High Technology Benchmarks
September 13th 2008

1 Purpose of this Document

This document serves several purposes:

1. We are providing benchmark values in key technologies in order to summarize the current state of key technologies.
2. However in today's world the successful integration of several technologies is more important than a "world record" in a single technology. So the benchmark values are significant for progress we are making but they need to be put into the context of benchmarks in other technologies.
3. We are keeping track of the published values and put them in perspective by publishing also the previous benchmarks and respective market sizes for the technologies. Should you find any value questionable or to be updated, please contact us at **office@mqs.at.**

2 Executive Summary

Light Emitting Diode (LED) Street Lights:	136 lm / Watt
Organic LEDs (OLEDs):	120 lm / Watt
Photovoltaic Cells:	42.8 % conversion efficiency
Cars:	50 miles per gallon
Memory Storage Density (hard drives):	455 Gbit/in^2
Batteries:	590 Wh / kg

3 Figures of Merit (FoM) for Single Technologies and the combined FoM: cFoM

A figure of merit (**FoM**) describes the characteristic output of a component based on a certain technology divided by the respective input. In the subsequent chapter you can find "lumen per Watt", "miles per gallon" and others as example.

In order to assess the successful combination or integration of technologies one has to combine several figures of merit. This is called the **cFoM**, combined Figure of Merit of technologies.

Example 1: For a simple pocket light one can combine the luminous efficacy and the gravimetric or volumetric battery density. Hence with LEDs a huge step was made as the light production efficiency increased by an order of magnitude which allows to reduce the requirements for the battery tremendously – basically the battery, and hence the lamp, size can be decreased by an order of magnitude while maintaining the same product performance. So the cFoM would be in units of (lm / W) * (Wh / kg).

Example 2: For modern cell phones the cFoM is even more complex. It is determined by the luminous efficacy of the display, the gravimetric or volumetric battery density, the processing power per energy of the chips on board, the storage or memory density and the bandwidth of its wireless communication technology. Hence it is very easy to see that a cFoM can be increased by more than two orders of magnitude when the 5 corresponding single FoMs are improved by a factor of 3 each => 3^5 = 243. A factor of 243 of improvement of a cFoM can then be used e.g. in a reduction of size by 243, or increase of performance, e.g. real time movies on a cell phone. It is evident that such huge steps in cFoM enable absolutely new applications and products.

4 Light Emitting Diodes (LED) - Street Lights

Motivation: the luminous efficacy determines the amount of light, usable for human vision, in Lumen (lm) divided by the electric energy in W, that was used to generate this light. Hence this value for street lights determines how efficient we are able to illuminate our environment [5].

Value	Date	Comment	Link
136 lm/Watt	2008-07-26	136 lm/W at 350 mA, 155 Lumen total, 5000 K color temp. (white)	Osram [13]
115 lm/Watt	2007-01-23	115 lm/W at 350 mA, 61 lm/W at 2000 mA, 4685 K color temp. (white)	Lumileds [14]
114 lm/Watt	2007-11-28	2760 K color temp. (“warm white”)	LLF Inc.[15]
~ 10 lm/Watt	Incandescent source		
~ 30 lm/Watt	Fluorescent source		

5 Organic LEDs (OLEDs)

Motivation: the luminous efficacy in lm / W was explained above. As OLEDs are being discussed as light sources for illumination and displays this value determines how efficient we are able to illuminate our environment but also the efficiency of active displays.

Value	Date	Comment	Link
120 lm/Watt	-	green	Novaled [17]

5.1 Flat Panel Display Market

Value	Date	Comment	Link
70 b$ in 2006	Jan 2008	-	Printed Electronics World
100 b$ in 2010	Jan 2008	-	Printed Electronics World

6 Photovoltaic Cells (Research)

Motivation: the power conversion efficiency of photovoltaic cells in % determines how efficient we can generate electrical energy directly out of sunlight.

Value	Date	Comment	Link
42.8 %	2007-08-06	Multi junction cell	EET Asia
40.7 %	2006-12-05	**[a]**	US DOE [11]
24.7 %	2008-02-25	Single-junction GaAs cell, grown epitaxially on a Ge substrate. Fill factor of 83.2%.	IMEC [12]
5.9%	2008-09-02	Organic Solar Cells	Plextronics [16]
3 $ per Watt	Based on **[a]**	Installation cost predicted	
8-10 cents per kWh	Based on **[a]**	Electricity production cost predicted	

6.1 Photovoltaics (PV) Market

Value	Date	Comment	Link
2500 MW in 2004	Jan 2008	Total Installed Cell Capacity	CanSIA
1600 MW in 2006	Jan 2008	Annually Installed Cell Capacity	Solar Server [10]
2300 MW in 2007	Jan 2008	Annually Installed Cell Capacity	Solar Server [10]
0.8 b$ in 2004	Jan 2008	Global PV Market	USW of Australia [9]
1.2 b$ in 2005	Jan 2008	Global PV Market	USW of Australia [9]
1.8 b$ in 2006	Jan 2008	Global PV Market	USW of Australia [9]
2.3 b$ in 2007	Jan 2008	Global PV Market	USW of Australia [9]
2.6 b$ in 2008	Jan 2008	Global PV Market	USW of Australia [9]
3.0 b$ in 2009	Jan 2008	Global PV Market	USW of Australia [9]
3.3 b$ in 2010	Jan 2008	Global PV Market	USW of Australia [9]

7 Fuel Efficiency of Cars in Miles per Gallon (MPG)

Motivation: the fuel efficiency of conventional passenger cars in miles per gallon (mpg) determines the economic and environmental price for our individual mobility.

Value	Date	Comment	Link
150 mpg **(fake !!!) – see [2]**	2008-01-12	GM prototype	Metaefficient
50 mpg	2005-10-05	Honda Civic, Toyota Prius Hybrids	Metaefficient
45 mpg	2008-09-12	Mercedes, C250 CDI BlueEfficiency Prime Edition; a 204 horsepower four-cylinder 2.2-liter engine, which uses direct injection technology and a dual stage supercharger	Cnet-reviews

In the Table above we have also listed an interesting "fake" – a surprisingly low MPG-value for a car that drove partly on electric energy supplied through "the plug" and hence got "amazing" MPG-ratings [2]. For an overview of MPG ratings see Fueleconomy.gov [3].

8 Memory Storage Density

Motivation: the storage density of memory technologies determines the amount of data we store per volume. While for archiving purposes this just determines the need for space, for mobile applications this can mean a go / no-go decision for a device or application on the device.

Value	Date	Comment	Link
8.6 Mbyte/mm^3 57 Gbyte/in^2 455 Gbit/in^2	2008	250 Gbyte on 2.5 inch drive 9.5 mm high	[7]
100 - 150 Gbit/in^2	2005	Typical hard drives on the market	[8]
2000 bit/in^2	1956	First hard drive by IBM	[8]

9 Energy Density of Batteries and Ultracapacitors

Motivation: the energy density of batteries in Wh/kg determines how applicable mobile economic devices and electrically powered cars are. So battery technology is a typical enabler for the application of other technologies. For a broader comparison of energy densities see [6].

Value	**Date**	**Comment**	**Link**
590 Wh/kg	2008	Lithium Carbon Monofluoride	Quallion
270 Wh/kg	2008	Vanadium Chemistry	Quallion
230 Wh/kg	2008	Li Mn Dioxide	Quallion
45 – 80 Wh/kg	2005	NiCds	Battery University [4]
60 – 120 Wh/kg	2005	NiMH	Battery University [4]
30 – 50 Wh/kg	2005	Lead Acid, sealed	Battery University [4]
150 – 190 Wh/kg	2005	Li Ion, cobalt	Battery University [4]
100 – 135 Wh/kg	2005	Li Ion, manganese	Battery University [4]
90 – 120 Wh/kg	2005	Li Ion, phosphate	Battery University [4]
280 Wh/kg	2008	EEStor claims - high-purity barium titanate coated with aluminum oxide and glass	Wikipedia [18]
21 Wh/kg	2008	PbC Ultracapacitor	Axion Power Intl. [19]
12500 Wh/kg (or 45 MJ/kg)	2008	Energy density of gasoline – 20% of it is used in gas engine	Wikipedia [18]
=> 2500 Wh/kg	2008	"Effective energy density" of gasoline	Wikipedia [18]

10 Conclusions

We have provided a summary of high technology benchmarks and put them into perspective of traditional values and respective markets. Updates of this document will appear whenever relevant data are available to re-assess the annual global figures or the decision is made to include additional indicators. If you should find Sections not clear enough or if information, you expected, was missing, please contact us at **office@mqs.at**.

11 References

[1] For training, consulting, project management and part-time engineers/managers please contact us under **office@mqs.at**.
[2] Amazingly in this article the authors calculated a "miles per gallon value" for a hybrid mode of operation where part of the energy came from the power grid. So this value is useless – the true value for this car can be calculated to 26 mpg.
[3] http://www.fueleconomy.gov/feg/calculatorSelectYear.jsp
[4] Battery technology summary - http://www.batteryuniversity.com/partone-3.htm
[5] Wikipedia on luminous efficacy - http://en.wikipedia.org/wiki/Luminous_efficacy
[6] Wikipedia on energy density - http://wiki.xtronics.com/index.php/Energy_density
[7] http://www.engadget.com/2008/01/22/seagates-250gb-laptop-drive-now-shipping-for-165/
[8] Wikipedia on memory storage density - http://en.wikipedia.org/wiki/Computer_storage_density
[9] USW of Australia: http://www.ceem.unsw.edu.au/content/documents/Feed-inTariffOptionsv3.pdf
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[16] http://www.edn.com/article/CA6592016.html?nid=3572&rid=668789659
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[18] http://en.wikipedia.org/wiki/EEStor
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