Karlsruhe Institute of Technology

LIQHYSMES – a Novel Hybrid Energy Storage Option for Buffering Short- & Long-Term Imbalances between Electricity Supply & Load

Michael Sander

Institute for Technical Physics

- Introduction: Energy Storage Options
- Former SMES Activities at the Research Centre Karlsruhe
- Today's Motivation I: New Conductor Options
- Today's Motivation II: Renewables
- LIQHYSMES: Concept & First System Studies
- LIQHYSMES: Model Plant & Buffering Process
- Some Implications of Size & Cost Estimate
- Summary & Conclusions

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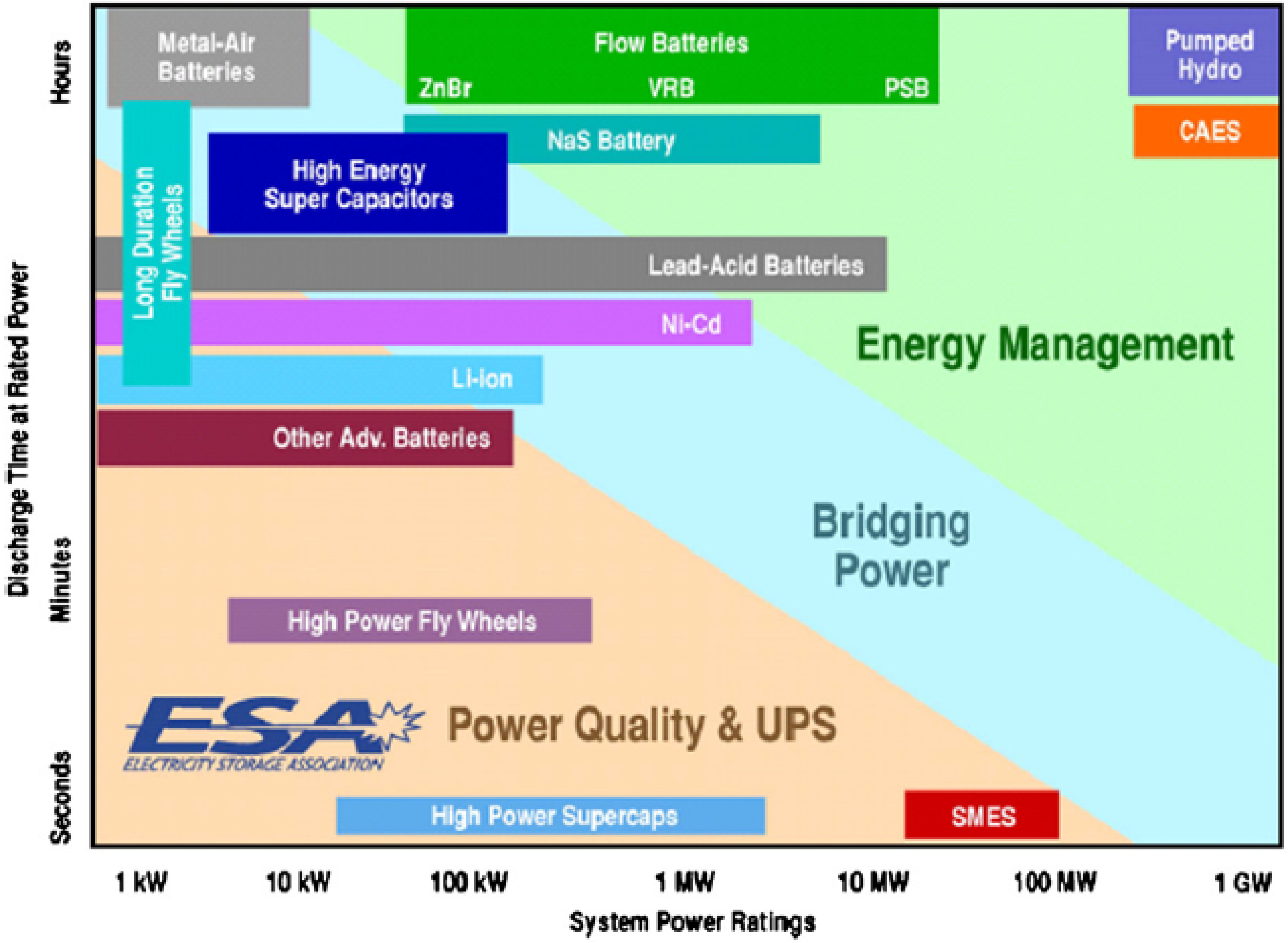
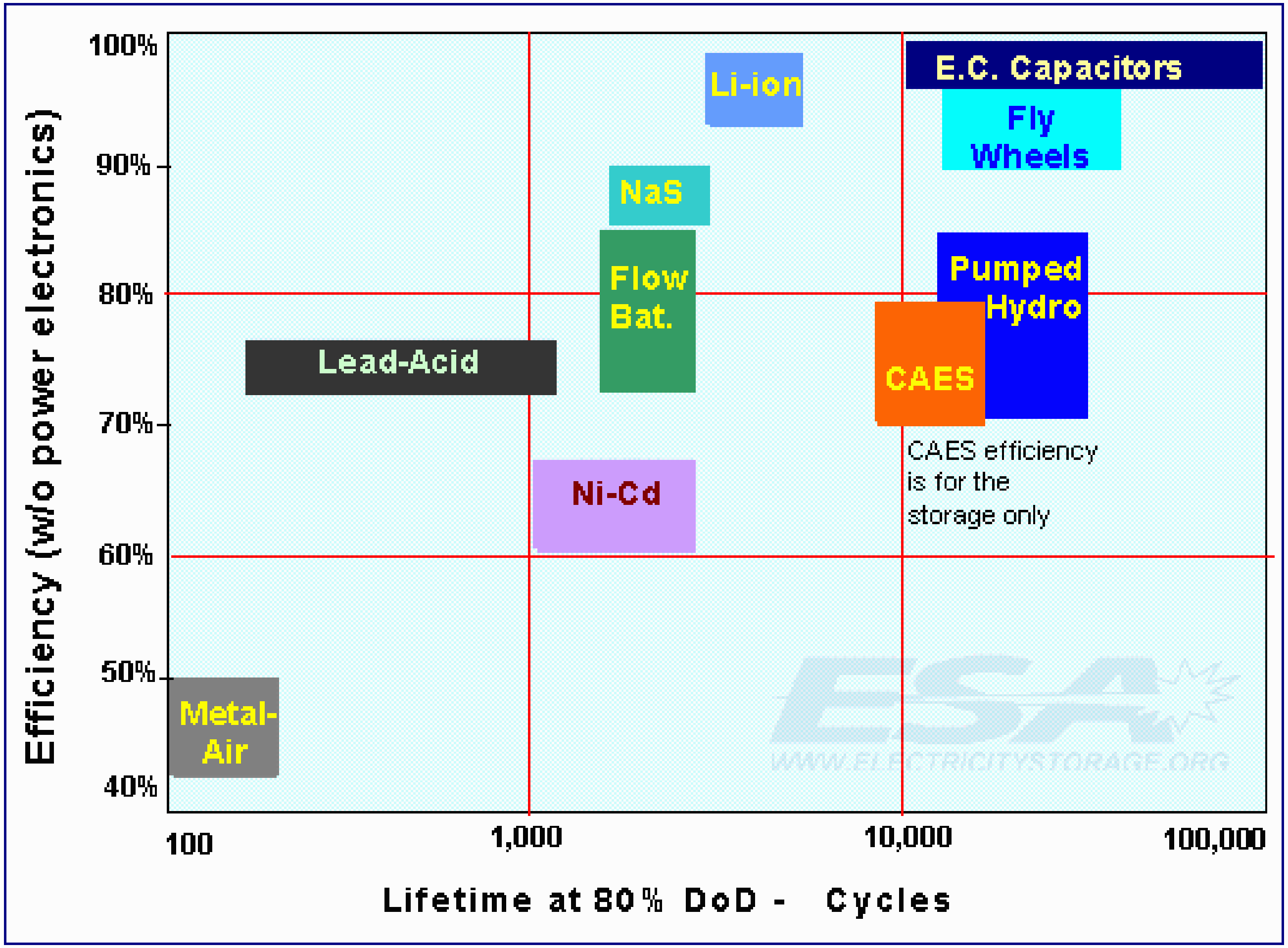
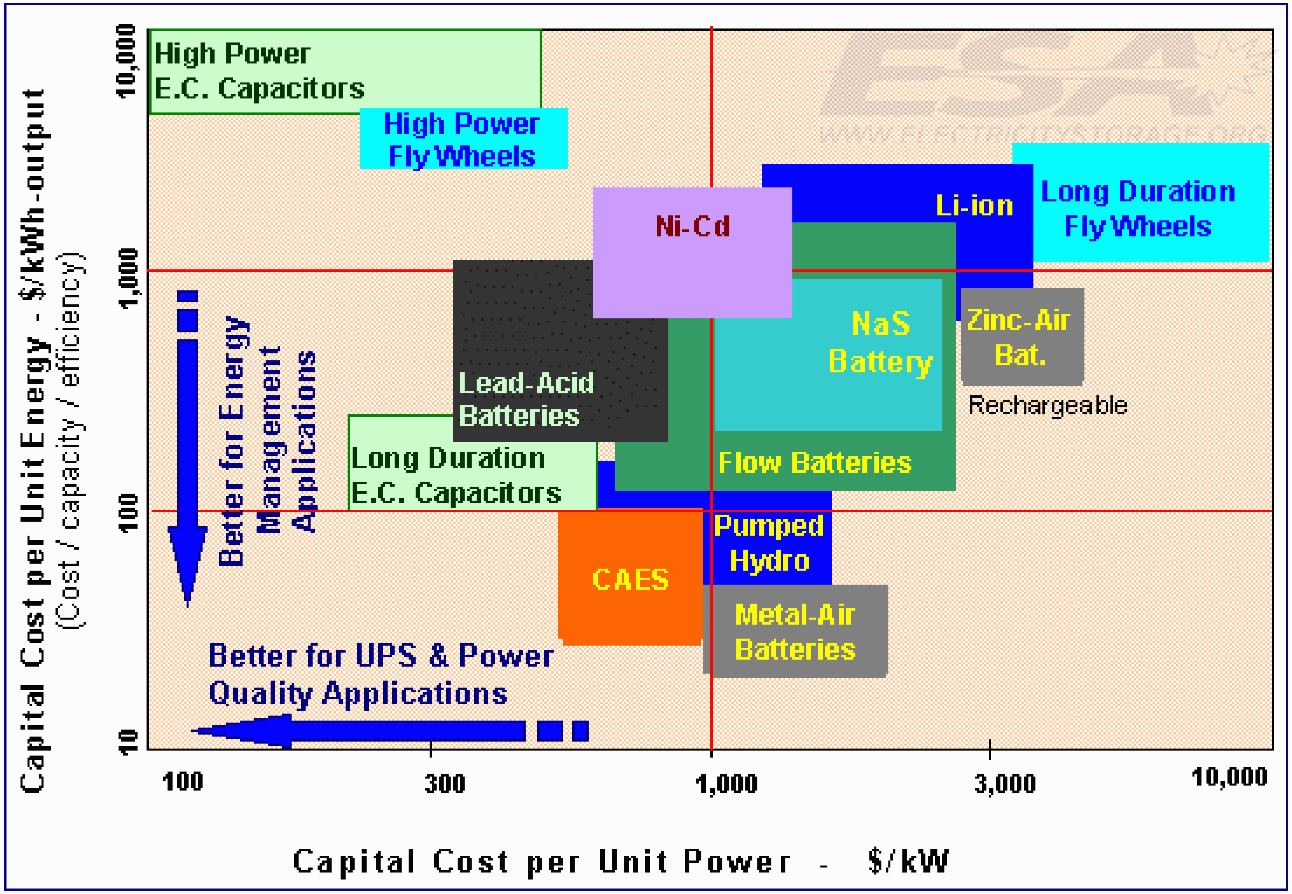
Energy Storage: Power & Energy Ratings



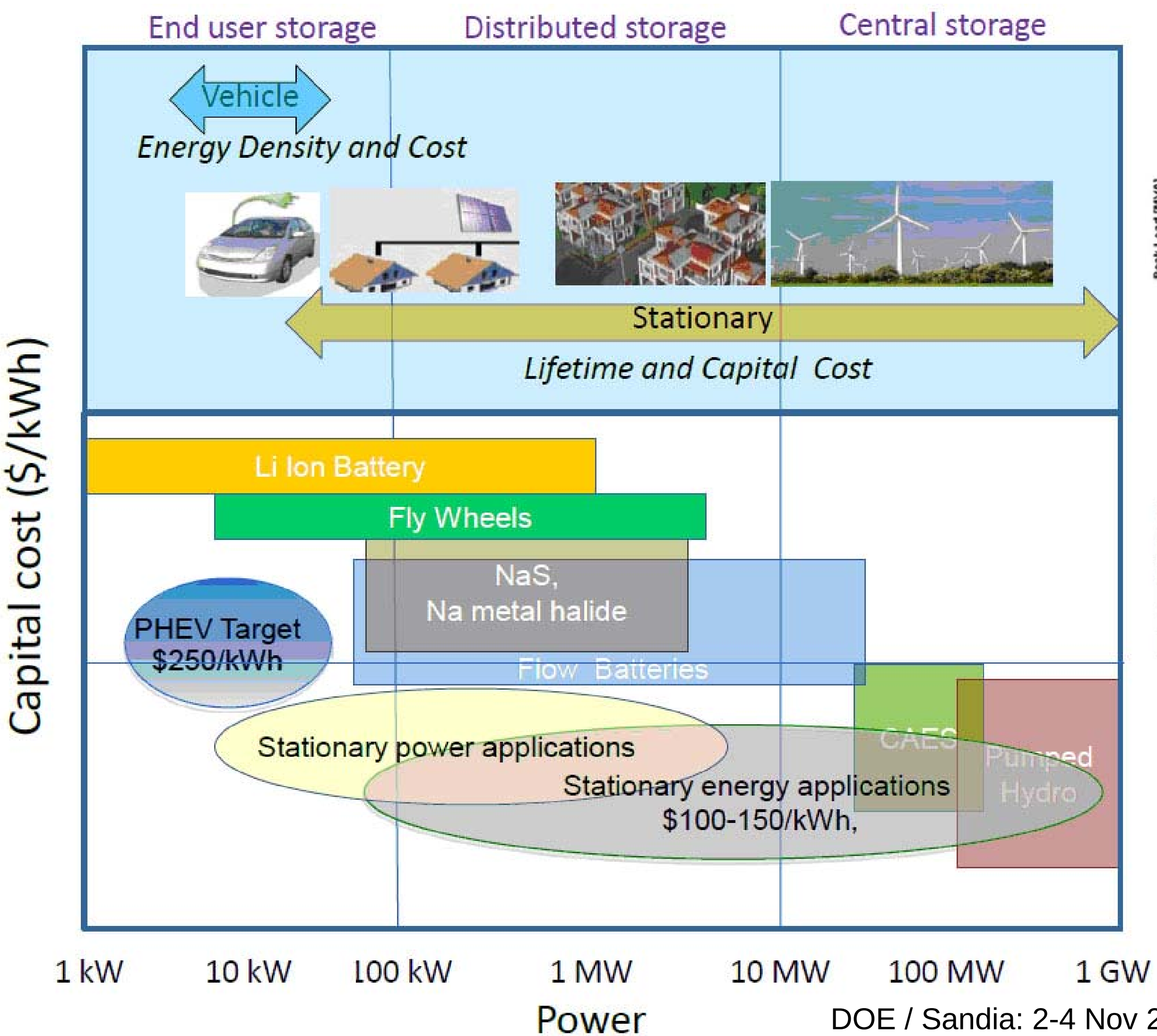
Energy Storage: Efficiency & Lifetime



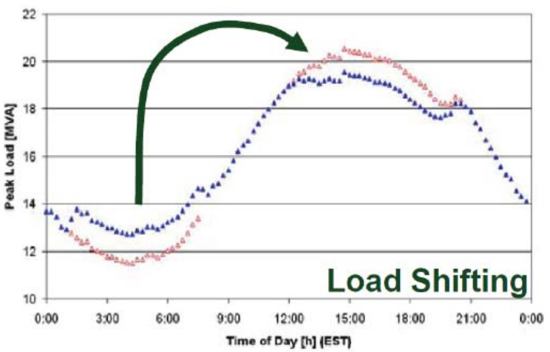
Energy Storage: Cost per Power & Energy

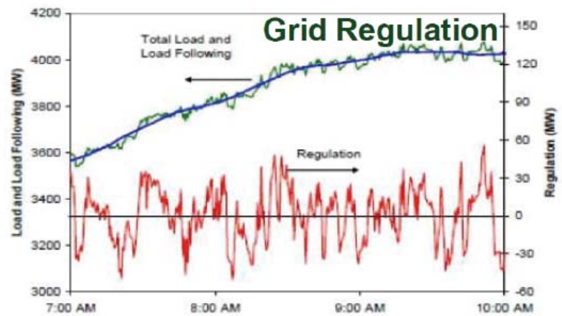


Energy Storage: Cost & Cost Targets



1 minute to hours:
power / energy





1 cycle to 1 minute:
frequency / voltage

DOE / Sandia: 2-4 Nov 2010 Energy Storage Systems Program

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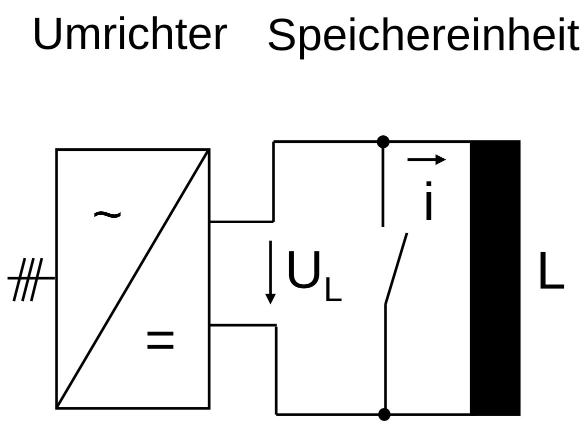
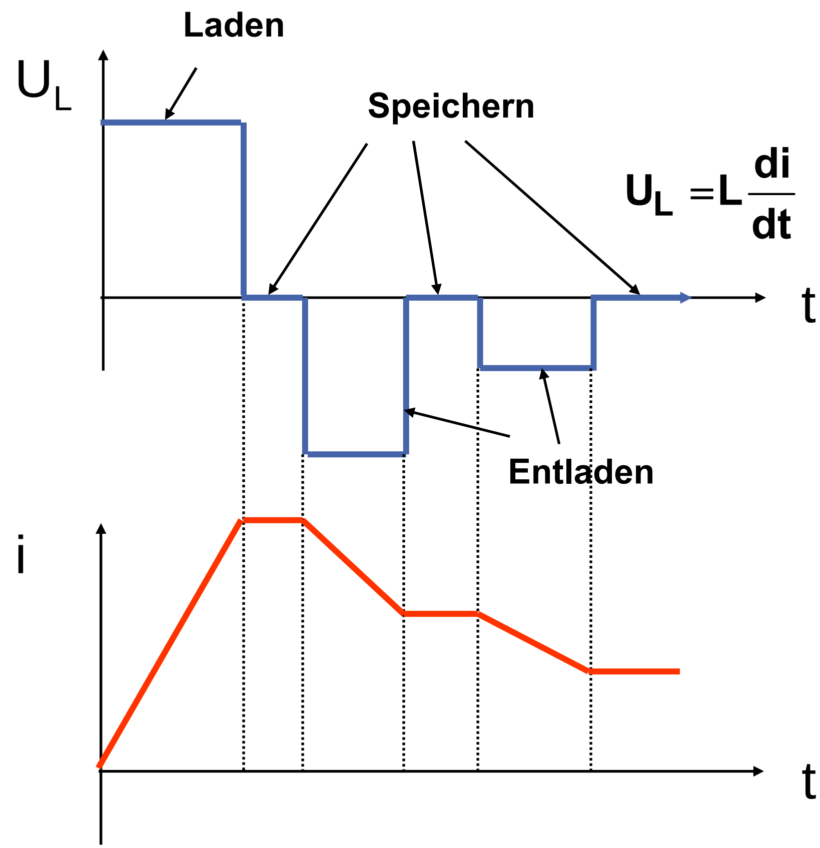
Das SMES Speicherprinzip





Gespeicherte Energie $Q = \frac{1}{2} L\, I^2$

Übertragene Leistung $P = U_L\, I$

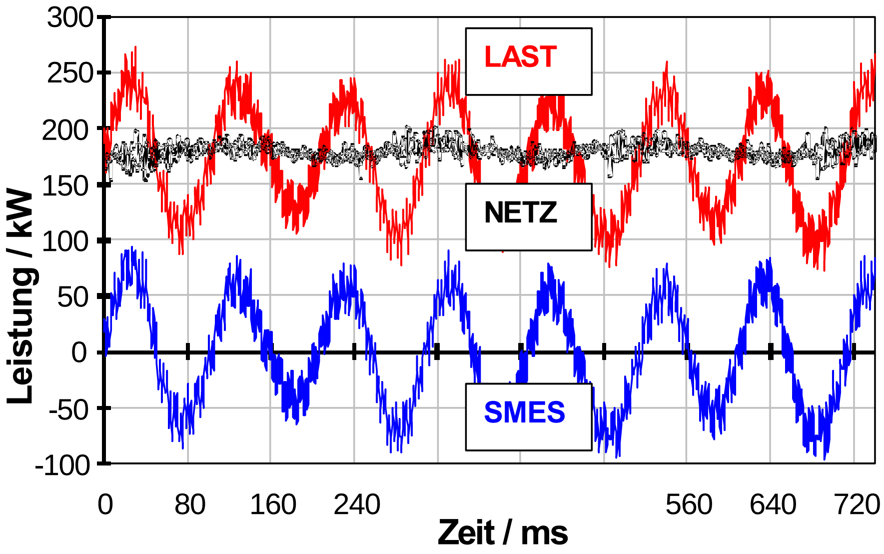
SMES Energiedichte $\frac{Q_{max}}{V} = \frac{B^2}{2\,\mu_0}$

SMES Kompensator zur Flickerkompensation

Daten

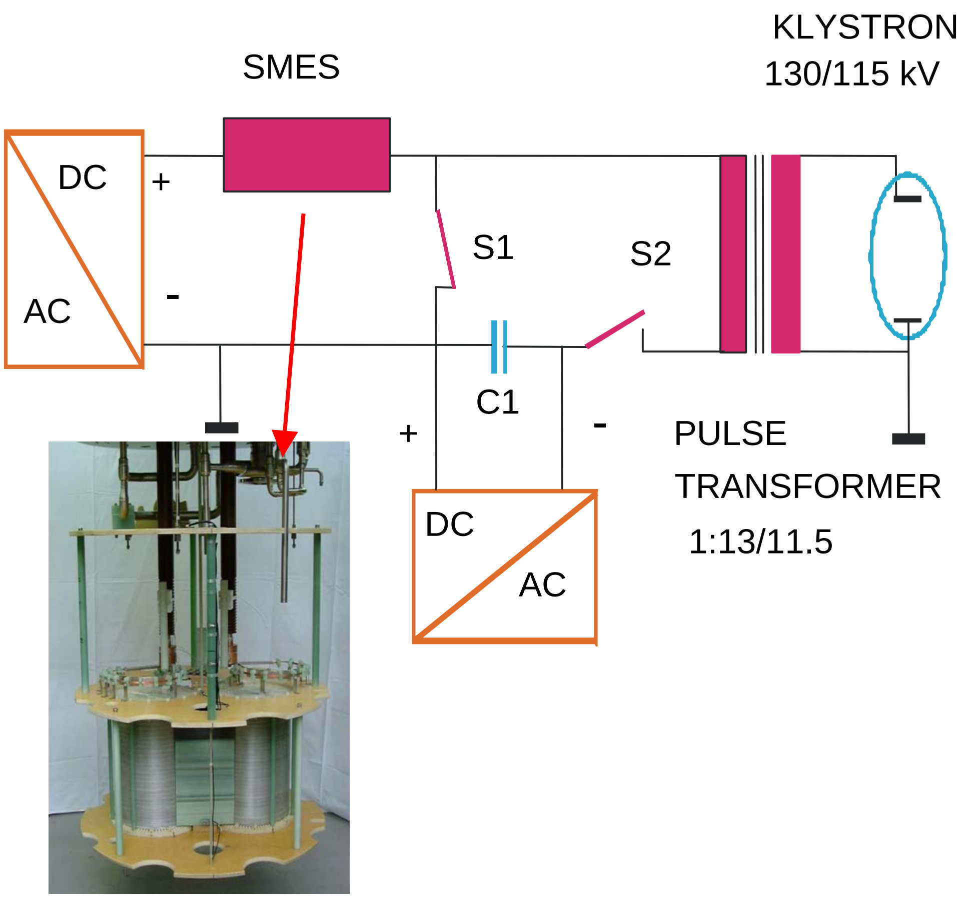
• Anzahl der Spulen	10
• Betriebsstrom	300 A
• max. Strom	430 A
• Gesamtinduktivität	4,5 H
• max. Feld	4 T
• Spannungsabfall	700 V
• Gesp. Energie @ 300 A	203 kJ
• Gesp. Energie @ 430 A	416 kJ

SMES Kompensator zur Flickerkompensation



Weltweit erster Feldtest eines SMES Systems in 1997 !

25 MW Pulsleistungsmodulator



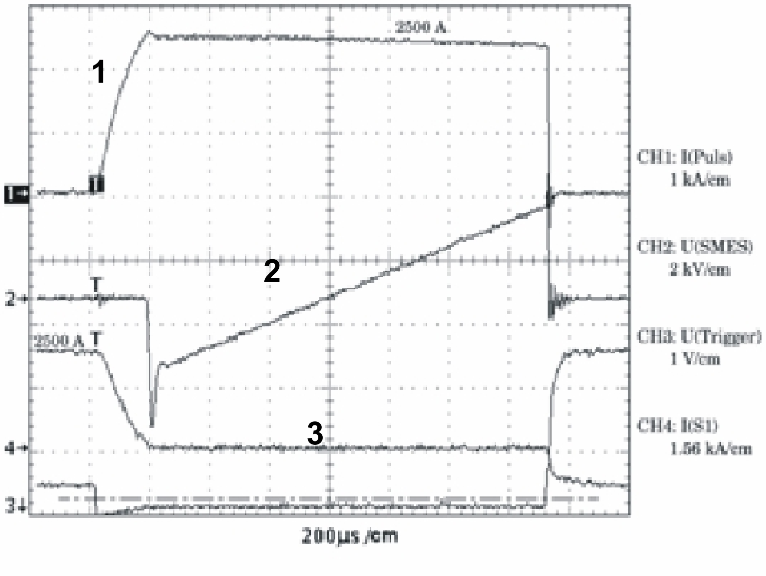
Pulsdaten

- Länge 1,7 ms
- Leistung 17..25 MW
- Frequenz 5..10 Hz
- Flat top ± 0.5 %

Spulendaten

- Induktivität 70 mH
- Magnetfeld 4T/2600 A
- Max. Spg. 7 kV
- Max. dB/dt 100 T/s
- Gesp. Energie 237 kJ

25 MW Pulsleistungsmodulator



1: Pulse current 0 – 2500 A – 0,
2: SMES-voltage max 4 kV
3: current in SMES-switch S1

Aufsicht auf SMES und Teile der Leistungselektronik

Weltweit erstes System für 25 MW Pulsleistung erfolgreich am ITP in 2003 getestet

Abschluss der Installation bei DESY in 2007

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SMES: LTS & New Conductor Options

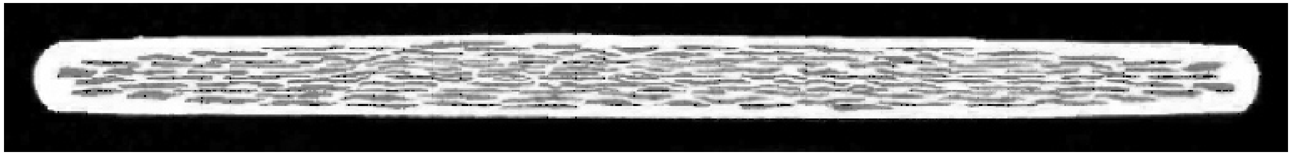
- **only small Low Temperature Superconducting (LTS) systems operated at LHe temperature (~4 K or -269 °C) have been commercially available up to now**
- **up to about 20 SMES systems of up to a few MW & a few MJ are or were in use worldwide for grid stabilization, UPS applications etc.; some devices may be in use for military purposes**

The cost for LTS-based SMES systems and their cryogenic infrastructure has prevented a broader utilization.

Current Options for Higher Operating Temperatures:

- **123-HTS (YBCO) operated up to ~ 4T@50K , 7T@30K or 10T@20K**
- **Bi-2223 operated up to ~ 4T@27K, 7T@20K or 10T@10K**
- **MgB2 operated up to ~ 4T@20K or 7T@10K**

SMES: New Conductor Option Bi-2223



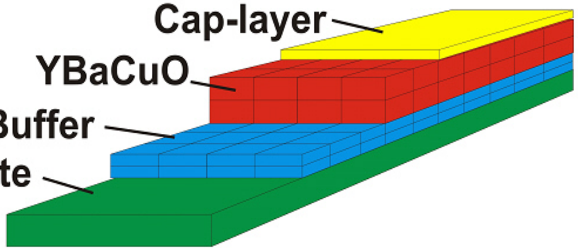
multi-filamentary tapes 4mm x 0.2mm

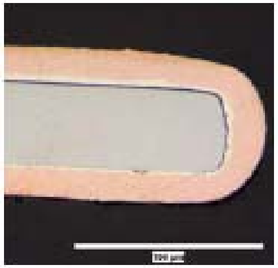
Sumitomo Electric Industries

8.1T@20K ; 20cm bore; cryogen-free

0.5T@77K ; 5cm bore; LN_2-cooled

SMES: New Conductor Option 123-HTS

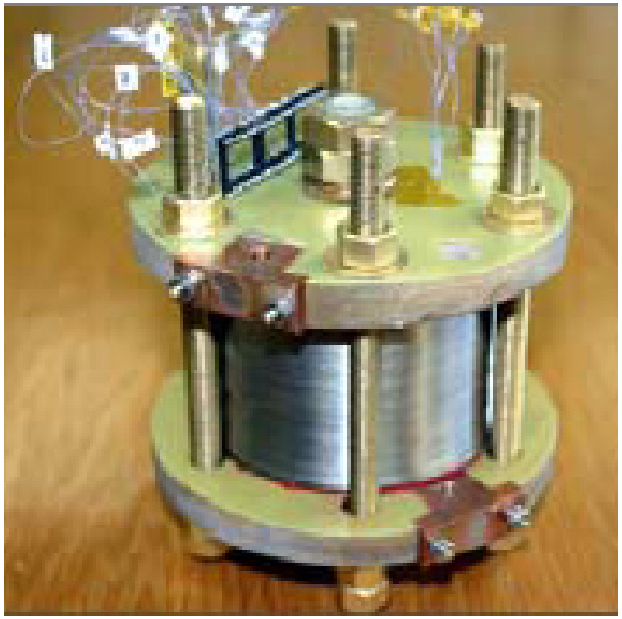




Roebel cable (Goldacker et al., ITP)

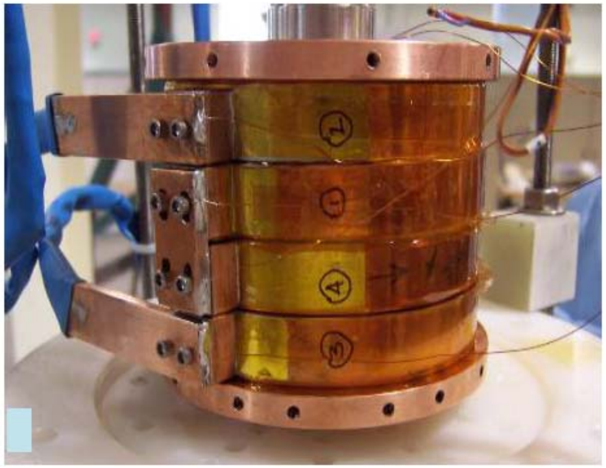
coated conductors

SuperPower Inc.

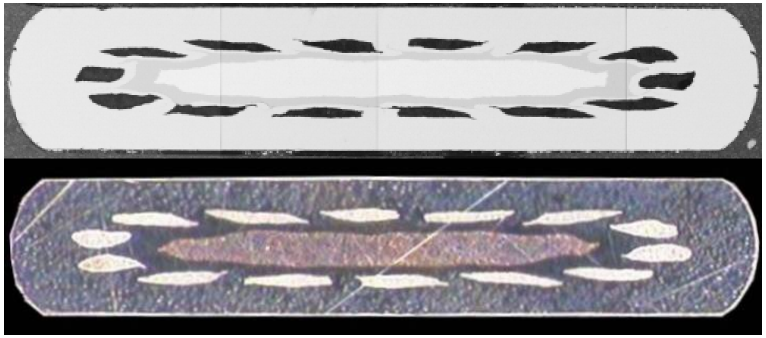


9.8T@4.2K or
26.8T@4.2K in 19T ;
1cm bore

1.1T@77K or
2.4T@64K



SMES: New Conductor Option MgB_2



2.1T@16K ;
racetrack coil with
iron yoke

multi-filamentary tapes & wires

Columbus Superconductors S.p.a.

0.5T@20K ;
60cm patient gap

3.9T@4K or
3.0T@15K or
2.4T@20K ;
3.8cm bore

HyperTech Inc.

SMES: New Conductor Options

The performances of conductors achieved already today, allow the design, manufacture and demonstration of SMES systems based on higher temperature superconductors.

AC losses especially for the 123-HTS require particular attention if not fundamental innovations. SMES systems should therefore first address those applications which do not require a fast ramping of the field.

Costs for the conductors (especially for Bi-2223 and 123-HTS) and (despite higher operating temperatures) also for the cryogenics remain key issues.

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Renewables (RES): EU & Germany by 2020

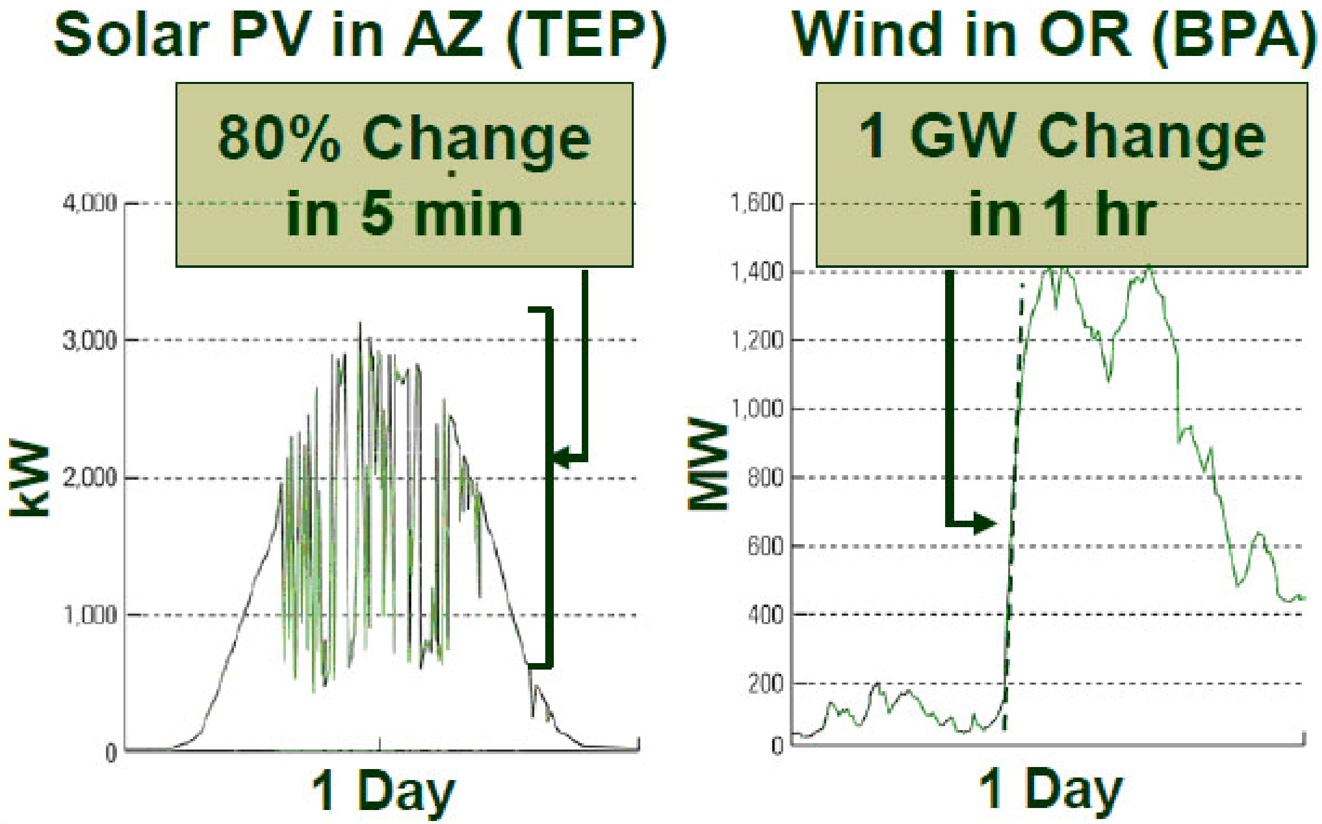
EU 2009 Renewable Energy Directive (2009/28)
& EREC Technology Roadmap 20 % by 2020

- overall **20% RES target for 2020**
- about **35% RES target for electricity production**: **1,370 TWh**
- **wind**: **~ 477 TWh & 180 GW** and **PV**: **~ 180 TWh & 150 GWp**
- transmission & distribution grid infrastructure, intelligent networks, **storage facilities** …
- **10%** of **transport** fuelled by RES
- international agreements - **30% ?**

Germany: Energiekonzept 2010 Bundesregierung & Nationaler Aktionsplan für EE 2010 (BMU):

- **35% to 38.6% RES target for electricity production in 2020**
- **wind**: **~ 104 TWh & 46 GW** and **PV**: **~ 41 TWh & 52 GWp**

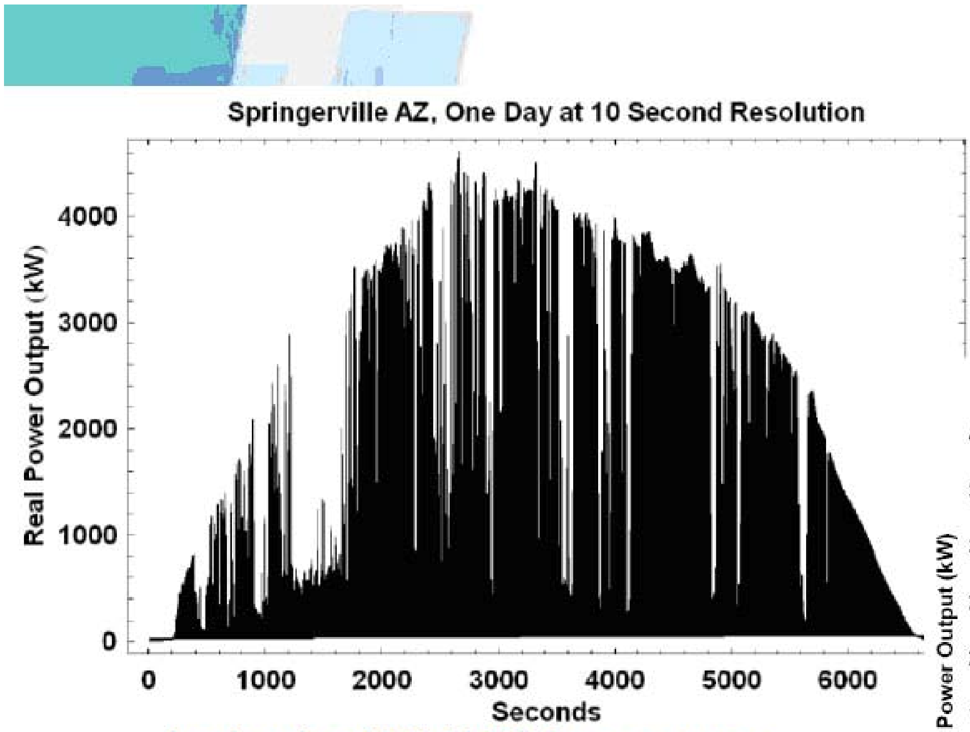
Renewables: Variations



Problem:
Minutes-to-Hours Changes in Power

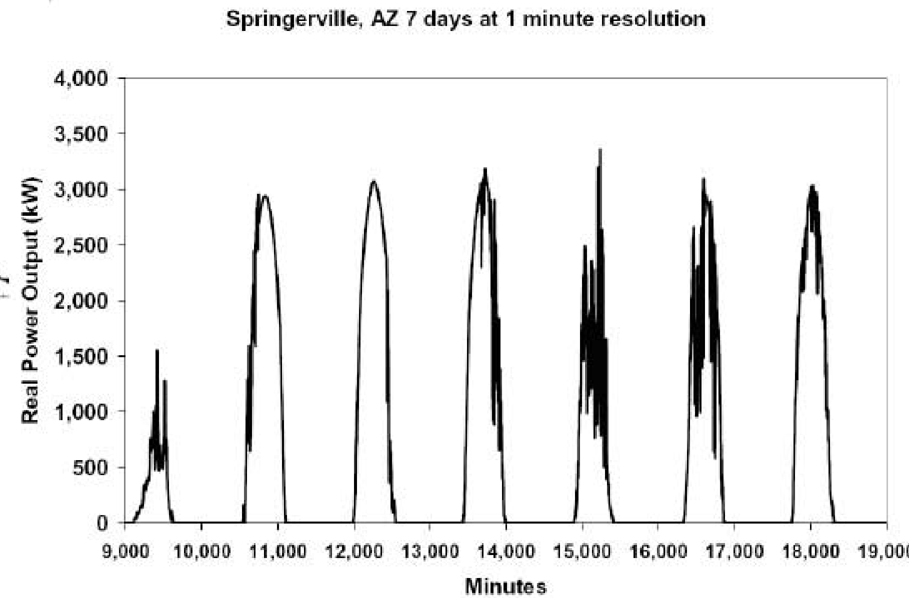
DOE / Sandia: 2-4 Nov 2010 Energy Storage Systems Program

Photovoltaics: Variations



A single 1MW PV resource (distributed generation) can push a feeder into high penetration

"High penetration" - Installed PV amounts to 15-20% of feeder peak load – issues are already being experienced – even at 5%



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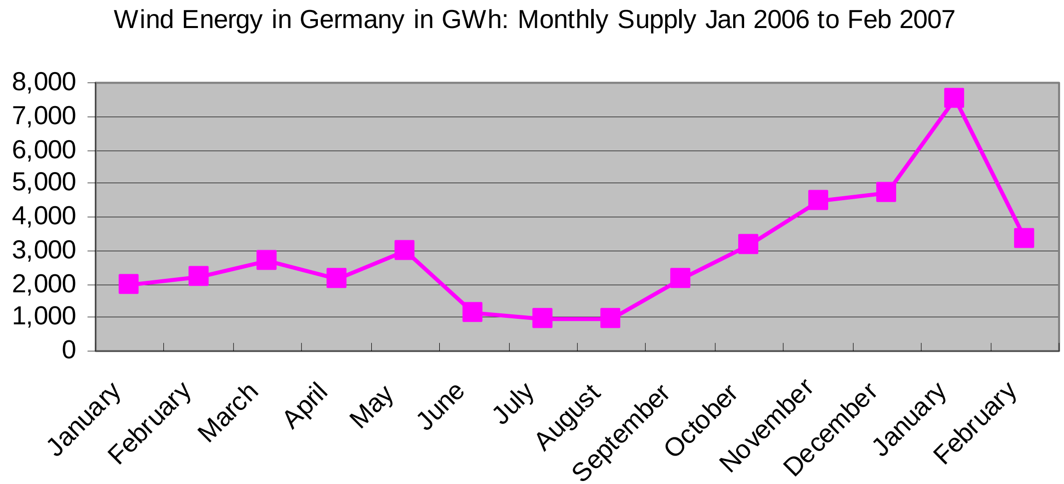
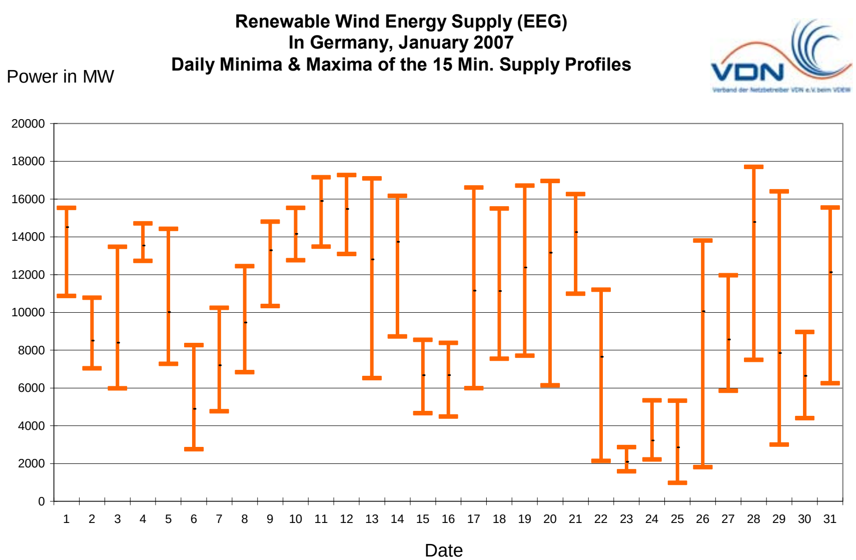
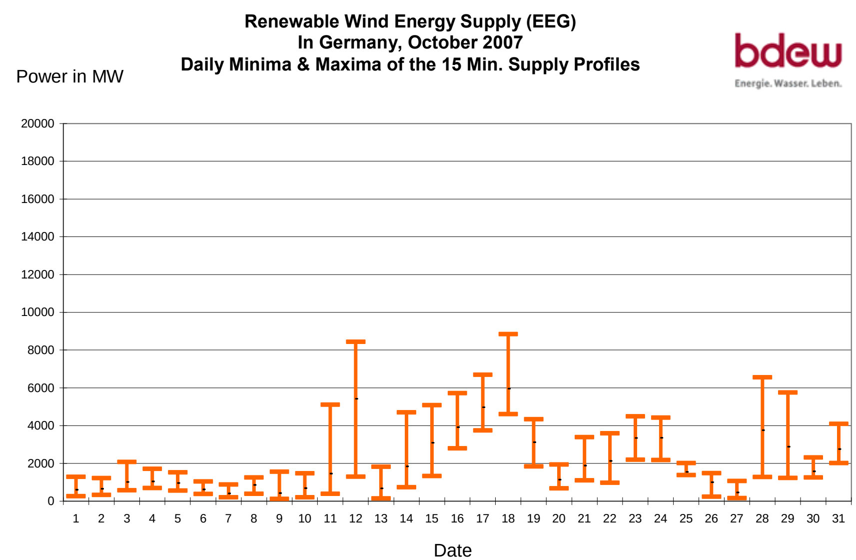
Wind: Variations I



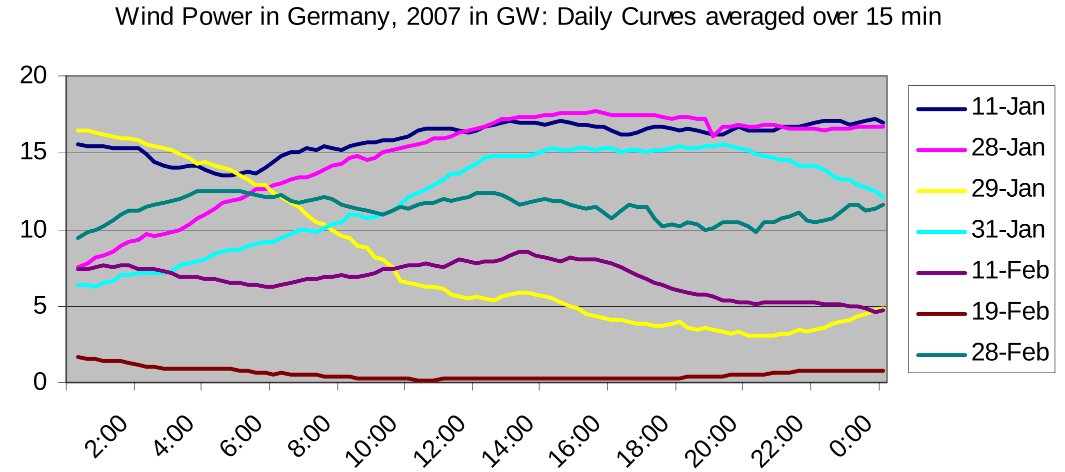
Monthly Supply in GWh
Period: 14 Months
Time resolution: 1 Month

Daily Minima & Maxima in MW
Period: 1 Month
Time resolution: 15 Minutes

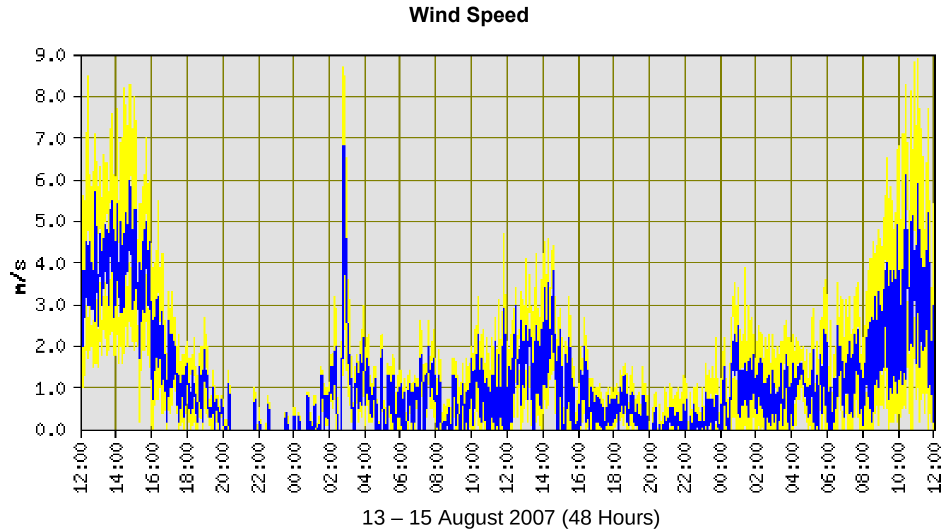




Wind: Variations II



Daily Supply in GW
Period: 1 Day
Time resolution: 15 Minutes

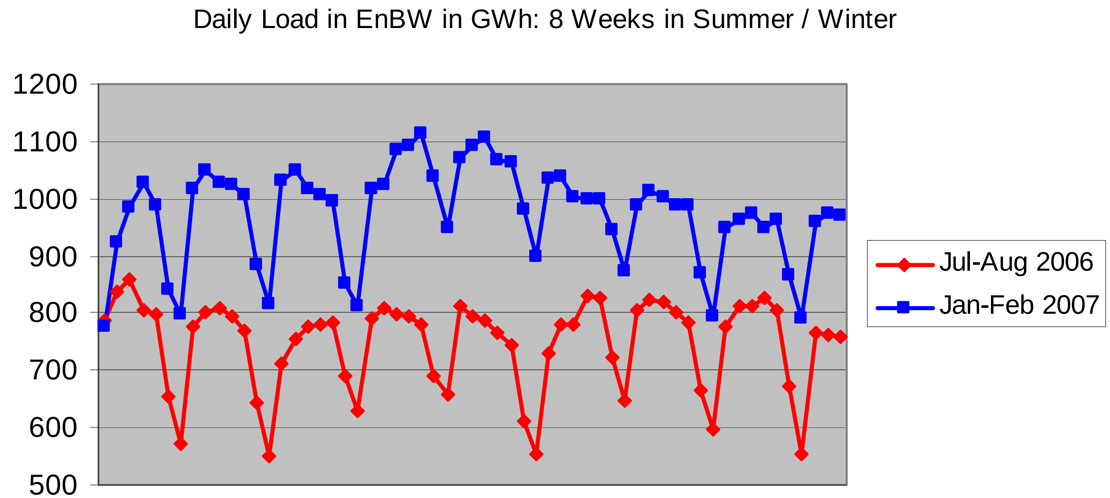


Average & Extreme Wind Speed
Period: 2 Days
Time resolution: 60 Seconds
(measurement well below)

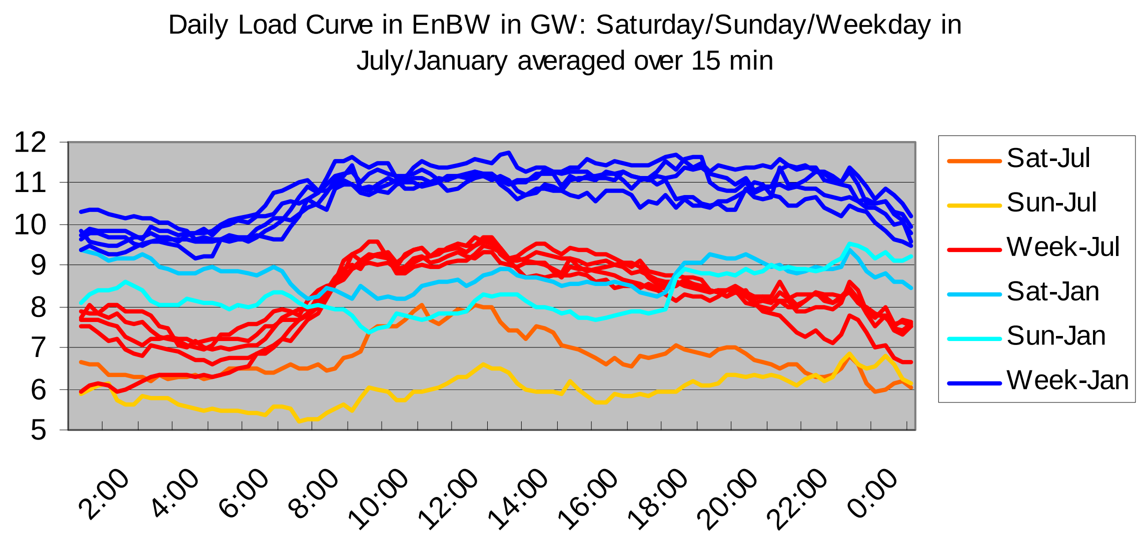
Inertia of Wind Turbine:
Reaction Time ~ 10s of Seconds

Load: Variations I

Daily Load in GWh
Period: 8 Weeks
Time resolution: 1 Day

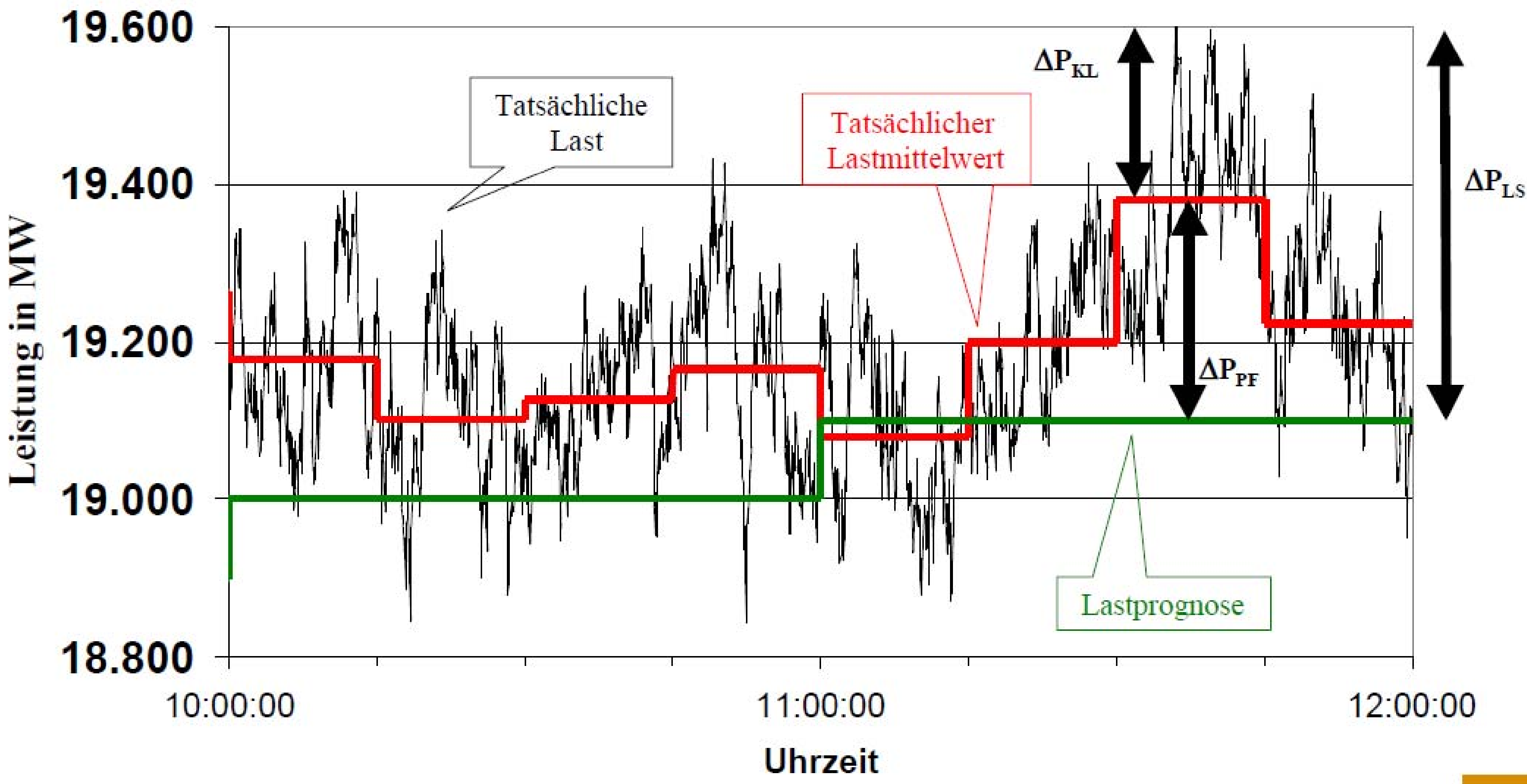


Daily Load in GW
Period: 1 Day
Time Resolution: 15 Minutes



Load: Variations II

Lastprognose und tatsächliche Last

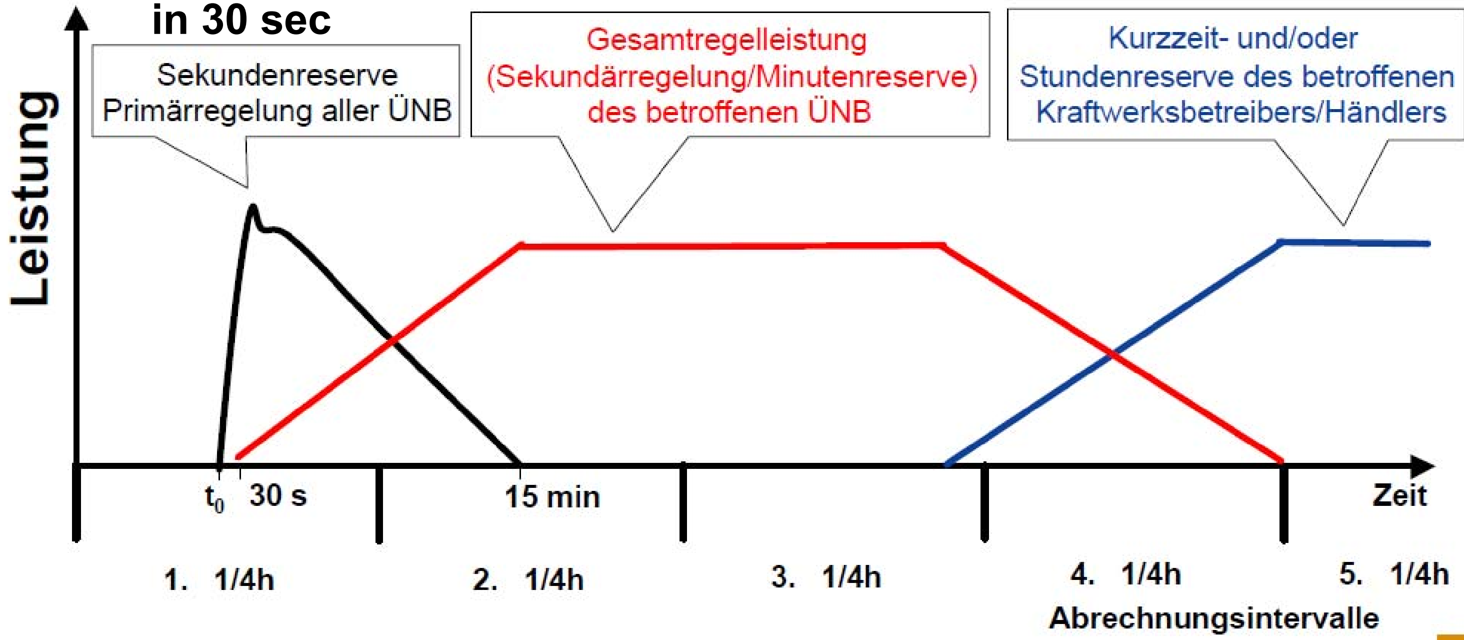


© RWE Net AG - Netzvertrieb

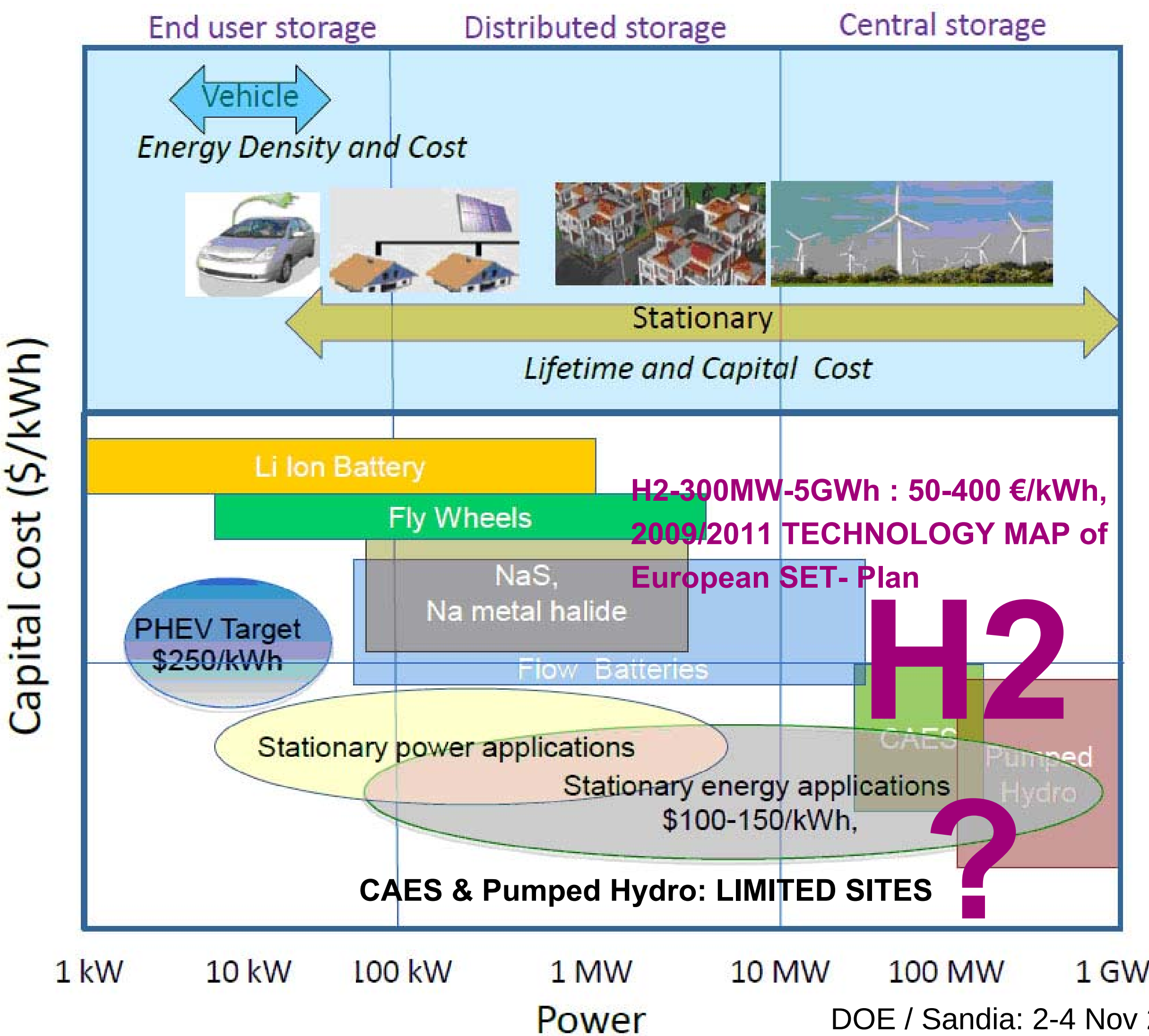
Imbalances: Second, Minute & Hour Control

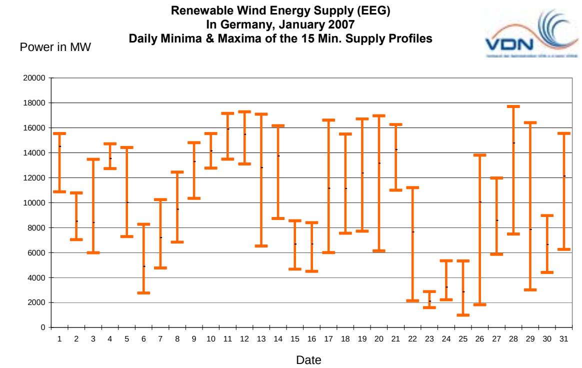
Zeitlicher Ablauf und Abgrenzung des Regelleistungs- und Reserveeinsatzes

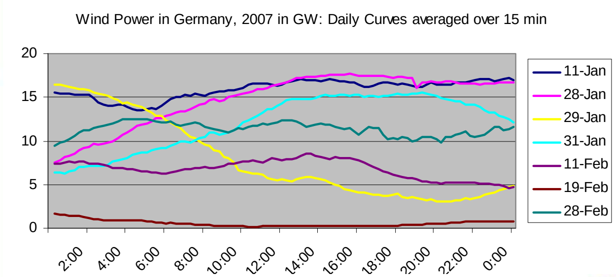
ENTSO-E:
3,000 MW
in 30 sec

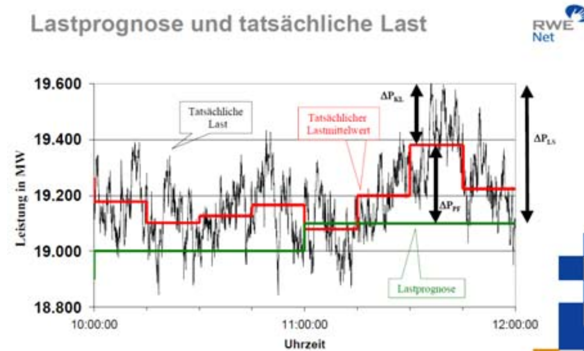


Energy Storage: Cost & Cost Targets









1 cycle to days or weeks …

DOE / Sandia: 2-4 Nov 2010 Energy Storage Systems Program

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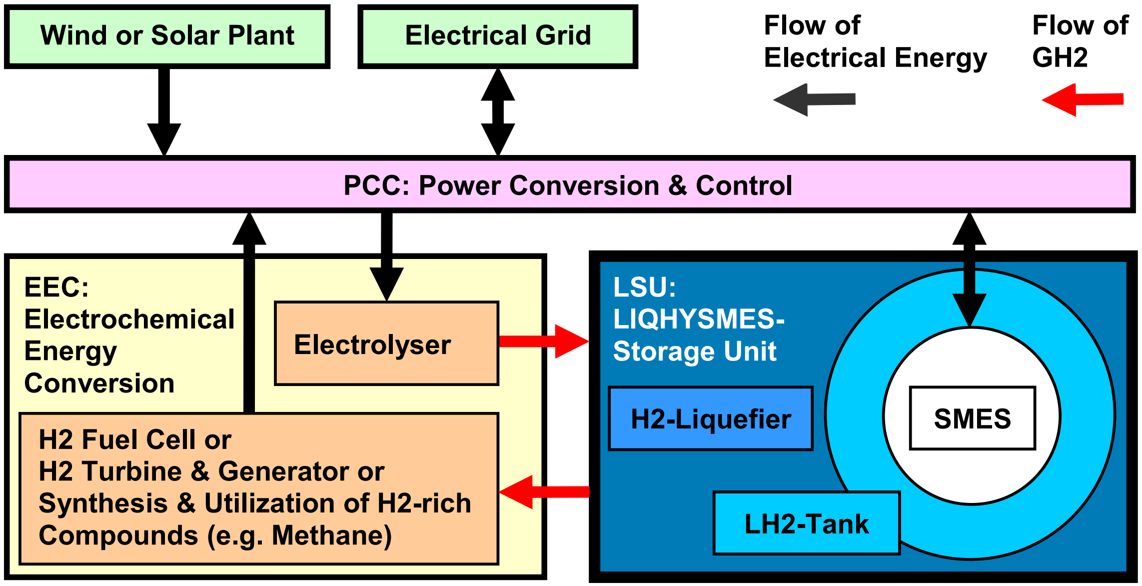
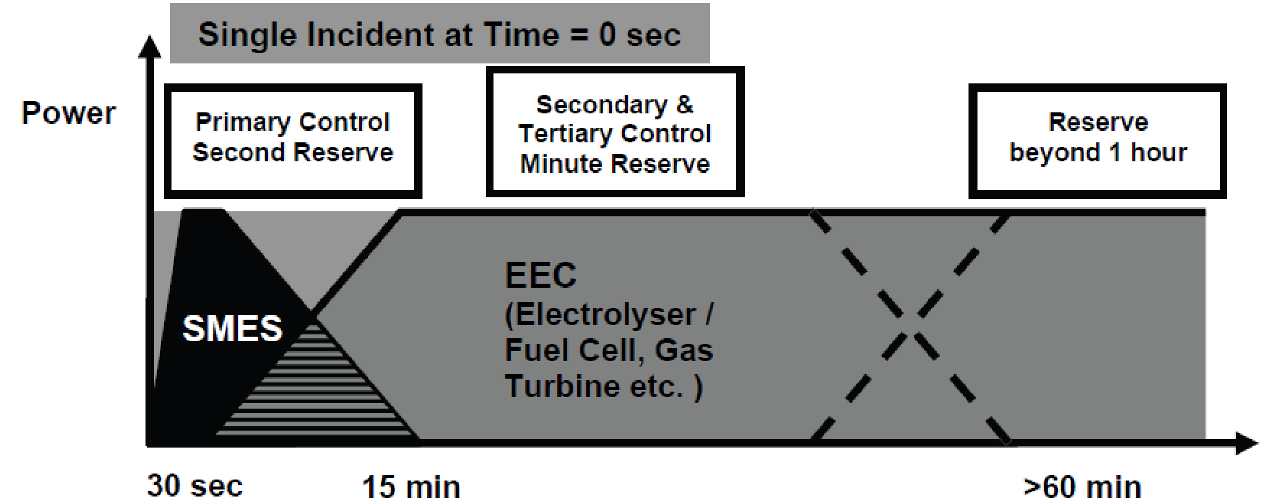
Energy Storage: LIQuid HYdrogen & SMES

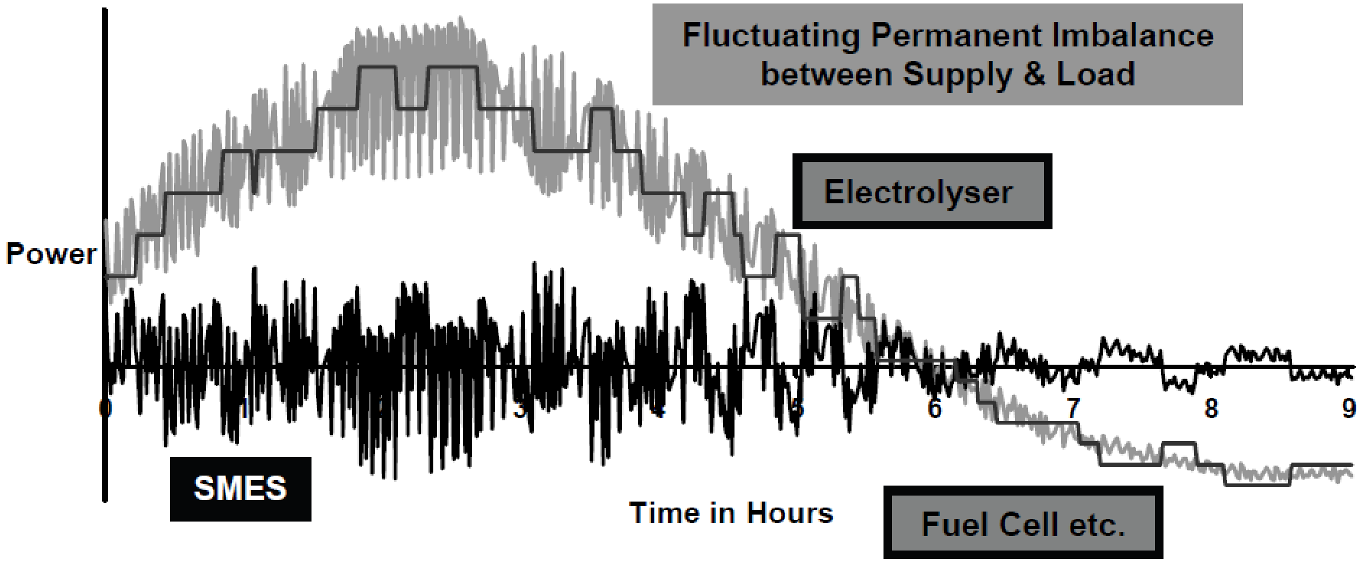


- Power Conversion & Control Unit (**PCC**), Electrochemical Energy Conversion (**EEC**) & LIQHYSMES Storage Unit (**LSU**)
- LH2 fuel & bulk energy carrier: generally applicable & highest volumetric energy density
- SMES: fast & efficient short term electrical energy storage
- LSU: joint use of cryogenic infrastructure
- SMES & modular EEC: smooth flow control & EEC operation close to optimum
- hybrid energy storage to buffer supply / load imbalances from sec up to days

M. Sander, R. Gehring, H. Neumann, T. Jordan, Int. J. of Hydrogen Energy 37 (2012) 14300

LIQHYSMES: Second, Minute & Hour Control





H2 Storage Losses: Compressed GH2 vs. LH2

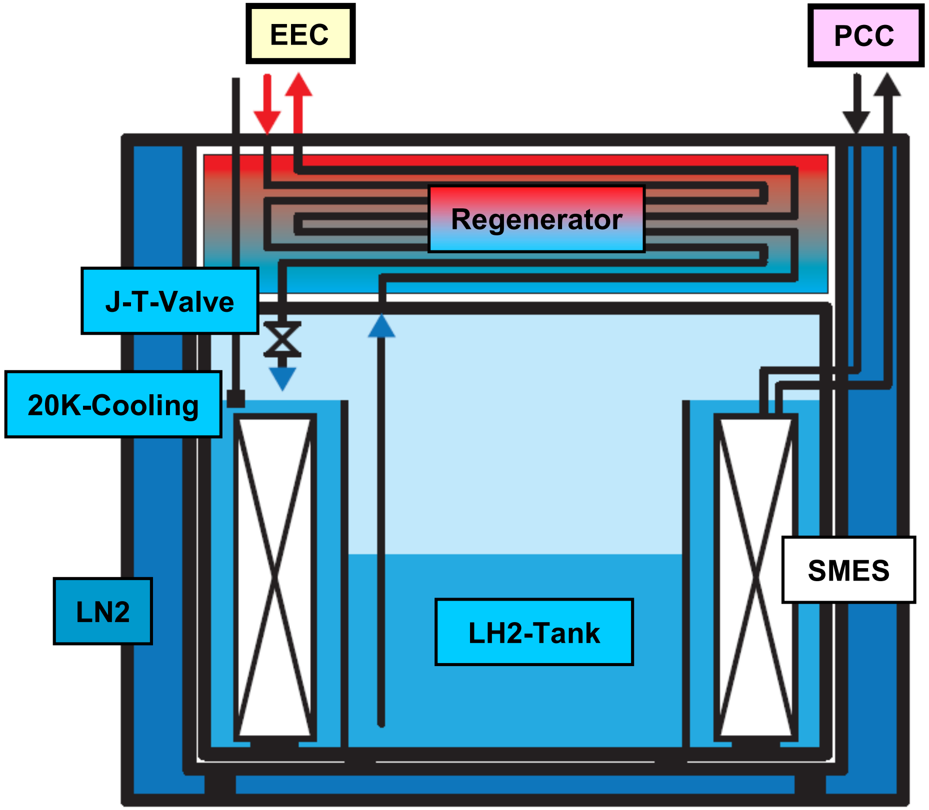
GH2 @ 150-200 bar: natural gas caverns for large central storage systems (appropriate geological formations NEEDED)
LH2: ~ 6X volumetric energy density; distributed GWh-class energy storage @ arbitrary sites

LIQHYSMES Storage Unit LSU:

- Regenerative H2 Liquefier
- LH2 storage tank
- SMES

Regenerative Liquefaction = "Cold Recovery"

Losses should become fully comparable with compressed GH2 @ 150-200 bar

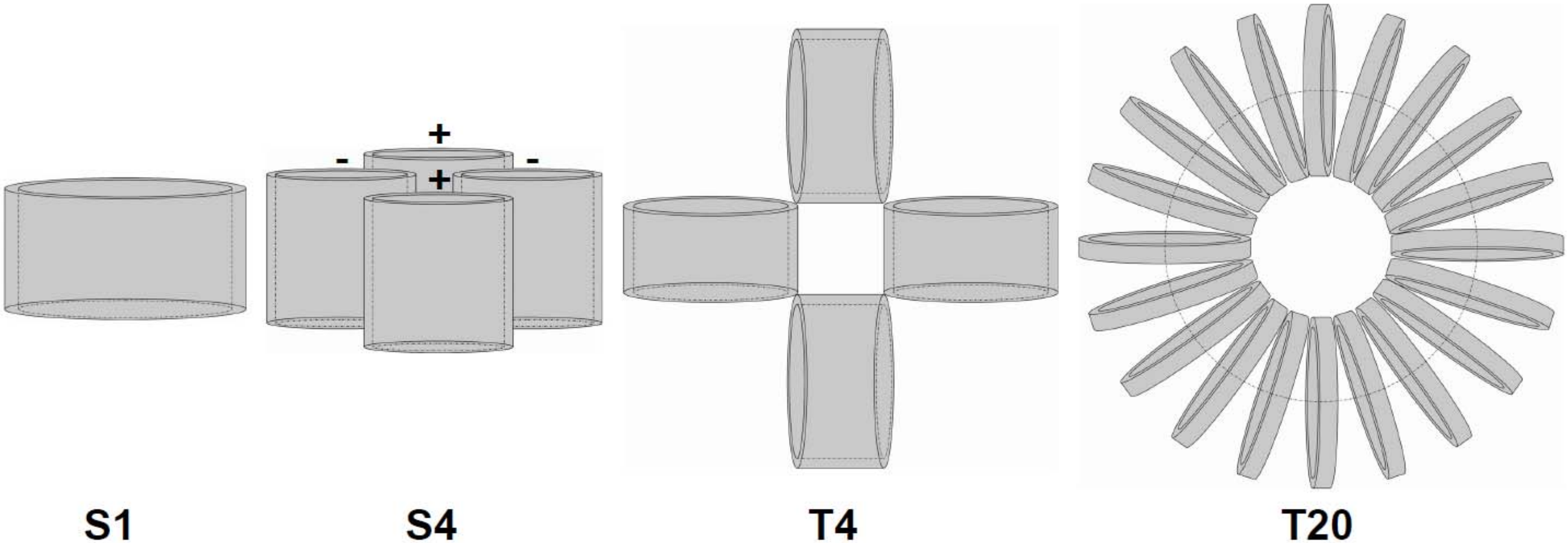


Regenerative Liquefaction: Target Parameters

Inlet GH2 Temperature & Pressure at Warm End of Regenerator	300 K / 1.50 MPa
Outlet GH2 Temperature & Pressure at Cold End of Regenerator	27 K / 1.35 MPa
Outlet GH2 & LH2 Temperature & Pressure at Cold End of J-T-Valve	21 K / 0.12 MPa
Percentage of LH2 after J-T-Valve	~ 80 %
Inlet LH2 Temperature & Pressure at Cold End of Regenerator	21 K / 0.12 MPa
Outlet GH2 Temperature & Pressure at Warm End of Regenerator	294 K / 0.10 MPa
Percentage of p-H2 in LH2	> 98.5 %
Electric Energy for Compression of GH2 at Ambient Temperature (isothermal compressor efficiency ~ 60 %)	~ 10.9 kJ/mol
Electric Energy for Liquefaction of GH2 after J-T-Valve at 21 K (cryocooler: 15 % Carnot efficiency)	~ 15.5 kJ/mol
Total Electric Energy required for the Storage Process	**~ 26.4 kJ/mol**
H2 Liquefaction Loss per Stored Chemical Energy (total enthalpy change for the water splitting / formation process ~ 286 kJ/mol)	~ 9 %
H2 Liquefaction Loss per Stored Chemical Energy in Large Conventional H2 Liquefaction Plants	~ 30 - 38 %

Solenoidal & Toroidal 10 GJ SMES Systems I

SMES Configurations storing the same Energy at the same Maximum Magnetic Field



10 GJ SMES Systems:
total stored energy: 13.3 GJ
discharged @ 50 % of maximum operating current

M. Sander, H. Neumann, Supercond. Sci. Technol. 24 (2011) 105008

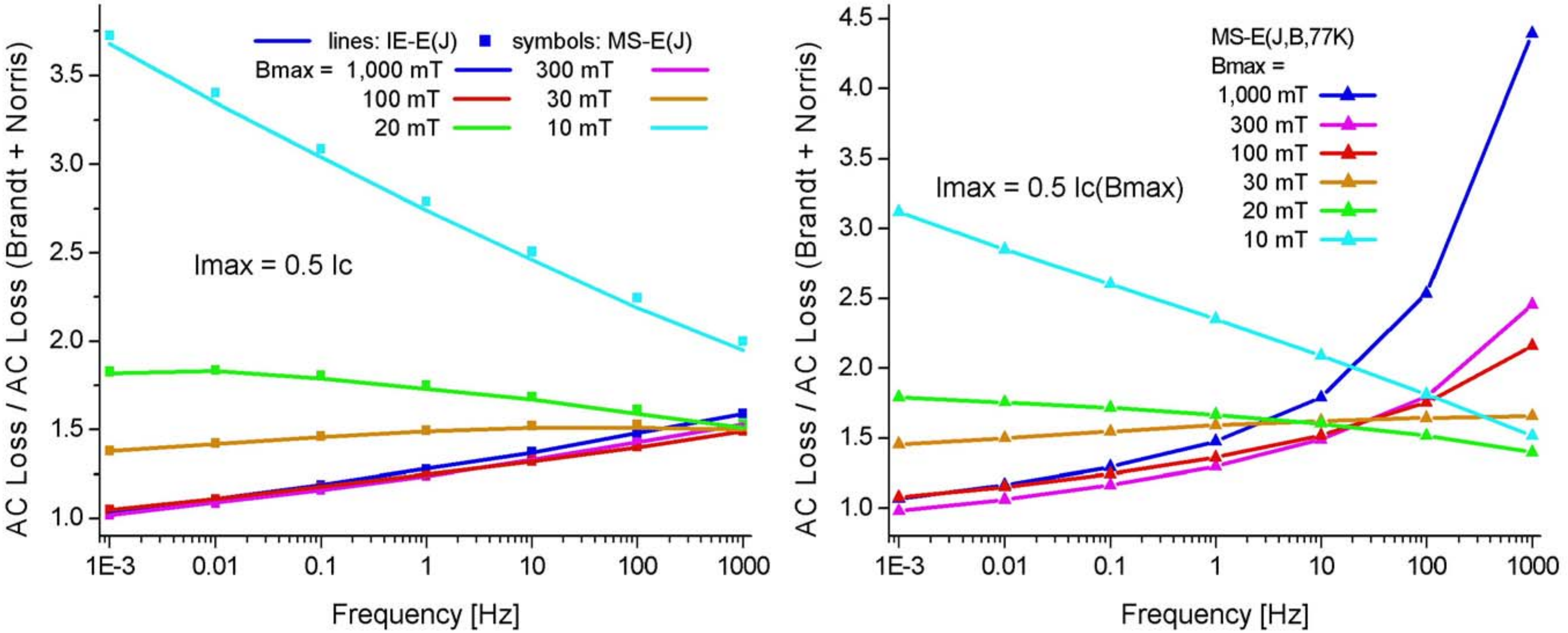
Solenoidal & Toroidal 10 GJ SMES Systems II

	S1	S4	T4	T20
Total Number of Solenoidal Coils				
	1	4	4	20
Outer Radius / Inner Radius / Height of Individual Coil				
8T	5.66 / 5.01 / 5.66 m	3.14 / 2.78 / 6.29 m	4.02 / 3.56 / 4.02 m	4.13 / 3.65 / 0.83 m
4T	8.98 / 7.95 / 8.98 m	4.99 / 4.41 / 9.98 m	6.38 / 5.64 / 6.38 m	6.55 / 5.80 / 1.31 m
2T	14.3 / 12.6 / 14.3 m	7.92 / 7.01 / 15.8 m	10.1 / 8.96 / 10.1 m	10.4 / 9.21 / 2.08 m
Total Radius / Height of SMES System				
8T	5.66 / 5.66 m	7.86 / 6.29 m	10.25 / 8.04 m	11.36 / 8.26 m
4T	8.98 / 8.98 m	12.47 / 9.98 m	16.3 / 12.8 m	18.0 / 13.1 m
2T	14.3 / 14.3 m	19.8 / 15.8 m	25.8 / 20.3 m	28.6 / 20.8 m
Radial / Vertical Distance for Heart Pacemaker Limit (0.5 mT)				
8T	103 / 122 m	34 / 30 m	37 / 23 m	16 / 7.2 m
4T	129 / 155 m	47 / 40 m	53 / 32 m	25 / 11 m
2T	163 / 194 m	65 / 55 m	74 / 45 m	38 / 17 m
Mean Operating Current Density in Winding				
8T	1,404 A/cm2	1,860 A/cm2	1,547 A/cm2	1,716 A/cm2
4T	442 A/cm2	586 A/cm2	487 A/cm2	541 A/cm2
2T	139 A/cm2	185 A/cm2	153 A/cm2	170 A/cm2
Total Conductor Length x Operating Current (=Ic/2)				
8T	1.73 GAm	3.15 GAm	2.73 GAm	3.29 GAm
4T	2.18 GAm	3.96 GAm	3.44 GAm	4.15 GAm
2T	2.75 GAm	4.99 GAm	4.34 GAm	5.22 GAm

Ramping Losses: Frequency Dependence

for high magnetic fields + very low frequencies:
hysteretic AC losses well approximated by critical state model

Journal of Physics: Conference Series 234 (2010) 022030: FEM-Calculations on the Frequency Dependence of Hysteretic Losses in Coated Conductors, M Sander and F Grilli, EUCAS 2009



Ramping Losses of SMES: Assumptions

for high magnetic fields & very slow ramping processes:

- eddy current & coupling losses neglected
- hysteretic magnetization losses *HML* approximated by critical state model, transport losses neglected
- individual filaments (e.g. CC tapes in a Roebel cable) essentially decoupled => losses don't explicitly depend on cable *Ic* or its geometry
- orientation dependence of *Ic(B)* for CC & Bi-HTS
- misorientation angle of 2 degrees relative to solenoid axis for CC

Differential Ramping Loss DRL:

$$HML = I_c W B_{\max} \frac{2B_c}{B_{\max}} [\ln\cosh\left(\frac{B_{\max}}{B_c}\right) - \tanh\left(\frac{B_{\max}}{B_c}\right)]; B_c = \mu_0 J_c / \pi$$

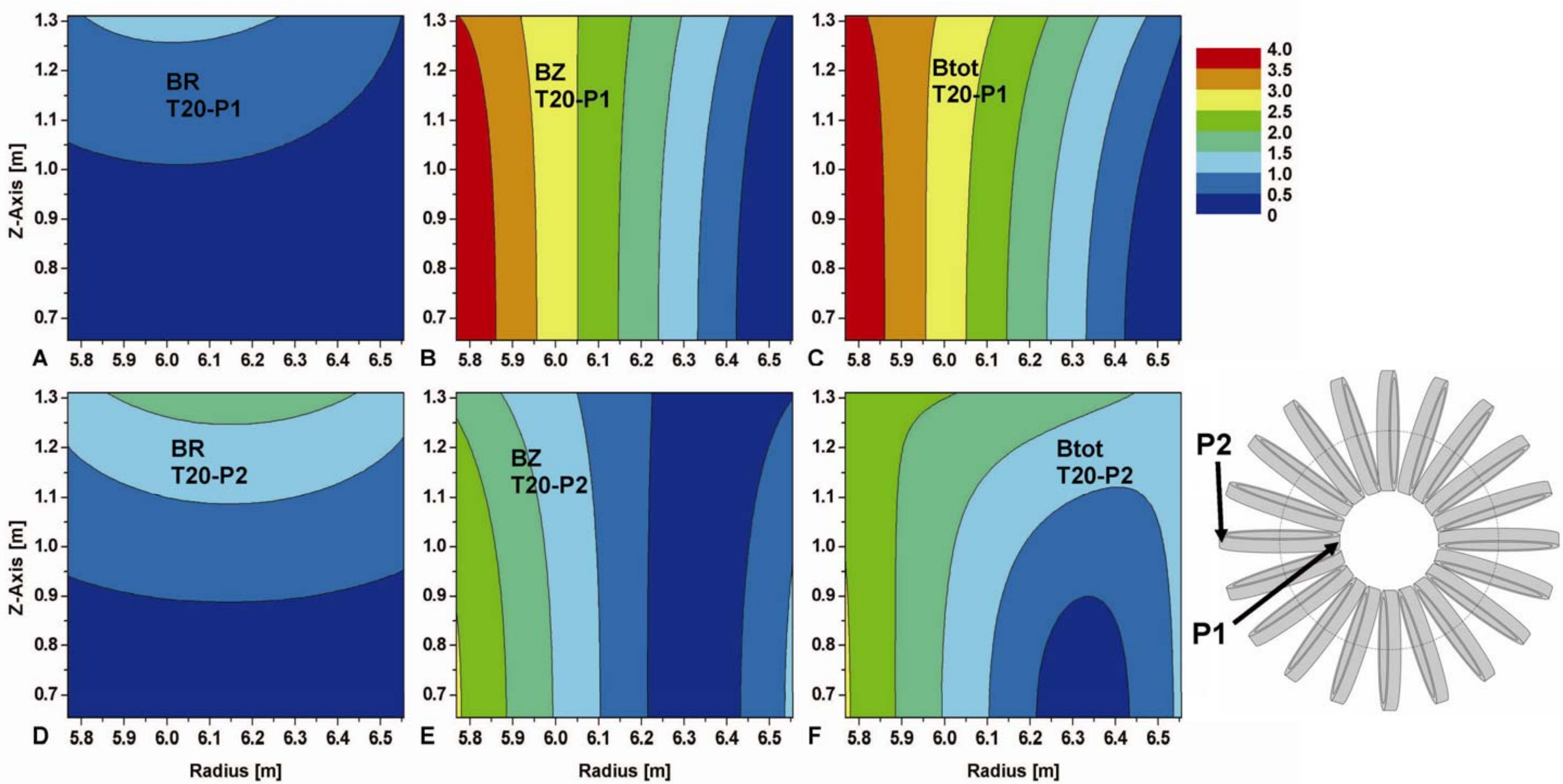
$$HML = I_c R B_{\max} \frac{16}{3\pi} - \ldots$$

$$DRL = [HML(I_c(B), B + \Delta B) - HML(I_c(B), B)]/(4\Delta B)$$

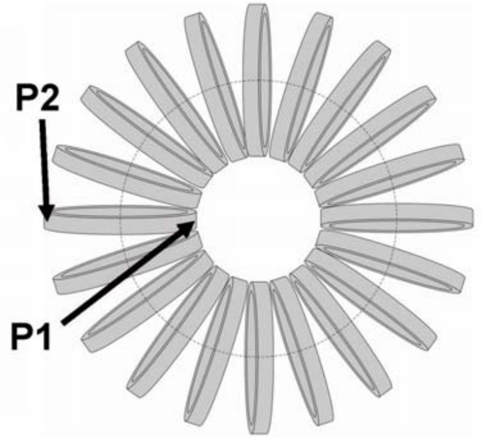
M. Sander, R. Gehring, ASC, Washington DC, August 2010, IEEE Trans. on Appl. Supercond. 21 (2011) 1362

Magnetic Field Distribution T20

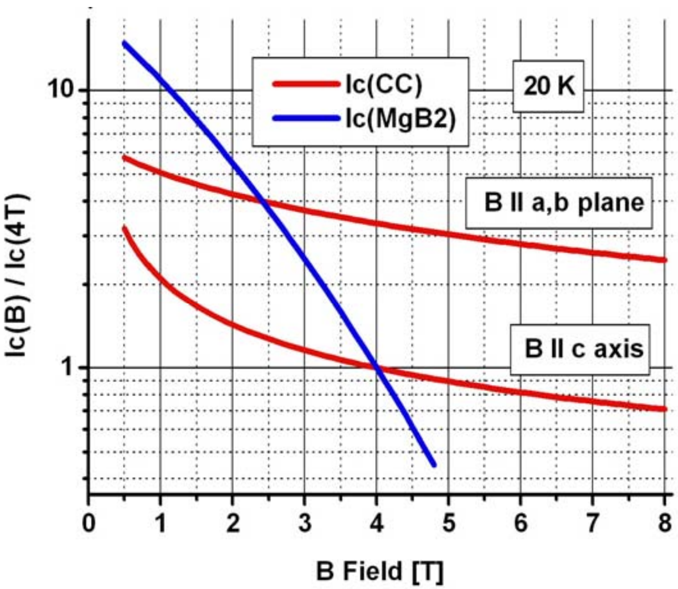
BR, BZ & Btot @ P1 & P2:

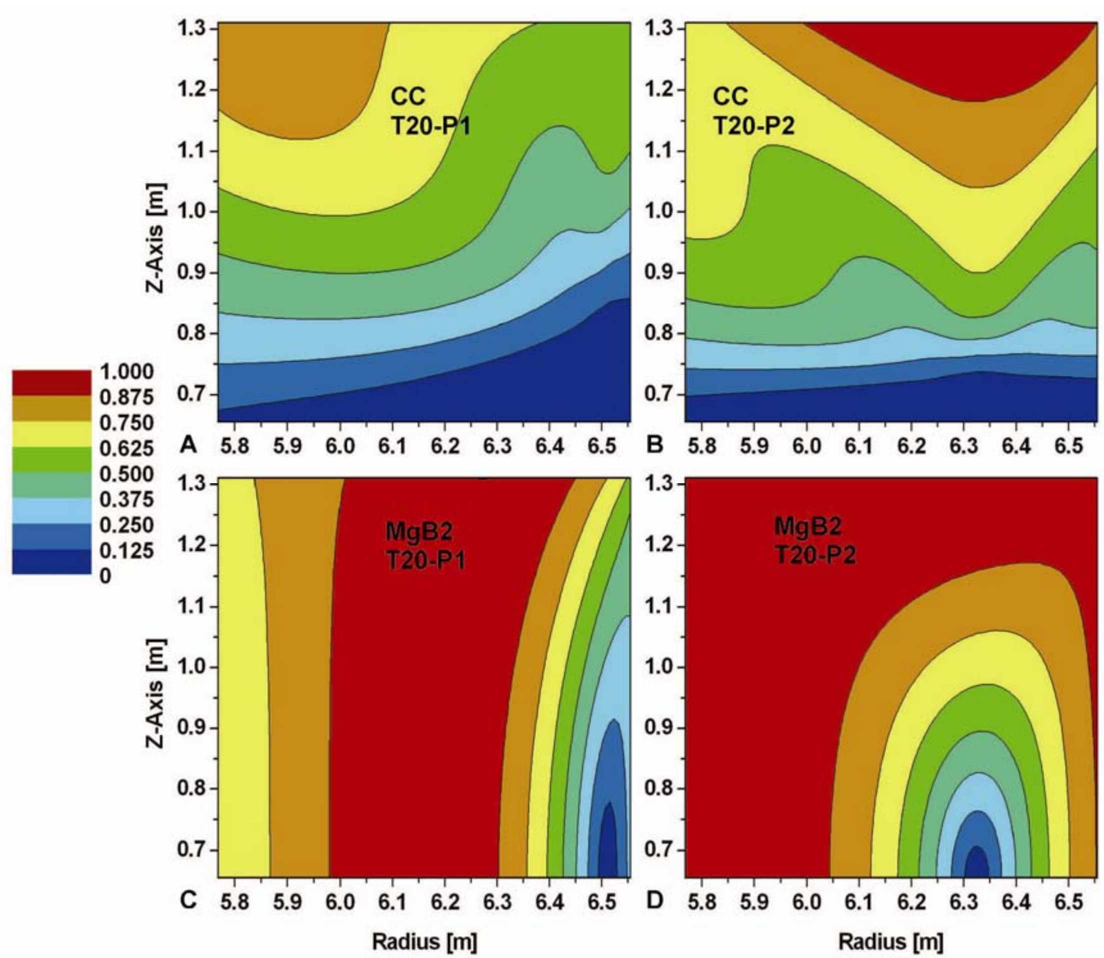


Spatial Distribution Ramping Losses T20



Full-Cycle Ramping Losses





Solenoidal & Toroidal 10 GJ SMES Systems III

	S1	S4	T4	T20
Total Conductor Length x Operating Current (=Ic/2)				
8T	1.73 GAm	3.15 GAm	2.73 GAm	3.29 GAm
4T	2.18 GAm	3.96 GAm	3.44 GAm	4.15 GAm
2T	2.75 GAm	4.99 GAm	4.34 GAm	5.22 GAm
CC Ic(B)/Ic(4T) : Relative Required Conductor Quantity (Basis S1,4T)				
8T	1.12	2.03	1.80	1.65
4T	1.00	1.81	1.61	1.47
2T	0.88	1.59	1.41	1.28
CC (width: 2 mm; sheet critical current density: 471A/cm@4T): Full-Cycle Ramping Loss / Resulting Cycle Efficiency (loss of power conversion: 3 %; cryocooler: 15 % Carnot efficiency)				
8T	7.19 MJ / 87.9 %	11.0 MJ / 84.8 %	10.1 MJ / 85.5 %	8.54 MJ / 86.8 %
4T	4.39 MJ / 90.3 %	6.53 MJ / 88.5 %	6.09 MJ / 88.8 %	5.08 MJ / 89.7 %
2T	2.55 MJ / 91.9 %	3.54 MJ / 91.0 %	3.42 MJ / 91.1 %	2.78 MJ / 91.7 %
MgB2 Ic(B)/Ic(4T): Relative Required Conductor Quantity (Basis S1,4T)				
4T	1.00	1.82	1.58	1.90
2T	0.23	0.42	0.36	0.44
MgB2 (round wire, diameter 100 μm): Full-Cycle Ramping Loss / Resulting Cycle Efficiency (loss of power conversion: 3 %; cryocooler: 15 % Carnot efficiency)				
4T	0.92 MJ / 93.3 %	1.67 MJ / 93.3 %	1.58 MJ / 92.7 %	2.09 MJ / 92.3 %
2T	0.29 MJ / 93.8 %	0.51 MJ / 93.6 %	0.44 MJ / 93.6 %	0.53 MJ / 93.6 %

Solenoidal & Toroidal 10 GJ SMES Systems IV

- **Lower magnetic fields seem to reduce both the overall quantity of required superconductor and the losses during the ramping processes.**
- **MgB2-SMES seem to have lower ramping losses than CC-SMES.**

Up-Scaling & Modularity: Geometrical Ratios fixed i.e. for solenoid Ri/R, R/H ~ const.	
Operating Current Density Jop (for small R Jop is limited by the maximum Jop_max)	~ Bmax x 1/R
Inductance (single winding; ~ area R^2/ length H)	~ R
Total Operating Current over whole Coil Cross Section Iop ~ Jop x (R-Ri) x H	~ Bmax x R
Cable Length (single winding) ~ (Ri+R)/2	~ R
Conductor Quantity ~ Iop x Cable Length	~ Bmax x R^2
Full Cycle Ramping Loss ~ Iop x Cable Length	~ R^2
Stored Energy ~ Volume x $Bmax^2$	~ R^3 x $Bmax^2$
Required Conductor Quantity per stored Energy *E*	~ 1/R
Ramping Loss per stored Energy *E*	~ 1/R

- **Increasing R reduces conductor quantity & losses per stored energy !**

H2 + Short-Term Storage Devices: Cost I

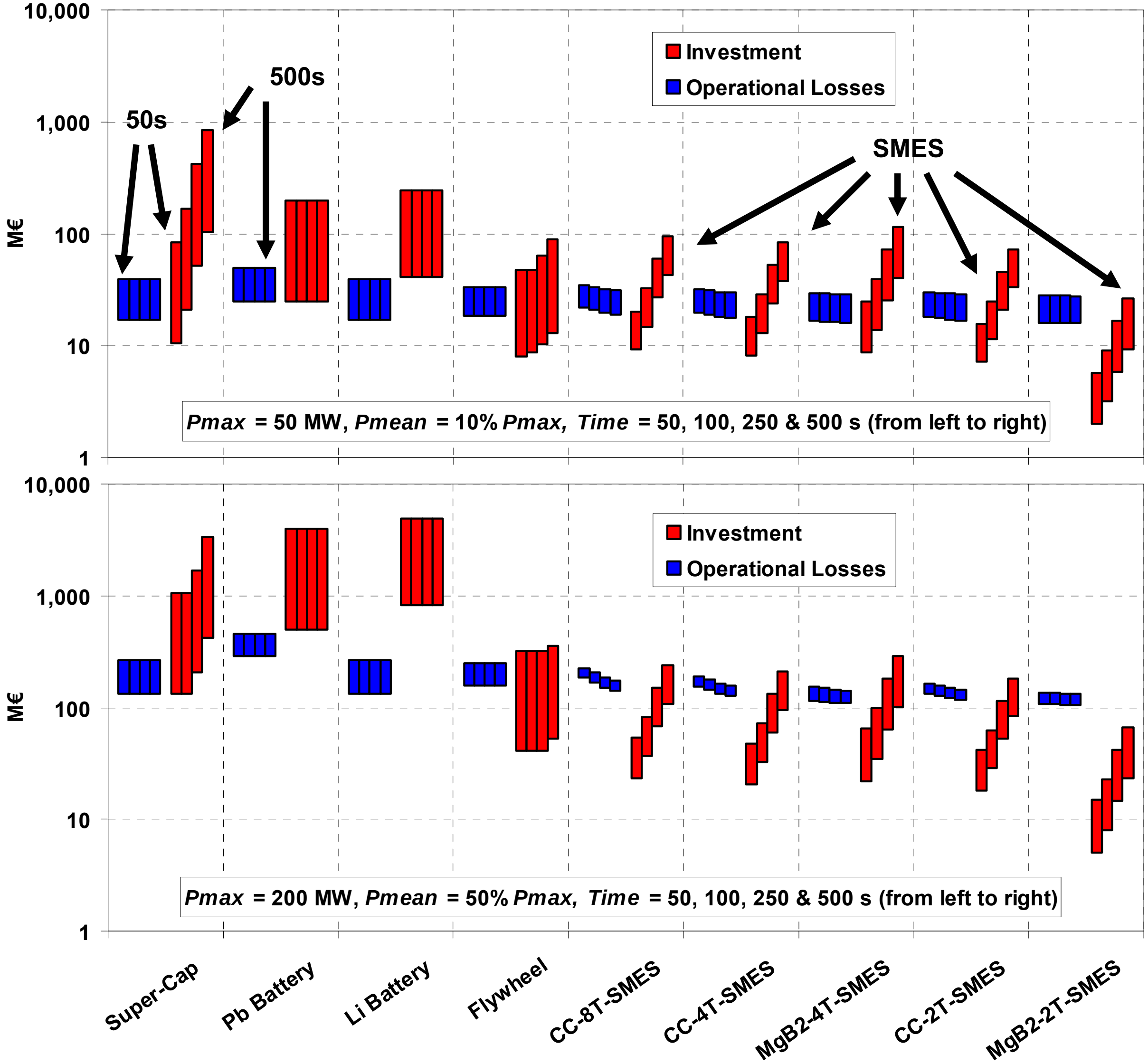
LSU: "joint use of cryogenic infrastructure" -
SMES already cost-competitive ?
or
Combination of H2 storage with alternative short-term storage devices ?

Simple cost estimates for investment and operational losses (valued at 0.10 €kWh−1) over a period of 30 years of operation for different rated power levels Pmax, different mean utilizations Pmean and rated supply periods between 50 and 500 s; 5 €kAm−1 @ 4 T, 20 K assumed as the common cost basis for the finished SMES magnet systems

Parameters used for Cost Estimates

	Super-Capacitor	Pb-Battery	Li-Battery	Fly-wheel	SMES
Investment Cost / Energy in k€/kWh	5 - 20	0.15 - 0.6	0.5 - 1.5	0.8 - 5	scaled
Investment Cost / Power in k€/kW	-	-	-	0.15 -0.5	-
Number of Deep Discharge Cycles in 10^3	250 - 500	2 - 4	4 - 8	500 -1,000	3,000 - 5,000
Lifetime without Load in Years	5 - 10	4 - 8	4 - 8	20 - 30	20 - 30
Standby Loss per Rated Power in %	1.0-2.5	1.0-2.5	1.0-2.5	1.0 - 2.0	1.0 - 2.0
Cycle Loss per Rated Energy in %	8 - 15	20 - 30	8 - 15	10 - 15	scaled

H2 + Short-Term Storage Devices: Cost II



Higher rated power levels and higher mean utilizations tend to make the SMES more cost-effective

LIQHYSMES – a Novel Hybrid Energy Storage Option for Buffering Short- & Long-Term Imbalances between Electricity Supply & Load

- Introduction: Energy Storage Options
- Former SMES Activities at the Research Centre Karlsruhe
- Today's Motivation I: New Conductor Options
- Today's Motivation II: Renewables
- LIQHYSMES: Concept & First System Studies
- **LIQHYSMES: Model Plant & Buffering Process**
- Some Implications of Size & Cost Estimate
- Summary & Conclusions

LIQHYSMES Model Plant: EEC & PCC

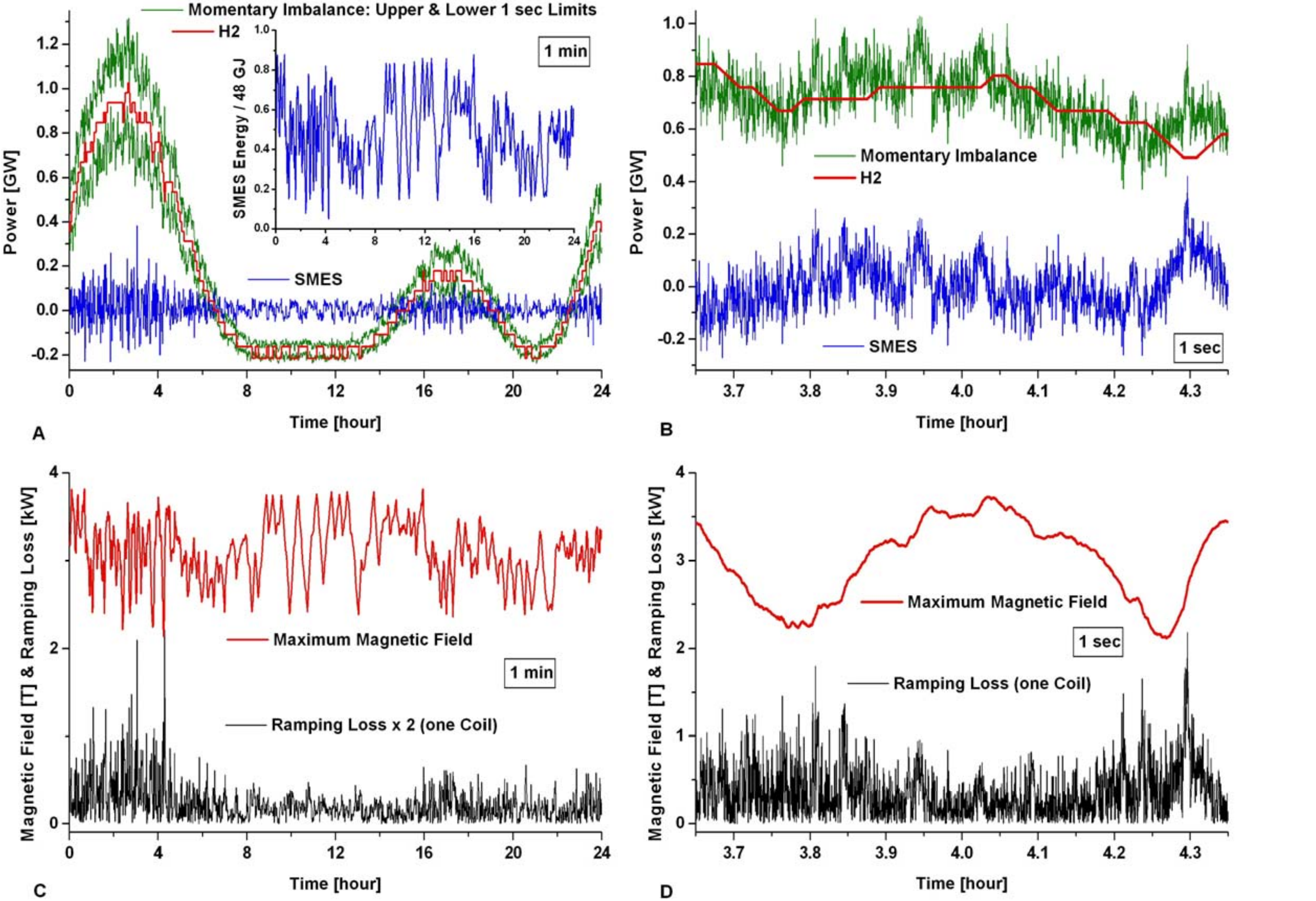
Electrochemical Energy Conversion - EEC:	
Rated Power for Electrolyser	25 x 40 MW
Rated Power for Gas Turbines & Generator	4 x 55 MW
Efficiency of Electrolyser / Gas Turbines & Generator	~ 85 / 55 %
Power Conversion & Control Unit - PCC:	
Operational Loss per Momentary EEC or SMES Power	3 %
Standby Loss per Rated EEC or SMES Power	1 %

M. Sander, R. Gehring, H. Neumann, ASC, Portland, OR, October 2012, to appear in IEEE Trans. on Appl. Supercond.

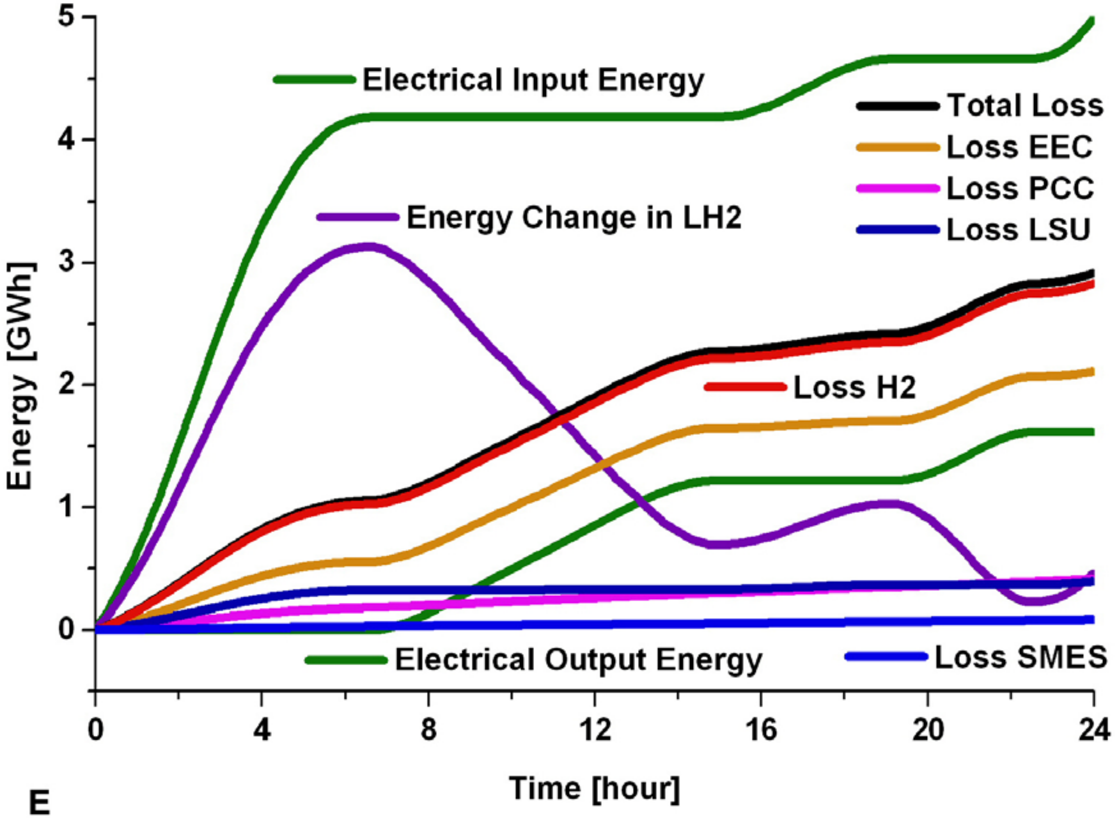
LIQHYSMES Model Plant: LSU

Outer Radius / Inner Radius / Width of Individual Solenoidal Coil of MgB2-SMES (Total: 20 Coils in a Toroidal Configuration)	11.1 / 9.79 / 2.21 m
Total Radius / Height of SMES System & LH2 Cryostat	30.4 m / 22.1 m
Radial / Vertical Distance for Heart Pacemaker Limit (0.5 mT)	~ 42 / 19 m
Rated Power x Supply Period of SMES = Rated Energy of SMES (discharged @ 50 % Coil Current) / Total Stored Energy	200 MW x 240s = 48 GJ / 64 GJ
Mean Operating Current Density in Winding	~ 320 A/cm2
Total Conductor Length x Operating Current (=Ic/2)	~ 11.8 GAm
Max Operating Current / Magnetic Field of SMES / Voltage over a single Coil	10 kA / 4 T / 5 kV
Cable Length per Coil / Number of normalconducting Joints per Coil / Number of Windings per Coil	~ 30 x 2 km / 29 / ~ 30 x 30
Self Inductance of a single Coil / Mutual Inductance of the other 19 Coils	~ 28 H / ~ 35 H
Full-Cycle Ramping Loss of SMES (round MgB2 wire, diameter 100 μm) / Electric Loss in % of Rated Energy (cryocooler: 15 % Carnot efficiency)	5.94 MJ / 1.16 %
Chemical Energy of LH2 (max. 70% of cryostat filled with LH2) / Deliverable Electrical Energy of LH2 / max. EEC Electric Output Power x Supply Period	~ 125 GWh /~ 69 GWhe / 220 MWe x 13 d
H2 Liquefaction Loss per Stored Chemical Energy (regenerative process)	10 %
Standby Losses of Cryostat / Current Leads (cryocooler)	595 / 75 kW

Buffering Process: Simulations I



Buffering Process: Simulations II



E

- LIQHYSMES seems to be capable of safely balancing supply/load imbalances from seconds up to days
- EEC losses widely dominate over PCC & LSU losses
- summed up H2 losses (EEC, PCC & LSU) far exceed summed up SMES losses (PCC & LSU)

Buffering Process: Results & Loss Analysis

Buffering Capability, Energy Shifting & Balances	
Max. Positive / Negative. Imbalance over the 24-Hour Period	+1,316 MW / -238 MW
Max. Buffered 1-min- / 1-sec-Fluctuation of the Imbalance	~ 147 MW/ 284 MW
Max. 1-sec Peak Power / Mean Power (over 24 Hours) of SMES	~ 421 MW / ~ 36 MW
Electrical Energy Uptake / Delivery	4.990 GWh / 1.614 GWh
Chem. Energy Balance of LH2 / Mag. Energy Balance of SMES	+ 0.460 GWh / + 0.001 GWh
Losses	
PCC Loss of H2	0.338 GWh
EEC Loss (Electrolyser and Gas Turbines & Generator)	2.109 GWh
LSU Loss of H2 (Cryostat, H2 Liquefaction & Compression)	0.384 GWh
Total Loss of H2	2.831 GWh
PCC Loss of SMES	0.075 GWh
LSU Loss of SMES (n.c. Joints of ~1nΩ ~ 0.08 MWh, Current Leads ~ 1.8 MWh & Ramping Loss ~ 7.3 MWh)	0.009 GWh
Total Loss of SMES	0.084 GWh
Total Loss	2.914 GWh

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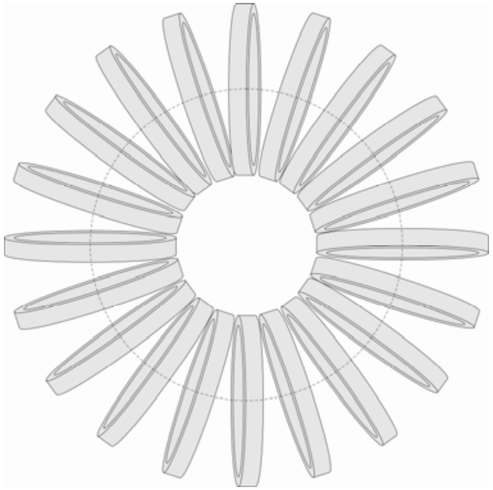
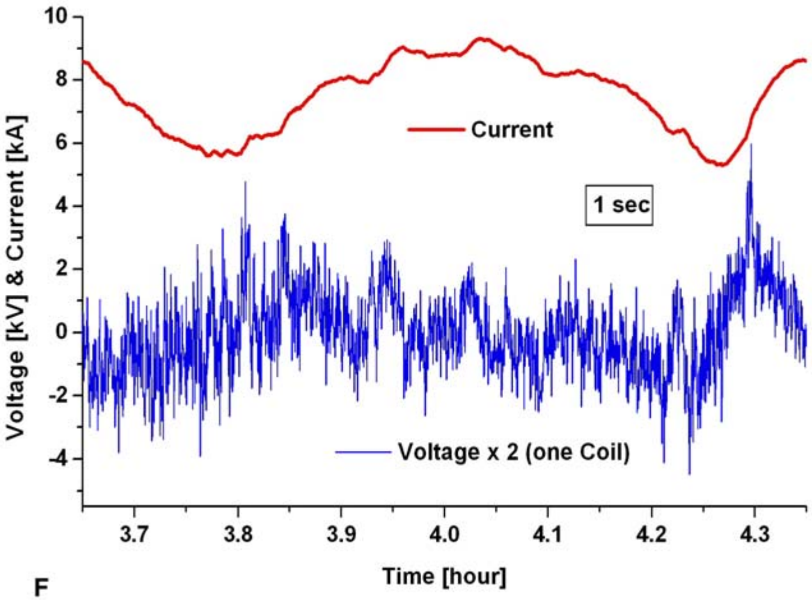
Some Implications for SMES: Size, size, size …

Karlsruhe Institute of Technology

Cabling, Winding, Assembling, Connecting

- torus: 20 solenoidal coils each of 11.1 m outer radius & 2.21 m of height
- mean operating current density of only ~ 320 A/cm2 in winding
- ~ 30 x 2 km MgB_2 cable length, 29 nc. joints & 30 x 30 windings per coil
- losses: nc. joints of ~1nΩ ~ 0.08 MWh, current leads ~ 1.8 MWh & ramping loss ~ 7.3 MWh
- peak ramping loss ~ 2.2 kW over sec; local heat load well below 100 μW/cm3 @ 20 K
- max. operating current of 10 kA & voltage of < 5 kV (~ 3 kV) over a single coil
- self inductance (one coil) of ~ 28 H vs. mutual inductance (19 coils) of ~ 35 H
- current feeding: each coil individually connected to the modular PCC





F

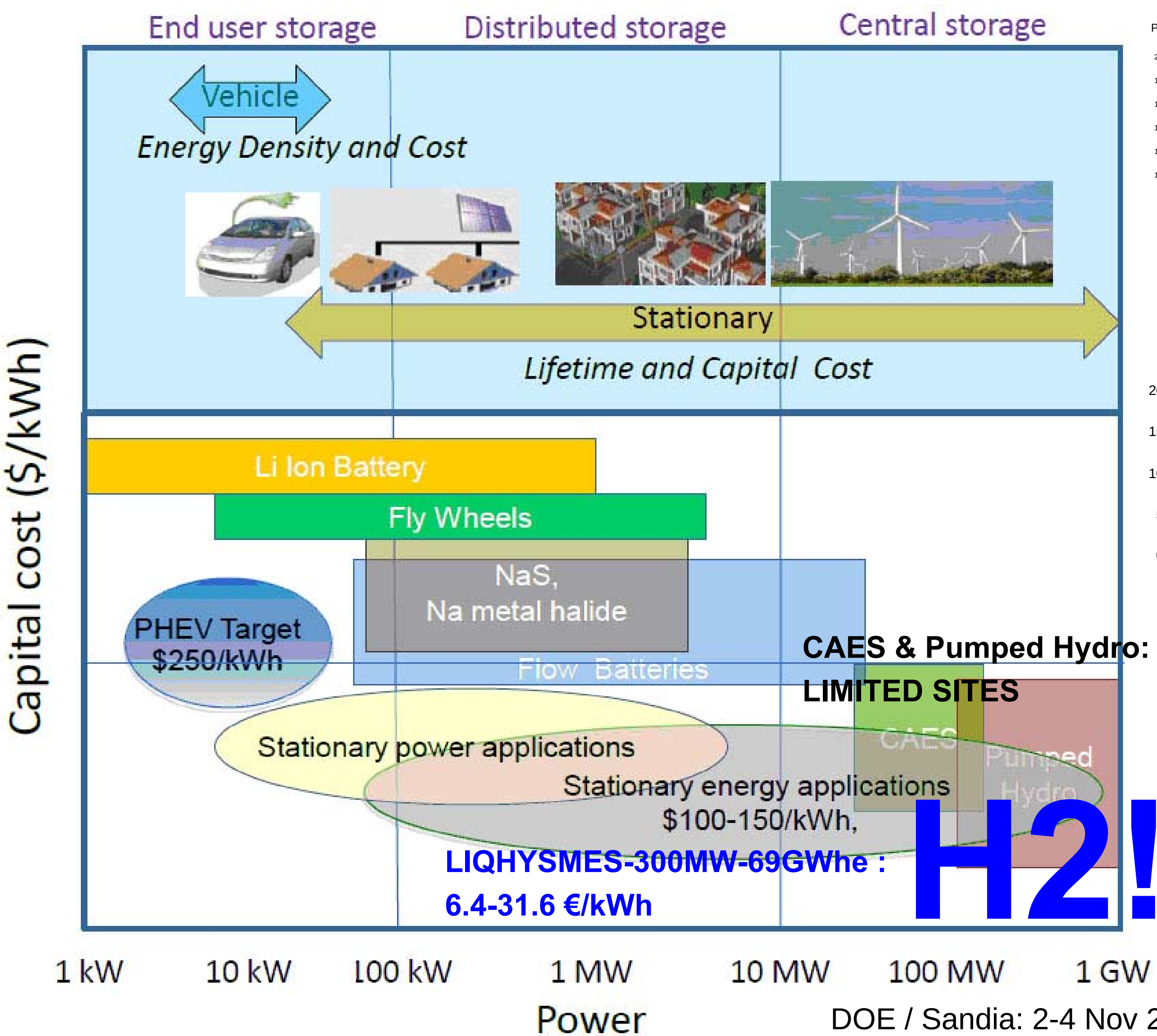
Cost Estimate: LSU

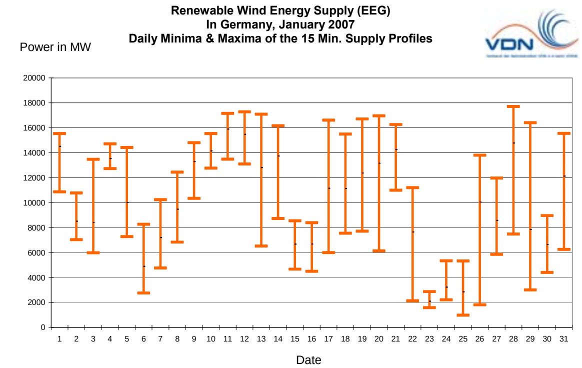
Rated Power / Peak Power of SMES	200 MW / 421 MW
Rated Energy of SMES @ 4 T (Rated Power x 240 s)	48 GJ
Chemical Energy / Deliverable Electrical Energy of LH2	~ 125 GWh / ~ 69 GWhe
Total Cost of LSU SMES (assumed 5 €/kAm@4T,20K) + Cryogenic Infrastructure (cryostat, liquefaction part, cooling, current leads)	~ 200 M€
Cost of LSU per Rated Energy of SMES	~ 15,000 €/kWhe
Cost of LSU per Rated Power of SMES / Cost of LSU per Peak Power of SMES	~ 1,000 €/kWe / ~ 475 €/kWe
Cost of LSU per Chemical Energy of LH2 / Cost of LSU per Deliverable Electrical Energy of LH2	~ 1.6 €/kWh / ~ 2.9 €/kWhe

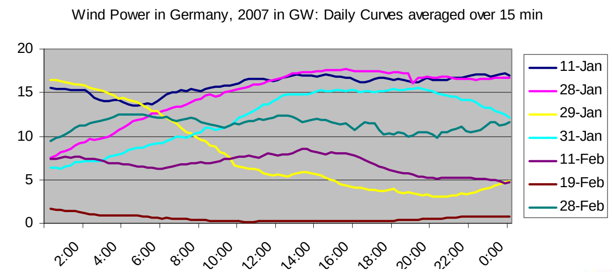
Cost Estimate: LIQHYSMES Model Plant

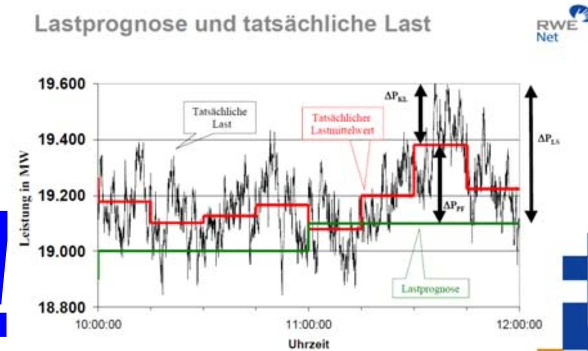
Cost Estimates for **GH2-based Systems & LIQHYSMES Systems**	Total Cost M€	Cost per Power €/kW	Cost per Energy €/kWh
Cost Estimate **2009/2011 TECHNOLOGY MAP of European SET- Plan** 300 MW / 5 GWh **GH2** system based on **electrolysis,** **salt cavern based storage and open cycle gas turbine**	240-495	800-1,650	48-99
Crude Cost Estimate for **LIQHYSMES System (~ GH2 System + Model LSU)** **~** 300 MW / 69 GWhe **LH2** system based on **electrolysis,** **LSU based storage and open cycle gas turbine**	240-495 + 200 = **~ 440-695**	**1,470-2,320**	**6.4-10.1**
Preliminary Cost Estimate **2009/2011 TECHNOLOGY MAP of European SET- Plan** 300 MW / 5 GWh **GH2** system based on **electrolysis,** **salt cavern based storage and fuel cells**	600-1,980	2,000-6,600	120-396
Crude Cost Estimate for **LIQHYSMES System (~ GH2 System + Model LSU)** **~** 300 MW / 69 GWhe **LH2** system based on **electrolysis,** **LSU based storage and fuel cells**	600-1,980 + 200 = **~ 800-2,180**	**2,670-7,270**	**11.6-31.6**

Energy Storage: Cost & Cost Targets









1 cycle to days or weeks …

DOE / Sandia: 2-4 Nov 2010 Energy Storage Systems Program

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Summary & Conclusions I

The proposed LIQHYSMES Hybrid Energy Storage Concept

- simultaneously offers highest volumetric and independently scalable (short- & long-term) power & energy ratings for stationary applications
- uses the SMES for covering periods of seconds up to minutes and H2 for time scales of minutes up to days or weeks
- reduces the storage losses of LH2 to a level comparable with compressed GH2, but simultaneously offers higher safety margins
- offers substantial gains with up-scaling both in terms of efficiency and cost reduction, and thus addresses especially the range of tens to hundreds of MW and GWh
- is widely modular, allows the flexible adaptation of plant parts to different application requirements and reduces costly on-site manufacture / assemblies
- targets power- and energy-specific investment costs for the LSU of 500-750 €/kW and 2-3 €/kWh , based on the SMES power and the LH2 energy

Summary & Conclusions II

The proposed LIQHYSMES Hybrid Energy Storage Concept

- is essentially greenhouse gas neutral
- doesn’t require any rare / precious (raw) materials (like nano-porous storage materials)
- doesn’t require any specific geological formations (like salt caverns) and has minimum space requirements which allow flexible positioning e.g. an installation in cities
- is open and applicable to ANY combination of (high-pressure) electrolysers, fuel cells or gas turbines, to ANY H2-based supply network (GH2, LH2 or H2-rich compounds like methane) and to ANY centralized or spatially separated “virtual” plant configuration

Summary & Conclusions III

The proposed LIQHYSMES Hybrid Energy Storage Concept

- contributes to the large scale integration of variable RES as well as to the power quality & frequency control
- optimizes the utilization of electricity transmission & distribution networks thereby avoiding / deferring otherwise needed upgrades / overcapacities

New system approaches are needed for the design & integration of

- the LSU i.e. the regenerative liquefier, LH2 storage tank and SMES
- the whole LIQHYSMES plant i.e. the PCC, EEC and LSU.

An appropriate PCC given - ANY grid-relevant short-term disturbance could be buffered by the SMES:
Link to EUCARD-2 & Accelerator Systems ?

THANK YOU


Good Companions :
Renewable Energies +
Hydrogen +
Superconductors