Bank. "World Bank - Typical Coals of the World" http://www.virtualglobe.com/html/fpd/em/power/sources/coal_tcw.htm Accessed August 19, 1999

13. World Bank. "World Bank - Typical Analyses and Properties of Fuel Oils*" http://www.virtualglobe.com/html/fpd/em/power/sources/oil_tapfo Accessed August 19, 1999

14. China Steel Corporation study for chemTEK. Received August 21, 1999 from chemTEK.

15. Joan Ogden, Margaret Steinbugler, Thomas Kreutz. "Hydrogen as a fuel for fuel cell vehicles: a technical and economic comparison"

16. *ibid*

17. Joan Ogden, Princeton University. Personal communication July 22 1999