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Human Power: Energy Recovery from Recreational Activity

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The conversion of food energy to external mechanical energy during physical activity has efficiencies in the range of 2.6 - 6.5%, depending on the type of physical activity being performed. Despite the low efficiency of this conversion process, the high availability of mechanical and thermal energy during physical activity makes it a potentially useable form of renewable energy. Out of the variety of energy recovery techniques that exist, pedal-motion electricity generation shows the most promise for large-scale recovery. A case study utilizing pedal electricity generation for energy recovery at a fitness facility was conducted, and it was determined that although 7.9% of the facility's total electrical power demand could be recovered with pedal generation, the process was not economically feasible. Decreases in generation technology costs, improvements in generation efficiency, and rising electricity costs could make the implementation of pedal generation an economically feasible alternative for fitness facilities.

Nomenclature

ME = metabolizable energy
GE = gross energy
FE = fecal energy
UE = urinary energy
SE = surface energy
LE = lost energy
eff = conversion efficiency from GE to Atwater ME
BMR = basal metabolic rate
$CFPG$ = coulomb force parametric generator
HEC = human energy converter
USD = US dollars
m_p = mass of consumed protein
m_c = mass of consumed carbohydrates
m_f = mass of consumed fat
m_a = mass of consumed alcohol
m_{df} = mass of consumed dietary fibre

I. Introduction

Growing demands for energy, coupled with diminishing natural resources, has resulted in a demand for the development of renewable energy sources. Human power is one such form of renewable energy that has been used historically to varying degrees. Since the industrial revolution, reliance on human power in the Western World has declined substantially. Despite a decline in practical usage, large amounts of human power continue to be generated by North Americans on a daily basis. Recreational sporting activities are an example of how human power is commonly used. The recovery of energy dissipated during these recreational activities has been proposed and attempted in some small-scale applications. The purpose of this study is to present a number of electrical generation methods that recover metabolic energy spent during recreational activities, and to discuss the feasibility of applying these methods in large-scale energy recovery. Some attention will also be given to the recovery of heat energy generated during metabolic processes.

II. Converting Food Energy to External Mechanical Energy

A. Food Energy

The primary fuel used in the production of human power is consumed food. The human body utilizes energy stored in the chemical bonds of consumed compounds such as carbohydrates, proteins, fats and fibers to fuel metabolic processes. These processes include basal metabolic functions that sustain life, and advanced metabolic functions used during physical activity.

Food energy is commonly measured in the imperial units of Kilocalories (*kcal*) or Food Calories (*C*), where 1 kcal = 1 C. In the metric system, food energy is measured in Joules (*J*), where *4184* J = 1 C (FAO, 2002).

There are two common ways of reporting energy content of food: gross energy content (*GE*), and metabolizable energy content (*ME*). GE is the total energy content of the food prior to human ingestion, and is commonly measured using calorimetry. ME is the total energy that can be utilized for metabolic functions. ME values are always less than GE values, since a number of energy losses occur during the digestion process. These loses include fecal losses (*FE*), urinary losses (*UE*), and surface losses (*SE*). The combination of these losses is termed lost energy (*LE*). ME is calculated by subtracting LE from GE.

The determination of appropriate ME values is commonly done using the Atwater general factor system (FAO, 2002). The determination of ME using the Atwater general factor system is dependent on a number of factors including individual digestive effectiveness, consumed food properties, and geographic location. An ME value assigned using the Atwater system is referred to as an Atwater general ME value. It is commonly assumed that people in the same country have similar diets and digestive traits, and can be assigned average GE to Atwater general ME conversion efficiencies for all foods. Table 1 provides the North American average conversion factors for major food energy constituents (Charrondiere et al., 2004).

Table 1. Energy conversion factors in kJ (kcal)/g. ***(from Charrondiere et al., 2004)***

	Protein	Carbohydrates	Fat	Alcohol	Dietary Fibre
Gross Energy	24 (5.65)	17 (4)	40 (9.4)	30 (7)	17 (4)
General Atwater	17 (4)	-17 (4) -16 (3.74) for carbohydrates as monosaccharide equivalent	37 (9)	29 (7)	-0 (0) -8 (2) as newly recommended

From Table 1 it is apparent that conversion efficiency varies depending on the percentage of each of the major constituents in the consumed food. Equation 1 is used to calculate the overall conversion efficiency (*eff*) from GE to Atwater general ME.

$$eff = \frac{m_p ME_p + m_c ME_c + m_f ME_f + m_a ME_a + m_{df} ME_{df}}{m_p GE_p + m_c GE_c + m_f GE_f + m_a GE_a + m_{df} GE_{df}} \qquad (1)$$

Where m_p, m_c, m_f, m_a, and m_{df} are the consumed masses of protein, carbohydrates, fat, alcohol, and dietary fibre (*g*), ME_p, ME_c, ME_f, ME_a, and ME_{df} are the metabolizable energy densities of protein, carbohydrates, fat, alcohol, and dietary fibre (kJ/g), and GE_p, GE_c, GE_f, GE_a, and GE_{df} are the gross energy densities of protein, carbohydrates, fat, alcohol, and dietary fibre (kJ/g).

Following the Canada Food Guide requirements for daily servings and energy consumption, the conversion from GE to ME may range from 50% to 80% depending on the specific foods consumed from each group. The daily ME requirement specified by the Food Guide also varies from 4600 kJ to 13800 kJ depending on sex, age, and level of activity (Federal Government of Canada, 2007). For the purpose of this study, it is necessary to derive average conversion efficiency from GE to Atwater general ME using a standard daily diet. A conversion efficiency of 65% and a daily ME requirement of 8370 kJ are therefore assumed to be midrange values that would represent averages for the North American population.

B. Metabolic Processes

The human body uses a significant portion of consumed ME to fuel the metabolic functions necessary for sustaining life (basal metabolic functions). Once the energy requirements for the basal metabolic functions have been met, excess energy is used to power muscle tissue and generate kinetic energy. Physical activity is an example of how humans use kinetic energy generated in muscles to do work.

The amount of ME required for basal metabolic functions varies from person to person, depending on sex, age, ethnicity, body mass, activity level, and metabolic efficiency (Wong et al., 1996).

Typically, the range for BMR as a percentage of daily consumed ME is 50% to 70% (Wong et al., 1996). For the purpose of this study, an average BMR of 60% is assumed to be representative of the North American population. This implies that 60% of the assumed daily ME requirement of 8370 kJ is used up by basal metabolic processes. The daily ME requirement may therefore be broken up into approximately 5022 kJ of basal ME, and 3348 kJ of excess ME available for physical activity.

C. Converting ME to External Mechanical Energy

The conversion of ME to external mechanical energy is the process used during any physical activity. The efficiency of the conversion depends mostly on the activity being performed. Efficiencies for common activities such as cycling, lifting, walking, and running have been researched to varying degrees.

Cycling is considered one of the most efficient forms of transferring ME to mechanical energy (McCullagh, 1977). A detailed analysis of the metabolic energy cost of cycling presented in McDaniel et al. (2002) suggests that cycling is approximately 25% efficient. Field tests by McDaniel documented a very consistent linear relationship between ME input and mechanical energy output ($R^2 = 0.95$) suggesting that the ability of humans to convert ME to mechanical energy during cycling is a remarkably stable linear relationship. The efficiency of cycling is attributed mostly to the smooth rotating motion used while pedaling. Minimal friction and momentum losses are observed during the motion (McDaniel et al., 2002).

Lifting is a common form of physical activity that is used for recreational and practical purposes. The efficiency of lifting has been investigated with some variability between results (De Looze et al., 1994). The variability is caused by uncertainty in muscle contributions during lifting. Positive muscle displacement (muscle contraction) is significantly less efficient than negative muscle displacement (muscle elongation) during lifting. Since both positive and negative muscle displacement may be used during the lifting motion, the determination of efficiency becomes complicated. In De Looze et al. (1994) it is suggested that positive lifting and pushing is 14-19% efficient at converting ME to external mechanical energy, while negative lifting and pushing is 28-62% efficient. Despite the discrepancy though, De Looze et al. (1994) suggest that positive displacement is still the dominant mechanism in most lifting and pushing activities. A lifting and pushing efficiency range of 14-19% is therefore assumed.

Walking and running are lower efficiency forms of physical activity that have been thoroughly investigated in a number of studies (Pierrynowski et al., 1980). Walking is considered more efficient than running, mainly due to additional elastic, friction, and momentum losses incurred while running. Since walking and running efficiencies are mainly dependent on individual attributes, efficiencies may vary significantly from person to person. Despite this variance, efforts have been made to determine average walking and running efficiencies that are applicable to the masses. Cavagna et al. (1963) proposed that the maximum external mechanical work generated while walking at the optimal speed of 4 km/hr is 0.1 kcal/km•kg, with an ME consumption of 0.48 kcal/km•kg. Taking the ratio of mechanical work to ME consumption yields a walking conversion efficiency of approximately 21%. Comparatively, running at a speed of 8 km/hr yields the same external mechanical work output but consumes twice the ME, making it half as efficient as walking at 4 km/hr. It is therefore assumed that the efficiencies of walking and running are 21% and 10% respectively.

D. Overall Conversion Efficiency from Food Energy to External Mechanical Energy

In order to determine overall conversion efficiencies from food energy to external mechanical energy, it is necessary to summarize the energy losses through each of the processes leading to the respective forms of physical activity. Figure 1 is a conversion flow chart, displaying the overall conversion efficiencies for each activity. Overall efficiencies are calculated by dividing the energy available for the activity by the GE value.

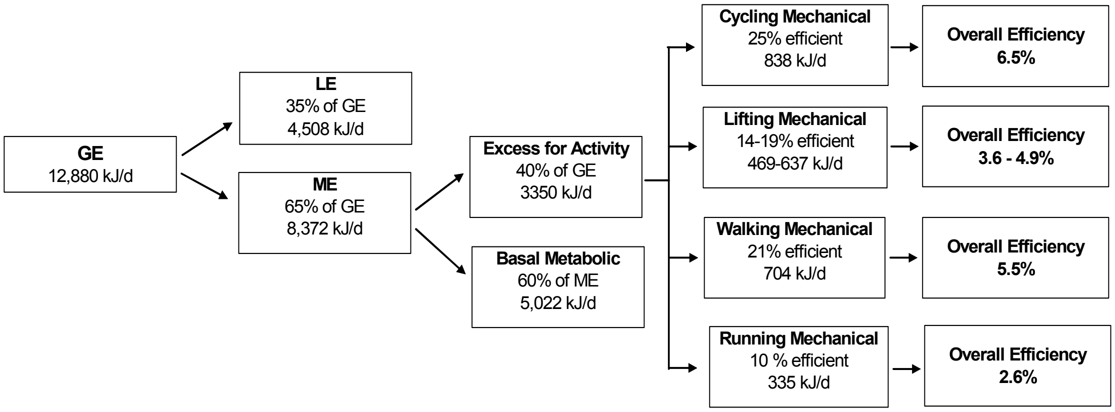

Figure 1. Conversion flow chart. *The overall conversion efficiencies for respective activities range from 2.6-6.5%.*

A GE value of 12,880 kJ/d was chosen in order to satisfy the ME daily consumption of 8,370 kJ/d discussed in section 2.B.

Given the range of overall conversion efficiencies, it may be concluded that the process of converting food energy to recoverable mechanical energy is somewhat inefficient. This does not imply that human power should not be considered as a potentially effective form of renewable energy. Due to the abundance of human mechanical energy released on a daily basis, potential methods of recovery should be investigated. The recovery of mechanical human energy used during recreational activities is a good focus area. Since this mechanical energy is being used for enjoyment and health purposes anyway, it makes sense to attempt to recover it.

E. Body Heat Production

A significant percentage of ME is converted to heat energy during the metabolic process. A percentage of heat is released in the chemical breakdown process of readily available ME or stored ME in body tissues any time energy is required. Approximately all of the ME used to fuel basal metabolic functions is converted to heat (body heat) and kinetic energy (heart movement during beating), with the kinetic portion being significantly smaller than the heat portion. It is therefore assumed that 100% of the ME used to fuel the basal metabolic functions is converted to heat. The amount of excess ME converted to heat during physical activity can be approximated from the internal mechanical efficiency of muscular motion (Pierrynowski et al., 1980). This relationship follows the assumption that any losses from excess ME to internal mechanical efficiency are in the form of heat. Some small losses due to damping effects in the muscles and joints may also exist, but were not considered to have a significant outcome on the study results.

For reasons similar to those discussed in section 2.D, the recovery of human heat energy generated from the basal metabolic process and from physical activity is a potentially useable form of renewable energy, and should be investigated further.

III. Techniques for Energy Recovery from Metabolic Processes

Techniques for recovering energy released by human metabolic processes may be divided into two categories: 1) active recovery, involving the recovery of external mechanical power generated during physical activity, and 2) passive recovery, involving the recovery of body heat power.

A. Active Recovery Methods

1. Pedal Generation

Pedal generators convert mechanical energy generated from the pedaling motion to electrical energy using a generator or alternator. Common configurations for pedal generators mimic bicycles, with the cyclist sitting in a forward or recumbent position. Some manufacturers of pedal generators have created retrofitting packages, where exercise or outdoor-use bikes are hooked up to an external generator. Electrical power generated from the pedaling motion may be stored in a battery or used instantaneously. Other circuit components may include an inverter for conversion from DC to AC power, and a charge controller protecting the battery from deviating voltage and current outputs.

One commercially available example is a pedal generator configuration for a retrofit unit: "the Human Power Trainer" manufactured by Windstream Power LLC. In this configuration, the generator pulley contacts the bike tire. The rotary motion of the tire is transferred to a permanent magnet DC generator, which produces DC power. When using pedaling power to turn a generator that charges a battery or power a load directly, little resistance is initially felt because the voltage (V) of the generator is less than the charging voltage of the battery or the operating voltage of the load. The voltage of the generator increases as the pedaling rate in revolutions per minute (rpm) increases, and charging or powering begins when the voltage of the load is met and exceeded by the generator. At this point the pedaling resistance increases significantly.

The "Human Power Trainer" has a maximum intermittent DC current of 20 A, and DC voltage operation range between 12 – 48 V (depending on pedal speed and load characteristics). A generated voltage of 12 V, which is required to charge the 12 V battery included in the package, is achieved with generator shaft speeds between 300 – 1,400 rpm, producing power outputs in the 0 – 250 W range. Windstream Power LLC claims that an average person is capable of sustainably generating 100 – 150 W with this system.

Stuart Wilson conducted a series of tests of a pedal generator at Oxford University (McCullagh, 1977). The tests were conducted with a 24 V (at 1,800 rpm), 20 A generator, used to charge a 12 V car battery. A belt-drive was used to connect a 15.5" diameter bike flywheel to a 2.5" diameter pulley that turned the generator. During these tests, an average cyclist could easily produce 75 W of sustainable electrical power at 12 V (900 rpm) for a period of one hour. A maximum electrical power output of 750 W was achieved at 37.5 V, but only for a very brief period.

Realistic generator voltage, current, and power outputs for individual pedal generators are therefore in the ranges of 12-40 V, 0-20 A, and 0-150 W (with instantaneous peaks up to 750 W). Losses occurring during the conversion of mechanical pedaling power to electrical power are assumed to be small (generators are 80-90% efficient), due to the efficiency of small permanent magnet DC generators (Spooner & Chalmers, 1992). Additional power losses will be incurred if an inverter is used to convert from DC to AC. The efficiency of inverters converting from 12 VDC to 110 VAC is in the 85-95% range, depending on the characteristics of attached loads (Northern Arizona Wind & Sun, 2007). Efficiency of converting mechanical pedaling energy to electrical energy therefore varies significantly depending on what type of current is desired. Efficiencies for DC and AC current are in the 80-90%, and 70-85% range respectively. Efficiency ranges for the conversion of food energy to electrical energy for DC and AC currents are therefore 5-6%, and 4-5% respectively.

2. *String generation*

String generators convert lifting and pulling energy to electrical energy. A cable is attached to a free-wheel hub or spring that spins a generator shaft. When a force is applied to the cable, the generator begins producing power as the shaft spins. An example is the "Yoyo Power Generator" prototype by Potenco. This string generator is proposed as a power source for laptops and other electronic devices.

Although no specific power output ratings or efficiencies have been published, Potenco claims that one minute of pulling the "Yoyo Power Generator" can generate enough power to run a mobile phone for 25 minutes, or a Nintendo DS for 45 minutes. Independent reviewers speculate that the technology has a maximum conversion efficiency from mechanical pulling or lifting energy to electrical energy of 50% (Felsenstein, 2007).

Assuming that the "Yoyo Power Generator" and other potential string generation techniques are 50% efficient at converting mechanical energy to electrical energy, conversion efficiency from food energy to electrical energy in the range of 2-3% is realistic.

3. *Heel Strike Generation*

A proposed method for the recovery of energy spent walking or running is Heel Strike Generation. This technology involves the installation of rotary magnetic generators, or dielectric elastomer generators in shoes. In the case of rotary magnetic generation, the rotary magnets in the shoes spin as momentum from walking or running is transferred to them. The spinning action of the magnets generates an electric current that can be stored in a battery. Dielectric generators function by separating capacitor plates with polymers that undergo significant area and thickness changes when stretched or compressed. These area and thickness changes cause a change in capacitance across the electrode plates, generating an electrical current (Pelrin et al., 2000). By placing a dielectric generator on the sole of a shoe, an electrical current is generated by the compression and decompression cycle of the sole during walking or running. Figure 6 demonstrates how changes in the polymer thickness create capacitance changes.

Pelrin & Kornbluh (2002) presented study results showing that heel strike generation shoes with built in dielectric generators outperform rotary magnet generators. Dielectric generators are lighter weight than rotary magnet generators, and mechanically simpler. Pelrin & Kornbluh (2002) presented a dielectric boot generator with a power output of 1 W at a walking speed of 5 km/hr. The power output of the boots was stored in a battery carried by the test subject wearing the boots. Given that walking on a level surface at this speed requires approximately 8 W of external mechanical energy, the boot generator is approximately 13% efficient at converting mechanical energy to electrical energy. Future models of dielectric heel strike generators are anticipated to produce 2.5 W at the same speed (Pelrin & Kornbluh, 2002). The total power available to be stored by heel strike generators is largely dependent on the capacity of battery storage devices used in conjunction with the generators. Since little effort has been placed into the development of heel strike battery mass storage devices, it is difficult to estimate the overall efficiency of the technology.

Military application is currently the main focus for heel strike generators. Dielectric generators placed in the soles of soldier boots have been suggested as a means of powering portable communications equipment in the battlefield (Pelrin & Kornbluh, 2002).

4. *Vibration Generators*

Vibration generators convert vibration energy existing in the environment to electrical energy. Vibration energy comes from a variety of sources, including human physical activity. Attaching a small mass to a vibration source, and allowing the mass to vibrate next to a fixed plate creates changes in capacitor plate separation and induces a current. An example of this technology is the Coulomb Force Parametric Generator (CFPG), a small-scale vibration generator for human power application.

Assuming that human power applications involve movements at 1 Hz and 5 mm amplitude, a CFPG power density of 4 μW / CFPG unit volume in cm^3, is predicted. A CFPG is approximately 100% efficient at converting mechanical vibration energy to electrical energy. Due to a very low power density, CFPG technology is not likely applicable for large-scale recovery of human power energy. It should be noted though that the observed power outputs are sufficient to power some small-scale electronics devices (Mitcheson et al., 2004).

Although vibration generation is a relatively new technology with low-density power production, it has been the focus of significant research studies and funding. For example, the VIBES project is a European-Union funded project for the investigation of vibration energy scavenging receiving $4.3 million in funding (The Facility, 2007).

B. Passive Recovery Methods

1. *Biothermal Power Source*

A biothermal power source recovers heat energy released from the surface area of the human body, and converts it to electrical energy. This conversion is achieved through the Seebeck Effect, where a heat differential across two plates interconnected with a semi-conductor material induces an electrical current. Biothermal power patches that function under Seebeck conditions function very similarly to PV panels, with N and P junctions acting as electron donors and electrons acceptors respectively. Figure 8 provides a simple schematic showing how a biothermal power source uses the Seebeck effect to create electricity.

Biophan Technologies Inc. has produced a prototype model of a biothermal patch to be used in pharmaceutical applications. Examples of applications include, pacemaker power supply, and drug pump power supply. Figure 9 is a picture of the prototype biothermal patch model proposed for manufacturing by Biophan Technologies Inc.

Specific power output ranges for the Biophan patch are not listed, but the power production order of magnitude can be approximated from research evaluating theoretical potentials of thermoelectric plates using the Seebeck effect. High range voltage values per temperature differential and resistance values of 5-50 mV/K and 2-200 kΩ are respectively achievable using doped silicon as the semi-conductor material (Van Herwaarden, 1985). Under room temperature conditions (294°K), and assuming a human body temperature of 310.5 °K, the maximum possible heat differential across plates used in a human power application is 16.5 °K. Therefore, voltages in the range of 83-825 mV are theoretically possible. Assuming resistances of 2-200 kΩ, current values range from 0.4–412.5 μA. Theoretical power outputs are therefore in the range of 0.03-340 μW, making biothermal patches small-scale power producers. It should be noted that a consistent temperature differential across the plates is difficult to achieve due to the warming effect of the "hot side" on the "cold side". This phenomenon would likely reduce the estimate for maximum power output. Due to the low power production potential of biothermal patches, they should not be considered for large-scale energy recovery from body heat.

IV. Electricity Generation by Cycling

This section considers the recovery of energy from cycling, since it is the most efficient conversion method. A larger-scale application of human energy recovery based on an example from Humboldt State University is presented and discussed.

A. Retrofitting a Fitness Facility for Human Power Recovery

From the analysis in section 2, the most energy efficient method of recovery with the most potential for a useable power yield is pedal generation. The case study will therefore discuss how this method can be used for recovery in a large-scale fitness facility. The facility has 14 exercise bikes, and the average daily usage for all bikes is 5 hours/day out of the 8 hours/day the facility is open. The facility is open 7-days a week, year round (assume no holiday closures). The facility has an average daily electrical demand of 100 kWh/d.

1. Equipping Exercise Bikes with Pedal Generators

As discussed in section 2, an exercise bike retrofitted with the Windstream "Human Power Trainer" can produce 150 W of electrical power sustainably. Assuming that the gym is equipped with 14 of these assemblies occupied by able-bodied cyclists, there are 2.1 kW of DC power theoretically available. For a 5-hour occupancy period, a daily DC power production of 10.5 kWh/d is achieved.

Since the facility runs on mostly AC appliances, an inverter must be hooked up to the generators to convert from DC to AC power. If the inverter used has a conversion efficiency of 75%, the daily AC power production is 7.9 kWh/d, resulting in a 7.9% reduction in the daily power demand for the facility.

A hookup configuration for the bike power system could follow the configuration used by the Humboldt State University Campus Center for Appropriate Technology (CCAT) "Human Energy Converter" (HEC). This device consists of 14 exercise bikes equipped with 12 V pedal generators. Each set of 7 generators charges a deep cycle 12 V battery through a charge controller. Once the batteries have been fully charged, the charge converter breaks the generation circuit to avoid battery damage through overcharging. A diode is included in each charging circuit to prevent backflow of power from the charged batteries to the generators. The two batteries are wired to two Trace inverters that convert the DC power to clean AC power. The HEC is capable of producing 1 kW of power sustainably for extended periods of time (Erickson, 1997). The smaller power production of the HEC compared to the predicted power production of the fitness facility exercise bikes is due to lower individual generator power production ranges for the generators used in the HEC (50-100 W).

A capital cost estimate for the fitness facility pedal generation system is included in Table 2. Some component costs were estimated based on a survey of online retail outlets including E-Bay. Estimated costs are not exact since they are subject to change.

Table 2. Capital cost estimate for pedal generation system to be installed in the fitness facility.

Component	Qty	Model/ Manufacturer	Unit Cost (USD)	Total Cost (USD+15% tax)	Source
12 V Generator + Mounting	14	HPT / Windstream Power LLC	$595.00	$9,579.50	(Windstream, 2007)
12 V Battery	2	X-cell / AGM Batteries	$220.00	$506.00	(E-Bay, 2007)
Charge Converter	2	PD 9260C / Progressive Dynamics	$159.00	$365.70	(E-Bay, 2007)
Diode	2	Heavy duty blocking diode / N/A	$8.00	$18.40	(E-Bay, 2007)
Inverter	2	DR 1512 / Xantrex	$600.00	$1380.00	(E-Bay, 2007)
Misc. Wiring	L.S.	NA / NA	$100.00	$115.00	(E-Bay, 2007)
Total				$11,964.60	

The capital cost (including tax) associated with implementing the pedal generation system is calculated to be approximately $12,000 USD. If an average electricity cost of 0.11 $/kWh is assumed, the AC power production of 7.9 kWh/d will result in a savings of $0.87/d. Using simple payback calculations, the payback period for the pedal generation system is approximately 37.7 years.

Since the payback period is much longer than the anticipated design life of the system (approximately 5 years), the pedal generation alternative is not economically feasible. This analysis is obviously sensitive to the cost of electricity. Rising electricity prices in the future could significantly reduce the estimated payback period of the pedal generation system, making it economically feasible. For a payback period 5 years, the cost of electricity would have to rise to 0.82 $/kWh.

V. Conclusion

Human power is a low-density form of renewable energy that has large-scale generation potential due to its abundant availability. Due to high costs associated with purchasing the technology required to recover small amounts of recreationally spent human energy, applications are limited by economic feasibility. Refinement and development of recovery technology could result in improved effectiveness and reduced capital costs, therefore decreasing limitations caused by economic feasibility. Rising electricity costs could also make recovery more feasible by decreasing the capital cost payback periods of recovery technology.

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