APSC 262
Term Paper

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The Energy Cost of Electric and Human-Powered Bicycles

Background

The Power-Assisted Bicycle is an emerging form of transportation that attempts to merge the health and environmental benefits of a bicycle with the convenience of a motorized vehicle. According to recent amendments to the Motor Vehicle Safety Act, a power-assisted bicycle may have up to 500 watts of electrical output and still be legally equivalent to a human-powered bike on the road (Canada Gazette 658-659).

Compared to other forms of transportation, the conventional bicycle is among the most efficient means of human locomotion. To travel one kilometre by bike requires approximately 5-15 watt-hours (w-h) of energy, while the same distance requires 15-20 w-h by foot, 30-40 w-h by train, and over 400 w-h in a singly occupied car. (Bouwman, 2) It would be expected then that the overall environmental impact of an electric bike would similarly be an order of magnitude more favourable than cars, busses, or other forms of urban transit.

There is none-the-less some reservation expressed over the use of electric bicycles by people who are otherwise capable of riding conventional bikes. Surely, it is argued, if people can get by under muscle power alone then the addition of batteries and electricity only adds to the environmental costs of a bicycle.

However, this conclusion is premature because it fails to recognize that the electric motor is replacing human work, and that human work comes at the expense of increased food consumption. The only way to properly address the relative sustainability of electric bikes compared to ordinary bikes is through a complete life-cycle analysis.

Assumptions

Several assumptions will be made in order to simplify the life-cycle comparison. The first is that the electric bike and the conventional bike have similar energy consumption per kilometre. This simplification is reasonable because electric bikes have the same aerodynamic profiles of regular bicycles, and the additional weight of the motor and battery pack is small compared to the gross vehicle weight. It fails to be true if an individual travels faster on an electric bike than they would under pedal alone, as air resistance adds considerably to the power requirements. But since the electric assistance is limited to 32 km/hr, about the same average speed of a skilled cyclist, it is fair to ignore this factor in a first order approximation.

Only the consumables of both transportation modes will be considered in the comparison. Electric bikes have the same components of an ordinary bike, with the addition of a motor, motor controller, battery pack, and battery charger. They therefore have a larger up-front cost to produce. However the electric motor, controller, and charger, are all maintenance-free with an indefinite life-span, so beyond their initial manufacture there is little associated environmental cost. The one component that does require replacing is the battery pack and this will be included in all calculations.

This treatment is also ignoring all secondary effects. For instance, the health benefits and costs of exercise will not be addressed, nor will the disposal of toxic materials in batteries be considered. Accounting for the former would be a complex task, while the later is less of an issue as battery recycling becomes more commonplace.

Under these assumptions, the life-cycle analysis comes down to a relatively simple energy comparison. It suffices to determine how much primary energy is needed to make the food that produces a given amount of muscle work. This is then compared to the primary energy necessary to achieve the same amount of work through a battery and motor.

Primary energy is defined as any man-made energy source, such as from the electric grid or from the direct combustion of fossil fuels. It does not include the solar radiation used to grow crops. Throughout this paper, primary energy is expressed in MegaJoules (MJ), while the energy in a charged battery is given in watt-hours (w-h), and the energy in food is expressed in Calories (kcal).

1 MJ = 1,000,000 Joules
1 kcal = 4,200 Joules
1 w-h = 3,600 Joules

Energy of Food Production

Food production is a major consumer of energy in Western Society. In a comprehensive survey of Canadian Food Production, CAEEDAC found that the food sector accounted for 11% of Canada's total energy use (33). This number includes the direct energy consumed by the agricultural industry, the energy used to produce fertilizers, pesticides, farm machinery, and the energy associated with the processing, packaging, transportation, and cooking of food products. Per-capita it amounts to 56 MJ or 13,400 kcal per day (CAEEDAC, 36).

By comparison, the average amount of food calories consumed per person over the whole age distribution is approximately 2000 kcal per day. One can therefor calculate that the overall food production efficiency in Canada as 2:13.4, so that for each calorie available as food energy, approximately 7 calories went into producing it. This efficiency ratio of 1:7 is similar to the results quoted by Günther, who gave Sweden an efficiency of 1:7, the USA 1:11, and western society an average of 1:9.5 (3).

Metabolic Efficiency

The metabolic efficiency of a human on a bicycle is remarkably good. Calorimetric studies have shown that a properly trained athlete will have efficiencies of 22 to 26% depending on pedal cadence and power output (Prempero 348). This means that every calorie of mechanical energy delivered to a bike consumes approximately 4 calories of food energy.

By combining the metabolic efficiency with the food production efficiency, a net figure for the human power efficiency is produced.

N human = 1:7 * 1:4 = 1:28

In other words, on average each unit of mechanical energy that a cyclist delivers to the pedals comes at the expense of 28 units of primary energy (i.e. Fossil fuels).

Production of Batteries

The energy storage source of an electric bicycle is the rechargeable battery. At present, there are 4 battery chemistries that are observed in use. The Lead Acid (PbA) battery is by far the most common, while Nickel Cadmium (NiCad) is occasionally seen, and Nickel Metal-Hydride (NiMH) and Lithium Ion (Li-ion) batteries are both making headway as the choice for the future.

The task of choosing battery chemistry typically comes down to weighing the high energy density advantages lithium and NiMH over the considerably lower cost of Lead Acid and the long cycle life if NiCad. Rarely is the total environmental impact of each choice considered. Therefore, the life-cycle energy use of each of these four battery chemistries will be examined individually.

Comprehensive data on the total energy required for the production of rechargeable batteries has been difficult to find. The most thorough analysis available is that from Rydh and is summarized in Table 1 (3). Units are megaJoules of primary energy necessary to produce one watt-hour of battery capacity. Rydh derived the manufacturing energy costs from plant data, and provided the materials cost of both virgin and recycled sources. Only the virgin materials are included here although it should be noted that the material energy costs are considerably less with recycled sources.

Table 1: Energy Cost to Manufacture Batteries. Source: Rydh, 2003

Battery Type	Materials Recovery (MJ/w-h)	Manufacturing (MJ/w-h)	**Total** (MJ/w-h)
Li-ion	0.67	1.2	**1.9**
NiCad	2.0	2.1	**4.1**
NiMH	1.6	2.1	**3.7**
PbA	0.77	0.42	**1.2**

These figures take into account the transportation of raw materials to the manufacturing plant. In addition, there is the transportation of the finished battery pack to the end user. At present, most rechargeable batteries for electric bikes are produced in China or Taiwan and shipped by air to North America.

Table 2 calculates the total energy cost to ship the battery packs based on their energy density, using a trip distance of 10,000 km (Taiwan->Vancouver), and an air-freight efficiency of 20 MJ/km-tonne (Rydh, 3). It can be seen that in the case of Lithium and NiMH, the transportation energy is comparable to the total manufacturing energy, while lead-acid takes nearly 7 times more energy to ship than to produce.

Table 2: Energy Cost for the AirFreight of Batteries

	Energy density (w-h/kg)	**Transportation Eff. (MJ/tonne-km)**	**Distance (1000 km)**	**Transportation Cost (MJ/w-h)**
Li-ion	120	20	10	**1.7**
NiCad	40	20	10	**5.0**
NiMH	60	20	10	**3.3**
PbA	25	20	10	**8.0**

Battery Life-Cycle

The total energy that can be extracted from a battery is equal to its capacity in watt-hours times the number of complete charge and discharge cycles it can deliver. The mechanical energy delivered to a bike is simply this total energy multiplied by the motor efficiency.

The total energy consumed by the battery pack through the recharging process is higher than the energy delivered to the motor because of various inefficiencies at each conversion stage from the utility grid to the pack.

Both of these totals are calculated in the last two columns of table 3. The low values for the number of charge cycles of both NiMH and PbA are based on realistic experiences that have been obtained by electric bike users. The normally published value of 500 cycles is considered optimistic for the high rate demands of a vehicle. Buchman has tested NiCad batteries to over 2000 cycles under proper maintenance (Ch. 6), so a value of 1000 cycles for an electric vehicle is reasonable. The lithium cells are too recent to have reliable life-cycle documentation and hence the manufacturers estimate of 500 cycles is used.

Table 3: Input and Output Energy from Batteries

	Cycles	Grid Efficiency	Charging Efficiency	Charger Efficiency	Bike Motor Efficiency	Tot. Energy In (MJ/w-h)	Tot. Energy Out (MJ/w-h)
Li-ion	500	0.5	0.95	0.85	0.75	**4.5**	**1.4**
NiCad	1000	0.5	0.8	0.85	0.75	**10.6**	**2.7**
NiMH	300	0.5	0.6	0.85	0.75	**4.2**	**0.8**
PbA	250	0.5	0.8	0.85	0.75	**2.6**	**0.7**

The charging efficiency is the ratio of the energy that comes out of a battery pack over the electrical energy put in. Lithium has a nearly perfect value in this regard, while the other chemistries have secondary cell reactions that consume a considerably amount of energy during the charge cycle. The charger efficiency of 85% is a reasonable approximation of modern power circuitry, and a conversion factor of 75% is achieved by most bicycle hub motors. The grid efficiency of 50%

was used to approximate the efficiency of the utility system, which in Canada is derived from fossil fuel, nuclear, and hydro sources.

All the data has been presented to calculate the energy input to output ratio for an electric bicycle. This is done by taking the Energy Out of Table 3 divided it by the sum of the Energy In, the transportation energy of Table 2, and the manufacturing energy of Table 1. The ratios for each chemistry are presented in Figure 1 along with the previously calculated cost for human power.

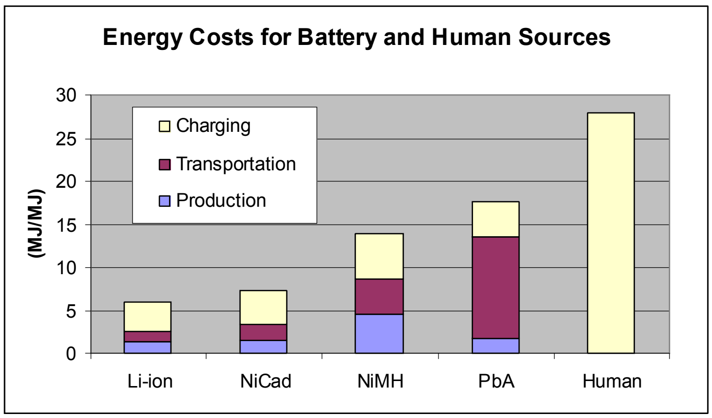

Figure 1: Life Cycle Energy Requirements

The results show that lithium-ion is clearly the most energy efficient chemistry, due to it's light shipping weight, low manufacturing costs, and high charging efficiency. The NiCad cells are close behind because the large number of charging cycles compensates for high manufacturing and shipping expenses. Lead acid fared the worse, requiring a full 17MJ of primary energy for each MJ of mechanical output. Most of the energy is tied to the shipping cost for these heavy cells. In spite of this, the lead acid battery still consumes over 1/3rd less energy than a human rider.

The above figures were all produced by assuming average or typical cases. To be fair, it is entirely possible for a bicycle rider to deliberately eat only locally grown and unprocessed foods. In that case, the ratio of primary energy to food calories is closer to 1:1 (Günther 3). Combined with a metabolic efficiency of 25%, this increases the human energy efficiency to 1:4, slightly better than the lithium-ion electric bike.

A similar best-case scenario can be made for the battery packs. In Vancouver BC, the electricity grid is mostly hydro-powered and has close to unit efficiency. As well, there is at least one local manufacturer of lithium batteries and numerous nearby producers of lead acid cells. The same graph using only local battery sources and hydropower is shown in Figure 2, in comparison with a rider consuming local foods.

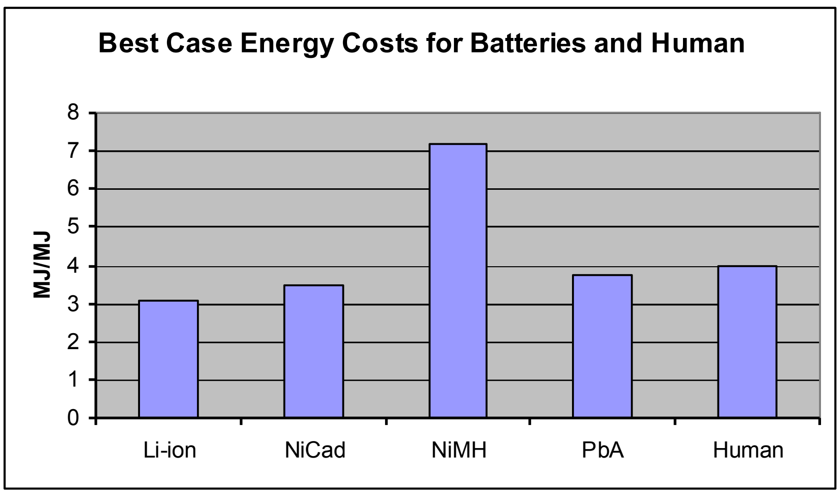

Figure 2: Energy Requirements with Local Sources

Interestingly the best case situations for electric and human power are quite similar. In this case, NiMH require the largest energy input, while lead acid and NiCad are nearly on par with Lithium at ~1:3½.

Conclusion

Despite the intuitive sense that electric bikes would require more resources than regular bikes, life-cycle analysis shows that they actually consume 2-4 times less primary energy than human riders eating a conventional diet. This conclusion is largely due to the considerable amount of transportation and processing energy that is associated with our western food system.

From a sustainability perspective, the best battery chemistry for electric bicycles is the lithium-ion cell. In the optimum scenario it can deliver nearly 1/3rd of all the energy put into manufacturing and charging to the wheels of a bike. Since lithium batteries have a high energy density, they are also desirable from a rider's perspective because only a lightweight pack is required. Unfortunately, the current high-cost of lithium batteries generally makes them less favorable then other chemistries from an economic perspective.

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