Beacon POWER™

Joint ARPA-E/ASD(R&E) Workshop Energy Storage

Flywheels for High-Power Applications

Matt Lazarewicz

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Beacon Power Corporation

Thank You!

- DOE
- ARPA –E
- DOD
- DARPA
- NYSERDA
- CEC

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Agenda

- Hybrid Storage – PC Analogy
- Basic flywheel and battery comparison
- High Power Frequency Regulation application
- Cost paradigms
- Next Step in Flywheel technology
- Combining High Power with High Energy

PC Hybrid Storage Analogy

PC memory storage example:

Application	MBytes	Speed	Portable
RAM	1	5	0
Hard Drive	2	2	0
DVD	1	1	4
External HD	5	1	3
Thumb Drive	1	3	5

One type of memory does not fit all

Scale on chart is 0 (low) to 5 (high)

Many Storage Choices Available

Type	Storage Mechanism	Common Duration	Cycles
Capacitor	Electrical charge	Seconds (minutes)	100,000's
Flywheel	Kinetic energy	Seconds / Minutes	1000's - 100,000's
Battery	Electro-chemical	Minutes (hours)	100's-1000's
Pumped Hydro	Potential energy	Hours	1000's
Thermal	Ice, Molten Salts	Hours	1000's

Storage Types

Laptop Computer

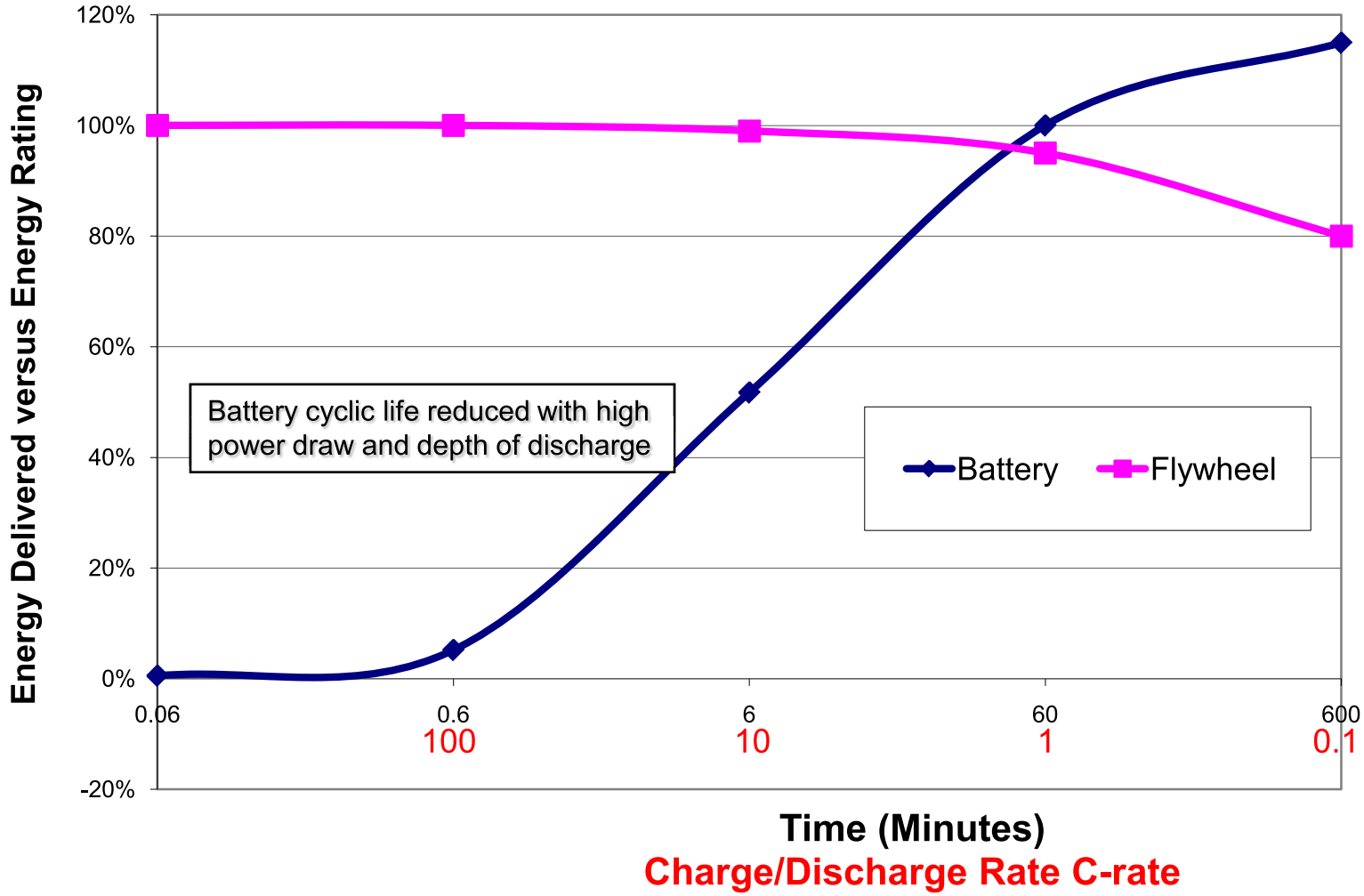
- RAM
  - Millions of operations/min
- Hard Drive
  - Current work
- DVD
  - Occasional Usage

Power Grid

- Flywheels, Capacitors
  - >>10^5 deep 15 min cycles
- Batteries
  - < than 10^4 deep 4 hour cycles
- CAES and Pumped Hydro
  - >1 day cycles

Technologies can do other functions – but not well

Why Flywheels for Power?



Which would you choose for high power? Long duration?

Battery curve is sample for illustration based on 10 year old data for VRLA

Typical "Regulation" Profile

ISO Goal:

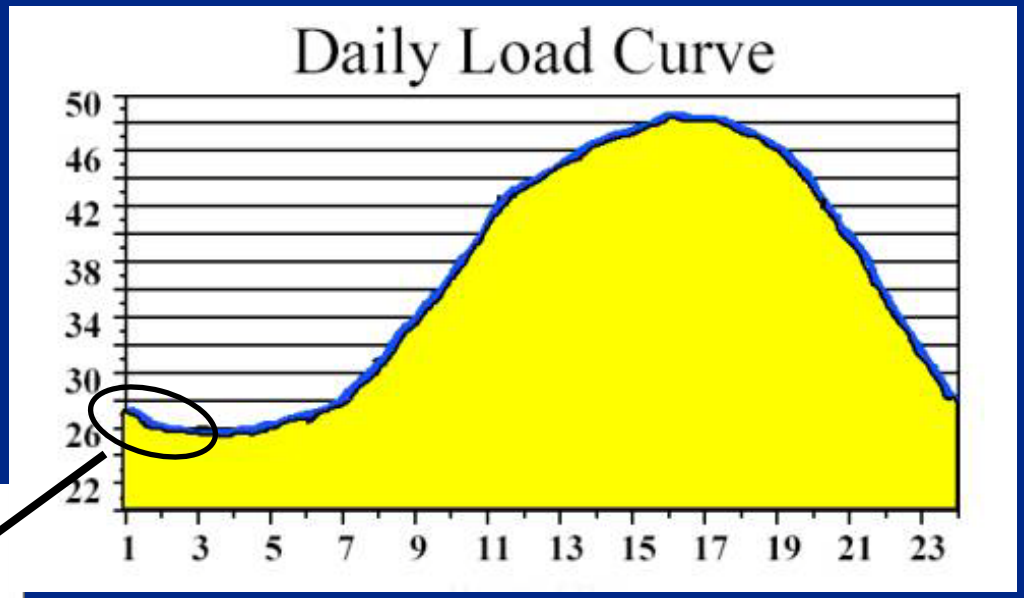
Load = Power Generated

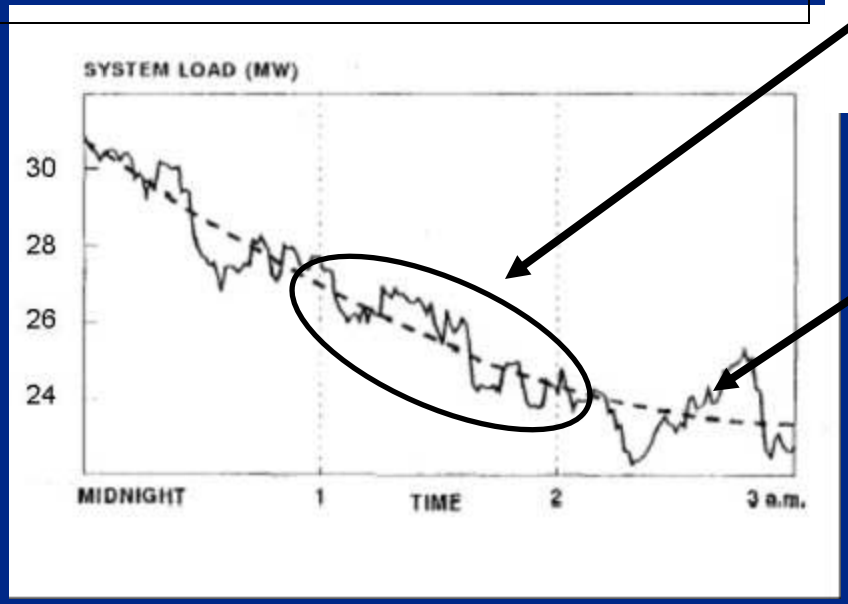
Power < Load:

– Frequency drops under 60 Hz.

Power > Load:

– Frequency rises over 60 Hz.

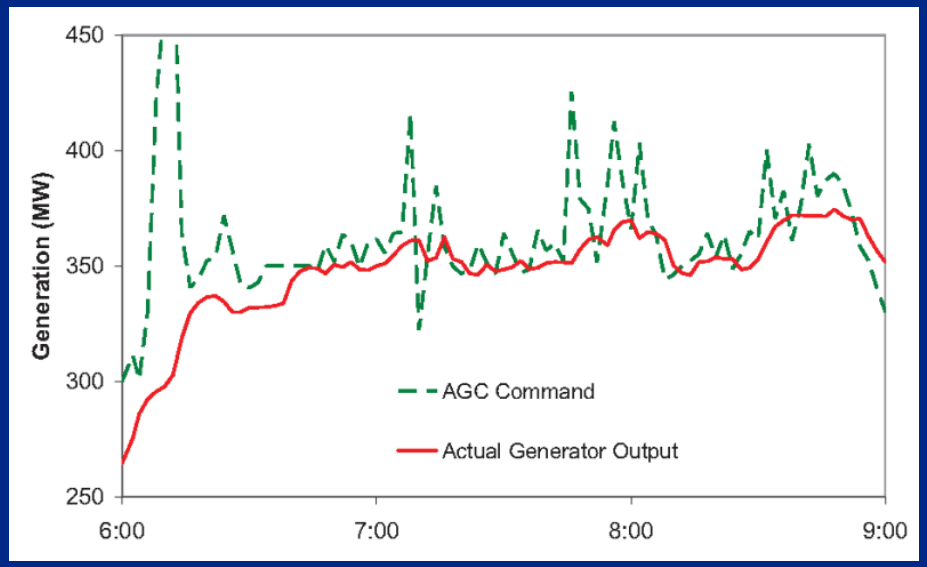




Short term variation

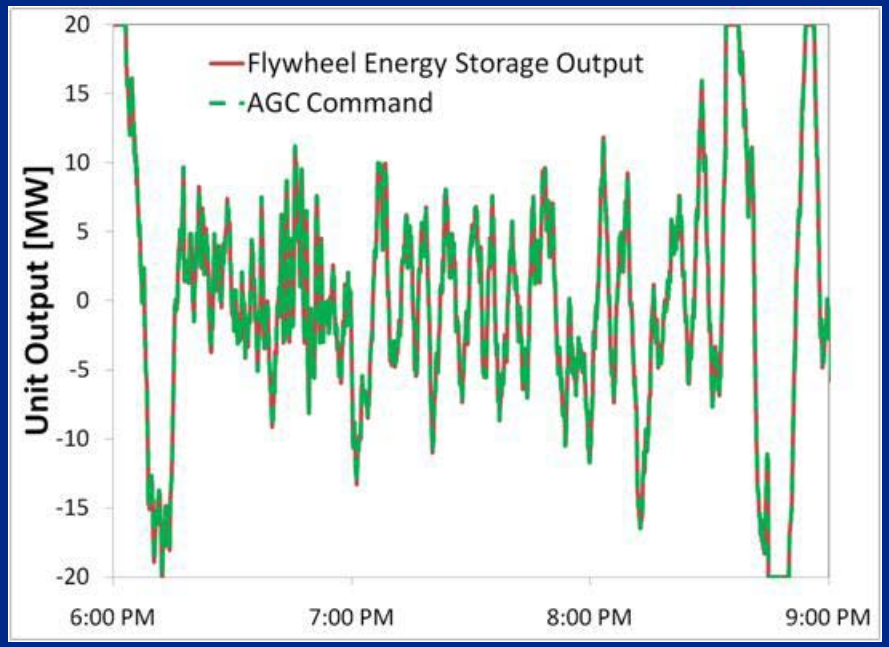
- ~ 1% of daily load
- Managed via regulation
- Fluctuation is net zero

Fast Regulation: Speed Matters…



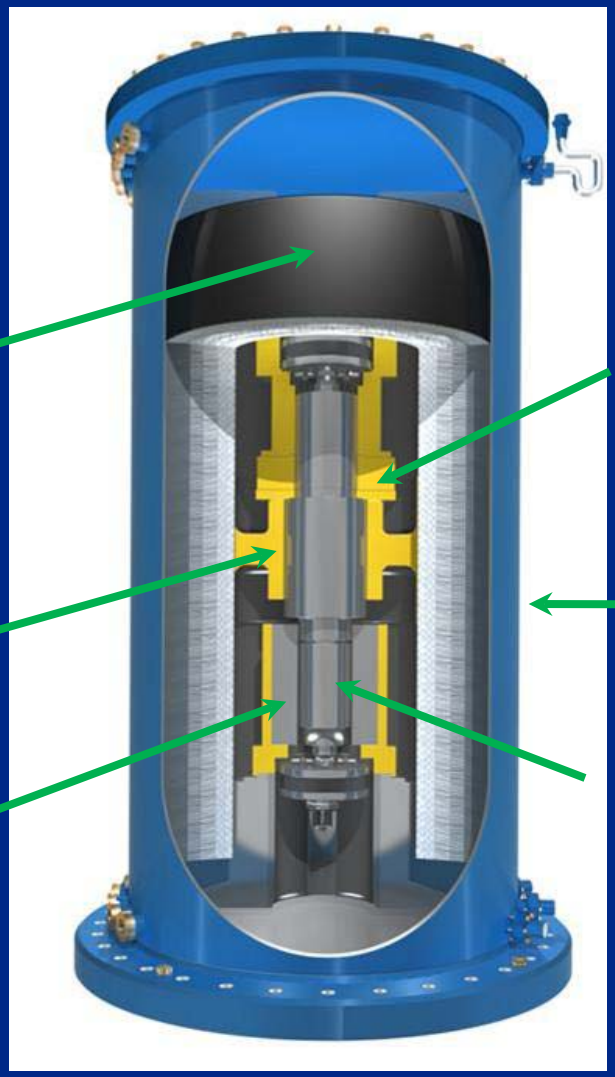
A coal fired power plant poorly following an AGC regulation command signal

Energy Storage accurately following an AGC regulation command signal



Storage provide near-instantaneous response

Flywheel Technology



- Up to 17 times more effective than fossil generators
- 20-year design life
- >125,000 equivalent cycles
- Available à la carte
- Low operating cost
- Zero emissions
- High AC/AC efficiency ~85%

Flywheel Product Evolution

2000

Gen 1
Telecom
2 kWh / 1 kW

2001

Gen 2
Telecom
5 kWh / 2 kW

2004

Gen 3
Grid
4 kWh / 15 kW

2005-6

(2) 100 kW demo system
(DOE co-sponsored)

2006-2007

Gen 4
Grid
25 kWh / 100 kW

2008

1 MW Module
10 Gen 4 Flywheels

2010

20 MW Plant Constructed in Stephentown NY

- Over 650,000 hours of operation in the field. Units running continuously without service 9 years
- Technology is product of 10 years of R&D and testing at a cost of $180M

Flywheel Manufacturing

1 MW / 250 kWh Module

- Ten 100 kW / 25 kWh flywheels

- Transformers and support equipment
- Electronics and controls inside container

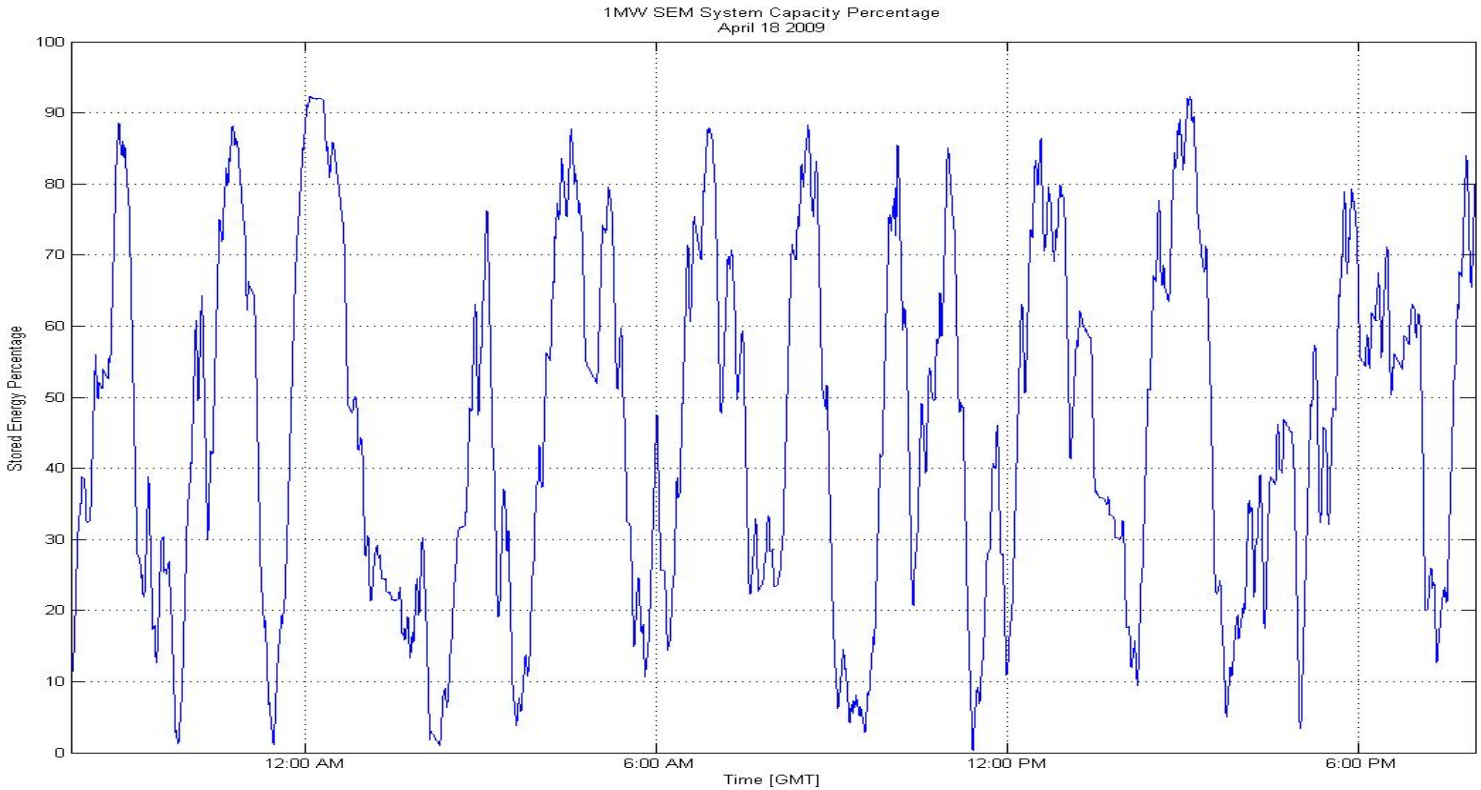
1st 20 MW Plant — NYISO

Highlighted by the White House as one of the
100 Recovery Act Projects that are Changing America

Cyclic Content: ISO-NE Pilot Program

April 18, 2009

State of charge (Percent)



Cyclic content for regulation is demanding:
6,000 to 8,000 equivalent full charge/discharge cycles per year!

Energy Throughput Comparison

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Frequency Regulation

- 20MW / 5MWh
- 16-20 full cycles/day
- 125-150K cycles in 20 yrs
- 80 -100 MWh per day throughput
- Operates at 1.5C to 4C charge/discharge rate

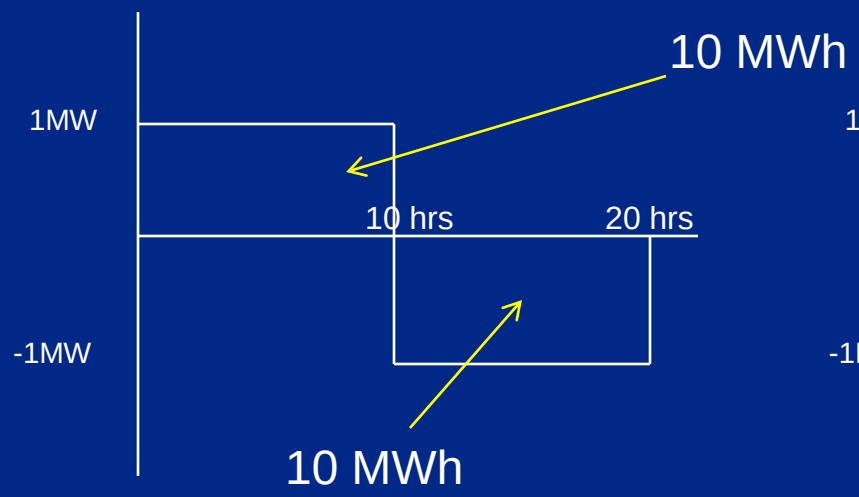
Diurnal storage

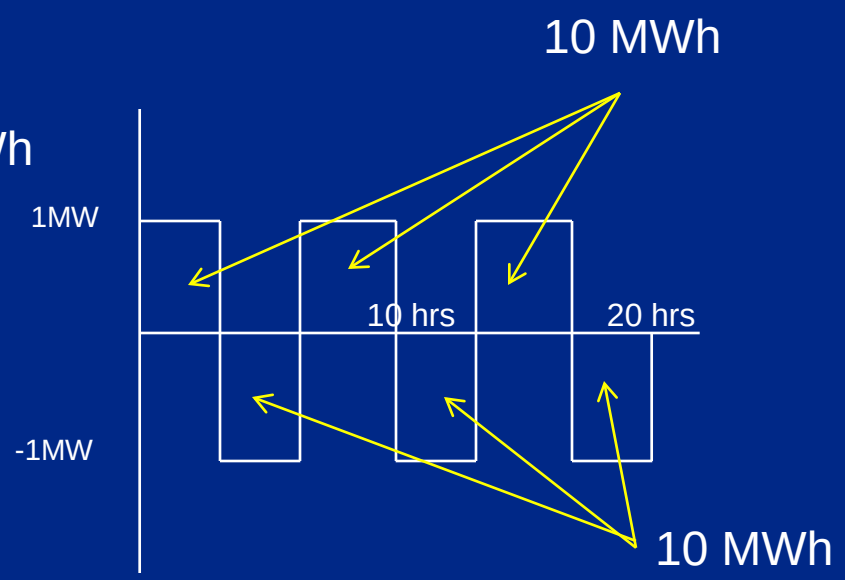
- 20MW / 100MWh
- 1full cycle/day
- 7.5K cycles in 20 yrs
- 100MWh per day throughput
- Operates at C/5 charge/dischrge rate

Energy **throughput** is similar, C-rate severity is very different

Breaking Cost Paradigms

- What is worth more?





	Storage 1	Storage 2
Nameplate Power	1MW	1MW
Nameplate Energy	10MWh	3.33MWh
Cost	$1M	$0.5M
Cycles in 20 hrs	1	3
Energy delivered	10MWh	10MWh
$/kWh nameplate	**$1000/kWh**	**$1666/kWh**
$/kWh delivered	**$1000/kWh**	**$500/kWh**

What is the Right Cost Question?

		C1 charge/discharge rate (1hr duration)							
	Nameplate Energy Cost	Power Cost	Cyclic Life	Useable Depth of Discharge	Nameplate Energy Extracted	Installation oversize factor	Lifetime Delivered Energy Cost	Required cycle life	Cost of required cycle life application
	$/kWh	$/kWh	Cycles	%	%		$/kWh	cycles	$/kWh
Lead Acid	300	300	2,500	50%	100%	100%	$0.24	5,000	$0.24
Li-ion	1,000	900	5,000	90%	100%	11%	$0.22	5,000	$0.22
Flywheel	4,000	4,000	150,000	100%	100%	0%	$0.03	5,000	$0.80
Ultracapacitor									
Flow battery									

Nameplate based Lifetime delivered energy based Cycle limited based

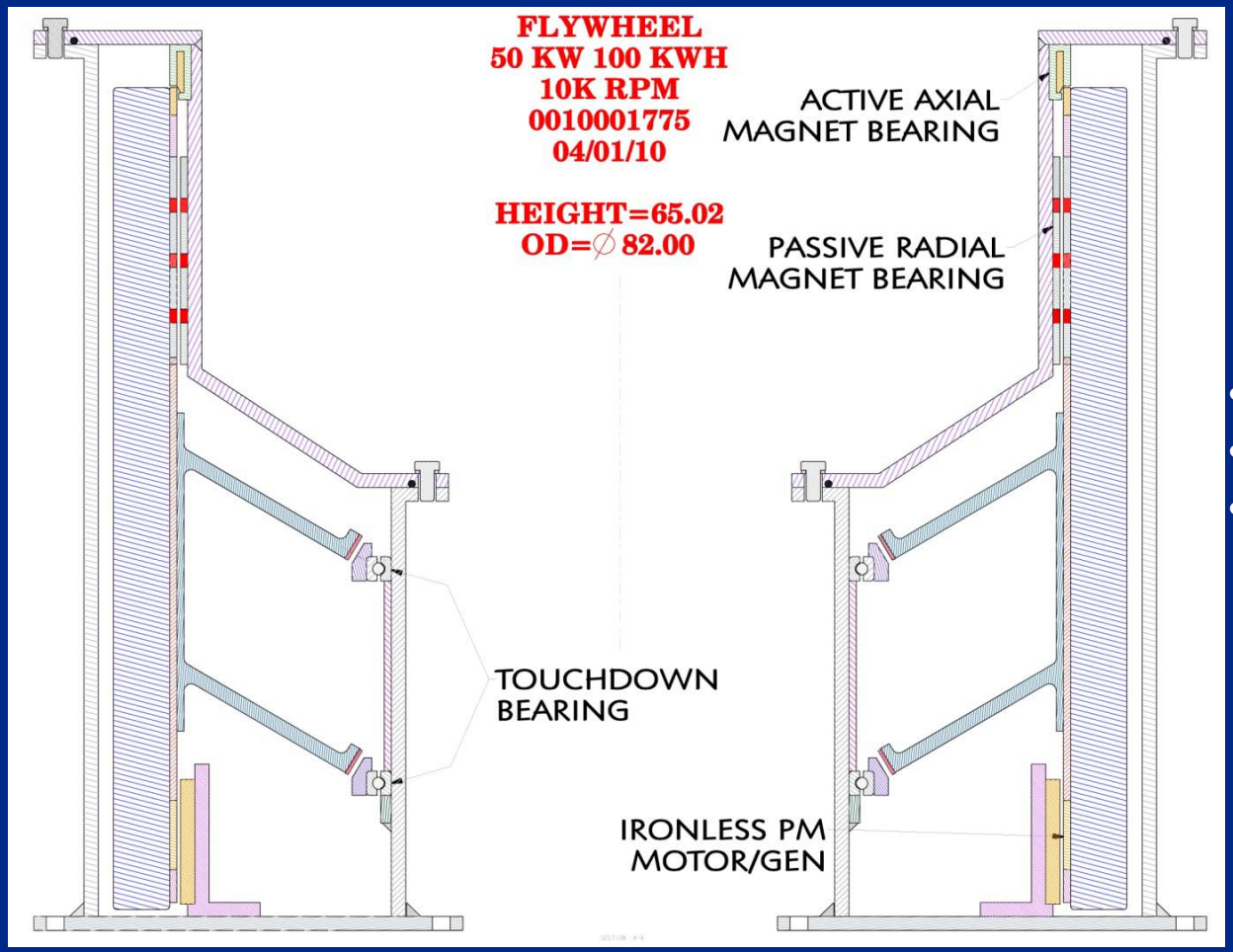
- Ask the wrong cost question; maybe get a wrong decision
- At higher C-rates, difference is much higher
- Flywheels are best for high cyclic, high power applications

Flywheels in Grid Applications

- First Application is Frequency Regulation
- Coming up:
  - Frequency Response
  - Renewable energy ramp mitigation
  - Mini-grid load following stability
  - Light Rail Applications
  - Pulse power
  - Ship Power

All are high C-rate (5C to 50C), high cyclic applications

ARPA-E: 360 MJ "Flying Ring"



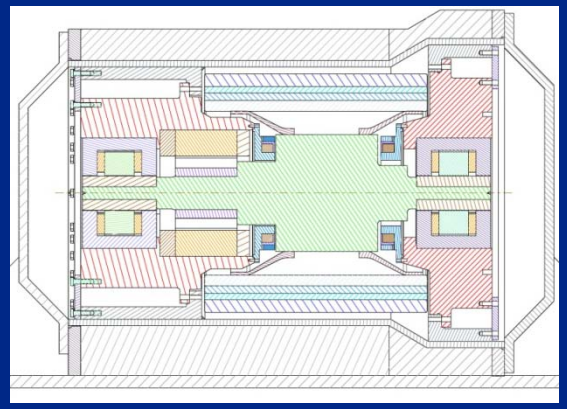
- Bonded magnetics
- E-beam curing
- Touch-down system

ARPA-E “Flying Ring” Flywheel

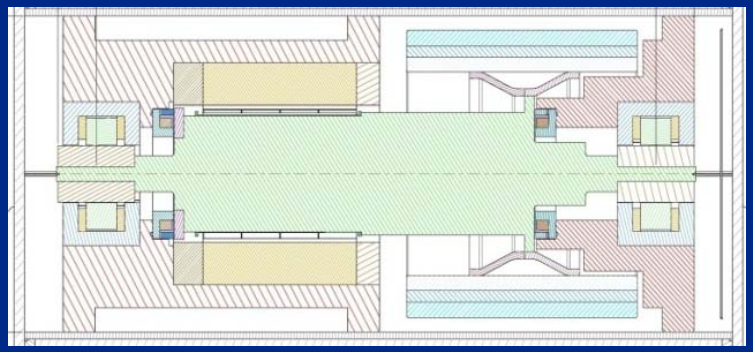
- Features
  - 100 kWh, 100 kW
  - 1 hr. duration
  - Cost / kWh 1/8th current
  - Response time < 4 sec.
  - Very low parasitic losses
- Applications
  - Ramping, wind and solar
  - Peak power shaving / demand limiting
  - UPS
  - Fast Reserve

Naval Ship Flywheel Layouts

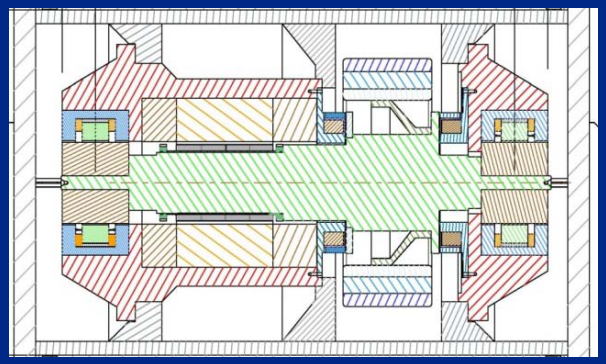
300 kW/110 MJ Assembly
7.2 feet long



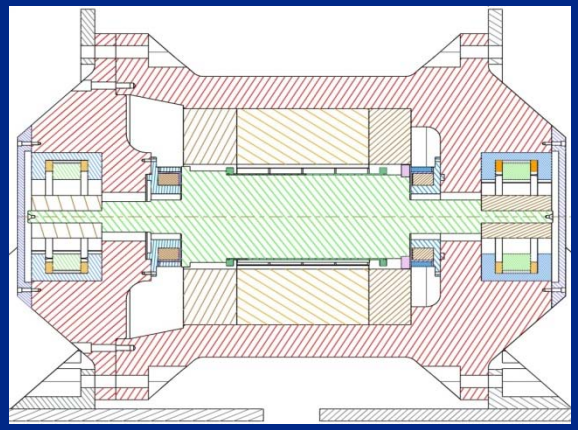
10 MW/100 MJ Assembly
9.4 feet long



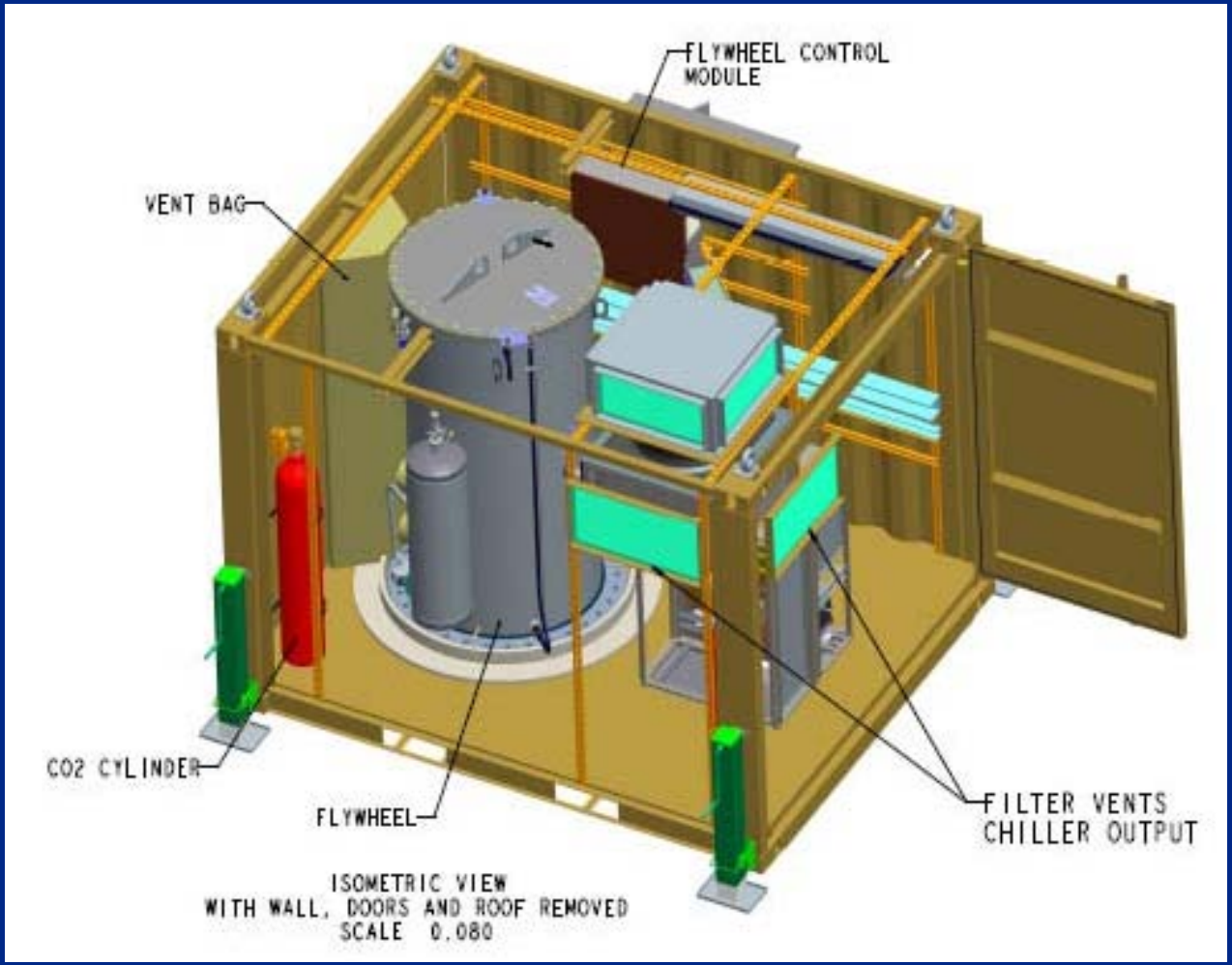
270 kW/1.4 MJ Assembly
3.6 feet long



1 MW/0.4 MJ Assembly
3.3 feet long



Single Flywheel Module



Safety & Reliability

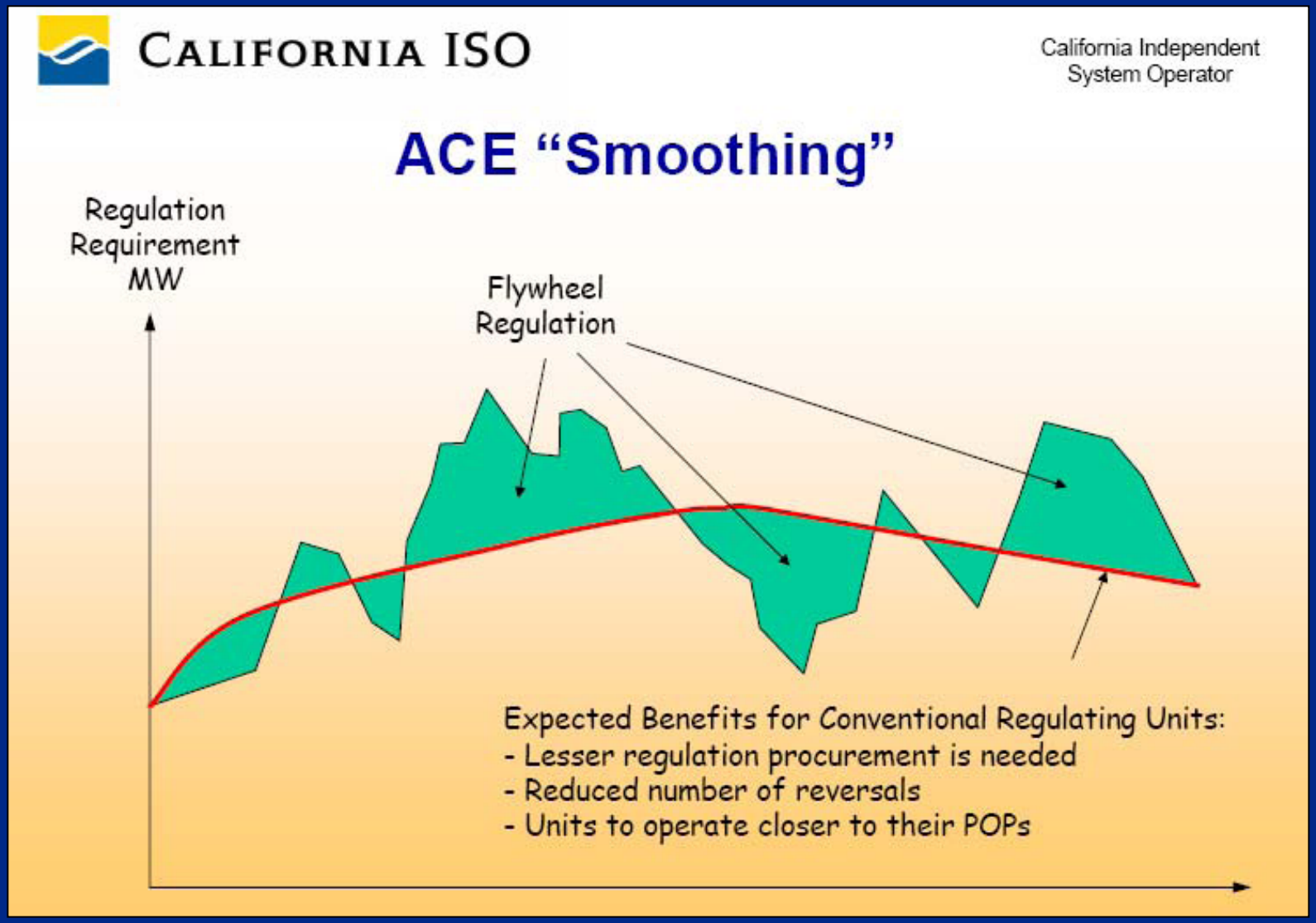
- Composite flywheel rotor is wound like fishing reel
  - Chunks can’t break off like on a steel wheel
  - Circumferential crack leads to loss of balance
- All failure modes leave to imbalance and slow shutdown

Hybrid Storage Concepts

- The models show:
  - Flywheels are much lower $/kWh than bulk storage for highly cyclic applications
  - Bulk storage is a lot cheaper than Flywheels for long storage cycles
- What about mixed applications?

Can hybrid systems be cheaper than straight systems?

CAISO Integration of Energy Storage



Energy Storage for Use in Load Frequency Control

Olivia Leitermann
James L. Kirtley

IEEE Conference on Innovative Technologies
for an Efficient and Reliable Electricity Supply
28 September 2010

Massachusetts Institute of Technology

Research at MIT suggests fluctuating signals can be separated into long term and high frequency signals

Contact:

Matt Lazarewicz
978-661-2832
lazarewicz@beaconpower.com

www.beaconpower.com