Universidad Politécnica de Cartagena
Departament of Electrical Engineering

Doctoral Course on “Industrial Technologies”.

Subprogram “Neurotech, Control, Robotics and Energy Management”

Analysis of Distributed Energy Resources: an Introduction to Demand Response

Cartagena, 2011

Lesson 5

Energy Storage

- **Energy storage in Power Systems (PS):**
  - Hypothesis: Load increases/decreases outside forecasts.
  - We need to maintain demand vs. supply equilibrium every time.
  - How can we do this?
  - Through capacitors, Inductors (lines): low storage capacity

$$w_C(t) = \frac{1}{2}Cu^2(t); w_L(t) = \frac{1}{2}Li^2(t)$$

  - Example: 400kV line, 500 km length, $C=10*10^{-8}F$
    - Energy stored is around 5MW with a complete discharge.
    - This is not an alternative: We need to maintain a minimum voltage level (e.g. 90%) in our power system.
    - Is this storage policy suitable to maintain PS equilibrium?

- **Energy storage in power systems (II)**
  - Inertia: kinetic energy (Wkin of all rotating equipments: generators, turbines, …)

$$W_{kin}(f_0+\Delta f)\approx W_{kin}(1+2\frac{\Delta f}{f_0})$$

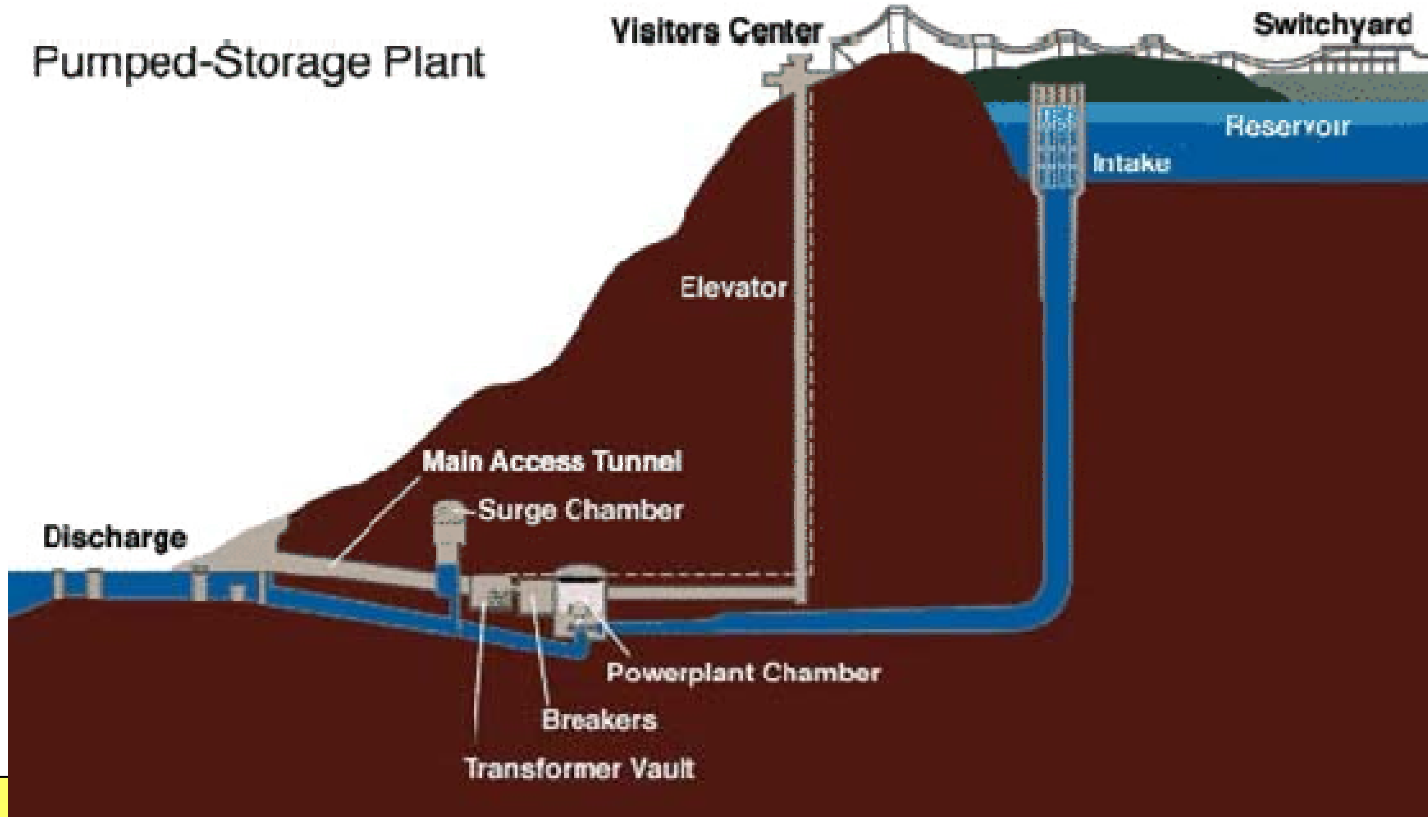
    - Per unit inertia constant H: it is essentially independent of system size (generator size Pr). H ranges from 2 to 8s
    - Problem: frequency drop in the power system!!

$$H\equiv\frac{W_{kin}(f_0)}{P_r};P_{add}=\frac{\partial W_{kin}}{\partial t}=\frac{2H}{f_0}\frac{\partial\Delta f}{\partial t}$$

    - Example: frequency drop of rotating masses 0.06Hz/s; H = 5s; f_0 = 60Hz
      - Additional power supply P_{add}: 0,01MW pu
      - This can be used during some seconds.
  - We have a lack of capacity to store and use energy!

- **There are different power plants according to their ability and controllability**
  - Base load plants (they maintain a constant level): large nuclear and coal units
    - Very efficient
    - Long life
  - Controlled generation plants: thermal (including gas) and hydropower.
    - Can regulate their generation according to demand
  - Peak Units: ex. gas turbines can peak up load very fast
  - “Green Plants”: renewable power plants
    - Politically encouraged
    - Generation depends on "natural forces" (uncontrolled in a great percent)
  - Reserve units: the margin of generation, i.e. generators maintained at partial output or Standby generators. Spinning reserve,

- **Traditionally**
  - Pumping plants of utilities have been used for "storing" energy, but present some problems from the "Supply-Side"
    - Water resource availability?
    - Environmental impact (little justification)
    - Example (source: IEEE PES)



Energy Storage: concerns

- **It is increasingly difficult to manage the power system.**
- **Energy Storage is a buffer between:**
  - Variable energy sources (renewable) and
  - End-Users (quality, reliability, reduced peak demand)
  - Grid constraints
- **It is necessary to study its actual technical possibilities**

Energy Storage

- **System requirements according to each specific application (source: Sandia Labs, USA)**

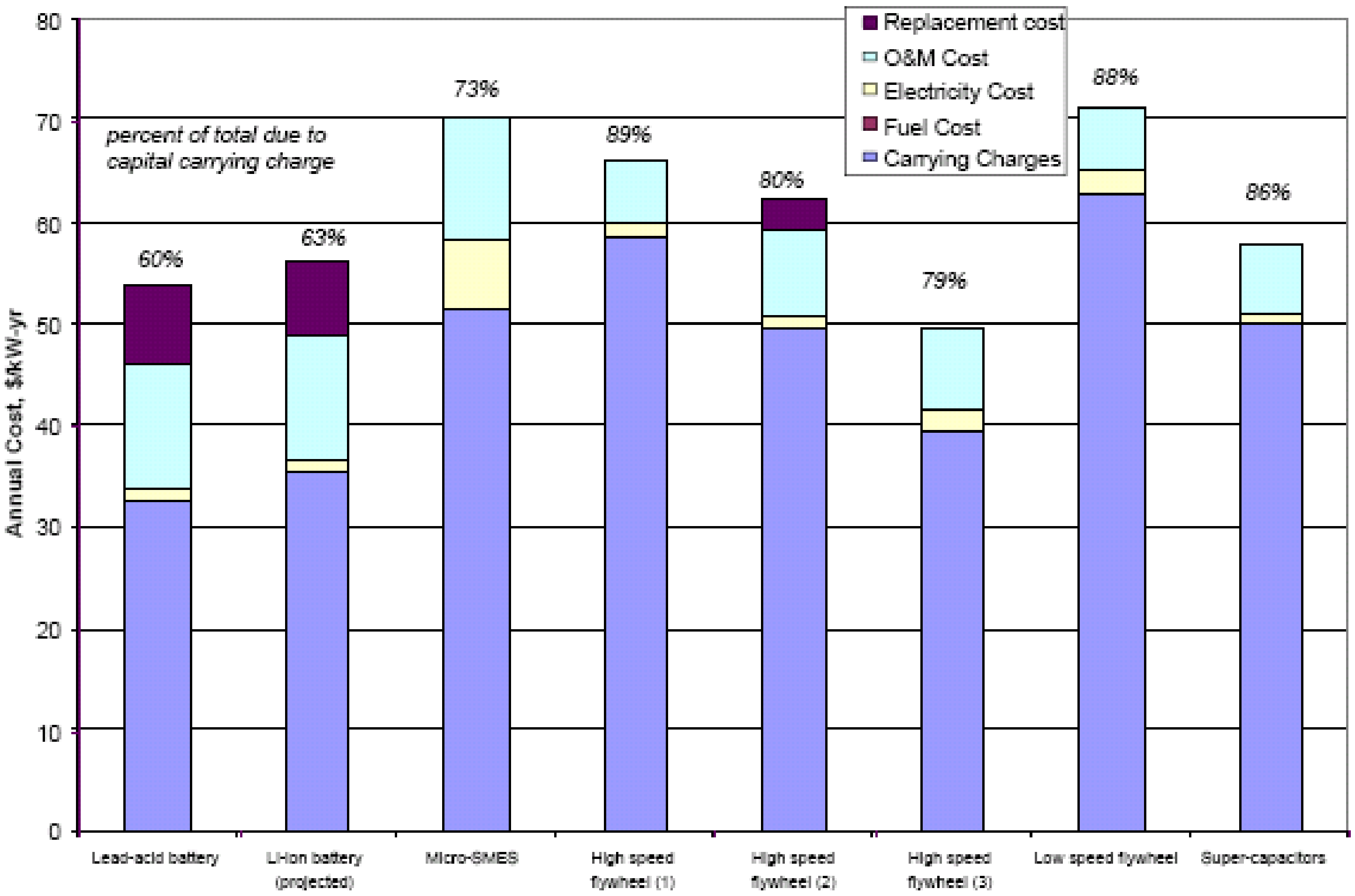
Application Category	Discharge Power Range	Discharge Time Range	Stored Energy Range	Representative Applications
Bulk energy storage	10 - 1000 MW	1 - 8 hrs	10 - 8000 MWh	Load leveling, spinning reserve
Distributed generation	100 - 2000 kW	0.5 - 4 hrs	50 - 8000 kWh (0.05 - 8 MWh)	Peak shaving, transmission deferral
Power quality	0.1 - 2 MW	1 - 30 sec	0.1 - 60 MJ (0.028 - 16.67 kWh)	End-use power quality and reliability

- **Available technology**

Bulk Energy Storage	Distributed Generation	Power Quality
Lead-acid batteries	Lead-acid batteries	Lead-acid batteries
Na/S batteries	Na/S batteries	Li-ion batteries
Regenesys	Ni/Cd	High-speed flywheels
Zn/Br batteries	Li-ion batteries	Low-speed flywheels
Ni/Cd	Zn/Br batteries	Micro-SMES
CAES	V-redox batteries	Super-capacitors
Pumped hydro	High-speed flywheels	
Asymmetric lead-carbon caps	Surface CAES	
	Asymmetric lead-carbon caps	
	Hydrogen fuel cell	
	Hydrogen engine	

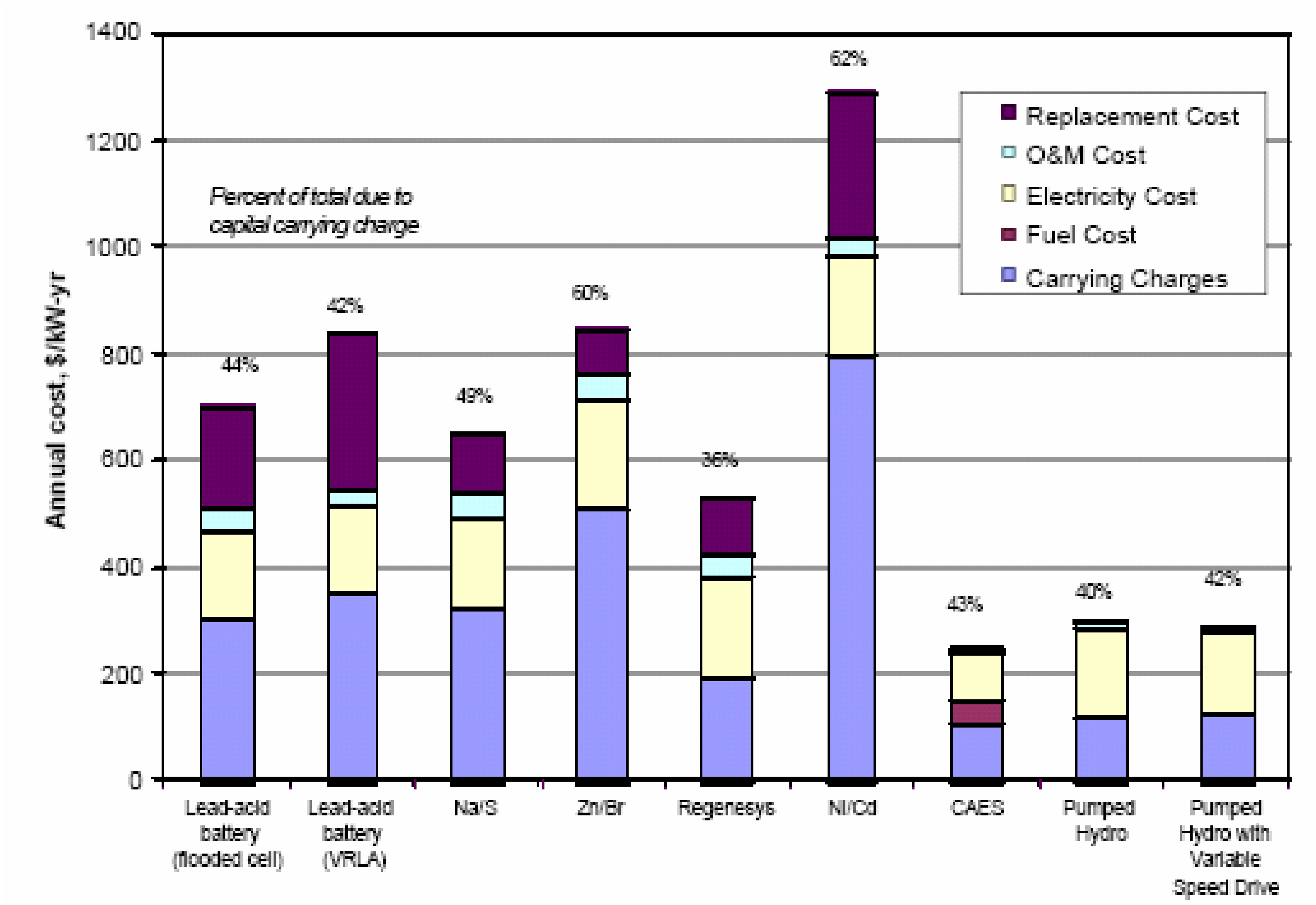
Costs vary depending on your application

- Annual cost components for 20 seconds Power Quality Technologies (source Sandia Nat. Lab., USA, 2007)

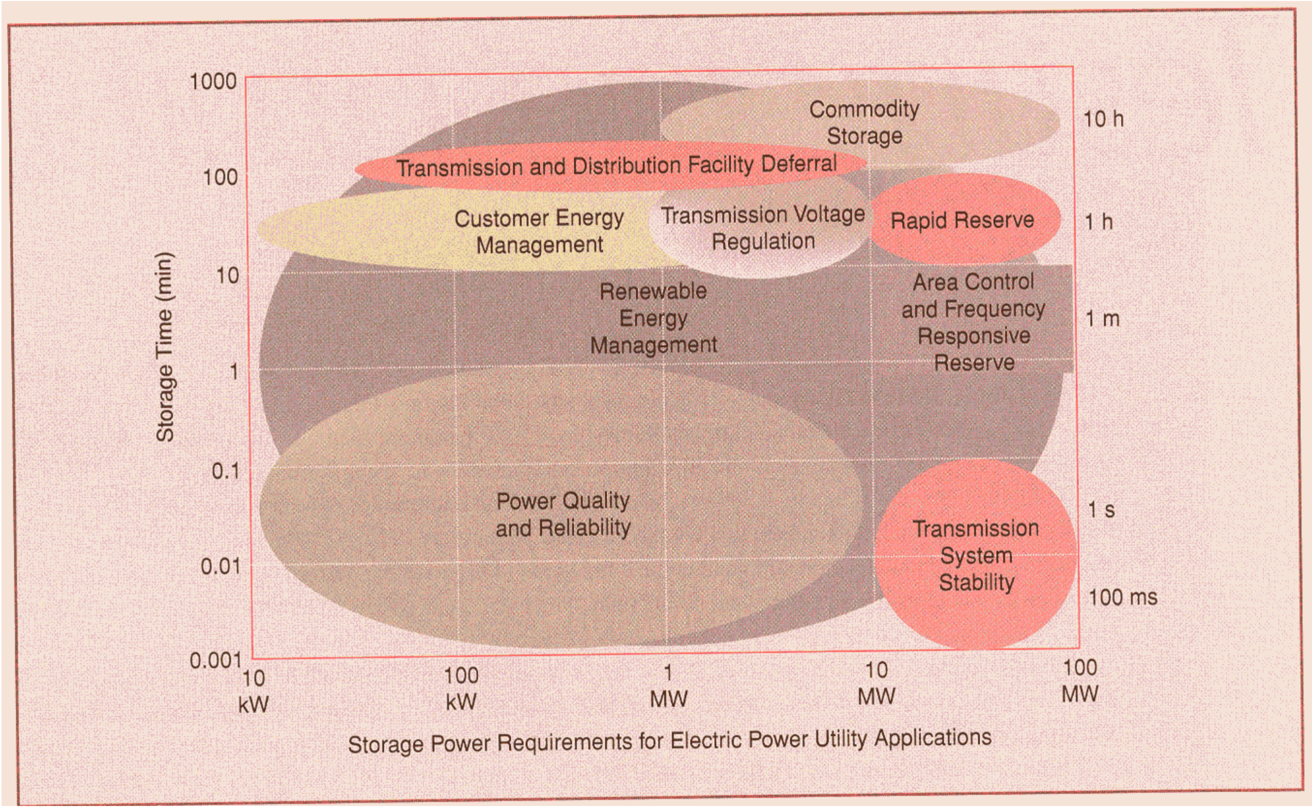


And systems for 8 hr bulk energy storage

- Source Sandia Nat. Lab., USA, 2007.



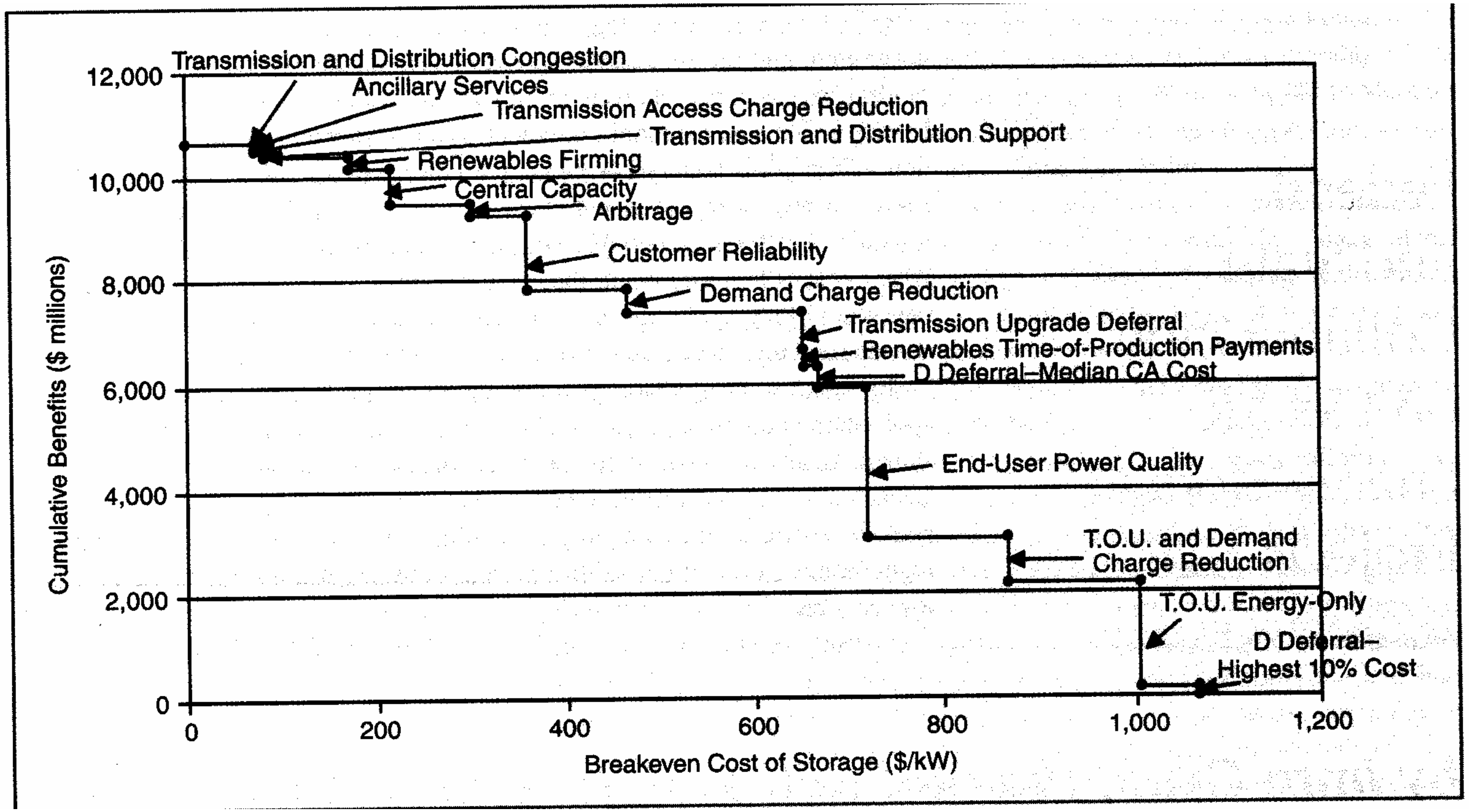
- **A time of change (e.g. liberalized markets) is an opportunity for new Energy Storage applications (source: Sandia National Lab, USA, 2005)**
  - System operation (ex. stability): flexibility
  - Peak demand reduction, maintenance, system expansion
  - The improvement of service: quality and reliability index



- **Benefit attributable to storage at each level of the Power System**
  - In Generation level:
    - Reduces spinning reserve
    - Helps Frequency Control
    - Support for renewables
    - Defers investment in generation
  - In Transportation and Distribution levels:
    - Defers investment in lines and transformers
    - Increases System Stability
    - Better voltage regulation
  - Consumer Side (end-use):
    - Quality and reliability of service
    - Peak load reduction (load leveling)
    - Support for distributed generation

Storage options

- Very classic: batteries and hydro pump
- Classics: thermal storage (heat / cold)
- Modern: electric storage
- Example: estimated benefits in California (1/ 8 USA)



Electric Energy Storage Systems:

- Batteries: very well known
- Flywheels: kinetic energy
- SMES: Superconducting magnetic energy storage
- Supercapacitors/Ultracapacitors
- CAS/CAES: Compressed Air Energy Storage

System	State of the Art
Batteries	Lead Acid, Li-ion, NaS, etc. Under continuous research
Flywheels	Commercial systems. Further R&D is needed
SMES	Prototypes. Further R&D is needed
Super-C	Commercial
CAES	Problem: site and costs. The technology is available

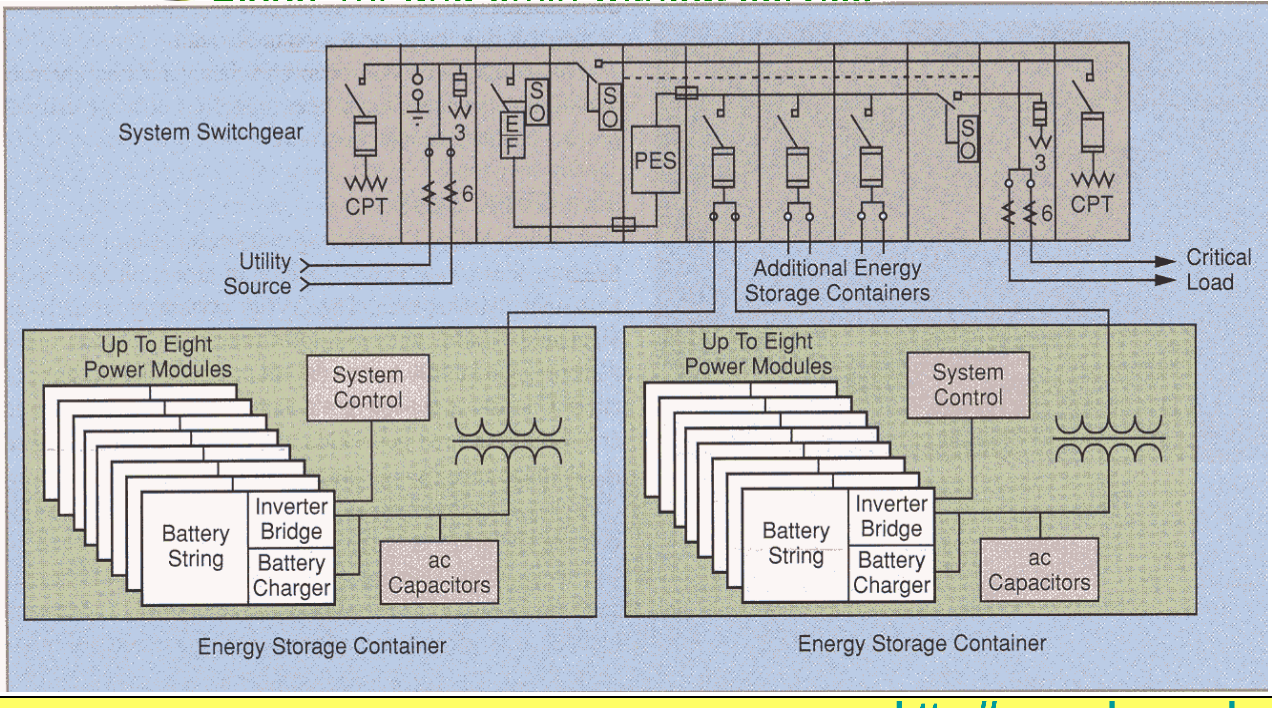
- **Do not forget Power Electronics (Power Conversion Systems, PCS)**
  - The systems usually need to store in DC. DC&AC flows are necessary.
  - It accounts for over 25% of system cost.
  - Its size is determined by the need to store energy / power generation (i.e. large needs)
- **Problem: some systems do not have the desired reliability level (from PS people viewpoint)**
  - New devices, ETOs:
    - ETO (Emitter Turn-Off Thyristor)
    - High power
    - Fast switching
  - Sandia Lab in collaboration with Navy-NSWC
- **PCS Costs: 100 $/kW to 1200 $/kW**

- **Battery systems**
  - The battery problems are its cost, volume, the evaluation of the state of charge, cycles of work and lifetime.
  - Storage Capacity: 10-60 minutes
  - Power Utilities (traditional: UPS)
  - New uses for DER: Reduction and Limitation of peak demand
  - Benefits: Improve the quality and supply reliability
  - Latest developments: Li-ion batteries, Hybrid systems (battery.-capacitors)

System attribute	Lead-acid	Nickel metal hyd.	Lithium polymer	Sodium sulfur	Sodium-salt
Specific energy – kWhr/cu.ft.	2	5	6	7	5
Specific power – kW/cu.ft.	3	6	11	15	15
Efficiency - % over 24 hours	92	92	88	88	87
Lifetime, deep cycles	400	800	600	1000	800
Cost per kWhr	$125	$375	$550	$350	$300

- **Example of Battery Energy Storage System in Golden Valley (GVEA, Fairbanks, Alaska, USA)**
  - 90000 inhabitants
  - Virtually isolated power system
  - A power link with Anchorage exists (400km) for extracting the maximum generation (hydraulic)
  - Politics: try to reduce costs by minimizing the rotating reserve (spinning reserve).
  - They have a load shed system (apparently insufficient)
- **GVEA BESS objectives**
  - Get static spinning reserve (alternative to expensive and conventional rotating one)
  - + Reactive Control (VAR support)
  - + Power system stabilizer (P-Freq oscillations)
  - Compensation while large motors stars (large currents)
  - Maintain the system if protections act

- **BESS characteristics (I) (source: GVEA)**
  - 3,760 liquid electrolyte-filled Ni-Cd cells
  - Each battery is roughly the size of a large PC and weighs 165 pounds
  - Batteries have an anticipated life of 20-30 years
  - PCS: Integrated Gate Commuted Thyristor
  - Generation hints (starts in 2003):
    - 46MW (during 5 minutes) or 27MW (during 15 minutes)
    - 2006: 1hr and 6min without service



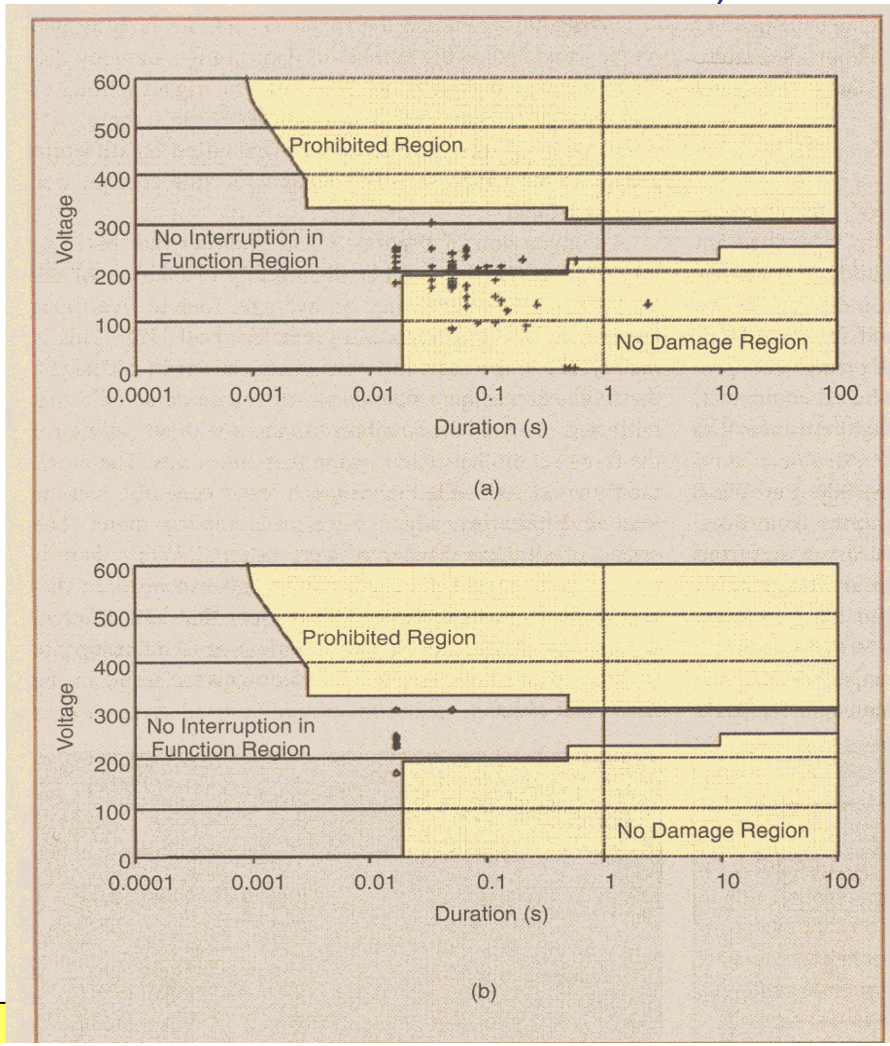
- **BESS characteristics (II) (photos: GVEA)**
  - Lets start generators without being in standby (5-15 minutes)
  - 60% reduction in service problems (none in January 2005, 20 minutes in February 2005)
  - 28 outages covered in 2009
  - Cost $ 35 Million (estimated 20-30 year life)
  - Weight 1500 tons
  - ABB (engineering)
  - Saft (batteries)

- **Another example: substation in Phoenix (Arizona, USA)**
  - Rated power: 12,5 MVA
  - End-use (BEES): 20 op./year
  - Cost: 300$/kVA

- **Example: American Electric Power (AEP)**
  - 36GW generation company (the largest in USA)
  - Load growth: 2%
    - Energy Storage systems used (BESS) since 1920 in its substations and offices
    - Lead-acid systems: since 1920
    - NaS (Lead Sulfide): since 2002
    - Li-ion: since 2003 (in testing)

    - BESS for control systems (250kW-30s,)

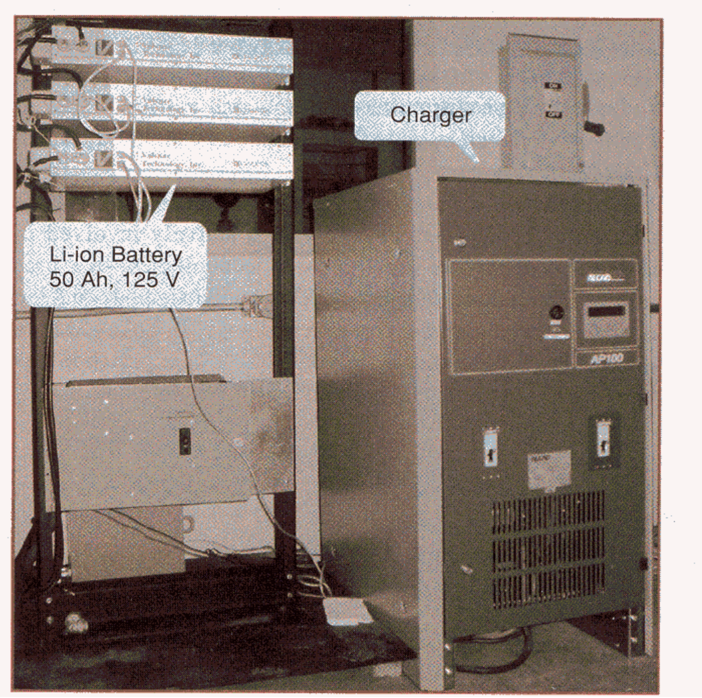
- **BESS example: American Electric Power (AEP)**
  - BESS-NaS under operation (150 m^2/MW). A considerable improvement in the dynamic response (each quality problem is a dot in CBEMA curve)

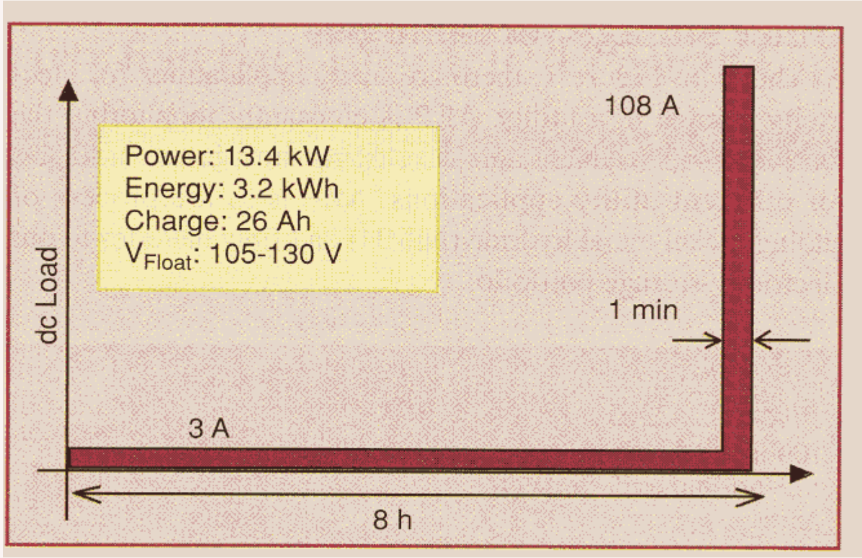


Without BESS

With BESS

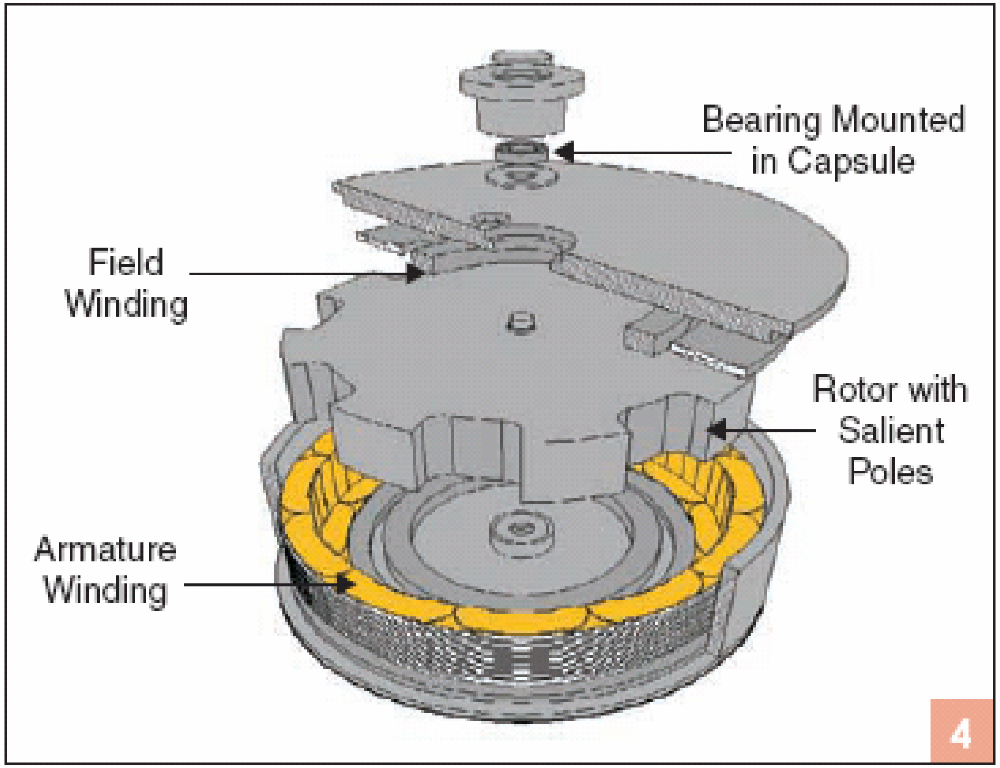
- **BESS: American Electric Power (AEP)**
  - BESS-Li-ion (power substation 138/34.5 kV)
    - Li-ion? Less maintenance than traditional batteries
  - Supply of security monitoring systems
  - 20% of the area of traditional batteries
  - Avoid the cost of maintenance and environmental problems due to lead-acid batteries.



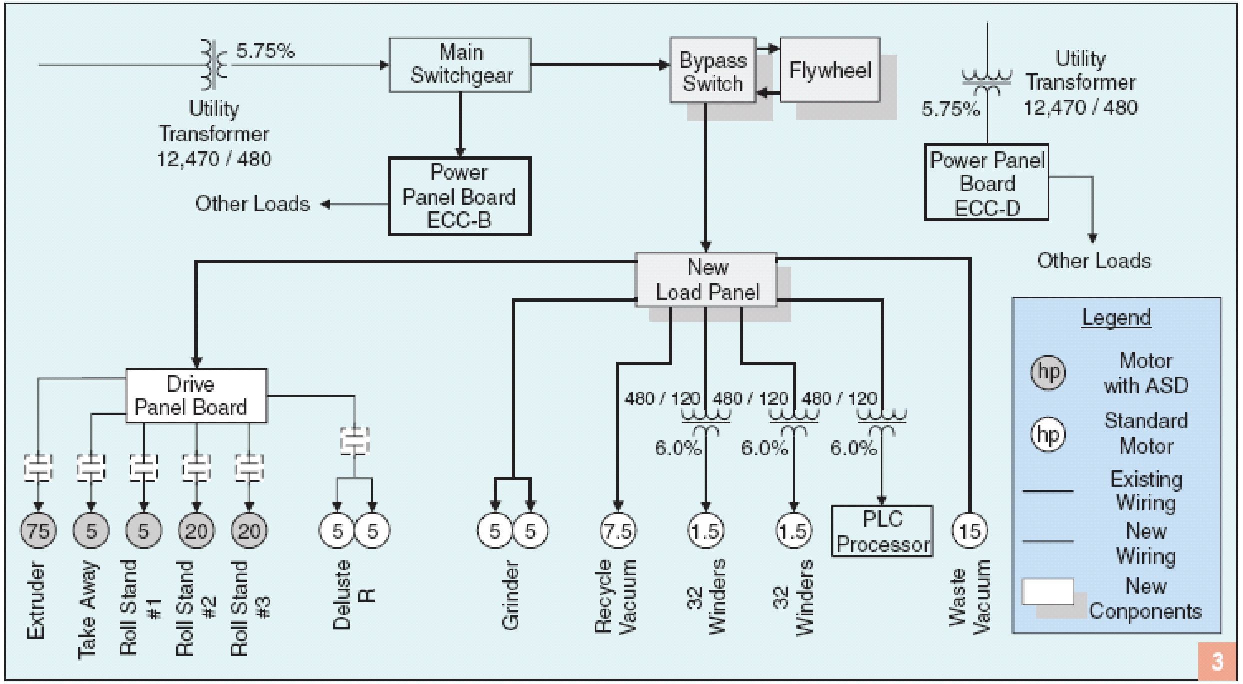


Kinetic storage: Flywheels

- Definition: a motor-generator coupled with a rotating mass
- Could resolve > 90% of disturbances
- Traditional storage (low speed): steel at "low" rpm (<10000).
- Manufacturers: Pillar, Caterpillar, Active Power



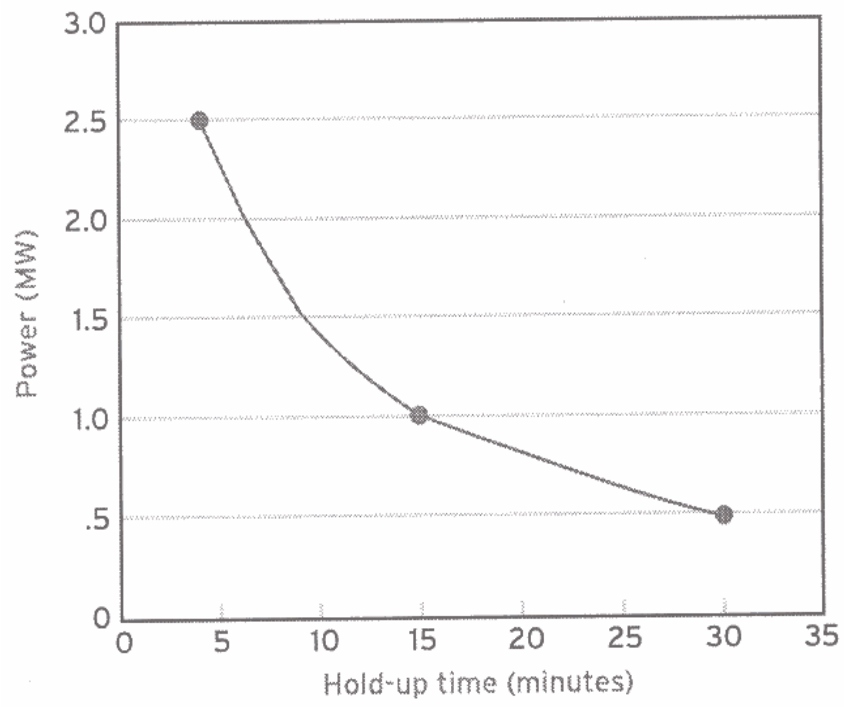
- **At present (high speed developments): rotating masses made on carbon fiber (40k-60krpm)**
  - Manufacturers: Urenco, Beacon Power
    - Developing prototypes: Boeing, AFS
  - Magnetic bearings to reduce friction
  - Advantages: less maintenance, long life, high power density, greater efficiency (a battery)
  - Used in metropolitan railways around the world!!! (London, Paris, Tokyo, ...)

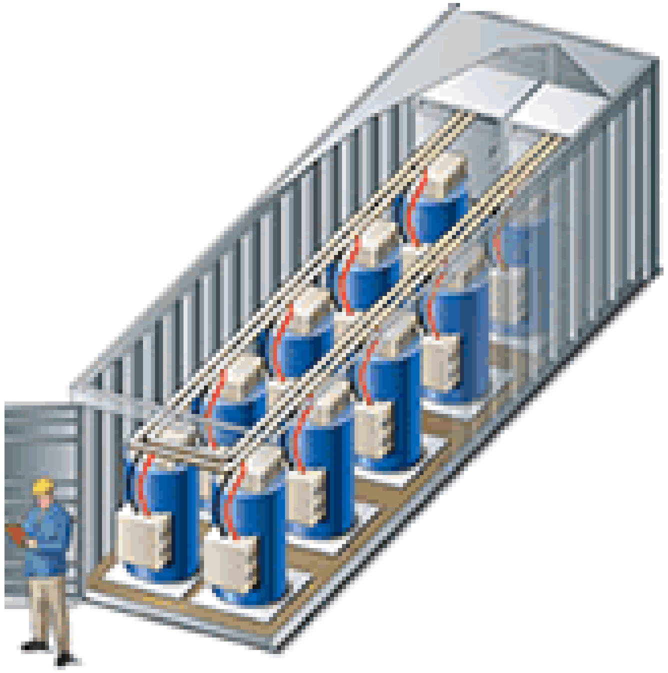


Flywheels: characteristics

- They provide energy from 1 to 20 seconds (while a conventional generator starts. Advantage: the generator is OFF, i.e. no cost)
- Examples
  - (Beacon Power): 15-25kW (6kWh) (right)
  - Diesel-electric locomotive (2 MW) (left).

- **Another Flywheel example: Smart Energy Matrix System (Beacon Power)**
  - 10 * 250kW units: standard container size ► Mobile (supply peaks of seasonal demands: winter, summer)
  - Weight: 18 ton
  - Standby losses: <2%





- **Applications of Flywheels**
  - (source: University of Texas)

Application-Specific Flywheel Battery Designs

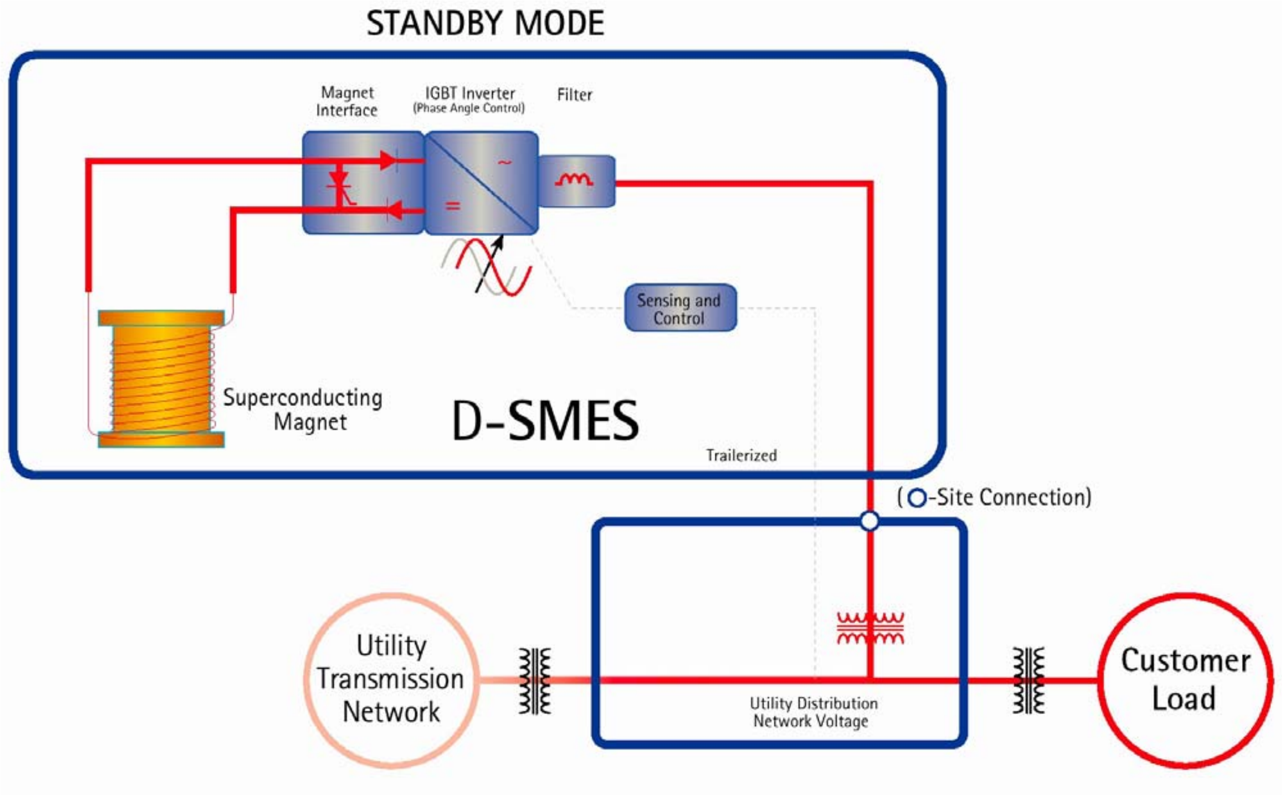
	Peak power	Stored energy, MJ (kWh)	Maximum rotational velocity, rpm	Rim speed, m/s	Rotor material	Rotor mass, kg
Satellite	2 kW	1.4 (0.4)	53 000	900	Composite	30
Power quality	400 kW	4.7 (1.3)	10 000	400	Steel	1400
Hybrid bus	150 kW	7 (2)	40 000	900	Composite	60
Space station	3.6 kW	13 (3.7)	53 000			75
Hybrid combat vehicle	11 MW pulsed; 350 kW continuous	25 (14)	18 000	540	Composite/ metallic	280
Electromagnetic launcher	5–10 GW	50–150 (14–42)	10 000	450	Composite	4000
Train	2 MW	470 (130)	15 000	950		2500

Source: University of Texas

Superconducting Magnetic En. Storage (SMES)

- Energy in a magnetic field, without losses due to Joule effect
- Hint!: R = f (temperature)

$$w_L(t) = \frac{1}{2} L i^2(t)$$

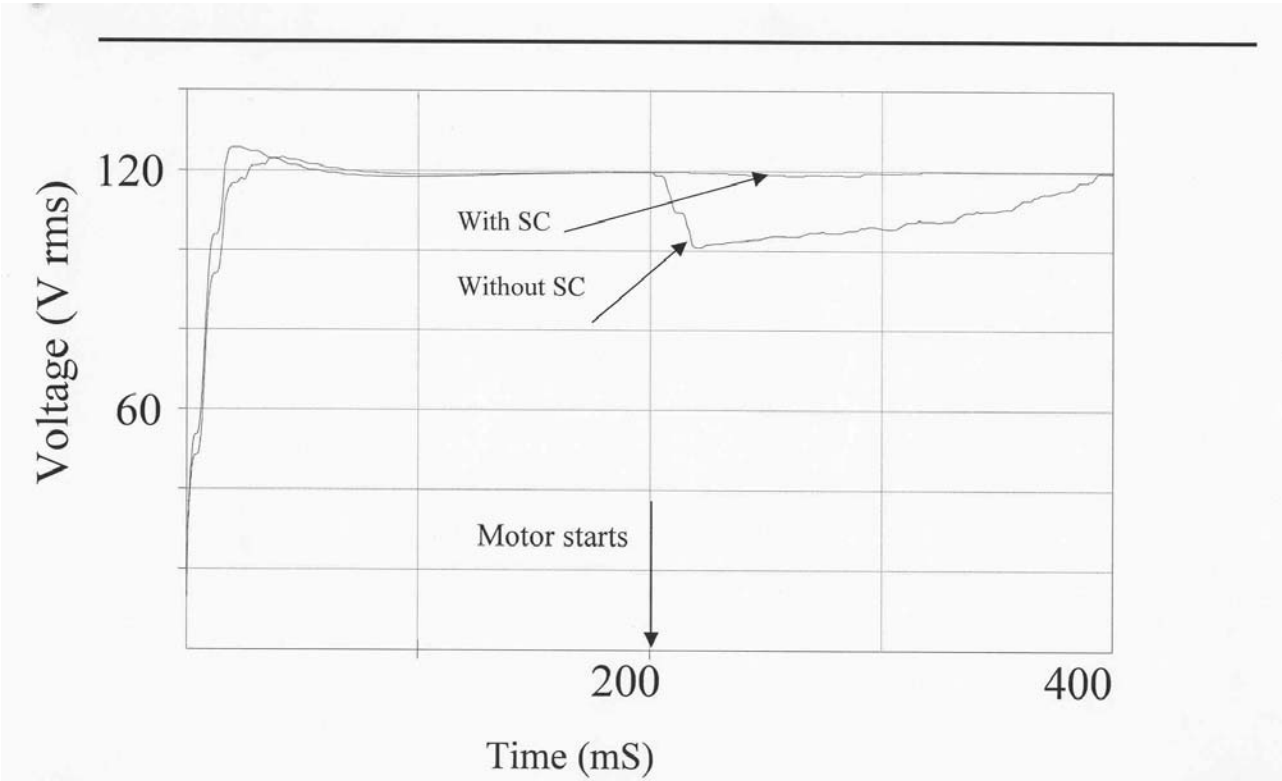


- **Manufacturers and features**
  - ACCEL Instruments GmbH (Germany)
    - Developing a plant in Dortmund
    - Energy: 2.1 MJ
    - 200kW of avg power (over 8s)
    - Maximum power 800kW
    - Inductor (4.1 H), induction (4.1 T)
    - Size 760x600mm
  - Other manufacturers (GE, D-SMES, 3 MJ)

Super capacitors (ultracapacitors)

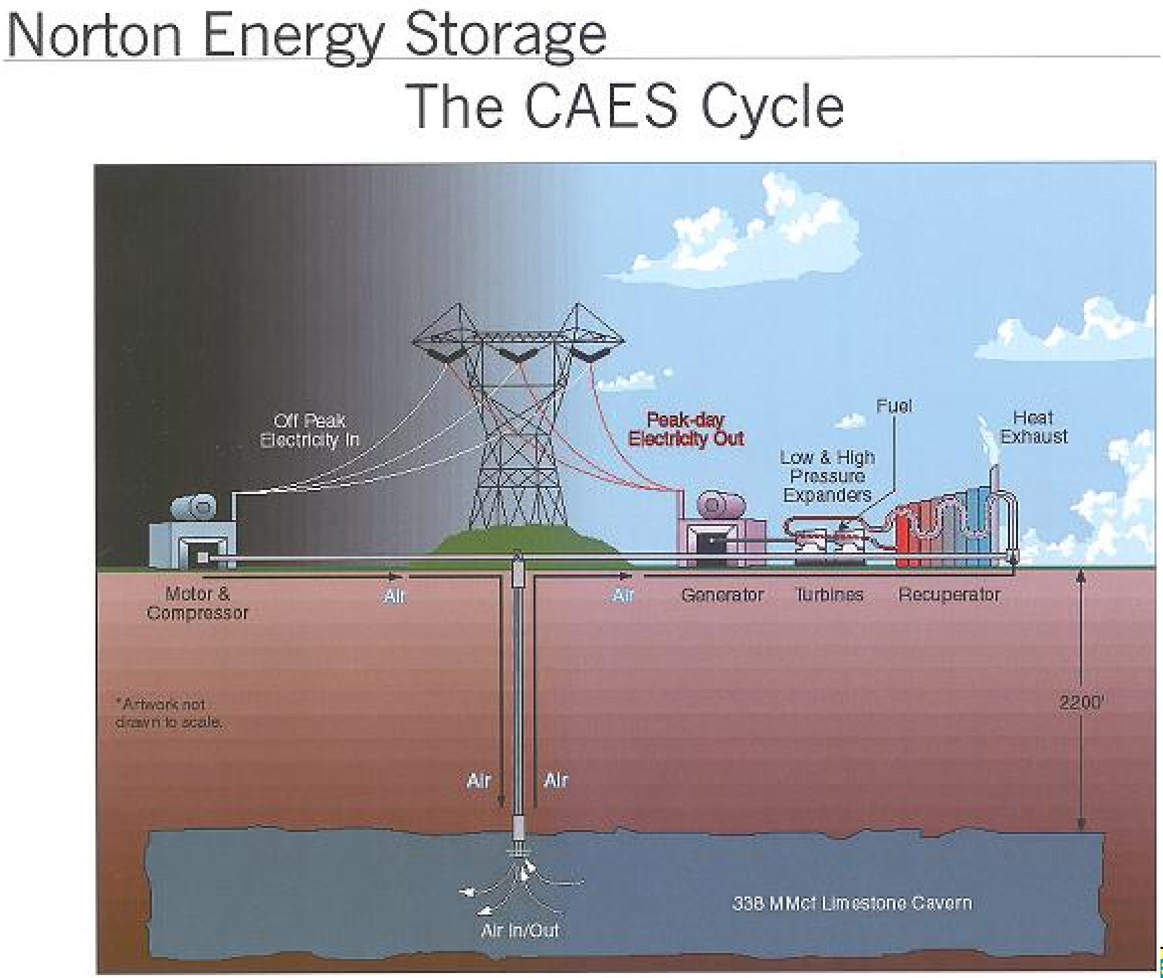
- Usefulness: two examples
  - Support service interruptions for small batteries (imporve the life of UPS systems)
  - Support for renewables
  - Regenerative braking: railways.
- Example: MAXWELL capacitors
  - 2500F 10 years of life (500,000 cycles)
  - 2.5 V; 0.001Ω (internal R)
  - 8400 J (storage)

- **Renewable Energy Management (eg. microturbines)**
  - Fast Response to current peaks when a motor starts. These peaks could trigger off a microturbine (provide additional strength)
  - Example of a voltage sag



CAES

- Air compressed storage in aquifers or abandoned mines (eg salt mines).
- There aren´t many sites available.

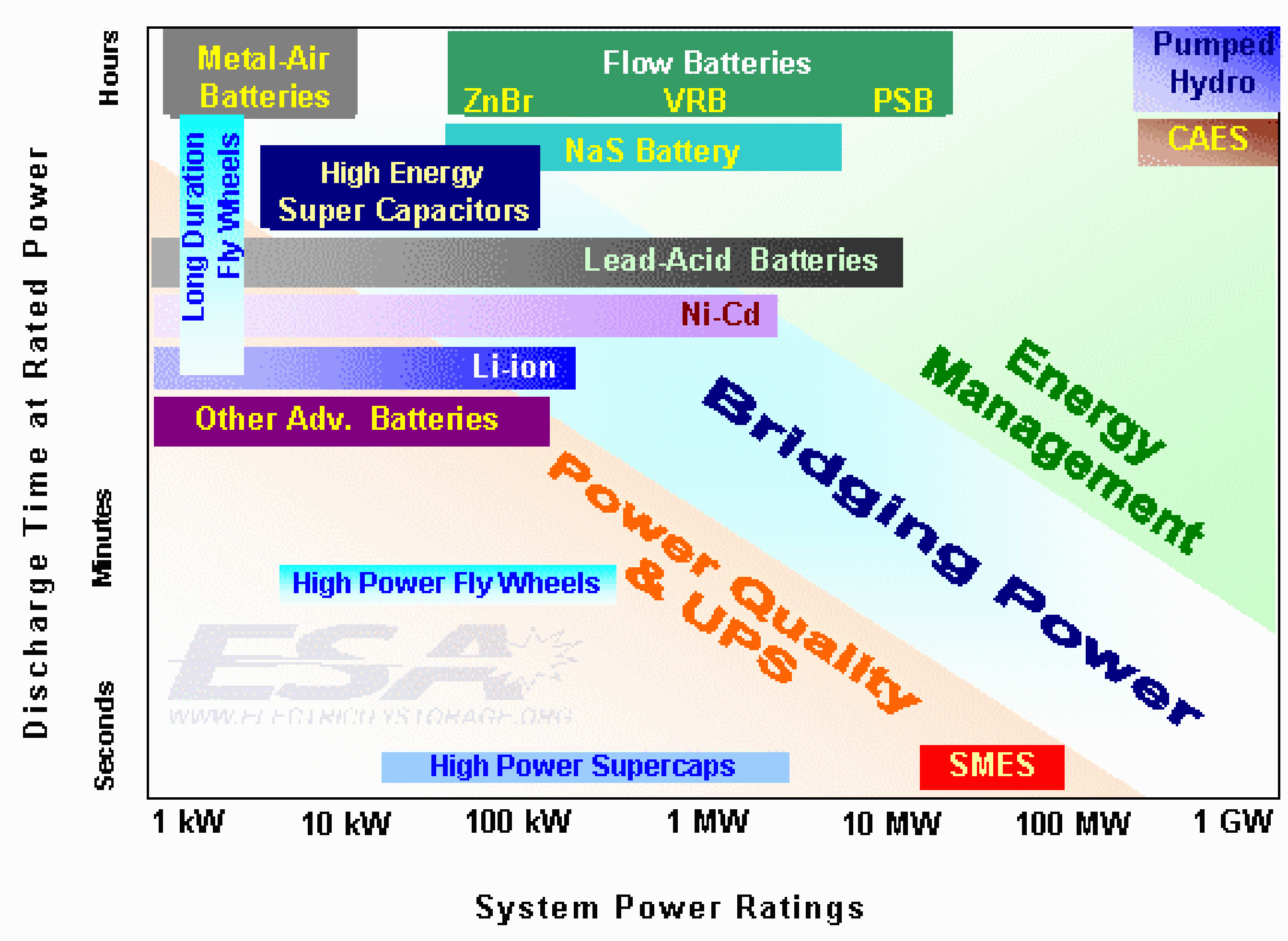


CAES: Pilot projects

- **Alabama (EEUU, 1991)**
  - Abandoned salt mine. Rated power 110 MW
  - Capacity: Electricity supply to 11000 homes for 26 hours
  - Air pressure: from 50 to 75 bar
  - Cost M$ 65 (591 $/kW)
  - Availability: In 14 minutes is ready to generate
- **Huntorf Plant (Germany, 290MW)**
  - It is associated with a gas turbine for power generation
  - Reduce to 1 / 3 full costs of gas consumption (gas compression of the turbine)
  - Volume: 300.000m3
- **Future: Norton Energy Storage (USA)**
  - 10M m3, 480MW peak power at 2.5 GW
- **Future: PG&E (USA)… M$ 50 in prototype**
- **Future?: CAS systems (ground storage)**

Review of Technologies

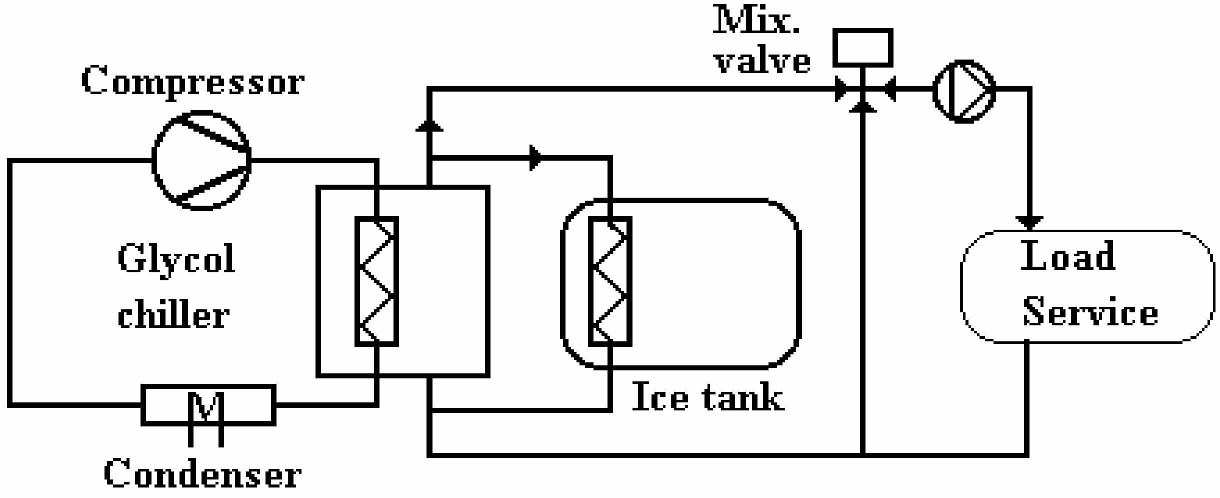
- Source: Energy Storage Association, USA



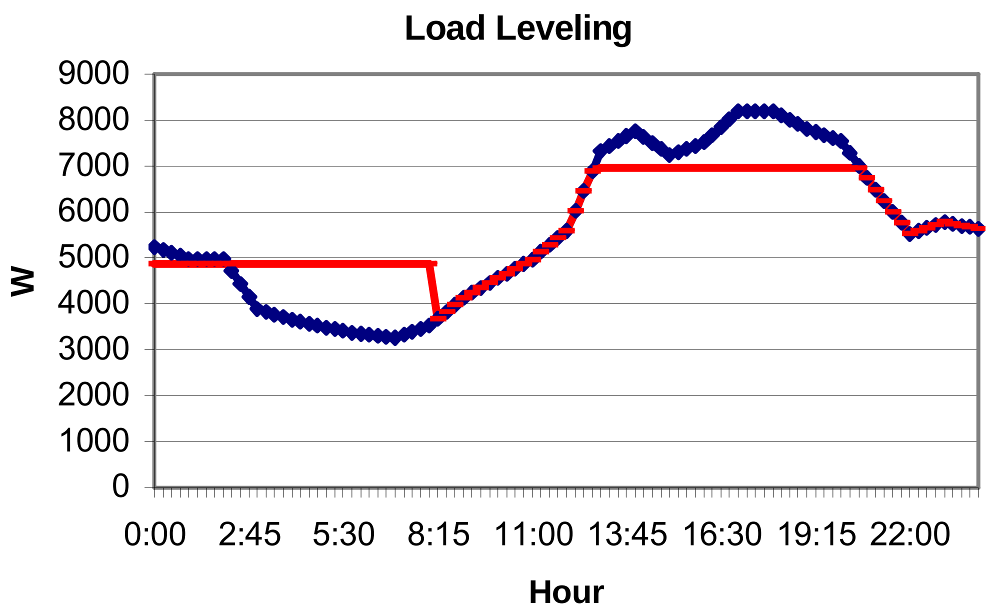
- **Thermal Storage (TES)**
  - Cold storage
  - Heat storage

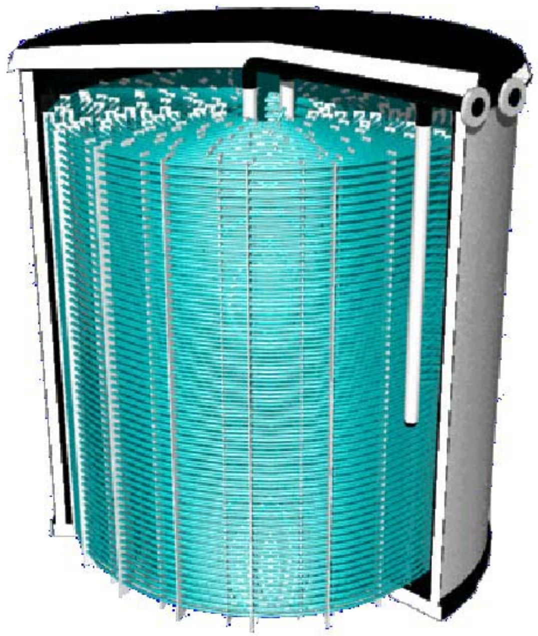
Cold Storage: technologies (TES)… ice or water?

- Ice can store energy through:
  - Specific heat (water or ice): 42 kJ / kg
  - Heat of fusion (change of state): 335kJ/kg
- Advantages ice vs. Chilled water:
  - Ice requires less storage space (residential customers).
  - The chilled air is cooler (smaller sizes of pipes and fans)
- Pilot projects: ECO Japan Mini ICE (TEPCO & SANYO)
- Manufacturer: Calmac Corporation (Roofberg ®)



- **Is it efficient? What about storage losses?**
  - Yes, there are losses: Obviously storing → energy losses
  - But, it has some advantages (€,$, and efficiency):
    - Operation at night (cooler temperature ► more efficient chiller)
    - Lower price of electricity at night.
    - Lower peaks in the electrical power system.
  - Residential example: load leveling … break-even!!!
    - Source (www.demanresponse.eu)





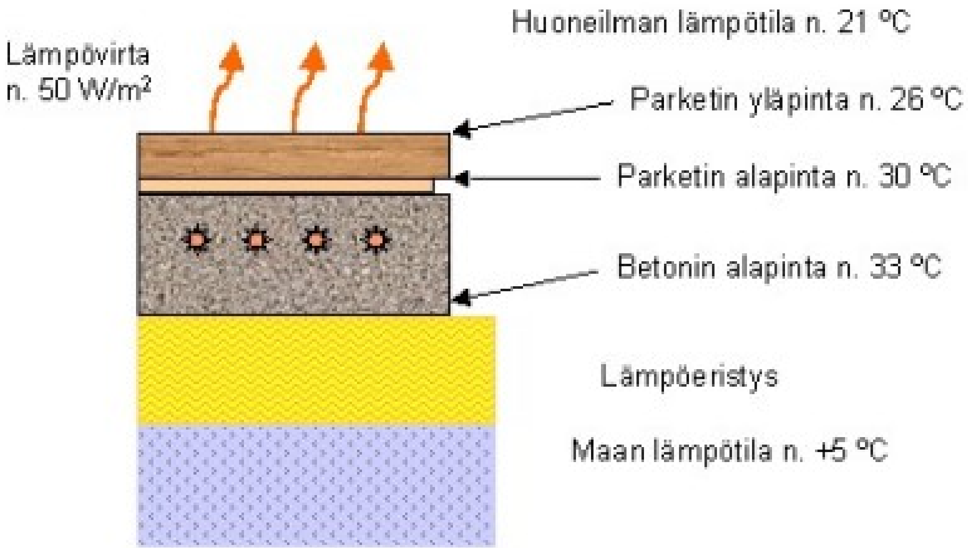
- **Heat Storage Systems**
  - Ceramic batteries
  - Iron oxides 2 and 3 (Histor 10)
  - Density: 4000 kg/m3
  - Weight: 70-300 kg
  - Specific heat Ce = 0.9 kJ / kg K
  - New : silicate ceramics
    - 1340 kg/m3
    - 1.5 kJ / kg

Heat Storage Systems (II)

- **There are two systems**
  - Static: natural convection
  - Forced: forced convection (bricks + ventilation)
- **Weights and power**
  - From 1 to 9kW
  - Weight: 80kg to 200kg (nice problem!!)
  - Prices: from € 500-600
  - Question: Is Joule effect effective from an efficiency perspective?
    - Price of electricity?
- **UE Manufacturers**
  - Gabarrón-Elnur SA, Spain

Floor and ceiling heating

- The thermal capacity of the floors and ceilings make storage element (source: Finland, VTT Energy)
- Concrete with heating cables (conduction to dwelling house)



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