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ORIGINAL PAPER

Human-Powered Electricity Generation as a Renewable Resource

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Abstract

Energy and human's ability to transform energy into useful work has been the cornerstone of the development of civilizations. Throughout the majority of human existence, we relied solely on metabolic energy derived from plants and animals. In only a few centuries, society has almost completely transformed, from relying on somatic energy to become almost entirely dependent on fossil fuels. The combustion of hydrocarbon energy resources has had detrimental impacts on our environment, which has initiated a push for clean energy. This research study explores the metabolic energy output of humans, specifically within an exercise facility, to evaluate the feasibility of electrical power to be sustained from human-powered energy. Two rowing workouts were evaluated and then compared to solar photovoltaic as an alternative renewable energy. The result of the study demonstrates that 40 members of various physical abilities can collaboratively provide 3–5% of the gym's average daily electricity demand if converted at an efficiency of 64%. The cost of converting the rowing machines resulted in a 33-year payback period.

Keywords Energy systems analysis · Biophysical economics · Energy systems modeling · Renewable energy

Introduction

The development of pre-industrial civilization was powered by metabolic energy of humans and animals. Over time, advancements in technology and engineering have moved us away from human's endosomatic[1] (metabolic) power to become almost entirely dependent on fossil fuels. Growing populations, increasing quality of life, and diminishing resources have put significant stress upon the energy sector to meet increasing demand for fossil fuels, whereas environmental concerns, most notably climate change, have prompted decreasing usage. In 2016, the Environmental Protection Agency (EPA) implemented the Clean Power Plan, issuing carbon dioxide emission goals and encouraging the use of clean energy resources. Many states have also developed renewable portfolio standards (RPS) to promote the adoption of renewable electricity generation, energy efficiency, and other clean energy technologies, for example carbon capture and storage. The state of South Carolina has recently passed the House Bill 1189, which requires 2% of electricity generation from renewable energy resources by 2021 ((2013–2014) Bill 1189 Text of Previous Version 2014). One potential resource that is not included in the bill is human-powered electricity. It seems reasonable to explore this resource since, historically, the majority of our existence has been sustained from metabolic energy. This study first discusses the transition of energy flows throughout society before assessing the feasibility of human-generated electricity as a means of meeting a RPS with a case study of a gym in Greer, South Carolina.

Units and Terminology

The energy units used in this analysis are joules [J], however, food energy is also defined in kilocalories (kcal, 1 kcal = 4184 J). Power is defined in terms of watts [W] or kilowatts [kW]. To give some perspective, a cheeseburger has 2.2 MJ (520 kcal). A human at rest or sleeping expends 81 W (70 kcal/h). Thus seven and a half hours of sleep would be required to burn off one cheeseburger. Kilowatt-hours

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[1] Endosomatic : within or part of the biological body. Endosomatic energy is the metabolic transformation of food energy into muscle energy occurring within the human body (Sterrer 1993).

[kWh] are frequently used in preference to joules, especially when counting electric power.

Background

Energy is an essential part of our society and quality of life. Over the past 10,000 years we have grown from hunter-gatherers, to primitive societies, to metropolitan cities. Throughout this period our energy resources have transitioned from depending on our own endosomatic energy to dependence on hydrocarbon fuels; so-called 'fossil slaves.' This accelerated growth in our usage of energy has unequivocally contributed to polluting the environment, promoting climate change, and geologically transforming the Earth's natural topography, earning the current geologic era to be aptly named the Anthropocene (Bardi 2016). These environmental problems, rising energy costs, and diminishing resources have motivated a shift to non-carbon-based energy resources. Many states have developed RPSs to provide benchmarks or future goals to meet with renewable energy. This section will discuss our society's transition in energy sources, South Carolina RPS, and human energy.

Historic Transition in Energy Use

Our ability to harness and transform Earth's energy resource into useful work has accelerated progress in civilization and improved quality of life for nearly all. As civilizations grew, our dependence on endosomatic energy transitioned to a reliance on exosomatic [2] energy resources. This transition in energy production can be seen throughout the development of civilization.

Hunters and gatherers relied mostly on somatic energy and muscle mechanics to obtain metabolic energy by hunting, fishing, trapping, and gathering until approximately 12,000–10,000 B.C. (Smil 2004; Mattick et al. 2009). However, the first exosomatic energy utilized by these prehistoric societies began at least 250,000 years ago with the burning of fuel wood which was used for cooking (expanding the food that humans could eat) and warmth (Smil 2004). The cultivation of plants is estimated to have begun 6000–10,000 years ago and over time transformed food-gathering tribes into food-producing villages (Smil 2004; Mattick et al. 2009). Populations grew into agrarian societies and extensive farming with laborious plowing was required to meet nutritional needs. Work animals quickly became domesticated to assist in this task as an exosomatic energy resource, powered by biomass and ultimately, the sun, as well as providing an energy storage mechanism. The domestication of animals and improvement in agricultural practices allowed population growth to accelerate and human energy became an abundant resource in early civilizations. Civilizations that commanded a surfeit of muscle power were able to complete complex projects and construct megalithic structures that can still be seen today. Building the Great Wall of China, a 13,170-mile accomplishment, took an estimated 2000 years and millions of laborers (Tackett 2008). In Egypt, the construction of the Great Pyramid in Khufu, comprised 2.3 million blocks, each weighing from 2.5 to 80 tons, is speculated to have required 25,000 laborers and 20 years to construct (Fonte 2007; Bartlett 2014). Based on today's energy expenditure of similar labor trades, e.g., masonry, 548 kcal/h, and a 40-h work week, the construction of the pyramid required approximately 7×10^{11} kcal (3×10^{15} J) of human energy.

A few key designs for applying human and animal power more efficiently, that provided a significant mechanical advantage, are pulley systems, windlasses, tread wheels, and gear wheels. Windlasses allowed human power to be transmitted, by ropes or chains through a rotary motion, to perform some purpose. A rope attached to a wheel or revolving device rotated by animal or human muscle power is a simple windlass design for lifting heavy objects. Similar systems are seen in tread wheels, which provided a more efficient power transmission via gearwheels. This system was applied in large construction projects and dock cranes. An 8-person team of workers powering a vertical tread wheel could sustain a constant 700–800 W or a peak power output 1.5 kW for short durations (Nersesian 2010).

Fossil fuels represent highly concentrated stores of energy which took over as the primary energy resources through the nineteenth and twentieth centuries. Industrialized countries have become dependent on fossil energy to sustain their quality of life, leading to the 'fossil slave' era (Smil 2004). Electricity has become an essential part of our everyday life increasing coal consumption. The internal combustion engine, inaugurated the auto industry and over 60 million motor vehicles were registered by 1960 (Davis et al. 2016). Vehicles on the road more than doubled (143 million) by 1990 and 'fossil slaves' spread to aviation, trains, heavy construction, and agriculture equipment (Davis et al. 2016). According to the U.S. Energy Information Administration (EIA), primary energy supply in the US reached around 100 EJ in 2013, producing an associated 5402 million tons of CO_2 emissions (EIA 2013).

South Carolina Energy Landscape

South Carolina (2015) ranked eighth in the nation for per capita retail electricity sales (EIA 2016). In that year,

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[2] Exosomatic: external to the human body. Exosomatic energy is generated outside of the human body, such as burning coal (Sterrer 1993).

electricity was predominately generated from nuclear (57%), coal (25%), and natural gas (12%), with hydroelectric and other renewable energy only making minuscule contributions to the State's electricity portfolio. Since that time, natural gas has increased, displacing nuclear to gain a 20% share of generation in May 2017 (EIA 2016). Renewable energy is a highly discussed topic academically, politically, and economically and many states have been motivated to develop RPSs. California pioneered this movement with standards requiring investor-owned utilities, electric service providers, and community choice aggregators to increase procurement from renewable energy resources to 33% of total procurement by 2020 (CA Energy Office 2016). In 2014, the South Carolina legislature passed SB 1189 providing the State's first renewable portfolio standard, that by 2021 renewable nameplate capacity should be equal to at least 2% of the previous 5-year average retail peak demand (S.C. Code Ann. § 58-39-110 et seq. 2013–2014). To help achieve this goal, the state created a voluntary program allowing utilities to create net-metering programs. Customers who generate their own electricity from renewable resources are allowed to sell the excess back to the grid. The SB 1189 mandates that the Public Service Commission (PSC) create a program to incentivize residential customers to become customer-generator and determine appropriate cost recovery to the utility, but must limit annual recovery costs to $12 for residential.

Human Metabolic Energy Expenditure

Humans store energy both as glucose (16 MJ/kg) and as fat (around 38 MJ/kg), which allows the human body to act as a mobile energy storage system, which can be unhealthy when too much fat is stored. Obesity is defined as a body mass index (BMI)[3] of greater than 30 (Flegal et al. 2012). Residents of South Carolina currently rank thirteenth in the nation with a 31.7% obesity rate (State of Obesity 2016), meaning South Carolina's population of 4.9 million people (in 2015) has at least 1.5 million citizens that have a BMI over 30 (State of Obesity 2016; Census 2015). Assuming each citizen carries an average of 5 pounds (2.27 kg) of excess fat, this amounts to approximately 133,000 GJ stored energy. This suggests that there are multiple non-energy benefits to human-generated electricity, in terms of health, such as reducing your risk of having diabetes, high blood pressure, heart disease, and having a stroke.

Primarily, humans expend energy both through heat and physical work. Table 1 shows the energy expended for a variety of daily activities that can range from 80 W to over 1600 W (70–1400 kcal/h) (Starner 1996). Research efforts related to harnessing energy released from physical activities have been through mechanical muscle movements and thermal heat transfer. A study by Starner (1996) indicates that harnessing potential energy from body heat is minimal. The main challenge that researchers have encountered is capturing the heat that is dissipated over the whole of the body (Starner 1996). An additional study investigated the heat transfer from the sole of a shoe and the ground using a thermoelectric generator. The experiment maintained an average power output of 0.62 W, enough to power a mobile 3G Wi-Fi router for three portable electronics (iPhone, iPad, and Samsung mobile phone) (Kuang et al. 2015).

Table 1 Power demands for a range of human activities, listed in both kcal/h and watts with data taken from (Starner 1996)

Activity	Power	
	[kcal/h]	[W]
Sleeping	70	81
Lying quietly	80	93
Sitting	100	116
Standing at ease	110	128
Conversation	110	128
Eating a meal	110	128
Strolling	140	163
Driving a car	140	163
Playing violin or piano	140	163
Housekeeping	150	175
Carpentry	230	268
Hiking, 4 mph	350	407
Swimming	500	582
Mountain climbing	600	698
Long-distance running	900	1048
Sprinting	1400	1630

Captured energy from mechanical movements has shown better results. Common designs involve the use of spring oscillations or a crankshaft system. A notable research study from spring oscillation created by 30 kg pack detected 10.6 W of power, enough to power a computer desktop (Donelan et al. 2015). The downfall of this approach is that the additional weight put on an individual limits the user's movement and can potentially increase fatigue. A crankshaft system was used in an energy-harvesting knee brace with assisted deceleration. The experiment configured the knee brace to drive a gear train through a one-way clutch transmitting the knee extension motions at an appropriate speed for a dc motor that serves as a generator. The generated electrical power is then dissipated with a load resistor. An average of 4.8 W of electricity was produced from test subjects walking with the device on each leg with an increased metabolic

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[3] BMI is a person's mass in kilograms (kg) divided by the square of their height (m^2). Obesity is a BMI of 30 or above for either sex (Flegal et al. 2012).

cost of 5 W. The power is sufficient to charge ten phones simultaneously (Donelan et al. 2015).

Over 54 million people (2014) in the United States are members of a fitness center, where their expended somatic energy through exercising is essentially wasted (Statista 2014). Typically, the fitness center possesses equipment that consumes electricity (treadmills, elliptical, stationary bikes, and rowers). Members exercising on these types of machines burn calories; converting stored chemical energy into kinetic or mechanical energy and dissipating thermal heat. This energy is wasted and requires additional work for the cooling unit to keep the facility at a comfortable temperature for its members. A significant amount of research on human energy is available (Starner 1996; Donelan et al. 2015; Sanjay 2014; Granstrom et al. 2007; Haji et al. 2010). However, no study has explored the contributing role that human-generated electricity from a stationary rowing machine may have in conserving energy resources within a gym setting. Toma and Kamnik characterized human power output of rowing techniques of expert and non-expert rowers (Toma and Kamnik 2011). Five subjects participated in the study where individual's pull force exerted on the handle of the rower was measured using a load cell for three different spins per minute (SPM). The involvement of a larger active muscle mass allows the peak power output of experienced rowing competitors to often be 10–16% higher than in cycling (Shephard et al. 2010). The energy released by physical exercise could potentially contribute to the collaborate effort of liberating society from hydrocarbon energy fuels. Therefore, this study investigates the energy exerted in rowing as resource for generating electricity.

Case Study

Goal and Scope

A crossfit gym in Greer, SC has allowed a pilot study to be done to assess the energy use within the facility and individuals exercising. The goal of the study is to assess the potential for human-generated electricity from members rowing to offset the electricity demand from the facility and to further compare the cost of such a system with a photovoltaic (PV) system, an alternative means of delivering the same amount of low-carbon electricity. The potential to harness energy expended from the members of the facility has been assessed using a stationary rower (Model D, manufactured by Concept 2) for a 10-month period. The potential power and energy output generated from the exercise equipment have been compared to the facility's power demand to determine the feasibility of supplanting some portion using human-generated electricity. Solar PV is an alternative energy resource that the gym can take advantage of to decrease their demand on electricity from the grid and also reduce their carbon footprint. The cost and payback periods for both options are compared.

The narrow scope of the study accounts the energy expended by the members as 'free' inputs to the system, since the same amount of energy would have otherwise been wasted if not converted to electricity. We assume that the cooling load is not diminished by the conversion of kinetic energy to electricity, since the electricity will be dissipated to heat in its use within the facility. A more general case of employing humans to generate electricity is discussed in the "Results and Discussion" section, which uses a broader system boundary, wherein the human energy input (and upstream energy requirements to produce food) are no longer discounted.

Gym Electricity Demand

The facility is approximately 2600 square feet and comprised two offices, two bathrooms, a welcome area, and a warehouse. The warehouse, approximately 1000 square feet, has been converted to an exercise room and does not receive heating, but relies solely on an industrial fan for cooling during the summer. The building has no shade and is exposed to the sun throughout the day. Duke Energy provides the electricity for the facility under the residential service schedule. Figure 1 shows a layout of the facility.

During 10 months (June 2013–March 2014) a total of 11,255 kWh (40.5 GJ) of electricity was consumed with the daily average usage ranging from 31 kWh/day (October) to 47 kWh/day (July). To better understand the facility's energy consumption, we took an inventory of appliances used in the facility and modeled the monthly power usage during the 10 months. [4] Fig. 2 shows the main appliances in the facility that contribute to the energy consumption throughout the year (see Table 4 in the "Appendix" for a breakdown of power consumption by appliances). This was done by estimating usage time for each appliance throughout the year. It is assumed that peak energy consumption for the facility is during hours of operation 6:00 AM–10:00 AM and 4:30 PM–7:30 PM.

Workout classes lasting 1 h are offered at the gym six times a day Monday through Friday and once on Saturday mornings. Figure 3 provides an electricity consumption profile during the hours of operations and includes appliances that members use directly (i.e., excluding refrigerator, heating, and cooling). The total amount of electricity for one weekday of operation is approximately 22 kWh. The electricity that could be generated by people exercising in

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[4] Minor appliances include computer, television, cable box, clock, microwave, cell phone charger, stereo, speakers, and coffee maker.

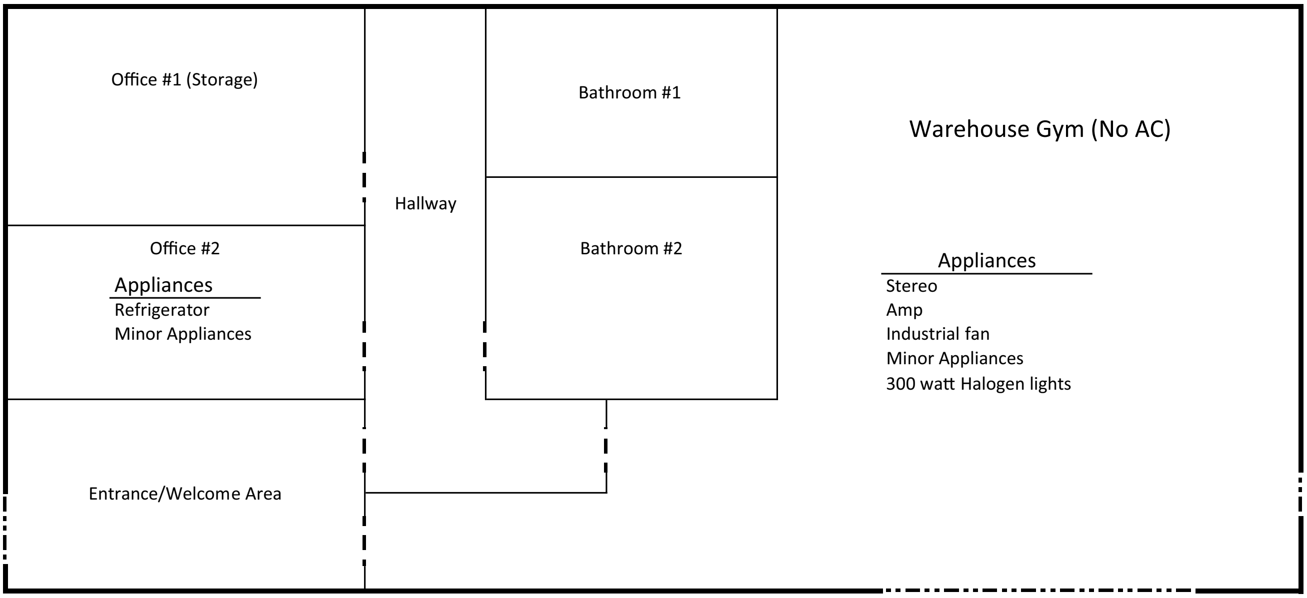

Fig. 1 Layout of gym facility

Fig. 2 Modeled daily electricity consumption over 10 months broken down by appliance

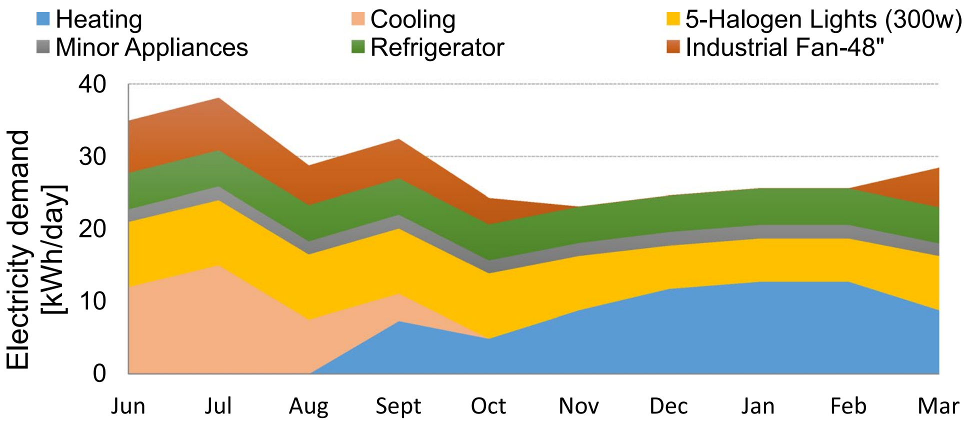

Fig. 3 Modeled average hourly electricity demand for appliances within the workout area

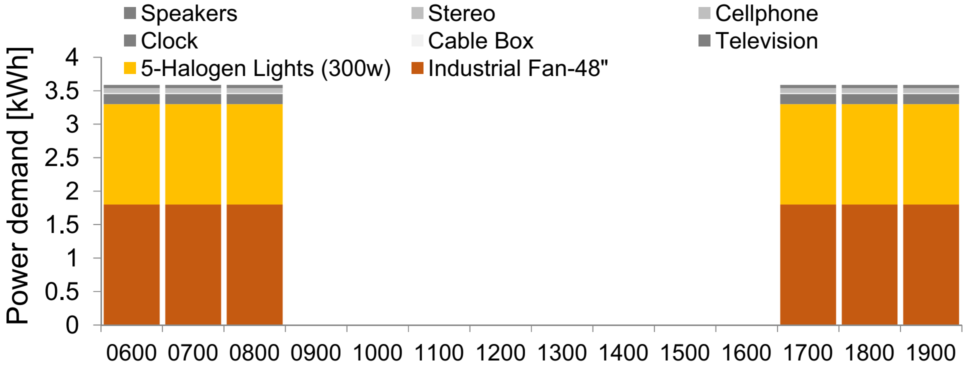

Table 2 Pace, flywheel average power, and electrical energy (assuming 64% generator-inverter efficiency) from all rowers in groups A–D for two workout scenarios: (1) a 5000 m row; and (2) seven, non-consecutive 500 m rows

Group	Members	Workout scenario 1				Workout scenario 2			
		Pace [s]	Power [W]	Duration [h]	Electricity [kWh]	Pace [s]	Power [W]	Duration [hr]	Electricity [kWh]
A	8	110	2104	0.31	0.41	105	2419	0.20	0.32
B	12	120	2431	0.33	0.52	115	2762	0.22	0.40
C	12	130	1912	0.36	0.44	125	2150	0.24	0.33
D	8	140	1020	0.39	0.25	135	1138	0.26	0.19
Total	40		7466		1.63		8469		1.24

the daily workouts will be compared to the average daily electricity needs of the facility.

Gym Members' Electrical Energy Generation

On average, the gym has 40 members that attend one class per day. For simplicity, this study divided the 40 members into four groups (A–D) based on their average pace [s] for 500 m (see Table 5). Groups A, B, C, and D have 8, 12, 12, and 8 members, respectively. The exercise routine for the class generally changes every day and involves various exercises. This study will evaluate two workout scenarios. The first workout is rowing only, for 5000 m. The second workout scenario requires members to row 500 m for 7 non-consecutive periods throughout the workout. In between rowing periods, members perform other exercises (running, pull-ups, pushups, etc.). Both workouts are performed three times per week for all 52 weeks of the year.

Members of the fitness center use Concept2 Model D rowing machines that have performance monitors, which display pace (time taken to cover 500 m), distance covered, strokes per minute (SPM), and average power over the rower's stroke. See the "Appendix" for a description of exertion during different phases of rowing. The power increases as the SPM increases.

Power generated by the rowers in the flywheel is shown in Eq. 1, which was received from the Concept2 manufacturer, in terms of v, 'linear velocity' (at which a boat being rowed would travel), which can be expressed in terms of pace, p, the time [s] required to row 500 m.

$$\text{Power [W]} = 2.8v^3 = \frac{3.5 \times 10^8}{p^3} \tag{1}$$

The electrical energy that members generate can be determined by the product of the average power and the total rowing duration time, assuming a kinetic–electrical conversion efficiency of 64%.

Cost

A stationary rower provides intermittent power generated through each row stoke, which can be converted to electricity via a DC electric pulley motor. It is assumed that the motor is 70% efficient. A grid tie power inverter converter for wind turbine system is designed to receive electricity intermittently and could be used on a rowing machine for the same purpose. IMeshbean is a company that manufactures these inverters that can manage power outputs ranging from 300–1000 W. The 300 W inverter is advertised as being 92% efficient and is adequate for the power output of a rower. The system has an overall 64% efficiency. The inverter and pulley motor have estimated a cost of approximately \$300 per rowing machine. Seven machines would need to be converted to supply an entire workout class, raising the total cost to \$2100.

The cost, savings, and payback period for installing solar PV panels was estimated using the System Advisor Model (SAM), provided by the National Renewable Energy Laboratory (NREL) which models performance costs for grid connected power systems based on the design specification inputted by the user (NREL 2016). Solar PV systems with a desired array size of 5, 10, and 20 kW_{DC} were simulated in SAM using the NREL Solar Prospector and weather data collected from the Greenville–Spartanburg airport weather station. A utility rate database is provided in the model and allows the user to choose from different rate schedules. Duke Energy Carolinas is the utility provider for this facility under the Residential Service schedule. Duke Energy offers an energy resource program allowing qualified residential customers to receive a \$1/W_{DC} rebate for systems up to 20 kW_{AC} (i.e., after accounting for inverter losses) on their property (Customer Generation and Solar Energy FAQ 2015). SAM accounts for this rebate and other incentives such as the federal and state tax credits of 30 and 25%, respectively. Financial parameters assumed a 25-year loan term at a 5% APR. The model accounts for the monthly electricity load for the facility to calculate the costs and savings.

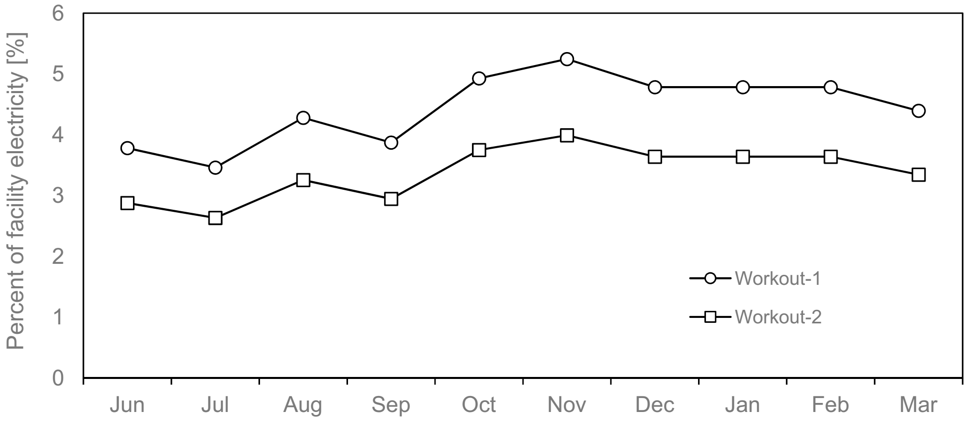

Fig. 4 Percent of facility electricity produce by rowers

Results and Discussion

Table 2 presents the amount of energy exerted throughout the rowing workout scenarios for a single individual within each group. As stated previously, groups A, B, C, and D comprised 8, 12, 12, and 8 members, respectively. The amount of electricity that could be generated with a conversion efficiency of 64% is 1.63 and 1.24 kWh. Figure 4 shows the percentage of the facility's daily electricity demand that could be generated from the rowers for the two workout scenarios over the 10-month period.

Assuming that both workout scenarios are performed three times a week for all 52 weeks of the year, the members could collaboratively generate 447 kWh for the year. Based on \$0.14 per kWh, the rowers can generate an annual retail value of approximately \$62.5 worth of electricity, making for a 34-year payback. Assuming a 35-year lifetime for the machines (which is somewhat unlikely), the levelized cost of electricity for this system (assuming zero operating and maintenance costs) would be \$0.13 per kWh.

Solar PV systems of three array sizes (4, 8, and 19 $\mathrm{kW_{AC}}$) were modeled in SAM. The results are summarized in Table 3. An array size of 19 $\mathrm{kW_{AC}}$ has a net present value of − \$145 with a payback period > 20 years, which is outside the model's range. The 4 and 8 $\mathrm{kW_{DC}}$ system both showed good results with payback periods of 10 and 12 years, respectively. Full report details are presented in the Supporting Information. Converting rowers for clean energy has a very high payback period of 34 years for the conversion of seven rowing machines to generate power. It is noteworthy to state that this payback period is achieved without any federal or tax incentives. Assuming that the same federal and state incentives as for PV were available, the system cost would be \$945, the payback period would be 15 years, and the LCOE would be \$0.06 per kWh.

Human-Generated Electricity in General

The case study presented above represents a very specific case in which we are generating electricity from effort that people are already expending. As such, we assumed that the human input of energy was 'free,' as it would otherwise have been wasted, i.e., it did not entail any additional energy expenditure on the part of the people involved. In the more general case, of employing humans specifically for the purpose of generating energy, we would need to include the upstream energy losses involved in the conversion chain, which we could account all the way back to extraction of resources from the environment. These include: (1) losses from conversion of chemical energy to kinetic energy in the flywheel through the human-rowing machine system, which Concept2 estimates to be around 25% efficient; (2) losses in the conversion of food energy to chemical energy stored in the human body, including losses in supporting non-electricity-producing activities, which has been estimated to be

Table 3 System adviser model (SAM) results for three different PV system capacities

	System size		
	4 $\mathrm{kW_{AC}}$	8 $\mathrm{kW_{AC}}$	19 $\mathrm{kW_{AC}}$
Annual generation [kWh]	5401	12,217	26,867
Capacity factor [%]	16.5	16.2	16.2
First year [$\mathrm{kWh_{AC}/kW_{D6.00C}}$]	1441	1419	1418
Performance ratio	0.79	0.78	0.78
LCOE (nominal) [¢/kWh]	7.58	10.15	8.26
LCOE (real) [¢/kWh]	6.00	8.03	6.53
Electricity cost w/o system [\$]	1456	1456	1456
Electricity cost with system [\$]	891	189	− 285
Net savings with system [\$]	565	1267	1741
Net present value [\$]	2920	3271	− 145
Payback period [years]	10.4	12.1	NaN
Net capital cost [\$]	7461	18,636	42,998

around 20% efficient (McArdle 1986); and (3) losses of food in the food delivery system, which have been estimated to be 10–50% of all food that makes it to the plate (Gustavsson et al. 2011). See Table 6 in the "Appendix," for details. For this broader system boundary, including all of these inputs and losses, the conversion efficiency of our system would be 64% (electricity generation) × 25% (work generation) × 20% (metabolic efficiency) × 70% (median food production and distribution efficiency) × 2%. Additionally, we might include non-food energy inputs along the food production, processing, and distribution system, which have been estimated to be 5–7 MJ per MJ of food across the entire system (Gifford and Millington 1975). The foregoing argument shows that, in general terms, employing people solely for their manual labor to generate electricity would be a highly inefficient and costly enterprise, if we account all of the losses and inputs to the broader system.

Conclusions

In conclusion, this study suggests that human-generated electricity should be further analyzed for better efficiencies in electricity conversion and further analyzed in remote areas that do not have access to dependable electricity providers or alternative renewable resources. Human-generated electricity may not be the ideal solution for replacing fossil energy, but may be worth exploring policies to count human-powered electricity under the RPS under very limited situations, i.e., within gyms. Adding it to the list of renewable generation could promote healthier lifestyles and ameliorate the obesity rate. However, this study concludes that solar PV is preferable to human-powered electricity in most economic respects, such as payback period or LCOE.

Acknowledgements This research was supported by the Department of Environmental Engineering and Earth Sciences (EEES) at Clemson University. We would also like to thank Andrew and Krissy Simmons for their cooperation and for allowing me to analyze their facility, Green City Crossfit. The utility data that they provided were a vital element of this research and is greatly appreciated.

Appendix

Energy is the product of the appliance power and the estimated usage time. Energy value is needed to be calculated for every month since the usage time varied (Table 4).

Table 4 Appliance power, operating time, and daily electricity use (MacKay 2008; Almeida et al. 2011)

Appliance	Power (kW)	Estimated operating time (h/day)	Energy (kWh)
Computer	0.1	3	0.3
Refrigerator[a]			5
Television	0.15	3	0.45
Cable box	0.02	3	0.06
Clock (timer)	0.003	24	0.072
Microwave	1	0.008	0.008
Cell phone charger	0.005	6	0.03
Stereo	0.06	5	0.3
Speakers	0.05	6	0.3
Heating	9.77	0	0
Cooling	3	4	12
Water heater[a]			9
Industrial fan-48″	1.8	4	7.2
Coffee	0.36	0.25	0.09
Vacuum cleaner	0.5	0.25	0.125
5-Halogen lights	0.3	6	9
		Total	43.9

[a] Energy values were cited as a daily average value

A stationary rower differs from the exercise machines used in previous studies by requiring an individual to engage multiple muscle groups. Figure 5 shows the rowing stroke consisting of four distinct yet interrelated movement phases; the catch, drive, finish, and recovery. The majority of the energy is exerted during the drive phase, where the rower applies force to the sprocket on the shaft of the flywheel by engaging muscles from the legs, then hips and back, ending with the arms at the finish stage. Rowers work in a transitional system, where power is produced from the force pulling the handle attached to a chain at a linear velocity. During the power stroke the rower's exerted effort drives a flywheel via a ratchet, and the cable recoils under tension from a bungee cord during the recovery.

The rower's average results for pull length [m], drive phase duration [s], and max force [N] for 20 SPM, 26 SPM, and 34 SPM from Toma and Kamnik (2011) were used to calculate the maximum power potential. Pull length is the difference between the maximum and the minimum distance of the handle pulled. Drive phase duration is the time required to achieve the pull length. Max force is the peak pull force on the handle and occurs midpoint of the drive phase duration.

The instantaneous maximum potential power (MPP) that a rower can generate is expressed (Eq. 2) with respect to the torque (τ) that the rower applies to the sprocket of the shaft and the angular velocity (ω) of the flywheel.

$$\mathrm{MPP} = \tau\omega \tag{2}$$

Torque is applied to the sprocket from the chain, which is connected to the handle that the rower exerts a pull force (F). Since the force is being applied perpendicular to the sprocket

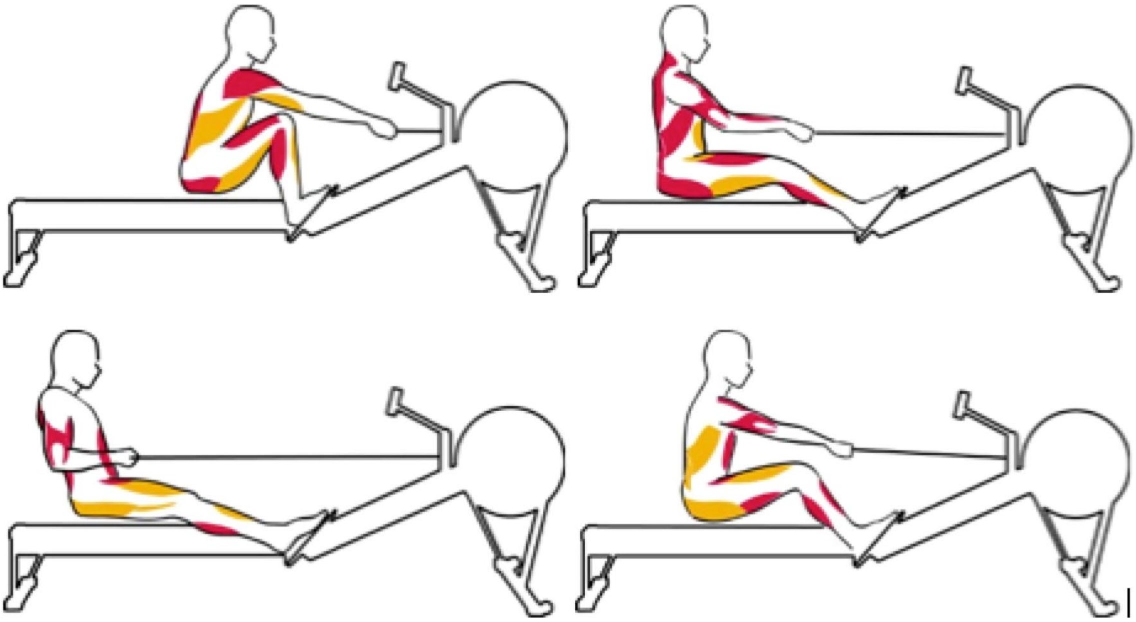

Fig. 5 The rowing stroke (from top left): catch, drive, finish, and recovery (Concept2 2016)

($\sin\theta = 1$), Eq. 3 can be simplified to the torque equaling the product of the force and the sprocket's radius.

$$\tau = rF\sin\theta \rightarrow \tau = rF \tag{3}$$

The flywheel angular velocity can be related to the handle linear velocity (V) by the radius (r) of the sprocket (14.3 mm).

$$\omega = \frac{V}{r} \tag{4}$$

Table 5 displays the instantaneous MPP generated per row stroke using Eqs. 2–4. An individual's electrical power output, at a 64% conversion efficiency, could power small appliances such as a clock, cell phone charger, vacuum cleaner, or a television, but not for sustained periods. A subject rowing at 34 SPM can produce an MPP of 1520 watts, which is enough to operate a microwave, but falls short of meeting the necessary power of an industrial fan of 1800 watts (Table 6).

Table 5 Results for different rowing stroke rates measured in strokes per minute (SPM)

Stroke rate [SPM]	20	26	34
Pull length [m]	1.59	1.61	1.57
Drive phase [s]	1.85	1.58	1.20
Max force [N]	1022	1088	1162
Linear velocity [m/s]	0.86	1.02	1.31
Angular velocity [1/s]	60.15	71.32	91.57
Torque [Nm]	15	16	17
Max potential power [W]	878	1109	1520
Electrical power output [W]	562	710	973

Table 6 Total wastage in food chain for different food commodities, with data from (Gustavsson et al. 2011)

Commodity group	Max (%)	Min (%)
Cereals	19	32
Oil crops and pulses	18	29
Roots and tubers	33	60
Fruit and vegetables	37	55
Meat	20	27
Fish and seafood	30	50
Milk	11	25
Egg	12	20

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