‘Energy Storage’

A presentation to All Energy, May 24th 2005

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Story line

- Some history
- Current state of the art
  - Market drivers
  - Technologies
  - Costs
- Killer apps
  - Fuel vectors
  - Making Renewable Energy more viable
- Conclusions

Historical note

- **Early man soon discover the advantages of storing energy.**
  - **Wood for fuel**
  - **Grains and animal fats for food**
  - **Flexible wood (bows and arrows)**
  - **Rocks (and gravity) early hammers**
- **So the concept of energy storage is not new.**

Industrial revolution

- **The industrial revolution was enable by stored energy.**
  - **Mill ponds and water wheels**
  - **High pressure steam – steam engines**
  - **Pressurised water and gas**
  - **Coal gas – a mixture of H_2 & CO**
  - **Black powder, TNT, Nitro Glycerine**
  - **Batteries**
  - **Diesel, petrol, methanol**
- **So there's a long history of R&D leading to useful forms of stored energy.**

So what's new?

- **In some ways the answer is:**
  - **VERY LITTLE!**
- **Technology is responding to consumer demand and it is this demand which is stimulating the development of energy storage systems.**
  - **Business as usual**

Market segments

- **There are three main energy storage market segments:**
  - **1. Utility / industrial** applications including: grid reinforcement, renewables integration and uninterruptible power supply (UPS) applications
  - **2. Transport / mobile** applications including: on-board power for vehicles, new drive trains (electric and hybrid electric vehicles) and leisure applications (caravanning)
  - **3. Portable applications including:** computing, cell-phones and cameras (the 3 ‘C’s’)

Market drivers

- There are five broad drivers of energy storage markets:

1. Political and Regulatory developments
    - power system de-regulation/regulation, green energy market assistance
2. Energy Supply Side developments
    - emergence of large and small scale distributed generation systems such as commercial and domestic gas fired Combined Heat and Power
3. Developments in Power Delivery Systems
    - weakened or ageing grid Transmission & Distribution systems
4. Developments in End Use Systems
    - vehicles, power tools, off-grid applications
5. Developments in End User Requirements
    - increasing demand for portable power

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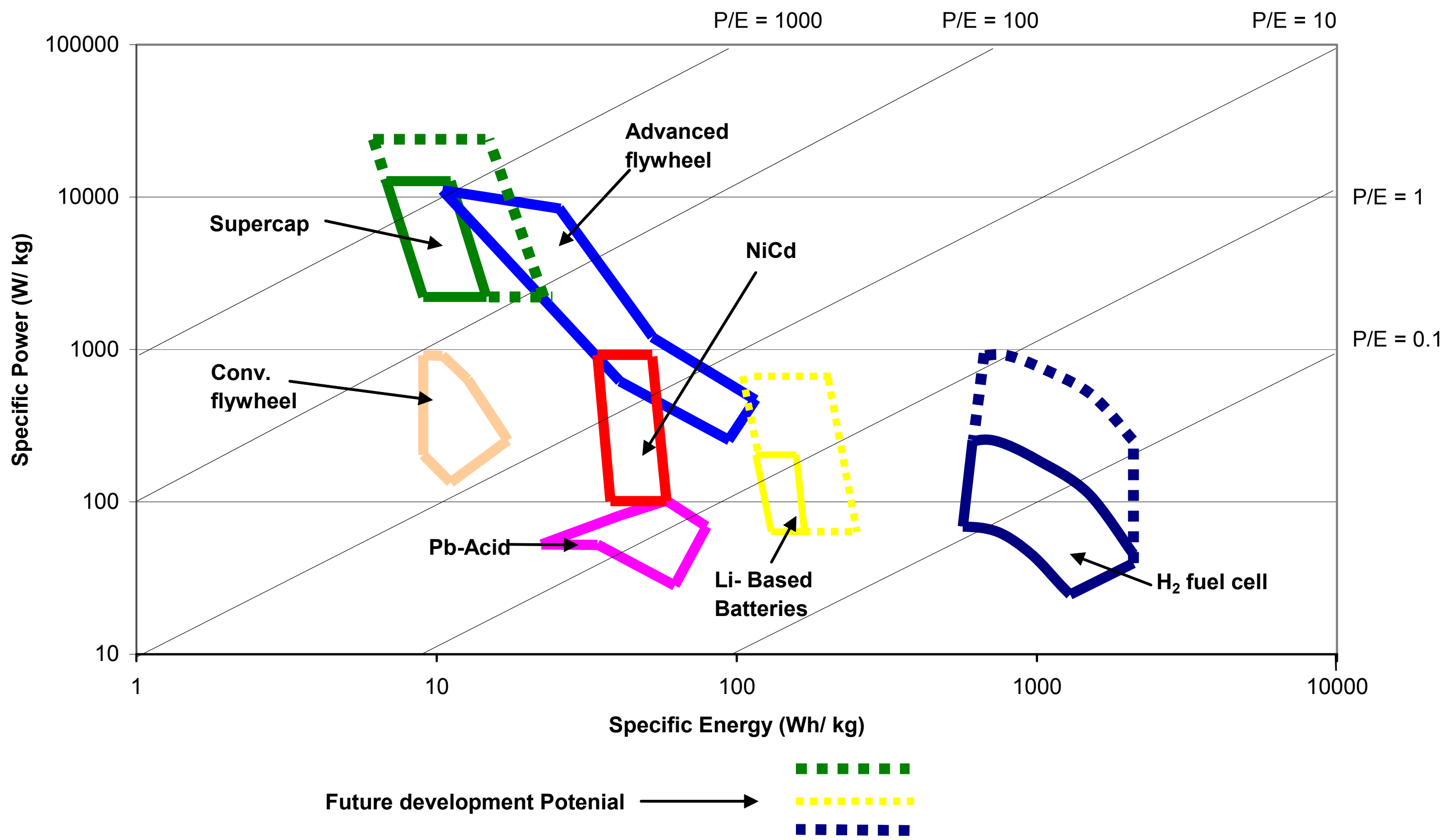
Generic storage “systems”

- **Electrochemical systems**
  - **batteries and flow cells**
- **Mechanical systems**
  - **fly-wheels and compressed air energy storage (CAES)**
- **Electrical systems**
  - **super-capacitors and super-conducting magnetic energy storage (SMES)**
- **Chemical systems**
  - **hydrogen cycle (electrolysis -> storage -> power conversion)**
- **Thermal systems**
  - **sensible heat (storage heaters) and phase change**

Ragone Plot



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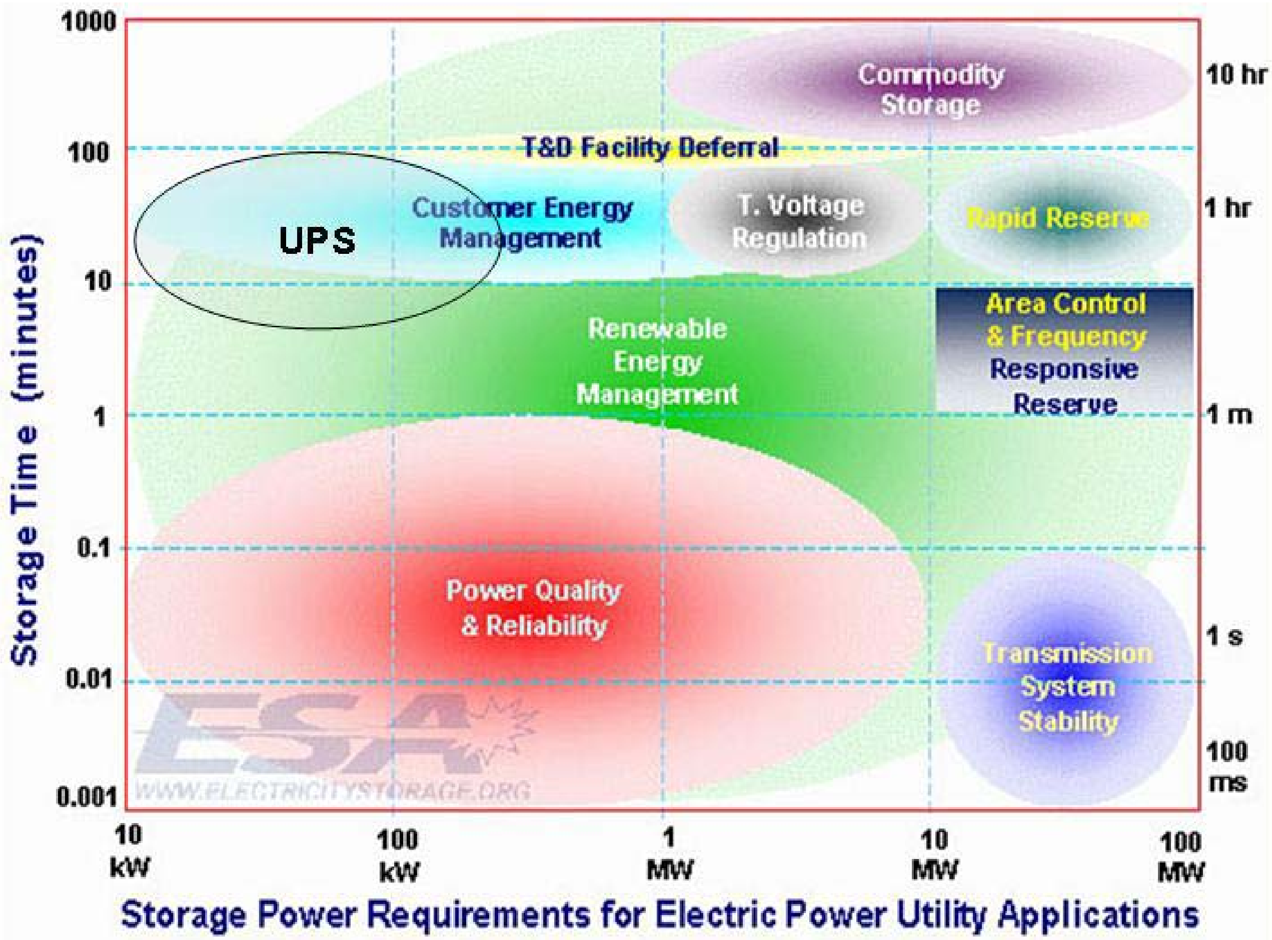
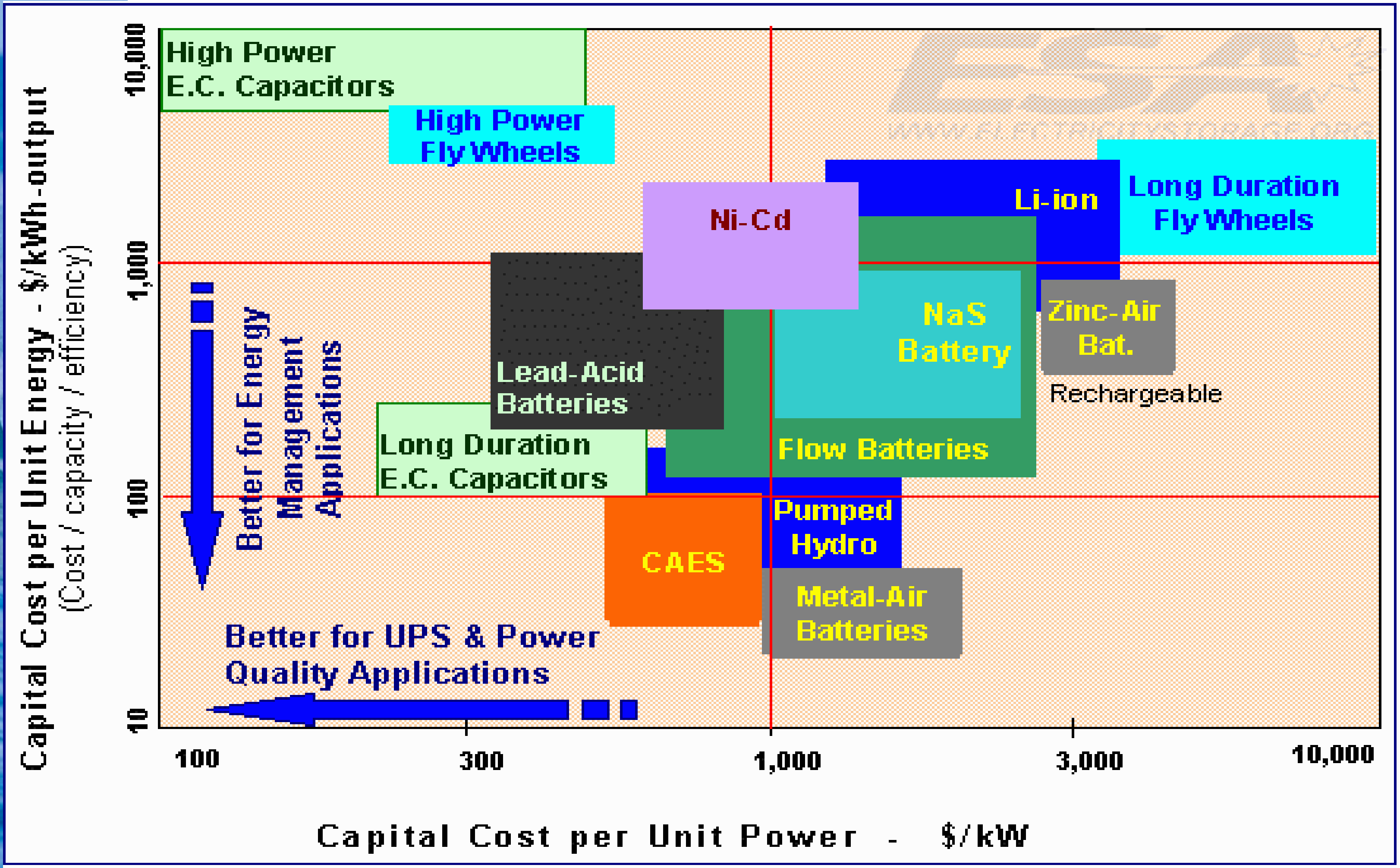
Stored power/Time plot



Storage technology cost comparisons



Key applications for energy storage

- **Energy sources for transport, sometimes referred to as "Energy Vectors"**

- **Load levelling, arbitrage and fault ride through for renewable energy sources**
  - **Varying the time at which power is delivered to the Grid**

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Energy vectors

- **Energy sources for transport, sometimes referred to as “Energy Vectors”**
  - **Chemicals which can be generated from renewable sources**
  - **Which store energy**
  - **And can be easily converted into useful power**

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Potential future fuel (fuel vectors)

Fuel Vector	Typical Chemical Energy Density
Hydrogen	**142.0 MJ/kg**
Ethanol	**29.7 MJ/kg**
Ammonia	**17.0 MJ/kg**
Automotive Gasoline	**45.8 MJ/kg**
Methane	**55.5 MJ/kg**
Methanol	**22.7 MJ/kg**

(Source: Chemical Energy, The Physics Hyper text Book)

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Energy Density with realistic storage

Fuel Vector	Typical Stored Chemical Energy Density	
Hydrogen	**7.1 MJ/kg**	**@ 5wt%**
Ethanol	**26.7 MJ/kg**	**@ 90wt%**
Ammonia	**13.6 MJ/kg**	**@ 80wt%**
Automotive Gasoline	**41.2 MJ/kg**	**@ 90wt%**
Methane	**44.5 MJ/kg**	**@ 80wt%**
Methanol	**20.4 MJ/kg**	**@ 90wt%**

Mass energy densities for various fuels

Fuel Vector	Hydrogen weight fraction	Ambient state	Mass energy density (MJ/kg)
Hydrogen	1	Gas	120
Methane	0.25	Gas	50 (43)[2]
Ethane	0.2	Gas	47.5
Propane	0.18	Gas (liquid)[1]	46.4
Ammonia	0.18	Gas (liquid)[1]	17.0
Gasoline	0.16	Liquid	44.4
Ethanol	0.13	Liquid	26.8
Methanol	0.12	Liquid	19.9

(1) A gas at room temperature, but normally stored as a liquid at moderate pressure.
(2)The larger values are for pure methane. The values in parantheses are for a “typical” Natural Gas.

Maximum energy density is achieved in liquid state

Fuel Vector	Hydrogen weight fraction	Ambient state	Liquid volumetric energy density (MJ/liter)	Hydrogen volumetric energy density in liquid (MJ/liter)
Hydrogen	1	Gas	8.4 – 10.4[3]	8.4 – 10.4[3]
Methane	0.25	Gas	21 (17.8)[2]	12.6 (10.8)[2]
Ethane	0.2	Gas	23.7	12
Propane	0.18	Gas (liquid)[1]	22.8	10.6
Ammonia	0.18	Gas (liquid)[1]	13.1	16.3
Gasoline	0.16	Liquid	31.1	13.2
Ethanol	0.13	Liquid	21.2	12.3
Methanol	0.12	Liquid	15.8	11.9

(1)A gas at room temperature, but normally stored as a liquid at moderate pressure.
(2)The larger values are for pure methane. The values in parantheses are for a “typical” Natural Gas.
(3)The higher value refers to hydrogen density at the triple point.

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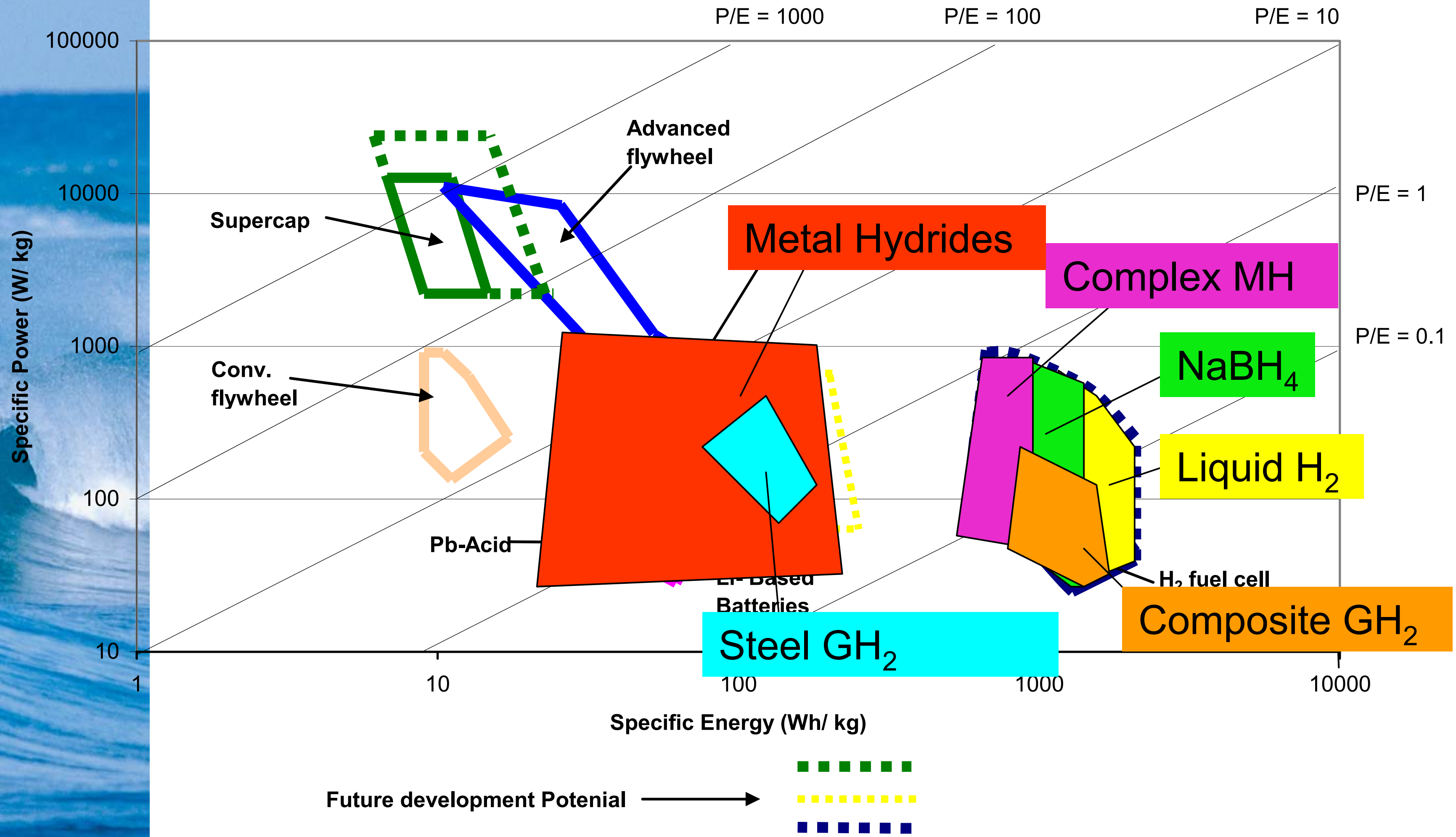
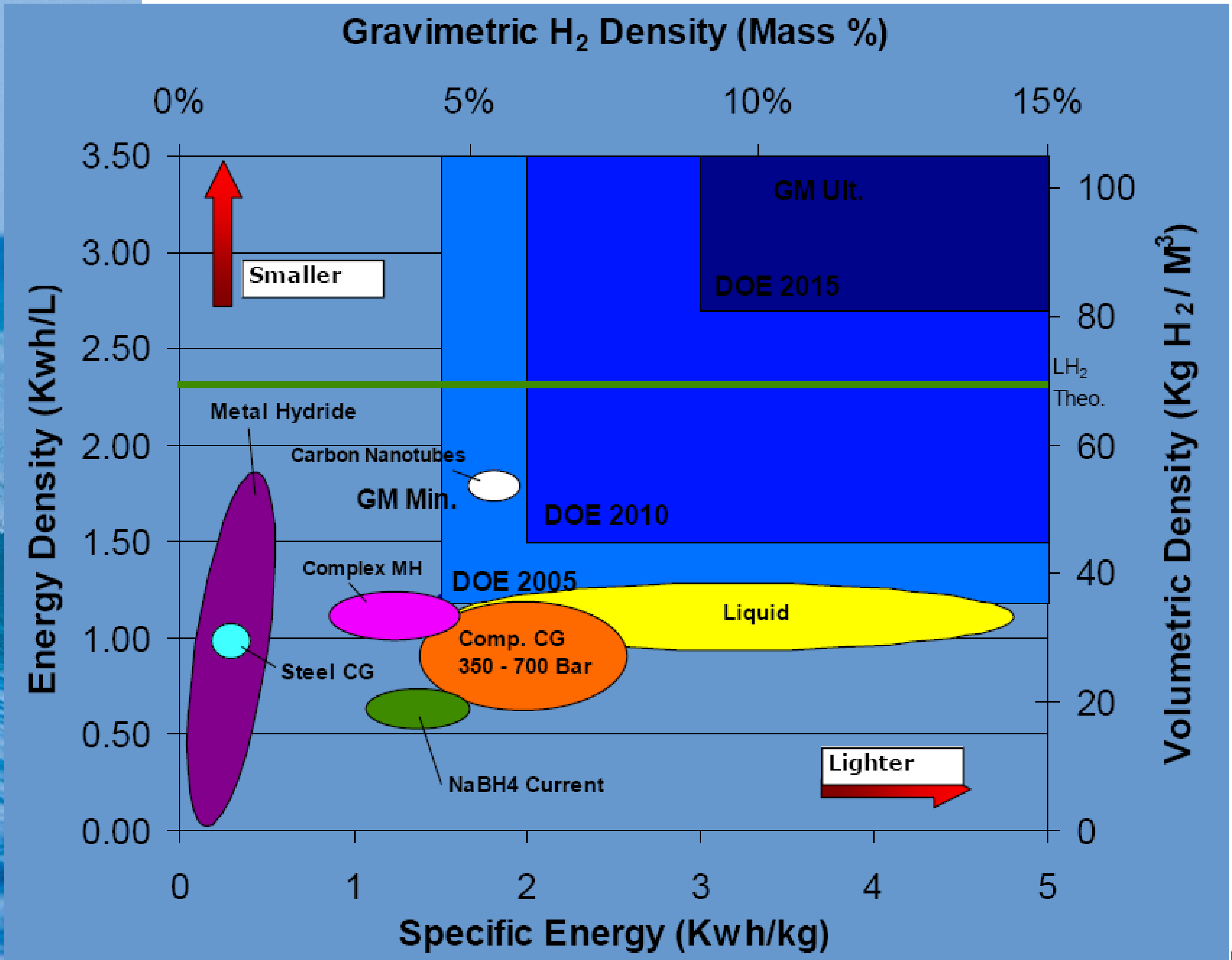
Hydrogen energy content in liquid fuels

Fuel Vector	Hydrogen weight fraction	Ambient state	Liquid volumetric energy density (MJ/liter)	Hydrogen volumetric energy density in liquid (MJ/liter)
Hydrogen	1	Gas	8.4 – 10.4[3]	**8.4 – 10.4[3]**
Methane	0.25	Gas	21 (17.8)[2]	**12.6 (10.8)[2]**
Ethane	0.2	Gas	23.7	**12**
Propane	0.18	Gas (liquid)[1]	22.8	**10.6**
Ammonia	0.18	Gas (liquid)[1]	13.2	**16.3**
Gasoline	0.16	Liquid	31.1	**13.2**
Ethanol	0.13	Liquid	21.2	**12.3**
Methanol	0.12	Liquid	15.8	**11.9**

Ragone Plot

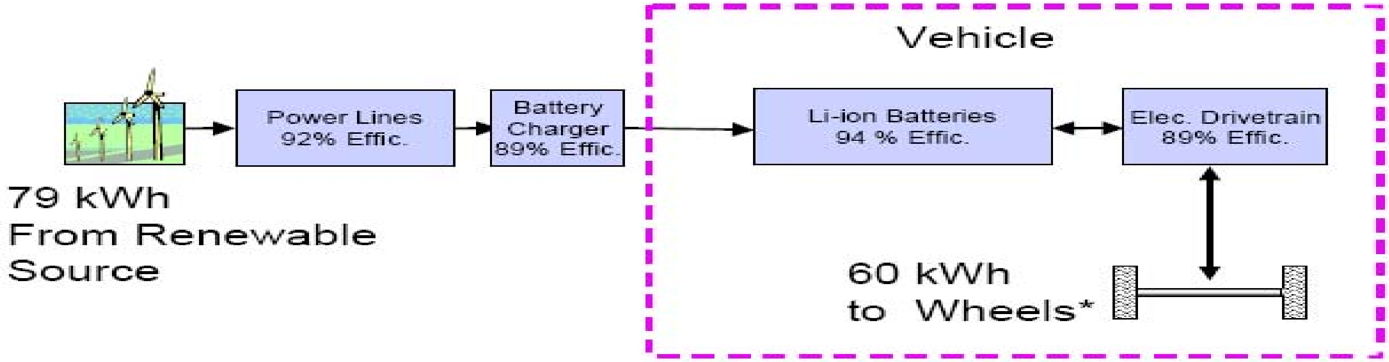


P/E = 1000
P/E = 100
P/E = 10
P/E = 1
P/E = 0.1
100000
10000
1000
100
10
1
10
100
1000
10000
Specific Power (W/ kg)
Specific Energy (Wh/ kg)
Advanced flywheel
Supercap
Conv. flywheel
Pb-Acid
Batteries
Metal Hydrides
Complex MH
$NaBH_4$
Liquid H_2
H_2 fuel cell
Composite GH_2
Steel GH_2
Future development Potenial



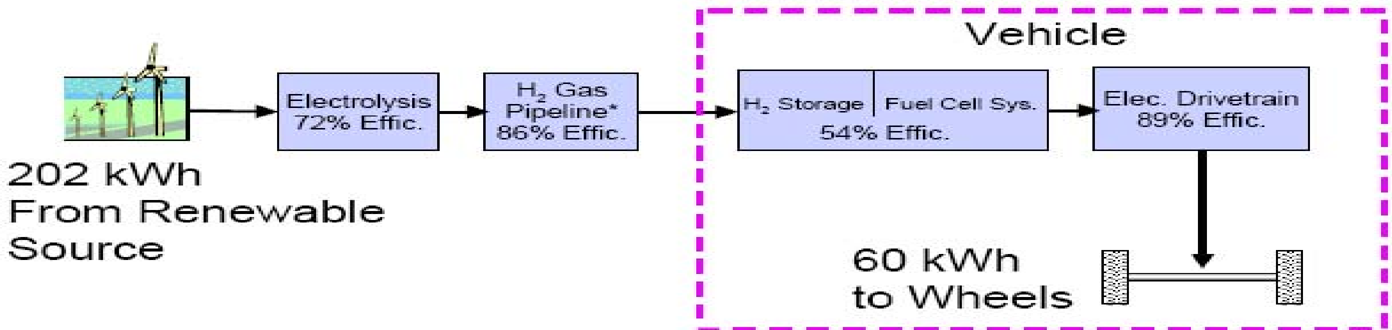
Gravimetric H2 Density (Mass %)
0%
5%
10%
15%
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Smaller
GM Ult.
DOE 2015
100
80
60
40
20
0
LH2
Theo.
Metal Hydride
Carbon Nanotubes
GM Min.
DOE 2010
Complex MH
DOE 2005
Liquid
Comp. CG
350 - 700 Bar
Steel CG
NaBH4 Current
Lighter
Energy Density (Kwh/L)
Volumetric Density (Kg H2 / M3)
0
1
2
3
4
5
Specific Energy (Kwh/kg)

Is H_2 a real alternative?



*The BEV regeneration capability reduces the 60kWh requirement by 6kWh while achieving the same range

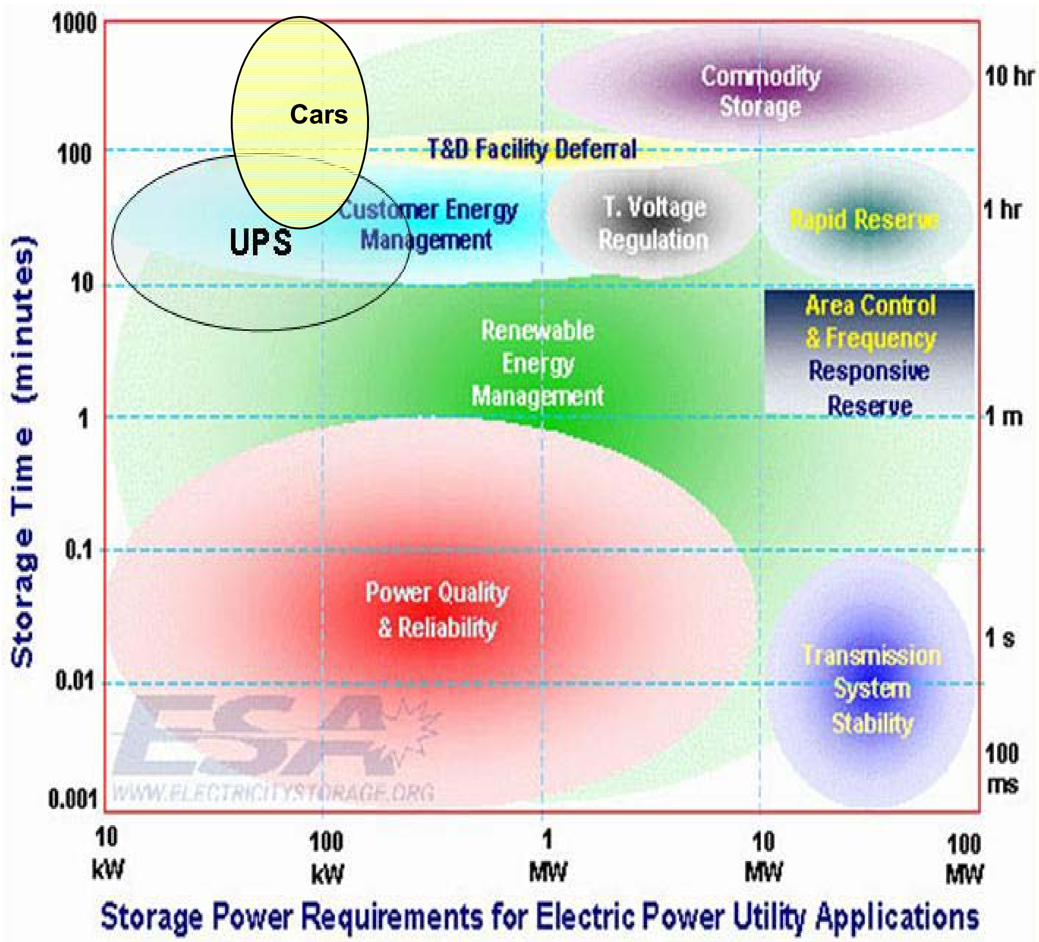
Figure 1 – "Well to Wheel" Energy Pathway for Battery Electric Vehicle



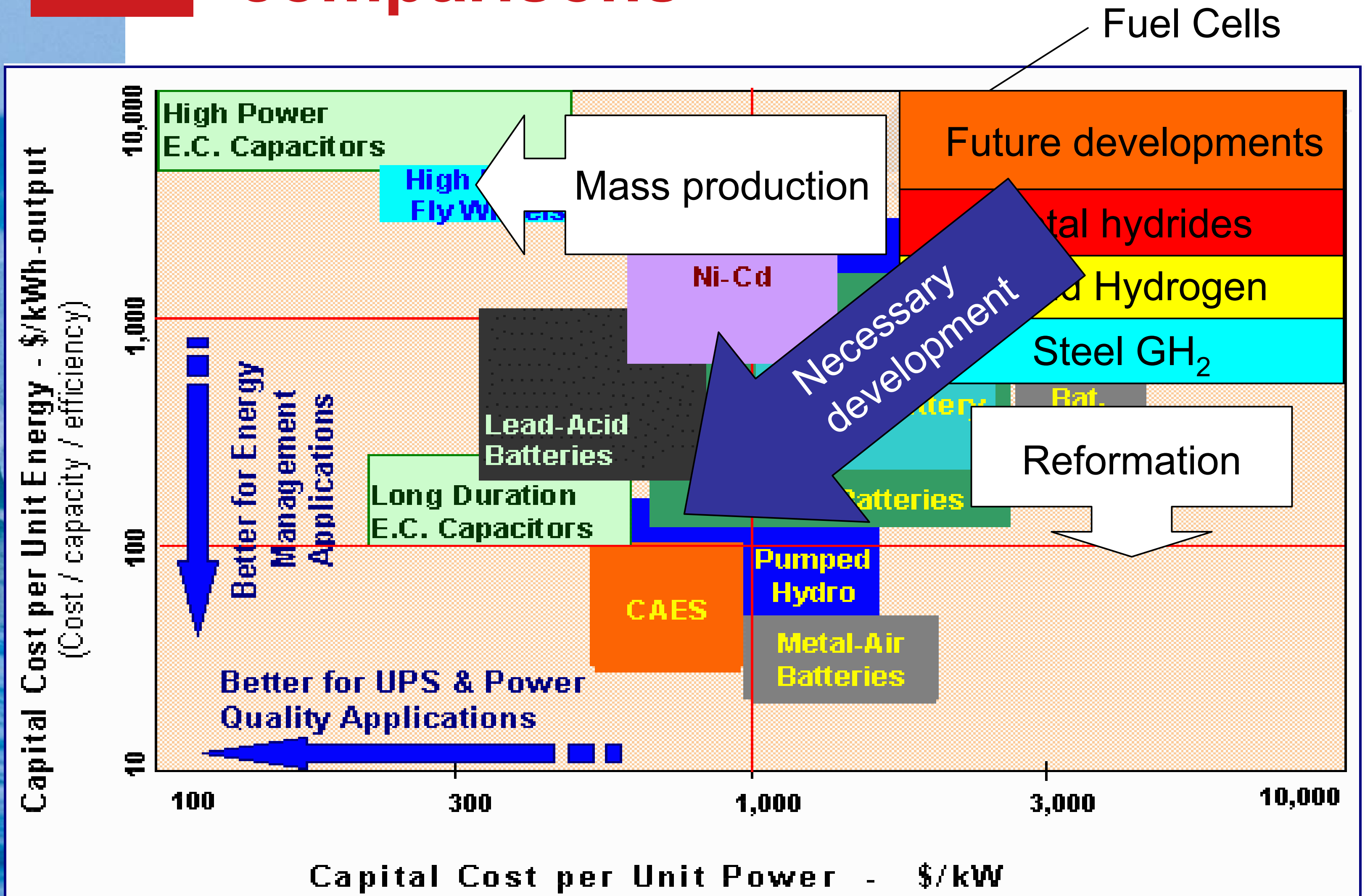
* "Pipeline" includes losses from compression, expansion, storage and distribution

Fuel-Cell Vehicles: Solution or Shell Game? Stephen S. Eaves & James E. Eaves - 2003

Stored power/Time plot



Storage technology cost comparisons



H_2 or NH_3 ???

- **Hydrogen is still problematic**
  - **Difficult to store as a gas or liquid**
  - **Expensive to manufacture from renewable sources**
  - **Expensive (to the environment) if manufactured from Hydrocarbons**
  - **Excellent for use in Fuel cells**
- **Hydrocarbons are a good source of hydrogen**
  - **Easy to store**
  - **Common**
  - **But tend to release CO_2 when reformed for use in fuel cell**
- **Ammonia is still difficult to produce from Renewable sources**
  - **"borrows" nitrogen from the atmosphere**
  - **Is effective hydrogen carrier and reforms easily**
  - **Easy to transport**

Load levelling and arbitrage for renewable energy sources

- There is no correlation between renewable energy supply and consumer demand.
- This limits the % renewable energy which can be supplied to a grid to maximum of ~30%.
- Demands significant spinning reserve to cope with natural fluctuation, particularly in wind and wave energy devices.
- Demands significant ramp rates from conventional generators.
- Causes reactive power problems, caused by inductance and capacitance in the transmission system.

Load levelling

- **Load levelling, arbitrage and fault ride through for renewable energy sources**
  - **Varying the time at which power is delivered to the Grid**

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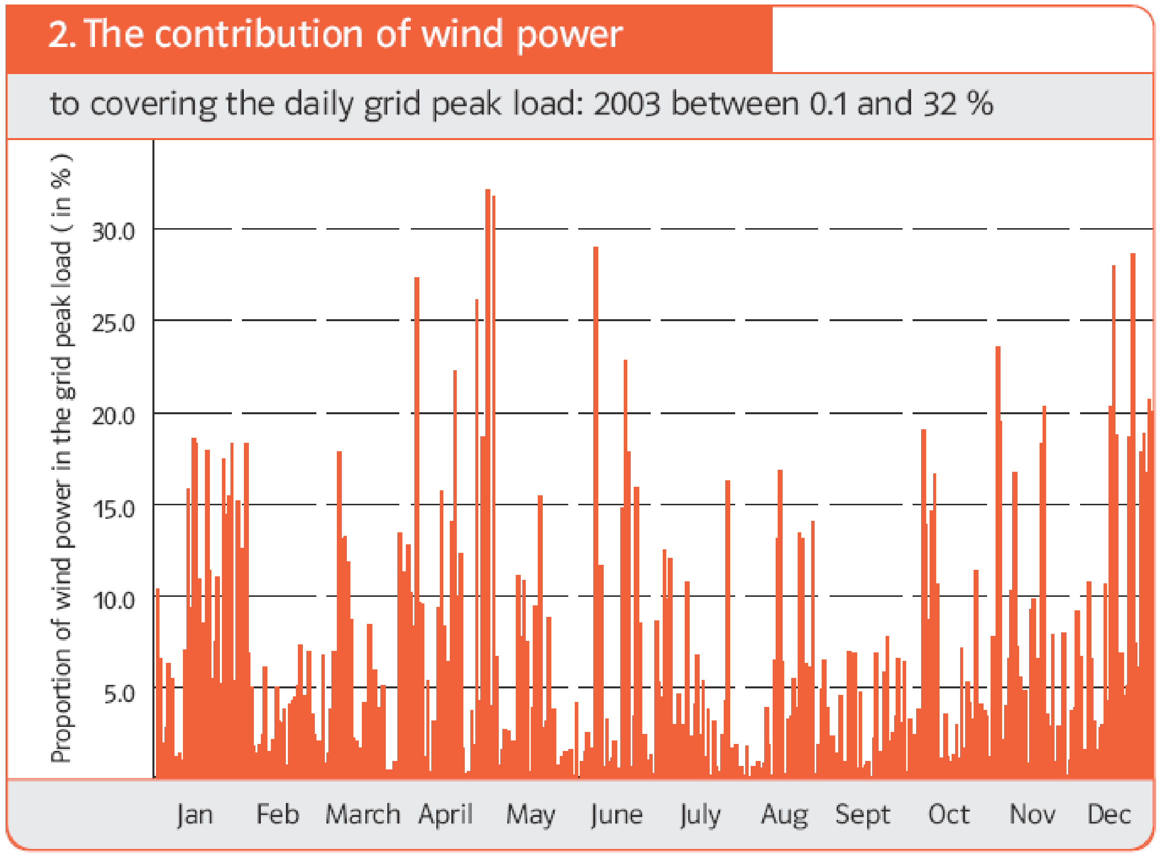
Annual generation rates



average in-feed = ~1/6th of installed capacity

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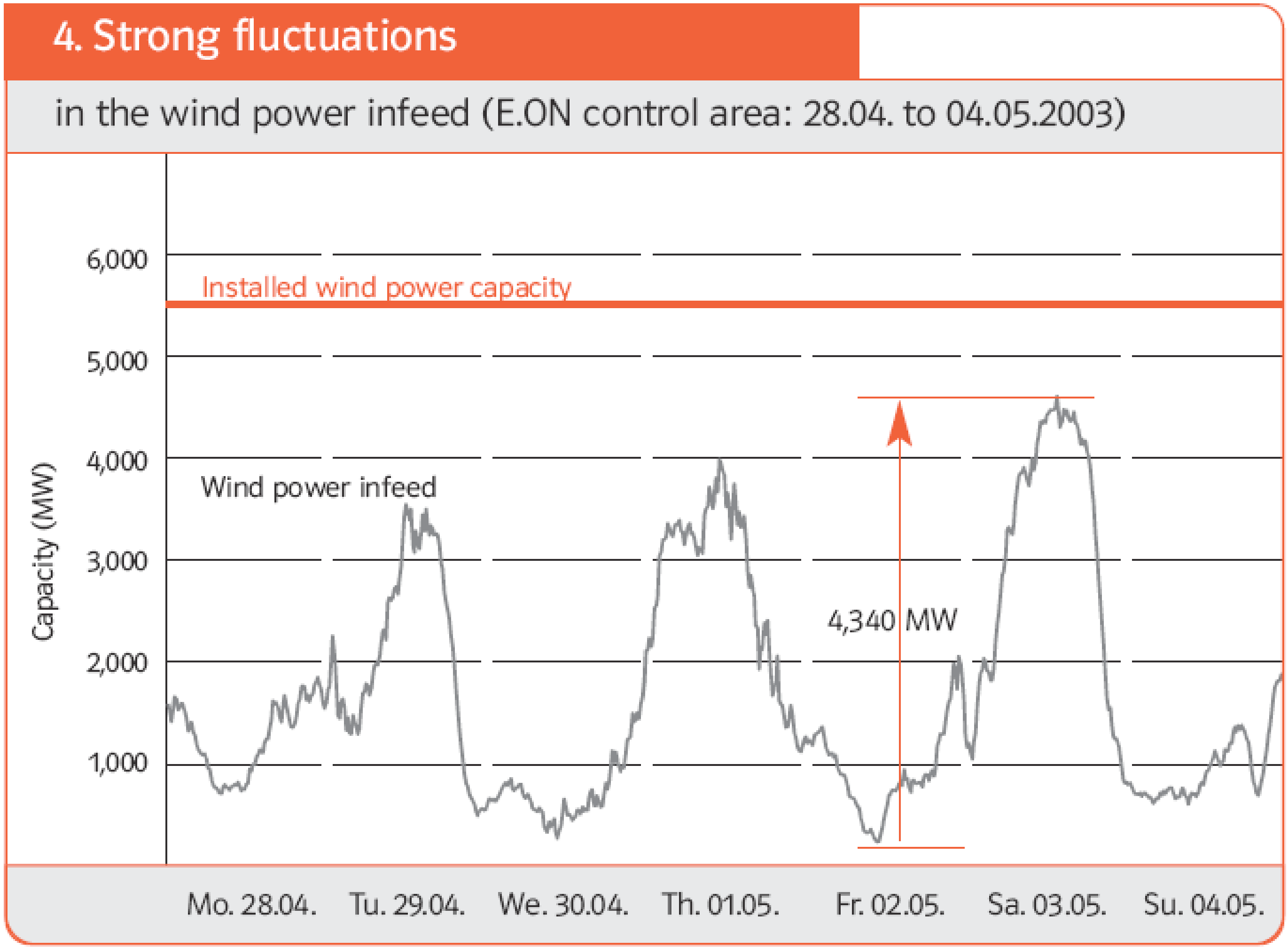
Daily generation rates



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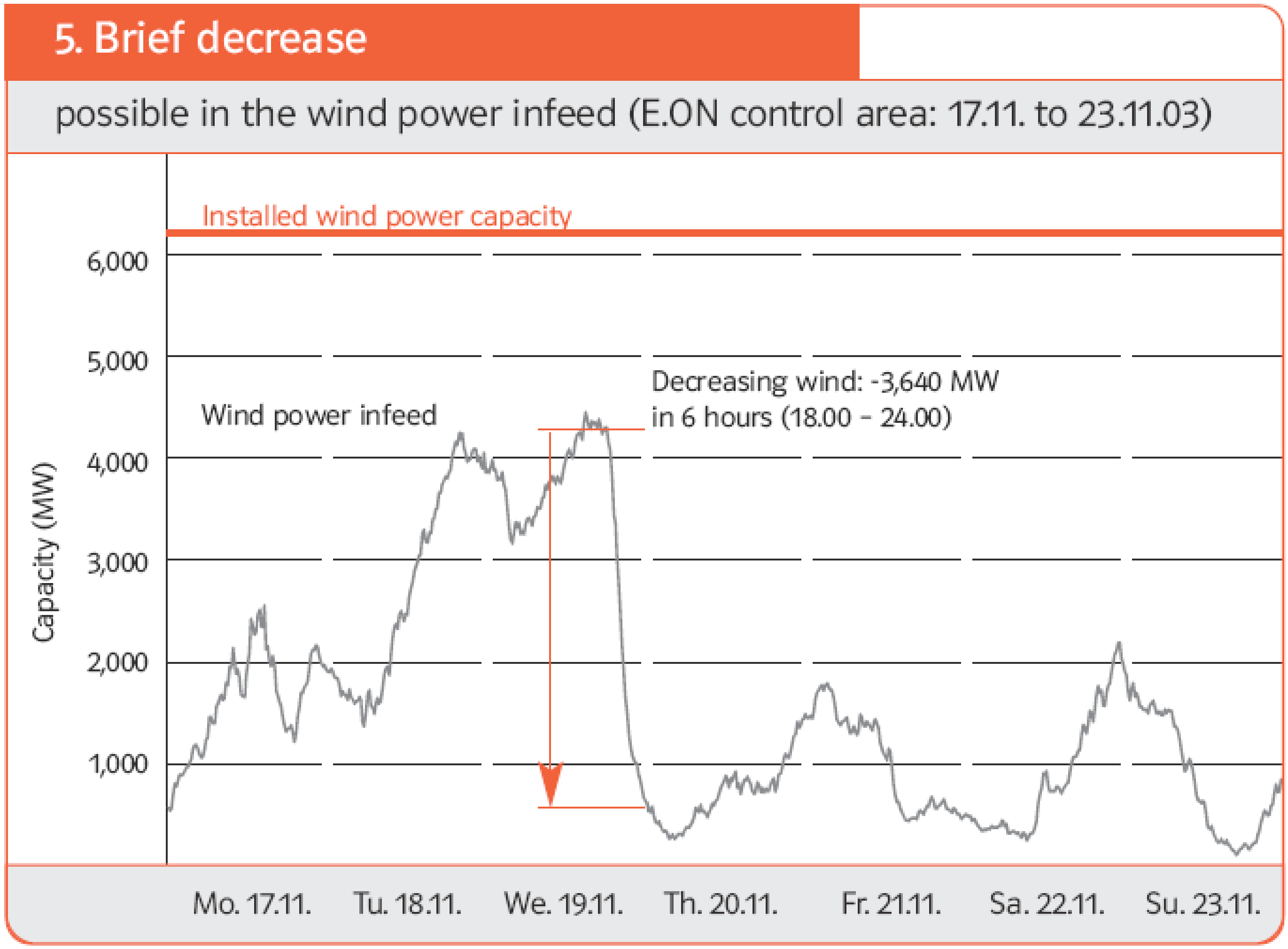
Extreme daily rates



Hourly generation rates

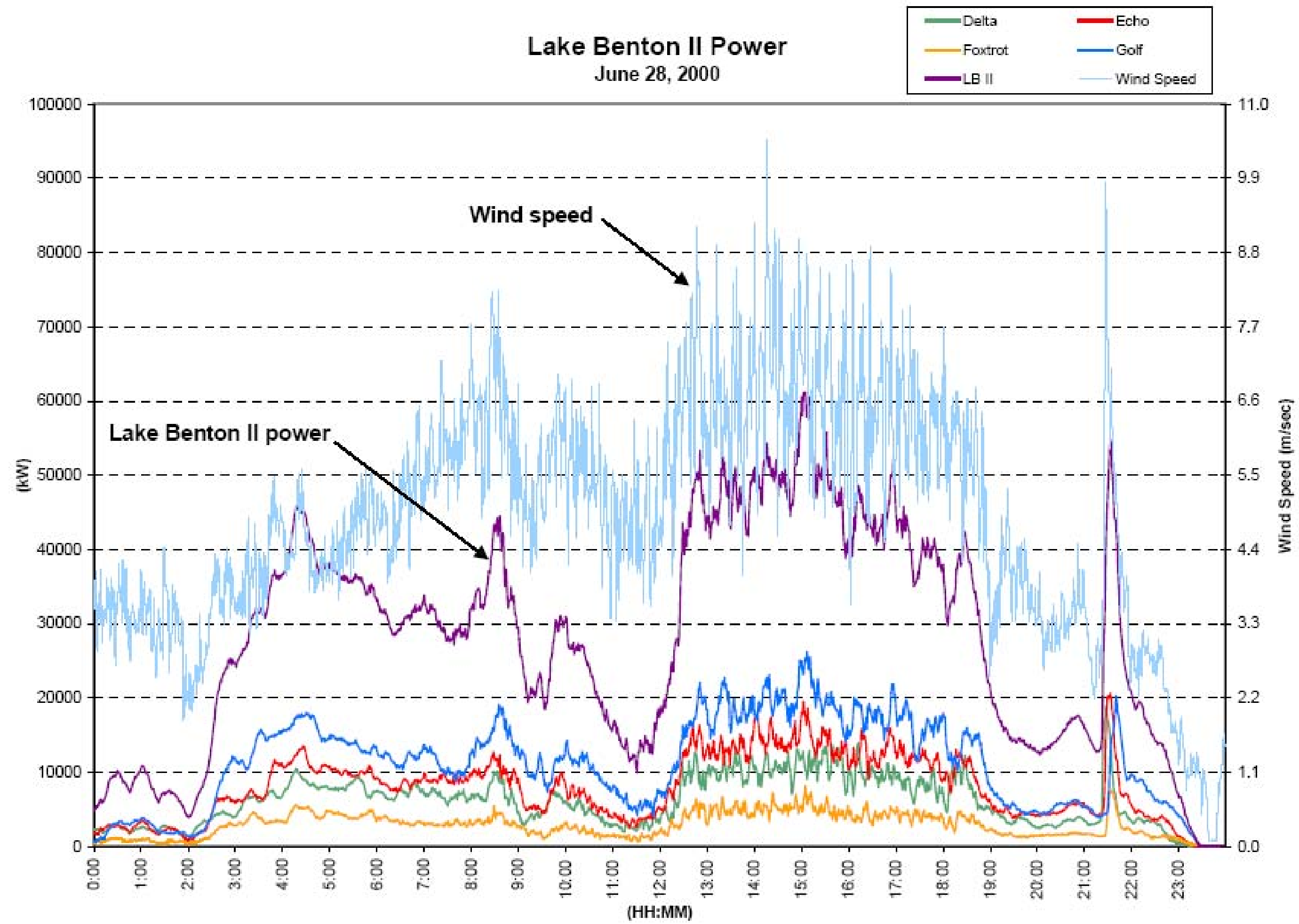


Figure 4-6. Sample daily power output profile

Second by second Ramp rates

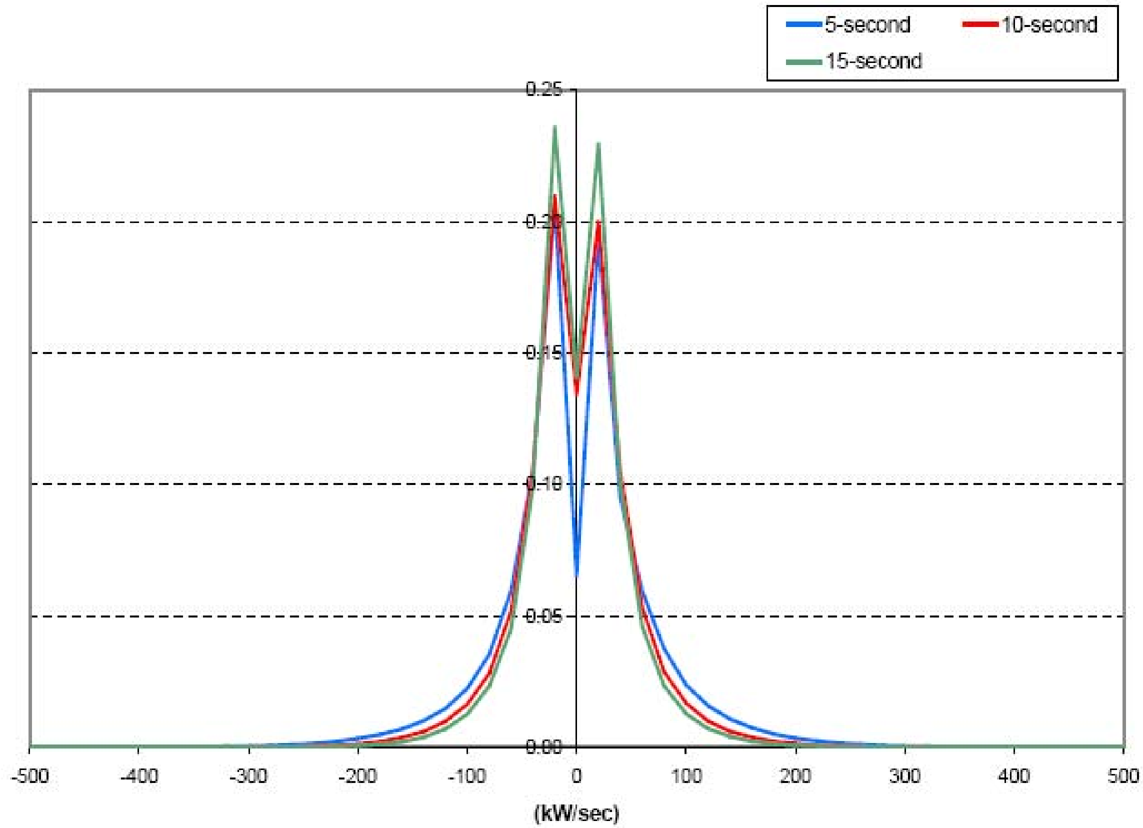


Figure 4-4. Distribution of ramping rates (1)

To regulate the output ±220 kW/s (or about 0.2% of the total installed capacity). This range would cover 99% of all ramping rates for 103.5 Mwatt of wind capacity

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Possible energy storage solution for renewable sources

- **Fuel vectors (hydrogen carriers)**
  - **Use the renewable energy to generate a Storable fuel**
  - **Combined with fule cells to generate electricity**
- **Flow cell or Redox system**
  - **Regenersys**
  - **VBR**
  - **Plurion**
- **Flywheels for sort term power surges and power factor correction**

Conclusions

- **Energy storage report contains lots of valuable background information**
- **“killer apps” for storage are:**
  - **Fuel vectors**
    - **To provide fuel for future transport requirements**
    - **To match electric grid supply with demand**
  - **Renewable energy power optimisation**
    - **Redox (flow cells)**

Data sources

Principle references:

E.ON Netz GmbH-Wind power 2003 – statistics

Institut für Solare Energieversorgungstechnik (ISET)

Wind Power monitoring report - Yih-Huei Wan
July 2001 NREL/TP-500-30032

Wind Power Plant Monitoring Project Annual Report
Yih-Huei Wan July 2001 . NREL/TP-500-30032

ITI Energy Storage Members Report