# Charging of Batteries through Human Motion: First Principle Analysis

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# Summary

We studied the energy balances of a hypothetical system for electric power generation from human motion and its storage into rechargeable batteries. The concept has been proposed by M2E, Inc. from Idaho and funded by OVP Venture Partners, with additional participation from @Ventures and Highway 12 Ventures.

M2E's innovative differentiation is in improved and efficient implementation of electromagnetic induction, for which the company has filed a series of patents.
For the purposes of this study we assumed that M2E's implementation is fully achievable and reaches **100%** efficiency, i.e. we have not estimated any technological risk associated with the development of M2E's proprietary technology.

Despite assuming such remarkable breakthrough, M2E's business idea is unworkable due to simple thermodynamic constraints. This is evident using basic calculations and first-order approximations, which we have presented in a simplified illustrative example. Furthermore, we have done a more detailed breakdown to aid potential evaluators in modelling the limitations of this and similar approaches.

The investment of **$8M** into M2E is another example of irresponsible investment decisions amidst the hype of alternative energy.

# Background

## *1. Market*

### a) Powering Soldier- Borne Equipment

The modern combat soldier carries multiple pieces of technologically advanced gear with substantial energy consumption. Meeting these energy demands has become a priority for the Armed Services, thus opening opportunities for vendors of portable energy sources. A White Paper by Jane's states that "with heavily armed, and electronics-laden, troops increasingly confronting light, irregular forces, issues of weight and power-driven equipment reliability are becoming more important than ever."

### b) Disposable vs. Rechargeable Batteries

The high cost and logistical burden of heavy battery use was first addressed by the US Army in 1996 through an initiative to reduce battery expenditures, (US$96 million in 1996) by 50%. By 2001 expenditure on batteries had been cut to US$75 million, with much of the savings coming from transition to rechargeable batteries, which due to their multiple use have significantly lower cost of ownership.

Another advantage of rechargeable batteries is their better discharge efficiency at higher currents. By specification, disposable alkaline batteries have rated energy densities of **~210 Wh/kg**, surpassing that of even the best rechargeable Li-Ion batteries (**~160 Wh/kg**). The caveat in this direct comparison is that alkaline batteries are rated at low loads (25mA) while their discharge efficiency drops dramatically with increased loads, in which conditions the effective energy density compares unfavourably with rechargeable batteries.

It is expected that the transition to rechargeable batteries will continue going forward, despite some apprehensions about their use by combat troops and some logistical hurdles (slow penetration of battery life indicators, chargers, etc.)

### c) M2E approach

M2E's idea is to take the rechargeable battery concept a step further, where it can be recharged from soldier-generated mechanical energy via M2E's proprietary generators. The idea is to relieve soldiers on a platoon mission, having no access to a charging generator, from carrying excessive load of spare batteries and instead charge their batteries constantly "on-the-go".

## *2. Energy Conversions*

The proposed energy conversion chain is shown in Figure 1.

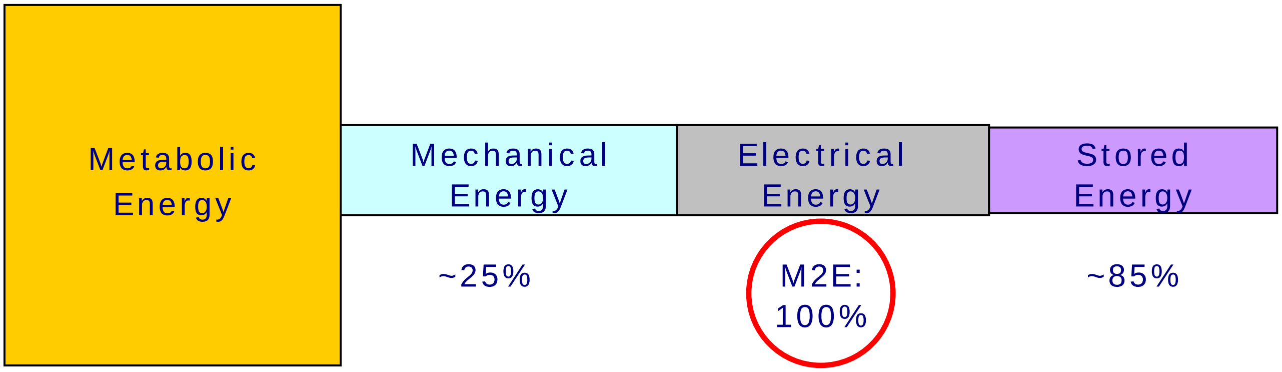

**Figure 1.** Energy conversions with top efficiencies for the proposed technology.

Human muscles are metabolic motors converting metabolic into mechanical energy with top efficiencies of **~25%**. Mechanical energy can be converted into electricity via electromagnetic induction: this is the area where M2E has focused its innovation and has filed several patents (red circle in the diagram).

Faraday's law states that the electromotive force (emf, voltage) is dependent on the time rate of change in the magnetic induction. For example, in rotary electro-generators, the voltage is given by $\mathbf{V} = \mathbf{k}\cdot\omega$, where $\mathbf{k}$ is the torque constant and $\omega$ is the angular frequency. This dependency on frequency is highly problematic for electro-generation from repetitive human motion as it is difficult to achieve frequencies higher than 10Hz: generally insufficient to support the voltage requirement, within reasonable values of $\mathbf{k}$. Use of a gear train can step up the mechanical frequency, however it introduces friction losses, thus reducing the generator efficiency.

For these reasons use of regular induction generators is inefficient in mobile generation that relies on human motion and alternative designs have been sought (see for example U.S. patent **6,140,730** owned by General Electric).

For the purposes of this study we have not looked up any M2E patents and assume that the good people from M2E have found a way to make electromagnetic induction work with theoretical **100%** efficiency. Thus, any technological risk associated with the development of such an innovation is safely neglected.

Finally, once electrical power is generated, it can be stored in regular rechargeable batteries. Modern power circuitry achieves **~85%** charging efficiency.

### 3. *Energy Breakeven Distance*

Soldiers expend energy while carrying heavy loads of spare batteries; fatigue and exhaustion is directly proportional to the amount of metabolic energy expended. Therefore, a theoretical point exists where the energy expended on carrying spare batteries equals a soldier's metabolic cost needed to generate the amount of electricity contained in them, using his own muscles. We will call this the *Energy Breakeven Distance* (**EBD**), measured in *kilometres*.

Rephrased, **EBD** is the distance a soldier has to carry batteries in his backpack to make his energy expenditure equal to the energy required to generate the same amount of electricity using M2E-type - **100% efficient** - gear. If a mission is shorter than **EBD**, it is more energy efficient to carry spare batteries; if the mission is longer than **EBD** it becomes more efficient to generate muscle-driven power "on-the-go".

To describe **EBD** we will introduce two auxiliary values: $\mathbf{M_c}$, ($J.km^{-1}$) is a measure of the metabolic energy needed to carry a load of batteries with certain electric energy content for one *kilometre*. $\mathbf{M_g}$ ($J$) is the amount of metabolic energy needed to generate and store in rechargeable batteries the same amount of electric energy, using muscle-driven generation.

Thus, **EBD** can be simply described by Equation 1:

**(1)**

$$\mathrm{EBD} \cdot M_c = M_g$$

which rearranges into Equation 2:

**(2)**

$$\mathrm{EBD} = \frac{M_g}{M_c}$$

It should be noted that **EBD** varies very little with battery weight, which affects both $\mathbf{M_c}$[1] and $\mathbf{M_g}$.

### 4. *Parameters needed for calculation of* EBD

Aside from the energy conversion efficiencies described in Figure 1, we only need two other parameters to calculate **EBD**:

#### a) Metabolic Expenditures for Carrying a Load

Energy expenditures for walking and backpack load carrying were studied extensively in the 1970s by the U.S. Army Research Institutes (Pandolf et al., 1977). A universal predictive formula is given by Equation 3:

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[1] $\mathbf{M_c}$ dependence on load-weight is non-linear, (see Equation 3), thus **EBD** is, in fact, slightly sensitive to weight, however in the context of reasonable human loading this dependence is negligible.

**(3)** $\mathrm{M} = 1.5\mathrm{W} + 2.0(\mathrm{W}+\mathrm{L})\cdot(\mathrm{L}/\mathrm{W})^2 + \eta(\mathrm{W}+\mathrm{L})\cdot[1.5\mathrm{V}^2 + 0.35\mathrm{VG}]$

where **M** = metabolic rate, *watts*; **W** = subject weight, *kg*; **L** = external load, *kg*; **V** = speed of walking, $m\cdot s^{-1}$; **G** = grade (slope), *%*; and $\eta$ = terrain coefficient ($\eta$ = 1.0 for treadmill).

### b) Energy density of batteries

For the purposes of this study we assume that M2E devices would be used to replace regular Li-Ion rechargeable batteries, with energy densities of **~160 Wh·kg$^{-1}$**. This assumption offers a straightforward basis for comparison as M2E, too, plans to use rechargeable packs in their devices.

The model can also be easily applied to disposable batteries, if one can supply a value for their energy densities. As mentioned above, the rated energy density of disposable batteries is higher than that for rechargeable batteries, however, their discharge efficiency is dependent on the current, thus making it difficult to know the effective density without information on the equipment load requirements.

As a general rule-of-thumb, equipment that requires bursts of high power, (examples from civilian life are digital cameras with a flash, or portable power-drills) would result in lower effective energy densities for disposable as compared with rechargeable, while equipment with steady load (e.g. radio with long standby periods) would give higher energy densities for the alkaline disposables.

## *5. Power Considerations*

Similar to the energy balance considerations above, one can easily build a mechanical power model using simple formulae from elementary physics:

**(4)** $\mathrm{P} = \dfrac{\mathrm{E}}{\mathrm{t}}$,

the power **P** (*W*) equals energy, **E** (*J*) per time **t** (*s*)

**(5)** $\mathrm{E} = F \cdot d$ ,

mechanical energy **E** (*J*) equals the applied force **F** (*N*) times the distance ***d*** (*m*)

**(6)** $\vec{\mathrm{F}} = m \cdot \vec{a}$ ,

is Newton's Second law

Substituting (5) and (6) into (4) derives:

**(7)** $\mathrm{P} = \dfrac{\mathrm{m}\,|\,\vec{a}\,|\,\mathrm{d}}{\mathrm{t}}$,

however for repetitive motions $\dfrac{\mathrm{d}}{\mathrm{t}} = f \cdot d_0$ , where ***f*** (*Hz*) is the motion frequency and $\boldsymbol{d_0}$ (*m*) is the distance per stroke, thus giving us:

**(8)**

$$P = m\,|\vec{a}|\,d_0 \cdot f$$

In Equation 8 the acceleration $|\vec{a}|$ and the frequency ***f*** are bounded by human physiology: as discussed above, human repetitive motions would not exceed **10 Hz** and the acceleration of various body parts (e.g. hand) would not realistically exceed **50** $\mathbf{m \cdot s^{-2}}$ **(~5 g**) (Mohamed et al., 2005). Thus the mass and the distance per stroke are the two design parameters that could influence the mechanical power, which is being transformed into electric power.

## Simple Illustrative Example

A simple example is sufficient to illustrate how absurd it is to use a soldier's muscle energy to generate electricity in quantities sufficient to offset the need to carry spare batteries.

A **86kg (190 lbs)** soldier carries a **36 kg (80 lbs)** backpack, of which **9 kg (20 lbs**) are spare Li-Ion batteries. We assume a flat and easy terrain and a walking speed of **1.6** $\mathbf{m \cdot s^{-1}}$**.** From Equation (3), we calculate the energy expenditure for carrying **9 kg** of spare batteries as the difference in energy expenditure between a **36 kg** load **(L**) and a **27 kg** load (**L**):

$M_{36}$ = **646 W**
$M_{27}$ = **591 W**,

thus the metabolic penalty for carrying the spare batteries is **55W (**646-591). From here, we calculate $M_c$ by dividing the metabolic burn rate of **55W***(J/s)* by the velocity of **1.6** $\mathbf{m \cdot s^{-1}}$ to arrive at:

$$M_c = 34{,}375\ J \cdot km^{-1}$$

At the same time **9 kg** of batteries with energy density of **160** $\mathbf{Wh \cdot kg^{-1}}$ would contain **1440 Wh** of electricity. To generate the same amount of electricity, using the conversion efficiencies from Figure 1 would require:

$$M_g = \frac{1440}{0.25 \cdot 1.0 \cdot 0.85} = 6{,}776\,Wh = 24{,}395{,}294\,J$$

From here, we calculate **EBD** using Equation 2:

$$EBD = \frac{M_g}{M_c} = \frac{24{,}395{,}294J}{34{,}375J \cdot km^{-1}} = 709.68km$$

The conclusion of this simple example is that muscle-driven electric generation - using a <u>*weightless*</u> generator that operates at **100%** efficiency - would make sense only for missions that involve more than **709.68 km** of walking while carrying a load of spare batteries. To illustrate a distance of **709 km** is, we have superimposed it onto the map of Iraq in Figure 2. Since no mission would involve traversing almost the entire country on foot, it is **absurd** to think that muscle-driven generation *can ever make sense as relief from the need to carry spare batteries*.

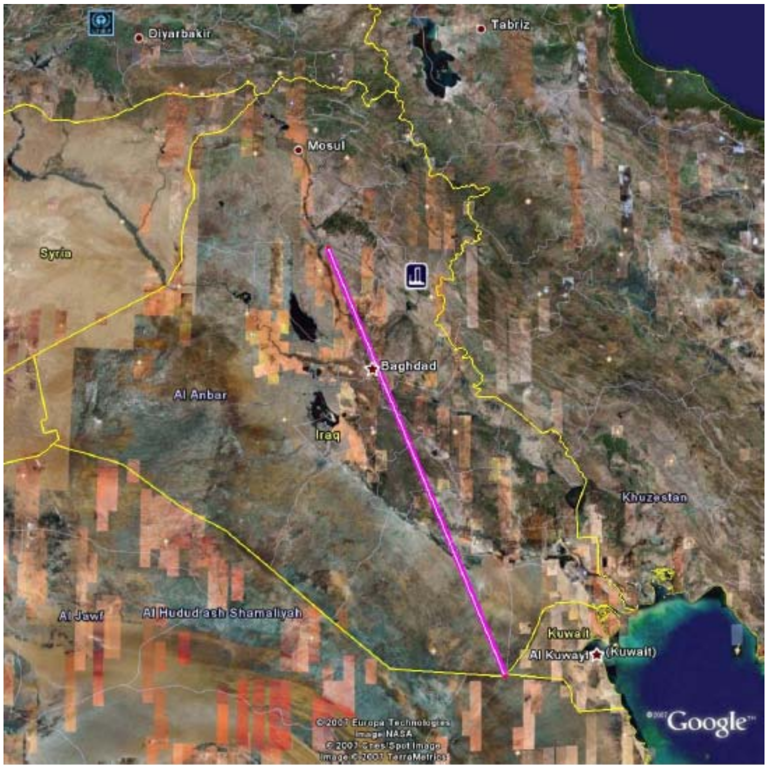

**Figure 2.** Map of Iraq with underlying satellite imagery. The magenta line represents a length of 709 km at the map scale, without taking terrain into consideration.

# Detailed Analysis

## 1. *Consequences of Embedding a Generator into a Battery Pack*

M2E is proposing to incorporate their generators into packages that match the form factor of existing batteries, which would offer convenience and neatness. Unfortunately, such design imposes numerous fundamental energy and power limitations.

### a) Accounting for generator weight

The mechanical generators proposed by M2E are not weightless. An “embedded” layout uses up some of the electricity storage space in the package, diminishing the amount of initial electric energy available at the start of the mission as compared to leaving with a fully charged battery that contains no supplementary mechanisms.

We believe that in the images of M2E prototypes shown in Figure 3, the area that we have marked with green-shaded rectangles are the rechargeable Li-Ion packs.

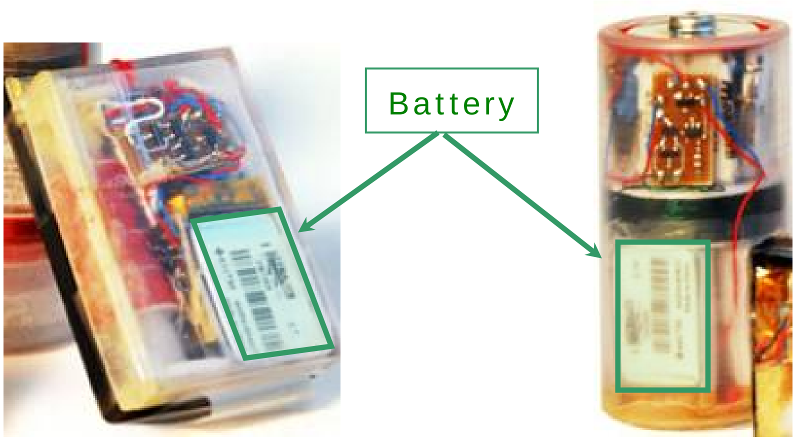

**Figure 3.** Images of prototype M2E devices, taken from media releases. The green shaded rectangles in our belief represent rechargeable Li-Ion packs.

As can be seen from the images, the generator gear takes up substantial fraction of the package, however, for this analysis we will assume that in future devices it can be reduced to 50%. To calculate the metabolic energy cost of the generator (manifested as reduced initial charge), we need to introduce another parameter, **n** that measures how many change-ups the spare battery load is worth. With low **n** (e.g. one set of spare batteries), the generator weight penalty will be high; when **n** increases, the generator weight penalty is spread among the increased number of battery change-ups.

Hence, the adjusted amount of energy to be generated, $\mathbf{M_g'}$ needs to reflect the generator weight penalty[2]:

**(9)**

$$M_g' = M_g + \zeta \frac{M_g}{n}$$

where $\mathbf{M_g}$ is the metabolic energy needed to generate electricity equal to that in the spare batteries, and the $\zeta \frac{M_g}{n}$ term represents the generator weight penalty, where $\zeta$ is the weight fraction of the generator gear (e.g. 50%) and **n** is the number of change-ups. Table 1 shows how the EBD for the Simple Illustrative Example would vary if we accounted for the generator weight penalty, for a spare battery load consisting of 1, 2 and 3 battery change-ups, respectively (note how EBD diminishes as the generator weight penalty is amortized over several battery changes)

| n | EBD, km |
|---|---|
| 1 | 1,064.52 |
| 2 | 887.10 |
| 3 | 827.96 |

**Table 1**. EBD values for various numbers of battery change-ups, calculated according to Equation 9 and assuming $\zeta$ = 0.5 (50%)

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[2] $\mathbf{M_g}$ ***/n*** represents the metabolic equivalent of the energy content of batteries that are already loaded in the equipment at the start of the mission. In the study case, it is reduced by the weight fraction of the generating mechanism, as compared to the reference case (fully charged battery at the start).

### b) Lack of Pivot

Electromagnetic induction requires movement of a conducting wire relative to a magnetic field or vice versa. In conventional generators such relative motion is achieved through rigid attachment of a first element (e.g. stator) to a relatively unmovable platform (e.g. earth, car chassis), thus creating pivot, and moving a second element (e.g. rotor) relative to the first one. If both parts are unattached and mobile -- as is proposed by M2E – there is no apparent pivot and the mechanical work needs to be channelled towards introduction of "slip" between the two parts.

For example, if a battery package contains a permanent magnet core in a shaft, shaking the battery would create slip between the shaft and the permanent magnet (Figure 4).

**Figure 4.** Images of a prototype M2E devices; the orange shaded rectangle in our belief represents a shaft for a sliding magnetic core.

The challenge of such approach is to transform the applied mechanical energy input into slippage with high efficiency, something that is not an issue in situations where solid pivot is available.

### c) Power considerations

As discussed above, the mass **m** and the distance per turn $d_0$ are the only parameters from Equation 8 that can be affected by design to boost the power. Unfortunately, the decision to incorporate the generator in the battery packs severely constraints how much **m** and $d_0$ can be raised.

More specifically, **m** in Equation 8 relates to the weight of the moving element in the device (e.g. a magnet core in the shaft). At a given acceleration, a heavier moving element could counteract larger Lentz forces arising from larger currents. At the same time a heavier device would conflict the goal of reducing the generator weight penalty discussed above.

Surprisingly, in a recent Wall Street Journal article, the future M2E devices were touted as being lighter than existing batteries. Given the very basic dependence of mechanical power on mass and acceleration described above, it is inconceivable to think that lighter devices would be able to achieve satisfactory power generation, especially in the context of normal human movements (e.g. walking), which are characterized with accelerations of **~1 g,** as opposed to more violent movements (e.g. shaking), which can achieve accelerations of up to **5 g** or more.

Similarly, incorporating the generator into the battery pack limits the travel distance per stroke $d_0$ to the dimensions of the package.

In conclusion, with respect to power, it would make much more sense to incorporate the M2E proprietary technology into longer and heavier devices, capable of generating higher mechanical power, which in turn can be converted into higher electrical power.

## 2. *Metabolic Efficiency*

In our calculations we have assumed **25%** metabolic→mechanical energy conversion, which is a maximum value observed with elite cyclists. Studies have shown that, due to genetic factors, the metabolic efficiency of the muscular system can vary as much as 20-30% between individuals. Fitness equipment manufacturers as a rule assume **12.5%** metabolic efficiency in their displays for the amount of calories burned during exercise.

The metabolic efficiency drops precipitously as the physical activity becomes more strenuous. The M2E's idea is to use muscle-driven generation by soldiers while walking during their missions. While the benefit of such approach is to save time by multitasking, one has to wonder if the metabolic efficiency will be high in situations where the soldier is already exerting heavily to walk with a heavy load. The task would become even more difficult if the soldier had to do so while walking a steep and uneven terrain, unlike the flat and easy terrain assumed in our example (irrespective of the fact that Mc would also be higher on such terrain).

## 3. *Intermittence of Supply and Demand*

The analysis so far only considered aggregate energy balances between bringing fully charged spare batteries for the mission versus generating the same amount of energy "on-the-go". Another factor to consider is the intermittence of demand relative to supply. When taking fully charged spare batteries at the start of a mission, the soldier has all of the required energy ready to be deployed whenever it is needed. The cost of equipment failure on the battlefield is extremely high and combatants prefer to take new batteries every time they go on a mission. In contrast, using muscle-driven rechargeable devices would expose the soldier to vulnerability if he needs energy before he has had the time to recharge the pack via physical work.

(Related to this issue is the pattern of apprehension towards rechargeable batteries that has been observed among combatants. Because of the high cost of equipment failure mentioned above, soldiers prefer to take new disposable batteries every time they go out on a mission. This practice appears wasteful as disposable batteries are often thrown away with substantial amount of energy left in them. On the other hand, taking several spare sets of disposable batteries has advantages over rechargeable batteries in that the soldier can dispose of the spent batteries in the field, thus progressively lessening his load. An evaluator of M2E devices would have to take this factor into consideration if comparing them to disposable batteries, as opposed to rechargeable ones, which has been mostly the focus of this study. )

## 4. *Energy from Walking*

An uneducated person, unfamiliar with the basic law of conservation of energy, may think that energy can be harnessed from walking, without exacting a metabolic charge. For example, Enrique Godreau from Voyager Capital has been quoted in the Seattle Post Intelligencer that he would like to see a company create a self-charging battery that harnessed the mechanical energy generated as people walked around, which could bring relief to his brother in the military and other soldiers.

Unfortunately, M2E Inc. has done nothing to discourage such thinking. Instead of pointing out the fallacy in Mr. Godreau's statement, the Director of Business Development at M2E called his remark "divine providence" in the same article.

Because of such equivocation by the company, we felt impelled to briefly but explicitly state these obvious concepts:

- The law of conservation of energy is still valid, energy cannot be created from nowhere.
- Human locomotion has evolved to be highly efficient; the energy inputs are small and dissipate as heat inside the body.
- Any electricity generation through electromagnetic induction requires exertion of (muscle-driven) mechanical force to counteract the Lentz force.

Thus it is absurd to think that one can get a "free lunch" from the highly economical motions of human walking, without impeding it and incurring an incremental metabolic cost. Recent study (Rome et al., 2005) has raised the possibility that there may be unproductive motions arising between a walking human and his load (backpack) that can potentially be tapped for energy generation. Soon after the study was published, though, the hypothesis was put to rest by the authors who stated that: *"You can't get around the fact that if you do additional mechanical work to turn a generator then it will cost you more energy than it would if you didn't turn the generator."*

The likely scenario that M2E is trying to pursue is to similarly overburden the motions of human walking to counteract the Lentz forces of their generators, which is what we have considered in this study.

## 5. Environmental Impact

Counterintuitively, human power has higher environmental cost, per unit of mechanical work, than power from rechargeable batteries. This is due to the metabolic inefficiency of the muscular system and the high environmental cost of food production. Therefore, using humans to generate electricity, via mechanical work, will have a negative environmental effect.

Nevertheless, people who exercise routinely - in order to burn off excess metabolic stores caused by overeating - perform mechanical work that dissipates as heat. Capturing some of this energy in usable form would have some (albeit very minor) positive environmental effect; in that regard M2E may be wise to target its products to environmentally conscious consumers with frequent work-out habits. It is not clear, however, what the differentiating advantages of their products will be in comparison to other products in this category, such as electricity-generating exercise bikes.

## 6. Alternatives for Soldier Power

The need for adequate and convenient electric supply for combatants on a mission is real and pressing; it has prompted the U.S DOD to announce a competition for wearable power supply with a **US$ 1 million** First Prize. The requirement for the competition is to deliver **1,920Wh** of electricity with **4kg** or less (energy densities of **480Wh/kg**). Based on the model in this report, it is obvious that muscle-driven generation would not be competitive in meeting such requirements.

In all likelihood the soldier-power needs will have to be met by hydrocarbon (or hydrogen)-based fuel cells, since these fuels have chemical energy densities far exceeding **10kWh/kg** and thus offer a great deal of latitude in the conversion efficiency to electricity. Other approaches may involve miniaturization of hydrocarbon fuelled mechanical generators.

# Other Markets

According to its press releases M2E's foray into the military market is only supposed to be a first step; the company's plans are for much broader applications including mobile consumer electronic devices and in utility power generators.

## *1. Mobile Consumer Electronic Devices*

### a) Market Specifics

Devices in this category include: mobile phones, portable media players, portable digital assistants (PDA), digital cameras and any hybrid devices thereof. A newsletter from OVP Venture Partners points out that M2E's lead investors consider this area to be the most lucrative, with a potential for an IPO exit. Specifically, the newsletter reveals OVP's perception that self-charging batteries hold high market appeal, and M2E's approach of integrating a generator within a battery-pack is considered highly attractive.

Continuing advances in integrated circuit technology have been able to meet customer demands for ever decreasing weight and size of these devices (consider for example the iPod Shuffle, the best-selling MP3 player for 2006). Ever-increasing integration and transistor density in accordance with Moore's law has delivered lower power consumption, however, the shrinking size of the devices and the lack of corresponding progress with battery power density has not led to significant extension of run/play time per charge. In other words, the devices consume less energy per function, however they also feature smaller batteries and run more applications, resulting in no net gain in time between charging.

In that regard, the specific demands of the mobile market are very different from the military market described above. The total energy needed for such devices is significantly less than the ~1,500-2,000Wh needed for a soldier mission and thus it is very likely that the incurred metabolic cost will be drastically lower, and the issue of fatigue and exhaustion will be irrelevant.

On the other hand, the mobile electronics market is extremely sensitive to weight and size, thus making M2E's approach of integrating a generator within a battery pack (self-charging battery) **unworkable** for the reasons discussed above:

- the generator weight effectively reduces the amount of initially available electric energy (see Page 6), and
- the small weight and size of a "self-charging battery" puts a fundamental constraint on the mechanical power that can be generated, even if its conversion to electricity is highly efficient (see Page 8).

### b) Example

To demonstrate the limitations of a "self-charging battery", the author performed a simple analysis based on his cell phone, a Samsung D600, featuring a BST4389E battery (see Figure 5).

**Figure 5.** Images of a Samsung D600 mobile phone and its BST4389E battery

The battery specifications are presented in the table bellow:

| | |
|---|---|
| Battery Type | Li-Polymer |
| Dimensions | 65.70 x 45.70 x 7.35 (mm) |
| Voltage | 3.70V |
| Capacity | 900 mAh (3.33Wh) |
| Weight | 23 g |
| Color | Black |

**Table 2.** Specifications for a Samsung BST4389E Li-Polymer battery

What would happen if the battery was replaced with a "self-charging battery" of the same size and weight? The "self-charging" options would require either overburdening of regular motions (e.g. walking) or dedicated, high-frequency/high-acceleration motions such as shaking. We used Equation 8 to calculate the mechanical power, assuming dedicated shaking, which would obviously produce greater values:

**(8)**

$$\mathrm{P} = m\,|\vec{a}|\,d_0 \cdot f$$

- For **m**, we made the following assumptions: the generator weight was assumed to be **50%** of the battery weight (11.5g), of which the moving element (e.g. permanent magnet core) was assumed to be **8 g**, and the stationary elements (e.g. shaft, coils, circuitry) were assumed to total 3.5 g
- For acceleration $|\vec{a}|$ we assumed constant value of **50 m·s**$^{-2}$, which is the peak hand acceleration when bouncing a basketball – a similar repetitive hand motion (Mohamed et al., 2005) (no data could be found for shaking in our brief search). Obviously, assuming constant high acceleration is an excessive overestimate for shaking - a bidirectional motion where the acceleration oscillates between a positive and a negative peak. The averaged $|\vec{a}|$ could very well be an order of magnitude lower.

- The distance per stroke was assumed to be the longest dimension of the battery **(65.7mm)**, which too, is an overestimate, as it is unrealistic to assume that the entire stroke can be utilized for electricity generation
- The frequency was experimentally determined by shaking the phone for intervals between 5 sec and 30 sec, and counting the strokes. After several "training" trials, the author was able to achieve consistent frequency of 5 - 5.2 Hz; for the model we assumed a value of **6Hz**.

The assumptions from above were plugged into Equation 8 to calculate a value for effective mechanical power of **0.156W**. We further assumed that this mechanical power can be converted into electric power with **100%** efficiency and into stored electrochemical power with **85%** efficiency, as discussed above, thus achieving final electric power (in the battery) of **0.133W**.

Therefore, based on our generous assumptions, one would have to intensely shake their mobile device for **2.5 hours**, to only get a **10%** (0.33Wh) of the full charge of a BST4389E (**25 hrs** for a full charge). We encourage the reader to attempt to shake their mobile phone or MP3 player with a frequency exceeding **5 Hz** to estimate the impossibility of this task. The author's hand was completely numb after 5 minutes.

If the "self-charging" battery was charged with normal motions (e.g. walking), the values for $|\vec{a}|$ and ***f*** would be significantly lower, thus requiring much longer hours of activity to achieve the same result. If we assume acceleration $|\vec{a}|$ of **~1 g** ($9.8\ m{\cdot}s^{-2}$) and frequencies of **~1Hz,** the time needed for a **10%** (0.33Wh) charge would rise to a staggering **76 hours**.

Finally, it is worth reminding that all this is happening at the expense of a **50%** penalty on the initial charge capacity. In other words, just making up the initial loss of charge capacity (and hence run time) would require **380 hours** of walking or **12.5 hours** of intense shaking! As discussed above, reducing the weight penalty would also result in reducing the weight of the moving element and hence further reduction in mechanical power.

The findings of our example are summarized in Figure 6.

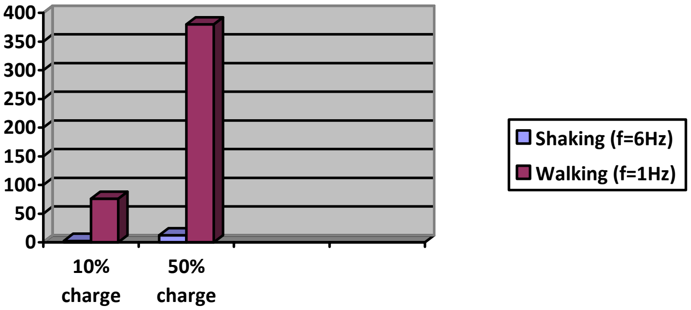

**Figure 6.** Time (in hours), needed to achieve a corresponding 10% and 50% charge of a Samsung BST4389E battery, based on the assumptions in the example above, including **100%** efficient transformation of mechanical power into electric.

### *2. Utility Power Generation*

The references by M2E to utility power generation are puzzling: induction generators have been shown to operate with **>90%** efficiency since the time of Edison, so it is unclear what improvements M2E can deliver in that regard.

A quote from the same Business Development person at M2E, given to Cleantech.com, *"If you were to retrofit M2E into an existing wind generator, they're about 40 percent efficient, so if you can increase the efficiency, suddenly you've got some of your renewable energy solutions that are now competitive with fossil fuels"* is preposterously **misleading**. The quoted 40% figure mostly represents the fundamental limitations of capturing the fluid flow energy, related to Betz Law, and not the efficiency of the generator, which is usually ~90%.

## Conclusions

- Muscle-driven electricity generation is impractical, due to basic thermodynamic limitations.
- The idea of supplying a combatant's ever increasing energy needs with muscle-generated electricity would lead to far greater physical exhaustion than the fatigue from carrying spare batteries.
- "Self-charging" batteries for mobile electronic devices are impractical - even assuming 100% efficient conversion into electricity – because of fundamental limitations on mechanical power.
- Muscle-driven generation may find applications in exercise equipment.

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