Alternative Power Sources for Portables & Wearables

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Personal Energy Systems programme
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Reader vs.11-2004
Preface

Since almost a decade the demand for portable power is increasing. More and more wireless products are integrated in our normal lives, like the cellular phone, personal digital assistant (PDA) and of course the remote control for your television set or VCR. Generally these portable consumer electronics are powered by alkaline batteries, and nowadays more and more by rechargeables.

This report describes the result of a research conducted at TNO Industrial Technologies in Delft and Eindhoven (the Netherlands) and at the Delft University of Technology, department of Industrial Design Engineering (the Netherlands). Its contents resulted from intensive literature and paper studies, internet research, and tests on the field of alternative power sources for low-power electronics. The results are an overview of available power sources ranging from fuel cells and solar panels to more exotics like thermo electric elements and human power. It will give the industrial designer a general idea of the possibilities of these power sources in comparison with batteries. Together with the described rules-of-thumb this report can help the industrial designer with idea generation and a fast comparison between different power sources.

The numbers and figures given in this report are all based on literature and own conducted tests. It is possible that they are outdated, because of the temporary status of this report. With the help of research studies conducted by students at the department of Industrial Design Engineering (DUT) these figures will be updated in following reprints.
## Notation and Units

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
<th>SI unit</th>
<th>Other unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power density (volumetric power)</td>
<td>W/m³</td>
<td>W/ltr</td>
<td></td>
</tr>
<tr>
<td>Specific power</td>
<td>W/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy density (volumetric power)</td>
<td>Wh/m³</td>
<td>Wh/ltr</td>
<td></td>
</tr>
<tr>
<td>Specific energy</td>
<td>Wh/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>η</td>
<td>Efficiency</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>ω</td>
<td>Angular velocity</td>
<td>rad/s</td>
<td>rpm</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td>kg/ltr</td>
<td></td>
</tr>
<tr>
<td>λ</td>
<td>Speed factor</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>ν</td>
<td>Poisson's ratio</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>σᵦ</td>
<td>Maximum bending strength</td>
<td>N/m²</td>
<td>Pa</td>
</tr>
<tr>
<td>σᵣ</td>
<td>Maximum failure stress</td>
<td>N/m²</td>
<td>Pa</td>
</tr>
<tr>
<td>τᵣ</td>
<td>Shear strength</td>
<td>N/m²</td>
<td></td>
</tr>
<tr>
<td>ΔL</td>
<td>strain</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>σₘₜₜ</td>
<td>Maximum tensile, failure or bending strength</td>
<td>N/m²</td>
<td>Pa</td>
</tr>
<tr>
<td>σₗ</td>
<td>Maximum tensile strength</td>
<td>N/m²</td>
<td>Pa</td>
</tr>
<tr>
<td>A</td>
<td>Surface area</td>
<td>m²</td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td>Alternate Current</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Electromagnetic radiation</td>
<td>μT</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Charge / discharge rate</td>
<td>C</td>
<td>A/Ah</td>
</tr>
<tr>
<td>C</td>
<td>Capacity of the capacitor</td>
<td>Farad</td>
<td></td>
</tr>
<tr>
<td>cₚ</td>
<td>Coefficient of performance</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Energy</td>
<td>J</td>
<td>kWh</td>
</tr>
<tr>
<td>E</td>
<td>Electric radiation</td>
<td>V/m</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Young's modulus</td>
<td>N/m²</td>
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<tr>
<td>EH</td>
<td>Evaporation Heat coefficient of a gas/liquid</td>
<td>kJ/kg</td>
<td></td>
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<tr>
<td>F</td>
<td>Force</td>
<td>N</td>
<td></td>
</tr>
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<td>f</td>
<td>Frequency</td>
<td>Hz</td>
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<td>FF</td>
<td>Fill factor</td>
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</tr>
<tr>
<td>flux</td>
<td>Strength of the magnetic flux</td>
<td>flux</td>
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</tr>
<tr>
<td>G</td>
<td>Irradiance</td>
<td>W/m²</td>
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<td>g</td>
<td>Gravity constant (9.81)</td>
<td>m/s²</td>
<td></td>
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<tr>
<td>gᵢ</td>
<td>Voltage constant</td>
<td>V/m</td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>Height / rotor placement</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>Magnetic radiation</td>
<td>A/m</td>
<td></td>
</tr>
<tr>
<td>l, i</td>
<td>Transmission ratio</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>l</td>
<td>Electric current</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>ipp</td>
<td>Current at maximum Peak Power</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
<td></td>
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<tr>
<td>--------</td>
<td>--------------------------------------</td>
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</tr>
<tr>
<td>$I_{SC}$</td>
<td>Short-circuit current</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>$J$</td>
<td>Polar moment of inertia</td>
<td>Nm</td>
<td></td>
</tr>
<tr>
<td>$L_v$</td>
<td>Heat of vaporization</td>
<td>kJ/kg</td>
<td></td>
</tr>
<tr>
<td>$m$</td>
<td>Mass / weight</td>
<td>kg/kg</td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>Rotational speed</td>
<td>rad/s</td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>Number of windings</td>
<td>rpm</td>
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<tr>
<td>$P$</td>
<td>Power</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>$P_{max}$</td>
<td>Power at maximum Peak Power</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>$P_{pp}$</td>
<td>Power at maximum Peak Power</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure</td>
<td>N/m²</td>
<td></td>
</tr>
<tr>
<td>$Q$</td>
<td>Heat</td>
<td>J</td>
<td></td>
</tr>
<tr>
<td>$q_{b,s}$</td>
<td>Form factor (b=bending, s=shear)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$R$</td>
<td>Electric resistance</td>
<td>Ω</td>
<td></td>
</tr>
<tr>
<td>$R$</td>
<td>Radius</td>
<td>m</td>
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<tr>
<td>$R$</td>
<td>Gas constant</td>
<td>J/molK</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>Effective surface area</td>
<td>m²</td>
<td></td>
</tr>
<tr>
<td>STC</td>
<td>Standard Test Conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t$</td>
<td>Thickness</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>K</td>
<td></td>
</tr>
<tr>
<td>$T_{NOCT}$</td>
<td>Normal Operating Cell Temperature</td>
<td>K</td>
<td></td>
</tr>
<tr>
<td>$T_a$</td>
<td>Ambient temperature</td>
<td>K</td>
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</tr>
<tr>
<td>$T_c$</td>
<td>Cell temperature</td>
<td>K</td>
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</tr>
<tr>
<td>$T_i$</td>
<td>Input temperature</td>
<td>K</td>
<td></td>
</tr>
<tr>
<td>$T_o$</td>
<td>Output temperature</td>
<td>K</td>
<td></td>
</tr>
<tr>
<td>$T$</td>
<td>Torque</td>
<td>Nm</td>
<td></td>
</tr>
<tr>
<td>$U$</td>
<td>Energy</td>
<td>J</td>
<td></td>
</tr>
<tr>
<td>$V$</td>
<td>Volume</td>
<td>m³</td>
<td></td>
</tr>
<tr>
<td>$V$</td>
<td>Speed e.g. wind speed</td>
<td>m/s</td>
<td></td>
</tr>
<tr>
<td>$V$</td>
<td>Voltage</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>$V_{nom}$</td>
<td>Nominal voltage</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>$V_{DC}$</td>
<td>Open-Circuit voltage</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>$V_{pp}$</td>
<td>Voltage at maximum Peak Power</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>$W$</td>
<td>Available Work</td>
<td>J</td>
<td></td>
</tr>
</tbody>
</table>
Contents

Preface ii
Notation and Units iii

Contents v

1 Introduction 7
1.1 Purpose of this paper 7
1.2 For whom to use? 7
1.3 Subdivision 7

2 The basics of energy 8
2.1 Basics of Energy 8
2.2 Energy conversion 8
2.3 Typical characteristics 9

3 Fuel power 14
3.1 Combustion engine 14
3.2 Turbine 16

4 Fuel cell 19
4.1 Polymer Exchange Membrane Fuel cells 20
4.2 Direct Methanol Fuel cells 23

5 Chemical 26
5.1 Photovoltaic 26
5.2 Thermo Electric Generator 30

6 Human 33
6.1 Muscle power 33
6.2 Electro magnetic generator 36
6.3 Piëzo generator 39
6.4 Gear efficiency 43

7 Other power sources 44
7.1 Wind power 44
7.2 Electro (ether) smog 47

8 Chemical storage 53
8.1 Batteries 53
1 Introduction

1.1 Purpose of this paper

Due to an increase of portable and wireless consumer products, the need for dedicated, energy-dense, cost-effective and above-all sustainable power sources is increasing. In general portable electronics are powered by batteries, single-use or rechargeables. The choice for this power source is mainly due to high availability and high energy density. But also because designers are not aware of other available, more exotic power sources, which may also be more applicable for the new to develop product, now and in the future. This booklet gives an overview of every power source imaginable which can be used in portable and wireless consumer electronics.

Because the state of this book is temporary a continuously updates will be available via the internet: www.io.tudelft.nl/pes.

1.2 For whom to use?

This work can be used during early-design phases of new to develop consumer electronics. Especially industrial designers can benefit of the figures, which can be used to estimate or calculate general characteristics of the product when in use. Please mind the speed of technological development in this field. The figures given in this book are very general and could be outdated at time of print.

1.3 Subdivision

This book is divided into two general parts power conversion and storage. In chapter 2 a general overview is given of different types of power conversion, e.g. from fuel-to-electricity or electric-to-mechanical power. Chapter 3 to 7 give a more in-depth vision on the different available power conversion technologies. Chapter 8 to 10 focuses on the storage technologies, like chemical, fuel and mechanical storage.
2 The basics of energy

2.1 Basics of Energy

Energy comes from the Greek *energeia*, meaning “there is work in it”. So the word expresses a relation with work, not work itself! Energy means something in which work is caught, or “potentially available power”. Energy conservation can be stated as follows:

\[ \sum_i U_i = K \]

Where \( i \) refers to any form of energy \( U \) in a system, and \( K \) is a constant to that system. Different energy forms are:

- *Kinetic* energy like a moving mass or spinning flywheel;
- *Potential* energy like gravitational energy, using the earth’s gravitational field as an energy storage;
- *Mechanical* energy, e.g. stored energy in stressed solids or springs, or compressed air;
- *Thermal*, temperature differences between quantities of matter (difference in state), e.g. heat engines convert thermal energy into motion;
- *Electric* energy, using electrons stored in a battery or transferred by means of an electric or magnetic field;
- *Chemical* energy present in quantities of compounds or reagents, e.g. E-M radiation;
- *Magnetic* energy;
- Other exotic energy forms like nuclear energy sources are not included here because they have only limited and very exotic applications.

2.2 Energy conversion

Energy in different forms can be transformed to another form by means of conversion technologies. In the figure below most of the known conversion techniques are described. E.g. a generator has a mechanical input (rotation or lateral movement) and converts this, by means of electromechanical physics, to an electrical current and voltage (electricity). When an electric current and voltage is converted to a mechanical movement, an electrical actuator, like an electromotor, is used.

In the following chapters all these conversion technologies are described.
2.3 Typical characteristics

To give an indication of the energy conversion techniques described in the above picture, a list of typical characteristics is given in the following table. It must be taken into account that all efficiencies (%), energy (J and Wh) and power (W) densities are based on literature and calculations. These figures can only be used for conceptual calculations and are not suitable for detailed design. It is advised to research the power source more in depth, when suited in a product.

The power-input and output are given in Watts. This isn’t always electric Watts, but depends on the “energy state” going in and out of the system. E.g. for the combustion engine the state-of-energy going in the system is a fossil fuel: the power-input is chemical. The state-of-energy going out of the system is a rotational force/moment (mechanical): the power-output is mechanical.
<table>
<thead>
<tr>
<th>energy conversion</th>
<th>state-to-state</th>
<th>efficiency (%)</th>
<th>power-output</th>
<th>power-output</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion engine</td>
<td>chemical-mechanical</td>
<td>10-20%</td>
<td>-</td>
<td>1700-2500W/kg</td>
<td>Honda GX (4-stroke): 740 Wout, weighing 3,300 grams (incl. tank, fuel and exhaust system). Cipolla Tiger Wasp: 120 Wout (0,17 ps), weighing 70 grams (excl. tank, fuel and exhaust systems). Super Tigre G/S: 1660 Wout (2,18 pk), weighing 712 grams (excl. tank, fuel and exhaust systems). A normal car engine has an efficiency of approximately 20-25% (100 kW of mechanical power plus 400 kW heat).</td>
</tr>
<tr>
<td>Turbine</td>
<td>chemical-mechanical</td>
<td>3-4%</td>
<td>5200-5600W/tr</td>
<td>4500-6500W/kg</td>
<td>The Mercury (9 kW) jet engine of AMT Jets (Helmond, NL), weights clean 1400 grams and airborne weight is 2005 grams. The Olympus (20 kW) jet engine weighs 3100 grams (airborne) [AMT Jets, 2002]. For jet engines the (high) rpm is very important for the efficiency of the engine. Low rpm (&lt;30,000 rpm) means a fast dropping of efficiency and power.</td>
</tr>
<tr>
<td>Electro magnetic generator</td>
<td>mechanical-electricity</td>
<td>20-70%</td>
<td>-</td>
<td>200-300W/kg</td>
<td>A low-rpm electromotor used as a generator has an efficiency of approximately 20% (based on own measurements). The efficiency of a HR-dynamo is much higher and reaches 70 to 90%</td>
</tr>
<tr>
<td>Piézo element</td>
<td>mechanical-electricity</td>
<td>0,5-5%</td>
<td>0,01-0,02 W/m²</td>
<td>&lt;1,2 W/cm³ (for ceramic Piezoxide PXE)</td>
<td>Problem with piézo materials (PZT and PVDF) is the high voltage it generates (PVDF&lt;20V and for PZT&gt;90V). The power-output characteristic is based on a walking man with a 7 mm deflection of the pieze element. Per step the power output of PZT is 1 mJ (1040 cm² plate, 20 mWpeak) and for PVDF this is 2 mJ (49 cm² plate, 80 mW peak) [Paradiso et al., 1998]. As shown by Waanders, 1991, the maximum energy density that can be achieved for a PiezoXide (PXE) generator is 1.2 W/cm³, under open circuit conditions.</td>
</tr>
<tr>
<td>Muscle power</td>
<td>chemical-mechanical</td>
<td>20-30%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>EM-electricity</td>
<td>5-15%</td>
<td>90-100 W/m²</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Photosynthesis</td>
<td>EM-chemical</td>
<td>20%</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>PEM Fuel cell</td>
<td>chemical-electricity</td>
<td>40-55%</td>
<td>34 W/tr</td>
<td>50 W/kg</td>
<td>Based on a low-power fuel-cell without the fuel and container (Hydrogen has an energy content of 120 MJ/kg (ρ=0.00009 kg/ltr)).</td>
</tr>
<tr>
<td>Direct Methanol Fuel cell</td>
<td>chemical-electricity</td>
<td>25-35%</td>
<td>20 W/tr</td>
<td>30 W/kg</td>
<td>Based on a low-power Direct Methanol fuel-cell without the fuel and container (methanol has an energy content of 22.7 MJ/kg (ρ=0.79 kg/ltr)).</td>
</tr>
<tr>
<td>Seebeck elements</td>
<td>heat/cold-electricity</td>
<td>2-5%</td>
<td>0.17 W/Km²</td>
<td>-</td>
<td>Eneco USA claim to have developed a TE element with an efficiency of 17% at a temperature difference of 250 to 300 °C, with a focus on more than 20% [<a href="http://www.eneco-usa.com">www.eneco-usa.com</a>]. They expect to take the generator in production in between 2004 and 2005. At low temperature differences (100-200K) the efficiency is in between 4 and 5%. Below 100K the efficiency drops to a 2% at 20K.</td>
</tr>
<tr>
<td>Bi-metal</td>
<td>heat/cold-mechanical</td>
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<td>-</td>
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<tr>
<td>Heat engine (Stirling)</td>
<td>Heat-mechanical</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>Heatpump</td>
<td>mechanical-heat/cold</td>
<td>1.5-3 (COP)</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Absorption cooler</td>
<td>chemical-heat/cold</td>
<td>0.5-2 (COP)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Power Source</td>
<td>Fuel Source</td>
<td>Efficiency (%)</td>
<td>Brightness (Lumen/W)</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>------------------------------</td>
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<td></td>
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<tr>
<td>Fuel-powered heater</td>
<td>Chemical-heat/cold</td>
<td>100%</td>
<td>-</td>
<td></td>
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</tr>
<tr>
<td>Gaslight</td>
<td>Chemical-EM</td>
<td>3-11%</td>
<td>-</td>
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</tr>
<tr>
<td>Incandescent lamp</td>
<td>Electricity-EM</td>
<td>1-3%</td>
<td>6-20Lumen/W</td>
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<td></td>
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<tr>
<td>Fluorescent lamp (TL, PL)</td>
<td>Electricity-EM</td>
<td>5-20%</td>
<td>20-95Lumen/W</td>
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<tr>
<td>Halogen light</td>
<td>Electricity-EM</td>
<td>4-5%</td>
<td>20-25Lumen/W</td>
<td></td>
<td></td>
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<tr>
<td>White LED</td>
<td>Electricity-EM</td>
<td>3-4%</td>
<td>15-24Lumen/W</td>
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<td></td>
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<tr>
<td>Electrolysis</td>
<td>Electricity-chemical</td>
<td>-</td>
<td>-</td>
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<td></td>
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<tr>
<td>TE-elements</td>
<td>Electricity-heat/cold</td>
<td>0.60-0.65 (COP)</td>
<td>331.6W/Km²</td>
<td></td>
<td></td>
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<tr>
<td>Electric heater</td>
<td>Electricity-heat</td>
<td>100%</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric motor</td>
<td>Electricity-mechanical</td>
<td>70-80%</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead Acid battery</td>
<td>Chemical-electricity</td>
<td>85-90%</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary battery</td>
<td>Chemical-electricity</td>
<td>90-95%</td>
<td>120-550Wh/ltr</td>
<td>300Wh/kg</td>
<td></td>
</tr>
<tr>
<td>NiCad</td>
<td>Chemical-electricity</td>
<td>90-95%</td>
<td>-</td>
<td>40-175Wh/kg</td>
<td></td>
</tr>
<tr>
<td>NiMH</td>
<td>Chemical-electricity</td>
<td>90-95%</td>
<td>-</td>
<td>150-250Wh/kg</td>
<td></td>
</tr>
<tr>
<td>Li-ion</td>
<td>Chemical-electricity</td>
<td>90-95%</td>
<td>-</td>
<td>140-300Wh/kg</td>
<td></td>
</tr>
<tr>
<td>Windenergy</td>
<td>Mechanical-electricity</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: General characteristics of different power sources [Schoen et al., 1991; Melcor, 2000; Paradiso et al., 1998; Meijerink, 2001; Raadschelders, 1999; Flipsen et al., 2001; Cool, 1997].
PART I: Power generation
3 Fuel power

The principle of a combustion and turbine engine is based on heat engines. The only difference between combustion and turbine engines is that the compression, explosion and expansion for the combustion engine all happen in the same chamber, meaning they all take place at different periods of time. The turbine engine has three chambers for these three phases: the compressor, combustion, and the turbine chamber, often meaning a complex overhead valve system. Also a fuel input and a exhaust output has to be available. For turbine engines all phases can be run through a continuous process. No valve system and media in- or output is needed [Cool, 1997]. Rocket engines and Ramjets are not described in this chapter.

<table>
<thead>
<tr>
<th>Combustion engine</th>
<th>Turbine</th>
<th>No moving parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal combustion</td>
<td>Otto</td>
<td>Gas turbine</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>Jet engine</td>
</tr>
<tr>
<td></td>
<td>Wankel</td>
<td></td>
</tr>
<tr>
<td>External combustion</td>
<td>Stirling</td>
<td>Steam turbine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Closed gas turbine</td>
</tr>
</tbody>
</table>

*Table 2: Overview of fuel powered energy sources.*

3.1 Combustion engine

3.1.1 Introduction
Four different combustion engines are available (named after their inventor):

- Otto, the petrol based explosion engine (standard car engine).
- Diesel, based on compression of the fuel instead of igniting the fuel.
- Wankel, based on the Otto engine with different placed cylinders (rotary).
- Stirling, the external combusted engine.

For the Otto engine a fuel is injected during compression. Pressure has to be kept low, because of a chance of self explosion. After the spark an explosion will occur, and the pressure will rise very quickly. For the Diesel engine only compression takes place, and no spark is needed. Both the Otto and Diesel engine are Open Cycle engines. The air is sucked from the atmosphere, and the heated gasses are blown back into the atmosphere. The main advantage of this system is that no cooler is needed to cool the input gasses (air.), and no cooler unit, to cool round going media, is needed.

In contrast with Otto, Diesel or Wankel engines, the Stirling engine is a Closed Cycle system, meaning the exhaust gasses are cooled down and returned into the system.

3.1.2 State-of-the-art technology
Because of the open cycle of internal combustion engines, and the lack a cooler, the Power-to-Weight ratio is very high. This is very attractive for transportable units, like cars.
(ranging from 30 to 100kW). Smaller scale internal combustion engines can be found in model aircraft and cars (0,1-1,5kW), gardening tools (ranging from hedge shear to lawnmower: 0,9-2,9kW) or as generators (range: 0,75-3,0kW).

Two types of combustion engines are available, the two and four-stroke engine. For a mechanical power output of about 740W, a 4-stroke petrol or gas-fuelled engine weighs about 3kg (Honda GX-22, see figure below). The fuel efficiencies reach 20%.

![Honda four-stroke mini-motor, GX22, and the two-stroke engine from NovaRossi.](image)

Smaller engines used as a power source for model aircraft (mainly 2 stroke engines) are designed only for a high Power-to-Weight ratio, which in turn leads to poor efficiency, noise pollution and very high emissions of CH, CO and NOx. Model engines are lubricated by mixing large amounts of lubricant into the fuel, and the power output is increased by using nitro-based fuels. NovaRossi and Cipolla are manufacturers of these 2 stroke engines.

![The mini-Wankel engine (butane or propane; 0,77cc; 2,5W) of Berkeley University and the Wankel engine of O.S. engines (5cc; 1,27ps).](image)

The most well-known application for the Wankel engine was used in the Mazda RX-7. At the University of California in Berkeley (USA), researchers have built a miniature rotary, internal-combustion engine (Figure 3). This mini-Wankel engine, which is only slightly bigger than a small stack of coins (Ø18,5mm, t~1,5mm), has a displacement of 77,5 mm³, providing electric power of 2,5W, resulting in a specific power of (1500W/lt). The researchers want to boost this electric power-output up till 30W in the future. The mechanical output of the Wankel engine now is in between 4 to 5W. The system uses 50 grams of Butane or Propane in 1 hour. The Berkeley team are looking beyond the mini-Wankel. They envision the micro-Wankel, a rotary engine etched in silicon using micro electro-mechanical systems (MEMS) technology. Though not bigger than an ants head, the micro version should provide enough electricity to power a cellular phone (3W).

Commercially available Wankel engines can be found at O.S. Engines in Canada, which produces mini-Wankel engines for the model aircraft market (Figure 3).
External combustion engines, or Closed Cycle engines, like the Stirling engine are well researched at Gasunie as a co-generator (electricity and heat) for households. These co-generators range from 500W to 5kW, and offer limited efficiencies between 10 and 20%. Small scale Stirling engines are also researched at different research institutes like Srimot (National Maritime Research Institute) in Japan, but aren’t very successful as an alternative power source for portables or wearables, because of their low efficiencies and obtainable power output.

3.1.3 Applications
At the moment most combustion engines are used as a power source for model aircraft, and as mobile electricity generators for building sites (Honda generators). Their noise and overall mass of more than 3 kg (740W system) are one or two orders of magnitude heavier than could be accepted in a handheld system.

Berkeley University thinks the micro-Wankel engine could be a good alternative for the common rechargeable battery. Hydro-carbon fuels (like petrol and gas) have a very high specific energy of about 40MJ/kg, in comparison with the battery with a specific energy of 1MJ/kg. Only 4% fuel conversion efficiency is needed to compete with common batteries. Besides this huge advantage of longer runtime, portable electronics could be made smaller and lighter. Refuelling is also much faster than recharging.

The military is the most eager potential customer, as it is worried how to power all the high-tech equipment to be carried by tomorrow’s soldiers. Next in line will be makers of consumer electronics.

3.1.4 Typical characteristics

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>Displacement [cm³]</th>
<th>Mechanical power output [W]</th>
<th>Power/Weight [W/kg]</th>
<th>Rotational speed &amp; torque [RPM / Nm]</th>
<th>Fuel eff. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cipolla</td>
<td>Tiger Wasp</td>
<td>0.99</td>
<td>120W (0.17ps)</td>
<td>1714</td>
<td>16.000 / 0.07</td>
<td>10%</td>
</tr>
<tr>
<td>Cipolla</td>
<td>Black Dragon</td>
<td>1.77</td>
<td>210W (0.29ps)</td>
<td>1707</td>
<td>17.500 / 0.11</td>
<td>10%</td>
</tr>
<tr>
<td>Magnum</td>
<td>XL-25-A ABC</td>
<td>4.07</td>
<td>600W (0.82ps)</td>
<td>2020</td>
<td>18.000 / 0.32</td>
<td>10%</td>
</tr>
<tr>
<td>Magnum 4-str.</td>
<td>XL-30-AR FS</td>
<td>5.00</td>
<td>330W (0.45ps)</td>
<td>1170</td>
<td>11.500 / 0.27</td>
<td>10%</td>
</tr>
<tr>
<td>Super Tigre</td>
<td>G-34</td>
<td>5.50</td>
<td>725W (0.98ps)</td>
<td>2636</td>
<td>16.500 / 0.42</td>
<td>10%</td>
</tr>
<tr>
<td>Honda 4-str.</td>
<td>GX22</td>
<td>22.00</td>
<td>740W (1hp)</td>
<td>234</td>
<td>7.000 / 1.01</td>
<td>13%</td>
</tr>
<tr>
<td>Honda 4-str.</td>
<td>GX31</td>
<td>31.00</td>
<td>1200W (1.6hp)</td>
<td>356</td>
<td>7.000 / 1.64</td>
<td>21%</td>
</tr>
<tr>
<td>Berkeley</td>
<td>Mini-Wankel</td>
<td>0.0775</td>
<td>5W (lab)</td>
<td>2500</td>
<td>3.000 / 0.016</td>
<td>0.7% (7%)</td>
</tr>
<tr>
<td>O.S.</td>
<td>Mini-Wankel</td>
<td>-</td>
<td>920W (1.27ps)</td>
<td>2749</td>
<td>17.000 / 0.52</td>
<td>10%</td>
</tr>
</tbody>
</table>

Table 3: Characteristics of different mini and micro combustion engines [Honda, Berkeley, O.S., Cipolla, Magnum & Super Tigre].

3.2 Turbine

3.2.1 Introduction
Turbines differ from combustion engines on one point: the process phases (compression, combustion and expansion) take place in three different chambers, placed in series of each others. Two examples of internal turbines are the gas turbine and the jet engine. External turbines are e.g. steam turbines (used in old fashioned trains) and closed gas turbines. Compared to other heat engines, gas turbine engines are simpler, more reliable and require fewer parts. Gas turbines also have a higher Power-to-Weight ratio. They work best with constant loads and operate at high rpm’s (>100.000rpm), making them ideal for power generation.

for a detailed list of manufacturers in the world go to www.twf8.ws
3.2.2 State-of-the-art technology
Massachusetts Institute of Technology (MIT) conducts research into the field of a micro gas turbine engine as an alternative power generator for low-power electronics. On a large scale, gas turbines are found in jet engines, helicopters and M-1 tanks. The gas turbine engine under development at MIT’s Gas Turbine Laboratory, however, is no bigger than a shirt button. Familiar, full-sized gas turbine engines utilize axial flow, with air and gases moving from front to back along the same line as the shaft. The micro-turbine engine at MIT employs radial flow (diameter of 21mm and a thickness of 3mm it generates 20W of electric power at 2 millions rpm). On the front end, air enters at the centre of a centrifugal compressor and is forced outward. At the compressor exit, fuel is injected into the compressed air, and both are forced into the combustion chamber. After ignition, the expanded gases discharge radially inward through the turbine, then exhaust at the centre.

In Helmond (the Netherlands) a company called AMT Jets produces micro axial flow gas-turbines for model jet-aircraft. The mechanical power output ranges from 88 (150,000 RPM) to 190N (at 110,000 RPM), and all use Kerosine-Parafine (Jet A1) as fuel.

3.2.3 Applications
Commercially gas-turbines are available for co-generation in households (0,5 to 1,5kW and larger) and as a mobile power-generator for larger equipment. Low power turbines are mainly used as jet-engines for model aircraft. Noise, fuel consumption and high RPM (>1 million) exclude these turbines as a useful power source for handheld.

MIT is working on the small scale gas-turbine generator, but this will probably be commercially available in 10 to 15 years (2015). Just like the Berkeley engine the military is the most eager potential customer, followed by makers of consumer electronics. These micro turbines could have power outputs in the region of Watts. A problem might be their very high RPM in the region of 1 million.
Closed gas turbines are under research as an alternative co-generator (40kW). Lower power generation is not researched or commercially available. Steam machines find their application in old-fashioned trains and small scaled steam-machine toys.

### 3.2.4 Typical characteristics

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>Mechanical power output [W]</th>
<th>Power/Weight [W/kg]</th>
<th>@ Angular velocity &amp; torque [RPM / Nm]</th>
<th>Fuel efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT</td>
<td>Micro marvel</td>
<td>35</td>
<td>20.000</td>
<td>2,4 mljn / 1.4E-4</td>
<td>20%</td>
</tr>
<tr>
<td>AMT Jet</td>
<td>Mercury</td>
<td>9.000</td>
<td>4.000</td>
<td>149.000 / 0.58</td>
<td>3.7%</td>
</tr>
<tr>
<td>AMT Jet</td>
<td>Pegasus</td>
<td>13.000</td>
<td>4.800</td>
<td>117.000 / 1.06</td>
<td>3.5%</td>
</tr>
<tr>
<td>AMT Jet</td>
<td>Olympus</td>
<td>20.000</td>
<td>6.450</td>
<td>110.000 / 1.74</td>
<td>4.4%</td>
</tr>
</tbody>
</table>

*Table 4: typical characteristics of mini and micro turbine engines [MIT, AMT Jet].*
4 Fuel cell

Fuel cell technology has received an increasing amount of attention over the last decade. Although the technical principle is known since 1849, only since the 1960s research, and small scale application of fuel cells has taken off. In recent years several automotive industries and utilities have embraced the technology as an alternative for current technologies. Motives are among others its potential in energy efficiency and low emissions. Fuel cells transform fuel (e.g. hydrogen) in electricity via a chemical process. Depending on the type of fuel cell the conversion efficiency is in between 35 and 70%. There are ranges of fuel cell types all with their specific characteristics, and in different stages of development:

- **Solid Oxide Fuel cell** (SOFC): a high temperature fuel cell (600-800°C).
- **Molten Carbonate Fuel cell** (MCFC): also a high temperature fuel cell with a very high efficiency (55-70%), mainly used as stationary electricity generation.
- **Polymer Exchange Membrane Fuel cell** (PEM FC): a low-temperature fuel cell (80-200°C).
- **Direct Methanol Fuel cell** (DMFC): low-temperature fuel cell, which uses methanol as a fuel instead of hydrogen.

In this report the focus will be on the low-temperature fuel cells, like the PEM and DMFC, which are most likely to be used in small portable products.

![MEA diagram](image_url)

**Figure 6: The working principle of the hydrogen fuel cell (PEM).**
4.1 Polymer Exchange Membrane Fuel cells

4.1.1 Introduction

The PEM cell converts hydrogen gas and ambient oxygen into water, heat (about 50%) and electricity (<50%). The power output of a small system is modest, but the main drawback is that compact hydrogen storage requires exotic materials, or a very high pressure tank. The one option will make the system very expensive, the other will make it very heavy and bulky.

The fuel cell system consist of two parts, the power-generator (referred as the fuel cell self, generating Watts) and the energy storage (in the form of fuel in the container or cartridge, Joules). Power conversion from fuel to electricity takes place in the fuel cell. Power conversion happens according to the following equilibrium:

Anode reaction: \(2H_2 \rightarrow 4H^+ + 4e^-\)

Cathode reaction: \(O_2 + 4H^+ + 4e^- \rightarrow 2H_2O\)

4.1.2 State-of-the-art technology

The PEM fuel cell is fuelled by pure hydrogen, which is stored in pressure vessels or metal-hydrate cartridges. Hydrogen reacts with oxygen taken from the air in a PEM fuel cell, producing electricity, heat and water. The PEM configuration combines good efficiency (in order of 50%) and splendid weight characteristics of the fuel (hydrogen has a very high specific energy: 120MJ/kg in comparison with e.g. petrol: 50MJ/kg). Most problematic is to store sufficient hydrogen into small volumes (10.8kJ/m³). To minimize the volume, hydrogen can be stored in pressure vessels or metha-hydrate cartridges. This will reduce the weight advantages because of the relatively high weight of the storage medium (steel or aluminium).

Figure 7: a Polymer Exchange Membrane fuel cell for a flash light (the "Maglite BZ" flashlight contains a three-cell stack with a four-watt maximum output. The integrated metal hydride cartridge delivers 30 watt-hours of energy) [ZSW].

4.1.3 Applications

At the moment fuel cells have four different application fields, depending on their power output (W):

1. Utilities, as a power generator for electricity.
2. Distribute power, where local energy is produced to power e.g. building sites.
3. Automotive and transportation.
4. Portable electronics, e.g. laptops and mobile phones.
Figure 8: category of applications vs. power output power of the fuel cell [Motorola labs].

Most of the research on PEM cells is done for the automotive, for the distributed power sector and co-generation units (heat and power for households). Low power research on PEM cells for portable electronics is done at the Fraunhofer institut (ISE), NovArs (Germany) and the ZSW, both in Germany. The NovArs hydrogen fuel cell will be capable of providing power for personal transportation (e.g. the Aprilia electric bike), portable electronics, power tools, emergency home generators, home and outdoor maintenance appliances, portable defense electronics and portable power systems for home and recreation. Commercial applications at the moment are more in the field of educational kits (e.g. from Heliocentris).

Figure 9: the educational fuel-cell kit from Heliocentris, and the NovArs & Manhattan Scientifics’ Hydrocycle.

4.1.4 Typical characteristics

The power-output difference between commercial available and research fuel cells is very large. Commercially fuel cell are student-kits, which are not designed for efficiency and lightweight but only for educational purposes.

Power conversion only takes place in the fuel cell, and energy is conserved in containers or cartridges. The fuel cells characteristics can be compared with that of the photovoltaic cell. Typical characteristics are the surface area (A) of the working cell, the Open Circuit voltage \( V_{oc} \), the Short Circuit current \( I_{sc} \) and the Peak Power Point \( W_{p} \), see Figure 10.
Alternative Power Sources for Portables & Wearables
S.F.J. Flipsen © Delft University of technology – vs. 1.2005

Figure 10: typical cell characteristic of a PEM-cell with an active area of 1cm². Explanation of the electrical characteristics of the fuel cell.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial available</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heliocentris</td>
<td>70 x 70 x 85</td>
<td>30 x 30</td>
<td>1,0</td>
<td>1,25</td>
<td>0,35</td>
<td>1,43</td>
<td>0,5</td>
<td>39%²</td>
</tr>
<tr>
<td>Heliocentris</td>
<td>68 x 68 x 21</td>
<td>35 x 35</td>
<td>0,93</td>
<td>4,0³</td>
<td>0,35</td>
<td>2,85</td>
<td>1,0</td>
<td>53%⁴</td>
</tr>
<tr>
<td>BZ12/16 (Conrad)</td>
<td>80 x 80 x 24</td>
<td>40 x 40</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2,6</td>
<td>5,00</td>
<td>13,0</td>
</tr>
<tr>
<td>FC store (1cell)</td>
<td>-</td>
<td>50 x 50</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2,6</td>
<td>5,00</td>
<td>13,0</td>
</tr>
<tr>
<td>FC store (4stack)</td>
<td>-</td>
<td>70 x 70</td>
<td>23,5</td>
<td>14,0</td>
<td>13</td>
<td>13,00</td>
<td>169,0</td>
<td>-</td>
</tr>
<tr>
<td>FC store (24stack)</td>
<td>-</td>
<td>105x200x130</td>
<td>50 x 50</td>
<td>-</td>
<td>0,87</td>
<td>1,15</td>
<td>0,45</td>
<td>0,80</td>
</tr>
<tr>
<td>H-tec</td>
<td>-</td>
<td>-</td>
<td>1,2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Prototypes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZSW</td>
<td>-</td>
<td>10 x 10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0,75</td>
<td>1,00</td>
<td>0,75</td>
</tr>
<tr>
<td>LANL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Table 5: overview of commercially available and prototype hydrogen PEM fuel cells [H-tec, ZSW, LANL, Heliocentris, Fuel cell store, Conrad].</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Characteristics of the fuel and its storage techniques are described in the following table. Hydrogen has a very high specific energy, 120MJ/kg, but a very low density (0,00009 kg/dm³ at a pressure of 1 bar and a temperature of 293K), meaning a very low energy per litre (10,8kJ/litre). To minimize the volume, hydrogen can be stored in pressured vessels or metal-hydrate cartridges (MH), reducing the weight advantages because of the relative high weight of the storage media. In the following tabular the thermodynamic maximum energy density of different storage techniques are described (heat losses due to conversion from fuel to electricity are not taken into account).

<table>
<thead>
<tr>
<th>Storage technique</th>
<th>Energy per kg (thermodynamic max) [MJ/kg]</th>
<th>Energy per litre (thermodynamic max) [MJ/ltr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No tank included:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncompressed</td>
<td>120⁵</td>
<td>0,0108</td>
</tr>
<tr>
<td>Compressed at 14,4 bar</td>
<td>120</td>
<td>1,50</td>
</tr>
<tr>
<td>Liquefied @ 20K (-253°C)</td>
<td>120</td>
<td>8,6</td>
</tr>
</tbody>
</table>

² Maximum of 7ml/min (~1,28J/s) of hydrogen @ 1000mA (0,5V)
³ At 80mV
⁴ 0,03 ml/sec (0,37J/s) @ 195mW
⁵ At LHV = Lower Heating Value
4.2 Direct Methanol Fuel cells

4.2.1 Introduction

The Direct methanol is a fuel cell which uses methanol instead of hydrogen as fuel. Methanol has a lower specific energy than hydrogen (19.9 MJ/kg versus un-pressurized hydrogen at 120 MJ/kg). The main advantage of methanol in comparison with hydrogen is the specific energy per unit of volume (17.9 MJ/ltr versus 0.0108 MJ/ltr\(^{10}\) for un-pressurized hydrogen), and the simpler storage of methanol in comparison with pressurized hydrogen. Power conversion happens according to the following equilibrium:

\[
\begin{align*}
\text{Anode reaction:} & & \text{CH}_3\text{OH} + \text{H}_2\text{O} & \rightarrow & 6\text{H}^+ + 6\text{e}^- + \text{CO}_2 \\
\text{Cathode reaction:} & & \frac{1}{2}\text{O}_2 + 6\text{H}^+ + 6\text{e}^- & \rightarrow & 3\text{H}_2\text{O}
\end{align*}
\]

4.2.2 State-of-the-art technology

The DMFC is not as efficient as the PEM-cell, only 25% instead of 50%, but it’s fuel, a 3% mixture of methanol in water, is very easy to store. Compact storage of pure methanol is possible, but then a fuel dilution system must be inserted between cell and tank. The cost of the cell itself is higher than the cost of the PEM-cell, but that has only limited influence on the cost of the whole system. It is very suitable for handheld applications (Figure 11).

Main developments are in the field of large-series production of the fuel cell, and research towards increasing the percentage methanol solution in water. A major breakthrough of methanol fuel cells would be a membrane which uses 100% methanol as fuel, instead of 3% diluted water. Developments in this field are done at the Manhattan Scientifics (USA), Fraunhofer Institut (ISE Germany) and other.

Figure 11: A Direct Methanol Fuel Cell used as a charger for a mobile phone (~1.5 Watt, on the right) [ZSW] and the NEC Methanol powered laptop computer [NEC, 2003].

\(^{6}\) Including the metal needed to absorb the hydrogen.
\(^{7}\) From [Kahrom, 1999], at LHV.
\(^{8}\) Very common in hydrogen storage for fuel-cell cars, but not for portables or wearables.
\(^{9}\) Commercial available MH reservoir from Conrad [www.conrad.com].
\(^{10}\) Hydrogen is always stored under pressure, in hydrates or at lower temperatures (~50K)
4.2.3 Applications
At the moment developments in the field of portable and wearable applications are focusing on methanol fuel cells and lesser on hydrogen (PEM) fuel cells. Applications are e.g. portable electronics, like laptops, cellular phones, and portable power units for military or outdoor applications. Most of the methanol fuel cells are researched and developed in laboratories as alternatives for rechargeable batteries (e.g. at the Fraunhofer Institut ISE). Commercial applications at the moment are more in the field of educational kits (e.g. from Heliocentris, Germany).

At the time of writing Smart Fuel Cell (SFC, Germany) have started up “commercial” methanol fuel cell production at the beginning of 2004. The first customers will evaluate the products during extended field tests in the areas of traffic systems, remote sensor applications, camping and outdoor equipment. From mid-2004 on, the system will be obtainable on order for additional customers. The fuel cells will be available in the power range between 10 to 1000 Watts.

Table 7: Overview of products from Smart Fuel Cell.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Professional video camera</td>
<td>2,9</td>
<td>0,120</td>
<td>120 x 160 x 170</td>
<td>25W; 12V</td>
<td>&gt;6h @20W</td>
</tr>
<tr>
<td>Mobile office systems</td>
<td>1,9</td>
<td>0,175</td>
<td>100 x 55 x 40</td>
<td>40W; 12V</td>
<td>&gt;8h @20W</td>
</tr>
<tr>
<td>Traffic system</td>
<td>2,8</td>
<td>0,120</td>
<td>120 x 160 x 170</td>
<td>25W; 12V</td>
<td>&gt;6h @20W</td>
</tr>
<tr>
<td>Remote power system</td>
<td>9,7</td>
<td>2,500</td>
<td>465 x 240 x 162</td>
<td>25W; 11,2-14V</td>
<td>100h @25W</td>
</tr>
</tbody>
</table>

Manhattan Scientifics (MHTX, USA) have developed prototype of an electric scooter in co-operation with Aprilia (3kW system). In co-operation with Electrolux (Germany) and Lunar Design MHTX is going to develop a fuel cell used in a vacuum cleaner (1kW) [MHTX, 2001]. Also different electronics OEMs, e.g. Toshiba and NEC, have produced a prototype of a fuel-cell powered laptop. They claim to introduce these laptops to the market at the end of 2004.

4.2.4 Typical characteristics
The DMFC is in concept identical with the PEM fuel cell, and can also be compared with the solar cell. Typical characteristics are the surface area of the working cell ($cm^2$), the Open Circuit voltage ($V_{oc}$), the Short Circuit current ($I_{sc}$) and the Peak Power Point ($W_p$).
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial available</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heliocentris</td>
<td>85 x 70 x 40</td>
<td>40 x 40</td>
<td>0.6</td>
<td>1</td>
<td>0.45</td>
<td>0.22</td>
<td>0.1</td>
<td>15%¹¹</td>
</tr>
<tr>
<td>H-tec</td>
<td>115 x 200 x 200</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>Smart Fuel cell</td>
<td>460x240x160</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>25Wc/80Wp &gt;25%</td>
</tr>
<tr>
<td>Prototypes</td>
<td>JPL laboratory</td>
<td>10 x 10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td>0.3</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 8: overview of commercially available and prototyped Direct Methanol fuel cells [Heliocentris, H-tec, JPL laboratory, Fuelcells.org].

Methanol can be stored in metal or plastic containers. The energy density (higher heat value) of methanol is 17.9MJ/litre, when cartridge is excluded. Including the tank the density will be around 10 to 15 MJ/litre.

¹¹ 20μmol/min (~0.33J/s) @ 100mA (0.5V)
5 Chemical

5.1 Photovoltaic

5.1.1 Introduction
Photovoltaic power is also called solar power and generated by PV or Solar cells. The PV effect was discovered by Becquerel in 1839. In the 1950’s PV cells were used for the first time in space industry which is the basis for current commercial applications.

A Silicon (Si) plate is exposed to sunlight. The energy of a beam of sunlight contains photons (or light quanta). When these photons (Figure 13) hit the cell its energy frees electron-hole pairs. Each photon with enough energy will free exactly one electron (negative charged) and results in one free positive charged hole. The electron wandering towards the junction will, under the influence of the electric field at the metal contact, be send to the n-side and the hole towards the p-side. When the n and p-side are short circuited electrons (current) will flow through the path to their original side (the p-side). At the p-side these electrons will recombine with the holes. The electron flow provides a current and the cell’s electric field causes a voltage, resulting in power as a product.

5.1.2 State-of-the-art technology
At the moment different solar panels are commercially available, and new technologies are being researched. At present, the main types of semi-conductor materials (commercially) used in PV cells (all inorganic) [Kan, 2002; Rauber 2001; Markvart, 2003] are:

1. Mono-crystalline silicon (mono-c-Si) main source for PV cells, with a market share of about 39%.
2. Poly-crystalline silicon (poly-c-Si), also called multi-crystalline silicon, there is a trend of growth, more than mono-crystalline cells (market share of about 44%).

Figure 13: Basic principle of a photovoltaic cell.
3. Amorphous silicon (a-Si), with a market share of 13%.
4. Micro-crystalline silicon (mc-Si), often treated the same as Poly-crystalline silicon.

**Figure 14:** A mono and a poly-crystalline cell, plus an amorphous cell used to power a mosquito repellent [www.conrad.nl/].

Research is done on:
- High-temperature thin-film crystalline silicon (Ht-f-Si, non-commercial)
- Low-temperature thin-film crystalline silicon (Lt-f-Si, non-commercial)
- Organic thin-film solar cells or Polymer PV (based on conductive polymers).
- Hybrid GaAs/polymer solar cells, especially interesting with respect to new consumer products like e-papers and e-books. GaAs/polymer cells work in a different spectrum than mono and poly crystalline cells.

### 5.1.3 Applications

Three types of commercial solar applications can be distinguished:

1. Grid connected PV systems
2. Autonomous PV systems
3. Mobile PV systems

Grid connected PV systems use the electricity grid as a buffer to store their energy. The direct current from PV systems is inverted by one or more inverters before being fed to the electricity grid. Normally grid-connected PV systems range from about 1kW<sub>peak</sub> to several MW<sub>peak</sub>.

**Figure 15:** Autonomous connected PV system from Go Solar © company (left), a portable PV-powered radio / flashlight (middle) and a portable charger for cellular phones (right).

In autonomous connected PV systems direct current produced by the PV-array is not fed into a electricity grid but is stored in one or more batteries or supplied directly to DC or AC appliances (Figure 15). Most of these systems are hybrid systems, meaning besides PV cells other means of power (e.g. grid, batteries or human power) is supplied as well. A specific type of autonomous PV system is the Solar Home System (SHS), which is designed to supply domestic electricity. Normally it consists of one or two PV modules, a battery and a charge regulator, and ranges from 25 to 200W<sub>peak</sub>. The cells used in
autonomous and grid-connected PV applications are mainly based on mono- or polycrystalline cells.

Especially portable products for outdoor applications are often equipped with solar cells. Figure 15 shows a mobile portable PV powered radio / flashlight and a charger for a cellular phone. Other mobile applications, like small solar-toys or solar-powered electronic calculators, are mainly built with amorphous silicon based cells. These systems often work directly under solar or artificial light. The electricity generated is buffered in a small button battery or gold cap. Typical ranges are from 1 mWpeak to several Wpeak. These amorphous cells are chosen because of their low price, despite of their low performance (efficiency).

5.1.4 Typical characteristics
When set-up correctly and in stationary situations, solar panels produce approximately 100W_{pp} (Peak Power\textsuperscript{12}) electric power per square meter (with a 1000W/m\textsuperscript{2} light intensity and a 10% efficiency of the cells). This means for the Netherlands with 1000 hours of sunlight per year, one square meters produces a maximum of 100kWh per year of electric energy. Smaller amorphous cells produce less per square meter (50-70W_{pp}), because of their lower efficiency (5-7%). Also direction towards the sun or an artificial light is very important for the efficiency of the solar panel.

Different cells have different characteristics. In general the electric power of PV cells depends on the following parameters:

- Light intensity and illumination level, resulting in a current (I). Low light intensity will decrease the efficiency of the cell. The efficiency (%) of the cell decreases logarithmically with the light intensity\textsuperscript{13}.
- Colour spectrum of the light (f).
- The surface area (A) is linear with the current production (I): \sim 5 mA_{pp}/cm\textsuperscript{2}.
- Temperature (T) of the cell. The cells efficiency decreases with increasing temperature: voltage drop per cell = 2.3mV/K, a current drop which is diminishable and a Peak Power drop of approximately 0.3-0.65%/K [Palz, 1978; Radziemska, 2002].
- The short-circuited resistor (R), resulting in the V-I characteristic of the cell (see Figure 16).
- The average value of the maximum PP Voltage (V_{pp}) can be estimated as 80% of the Open-Circuit voltage (V_{oc}) under standard irradiance conditions. Use at higher currents (>I_{pp}) results in a major power and efficiency drop. Use at lower currents (<I_{pp}) results in major power drop and an efficiency increase!
- Panel direction (angle) towards the sun or artificial light.

![Figure 16: Explanation of the electrical characteristics of solar panels.](image)

\textsuperscript{12} Peak Power (PP) takes place when efficiency of the cell is at its highest (see also Figure 16).
\textsuperscript{13} A mono-crystalline cell at 1000W/m\textsuperscript{2} light intensity has an efficiency of 24.7%. The same cell at 100W/m\textsuperscript{2} has an efficiency of 22.3%, and at 10W/m\textsuperscript{2} an efficiency of 19.4% \rightarrow P= \ln [\text{light intensity}] + 16.8 (for this particular cell under laboratory conditions).
The efficiencies of PV cells differ per type. In general the following efficiencies for larger panels may be used [Kan, 2002]:

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Single cell efficiency in laboratory [%]</th>
<th>Module efficiency in laboratory [%]</th>
<th>Module efficiency commercial [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono crystalline</td>
<td>24,7(^{(*)}) - 35%</td>
<td>22,7(^{(*)})</td>
<td>13-16%</td>
</tr>
<tr>
<td>Poly crystalline</td>
<td>16-19,8(^{(*)})</td>
<td>15,3(^{(*)})</td>
<td>12-14%</td>
</tr>
<tr>
<td>Micro crystalline</td>
<td>13,7-6,6(^{(*)})</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HT thin film crystalline</td>
<td>14%</td>
<td>12,5%</td>
<td>-</td>
</tr>
<tr>
<td>LT thin film crystalline</td>
<td>11%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Amorphous Silicon</td>
<td>8,6-12,7%</td>
<td>10,5%</td>
<td>7-9,2%</td>
</tr>
</tbody>
</table>

Table 9: Efficiencies of PV Cells, \(^{(*)}\)=measured under Standard Test Conditions (STC).  

Table 10 shows the efficiency and power-output of smaller panels, used in e.g. portable and wearable products. It can be seen that the efficiency of smaller solar panels (the poly crystalline thin film PV cells) is much smaller than for larger cells (the Siemens SM20 and the ST20). The Panasonic outdoor panels are very often used as back-up power for automotive batteries, power supplies for radio’s, teaching aids, and toys. Indoor applications are e.g. calculators, indoor clocks, remote control units and digital thermometers.

UniSolar (USA) produces flexible amorphous cells specially made for charging batteries for boats and automotive. In general amorphous cells produce a lower power output than crystalline, but they tend to generate more power during bad-weather conditions (like clouded weather). During full-sun conditions the crystalline cells produce more power. Overall taken the energy-production over a year is almost the same for both type of cells.

It must be taken into account that the efficiencies specified by the industry are measured under Standard Test Conditions (1000W/m² irradiation and at a temperature of 25°C). For some cells, especially for the multi-crystalline cells, the efficiency drops when the irradiation drops [Kan, 2003]. This happens indoors (irradiation<100W/m²) or at cloudy days.

<table>
<thead>
<tr>
<th>Manufacturer Type</th>
<th>Surface area (\text{[mm}^2])</th>
<th>(\text{V}_\text{OC}) ([V])</th>
<th>(\text{I}_\text{SC}) ([A])</th>
<th>(\text{V}_{\text{PP}}) ([V])</th>
<th>(\text{I}_{\text{PP}}) ([A])</th>
<th>Peak Power point (\text{[Wp]})</th>
<th>Max efficiency @ PP [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siemens SM20</td>
<td>mono-crystalline</td>
<td>567x328</td>
<td>18,0</td>
<td>1,6</td>
<td>14,5</td>
<td>1,38</td>
<td>20</td>
</tr>
<tr>
<td>Siemens SM10</td>
<td>mono-crystalline</td>
<td>360x330</td>
<td>19,9</td>
<td>0,71</td>
<td>16,3</td>
<td>0,61</td>
<td>10</td>
</tr>
<tr>
<td>Siemens ST20</td>
<td>poly-crystalline</td>
<td>329x748</td>
<td>21,0</td>
<td>1,48</td>
<td>15,6</td>
<td>1,29</td>
<td>20</td>
</tr>
<tr>
<td>Siemens ST10</td>
<td>thin film</td>
<td>329x387</td>
<td>21,0</td>
<td>0,74</td>
<td>15,6</td>
<td>0,64</td>
<td>10</td>
</tr>
<tr>
<td>Siemens ST5</td>
<td>thin film</td>
<td>329x206</td>
<td>21,0</td>
<td>0,37</td>
<td>15,6</td>
<td>0,32</td>
<td>5</td>
</tr>
<tr>
<td>Panasonic</td>
<td>poly-crystalline</td>
<td>55x55</td>
<td>2,05</td>
<td>0,115</td>
<td>1,2</td>
<td>0,105</td>
<td>0,13</td>
</tr>
<tr>
<td>(outdoor)</td>
<td></td>
<td>24x33</td>
<td>3,45</td>
<td>0,0185</td>
<td>1,8</td>
<td>0,017</td>
<td>0,031</td>
</tr>
<tr>
<td>Panasonic</td>
<td>poly-crystalline</td>
<td>53x23,5</td>
<td>4,3</td>
<td>10 E(^{-6})</td>
<td>3,2</td>
<td>10 E-6</td>
<td>32,0 E-6</td>
</tr>
<tr>
<td>Sunceram II</td>
<td>thin film</td>
<td>87,7x16,6</td>
<td>1,8</td>
<td>28 E(^{-6})</td>
<td>1,3</td>
<td>24 E-6</td>
<td>31,2 E-6</td>
</tr>
<tr>
<td>(indoor)</td>
<td></td>
<td>25x10</td>
<td>1,8</td>
<td>5,8 E(^{-6})</td>
<td>1,3</td>
<td>5,4 E-6</td>
<td>7,0 E-6</td>
</tr>
<tr>
<td>Free Energy 4-12</td>
<td>Amorphous cells</td>
<td>343x317</td>
<td>22</td>
<td>0,30</td>
<td>16</td>
<td>0,25</td>
<td>4</td>
</tr>
<tr>
<td>Free Energy 7-12</td>
<td>Amorphous cells</td>
<td>495x317</td>
<td>22</td>
<td>0,45</td>
<td>16</td>
<td>0,38</td>
<td>6</td>
</tr>
<tr>
<td>UniSolar USF-32</td>
<td>Amorphous flexible thin film</td>
<td>425x1420</td>
<td>23,8</td>
<td>2,40</td>
<td>16,5</td>
<td>1,94</td>
<td>32</td>
</tr>
<tr>
<td>UniSolar USF-11</td>
<td>Amorphous flexible thin film</td>
<td>425x554</td>
<td>23,8</td>
<td>0,78</td>
<td>16,5</td>
<td>0,62</td>
<td>10,3</td>
</tr>
<tr>
<td>UniSolar USF-5</td>
<td>Amorphous flexible thin film</td>
<td>247x554</td>
<td>23,8</td>
<td>0,37</td>
<td>16,5</td>
<td>0,30</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 10: typical specific characteristics of commercially available small poly and mono crystalline PV-cells. The Panasonic Sunceram II cells for indoor use have been tested under a fluorescent lamp of 200lux (~2W/m² radiant power) instead under STC (1000W/m², T=25°C).
5.2 Thermo Electric Generator

5.2.1 Introduction
A Thermo Electric Generator (TEG) is based on the ‘Seebeck’ effect, and is made of two kinds of metal that can both conduct electricity. They are connected to each other in a closed loop. If the two metals are at different temperatures (e.g. by heating one end), an electric potential will exist between them and electrons will start to flow, producing an electric current.

A TEG is a Thermo Electric element (TE, or Peltier element), used the other way around. A TE cell will produce a heat difference between the two metals, when powered with electricity.

Figure 17: De Hi-Z 19Watts Thermo Electric system (left) and truck carried out with 1kWatts of Hi-Z TEGs (right).

5.2.2 State-of-the-art technology
The conversion efficiency, even for large systems, is less than 10%. For sufficient output voltage, in the order of a few Volts, large temperature differences between hot and cold junctions are needed, and the number of junctions has to be large, in the order of a hundred or so. Both requirements make small applications difficult.

Most TE cell producers, offer also TEG cells, for generating electricity from waste-heat, e.g. from small engine exhaust, industrial operations such as cement plants, refineries, glass manufacturing, foundries etc., and other heated components. The HZ-2 module (a 2.5W TE generator from Hi-Z) consists of 97 thermocouples arranged electrically in series and thermally in parallel. The thermocouples consists of “Hot Pressed”, Bismuth Telluride based, semiconductors to give the highest efficiency at most waste heat temperatures as well as high strength capable of enduring rugged applications. The bonded metal conductors enable the HZ-2 module to operate continuously at temperatures as high as 250°C and intermittently as high as 400°C without degrading the module.

5.2.3 Applications
TEGs have a few applications in the field of wristwatches. The Seiko Corporation has manufactured and successfully marketed a thermal wristwatch in 1998 in Japan [Seiko, 1999]. Other applications can be found in radio-lamps, where the heat of the gas-fired lamp is converted in a low-power current used to power a radio (e.g. from GW industries).
Different manufacturers produce low-power TEGs: DTS (Germany) which manufacture low power (10-40uW) thin film thermoelectric power generators, and Hi-Z, manufacturing small generator modules ranging in output power from 0.3 watts to 20 watts. Applications are e.g. electricity production for larger trucks (Figure 17): 1kW system using the temperature difference between the engine exhaust and the outside (streaming) air. Other applications could be self-powered fans, or in general electric power form small or larger combustion engine exhaust.

Aspen Systems has developed a Thermoelectric Fan (TEF), used to circulate heat in an army tent, thus improving the comfort of the inhabitants. Since electricity is unavailable in the US army tents and barracks, the electric power required to run the fan must be generated by converting some of the heat output of the space heater into electric power. The power requirement of the fan is approximately 6W (@ $\Delta T = 240-350^\circ C$ and a surface area of 1020cm$^2$), so solid-state thermoelectric modules are used to convert a part of the heat into electricity.

For the US Army, Hi-Z is developing a lightweight portable battery charger, based on diesel or other military logistics fuel as the heat-source. The thermoelectric material used in this application is current state-of-the-art. However, Hi-Z is also developing advanced thermoelectric materials and devices that promise significantly improved performance in the near future.

5.2.4 Typical Characteristics

Typical TEGs depends generally on the temperature difference between the hot and cold side. Most TEGs are designed for temperature difference of 200 to 250°C, for which the efficiency is in between 4.5 and 5% (at $T_{cold} = 30^\circ C$). Low temperature differences (<50°C) mean low efficiencies (< 1%, see Figure 20). Generally the efficiency of a TEG is between 0.067% to 0.09% per degree temperature difference [Hakkesteegt, 2001].

TEGs are quite expensive. The material used in the Citizen and Seiko TE watches is Bi$_2$Te$_3$, which is extremely expensive.
Figure 20: measured efficiencies of low-power TE generators (TEGs) from Melcor Aztec [Hakkesteegt, 2001] (Tc = the temperature at the Cold side).

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>Surface area [mm²]</th>
<th>Voltage [V]</th>
<th>Current [A]</th>
<th>Generated peak power [W]</th>
<th>η [%] @ ΔT=200°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hi-Z</td>
<td>HZ-2</td>
<td>29 x 29</td>
<td>3.3</td>
<td>0.8</td>
<td>2.5</td>
<td>4.5%</td>
</tr>
<tr>
<td></td>
<td>HZ-9</td>
<td>62.7 x 62.7</td>
<td>3.3</td>
<td>2.9</td>
<td>9.6</td>
<td>4.5%</td>
</tr>
<tr>
<td></td>
<td>HZ-14</td>
<td>62.7 x 62.7</td>
<td>1.65</td>
<td>8.0</td>
<td>13.2</td>
<td>4.5%</td>
</tr>
<tr>
<td></td>
<td>HZ-20</td>
<td>75 x 75</td>
<td>2.38</td>
<td>8.0</td>
<td>19</td>
<td>4.5%</td>
</tr>
<tr>
<td>Aspen Systems</td>
<td>Thermolectric Fan</td>
<td>≈ π × 360²</td>
<td>-</td>
<td>-</td>
<td>6</td>
<td>3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>Surface area [mm²]</th>
<th>Voltage [V]</th>
<th>Current</th>
<th>Generated peak power [W]</th>
<th>η [%] @ ΔT=1°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seiko</td>
<td>Thermic watch</td>
<td>6 x 100</td>
<td>0.445</td>
<td>-</td>
<td>4.45 E-6</td>
<td>&lt;&lt;1%</td>
</tr>
<tr>
<td>Citizen</td>
<td>Eco Thermo</td>
<td>10x10</td>
<td>-</td>
<td>-</td>
<td>13.00 E-6</td>
<td>&lt;&lt;1%</td>
</tr>
</tbody>
</table>

Table 11: overview of available TE generators [Hi-Z, Aspen Systems, Seiko & Citizen].
6 Human

Human power is power generated by human activity, e.g. bicycling, winding and general movements of the body or body parts. Human movements can be converted in electric energy by means of electromagnetic generators and piezo-elements, but can also be converted to mechanical energy and storage (e.g. in springs or compressed gas). First the energy-conversion in the body and the available energy from the human body is described, followed by the electric conversion technologies (electromagnetic and piezo) useful for portable electronics.

6.1 Muscle power

6.1.1 Introduction

Crank radios and lights all use the technology described above. The total amount of energy and power a human can deliver is limited to his or hers stamina and physical strength. A human in good physical state can, only for a short period of time, deliver up to 300Watts of human power on a rowing machine or other fitness apparatus.

Two energy conversions can be distinguished, the conversion from food-to-muscles and that from muscle-to-mechanic or electric power. In general food-to-muscle power has an efficiency of 5-10%, for pushing and pulling, and 20-25% when cycling (see also Figure 21). Muscle-to-electric power efficiency depends on the technology used. E.g. for electromagnetic conversion the efficiency is 40-60%, and for piezo-to-electric conversion 5-10%.

![Figure 21: The efficiency of food-to-mechanic energy conversion [Grassman, 1987].](image)

Food power (W) | net power (W) | efficiency (%)
---|---|---
Cycling | | 
Pulling of a load | | 
Stair climbing | | 
Diagonal carry of a load | | 
Horizontal push | | 
Vertical pull down | | 
Stair climbing | | 
Diagonal carry of a load | | 
Horizontal push | |
6.1.2 State-of-the-art technology

Energy from muscles is limited by maximum power exertion of the muscle in question (in Watts) and the stamina of the person (in seconds). The maximum power generated depends on different subject variables [Daams, 1994]:

Subject variables

1. sex
2. age
3. laterality
4. anthropometric variables
5. clothing
6. psychological and physical factors (motivation, circadian rhythm)
7. other personal characteristics (experience, technical understanding, dexterity, intelligence, movement patterns and so on)

Interaction variables

- Posture
  22. part of the body used for contact
  23. part(s) of the body used in force exertion
  24. left, right or both sides
  25. position of product on segment
  26. angle of joints
  27. movements at same time either equal, alternating, or different

- Force
  28. required force level
  29. speed of movement
  30. acceleration of movement
  31. endurance
  32. direction of force
  33. change of direction (of force)
  34. repetition/frequency of handling (number of cycles and duration of force exertion and rest)

Product variables

- form
- size
- position
- material of contact area (coefficient of friction, hardness)
- determined vs. non determined movement
- static versus dynamic
- required precision

Environment variables

- support
- space limitation (limits freedom of movement)
- vibration
- temperature and humidity
- altitude

Figure 22: The 34 variables that influence force exertion. Subject, product and environmental variables also influence the interaction variables. This influence is indicated with an arrow [Daams, 1994].

6.1.3 Typical characteristics

It is not possible to give an average force exertion of the human body (and its limbs). Different variables decide how much force you can exert (see above [Daams, 1994]). For example a professional cyclist draws more power from an ergo-meter than an average person. The same accounts for rowers and sportspeople from other disciplines. The following numbers give an idea about the relation between potential energy production and the stamina of a person:

<table>
<thead>
<tr>
<th>Type of person</th>
<th>Peak power (W)</th>
<th>Mean power (t&lt;30 min)</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average sporty person</td>
<td>± 500</td>
<td>150-200</td>
<td>1</td>
</tr>
<tr>
<td>Trained cyclist</td>
<td>± 800</td>
<td>350-400</td>
<td>~2x average</td>
</tr>
<tr>
<td>Professional top cyclist (e.g. Lance Armstrong)</td>
<td>&gt;1000</td>
<td>650-700</td>
<td>~4x average</td>
</tr>
</tbody>
</table>

Table 12: Typical peak and mean power figures for different trained people who are cycling.

Typically a sleeping person produces 81 W of heat power. A soldier standing at ease produces 128 W, a walking person 163 W and a briskly walking person 407 W, a long-distance runner produces 1.048 W, and a sprinter 1.630 W, according to the Center for Space Power and Advanced Electronics (NASA) [Baard, 2001; Morton, 1952; Starner, 1996]. Capturing this power will be very difficult, especially when using the low-efficiency Thermo-Electric elements (2-5%, see chapter 5.2), and taking into account that decreasing of body temperature with more than one degree could be lethal.
In most of the cases dynamic forces are used to generate electricity in human powered products (e.g. a repetitive movement of a body limb like cranking the Baygen radio). The human body can peak for a very short period and attain a much lower power average for a longer period (endurance). For example an average cyclist can attain a 500 Watts ride for a few seconds, while attaining a 150 Watts (20-30% of the maximum peak power) ride for 30 minutes (see Table 12).

Sometimes a single force movement is enough to generate enough energy for the moment (e.g. with a piezoelectric powered remote control). Some literature state that a static force equal or less than 15% of the maximal force could be maintained indefinitely [Daam, 1994]. The correlation between strength of arm and leg muscles (F in Newton) is strongly correlated with endurance (t in seconds).

![Figure 23: Power of rowing and cycling in relation to duration exercise for a typical healthy male (30 years) and non-athlete [Kawai, 1997] and the mechanical power produced when hand-cranking for six different test subjects [Slob, 2000].](image)

In Figure 23 [Kawai, 1997] an endurance test gives an idea of the average power a typical healthy and non-athletic male (30 years) can withhold for a longer period of time. As a rule-of-thumb it can be stated that:

"a healthy human being can withhold a power continuously for a longer period of time, when this power is less than 10-15% of the maximum power."

An other factor influencing the stamina of a human being is (dis)comfort and its state-of-mind at the moment of exercise. No research on this field is known. In the following table an overview is given of different common "actions" typically used in human powered products, and its maximum force exertion (male and female).

<table>
<thead>
<tr>
<th>Action</th>
<th>Maximum force exerted (Nm)</th>
<th>Maximum force exerted (Nm)</th>
<th>Maximum power (W&lt;sub&gt;peak&lt;/sub&gt;)</th>
<th>Average power for a longer period of time (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>rowing&lt;sup&gt;15&lt;/sup&gt;</td>
<td>-</td>
<td>-</td>
<td>800</td>
<td>200</td>
</tr>
<tr>
<td>cycling&lt;sup&gt;15&lt;/sup&gt;</td>
<td>-</td>
<td>-</td>
<td>600</td>
<td>150</td>
</tr>
<tr>
<td>hand pinching (knijpkat)&lt;sup&gt;16&lt;/sup&gt;</td>
<td>490</td>
<td>300</td>
<td>-</td>
<td>0.50</td>
</tr>
<tr>
<td>finger pushing (button)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.002</td>
</tr>
<tr>
<td>hand pushing</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.037</td>
</tr>
<tr>
<td>hand pulling</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.10</td>
</tr>
<tr>
<td>torque jam jar (free posture)&lt;sup&gt;17&lt;/sup&gt;</td>
<td>(9.67 ± 2.2)</td>
<td>(5.91 ± 1.26)</td>
<td>-</td>
<td>0.22</td>
</tr>
</tbody>
</table>

<sup>15</sup> [Kawai, 1997]
<sup>16</sup> [Greenberg & Chaffin]
<sup>17</sup> [Daams, 1994]
### Table 13: Overview of generated mechanical power of different human activities, age 30 years [Kawai, 1997; references summarized by Daams, 1994; Pen, 1997].

<table>
<thead>
<tr>
<th>Activity</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grip</td>
<td>600 ± 100</td>
</tr>
<tr>
<td>Arm cranking (D=50cm)</td>
<td>350 ± 50</td>
</tr>
<tr>
<td>Foot pushing</td>
<td>-</td>
</tr>
<tr>
<td>Leg pushing</td>
<td>419 ± 198</td>
</tr>
<tr>
<td>Thumb pressure</td>
<td>81.3 ± 26.7</td>
</tr>
</tbody>
</table>

A very handy tool which can help with the feasibility check of a human powered consumer electronic is the **Energy Balance Ratio (EBR)** table [Pater, 2000]:

<table>
<thead>
<tr>
<th>Power generation (mW)</th>
<th>Power consumption (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swatch watch</td>
<td>0.001</td>
</tr>
<tr>
<td>Travel Clock</td>
<td>0.002</td>
</tr>
<tr>
<td>Hearing aid</td>
<td>0.05</td>
</tr>
<tr>
<td>Cardiac pacemaker</td>
<td>0.1</td>
</tr>
<tr>
<td>Tamagotchi</td>
<td>0.36</td>
</tr>
<tr>
<td>Philips pager Fiori (1998)</td>
<td>2</td>
</tr>
<tr>
<td>LED pointers</td>
<td>5</td>
</tr>
<tr>
<td>Nokia 6165 cell phone (1999)</td>
<td>18</td>
</tr>
<tr>
<td>Motorola StarTac 130 cell phone (1999)</td>
<td>37</td>
</tr>
<tr>
<td>Philips Gene cell phone (1997)</td>
<td>48</td>
</tr>
<tr>
<td>Philips portable radio AE6545</td>
<td>52</td>
</tr>
<tr>
<td>Sony ICF-B200 Radio</td>
<td>60</td>
</tr>
<tr>
<td>Philips Fizz cell phone (1996)</td>
<td>66</td>
</tr>
<tr>
<td>LED flashlight</td>
<td>80</td>
</tr>
<tr>
<td>Freepay FPR1 Radio</td>
<td>90</td>
</tr>
<tr>
<td>Philips cordless FM headphone</td>
<td>120</td>
</tr>
<tr>
<td>Philips MP3 player (2000)</td>
<td>220</td>
</tr>
<tr>
<td>Philips cassette player ACT688</td>
<td>276</td>
</tr>
<tr>
<td>Philips CD player ACT7062</td>
<td>432</td>
</tr>
<tr>
<td>Philips MP3 player (2000)</td>
<td>440</td>
</tr>
<tr>
<td>Motorola Tritium satellite phone</td>
<td>570</td>
</tr>
<tr>
<td>Philips VoVo 1 PDA</td>
<td>600</td>
</tr>
<tr>
<td>Incandescent Flashlight</td>
<td>700</td>
</tr>
<tr>
<td>Motorola 130 (during transmission)</td>
<td>720</td>
</tr>
<tr>
<td>Halogen flash light (torch)</td>
<td>2.000</td>
</tr>
<tr>
<td>Philips cordless phone Xalio (1997)</td>
<td>2.703</td>
</tr>
<tr>
<td>Philips Windows CE mini-notebook</td>
<td>3.400</td>
</tr>
<tr>
<td>Video 8 camera</td>
<td>6.000</td>
</tr>
<tr>
<td>Notebook computer</td>
<td>15.000</td>
</tr>
<tr>
<td>DVD player</td>
<td>20.000</td>
</tr>
<tr>
<td>Personal computer</td>
<td>35.000</td>
</tr>
<tr>
<td>TV (30cm)</td>
<td>50.000</td>
</tr>
</tbody>
</table>

**Figure 24: The Energy Balance Ratio, power generation vs. power consumption adopted from [Pater, 2000].**

### 6.2 Electro magnetic generator

#### 6.2.1 Introduction

A generator is a machine that converts mechanical energy into electrical energy by using the principle of magnetic induction. Magnetic induction is used to produce a voltage by rotating coils of wire through a stationary magnetic field, or by rotating a magnetic field through stationary coils of wire. The electro magnetic generator works according to Faraday’s discovery of the induction-effect. The most common example is the bicycle dynamo. The power output of the generator depends on:

- rotational speed of the rotor (rpm);
- the number of windings (n);
- the strength of the magnetic field (flux);

---

18 McCormick, 1993  
• the number of poles on the magnet (North and South);
• the Ohmic resistance (Ω).

Figure 25: The principle of DC electro-magnetic generator [tpub.com]

6.2.2 State-of-the-art technology
Different electro-magnetic principles are interesting for the use as a generator. In most human powered products, like the Freeplay wind-up radio the generator is plain DC electro motor used as a generator (Mubachi). The principle of the electromotor is the same as the generator, but used the other way around. This is because the production costs of a dedicated low-power generator (in small series) would be very high compared with existing mass produced, hence cheap, electro motors. The efficiency of dedicated generators will be higher compared to electro motors used as generators, but this flaw is taken for granted.

The most common electro motors used as generators are basic three phase AC or brushed/brushless DC motors, with permanent magnets. The efficiency of electric-to-mechanic energy is approximately the same as transformation from mechanic-to-electric energy. These generators work most efficient on high speeds (rpm's).

6.2.3 Applications
Electro-magnetic generators have applications at different power levels. Ranging form high power generators in GigaWatts \(10^9\) power plants, to microWatt \(10^{-6}\) generation in the Seiko Kinetic Quartz watch. Within this report the focus is on low-power generation, powered by human activities \(<100W_{\text{electric}}\).

The most common application is the bicycle generator, in other words the dynamo. This product is produced in large masses, produces 3Watts at a voltage of 6V. Different types are available: sideways, tread or in the hub of a wheel. Developments on the field of bicycle generators are in the hub generator (Shimano or Son in Germany), the high efficiency generators (AXA HR) and generators with integrated rechargeable batteries. These generators are specially designed for the use as a generator, with high efficiencies (ranging from 45\% to 95\%, according to Lightspin).
Other applications can be found in hand-cranked radio's and flashlights from Freeplay (South-Africa). These products use ordinary DC permanent magnet motors as generators. The efficiency is probably lower, but still good enough for its purpose. The efficiency of the generator itself is approximately 50%. The total efficiency of the system (cranking-to-harvesting in a spring-to-electric power) is nearly 40%, concluded from tests by [Van Pul, 2002].

At the moment some quartz watches are equipped with a micro-generator, the so-called Kinetic watches (Swatch and Seiko). These generators are designed for high-efficiency in a minimum volume.

On the internet much information can be found on Pedal Power, or power generated by cycling. Power as a result from pedalling could go up to 425Wepeak (25A at 17VDC) and a mean of 150W (for 30 minutes with a cyclist [Butcher, 2002]). Butcher used a permanent-magnet 36VDC motor, combined with a flywheel and a crankshaft.

### 6.2.4 Typical characteristics

The efficiency of rotating generators depends mainly on the rotational speed (rpm), the number of windings in de coil (n) and the strength of the magnet. Fast changes in the magnetic flux (or high rpm) will decrease the efficiency of the generator strongly but increases the power-output and the voltage. The hub-generator has a large overall efficiency because of no friction as with the sideways and tread generator wheel.

The Son hub generator is tested by tandem-fahren.de as the best hub generator at the moment with an efficiency of 65%. Other hub generators have a max efficiency of 35% to 65%. Sideway dynamo's range in between 28% and 38% (see figure below).
Alternative Power Sources for Portables & Wearables
S.F.J. Flipsen © Delft University of technology – vs. 1.2005

Figure 27: the efficiency of different hub generator (left) and sideway dynamos (right) with 28” wheels [tandem-fahren.de].

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>Volume of the generator [mm³]</th>
<th>Nominal rotation [rpm]</th>
<th>V_{nom} [V]</th>
<th>I_{nom} [A]</th>
<th>Nominal Power [W]</th>
<th>Max \eta @ PP [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Son</td>
<td>Hub generator 6V</td>
<td>-</td>
<td>80</td>
<td>6</td>
<td>0,5</td>
<td>3</td>
<td>65%</td>
</tr>
<tr>
<td>AXA</td>
<td>HR dynamo</td>
<td>-</td>
<td>3000(^{20})</td>
<td>5,8</td>
<td>0,46</td>
<td>2,7</td>
<td>37%</td>
</tr>
<tr>
<td>-</td>
<td>standard dynamo</td>
<td>-</td>
<td>3000</td>
<td>4,2</td>
<td>0,39</td>
<td>1,7</td>
<td>18%</td>
</tr>
<tr>
<td>Premotec</td>
<td>electro motor</td>
<td>-</td>
<td>3000</td>
<td>3</td>
<td>1,2</td>
<td>3,2</td>
<td>22%</td>
</tr>
<tr>
<td>Mubachi(^{21})</td>
<td>RF-500TB</td>
<td>-</td>
<td>3000</td>
<td>1,5</td>
<td>0,7</td>
<td>1,0</td>
<td>14%</td>
</tr>
<tr>
<td>Maxon</td>
<td>electro motor</td>
<td>-</td>
<td>3000</td>
<td>0,4</td>
<td>0,2</td>
<td>0,1</td>
<td>2%</td>
</tr>
<tr>
<td>Escap</td>
<td>electro motor</td>
<td>-</td>
<td>3000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Micromachine tech.</td>
<td>Micro generator</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 14: overview of electromagnetic generators, or dynamos [Son; Baygen; Micromachine technologi; Mubachi; tanden-fahren; Van Dam et al., 1997; Van den Berg et al., 2003].

Also normal electro motors can be used as generators. The efficiency of these motors is in general much lower (<25%) than dedicated dynamos or generators (30-65%). According to [Van den Berg et al., 2003] DC electro motors designed to operate on low-rpm's are better generators than high-rpm motors.

6.3 Pięzo generator

6.3.1 Introduction

By applying pressure to certain crystals (such as quartz or Rochelle salts) or certain ceramics (like barium titanate), electrons can be driven out of orbit in the direction of the force. Electrons leave one side of the material and accumulate on the other side, building up positive and negative charges on opposite sides, as shown in figure below.

![Pressure applied to certain crystals produces an electric charge](tpub.com)

When the pressure is released, the electrons return to their orbits. Some materials will react to bending pressure, while others will respond to twisting pressure. This generation of voltage is known as the pięzo-electric effect. If external wires are connected while pressure and voltage are present, electrons will flow and current will be produced. If the pressure is held constant, the current will flow until the potential difference is equalized. When the force is removed, the material is decompressed and immediately causes an electric force in the opposite direction. The power capacity of these materials is extremely small. However, these materials are very useful because of their extreme sensitivity to changes of mechanical force.

\(^{20}\) measured at a horizontal speed of the bike of 14,4km/h the rotational speed of the dynamo axis is approximately 3000 rpm.

\(^{21}\) Used in the Freeplay crank radio.
6.3.2 State-of-the-art technology

Piezo-materials are mainly used for actuators and for sensors. The materials can also be used as generators (compression, stretching or bending). Two different piezo materials for generating electricity can be distinguished, the Earth materials or ceramics (Lead Zirconate Titanate, PZT) and Polymer based piezo materials (PolyVinylidenFlouride, PVDF). PVDF is a special but exotic polymer, which can be produced in large quantities and at acceptable price. PVDF foil is flexible, which has to be glued to a other layer, to realize stretch or compression of the PVDF foil. The efficiency of these foils is very low (~0.5%). PZT on the other hand has a much higher efficiency (ranging from 1.5 to 5%), but is very fragile, and can only be used in compression. It must be taken into account that compression of materials is less efficient than stretching.

Also three different configurations can be distinguished, the single layer, two-layer and multi layer generators (or sensor). The single layer generator is actuated on compression, the two-layer generator on bending or extension and the multi-layer generator on compression (stack generator). When a two-layer generator is bend, one layer is compressed and the other is stretched.

The Open Circuit Voltage of piezo electric materials is very high. As an example the PZT (THR6R) and PVDF materials used in a shoe as a generator, have an open circuit (peak) voltage of respectively 150 and 50V, and a closed circuit voltage of 80 and 20V [Kymissis et al., 1998]. A converter is needed to reduce this high voltage to a normal useful voltage, which of course implies energy and efficiency loss.

<table>
<thead>
<tr>
<th>Single-layer generator</th>
<th>Two-layer generator</th>
<th>Multi-layer generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal generator</td>
<td>Bending Generator</td>
<td>Stack generator</td>
</tr>
<tr>
<td>Transverse generator</td>
<td>Extension generator</td>
<td></td>
</tr>
</tbody>
</table>

Table 15: Overview of different piezo generator configurations [Piezo Systems Inc.]

6.3.3 Applications

Piezo-materials are mainly used as actuators (electricity to mechanical power), noise generation or noise cancellation (high frequency vibration) or as a sensor (electricity as a measurement instrument). In human powered products, piezo materials are often investigated as an alternative power source. For example as a source for powering TV or car remote controls, or e.g. for powering a quartz watch (Seiko Epson Corp. patent).
A small number of piezoelectrically driven products are already marketed. Main developments can be seen in the electronics where one of the significant characteristics of piezoelectricity, its high voltage output, is being addressed. In the Safari Night vision monocular from Moonlight, the high voltage output of the piezoelectric generator is conveniently used to power the light amplifier without using a transformer. In piezoelectric gas lighters the high voltage is used to draw up a spark.

![Image of piezoelectric watch and generator](image1)

**Figure 29:** The piezoelectric watch from Seike-Epson (patent no. JP9182465) and the piezoelectric generator itself.

**Figure 30:** The Moonlight Safari night vision, powered by piezoelectric; and a standard piezoelectric gas lighter.

### 6.3.4 Typical characteristics

Piezoelectric elements are not often used as a generator. Typically, a piezoelectric element generates huge Voltages (up to thousands of Volts), high enough to draw a spark across an electrode gap. These high voltages aren’t practical in consumer electronics, where voltages range from 1.5 to 12VDC, meaning a transformer is needed to drop the voltage, which implies an inevitable energy loss.

The voltage difference generated by the piezoelectric element is proportional to the stress (N/mm²) applied on the element:

\[ V = -g_{33} \cdot h \cdot p_3 \]

Where:  
- \( V \) = the voltage (V)  
- \( g_{33} \) = voltage constant (Vm/N) e.g. for PXE42 = \( 25 \times 10^{-3} \) Vm/N  
- \( h \) = height (m)  
- \( p \) = applied stress in the z-axis (3) (N/mm²)
As a generator piezo-materials have to be triggered at a high frequency, to generate a constant voltage.

The performance of piezo elements depends on the manner in which the transducer is mounted and of course the nature of the electrical load. A piezo disk for example, compressed between two metal surfaces will never be able to expand in the radial direction as readily as would a long, thin cylinder, which is only constrained at its ends and assumes a barrel shape on radial expansion. The general rule therefore is to allow the piezo body some freedom to expand radially (or in all directions) since charge generation is coupled with the amount of deformation and the frequency (see Figure 32) [Waanders, 1991].

Another important parameter is the impedance of the load circuitry. If the charge is not allowed to flow away quickly (closed-circuited situations), the electrical field it generates will tend to act against depolarization, meaning the piezo element will break down. The time during which a force is applied has a marked influence on this, static or quasi-static forces tending to depolarize a material faster than dynamic forces of the same magnitude. All the piezo elements have a maximum allowable static stress (e.g. for PXE41 this is 85x10^6 Pa under closed circuit conditions).

In general piezo elements based on ceramic materials have a much higher efficiency (<5%) than polymer based elements (~0.5%). On the other hand ceramic elements generate a much higher Voltage and are more fragile than Polymer based. For some applications the higher voltage is a benefit, e.g. for the furnace lighter. For portable electronics polymer based sheets are more practical because of its lower Voltage output and durability.

In the table below an overview is given of different polymer based piezo electric generators [Piezo Systems Inc.]. The generators are split up into bending generators, where a Polymer piezo layer is attached on a second layer (piezo element or a metal sheet). When bending
the layers causes a stretching and contraction of each other. The second generator is based on extension (pulling) of the elements.

<table>
<thead>
<tr>
<th></th>
<th>thickness (mm)</th>
<th>weight (g)</th>
<th>stiffness (N/m)</th>
<th>capacitance (nF)</th>
<th>rated tip deflection (mm peak)</th>
<th>rated frequency (Hz)</th>
<th>V_{OC} (V peak)</th>
<th>Closed circuit Current (µA peak/Hz)</th>
<th>rated output power (mW peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bending generator</strong> (bending length = 5cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X-poled generator</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y-poled generator</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T215-H4-503X Y</td>
<td>0.38</td>
<td>6.0</td>
<td>1.6 x 10^7</td>
<td>160.</td>
<td>640.</td>
<td>± 2.1</td>
<td>50</td>
<td>± 10</td>
<td>± 69</td>
</tr>
<tr>
<td>T220-H4-503X Y</td>
<td>0.51</td>
<td>8.0</td>
<td>3.5 x 10^7</td>
<td>120.</td>
<td>480.</td>
<td>± 1.57</td>
<td>62.5</td>
<td>± 13</td>
<td>± 55</td>
</tr>
<tr>
<td>T226-H4-503X Y</td>
<td>0.66</td>
<td>10.3</td>
<td>0.9 x 10^7</td>
<td>85.</td>
<td>340.</td>
<td>± 1.22</td>
<td>87.5</td>
<td>± 18</td>
<td>± 39</td>
</tr>
<tr>
<td><strong>Extension generator</strong> (bending length = 5cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X-poled generator</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y-poled generator</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T215-H4-503X Y</td>
<td>0.38</td>
<td>6.0</td>
<td>8 x 10^6</td>
<td>160.</td>
<td>640.</td>
<td>± 25</td>
<td>500</td>
<td>± 47</td>
<td>± 172</td>
</tr>
<tr>
<td>T220-H4-503X Y</td>
<td>0.51</td>
<td>8.0</td>
<td>11 x 10^6</td>
<td>120.</td>
<td>480.</td>
<td>± 25</td>
<td>750</td>
<td>± 67</td>
<td>± 172</td>
</tr>
<tr>
<td>T226-H4-503X Y</td>
<td>0.66</td>
<td>10.3</td>
<td>15 x 10^6</td>
<td>85.</td>
<td>340.</td>
<td>± 25</td>
<td>1000</td>
<td>± 95</td>
<td>± 172</td>
</tr>
</tbody>
</table>

Table 16: overview of 6 two-layer piezoelectric generators: (1) Bending and (2) extension generators [Piezo Systems Inc.]

### 6.4 Gear efficiency

Because most generators work at higher speed or frequency, the crank speed has to be increased by a gearbox. This can be done by means of gearwheels, chains and hydraulics or pneumatics. The efficiency of these gearboxes decreases with the complexity, and the number of drives. The efficiency of gearboxes can be calculated as follows [Roloff et al., 1994]:

\[
\eta_{\text{total}} = \frac{P_{\text{output}}}{P_{\text{input}}} = \frac{\frac{T_o \cdot \omega_o}{\omega_i}}{\frac{T_o}{i}} = \frac{T_o}{T_i} \cdot \frac{\omega_o}{\omega_i} < 1
\]

Where \( T_o \) and \( T_i \) = the out- and input torque of the system (Nm), 
\( \omega_o \) = the rotational speed (rad/s), 
\( i \) = the transmission ratio.

The loss in power is a result of sliding of the teeth (\( \eta_Z \)), the friction in the bearings (\( \eta_B \)), and the status of greasing and sealing of the shaft (\( \eta_G \)).

\[
\eta_{\text{total}} = \eta_Z^{(n-1)} \cdot \eta_B^n \cdot \eta_G^n
\]

Where \( n \) is the total amount of gears. For inclined gears (under an angle) the total efficiency decreases with 1 to 2% because of the higher friction in the shaft. On basis of experience the following assumptions can be made [Roloff et al., 2000]:

\[
\eta_Z \approx 0.980 \text{ to } 0.995 \text{ for rough to shaped teeth}
\]
\[
\eta_B \approx 0.970 \text{ to } 0.990 \text{ for sliding bearings to two revolving ball bearings}
\]
\[
\eta_G \approx 0.980 \text{ for a closed lubricated shaft}
\]

As an example: the total efficiency for a one-step gear (a pair of gear wheels, shaped, realized with revolving ball bearings and closed shafts) is:

\[
\eta_{\text{total}} = \eta_Z (1) \cdot \eta_B \cdot \eta_G^2 = 0.995 \times 0.990^2 \times 0.98^2 \approx 94\%
\]
7 Other power sources

7.1 Wind power

7.1.1 Introduction
Wind energy has been a major provider of mainly mechanical energy, for e.g. millings and pumps. Nowadays wind turbines are in the Netherlands mainly used for generation of electric power. Since development of these wind turbines started the turbines got bigger, and with that the power-output. An application for portable power generation is still not available.

7.1.2 State-of-the-art technology
Nowadays a normal wind turbine generates more than 1,5MW, and rising. The main challenge is 4,5MW. Wind turbines with less than 750kW are more of an exception. The smaller wind turbine market is differentiated in small wind turbines ranging from 25W to 5kW (with shoot outs of 10 to 15kW). Between 15kW and 300kW no suppliers are known. Wind turbines are not very portable, that’s why turbines with a power-output larger than 300kW won’t be discussed in this paper.

The technology used to generate electricity with the wind is electro-magnetic conversion (see also the chapter 6, Human Power). Two technologies are common at the moment:

1. standard electro-magnetic generator with a gearbox
2. direct-drive generator

Figure 33: the standard layout of a windmill and the new direct-drive generator from Lagerwey or Zephyros, using no gearbox.

The input rpm of windmills is generally very low (<100rpm). Electromagnetic generators work best on high rpm, resulting in a speed conversion by means of a gearbox. This gearbox makes a lot of noise, and also decreases the efficiency of energy production. New developments have lead to the generators which don’t need any gearbox anymore, the so-
called “direct drive”. Especially in high-power windmills this new technology is used more-and-more often. In small-scale wind generators this technology is not yet applied.

7.1.3 Applications
Low power (<1000W) turbines are mainly used as a power source for e.g. marine applications on pleasure boats. E.g. Ampair (UK) builds 100W horizontal axis turbines for the marine market (see figure below).

Figure 34: an artist impression of the vertical axis wind turbine with diffuser from Ecofys, and a standard low-power wind turbine: the Pacific 100 from Ampair.

Ecofys (the Netherlands) is developing small low-power wind turbines for urban applications, the so-called Urban Turbines. Two different types of turbines can be distinguished in urban areas:

1. Vertical Axis Turbine (the Darrieus)
2. Horizontal Axis Turbine with/without a diffuser

Figure 35: Artist impressions of two vertical axis Darrieus type turbines (left the Neoga and in the middle the Viking) from Ecofys, and the Savonius type turbine from Windside (right).

At the moment most of the developments occur in the high-power turbine market. The turbines get larger and larger. New developments can be found in integration of turbines in new-building projects.

Small scale application for e.g. Savonius type turbines are the ventilators on car roofs using the wind (while driving) to ventilate the inner space of the car. Also small scale power generation is used on far away buoys.

7.1.4 Typical characteristics
The power (P) of a wind turbine depends on four factors:

1. rotor placement (h) above the ground,
2. effective surface area of the rotor (S),
3. wind speed (V),
4. type of wind turbine used.

The higher the rotors are placed above the ground, the better its performance. Close to the ground, ground effects and obstacles break down wind speed (see figure below), and make them less effective for use with wind turbines.

![Figure 36: influence of obstacles and the ground effect on the effective wind speed.](image)

The power of a standard horizontal turbine can be described as follows:

\[ P = 0.00502 \cdot S \cdot V^3 \]

Where:  
- \( S \) = the effective surface area of the turbine \( \left( \frac{1}{4} \pi D^2 \right) \)  
- \( V \) = the wind speed (m/s)

The previous formula can generally be used for standard horizontal three wing rotor turbines. Other types of wind turbines are less effective than this type of turbine. In the figure below an overview is given of different types of wind turbines vs. the coefficient of performance (\( c_p \)):

\[ P = c_p \cdot \sqrt{\lambda} \rho V^2 \cdot S \]

\( \lambda \) is the speed factor meaning the rotational speed over the wind speed. When \( \lambda \) is equal to 1 the rotational speed of the turbine is equal to the wind speed. E.g. for the vertical turbine, the Savonius, the rotational speed will never exceed the speed of the wind (\( \lambda < 1 \)), and its performance is very low (\( c_p < 0.15 \)).

![Figure 37: rotor power co-efficiency of different types of wind turbines.](image)
7.2 Electro (ether) smog

7.2.1 Introduction
Microelectronics has penetrated all areas of public life. This penetration results in an increase of the Electromagnetic Field (EMF) exposure of men and machines. EMF consists of electric (E in V/m), magnetic (H in A/m) and electromagnetic (B in μT) radiation, and is a result of “leaking” telecom applications, radio (AM/FM) and TV (UVF/UHF) broadcasts. With large electric and magnetic antennas, e.g. ferrite aerials, energy can be intercepted from these, high and low frequency, electro magnetic fields. Especially AM microwave frequencies (0.5-600MHz) could be a good energy source. In the Netherlands the total amount of energy distributed is in the range of some MegaWatts.

Figure 38: Cristal-radio set used to intercept energy from the ether [MSB, 1999] and a more current version self-build kit from Smithsonian Science (Yellowloop.com).

To intercept these frequencies you need a antenna, like a ferrite bar (in Figure 38 and Figure 39) or a dipole aerial (Figure 41). The power generated by a ferrite bar is a few microWatts [Jongeneel, 1998]. A hand radio (2W, 150-450MHz) has electric field strength of 10V/m on a distance of 30 cm. A part of this power can be caught with a ferrite bar.

7.2.2 State-of-the-art technology
Technology of picking up ether smog is hardly developed. Best known technique is a Ferrite bar coil, a copper wire winded on a ferrite bar (see figure below). The ferrite bar coils pick up AM frequency and converts it to a voltage and a current.

Figure 39: Different ferrite bar coils to pick up AM frequency.

An increase in consumer electronics results in an increase of EMF radiation in our surroundings. According to [Jongeneel, 1998] not even 1/100th percent (0.01%) of the
energy broadcasted by cellular phones reaches the receiving station. The rest of the electromagnetic radiation is transformed into heat, and lost.

7.2.3 Applications

Typical applications can be found in EMF stress relievers or gadgets used with cellular phones. Stress relievers pick up EMF radiation from e.g. computer screens resulting in a lower exposure of the human being. Examples can be found in underneath products from Clarus. Also gadgets using the EMF radiation from the cellular phone can be found in many shops nowadays. When receiving or making a phone call, the flash sticker will light up because of the emitted and received radio waves (900MHz to 1800MHz).

![Figure 40: The Clarus Qlink (left), stress reliever, protecting from EMF radiation. The flash sticker (on the right) from Haimei.com, flashes when receiving or making a phone call, working on GSM mobile phones without antenna.](image)

An other application is the battery less crystal radio-receiver, also seen in Figure 38. At Delft University of Technology research has been conducted to use the electromagnetic radiation from cellular phones for recharging hearing aids or pacemakers [Jongeneel, 1998].

Difficult obstacle for the hearing aid is that the EMF may not disturb the aid itself, but should penetrate to the battery charger. Also the cellular phone could transmit energy (and recharge) to the pacemaker by pushing the phone to the chest. These antennas or pick-up spools can potentially be used for micro-power products, like hearing aids or insulin pumps. The picked up power is in general extremely low.

7.2.4 Typical characteristics

The intensity of the electrical fields depends on the distance to the device and the 'common mode' power consumed by the device. The electric and electromagnetic fields produced by electric devices can be captured by a coil wrapped around a ferrite antenna. Capturing AM frequencies is believed to be most effective. The power retrieved from an electric field with a coil-antenna can be calculated with the following equation:

\[ P_c = \frac{E^2 \times A}{Z} \]

Where: 
- \( P_c \) = power captured (Watts)
- \( E \) = Emitted Magnetic Field Strength (V/m)
- \( A \) = Surface area of the coil (m²)
- \( Z \) = Wave-impedance (Ω) = 120π

<table>
<thead>
<tr>
<th>Frequency f</th>
<th>Source emitting the waves</th>
<th>Field strength E (V/m)</th>
<th>Electro-magnetic field B (µT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10 MHz</td>
<td>AM radio</td>
<td>87 / f</td>
<td>0,92 / f</td>
</tr>
</tbody>
</table>
High frequencies can be captured with small aerials. The length of an aerial is always proportional to half the length of the frequency. For high frequencies, like GSM, the optimal length of the aerial is 16cm for 800MHz and 8cm for 1800MHz (dipole antenna, Figure 41).

The power emitted by an emitter like a base GSM station (continuous) or a cellular phone (infrequent) is reversed proportional to the square distance (R):

$$P_{density} = \frac{P_{emitted}}{4\pi R^2}$$

In the following table an overview is given of the radiated power available (P\text{density} in mW/m²) measured from a continuous sending base station and a sending cellular phone. More base stations (like in cities) increase the power density of the area by up to 6 times. In general the power density in a city environment ranges in between 0,1 and 0,6mW/m². Capturing this power with an efficiency of 50% and an aerial of 1m², aimed at the power source, a maximum of 0,15mW can be produced by the receiver, not even enough to power a small LED (of 4mW).

<table>
<thead>
<tr>
<th>Distance to transmitting base station (m)</th>
<th>Radiated power (mW/m²)</th>
<th>Distance to transmitting cellular phone (m)</th>
<th>Radiated power (mW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>318</td>
<td>0,5</td>
<td>6</td>
</tr>
</tbody>
</table>

22 GSM = 900-1800MHz
VHF / UHF = 450-800MHz
FM radio = 30-300MHz
AM radio = 0,03-3MHz
Table 18: The radiate power from a base station (left) and a transmitting cellular phone (right). The effective power of a base station is approx. 400W and for a cellular this is max 2W (when far away from the base station) and 0.25W nominal power.

<table>
<thead>
<tr>
<th></th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>500</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>left</td>
<td>12</td>
<td>3</td>
<td>0.8</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>right</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.2</td>
<td>0.05</td>
<td>0.002</td>
<td>-</td>
</tr>
</tbody>
</table>
PART II: Storage
8 Chemical storage

8.1 Batteries

8.1.1 Introduction
Batteries are the most used power-source or energy capacitor for daily use. Different types are available, single-use (primary) and rechargeable (secondary). Batteries work according to the voltaic process. Often used is the process in between two metals like copper and sink, when they are electrically coupled by means of a salt sour solution, the electrolyte.

8.1.2 State-of-the-art technology
Two different types of batteries are available: single-use and rechargeable, or primary and secondary batteries. The first choice to be made is whether a primary or secondary battery is required. In general the primary batteries have the following advantages compared to secondary batteries:

- larger energy density (Wh/kg) and specific energy (Wh/ltr);
- less subject to self-discharge, in other words have a longer shelf-life;
- larger power-per-use;
- the initial costs are lower.

Both types of batteries are constantly evolving. Higher energy densities are developed, and the price of batteries is decreasing.

Main primary batteries are: Carbon-Zinc (or Leclanché), Alkaline-Manganese dioxide (Alkaline), Zinc-Air, Silver-Zinc oxide, and Lithium-Manganese Dioxide [House of Batteries]:

1. Carbon-Zinc (Leclanché): the zinc-carbon-ammonium chloride "dry", or Leclanche cell, system is old having been developed in the 1800s. The Carbon-Zinc Chloride system is a heavy-duty version of the Leclanché cell. These cells are now made almost exclusively in Asia.
2. Alkaline-Manganese Dioxide (Alkaline): batteries have many advantages over Carbon-Zinc cells. They have a higher power output, longer shelf life, better leakage resistance, and better low temperature performance. Compared with the Carbon-Zinc cell the alkaline cell delivers up to 10 times the ampere-hour capacity at high and continuous drain conditions. Its more effective, secure seal provides excellent resistance to leakage and corrosion. The Alkaline battery is the most popular primary battery and is improved constantly.
3. Zinc-Air: cells are small size and lightweight, have a large capacity, start-up quickly with a very stable voltage. Zinc-Air batteries are used in hearing aids and absorb atmospheric oxygen into the electrolyte through a gas-permeable, liquid-tight membrane. The cell won’t work when oxygen is not available. With the removal of a sealing tab, oxygen from the air is introduced into the cell.
4. Silver-Zinc: The silver oxide primary battery is used widely in electronic equipment that requires a small compact power source. The high volumetric energy density of the
Silver Oxide button cell, and its ability to deliver the energy at relatively high current drains, makes it ideal for miniature devices where space is limited.

5. **Lithium-Manganese Dioxide**: lithium’s negative potential is higher than any other metals and is the lightest non-gaseous metal. Batteries based on lithium chemistries have at the moment the highest specific energy (Wh/kg) and energy density (Wh/ltr) of all types. Lithium batteries are used in a wide range of applications, from powering all functions of full-automatic cameras to providing long-term standby power for computer clocks.

Main **secondary batteries** are: Lead-Acid, Nickel-Cadmium, Nickel Metal Hydrides, Lithium Ion and Lithium Polymer [Buchmann, 2002; Crompton 2000]:

1. **Sealed-Lead Acid (SLA)**: most economical for larger power applications where weight is of little concern e.g. in the car, Universal Power Sources or wheelchairs. Among modern rechargeable batteries, the lead acid battery family has the lowest energy density. The SLA is cheap but the operational costs can be more expensive than the NiCd when full repetitive cycles are required. The SLA is difficult to recharge when in a discharge condition. Furthermore the SLA cannot be discharged to more than 80% of its capacity, which means a performance drop. When discharged

2. **Nickel-Cadmium (NiCd)**: is a mature and well understood battery. Its energy density is compared to NiMH and Li-ion batteries very low. The NiCd is used where long life, high discharge rate and a low price are important. Unlike other rechargeable batteries the NiCd battery prefers fast charge (up to 10C) to slow charge (0,1C) and pulse charge to continuous charge. Also the NiCd is the only rechargeable that performs best under heavy working conditions meaning high discharge currents. Because of the ‘memory’ effect the NiCd battery should be fully discharge periodically to keep the battery in good shape. Main applications are two-way radios, biomedical equipment, professional video camera’s and power tools. At the moment this battery is rapidly replaced by the Nickel-Metal Hydrate cell.

3. **Nickel-Metal Hydride (NiMH)**: has a higher energy density compared to the NiCd at the expense of reduced cycle life. NiMH contains, in contrast with the NiCd battery, no toxic metals. Applications include mobile phones and laptop computers.

4. **Lithium Ion (Li-ion)**: are increasingly used in new mobile electronics. The Li-ion is used where high-energy densities and light weight is important. The Li-ion is more expensive than other systems and must follow strict guidelines to assure safety when charging. The voltage is typically 3,6-4V (open circuit voltage). Applications include laptop computers and mobile phones.

5. **Lithium Ion Polymer (Li-ion polymer or Li-poly)**: a potentially lower cost version of the Li-ion, when mass-produced, with potentially a similar energy density compared to Li-ion. For now the energy density is lower than that of the Li-ion, and the battery is very expensive to produce. This is changing fast because of the fast-moving cellular phone industry. Li-poly batteries enable very slim batteries (up to 1mm) and allow simplified packaging. Main applications are mobile phones.

Because of the increasing environmental pressure on batteries, new environmentally friendly batteries are developed. NiCd batteries will be banned in the next 10 years, because of the use the heavy metal cadmium. Other heavy metals which are ruled out by the governments are mercury (Zinc-Mercury cells, now only used in button cells) and lead [Crompton, 2000].

There are four major types of construction for primary cells: button coin, bobbin cylindrical and spiral cylindrical.

### 8.1.3 Applications

<table>
<thead>
<tr>
<th>Primary batteries</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Typical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Zinc</td>
<td>Low cost, good shelf life.</td>
<td>Output capacity decreases as it drains; poor performance at low temperatures.</td>
<td>Useful for flashlights, toys, and small appliances.</td>
</tr>
<tr>
<td>Carbon Zinc</td>
<td>Good service at high</td>
<td>Relatively expensive for</td>
<td>Useful for flashlights, toys, and small appliances.</td>
</tr>
</tbody>
</table>

54 Alternative Power Sources for Portables & Wearables
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<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride</td>
<td>drain; leak resistant; good low-temperature performance.</td>
<td>novelty usage.</td>
<td>and small appliances.</td>
</tr>
<tr>
<td>Alkaline</td>
<td>High efficiency under moderate, continuous drains; long shelf life; good low-temperature performance.</td>
<td>Primary cells are expensive for novelty usage.</td>
<td>Useful for camera flash units, motor-driven devices, portable radios; will always run longer than Carbon-Zinc cells.</td>
</tr>
<tr>
<td>Zinc Air</td>
<td>High energy density in small cells; flat discharge rate; long shelf-life when covered by a thin foil during storage; Carbonaire batteries may be activated by seawater.</td>
<td>Dries out quickly (needs to be wet); needs air to operate.</td>
<td>Navigational aids like: reef, dock, pier and offshore lights; buoys; portable warning lights; for navigational aid services the carbonaire batteries can be transported dry to location.</td>
</tr>
<tr>
<td>Zinc-Mercury</td>
<td>Flat discharge curve; relatively high energy density; good high-temperature performance; good service maintenance.</td>
<td>Poor low-temperature performance in some situations; contains mercury (heavy metal).</td>
<td>Useful for critical and miniature appliances, such as walkie-talkies, paging, hearing aids, pacemakers, and test equipment.</td>
</tr>
<tr>
<td>Silver Zinc</td>
<td>High energy density; flat discharge curve.</td>
<td>Silver is very expensive; poor storage and maintenance characteristics. Rechargeable cells have a very limited number of cycles.</td>
<td>Useful for very small appliances such as calculators, watches, and hearing aids.</td>
</tr>
<tr>
<td>Lithium Manganese</td>
<td>High energy density; medium self-discharge; high voltage; excellent discharge characteristics; good leak resistance; good storage characteristics; wide operating temperature; stable and save.</td>
<td>Susceptible to damage from even small reverse currents.</td>
<td>Button-size lithium batteries for: LCD watches; pocket calculators; CMOS memory protection; measuring instruments; electronic alarms; pace setters. Excellent for applications where changing the battery is difficult, and a long lifetime is desired.</td>
</tr>
</tbody>
</table>

Table 19: the advantages, disadvantages and typical applications of different primary batteries [NTBG, 1998; Crompton, 2000; Buchmann, 2001].
<table>
<thead>
<tr>
<th>Secondary batteries</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sealed Lead Acid</td>
<td>Low-priced, spill resistant (sealed batteries).</td>
<td>Limited low-temperature performance. Vented cells require maintenance. Cells are relatively heavy.</td>
<td>Useful for automobiles and cordless electric lawn mowers.</td>
</tr>
<tr>
<td>Nickel Cadmium</td>
<td>Excellent cycle life; flat discharge curve; good high- and low-temperature performance; ability to accept permanent overcharge; total absence of maintenance; high resistance to shock and vibration; fast charging.</td>
<td>Medium initial cost; only fair charge retention; memory effect.</td>
<td>Useful for any noncritical small appliances that have periodic usage cycles, such as portable hand tools, tape players, and toys. When batteries are exhausted, they can be recharged before the next needed use.</td>
</tr>
<tr>
<td>Nickel Metal Hydrate</td>
<td>No memory effects; good high-power performance, good low-temperature performance.</td>
<td>High initial cost, relatively high rate of self-discharge.</td>
<td>Useful for portable devices where the duty cycle varies.</td>
</tr>
<tr>
<td>Lithium Ion</td>
<td>Good energy density; lower per-use cost; low self discharge compared with NiCd and NiMH; low maintenance.</td>
<td>Limited high-rate capacities; safety concerns (explosion danger when in contact with water); expensive to manufacture (140% of that of NiCd); charge and discharge management needed (thermal); requires protection circuit; subject to aging; subject to transportation regulations.</td>
<td>More expensive mobile phones and laptop computers (where mass-production feasible).</td>
</tr>
<tr>
<td>Lithium Ion Polymer</td>
<td>Credit-card thickness possible (&gt;1mm); flexible form; lightweight packaging of cells; more resistance to overcharge than Li-ion.</td>
<td>Lower energy density than Li-Ion; less charge-cycles; very expensive to manufacture (at the moment just in small series);</td>
<td>Increasingly used in mobile phones.</td>
</tr>
</tbody>
</table>

Table 20: the advantages, disadvantages and typical applications of different secondary batteries [NTBG, 1998; Crompton, 2000; Buchmann, 2001]

8.1.4 Typical characteristics
The parameters of secondary batteries depend very much on charge and discharge current (Ampere), ambient temperature (°C), storage time, and the quality of the charging process [Havlík, 2001].

Figure 42a. shows the charging process. This process is very important for the quality of the battery and its cycle life. When the battery is overcharged the number of charge cycles will decrease. Normal charges are done at a rate of max 1C\(^{23}\). In this particular example the charge rate is 1/10C.

\(^{23}\) 1C means that the battery is charged or discharged at 1 times its capacity. E.g.: when the capacity is 600mAh, the (dis)charge-rate at 1C is 1x600=600mA. Most batteries are charged at a rate equal or less than 1C. the NiCad Battery can be discharged at a maximum rate of 20C. For newer batteries, like NiMH and Lithium based, the maximum discharge rate is much lower, approximately 3C.
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Figure 42: Typical characteristics of a secondary battery depending on the (a) charge and (b) discharge current.

Figure 42b. shows the voltage change when discharged at a higher rate. NiCD batteries can handle over-discharging (with a maximum discharge rate of 20C) much better than newer batteries, like NiMH and Lithium (with a maximum discharge rate under 3C). It can be seen that the voltage is decreasing with increasing discharge rate (see the difference between ½C and 2C). Also the voltage is decreasing dramatically at the end of every discharge (or when the battery is almost drained).

Figure 43a. shows the available capacity of a battery, when used in different ambient temperatures. The capacity decreases with temperatures higher and lower than ~22°C (normal ambient temperature).

Figure 43b. shows the decreasing capacity of the battery when the discharge ratio (C) is higher. At a normal discharge (C=1) the maximum capacity of a battery is, in this example, more than 90%. When discharged at a higher rate (e.g. C=4), the capacity of the battery decreases dramatically (in this example from 90 to 65%).

A battery has, a typical V-I characteristic. When the discharge rate increases (C) the voltage of the battery will drop almost linear. At a certain discharge current the power drawn from the battery is maximum, also called the Power Point (P_{pp}, in the figure below).

Figure 44: Typical V-I characteristic of a battery.
Figure 45: Performance comparison, discharge curves, of primary and secondary alkaline and Ni-Cd batteries (adapted from Design Note: Renewable Reusable Alkaline Batteries) [NTBG, 1998].

When the battery is discharged at a constant rate (e.g., 100mA, Figure 45) you notice the flat discharge voltage of the NiCd battery in comparison with the primary and rechargeable (secondary) alkaline battery. It must be taken into account that most electronic products function at a minimum voltage. The battery is dead for this application when the voltage is below this minimum.

The power density and the energy density of batteries are increasing with the composition of the cells. In Figure 46 the rated energy and power density versus the specific energy and power is given for different mobile-phone batteries (mean literature values for mobile phones in between 1995 to 2004).

Figure 46: The rated energy density versus the rated specific energy (left) and the rated power density versus the rated specific power (right) of different mobile phone batteries (NiMH, Li-ion and Li-poly).

In the following table an overview is given of different primary and rechargeable batteries and its characteristics.
Table 21: Overview of the characteristics for primary and rechargeable batteries [Crompton, 2000].

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Alkaline</th>
<th>Lithium Manganese Dioxide</th>
<th>NiCd</th>
<th>NiMH</th>
<th>Lithium-ion</th>
<th>Lithium polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shape</strong></td>
<td>Cylindrical/prismatic</td>
<td>Cylindrical/prismatic</td>
<td>Cylindrical/prismatic</td>
<td>Cylindrical/prismatic</td>
<td>Prismatic</td>
<td>prismatic</td>
</tr>
<tr>
<td><strong>Capacity [mAh]</strong></td>
<td>&gt; 580</td>
<td>&gt; 160</td>
<td>&gt; 300</td>
<td>&gt; 400</td>
<td>&gt; 500</td>
<td>&gt; 100</td>
</tr>
<tr>
<td><strong>Energy [Wh/kg]</strong></td>
<td>130</td>
<td>95 - 270</td>
<td>40 - 60</td>
<td>50 - 60</td>
<td>70 – 110</td>
<td>115 - 150</td>
</tr>
<tr>
<td><strong>Energy [Wh/ltr]</strong></td>
<td>320</td>
<td>400 - 700</td>
<td>105 – 110</td>
<td>150 - 175</td>
<td>190 – 250</td>
<td>200 - 300</td>
</tr>
<tr>
<td><strong>Cycle life 80%</strong></td>
<td>1</td>
<td>1</td>
<td>300 – 700</td>
<td>400 - 500</td>
<td>400 – 500</td>
<td>400 - 500</td>
</tr>
<tr>
<td><strong>Normal voltage [V]</strong></td>
<td>1.5</td>
<td>3.0</td>
<td>1.2</td>
<td>1.2</td>
<td>3.6</td>
<td>3.6V</td>
</tr>
<tr>
<td><strong>End-Voltage [V]</strong></td>
<td>0.8</td>
<td>2.0</td>
<td>0.85</td>
<td>1.0</td>
<td>3.0</td>
<td>3.0V</td>
</tr>
<tr>
<td><strong>Charging voltage [V]</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.1-4.2 ±50mV</td>
<td>4.1-4.2 ±50mV</td>
</tr>
<tr>
<td><strong>Impedance 1kHz [Ω]</strong></td>
<td>1.0</td>
<td>0.2 – 18</td>
<td>0.012 – 0.018</td>
<td>0.035</td>
<td>4.1-4.2 ±50mV</td>
<td>4.1-4.2 ±50mV</td>
</tr>
<tr>
<td><strong>Discharge current</strong></td>
<td>1C</td>
<td>20C</td>
<td>3C</td>
<td>3C</td>
<td>3C</td>
<td>3C</td>
</tr>
<tr>
<td><strong>Charge current</strong></td>
<td>-</td>
<td>-</td>
<td>1C</td>
<td>1C</td>
<td>1C</td>
<td>0.6C-1C</td>
</tr>
<tr>
<td><strong>Self discharge @ 25°C [%/Month]</strong></td>
<td>0.1%</td>
<td>0.083%</td>
<td>15%</td>
<td>20%</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td><strong>Discharge profile</strong></td>
<td>flat</td>
<td>flat</td>
<td>flat</td>
<td>flat</td>
<td>sloping</td>
<td>sloping</td>
</tr>
<tr>
<td><strong>Memory effect</strong></td>
<td>-</td>
<td>-</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
<td>Medium/high</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td><strong>Charging algorithm</strong></td>
<td>-</td>
<td>CC</td>
<td>CC</td>
<td>CC-CV</td>
<td>CC-CV</td>
<td></td>
</tr>
<tr>
<td><strong>Primary termination</strong></td>
<td>-</td>
<td>DT/dt</td>
<td>DT/dt, dV/dt, -dV, σTCO</td>
<td>C/10 + Timer</td>
<td>C/10 + Timer</td>
<td></td>
</tr>
<tr>
<td><strong>Secondary termination</strong></td>
<td>-</td>
<td>TCO, timer</td>
<td>TCO, timer</td>
<td>TCO, Timer</td>
<td>TCO, Timer</td>
<td></td>
</tr>
<tr>
<td><strong>Charging T [°C]</strong></td>
<td>-</td>
<td>-</td>
<td>5 - 45</td>
<td>5 - 45</td>
<td>5 - 45</td>
<td></td>
</tr>
<tr>
<td><strong>T range [°C]</strong></td>
<td>-20 - +55</td>
<td>-40 - +70</td>
<td>-40 - +70</td>
<td>-10 - +55</td>
<td>-10 - +55</td>
<td></td>
</tr>
<tr>
<td><strong>Remarks</strong></td>
<td>Long shelf life products</td>
<td>Long shelf life products</td>
<td>Low cost, high power products</td>
<td>Low cost products</td>
<td>High-end products</td>
<td></td>
</tr>
</tbody>
</table>

24 'flat' means that the voltage during discharge is relatively constant. When the discharge curve is ‘sloping’, the voltage decreases slowly when discharged.
8.2 Supercapacitors

8.2.1 Introduction
Super capacitors (also known as Ultra capacitors and Double Layer Capacitors) are high power energy storage devices. They are a cross between a regular capacitor and an electro-chemical battery. While batteries store charges chemically, super capacitors store them electro statically. Super capacitors behave like a capacitor: the voltage is depending on the charge of the capacitor.

The super capacitor is a cross between a regular capacitor and an electro-chemical battery. Instead of the dielectric the super capacitor uses a dry insulating material called the dielectric (plastic, paper film or ceramic). Instead of the dielectric the super capacitor uses an aqueous or organic electrolyte. The super capacitor most economical to manufacture, is the one using high surface area activated carbons, also called Double Layer Capacitor (DLC). Projected energy densities for super capacitors range in between 1 and 10Wh/kg (1/10th of a NiMH battery).

8.2.2 State-of-the-art technology
Super capacitors are almost always Double Layer Capacitors (DLCs). Super capacitors come both in small as large-size cells. Small-size cells are roughly the size of a postage stamp (5F to 10F). Large-size cells are roughly the size of soda cans (1200F to 2700F) [Smith, 2000].

8.2.3 Applications
The main advantages of capacitors in comparison with batteries are that they can be recharged and discharged incrementally and very fast (high power in- and also output). Batteries have a limited power output, whereas the capacitor can give a power burst. Thus capacitors would be most useful in hybrid systems, where the super capacitor can improve the current handling of a battery. This is very useful when high peak powers for short periods of time are needed, e.g. in electric buses, where brake power is cached to give a power burst during acceleration (Hill tech and Maxwell, see Figure 48).
Figure 48: applications of a super capacitor to cache power when braking, and give a power burst when accelerating [Hill tech, 2001].

The stored energy kicks in when a high load current is requested, enhancing the battery’s performance and prolongs its runtime and cycle life. Super capacitors are mainly used because of their high power output (W/kg), compared with batteries. This is very useful when high peak powers for short periods of time are needed, e.g. in electric buses, where brake power is cached to give a power burst during acceleration (Hill tech, and Maxwell, see Figure 48). Their energy densities (Wh/kg) are much lower than batteries (10 to 50 times lower), which implies no serious energy intensive applications (like laptops, or cellular phones).

The energy densities of super capacitors are much lower than batteries (10 to 50 times lower), which implies no serious energy intensive applications (like laptops, or cellular phones). The super capacitor could find a ready market for portable fuel cells to compensate for the sluggish performance of some systems and enhance peak performance [Buchmann, 2001]. Super capacitors are used for different purposes:

- As back-up power in electronic devices, when data has to be kept during power-down of the device, e.g. data memory of TV sets and tuners, computer memory or LCD clocks.
- Because super capacitors cannot be overcharged, they don’t need charging electronics.
- They capacitors would also be very useful when high peak-powers (power bursts) are needed (e.g. when data has to be transmitted wireless or for drills).
- Super capacitors allow batteries to be sized for energy requirements instead of power, meaning batteries could be smaller and cheaper.

8.2.4 Typical characteristics

In general the energy stored in capacitors depends on the capacity $C$ (Farad) and the potential $V$ across the plates (in a parallel plate capacitor or thin film polymer caps) as follows:

$$E = \frac{1}{2} \cdot C \cdot U^2$$

Where: $E =$ energy available in the supercapacitor (Joules)
$C =$ capacity of the capacitor (Farad), printed on the capacitor.
$U =$ capacitor voltage (V).

Rechargeable batteries are completely different from capacitors. The cell voltage of batteries is chemically defined. The voltage is almost constant during charge and discharge (1,2V). The cell voltage of a capacitor increases and decreases linear with the charge and
discharge (see Figure 49). If, for example, a 6V battery is allowed to discharge to 4,5V before the equipment cuts off, the super capacitor reaches that threshold within the first quarter of the discharge time. The remaining energy slips into a unusable voltage range (<4,5V). A DC-to-DC converter can be used to increase the voltage range but this option adds costs and introduces inefficiencies of 10 to 15%. Also the charge voltage for capacitors is limited. If the capacitor is charged at a voltage higher than specified, it will break down [Buchmann, 2002].

Capacitor:  
Rechargeable battery:

Figure 49: a typical charge and discharge curve for a capacitor (left) and a battery (right). The voltage is increasing and decreasing with the charge and discharge time (at a constant charge and discharge current).

Ultra capacitors can store energy for a limited period. Normal primary and secondary batteries have a energy leakage (self discharge) of 0,1 to 20% per month (see also Table 21). Elna America Inc. claims that the capacity of a Dynacap DZ series (2V, 50F) ultracapacitor drops 10% within 1000 hours, or approximately 7% per month [Elna America Inc., 2002]. Other, more undependable, references like “Batteries in a portable world” from [Buchmann, 2002] state:

- The voltage drop of organic electrolyte supercapacitors drops from full charge to the 30% level in as little as 10 hours (70% voltage drop).
- Other supercapacitors retain the charged energy longer, the capacity drops from full to 85% (15% drop) within 10 days, and to 65% (35% drop) in a month.

In the following tables the general characteristics of different capacitors are described (Table 22). Figure 50 gives an overview of the energy and power density of different commercial super capacitors.

<table>
<thead>
<tr>
<th></th>
<th>Lead Acid battery</th>
<th>NiCd battery</th>
<th>Super capacitor</th>
<th>Single layer cap.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Density (Wh/kg)</td>
<td>10 to 100</td>
<td>40 to 60</td>
<td>1 to 10</td>
<td>&lt;0,1</td>
</tr>
<tr>
<td>Power Density (W/kg)</td>
<td>&gt;1000</td>
<td>&lt;200</td>
<td>&gt;10.000</td>
<td>&gt;100.000</td>
</tr>
<tr>
<td>Time of charge</td>
<td>1 to 5 hrs</td>
<td>-</td>
<td>0.3 to 30 s</td>
<td>10⁻⁶ to 10⁻⁷ s</td>
</tr>
<tr>
<td>Time of discharge</td>
<td>0.3 to 3 hrs</td>
<td>-</td>
<td>0.3 to 30 s</td>
<td>10⁻⁶ to 10⁻⁷ s</td>
</tr>
<tr>
<td>Cyclability</td>
<td>500</td>
<td>300-700</td>
<td>1.000.000</td>
<td>10.000.000.000</td>
</tr>
<tr>
<td>Typical lifetime (years)</td>
<td>5</td>
<td>2</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Efficiency</td>
<td>70 to 85%</td>
<td>-</td>
<td>85 to 98%</td>
<td>&gt;95%</td>
</tr>
<tr>
<td>Self-discharge (% / month)</td>
<td>&lt;&lt;1%</td>
<td>15%</td>
<td>35%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 22: general characteristics of single layer and double layer capacitors compared with general batteries [Smith, 2000, Buchmann, 2002].
Figure 50: The Ragone plot shows the energy vs. power density [Schneuwly et al., 1999]. The power density of super capacitors is very high, in contrast with the energy density, when compared with batteries.

<table>
<thead>
<tr>
<th>Companies</th>
<th>Voltage (V)</th>
<th>Capacity (Farad)</th>
<th>Energy (Wh/kg)</th>
<th>Power (kW/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asahi Glass (J)</td>
<td>2.5</td>
<td>3000</td>
<td>7</td>
<td>0.4</td>
</tr>
<tr>
<td>Epcos (G)</td>
<td>2.3</td>
<td>2700</td>
<td>2.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Maxwell (USA)</td>
<td>2.5</td>
<td>2700</td>
<td>2.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Montena (CH)</td>
<td>2.5</td>
<td>800</td>
<td>2.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Evans (US)</td>
<td>100</td>
<td>200</td>
<td>1.1</td>
<td>-</td>
</tr>
<tr>
<td>Matsushita (J)</td>
<td>2.3</td>
<td>470</td>
<td>1.1</td>
<td>0.35</td>
</tr>
<tr>
<td>Polystor (USA)</td>
<td>2.5</td>
<td>7</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Nec-Tokin (J)</td>
<td>2.7</td>
<td>100</td>
<td>1.56</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 23: Overview of available super capacitors [Schneuwly et al., 1999]
9 Fuel storage

9.1.1 Introduction
Chemical energy is stored in fuels, e.g. hydrogen and petrol. Via a burning process (with a combustion engine) or a chemical process (as in the fuel-cell) the energy can be converted to mechanic or electric work. In previous chapters the different converters are described. In this chapter more focus will be on the storage medium, and the means of storing the fuels.

9.1.2 State-of-the-art technology
Different high-power and wireless products are powered by combustion engine technology, e.g. the Honda four-stroke handheld generator (1-2kW electric power). In this field of power the use of batteries cannot comply with the demands. Either they will run out in a short period of time or the portable power generator will be to bulky and extremely heavy. In comparison with batteries, the energy density of fuel is much higher (up to 2,000 times), meaning the time of use could be extended or the power demand could be higher.

The fuel used in most high-power applications is diesel or petrol. Camping products make use of a Butane / Propane mixture. At the moment fuel cells are much in development (chapter 4). Portable applications can either be fueled with hydrogen (H₂) or methanol.

9.1.3 Applications
Applications of fuel power can be found in either high power demanding products like gardening tools and heating (or lighting) products like camping burners or products which are used for a extended period of time like generators.

Professional garden tools are either powered by the grid, rechargeable batteries or fueled with gasoline or Diesel. Figure 51 show different motorized products from Husqvarna, e.g. the chainsaw, lawnmower, hedge shear, leaf blower, and the trimmer.
All these products are fueled with normal diesel or petrol which is poured in a fuel tank. In other fields of applications fuel cartridges are used to fuel the product. For example the Trakfast fastening system from Ramset-Redheat. This tool pins nails into wood or stone, using a 600cc pulsating internal combustion engine.

Furthermore natural gas cartridges can be found in camping applications like the mantle lights or burners from Campingaz and Coleman. More exotic applications have been though of like the Butane/Propane (B/P) powered espresso-machine, hairdryer and iron by Van Holsteijn and Kemna. These products have only been made as a mock-up. The electronics in the iron are also powered by the heat with Thermo-Electric elements (see also chapter 5.2).
9.1.4 Typical characteristics

Most fuels have a high energy density. In the following table an overview is given of the energy-densities and other characteristics of different fuels. Also the different power-conversion technologies used to produce functional power are described. When using fuel as a powersource a cartridge or tank is needed in your product. Together with the conversion technology (e.g. an internal combustion engine) and its efficiency the power and energy densities of the total system will drop.
<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Hydrogen</th>
<th>Methane</th>
<th>DME</th>
<th>LPG</th>
<th>Butane</th>
<th>Propane</th>
<th>Methanol</th>
<th>Ethanol</th>
<th>Petrol</th>
<th>Diesel</th>
<th>Stearine</th>
<th>PE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy content, MJ/kg</td>
<td>120</td>
<td>50</td>
<td>27</td>
<td>46</td>
<td>49,3</td>
<td>50,0</td>
<td>22,7</td>
<td>27</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Density, g/cm³ (kg/ltr)</td>
<td>0,00009</td>
<td>0,00072</td>
<td>0,8</td>
<td>0,5</td>
<td>0,585</td>
<td>0,61</td>
<td>0,79</td>
<td>0,8</td>
<td>0,72</td>
<td>0,8</td>
<td>0,9</td>
<td>0,9</td>
</tr>
<tr>
<td>Energy density, kJ/cm³, liquid</td>
<td>9000</td>
<td>-</td>
<td>21,6</td>
<td>23</td>
<td>28,8</td>
<td>30,5</td>
<td>17,933</td>
<td>21,6</td>
<td>36</td>
<td>40</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Energy density, kJ/cm³, gas</td>
<td>0,0108</td>
<td>0,036</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Energy content of 50 g. fuel + container (kJ)</td>
<td>6000</td>
<td>2500</td>
<td>1350</td>
<td>2300</td>
<td>2465</td>
<td>2500</td>
<td>1135</td>
<td>1350</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>Weight of 50g fuel + container (g)</td>
<td>80</td>
<td>80</td>
<td>75</td>
<td>72</td>
<td>72</td>
<td>72</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Fuel pressure at 20°C, (bar)</td>
<td>150</td>
<td>150</td>
<td>5,2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Energy content of a 24cm³ cartridge (kJ)</td>
<td>0,26</td>
<td>0,86</td>
<td>518</td>
<td>552</td>
<td>692</td>
<td>732</td>
<td>430</td>
<td>518</td>
<td>864</td>
<td>960</td>
<td>1080</td>
<td>1080</td>
</tr>
<tr>
<td>Energy content of a 52cm³ cartridge (kJ)</td>
<td>0,56</td>
<td>1,87</td>
<td>1123</td>
<td>1196</td>
<td>1500</td>
<td>1586</td>
<td>933</td>
<td>1123</td>
<td>1872</td>
<td>2080</td>
<td>2340</td>
<td>2340</td>
</tr>
<tr>
<td>Availability</td>
<td>poor</td>
<td>poor</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Conversion technologies</td>
<td>FC</td>
<td>FC, Comb</td>
<td>FC, Comb</td>
<td>Comb</td>
<td>Comb, Burn</td>
<td>Comb, Burn</td>
<td>FC, Comb</td>
<td>Comb</td>
<td>Comb</td>
<td>Comb</td>
<td>Burn</td>
<td>Burn</td>
</tr>
</tbody>
</table>

*FC*=fuel cell  *Comb*=combustion engine  *Burn*=burning process

*Table 24: an overview of the energy density of different fuels.*
10 Mechanical storage

Mechanical energy can be stored in different ways as elastic (springs, vibration), kinetic (flywheel), pressure (compressed air) or as potential energy (weights). In this chapter these different storage systems are described.

10.1 Springs

10.1.1 Introduction
The energy stored in springs is a result of the elastic properties of materials (Figure 55). Materials have the ability to return to its normal stationary shape, when the force applied is relieved. Energy storage in springs is possible by means of springs stressed on bending or torsion (Figure 55).

Springs are most efficient when all fibres are subjected to the same maximum strain, e.g. in a steel wire under tension. A clockwork spring for instance has lower energy density, but could be stored in a smaller volume. Maximum energy densities depend very strongly on material properties: metals, glass fibres and elastomers. Energy densities for metals such as spring steel as well as for elastomers like silicones lie in the region of 100 kJ per litre. If low mass is a requirement, elastomer springs have an advantage.

10.1.2 State-of-the-art technology
The main material choice for springs is spring-steel, or carbon steel, because certain defined characteristics of springs can be influenced by changing the chemical composition, moulding the steal and heat treatment. Other non-ferro materials could be interesting.
because of special requirements like corrosion, electric and magnetic characteristics [Roloff et al., 1994].

Non-metalic springs are mainly naturally and synthetic rubbers, especially for pressure and shearing stress, at damping of vibration, impact pulses and noise, elastic couplings and rubber sprunged suspension (e.g. in bycicles). Also Carbon and Glass fibre springs are used, because of its lightness versus strength characteristics (e.g. in truck suspension).

Also gas and fluids are used as spring material in gas springs and shock absorption. Sporadic also wood is used as a spring material, for example in trash and farmer machine, and sieves. For relatively small spring forces, magnetic springs could be applied.

10.1.3 Applications
Main applications of springs can be found in:

- suspension (e.g. buffer springs in between rail wagons);
- energy conservation (springs in toys, and clockworks);
- recuperating springs (valves, and measurement instruments);
- force measurement in spring-pressure gauges (unsters);
- force distribution or cancelling out forces (frame constructions and cushions);
- and lock springs, contact springs, et cetera.

A good example of a spring energy-storage system can be found in old-fashioned windup toys and windup clocks. Older versions are fitted with steel power springs, whereas nowadays most small toys are fitted with nylon ones. Modern applications of power springs are the windup radio or flashlight from FreePlay, but they can also be found in cameras, and retractor mechanisms for electrical cords and seat belts. Many concept studies of the application of power spring in products have been executed or prototyped. For instance the windup toothbrush and shaver from MOY and different student projects at the Delft University of Technology.

![Image of spring systems](image)

*Figure 56: the Spinney (Critters collection) by Chico Bicalho (left), the FreePlay windup flashlight (middle), and the MOY concept windup-toothbrush (right).*

10.1.4 Typical characteristics
Springs can be subdivided in materials used (elastomers, spring steel, etc.), form and the type of applied load (torsion, pressure, etc.). For calculations the division to “type of applied load” is the best.
When the friction for energy conservation springs is supposed to be nil, the maximum energy stored in materials is equal to the surface under the F-ΔL graph (Figure 57):

\[ W = \frac{1}{2} \cdot F \cdot \Delta L = \frac{1}{2} \cdot \text{Vol} \cdot \frac{\sigma_f^2}{E} \]

Where:
- \( W \) = energy content of the spring (J)
- \( F \) = force on the spring (N)
- \( \Delta L \) = strain (m)
- \( \text{Vol} \) = volume of the spring (m³)
- \( \sigma_f \) = maximum failure stress (N/m²=MPa)
- \( E \) = Young’s modulus (N/m²)

Torsion bars and leaf springs are less efficient than axial springs (like a rubber band) because part of the material is not fully loaded; the material at the neutral axis, for instance, is not loaded at all. For the maximum energy stored in the springs the previous formula could be rewritten as follows:

\[ W_{\text{max}} = \text{Vol} \cdot \frac{\sigma_f^2}{E} \cdot q_b \quad \text{or} \quad W_{\text{max}} = \text{Vol} \cdot \frac{\tau_f^2}{G} \cdot q_s \]

Where \( q \) is the form factor, depending on the spring format, and for normal spring material it is assumed that \( \frac{\tau_{\text{max}}^2}{G} \approx \frac{\sigma_{\text{max}}^2}{E} \). The occurring stress in the material may never exceed the maximum failure stress \( (\sigma_f) \). As a rule of thumb the maximum allowable bending stress \( (\overline{\sigma}) \) in materials may not exceed as follows [Cool, 1997]:

\[
\frac{\sigma}{\sigma_{\text{failure}}} = \begin{cases} 
0, 4 - 0, 7 \times \sigma_{\text{failure}} & \text{at constant stress} \\
0, 3 - 0, 4 \times \sigma_{\text{failure}} & \text{at pulsating stress} \\
0, 2 - 0, 25 \times \sigma_{\text{failure}} & \text{at variable stress}
\end{cases}
\]

The failure strength for metals and polymers is the yield strength;
The failure strength for ceramics and glasses is the compressive strength;
The failure strength for elastomers and composites is the shear strength.
Table 25: typical form factor values of different spring types, plus typical energy-densities of different spring types. Densities are based on the total amount of volume used at maximum deflection of the spring [Barnes, 1981].

<table>
<thead>
<tr>
<th>Spring type</th>
<th>Form factor</th>
<th>Typical amounts of energy stored (when springsteel is used) [J/dm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bending load</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>axial extension spring</td>
<td>1/2</td>
<td>-</td>
</tr>
<tr>
<td>power spring</td>
<td>1/6</td>
<td>-</td>
</tr>
<tr>
<td>spiral spring</td>
<td>1/6</td>
<td>-</td>
</tr>
<tr>
<td>parabolic leaf spring</td>
<td>1/6</td>
<td>-</td>
</tr>
<tr>
<td>triangular leaf spring</td>
<td>1/6</td>
<td>-</td>
</tr>
<tr>
<td>trapezium leaf spring (range: triangular to rectangular)</td>
<td>1/6 – 1/18</td>
<td>-</td>
</tr>
<tr>
<td>glass/carbon fibre leaf spring</td>
<td>1/12</td>
<td>-</td>
</tr>
<tr>
<td>rectangular leaf spring</td>
<td>1/18</td>
<td>-</td>
</tr>
<tr>
<td>power springs, motor or clock</td>
<td>-</td>
<td>1.000-1.700</td>
</tr>
<tr>
<td>prestressed power</td>
<td>-</td>
<td>2.500-3.000</td>
</tr>
<tr>
<td>constant force spring motor</td>
<td>-</td>
<td>3.500-4.500</td>
</tr>
<tr>
<td>Belleville washer</td>
<td>1/10 – 1/40</td>
<td>50-500</td>
</tr>
<tr>
<td><strong>Torsion load</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>helical extension/compression spring (round wire)</td>
<td>1/4</td>
<td>150-1.500</td>
</tr>
<tr>
<td>helical extension/compression spring (square wire)</td>
<td>2/13</td>
<td>100-1.000</td>
</tr>
<tr>
<td>torsion bars</td>
<td>1/6</td>
<td>-</td>
</tr>
<tr>
<td>helical torsion spring (round wire)</td>
<td>1/8</td>
<td>100-500</td>
</tr>
<tr>
<td>helical torsion spring (square wire)</td>
<td>1/6</td>
<td>150-800</td>
</tr>
</tbody>
</table>

Metals, because of their high density, are less good springs than composites (CFRP, GFRP), and even worse than elastomers (rubber). You can roughly store 8 times more elastic energy, per unit weight, in a rubber band than in the best spring steel. Problem with elastomers is their high energy-loss.

Glass Fibre Composite springs can be found in e.g. leaf springs for trucks. Normal polymer springs have a very low maximum bending stress which results in a very low energy-storage density. Glass fibres seem to be preferred above Carbon fibre, because of its lower price but also because of its better characteristics in Joules per kg [Cool, 1997]. Ceramics seem to be a very good energy-conservator, but this only works when compressed. Ceramics are very brittle in tension. Wood, the traditional material for archery bows, are a very good alternative for lightweight energy conservation, but difficult to form.

The power spring, applied in the FreePlay windup radio (S360), is special type of spring, the so called constant force spring [Barnes, 1981]. The spring winds itself up and off on two axes. The energy contained by this power spring is approximately 270J [Van Pul, 2002]. The spring weighs 543g, which gives an energy density of almost 0.50kJ/kg²⁶. The energy contained by the first version of the windup radio (FPR 1) is 565J and weighs approximately 1kg. The energy density of this power spring is 0.56kJ/kg [Jansen 1997]. This is something more, probably because of down-scale influences.

Calculations on a power spring (also called normal power spring), used as an energy storage for a windup toothbrush [Van Hout et al., 2000], gives a mean energy density of 0.4kJ/kg. The energy storage capacity of prestressed power springs is higher due to residual stress distribution manufactured into the strip prior to placing the spring in its case. When a prestressed power spring is removed from its case, it assumes an S shape, while power springs assume a spiral shape [Barnes, 1981].

²⁶ For composite springs the spring volume is for 50% filled with fibres, that’s why the value of the form factor changes from 1/6 to 1/12.
²⁷ The energy input in the spring is 628J, and with an efficiency of approximately 90% (measured by [Van Pul, 2002] for the S360), the energy contained by this spring is 565J.
### 10.2 Flywheels

#### 10.2.1 Introduction
A flywheel is a type of electromechanical energy storage system. Energy is stored as rotational kinetic energy by spinning a disk. Energy loss is minimized by keeping frictional losses low (bearings at the axle and air resistance). Small ones, e.g. in children’s toys, are made of lead, while old steam engines have flywheels made out of cast iron. Most recently, flywheels have been proposed for power storage and regenerative braking systems for vehicles. A few have been build, made out of high-strength steel or sometimes of composites. Efficiencies of flywheels are reported greater than 90%. Friction is kept low by low-friction bearings, using magnetic supports, and less air resistance, by housing the disk in a vacuum. The flywheel spins at high rpm, what means the tensile strength of the material is the limiting factor.

#### 10.2.2 State-of-the-art technology
Research and development on the field of flywheels focuses most on materials, and low-friction bearings. New materials like carbon-fibers are used to make the flywheels lighter and stronger. Stronger material (failure strength) means higher rotation speeds, resulting in higher energy and power capacity.

#### 10.2.3 Applications
Small flywheels are used in children’s toys, made of lead. Well known flywheel storage systems are used in the Philips dynamo flashlight (squeeze torch) and spinner bikes and rowing machines from Schwinn (using cast-iron for their material).

---

![Figure 58: the first squeeze torch from Philips, the inner site of a Dynalite squeeze torch, and the Swinn Spinner bike using a large flywheel.](image)

Old steam engines have flywheels, made out of cast iron. More recently, flywheels have been proposed en researched for power storage and regenerative braking systems for vehicles, e.g. in cars and buses. The flywheel will conserve energy while braking and

---

\[1 \text{Pa} = 1 \text{N/m}^2 = 10^6 \text{N/mm}^2\]
returning it when the car or bus is accelerating (e.g. by Urenco). A few have been build, some of high-strength steel, some of composites.

Besides toys and regenerative braking, flywheels find applications in the field of Uninterruptible Power Supply (UPS) systems, backup systems during power-down situations (e.g. for server and data hotels). Active Power, Beacon Power and most of the other flywheel manufacturers produce these high power UPS systems (or flywheel batteries), ranging from 2 to 100kWh and maximum continuous powers ranging from 2 to 500kW. The generator is integrated in the flywheel. Because the specific strength of magnets is typically just fractions of that of the composite flywheel, they must spin at much lower tip speeds. In other words, they must be placed very near the hub of the flywheel (compromising the power density of the generator), or they must be mounted closer to the outer radius of the wheel, and contain their strength by the composite reinforcement.

![Figure 59: an explanation for the flywheel technology of the Active Power flywheel system, the Beacon Power BHE-6 UPS system (2kW, 6kWh).](image)

### 10.2.4 Typical characteristics

An efficient flywheel stores as much energy per unit weight as possible. The energy (W) stored in a flywheel can be calculated as follows:

\[ W = \frac{1}{2} \cdot m \cdot v^2 = \frac{1}{2} \cdot J \cdot \omega^2 = \frac{\pi}{4} \cdot \rho \cdot R^4 \cdot t \cdot \omega^2 \]

Where: 
- \( W \) = energy stored in the flywheel (Nm or J)
- \( J \) = the polar moment of inertia (Nm or J)
- \( \omega \) = rotation speed (rad/sec)
- \( \rho \) = density of the material (kg/m³)
- \( R \) = radius of the disk (m)
- \( t \) = thickness of the disk (m)

The efficiency of storing energy in a flywheel depends on the friction of air and the bearings. Air friction can generally be eliminated by housing the flywheel in a vacuum bottle. Friction from bearings is decreased by good lubricants or by avoiding contact using magnetic supports.

The efficiency is generally in between 90 to 95% (output / input energy). The energy stored in the flywheel is increasing when the rotation speed is increasing (rpm). This speed is also the limiting factor for the storage of energy per unit of weight. Because of the induced centrifugal stress, the material breaks when the maximum tensile strength of the material is exceeded. The maximum breakdown stress in a spinning disk of uniform thickness is equal to:
\[ \sigma_{\text{max}} = \left( \frac{2 + \nu}{8} \right) \cdot \rho \cdot R^2 \cdot \omega^2 = 0.2917 \cdot \rho \cdot R^2 \cdot \omega^2 \]

Where: \( \sigma_{\text{max}} = \sigma_f \) = the maximum failure, or tensile, strength of the material (Pa)
\( \nu \) = Poisson’s ratio \( \sim 1/3 \) for solids

The best material choice for high-performance flywheels are those with a high value of the performance index: \( \sigma_f / \rho \) (or the specific strength). Glass fiber reinforced plastics and ceramics are good materials to be used in flywheels. Recent designs use a filament wound glass fiber reinforced epoxy rotor, able to store around 150kJ/kg. In the table underneath an overview is given of the different materials used in flywheels. All steel, aluminum, magnesium and titanium alloys have approximately the same maximum energy density, but differ much in price. The performance index is the maximum stored energy per unit of mass. The flywheel never runs at maximum speed, but much lower, to prevent disintegration of the wheel.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Density ( \rho ) ((\text{kg/m}^3))</th>
<th>Failure strength ( \sigma_f ) ((\text{MPa}))</th>
<th>Performance index ((\text{kJ/kg}))</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon FRP (60%vol HT Carbon)</td>
<td>1.500</td>
<td>2.400</td>
<td>1.600</td>
<td>Best performance, but expensive</td>
</tr>
<tr>
<td>Glass FRP (60%vol E-glass)</td>
<td>2.000</td>
<td>1.600</td>
<td>800</td>
<td>Almost as good as carbon, less expensive</td>
</tr>
<tr>
<td>Ti alloys (TiAl6Zr5)</td>
<td>4.500</td>
<td>1.200</td>
<td>270</td>
<td>All about equal in performance.</td>
</tr>
<tr>
<td>High strength Steel (AlSi 4340)</td>
<td>7.800</td>
<td>1.800</td>
<td>220</td>
<td>Steel an Aluminium alloys are cheaper than Mg and Ti Alloys</td>
</tr>
<tr>
<td>High strength Mg Alloys (AlMnMg)</td>
<td>2.700</td>
<td>600</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>AlZnMgCu1.5 (7075)</td>
<td>2.850</td>
<td>530</td>
<td>186</td>
<td></td>
</tr>
<tr>
<td>Ceramics</td>
<td>3.690</td>
<td>228</td>
<td>62</td>
<td>Brittle in tension</td>
</tr>
<tr>
<td>Cast iron (GG-70)</td>
<td>7.100</td>
<td>250</td>
<td>35</td>
<td>Excellent choice when performance is velocity-limited, not strength limited</td>
</tr>
<tr>
<td>Lead alloys</td>
<td>11.300</td>
<td>32</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Table 27: materials for flywheels [Aspes; Idemat, 2002].

Than why are flywheels in children’s toys still made of lead? This is because the constraint in a child’s toy is different. No child, or grown-up, can spin up the flywheel up to its maximum velocity. The rotational velocity \( \omega \) is limited, what means, the energy density depends strongly on the density, resulting in lead to be perfect. In human activated applications the rotational velocity is also limited, because of the low induced forces. This means Lead or Cast Iron is the material of choice.

### 10.3 Compressed gas

#### 10.3.1 Introduction

A cylinder filled with a medium like a gas or fluid can be used as a storage for mechanical energy. The pressure difference inside the cylinder and the outside will invoke a flow. This flow can be used to rotate the blades of a turbine. When the turbine is coupled with a small electromagnetic generator, electricity is produced.

#### 10.3.2 State-of-the-art technology

The application of compressed gas can be found in different applications, e.g. the Super Soaker (Figure 60) in which air pressure has to be build up by pumping, or ready-to-use \( \text{CO}_2 \) cartridges for filling bicycle tires.
10.3.3 Applications
A very good example of the use of compressed air can be found in Super Soakers from Hasbro. Super soakers are built around a pump mechanism, but moving the pump doesn’t actually drive water out of the gun; it serves to build up water pressure before the blast. In the first wave of Super soakers, you built up this pressure by pumping air directly into a single water reservoir. As you pumped in more air, the air became more and more compressed and so applied greater pressure to the water inside. In later models, you built up pressure by pumping water instead of air (in a tank filled with air)\(^{29}\). Pressure is build up in the cylinder [HowStuffWorks, 2001].

CO\(_2\) (or other media) cartridges are used in paintball guns and as fillings for bicycle tires. Also in some model aircraft CO\(_2\) cartridges are used to power the motor. Different developers of CO\(_2\)-powered RC-engines are G-Mot, Gašparin, and Modela (Figure 61).

10.3.4 Typical characteristics
With the help of a piston the volume (V) of a cylinder can be decreased, what will result in a higher air pressure (p). For ideal gasses the following formula can be used:

\[
p \cdot V = nRT \quad \text{(ideal gas law)}
\]

\[
p \cdot V^{\gamma} = \text{constant} \quad \text{(adiabatic gas law)}
\]

Where:  
\(p\) = pressure (Pa)  
\(V\) = volume (m\(^3\))  
\(\gamma\) = moles of gas (1,4 for air)  
\(R\) = the gas constant \(\sim 8,314\) J/molK  
\(T\) = temperature (K)

The energy stored in a cylinder can power a small turbine or piston engine spun by the escaping gas in order to produce e.g. electricity. The total available work stored in a cylinder filled with air is equal to (when adiabatic process is assumed and no phase change occurs):

---

\(^{29}\) But still air is compressed, because water is incompressible.
\[ W = R \cdot T \cdot \ln \left( \frac{V_{\text{end}}}{V_{\text{begin}}} \right) = \frac{\gamma}{\gamma - 1} \cdot p_{\text{tank}} \cdot V_{\text{tank}} \cdot \left[ 1 - \left( \frac{p_{\text{atm}}}{p_{\text{tank}}} \right)^{\frac{\gamma}{\gamma - 1}} \right] \]

Where: 
- \( p_{\text{tank}} \) = the pressure in the tank
- \( p_{\text{atm}} \) = the atmospheric pressure (1 bar)
- \( V_{\text{tank}} \) = the volume in the tank, is constant
- \( V_{\text{end}} \) = the uncompressed volume of the gas at the end (at 1bar)
- \( V_{\text{begin}} \) = the compressed volume of the gas at the begin

The efficiency is very low. Air turbine and generator systems have a ballpark upper efficiency of 40%, with 20% probably being a more practical number for a small turbine [Johnson, 1999]. The amount of available energy depends on the volume, and the initial and final pressures \( p_i \) and \( p_f \). As a first approximation, a volume of air that expands slowly and isotherm\(^{30}\) from 1 litre at 10 bar to 5 litres at 2 bar can perform about 1,6kJ of work. When the expansion is adiabatic\(^{31}\), only about 1,2kJ will be available [Johnson, 1999].

Instead of using only compressed gas as in a super soaker, you can store "work"-energy in liquid CO\(_2\) or Helium. Because of the shifting from gas to liquid, the energy density stored can be much higher. When a cartridge filled with partially liquid and partially gaseous CO\(_2\), is opened, CO\(_2\) will dissipate through an outlet nozzle. Until the moment all liquid is shifted to gaseous CO\(_2\) the pressure will be constant. From that moment on the pressure will decrease very fast to surrounding pressure \( (p_0) \).

![Isothermal phase shifting of CO\(_2\). In point A the bottle is totally filled with liquid CO\(_2\). In point B the bottle is partially filled with liquid (1-x%) and partially with vapor (~x%).](image)

**An example:** When the filling in the cartridge is in state B (Figure 62), \( x \%) is vapor and \((1-x)\)% is liquid. Say \( x = 75\%\), and the volume of the tank is 1 liter, than 0,75ltr is vaporized and 0,25ltr liquid CO\(_2\). The pressure at \( T_0 = 20^\circ\text{C} \) is \( p_1 = 951.477\text{Pa} \) (9,5bar).

When an outlet is opened the pressure in the cartridge is released and the liquid CO\(_2\) will evaporate at a constant pressure \( (p_1) \) until state D \((x = 100\%)\). The heat input required for this process is equal to:

\[ Q = m \cdot L_v = 0,265 \times 230 = 61 \text{ kJ} \]

\(^{30}\) Isotherm = slow release at a constant temperature

\(^{31}\) Adiabatic = a reversible thermodynamic process that occurs without gain or loss of heat and without a change in entropy. A lower temperature means a lower pressure, what finally will result in a steady-state between the pressure inside and outside the tank (roompressure). From this point on no energy can be extracted anymore.
Where: \( m \) = the mass of liquid CO\(_2\) (kg) = 0.25 ltr x 1060 kg/ltr
\( L_v \) = Heat of Vaporatization (kJ/kg)

The work done by the CO\(_2\) is equal to:

\[
W = P \cdot \Delta V = p_1 \cdot (v_f - v_i)
\]

\[
= 5.9 \times 10^6 \text{ N/m}^2 \cdot (145 \times 10^{-3} - 0.25 \times 10^{-3} \text{ m}^3) = 853 \text{ kJ}
\]

Where: \( p_1 \) = the pressure in the cartridge = 855psi = 5.9MPa (59bar)
\( v_f \) = the finite volume in gaseous form:
\[
\frac{\rho_l \cdot \rho_i \cdot v_i}{\rho_i \cdot v_i}
\]
\( v_i \) = initial volume, in this case: 0.25ltr = 0.25x10\(^{-3}\) m\(^3\)

A 'full' CO\(_2\) tank used for e.g. paintball contains about 34\% wt (or 68\% vol) liquid CO\(_2\), under a pressure of 5.9MPa (855psi, at room temperature). If it is filled with more, the CO\(_2\) will become very sensitive to temperature changes. A small increase in temperature can cause a large increase in pressure, resulting in an explosion. This is a dangerous situation which is avoided by only partially filling the bottle [Warpig, 2001]. As an estimation the following calculations is in place. Assuming CO\(_2\) is an ideal gas and the release is isothermal, the energy stored in a 'full' tank, 68\% vol CO\(_2\) at 5.9MPa, is (see [1] in Figure 63):

\[
W_{\text{evaporate}} + W_{\text{pressure}} = EH \times m + \frac{R \cdot T \cdot \ln \left( \frac{V_{\text{end}}}{V_{\text{begin}}} \right)}{\text{molar weight}}
\]

\[
570 \text{ kJ/kg} \times 19\%_{\text{wt}} + \frac{8.3 \times 10^{-3} \cdot 294 \cdot \ln 57}{0.044 \text{ kg/mol}}
\]

\[
108 + 224 = 332 \text{ kJ/kg}_{\text{CO}_2} \text{ (excl. cannister)}
\]

Where: \( EH \) = the Evaporation Heat coefficient of a liquid-gas transformation (570kJ/kg)
\( m \) = the mass of liquid CO\(_2\) evaporating at a constant pressure of 855psi (68\%-30\% = 38\% vol = 19\% wt)

When all liquid CO\(_2\) is evaporated in a tank, the pressure in the tank will decrease very fast, and will be useless (see Figure 63). The energy density of CO\(_2\) under a pressure of 951.477 Pa (138psi), is equal to almost 88kJ/kg (isotherm\(^{32}\) number [2] in the figure below).

\(^{32}\) The volume is expanded to 5 times its original size \((V_{\text{end}} = 5 \times V_{\text{begin}}; P_{\text{tank}} = 5 \times P_{\text{atm}})\).
**10.4 Gravitational energy storage**

**10.4.1 Introduction**

Maybe one of the oldest forms of energy storage is weights in the earth’s gravitational field. In medieval Europe the mechanical clock was invented, which made use of this earth’s force. Clever arrangements of gears and wheels were devised that were made to rotate by weights attached to them. As the weights were pulled downward by the force of gravity, the wheels were forced to turn in a slow, regular manner. A pointer, properly attached to the wheels, marked the hours. Only since a couple of decennia the good old fashion mechanical clockwork is disappearing from living rooms, to be replaced by battery or grid powered alternatives (hardware clocks, software clocks and quartz clocks).

Since work is force (N) x displacement (m) the unit of work is Newton-meter. The Newton-meter is given the name Joule, in honor of Mr. Joule. One Joule is equal to lifting a mass of 1 kg up to 1 meter (1kg x 9,81m/s² x 1m = 1Nm = 1J).

**10.4.2 State-of-the-art technology**

In Switzerland energy is stored in large water basins. Overcapacity of electricity companies is used to transfer water to higher located basins. When the energy is needed electricity is produced with large hydro generators. In consumer products not much is going on in the field of gravity power.

**10.4.3 Applications**

A typical and common application is the mechanical clock.

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33 1 psi (pound per square inch) = 6895 Pa; p0 = 1atm = 101.325Pa = 14,7psi
10.4.4 Typical characteristics
Gravitational energy can be stored in weight and height according to the following formula:

\[ E = m \cdot g \cdot h \]

where: 
- \( m \) = mass (kg)
- \( g \) = gravitational constant (m/s\(^2\)) = 9.81 m/s\(^2\)
- \( h \) = height (m)

Potential, or gravitational, energy is used as a power-source for e.g. the mechanical wall clock. The efficiency of the total system depends on the transmission of slow-movement to high rotations, needed in the clockwork. The pendulum nicely demonstrates the repeated flow of energy from potential to kinetic and back (\( E=K+U=\text{constant} \)).
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Yellowloop [www.yellowloop.com](http://www.yellowloop.com), cristal radio set.

### 11.3 Special thanks

I would like to thank the following persons for their input, criticism, help, reviewing and assisting (in alphabetical order):

Tom van der Horst
Geert Timmers
Ruben Strijk
Petra Vos
Michel van Schie
Han Brezet
Menno Veeffkind
Sioe You Kan
Hans de Deugd
Aad Bremer
Flip Doorschot
Herman Broekhuizen
Martin Verwaal
12 Appendix

12.1 PV-cell calculation example

To determine the maximum power of a module of solar cells in real situations the following example can help you [Markvart, 2003]:

The manufacturer’s values under Standard Test Conditions are (STC, \( G=1000\text{W/m}^2 \), \( T_a=25^\circ\text{C} \)):

\[
\begin{align*}
I_{\text{SC}} &= 3\text{A} \\
V_{\text{OC}} &= 20,4\text{V} \\
P_{\text{pp}} &= 45,9\text{W} \\
\text{NOCT} &= 43^\circ\text{C} \text{ (Normal Operating Cell Temperature)}
\end{align*}
\]

Determine the parameters of a module formed by 34 solar cells in series, under the operating conditions \( G=700\text{W/m}^2 \) (irradiance), and \( T_a = 34^\circ\text{C} \) (ambient temperature):

The short-circuit current:

\[
I_{\text{SC}} = \frac{I_{\text{SC}}}{1000} \cdot G = 3 \cdot 0,7 = 2,1\text{A}
\]

Solar cell temperature:

\[
T_c - T_a = \frac{\text{NOCT} - 20}{0,8} \cdot \frac{G}{1000} = (43-20)/0,8 \times 0,7 = 20,12^\circ\text{C}
\]

\( T_c = 54,12^\circ\text{C} \)

Open-Circuit Voltage:

\[
V_{\text{OC}} = (V_{\text{OC}})_{\text{STC}} - \frac{dV_{\text{OC}}}{dT} \cdot \left(T_c - (T_a)_{\text{STC}}\right)
\]

\[
V_{\text{OC}} = (V_{\text{OC}})_{\text{STC}} - 0,0023 \cdot n_{\text{cells}} \cdot (T_c - (T_a)_{\text{STC}})
\]

\[
V_{\text{OC}} = 20,4 - 0,0023 \times 34 \times (54,12 - 25) = 18,1\text{V}
\]

The maximum Power Point will now be determined by using the simplifying assumption that the fill factor (FF) is independent of the temperature and the irradiance:

\[
\text{FF} = \frac{P_{\text{max}}}{V_{\text{OC}} \cdot I_{\text{SC}}}_{\text{STC}} = 45,9 \times (3 \times 20,4) = 0,75
\]

\[
P_{\text{max}}(G,T_c) = I_{\text{SC}} \cdot V_{\text{OC}} \cdot \text{FF} = 2,1 \times 18,1 \times 0,75 = 28,5\text{W}
\]

Thus, noting the manufacturer’s value of \( P_{\text{max}} \) at STC (45,9W), we see that the module in a real situation will operate at about 62% of its nominal rating.
13 Tables & figures

13.1 Figures

Figure 1: State of energy, and its conversion technologies..................................................9
Figure 2: The Honda four-stroke mini-motor, GX22, and the two-stroke engine from NovaRossi.................................................................15
Figure 3: The mini-Wankel engine (butane or propane; 0,77cc; 2.5W) of Berkeley University and the Wankel engine of O.S. engines (5cc; 1,27ps) ..............................................15
Figure 4: the Micro gas turbine of MIT (20W electricity)..................................................................................................................17
Figure 5: different AMT Jets. .............................................................................................17
Figure 6: The working principle of the hydrogen fuel cell (PEM). ..............................................19
Figure 7: a Polymer Exchange Membrane fuel cell for a flash light (the "Maglite BZ" flashlight contains a three-cell stack with a four-watt maximum output. The integrated metal hydride cartridge delivers 30 watt-hours of energy) [ZSW]. ..............................................20
Figure 8: category of applications vs. power output power of the fuel cell [Motorola labs]. 21
Figure 9: the educational fuel-cell kit from Heliocentris, and the NovArs & Manhattan Scientists’ Hydrocycle.................................................................21
Figure 10: typical cell characteristic of a PEM-cell with an active area of 1cm². Explanation of the electrical characteristics of the fuel cell.................................................................22
Figure 11: A Direct Methanol Fuel Cell used as a charger for a mobile phone (~1.5 Watt, on the right) [ZSW] and the NEC Methanol powered laptop computer [NEC, 2003]. ......23
Figure 12: The Direct Methanol Fuel cells of Smart Fuel Cell (Germany), for mobile applications as the professional video camera (25W), mobile office systems (40W) and traffic systems (25W)..............................................................................................................24
Figure 13: Basic principle of a photovoltaic cell. ................................................................26
Figure 14: A mono and a poly-crystalline cell, plus an amorphous cell used to power a mosquito repellent [www.conrad.nl/]. ..............................................................................................................27
Figure 15: Autonomous connected PV system from Go Solar © company (left), a portable PV-powered radio / flashlight (middle) and a portable charger for cellular phones (right). .............................................................................27
Figure 16: Explanation of the electrical characteristics of solar panels. ................................28
Figure 17: De Hi-Z 19Watts Thermo Electric system (left) and truck carried out with 1kWatts of Hi-Z TEGs (right). .................................................................30
Figure 18: The Seiko Thermic wristwatch, the Aspen Systems’ thermoelectric fan, and the Radio lantern from GW Industries. ..............................................................................................................31
Figure 19: The Hi-Z TEGs, producing 2.5W, 14W and 19W. ....................................................31
Figure 20: measured efficiencies of low-power TE generators (TEGs) from Melcor Aztec [Hakkesteegt, 2001] (Tc = the temperature at the Cold side).................................32
Figure 21: The efficiency of food-to-mechanic energy conversion [Grassman, 1987] ..........33
Figure 22: The 34 variables that influence force exertion. Subject, product and environmental variables also influence the interaction variables. This influence is indicated with an arrow [Daams, 1994]. .............................................................................34
Figure 23: Power of rowing and cycling in relation to duration exercise for a typical healthy male (30 years) and non-athlete [Kawai, 1997] and the mechanical power produced when hand-cranking for six different test subjects [Slob, 2000]. ..............................................35
Figure 24: The Energy Balance Ratio, power generation vs. power consumption adopted from [Pater, 2000].

Figure 25: The principle of DC electro-magnetic generator [tpub.com].

Figure 26: The Shimano HB-NX30 hub generator (6VDC, 3W), an old fashioned Gazette sideways dynamo, the Freeplay crank flashlight and the Kinetron generator for the Moonlight Safari night vision, powered by piezoelectric. A standard piezoelectric gas lighter. A piezoelectric watch from Seike-Epson (patent no. JP9182465) and the piezoelectric strain transducer.

Figure 27: The efficiency of different hub generator (left) and sideways dynamos (right) with 28" wheels [tandem-fahren.de].

Figure 28: The performance comparison, discharge curves, of primary and secondary alkaline batteries (NiMH, Li-ion and Li-poly). [NTBG, 1998].

Figure 29: The piezoelectric watch from Seike-Epson (patent no. JP9182465) and the piezoelectric strain transducer.

Figure 30: An artist impression of the vertical axis wind turbine with diffuser from Ecofys, and a standard low-power wind turbine: the Pacific 100 from Ampair.

Figure 31: A typical charge and discharge curve for a capacitor (left) and a battery (right). The power density of super capacitors is very high, in contrast with the energy density, when compared with batteries. The voltage is increasing and decreasing with the charge and discharge time (at a constant charge and discharge current).

Figure 32: An artist impression of the vertical axis wind turbine with diffuser from Ecofys, and the Savonius type turbine from Windside in the middle the Viking).

Figure 33: An artist impression of the vertical axis Darrieus type turbines (left the Neoga and in the middle the Viking) from Ecofys, and the Savonius type turbine from Windside (right).

Figure 34: Typical characteristics of a secondary battery depending on the (a) charge and (b) discharge current.

Figure 35: Typical characteristics of a secondary battery depending on the (a) ambient temperature and (b) discharge rate [Havlík, 2001].

Figure 36: Voltage vs. Current diagram of a piezoelectric generator [Piézo Systems Inc.].

Figure 37: The principle of DC electro-magnetic generator [tpub.com].

Figure 38: An artist impression of the vertical axis Darrieus type turbines (left the Neoga and in the middle the Viking) from Ecofys, and the Savonius type turbine from Windside (right).

Figure 39: A typical charge and discharge curve for a capacitor (left) and a battery (right). The voltage is increasing and decreasing with the charge and discharge time (at a constant charge and discharge current).

Figure 40: The Clarus Qlink (left), stress reliever, protecting from EMF radiation. The flashlight (on the right) from Haimei.com, flashes when receiving or making a phone call, working on GSM mobile phones without antenna.

Figure 41: The Lectrosonics Tunable Dipole Antenna adjustable from 550 MHz to 800 MHz.

Figure 42: Typical characteristics of a secondary battery depending on the (a) charge and (b) discharge current.

Figure 43: Typical characteristics of a secondary battery depending on the (a) ambient temperature and (b) discharge rate [Havlík, 2001].

Figure 44: Typical V-I characteristic of a battery.

Figure 45: Performance comparison, discharge curves, of primary and secondary alkaline and Ni-Cd batteries (adapted from Design Note: Renewable Reusable Alkaline Batteries) [NTBG, 1998].

Figure 46: The rated energy density versus the rated specific energy (left) and the rated power density versus the rated specific power (right) of different mobile phone batteries (NiMH, Li-ion and Li-poly).

Figure 47: The Maxwell Ultra capacitors, in different shapes.

Figure 48: Applications of a super capacitor to cache power when braking, and give a power burst when accelerating [Hill tech, 2001].

Figure 49: A typical charge and discharge curve for a capacitor (left) and a battery (right). The voltage is increasing and decreasing with the charge and discharge time (at a constant charge and discharge current).

Figure 50: The Ragone plot shows the energy vs. power density [Schneuwly et al., 1999].

Figure 51: Alternative Power Sources for Portables & Wearables

Figure 52: The Trakfast internal combustion powered fastening system (left) and its propane fuel cartridges (right).}

Figure 53: The Campingaz burner and mantle light (left) and the different cartridges used to fuel all of their products (right).

Figure 54: The Van Holsteijn and Kemna Butane/Propane powered espresso-machine...
13.2 Tables

Table 1: General characteristics of different power sources[Schoen et al., 1991; Melcor, 2000; Paradiso et al., 1998; Meijerink, 2001; Raadschelders, 1999; Flipsen et al., 2001; Cool, 1997].
Table 2: Overview of fuel powered energy sources.
Table 3: Characteristics of different mini and micro combustion engines [Honda, Berkeley, O.S., Cipolla, Magnum & Super Tigre].
Table 4: typical characteristics of mini and micro turbine engines [MIT, AMT Jet].
Table 5: overview of commercially available and prototype hydrogen PEM fuel cells [H-tec, ZSW, LANL, Heliocentris, Fuel cell store, Conrad].
Table 6: overview of the energy density of different storage technologies. Heat losses due to conversion from fuel to electricity are not taken into account.
Table 7: Overview of products from Smart Fuel Cell.
Table 8: overview of commercially available and prototyped Direct Methanol fuel cells [Heliocentris, H-tec, JPL laboratory, Fuelcells.org].
Table 9: Efficiencies of PV Cells, *(*)=measured under Standard Test Conditions (STC).
Table 10: typical specific characteristics of commercially available small poly and mono crystalline PV-cells. The Panasonic Sunceram II cells for indoor use have been tested under a fluorescent lamp of 200lux (~2W/m² radiant power) instead under STC (1000W/m², T=25°C).
Table 11: overview of available TE generators [Hi-Z, Aspen Systems, Seiko & Citizen].
Table 12: Typical peak and mean power figures for different trained people who are cycling.
Table 13: overview of generated mechanical power of different occupational human activities, age 30 years [Kawai, 1997; references summarized by Daams, 1994; Pen, 1997].
Table 14: overview of electromagnetic generators, or dynamos [Son; Baygen; Micromachine technologi; Mubachi; tanden-fahren; Van Dam et al., 1997; Van den Berg et al., 2003].
Table 15: Overview of different pięzo generator configurations [Pięzo Systems Inc.].
Table 16: overview of 6 two-layer pięzo electric generators: (1) Bending and (2) extension generators [Pięzo Systems Inc.].
Table 17: References for electric (E) and electromagnetic (B) fields (1MHz – 300GHz, undisturbed mean values) [Antennebureau, 1999].
Table 18: The radiate power from a base station (left) and a transmitting cellular phone (right). The effective power of a base station is approx. 400W and for a cellular this is max 2W (when far away from the base station) and 0,25W nominal power.
Table 19: the advantages, disadvantages and typical applications of different primary batteries [NTBG, 1998; Crompton, 2000; Buchmann, 2001] ...............................................................55
Table 20: the advantages, disadvantages and typical applications of different secondary batteries [NTBG, 1998; Crompton, 2000; Buchmann, 2001] ..............................................56
Table 21: Overview of the characteristics for primary and rechargeable batteries [Crompton, 2000] ..................................................................................................................59
Table 22: general characteristics of single layer and double layer capacitors compared with general batteries [Smith, 2000, Buchmann, 2002] .........................................................62
Table 23: Overview of available super capacitors [Schneuwly et al.,1999] .........................63
Table 24: an overview of the energy density of different fuels............................................67
Table 25: typical form factor values of different spring types, plus typical energy-densities of different spring types. Densities are based on the total amount of volume used at maximum deflection of the spring [Barnes, 1981] .................................................................71
Table 26: characteristics of different materials used in springs [Ashby, 1992; Simapro, 2002]. .........................................................................................................................72
Table 27: materials for flywheels [Aspes; Idemat, 2002]. ....................................................74
14 Keywords

Aspen Systems ............................................32
Chemical ................................................8, 26, 53, 64
Citizen.................................................... 31, 32
dynamo....................10, 36, 37, 38, 39, 72, 83
Electric...................................... iii, iv, 8, 11, 65
ergeia .........................................................8
Energy Balance Ratio ..................................36
exotic ............................................... 7, 8, 20, 40, 65
Hi-Z........................................................ 30, 32
Kinetic................................................ 8, 37, 38
Magnetic............................................. iii, 8, 36, 48
Mechanical ............................................. 8, 16, 18, 68, 79
Melcor Aztec ................................................32
Panasonic .....................................................29
Peltier ..........................................................8
Photovoltaic............................. 10, 26
piëzo..................10, 33, 39, 40, 41, 42, 43
Potential ...................................................8, 78
Seebeck ...................................................10, 30
Seiko ............................................ 30, 32, 37, 38, 40
Siemens ......................................................29
Thermal ....................................................8
Thermo Electric Generator .................30