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ADVANCES IN HUMAN-POWERED ENERGY SYSTEMS IN CONSUMER PRODUCTS

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1. Introduction

Nowadays we see a growing number of portable electronic consumer products, mainly powered by batteries. Examples are; audiovisual, communication and information products, in which the electronics provide the main functionality. Considering the clear advantages of (rechargeable) batteries (high energy density, widely available and international standardization), they will remain the main power source in the forthcoming period. Nevertheless, the use of batteries can be cumbersome as well and, due to the increasing number of battery-powered portable products, the environmental impact of battery-use will increase. Research at the Personal Energy Systems group (PES) at Delft University of Technology (DUT) into alternative energy systems for portable applications was initiated by environmental concern; it aims at exploring and understanding alternative energy systems in portable products. We focus at solar power, fuel cells and human power.

1.1 Human power explained

The term ‘human power’ is short for ‘human powered energy systems in consumer products, i.e. the human body delivers the power necessary to operate a product. The human body can be used in different ways to provide energy for a human powered energy system; work from force exerted by body parts, variation in temperature, blood flow and chemical reactions. The focal point of my research is the conversion of energy from muscular work exerted by humans into electricity. Straightforward energy considerations show us that the total amount of energy provided by the human body should be larger than the amount of energy dissipated both by the conversion system and the product. This mathematical model helps in assessing the feasibility of a human-powered energy system in specific products. The following equation is used.

$$\eta_a \cdot \int_{t_1=0}^{t_1=t} P_{human}(t)dt - \int_{t_2=0}^{t_2=t} P_{product}(t)dt \geq 0 \tag{1}$$

In which:

P_{human} [Watt]: Power input from human muscles
$P_{product}$ [Watt]: Power consumption of the product
$\eta_{a\ (a=1\ to\ n)}$ [%]: Efficiency of the total energy system ($E_{product}$/ $W_{human\ in}$), consisting of n steps (including : storage efficiency (E_{out}/ E_{in}), transfer efficiency, etc

Main challenges in the design of human-powered energy systems are:

- the design of integrated energy systems, taking optimal advantage of the specific characteristics of human power, matching input and output power, power management
- the ergonomics and behavioural aspects; how to keep it comfortable, convenient and fun
- the aesthetics of integrating human–powered energy systems into the product

Exploratory research into these aspects by means of case studies (design projects) leads to many new insights. This paper covers only a small part of the fourth challenge, aesthetics, and specifically ‘the role of volume’.

Figure 1. Results of design cases at DUT. From right to left; ‘My first wind-up Sony’ by Y. Dekking, A human-powered MP3 player by M. Pater for Philips Hongkong and a human-powered remote control by S. Weernink for Volvo Car

One of the distinguishing characteristics of human-powered energy systems is their relative low energy density and specific energy when compared to other power sources (batteries). This affects the way product designers assess the feasibility of human powered energy systems in the (re-)design of products. Products simply become larger due to the use of human-powered energy systems. In this research project I asked myself: “How does additional product volume affect product design” and “did this change in time”.

1.2 Design and volume

When designers design a product, the most direct representation of their design is a volume, a 3-dimensional object, so volume is a distinct product feature. The effect of changes in volume will be different for each product category. For some product a large volume might boost the social status of the owner (SUV, house, boats) in some products it might be the other way around (cell-phone or laptop computer). From personal observations I found consumer to be very sensitive for variations in volume, especially in handheld products. I would even argue these variations strongly influence consumer buying decisions. So, when modification of product-volume can actively be used by industrial designers as a design tool, how does this affect the use of alternative energy systems in consumer products?

2. Energy systems

Energy systems in consumer products can easiest be described in terms of ‘energy converters’ and ‘energy storage systems’. Although the term ‘energy storage’ as such is incorrect from a physics viewpoint (energy can only be converted, not stored), I will use this term since it is commonly accepted. In order to describe key features of energy storage systems in the context of this paper, I used energy density [Wh/liter], specific energy [Wh/kg], specific power [W/liter] and power density [W/kg].

2.1 Development in batteries

Modern batteries have a high (and steadily increasing) energy density and specific energy. The next graph presents improvement rates of the specific energy of rechargeable batteries, it shows the improvement rate of the oldest battery type (NiCd) is small while the newest batteries (Li-P) show a 6 to 7% yearly improvement rate. Adapted from [Hallmark 2002].

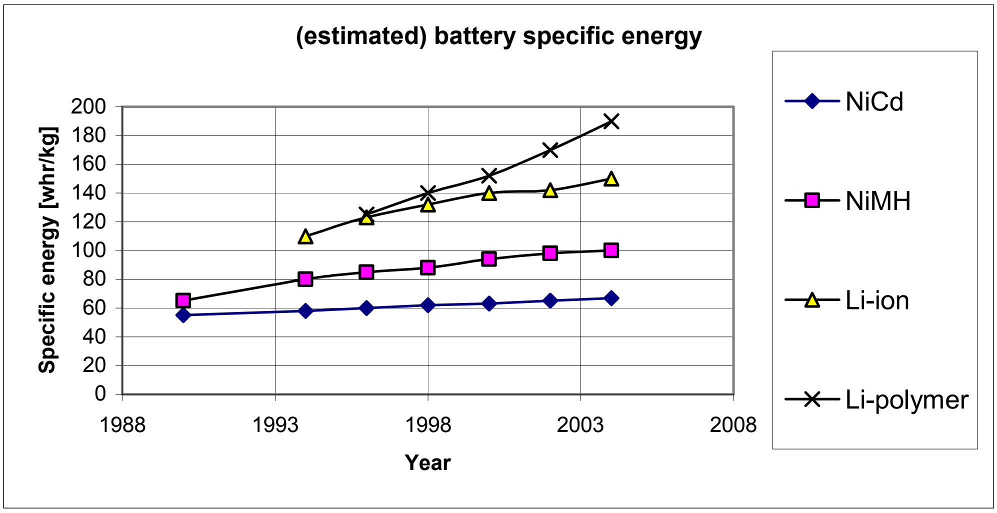

Figure 2. Specific energy of various types of secondary batteries, partly estimated. Adapted from [Hallmark, 2002]

2.2 Other energy systems, how to compare?

In order to be able to compare various energy (storage) systems, I defined the basis for comparison by looking at the electrical power input into the product, mostly a PCB. The energy consumed by this PCB was measured by integrating the electrical power over time (see figure 2).

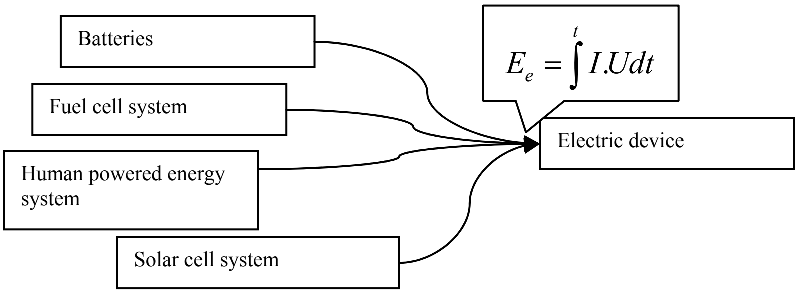

Figure 3. Basis of comparison for various types of energy sources

3. Case study: human powered energy systems in portable audio

In order to learn more about the role volume plays in human-powered products, I analysed five portable radios, see figure below. I focussed on portable audio because they constitute the majority of human powered products that emerged in recent years.

3.1 Similarities and differences

In all analysed radios, the muscular work from the user is entered the product as torque by means of a crank. The conversion step from movement (kinetic energy) into electricity is done using a rotational generator. There are two significant differences in types of energy storage; the BayGen II radio uses a constant torque motor spring (steel). In the later version, a battery is added (combined with solar panel). Both in the Philips, Outrider/Ranger and Sony radios, all energy is 'stored' into batteries (see figure 4).

BayGen S360 | Philips AE1000 | BayGen II | Coleman Outrider/ Freeplay Ranger | Sony ICF-B200

Figure 4. Portable radios analysed

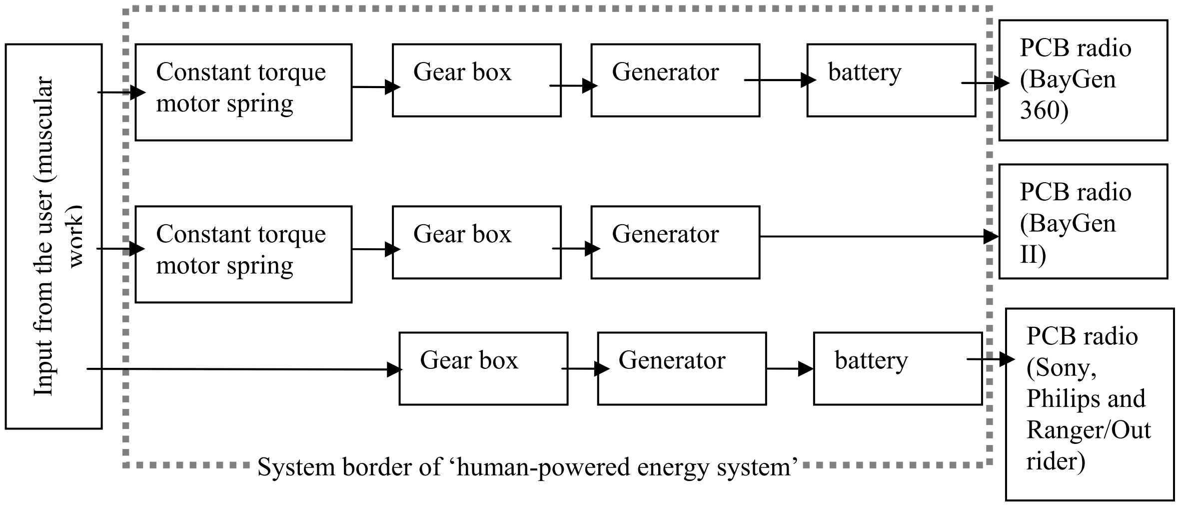

Figure 5. Schematic representation of energy systems in case study

3.2 Measurements

Besides volume and the mass of the energy systems inside these radios, we measured energy input, energy, the EBR (energy balance ratio), defined as the quotient of the time span of energy input divided by the time span of useful functioning of the product due to the users' energy input [Pater, 1999]. The data on specific energy/power and power/energy density are calculated using the energy system output. Data from different sources have been collected in order to compare the radio data with other energy storage devices. See table 1.

Table 1. Datasheet energy storage and energy conversion systems (various sources)

	Primary batteries	Secondary batteries			Fuel cell system
	Alkaline	NiCd	NiMH	Lithium-ion	PEM cell
Energy density [Wh/liter]	100 (iv) - 400 (iii)	100 (iii)- 130 (i)	200 (i)	310 (i) - 386 (ii)	500 (i; expected value for 2005)
Specific energy [Wh/kg]	66 (iv) - 145 (iii)	40 (i)	60 (i)	125 (i) - 165 (ii)	700 (i; expected value for 2007)

Notes
(i) from [Hallmark, 2002]
(ii) data ICP300548ALR cell, from [Takamoro, 2003]
(iii) from [Linden, 2002]
(iv) from [Crompton, 2000]

Table 2. Datasheet portable radios (mind notes!)

		BayGen 360 (2)	Philips AE1000	BayGen II	Sony ICF-B200	Coleman Outrider (2)
Radio	Mass	904 gram	342 gram	2.342 gram	318 gram	669 gr
	Volume	1435 cm^3	903 cm^3	8.352 cm^3	689 cm^3	1359 cm^3
	Market introduction [year]	1999	1999	1997/98	2000	2002
	Energy storage type	Constant torque motor spring (steel) and batteries (2 Ni-MH cells, in total 600 mAh / 2,4 V)	Batteries (2 Ni-MH cells, in total 550 mAh / 2,4 V)	Constant torque motor spring (steel) (4)	Batteries (2 NiCd cells, in total 300 mAh / 2,4 V)	Batteries (pack of Ni-NM cells, in total 1300 mAh / 3,6 V)
energy systems (3)	Energy system mass [gram] (1)	570	118	1421	122	210
	Energy system volume [cm3] (1)	568	65,5	2.132	67,6	208
	Energy input (from human work) (3) [Wh]	$4,9 . 10^{-2}$	$5,4 . 10^{-2}$	$17,4 . 10^{-2}$	$5,8 . 10^{-2}$	$19,2 . 10^{-2}$
	Energy output (energy system to PCB) [Wh]	$17 . 10^{-3}$	$7 . 10^{-3}$	$64 . 10^{-3}$	$11 . 10^{-3}$	$27 . 10^{-3}$
	Energy density [Wh/liter]	$2,9 . 10^{-2}$	$1,1. 10^{-2}$	$3,0 . 10^{-2}$	$1,6. 10^{-2}$	$13 . 10^{-2}$
	Specific energy [Wh/kg]	$3,0 . 10^{-2}$	$5,9 . 10^{-2}$	$4,5 . 10^{-2}$	$8,9 . 10^{-2}$	$13 . 10^{-2}$
	Power output (energy system to PCB) [watt]	$1,6 . 10^{-2}$	$4,0 . 10^{-2}$	$14 . 10^{-2}$	$2,4 . 10^{-2}$	$4,4 . 10^{-2}$
	Power density [W/liter]	0,03	0,60	0,07	0,35	0,21
	Specific power [W/kg]	0,03	0,33	0,098	0,20	0,21
	EBR: Energy Balance Ratio (6)	59	21	73	31	150
	Energy system efficiency (5)	35%	13%	37%	19%	14%

Notes

(1) energy system is defined as the total of any of the following components; input device(crank), gearbox, steel spring, generator, and batteries, it includes plastic mounting brackets etc.
(2) solar panel was disconnected during tests
(3) for all systems; data is based upon 30 seconds of human power input (!!)
(4) a large PCB mounted capacitor is not included in the energy system measurements
(5) energy system efficiency is defined as: total amount of energy dissipated by radio divided by total amount of human energy input (mind; this also includes battery efficiency)
(6) EBR is defined as the quotient of the time span of energy input divided by the time span of useful functioning of the product due to the users' energy input [Pater, 1999]

4. Discussion and conclusions

The differences in energy density and specific energy of batteries and human-powered energy systems are large, over 1 10.000. This is obviously due to the mass and dimensions of the user-interface, gears and generator in human-powered energy system. The fact I used a 30-second power-input time as a basis for comparison also plays a large role. From this we can conclude that human-powered energy systems do not fit into products where volume/mass restrictions are dominant design criteria.

We can see a changing approach towards the use of human power in portable audio products. In the early BayGen radios, the energy was stored into a (large and heavy) steel spring. In more recent radios energy is stored in secondary batteries and we can see hybrid energy systems; net current transformers and solar panels were added to enlarge the functionality of the product.

In earlier research, the Energy Balance Ratio (EBR) proved to be a valid nominator of the usefulness of a human powered product. If we compare the EBR and energy efficiency values, we could get contradictory statements on the usefulness of these energy systems. I.e.; comparing the EBR and energy efficiency for Philips and BayGen radios shows large differences. The input torque for the BayGen II however is three times as high as the input torque for the Philips radio. Further research will have to define robust, comprehensive nominators for the quality of human-powered energy systems.
Further integration of mechatronics in product design will result in smaller, lighter and more efficient combination of conversion and storage systems. The decreasing volume in radio's (starting from the first BayGen radio in 1996) and the shift towards hybrid power solutions shows there is a potential for human-powered energy systems in consumer products in the next future!

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