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Power sources compared: The ultimate truth?

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Abstract

Especially, during the last decade the demand for portable power is steadily rising due to the increasing wireless products integrated in our day-to-day lives (cellular phone, personal digital assistant (PDA) and of course the remote control for your television set or VCR). These portable consumer electronics are mainly powered by alkaline batteries, and nowadays more and more by rechargeables. Alternative power sources, like fuel cells and photovoltaic cells, can be used in portable consumer electronics, possibly making them more cost-effective, more environmentally and user friendly. For the consumer industry, the opportunities of these other alternative power sources is unknown, and designers are not known with the state-of-the-art of the technology. Opportunities for short-term but especially long-term developments in portable electronics are in that way overlooked. In this paper, the most interesting power sources available will be compared on the basis of power and energy characteristics, and costs. Emerging power sources like fuel cells are a very interesting alternative for the lithium-ion battery, but the road ahead for it is still long when we look at state-of-the-art developments. Other power sources described and compared are: ether-smog, human power, thermo-electric generators, piëzo generators, electro-mechanical devices, photovoltaic cells, micro-fuel cells and micro-combustion engines.

Keywords: Power sources; Review; Portable; Consumer electronics

1. Introduction

Especially, during the last decade the demand for portable power is steadily rising due to the increasing number of wireless products surrounding our day-to-day lives (cellular phone, personal digital assistant (PDA) and of course the remote control for your television set or VCR).

Designing with power sources is a complicated task for an industrial design engineer when designing portable electronics. Several research projects have discussed the possibilities of (alternative) power sources used in portable electronics [1–3]. Although these research projects give an excellent theoretical overview, our concern is directed towards more practical values. Within the literature reviewed we have not found studies describing applicable data on power sources, therefore this paper will review power sources and energy storage systems from a more practical point of view. Our goal is to give an overview of power source data based on commercially available power sources.

The content of this paper is as follows: Section 2 describes the methods used to acquire all practical values and data of the different power source and energy storage devices. Section 3 will give an overview and compares the different power sources to each other on power and energy density, specific power and energy and costs per Watt or Watt-hours. Section 4 will give a short discussion on the outcome of this research and gives further study opportunities.

2. Method

A desk search on the internet and in literature has been executed to acquire power source specifics. We defined the following specifics to be of importance for power sources: power output, voltage, dimensions, weight, conversion effi-

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Table 1
Power sources compared on the median of the power density (ρ_P), specific power (SP) and specific cost (SC_P) (the range is in between brackets)

	Median ρ_P ($W\,dm^{-3}$)	Median SP ($W\,kg^{-1}$)	Median SC_P (€ W^{-1})
Thermo electric ($n=4$)[a]	625 (351–701)	74 (63–185)	11.33 (7.71–18.40)
Piëzo ($n=24$)[b]	20 (5–29)	2.6 (0,6–3,7)	24e3 (10e3–75e3)
Electro-magnetic ($n=4$)[c]	106 (3–362)	33 (22–43)	6.85 (5.00–8.00)
PV ($n=34$)[d]	3.6 (1.6–136)	8.3 (2.8–54)	9.20 (5.69–230.88)
DMFC ($n=16$)[e]	8.8 (1–77)	12 (1.5–60)	111.84
PEM FC ($n=46$)[f]	50 (1–306)	20 (1.3–122)	52.78 (5.70–1160)
Four-stroke CE ($n=15$)[g]	54 (28–834)	162 (100–750)	0.25 (0.13–0.53)
Two-stroke CE ($n=51$)[g]	1651 (882–2933)	1241 (788–2265)	0.11 (0.06–3.47)
Human body ($n=12$)[h]	2.8 (2.1–3.5)	2.6 (1.9–3.2)	0.04

[a] Hi-Z, Globalte, Seiko.
[b] Piëzo Systems Inc.
[c] Soubitez, Mubachi, Axa, Kinetron.
[d] Osram, Panasonic, Conrad, Sunset, BP, Solarbotics.
[e] Smart Fuel cell, HelioCentris, Fuelcellstore [6–11].
[f] Fuelcellstore, Portapack HelioCentris, Ballard.
[g] Webra, Honda, SuperTigre, ASP, OS, Microflite, X-race [12].
[h] Based on a man cycling for 10 min; price is based on a loaf of bread and a cycle efficiency of 25% [13–15].

ciency (mechanical to electric) and retail price per item. For energy systems the defined specifics are nominal voltage, ampere-hour capacity, dimensions, weight and retail price per item.

Data are gathered in five ways. At first an internet search has been carried out to find price, power and energy specifics for different energy systems. More specific data were found in the second search field: specification sheets from manufacturers manufacturing power generators or storage devices. Third search field: storage devices, especially batteries used in cellular phones and laptop computers, were measured by students at Delft University of Technology [4,5]. The energy specifics for these batteries were looked after on the battery itself or via specification sheets on the internet. Fourth field of research consisted of acquiring data from scientific papers. A number of case studies [6–8] describe the power specifics of, for instance, fuel cells. When no data were available from literature it was generated by means of calculations based on theory and practical conversion efficiencies. The potential energy available for, e.g. fuels are calculated based on the lower heating value and literature-based conversion efficiencies.

To compare the power sources to each other general parameters are used like the power and energy density ($W\,dm^{-3}$ and $Wh\,dm^{-3}$) and the specific power and energy ($W\,kg^{-1}$ and $Wh\,kg^{-1}$). Also two new parameters are defined to give more insight in the cost price for a power source or energy storage device[1]:

$$\text{Specific cost power}: \quad SC_P = \frac{€_{retail}}{P_{output}} € \, W^{-1}$$

$$\text{Specific cost energy}: \quad SC_E = \frac{€_{retail}}{E_{electric}} € \, kW\,h^{-1}$$

[1] The SC_E is based on the initial price and not the life cycle costs.

3. Results

3.1. Power sources

In Table 1, an overview is given of the median of the power density, specific power and specific cost. All data are based on the power module itself without taking auxiliary systems into account.

Figs. 1–4 show results on specific power, power density and specific cost.

3.2. Energy storage systems

To compare the data acquired by the previous research fields, all data are transformed to the general parameters. In Table 2, an overview is given of the median of all available data. The range, if available, is in between brackets. All data are based on the energy system itself including the casing but without auxiliary systems.

Figs. 5 and 6 show results on specific energy, energy density and specific cost.

4. Discussion

The previous sections give an overview of power sources and energy storage systems available for the use in portable electronic devices. In our research, the focus lies on portable electronic devices in the range of 100 mW–30 W. This section discusses the application of power sources in portable products.

4.1. Power sources

Table 1 gives a good overview of the potential of some power sources and why some might not be commercially

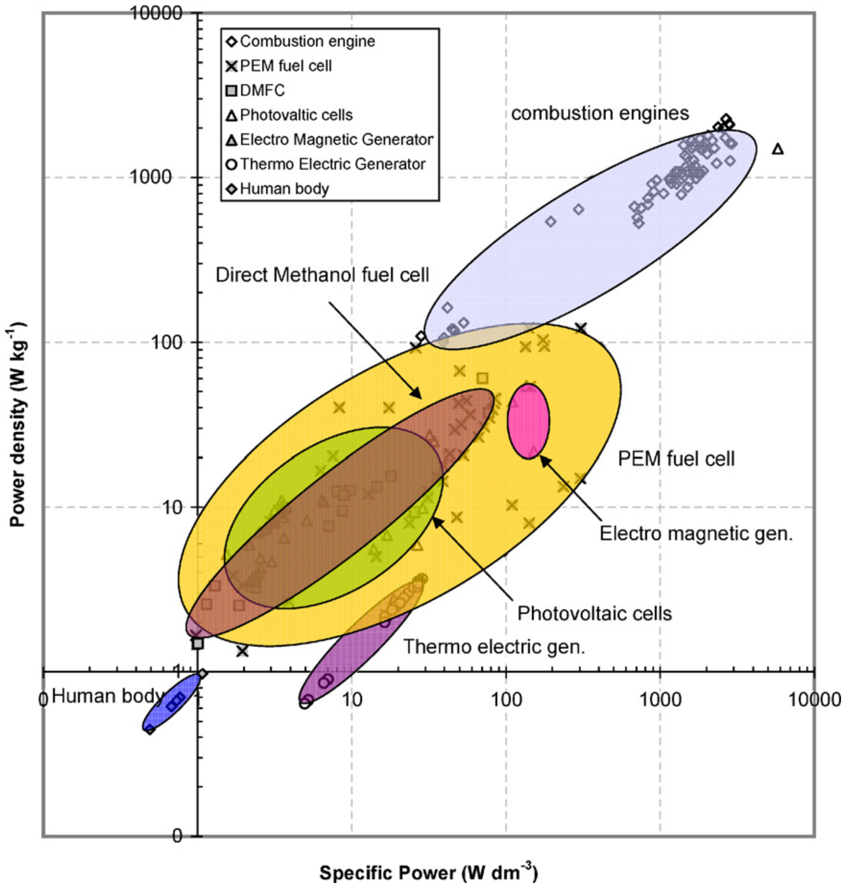

Fig. 1. Log–log plot of the power specifics for the different power sources.

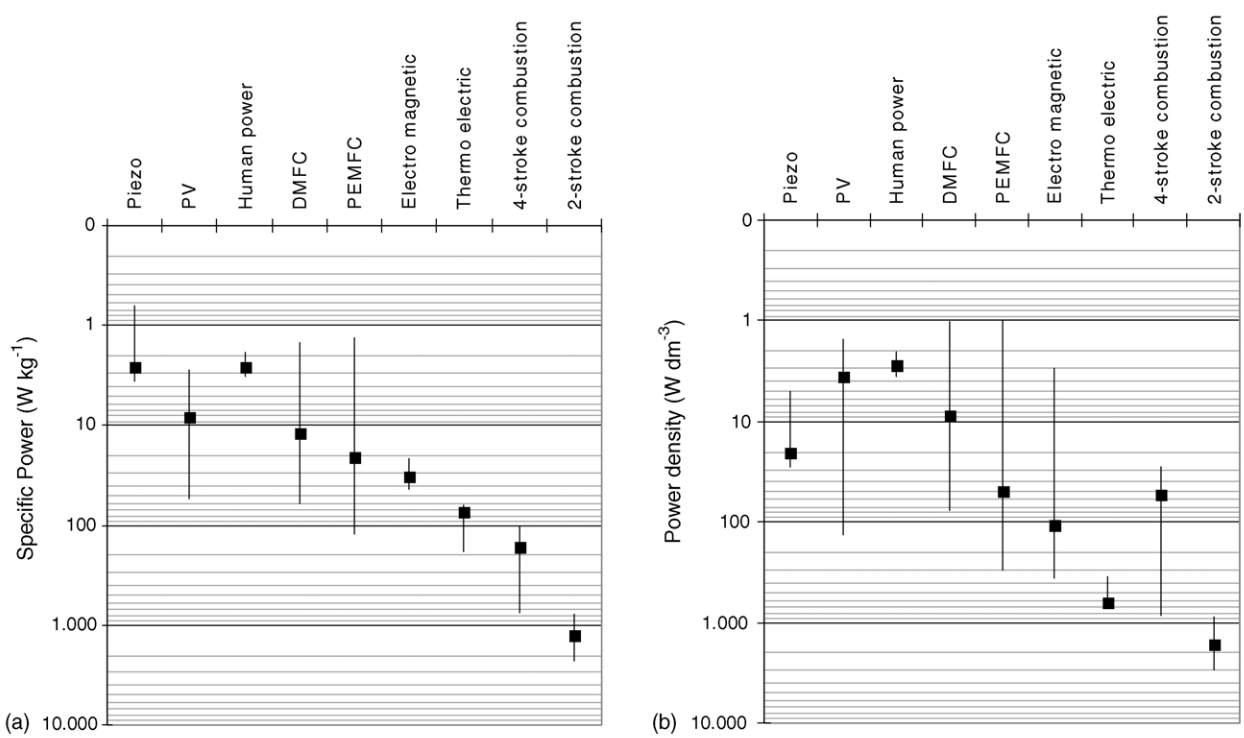

Fig. 2. The range of the data acquired for: (a) the specific power range and (b) the power density researched (median is plotted as a dot).

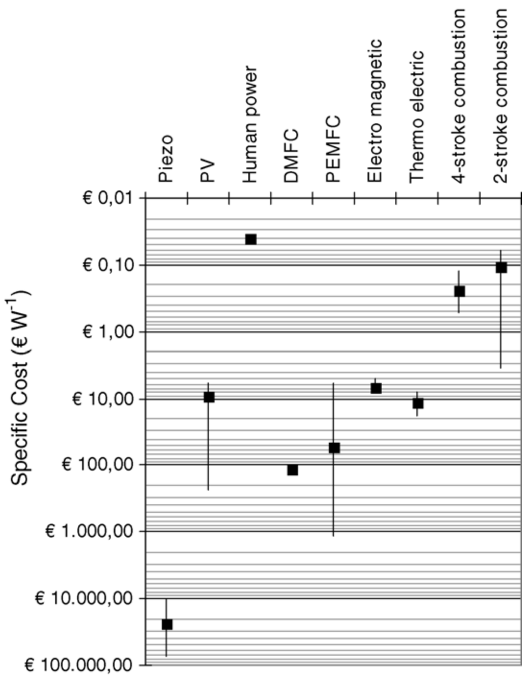

Fig. 3. The range of data acquired for the specific cost of all power sources researched (median is plotted as a dot).

successful. For instance, the piëzo materials can be used to generate power for portable electronics. The retail price for this power generator is more than €30,000 per delivered Watt. The retail price for the piëzo generator is based on mass-produced piëzo material by Piëzo Systems Inc. Piëzo generator as a power source will not be feasible.

Fig. 2 shows that the high power combustion-engine stand outs. The engines have a power density of more than 1.6 kW dm^{-3} (>1.2 kW kg^{-1}). Values are based on commercially available mini-engines used in model airplanes. It shows that the potential of this power source is very high as a power source for portable electronic products. They seem to be a very promising as an alternative power source for portable applications. Then, why is the combustion engine not used more often in portable products? Reasons are its high noise output, vibration, the toxic exhaust fumes and instability of electrical power from the system. The engine is a spinning mass at high angular velocities and is subject to angular velocity variation when load changes [2]. Besides output the engine needs an air intake as well as cooling. The smallest existing combustion engine is the Cox Tee Dee .010 two-stroke: it has a mechanical power output of 15 W at 32,000 rpm encapsulated in a volume of 37.5 mm × 38 mm × 27 mm and weighing only 14 g [18]. This production engine is still to large to be placed in, for instance, a laptop computer. MEMS and nano-technology could lead the way to miniaturizing the engines more so it

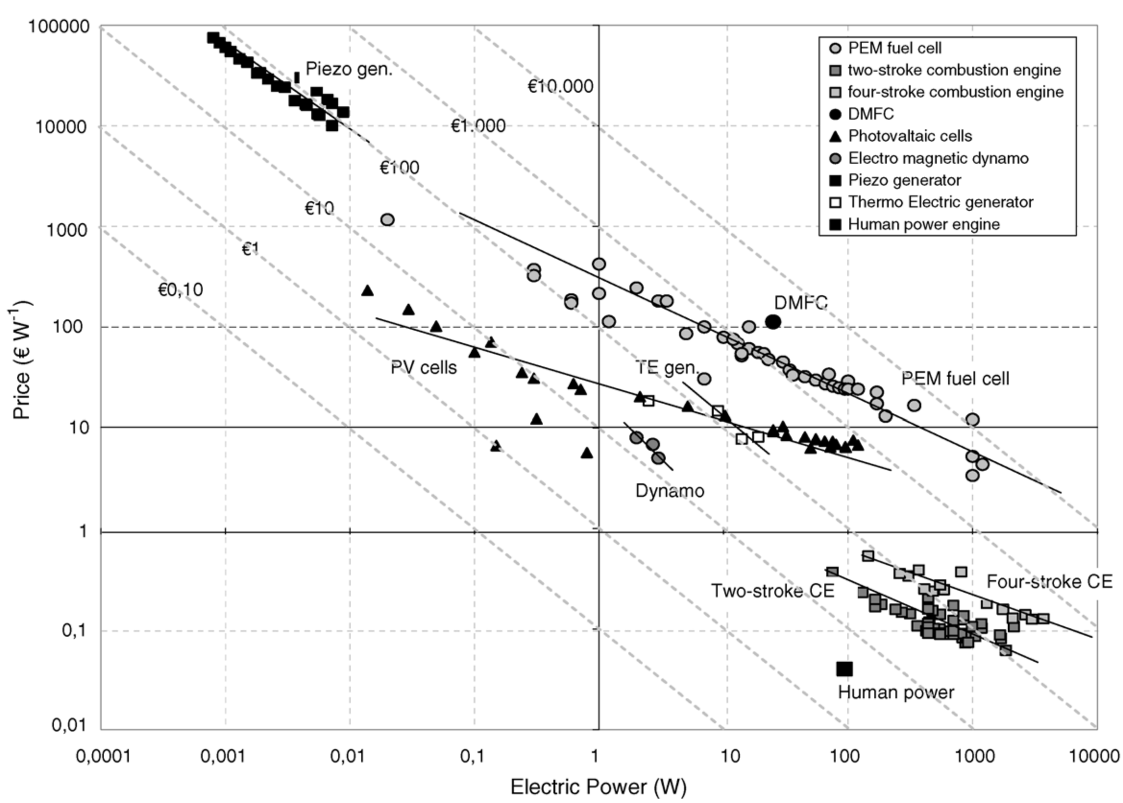

Fig. 4. Comparison of the power sources based on retail price.

Table 2
Energy storage systems compared on the median of the energy density, specific energy and specific cost (the range is in between brackets)

	Median ρ_E (Wh dm^{-3})	Median SE (Wh kg^{-1})	Median SC$_E$ (€ kWh^{-1})
Hydrogen (ambient)[a]	1	8890	5.25
Hydrogen (300 bar)[a]	55	2960	15.75
LPG[b]	319	639	1.94
Petrol[b]	500	694	2.50
Methanol[c]	830	1051	0.22
Alkaline (n = 18)[d]	438 (217–514)	162 (91–192)	0.40 (0.07–8.50)
Primary lithium (n = 9)[d]	565 (260–708)	248 (99–306)	2.07 (1.21–13.32)
Zinc-Air (n = 7)[d]	1138 (219–1496)	350 (182–434)	3.06 (0.90–10.34)
Rechargeable alkaline (n = 4)[e]	308 (278–342)	117 (105–132)	0.65 (0.27–1.58)
Lead acid (n = 31)[e]	80 (59–101)	32 (24–39)	0.50 (0.20–1.79)
Nickel cadmium (n = 47)[e]	86 (42–156)	37 (11–75)	3.00 (1.33–25.00)
Nickel MH (n = 76)[e]	147 (31–327)	53 (15–90)	3.77 (1.61–143.23)
Lithium-ion (n = 63)[e]	212 (20–1210)	121 (11–660)	9.45 (2.77–59.99)
Lithium-poly (n = 6)[e]	200 (115–237)	135 (103–146)	19.03 (17.30–22.21)
Ultra/super/boost cap (n = 25)[f]	0.3 (0.01–4.1)	1.7 (0.3–21.4)	3e6 (499e3–71e6)
Power spring (n = 8)[g]	0.05 (0.01–0.56)	0.03 (0.01–0.66)	337e3 (85e3–4e6)
Flywheel carbon FRP[h]	330	220	250.92
Flywheel HS steel[h]	240	30	15.97
Flywheel cast iron[h]	30	5	77.43

[a] Based on heating value and a conversion via PEM fuel cell.
[b] Based on heating value, and a conversion via combustion [16].
[c] Based on heating value, and a conversion via DMFC.
[d] Duracell, Varta, Renata, Instant Power, Energizer, Electric Fuel.
[e] Rayovac, Varta, SAFT, Conrad, Panasonic, Voltcraft Gates, GP, Emerich, Samsung, JVC, Canon, Sony [4,5].
[f] Epcos, Panasonic, Rutronik, Asahi, Econd, Elna, NEC, Matsushita, Maxwell, Montena, Evans, Polysor, Unite Chemi Con.
[g] Calculation based on eight cases: CFRP, E-glass NiTi and Austenitic steel; material data from [17].
[h] Based on material data from [17].

could be installed in portable electronics [12,19]. The high noise output can be decreased by muffler systems. The implication of miniaturization on noise output is unknown at the moment.

The next interesting power source is the PEM fuel cell and its more inefficient sister, the direct methanol fuel cell (DMFC). A major problem in this area is the storage of hydrogen. New developments could improve the total energy density of a PEM power system but do not seem to be commercially available in the next decade. The DMFC does not have this problem. Methanol is easy to refill when power is needed. The DMFC systems of today are fueled with a

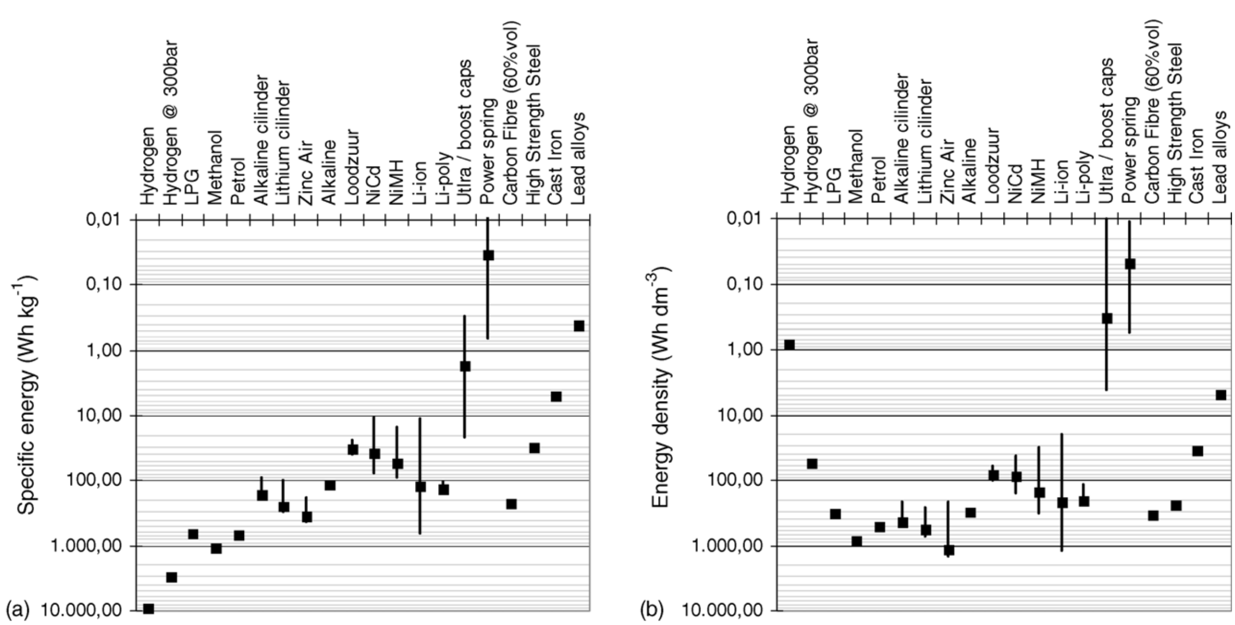

Fig. 5. The range of the data acquired for: (a) the specific energy and (b) the energy density of all energy storage systems researched (median is plotted as a dot).

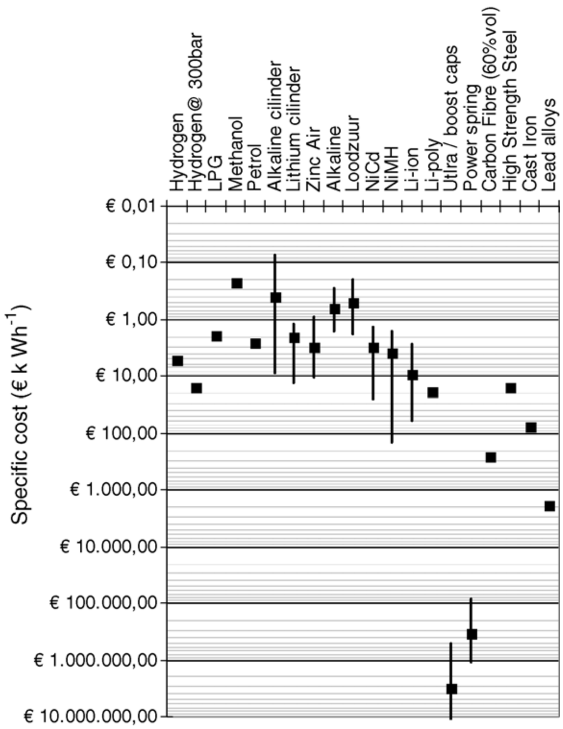

Fig. 6. The range of the data acquired for specific cost of all energy storage systems researched (median is plotted as a dot).

3 wt% methanol water mixture. Improvements are reported already by Toshiba and MTI fuel cells, which claim to have boosted the concentration up to 100%. This means a higher energy density of the total system and a smaller tank needed. This makes DMFC systems more interesting for applying in portable electronics. The technology is still in its research phase and industrial application seems to be still a long way.

When looking at costs the most cost effective power source is the human body when cycling (Fig. 3). The human body is only generating mechanical output, which has to be converted to electricity. Dynamos, thermo-electric elements and piëzo generators are good conversion technologies. The dynamo is a very cost-effective power converter. On the other hand, PV cells and thermo-electric generators are very cost-effective when compared to fuel cells. This is probably because of the longer period of time research is conducted on this field. For instance, PV cells are under investigation since 1950 at the Bell labs for use in the space application. At the moment large factories have been build by Siemens, Shell and BP to mass-produce the cells on the role. PEM fuel cells on the contrary are under research since 1960 at General Electric for the use in the NASA Gemini project. They got industrial attention since the 1980s by the car companies. Micro-direct methanol fuel cells were first presented by Robert Hockaday in the beginning of the 1990s. A lot of work is done since than to decrease the price of fuel cells by lowering the amount of platinum needed for the membrane and making it mass-produceable.

Tsuchiya and Kobayashi [20] analyzed the mass-production cost structure of PEM fuel cells for automobiles (50 kW) by a learning-curve model. A moderate scenario shows that production cost will decrease from €1.46 W^{-1} for the production of 40 cars to about €0.14 W^{-1} in 2010 for the production of 50,000 cars (a cut down of a factor 10 over 10 years). This price is in the same order as that for commercially available micro-combustion engines. If these numbers are applicable to low power fuel cells in the range of 100 mW–30 W has to be seen.

For DMFC systems the costs of materials used in fabricating are very high (especially the high cost of platinum electro catalysts). According to Dyer [21], the production costs for a direct methanol fuel cell could be US$ 5 per generated Watt, for a 20 W/60 Wh power system. For now the Smart Fuel Cell SFC-A25 still costs €112 per generated Watt, so there still is a long road ahead to cut-down the price by a factor 20.

4.2. Energy storage systems

Hydrogen seems to be a good option to be the next energy carrier for a wide range of applications. The storage of hydrogen in small volume is still a big issue researched for. Compression or other volume decrease of hydrogen is necessary. Problem with compression is the high pressures needed starting from 250 to 600 bar. These high compression rates call for a high tension casing like steel or even fibers. Alternatives like nano-tubes and liquefied hydrogen at low temperatures still seems to very far away especially when applying it to consumer electronics. Other carbon–hydrogen liquids like methanol are less energy dense but are more practical in use. In combination with a fuel cell these energy carriers are a great opportunity for powering portable electronic devices.

Petrol and other carbon–hydrogen liquids on the other hand seem to be able to carry lots of energy per volume and mass unit when using combustion-engine technology to convert from fuel-to-mechanical-to-electricity. When carbon–hydrogen liquids are directly converted to electricity, for instance, by means of a direct methanol fuel cell, the energy characteristics seems to improve. In comparison with the lithium-ion battery the methanol fuel cell combination could improve energy densities up to a magnitude of 3, and specific energies up to 7.

Another interesting energy storage system is the Zinc-Air battery. A proven technology used, for instance, in hearing aids, and lately also as a back-up charger for cellular phones and PDA's (www.Instant-Power.com). Problem with this battery type is the single use only, but it still can compete with hydrogen or methanol as an energy carrier.

Rechargeable batteries have improved very fast the last decades. Large improvement steps have been made between the NiCd cell and the lithium-ion battery. As can be seen in Fig. 5 the lithium-ion battery has a high energy density and specific energy, but is very costly when compared to other battery systems (Fig. 6). Apparently, the price of the battery

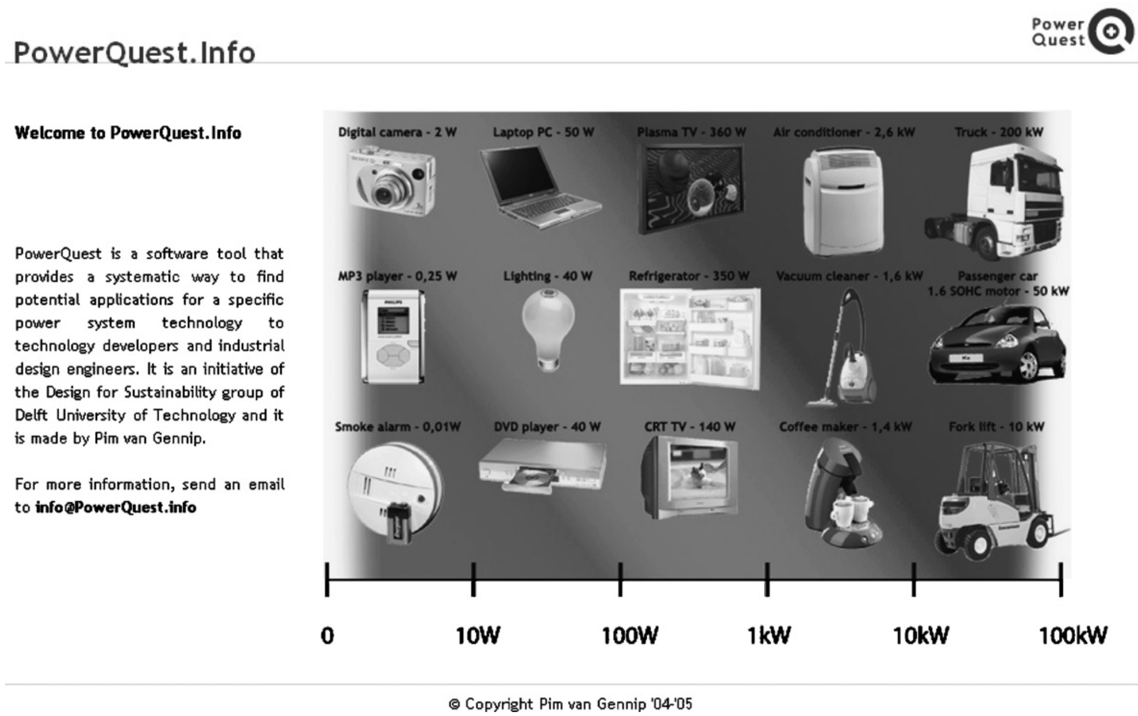

Fig. 7. The introduction page of the PowerQuest website (www.powerquest.info).

is of subordinate concern to the improvement in convenience and decrease of volume.

Within the group of mechanical storage devices the flywheel and especially the Carbon Fiber Resin Polymer has high energy specifics. Unfortunately, the price is still very high and can only decrease when the price of carbon fibers decreases. The price now is based only on mean material price for CFRP filled with 60 vol% HT-carbon (€188–314 kg^{-1} [17]). Because the energy stored in flywheels is related linear with mass and to the square of the angular velocity, smaller flywheels can only store significant energy when rotation speeds are high. The rotational speed is limited by the strength and density of the material. High rotation speeds introduce gyroscopic forces complicating movement of the total system. Implementing two contra-rotating flywheels will annul the total angular momentum, but introduces significant design problems, like a-synchronic acceleration [2]. Flywheels created from high tension steel seems to be a cheaper alternative but cannot compete with the energy density of rechargeable batteries in general.

The worst energy storage systems described in the previous figures are capacitors. Their energy storage specifics are both very low in comparison with batteries, and their retail price is too high to be of interest as the primary energy storage medium. On the other hand, capacitors are not made for energy storage but to boost power output. They are well known for their high pulsed power output, for the use in hybrid systems like in electric busses but also to increase run-time of portable electronics [22].

4.3. *What's next?*

Technology developers and industrial design engineers often have the mission to find applications for technologies in development. When designing an application in need of energy, difficulties arise. One of the main problems is that there is no systematic approach in acquiring exact knowledge of applications' energy demand in combination with power system characteristics. Also, there is very little knowledge about the added values of power systems compared to others. In other words, there is no systematic approach to the problem of finding suitable applications for a specific power system.

For this problem, the database described in this paper can be used. To increase user friendliness a software tool is developed by Pim van Gennip, a graduate student at the Delft University of Technology. The tool is called PowerQuest and it will provide "a systematic way to find potential applications for a specific novel technology power system to technology developers and industrial design engineers". It will be on-line from May 2005 (Fig. 7).

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