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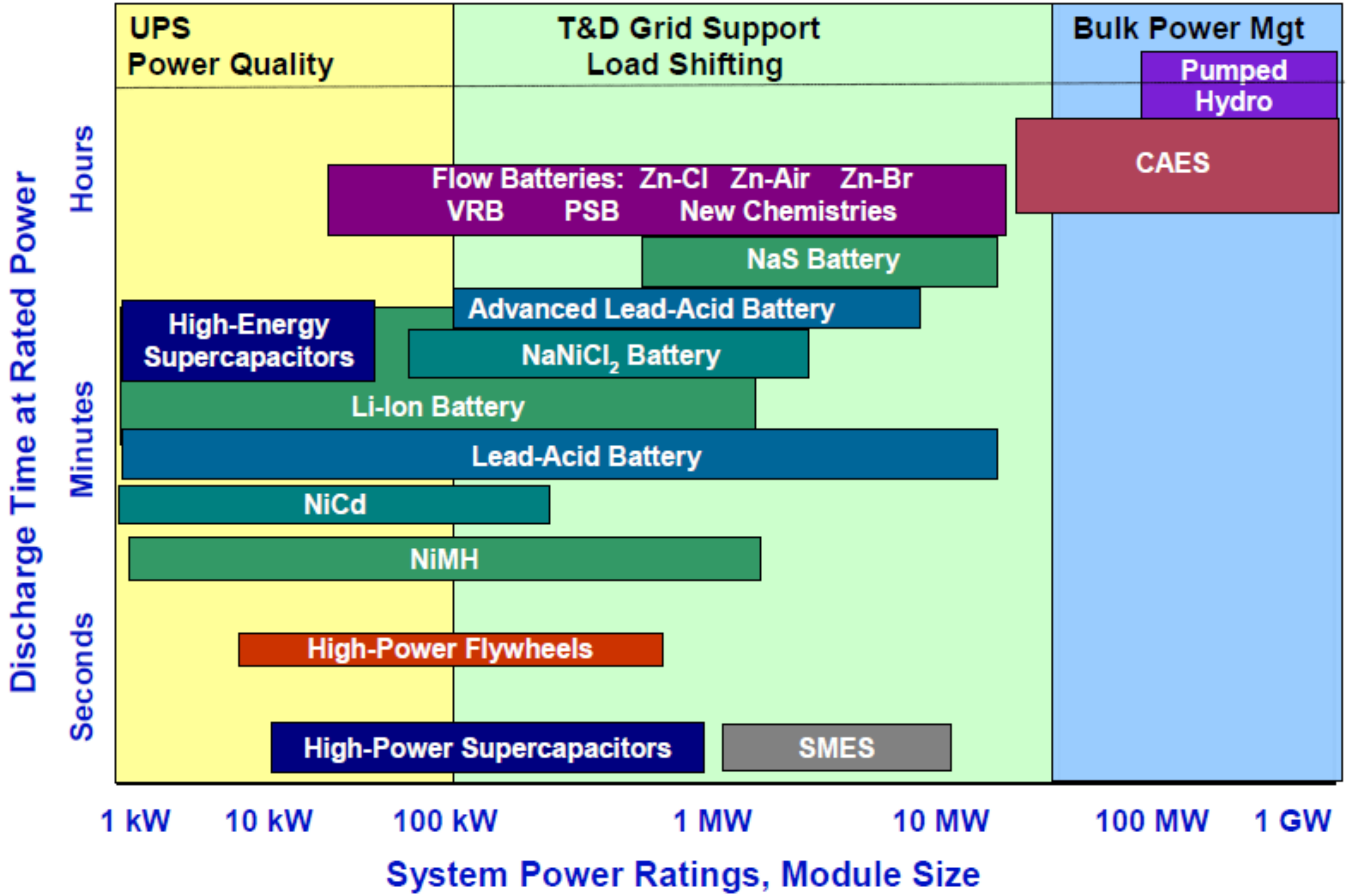
Energy Storage Technologies

- Energy Storage Systems
  - Electrical storage
    - Peak
    - Daily/Weekly
    - Seasonal
  - Thermal storage
    - Centralized
    - Distributed
    - Power to heat
  - Chemical storage
    - Power to fuels

- Electric energy storage technologies
  - Pumped hydroelectric storage
  - Chemical energy storage
    - Hydrogen
    - LAES
    - Flow batteries
  - Electrochemical energy storage
  - Compressed air energy storage
  - Flywheels
  - ???

- Thermal Energy Storage
  - Hot water tanks
    - District storage
    - Distributed storage
  - PCM
  - Heat recovery from hot water
  - MicroCHP with heat recovery
  - ???

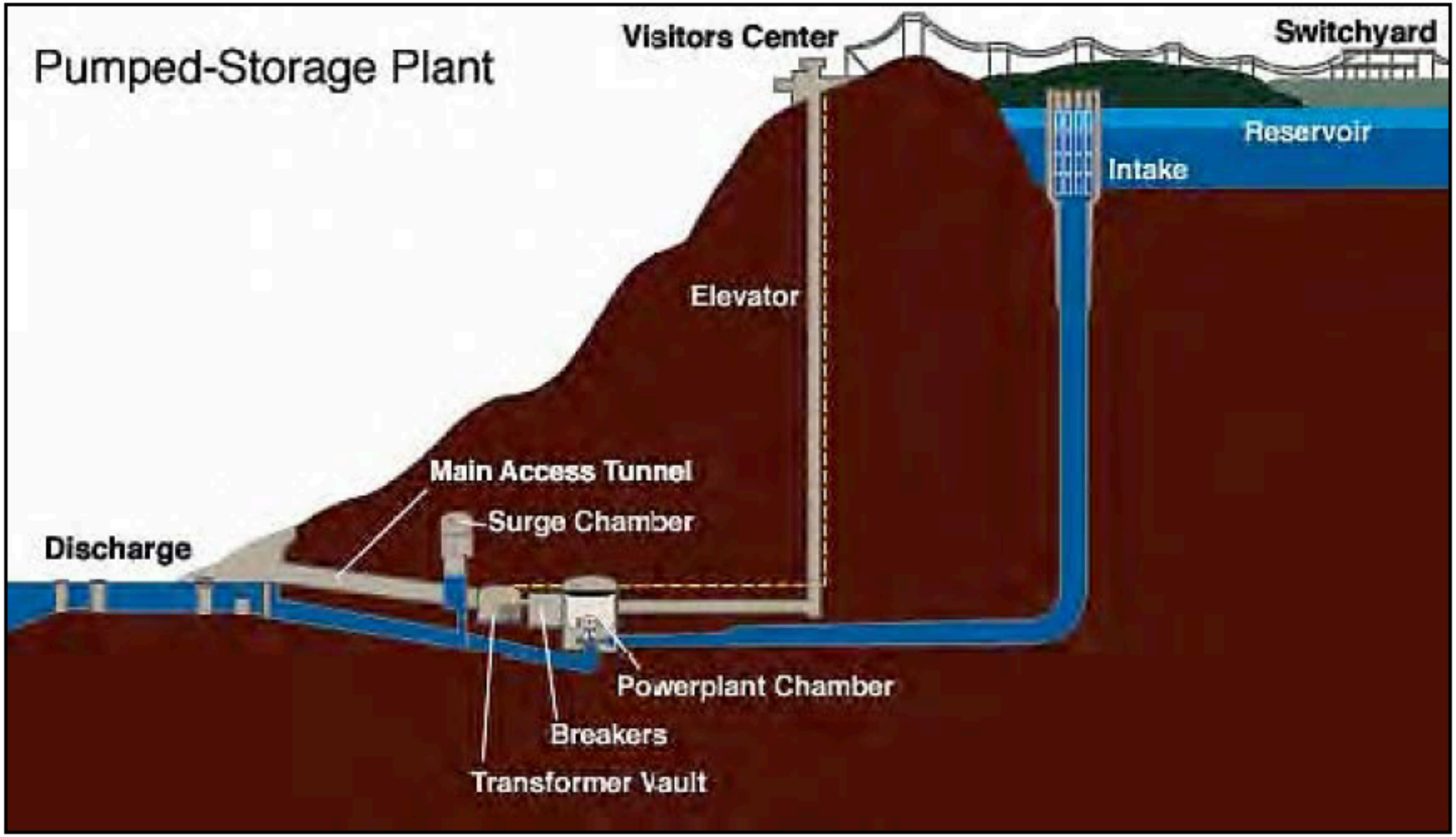
Comparison


UPS
Power Quality
T&D Grid Support
Load Shifting
Bulk Power Mgt
Pumped
Hydro
CAES
Flow Batteries: Zn-Cl Zn-Air Zn-Br
VRB PSB New Chemistries
NaS Battery
Advanced Lead-Acid Battery
High-Energy
Supercapacitors
NaNiCl$_2$ Battery
Li-Ion Battery
Lead-Acid Battery
NiCd
NiMH
High-Power Flywheels
High-Power Supercapacitors
SMES
Discharge Time at Rated Power
Hours
Minutes
Seconds
1 kW
10 kW
100 kW
1 MW
10 MW
100 MW
1 GW
System Power Ratings, Module Size

Pumped hydro

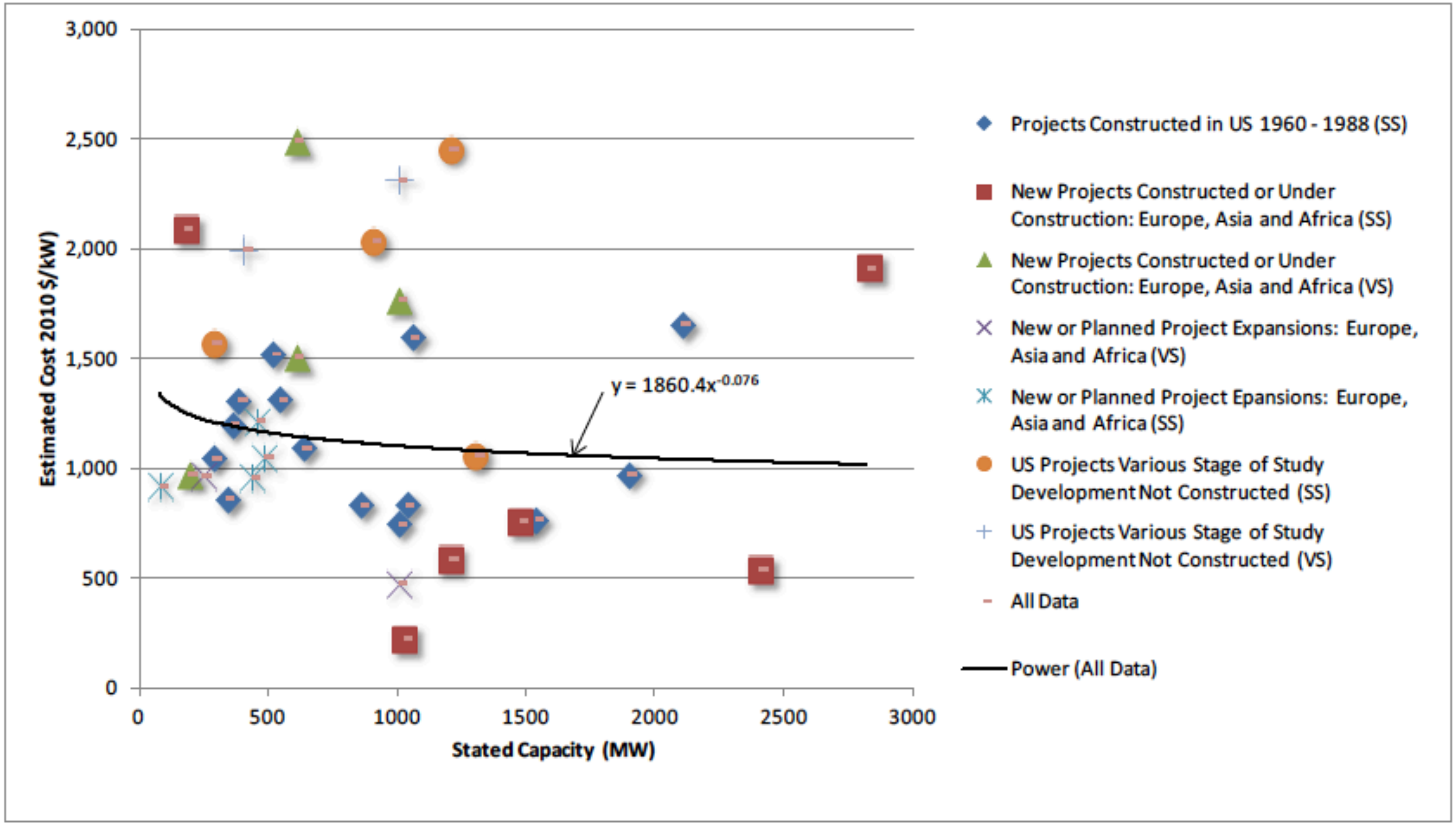
Technology Development Status	Mature	Numerous New Pumped Hydro FERC Filings in U.S.
Confidence of Cost Estimate	C	Preliminary; Based on planned actual site-specific projects
Accuracy Range	Commercial	-15% to +15%
Operating Stations	40 units (20+ GW) in U.S.	Over 129 GW in operation worldwide
Process Contingency	0%	Variable-speed drive technology being applied to new sites
Project Contingency	10-15%	Uncertainties in sitting, permitting, environmental impact and construction

Pumped hydro

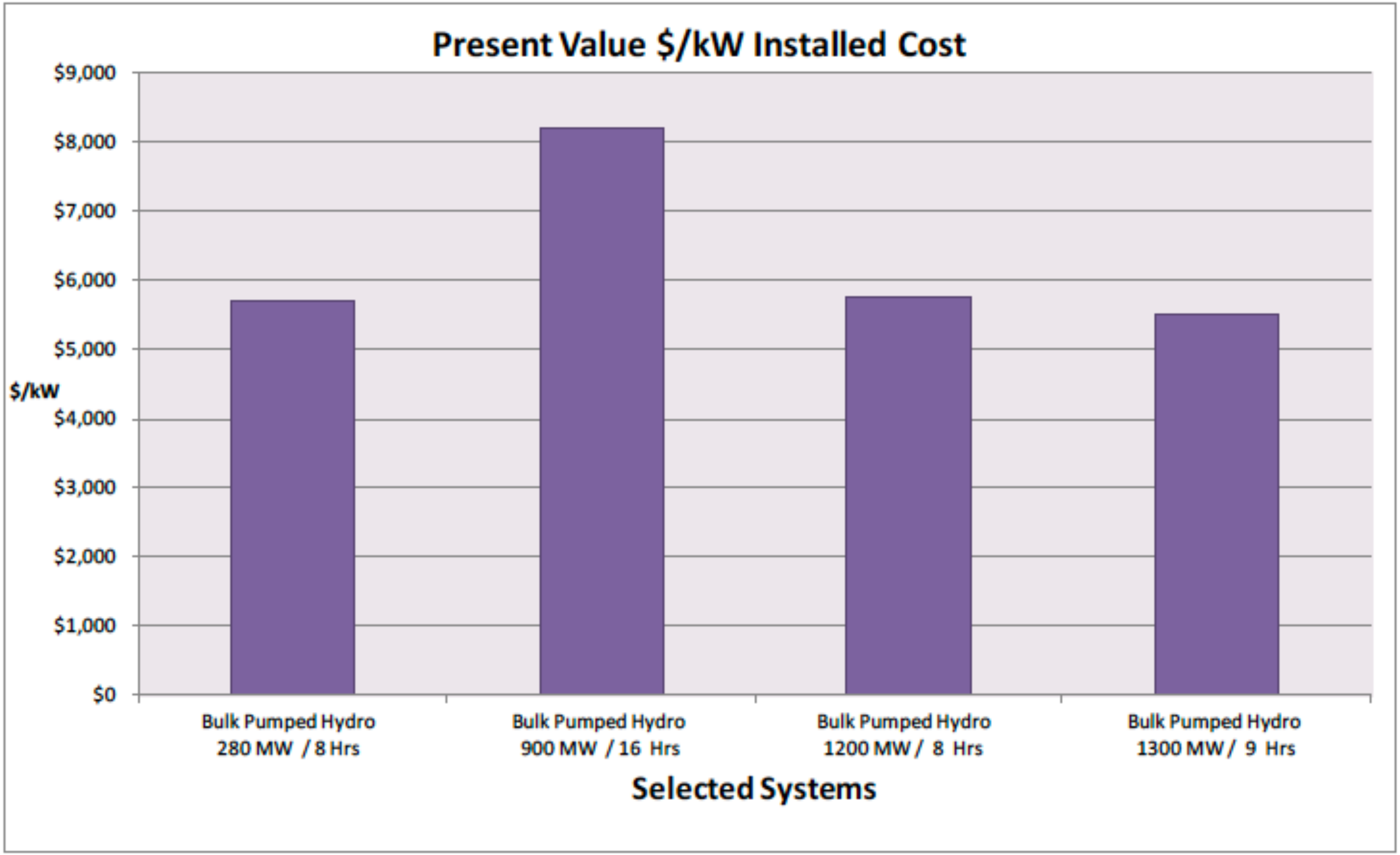


Pumped hydro

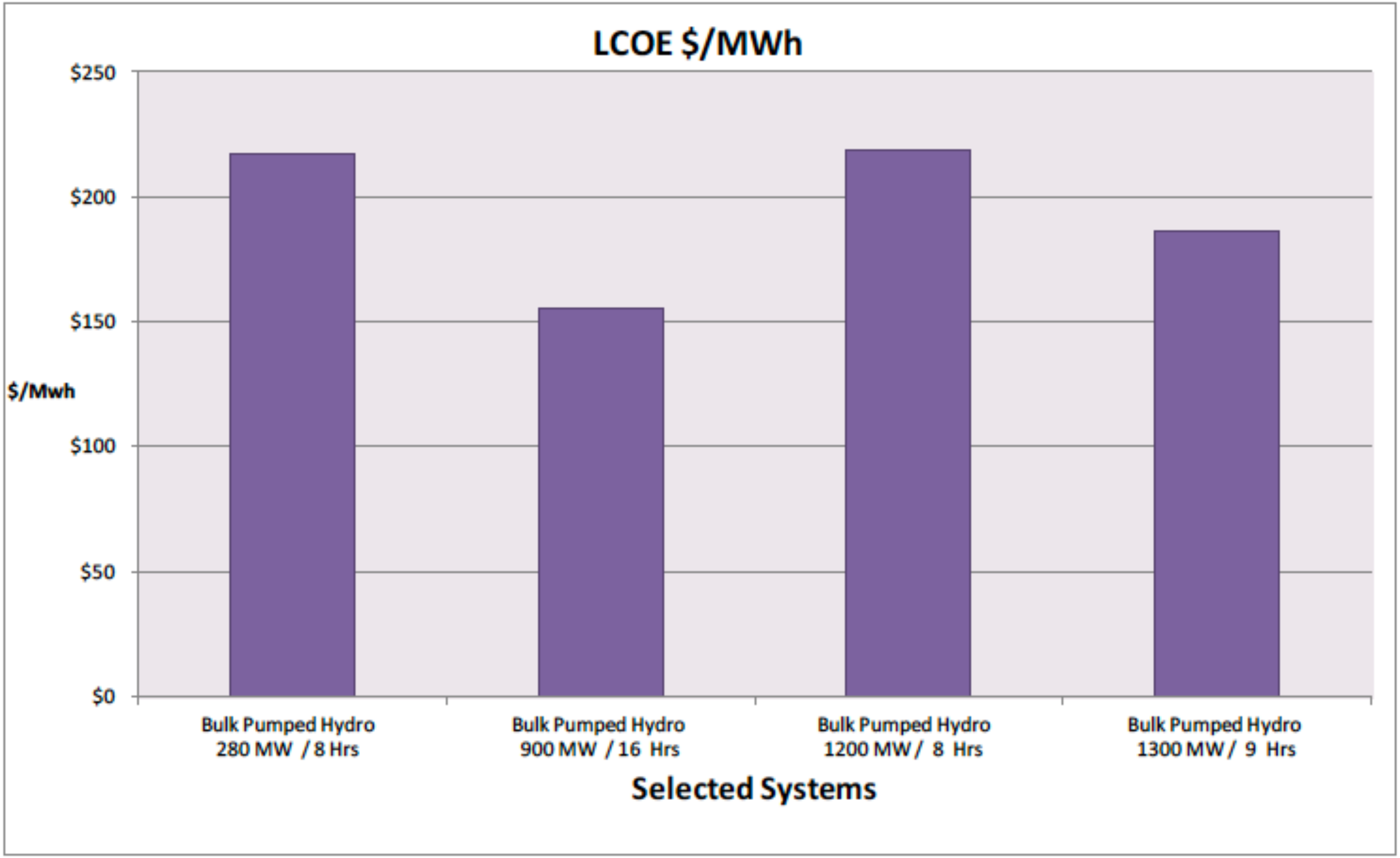
- Size: up to 4000 MW
- Efficiency: 75-85%
- Duration: 50-60 years



Pumped hydro



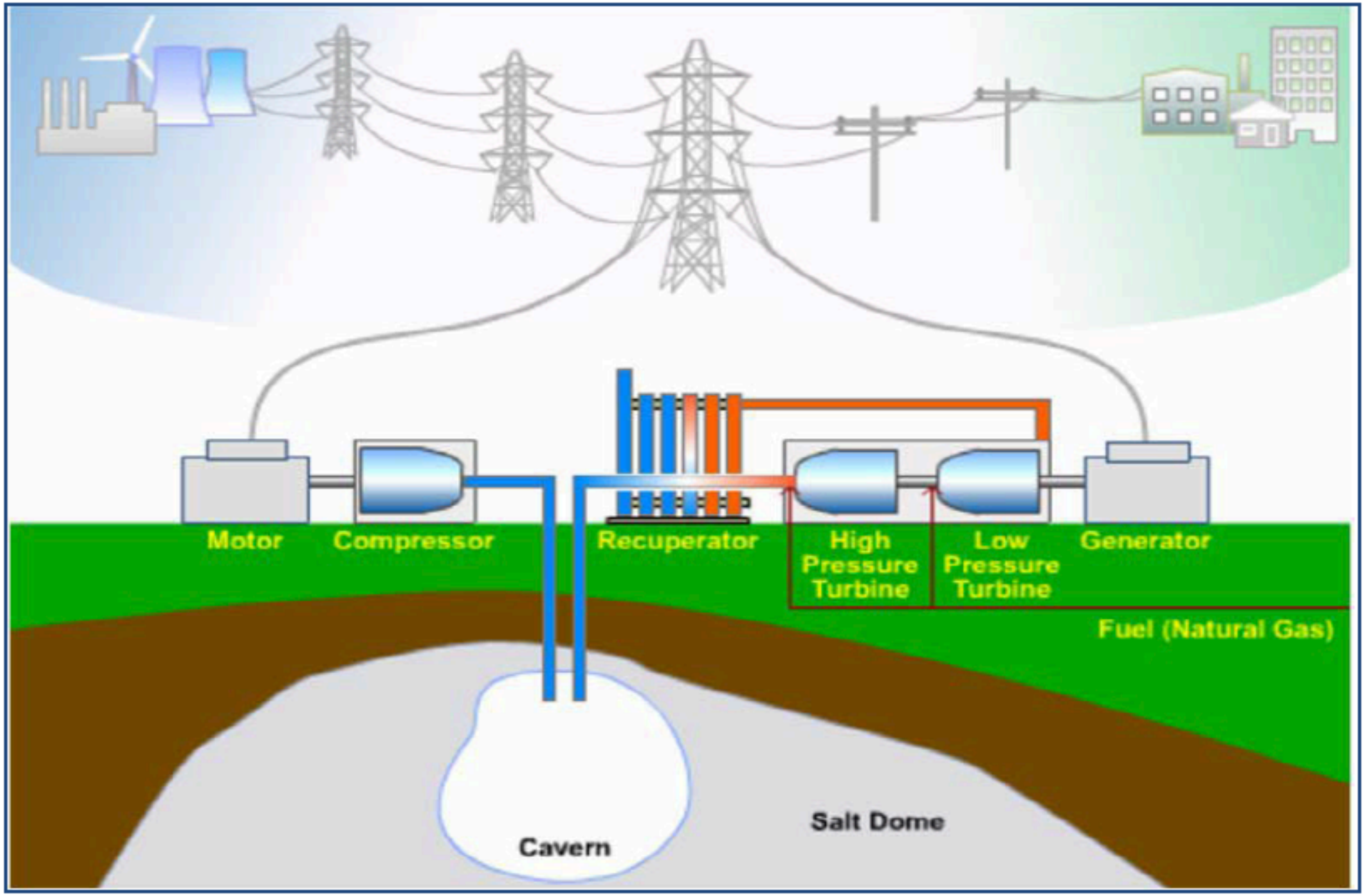
Pumped hydro



CAES

Technology Development Status	1st Generation - Mature 2nd Generation - Demonstration	Commercial offer possible System to be verified by demonstration unit
Confidence of Cost Estimate	C	Based on preliminary designs Owners' costs and site-specific costs not included; these costs can be significant. First-time-engineering costs can be significant.
Accuracy Range	C	-20% to +25%
Operating Field Units	2nd Generation - None	Two of first-generation type
Process Contingency	15%	Key components and controls need to be verified for second-generation systems.
Project Contingency	10%	Plant costs will vary depending upon underground site geology.

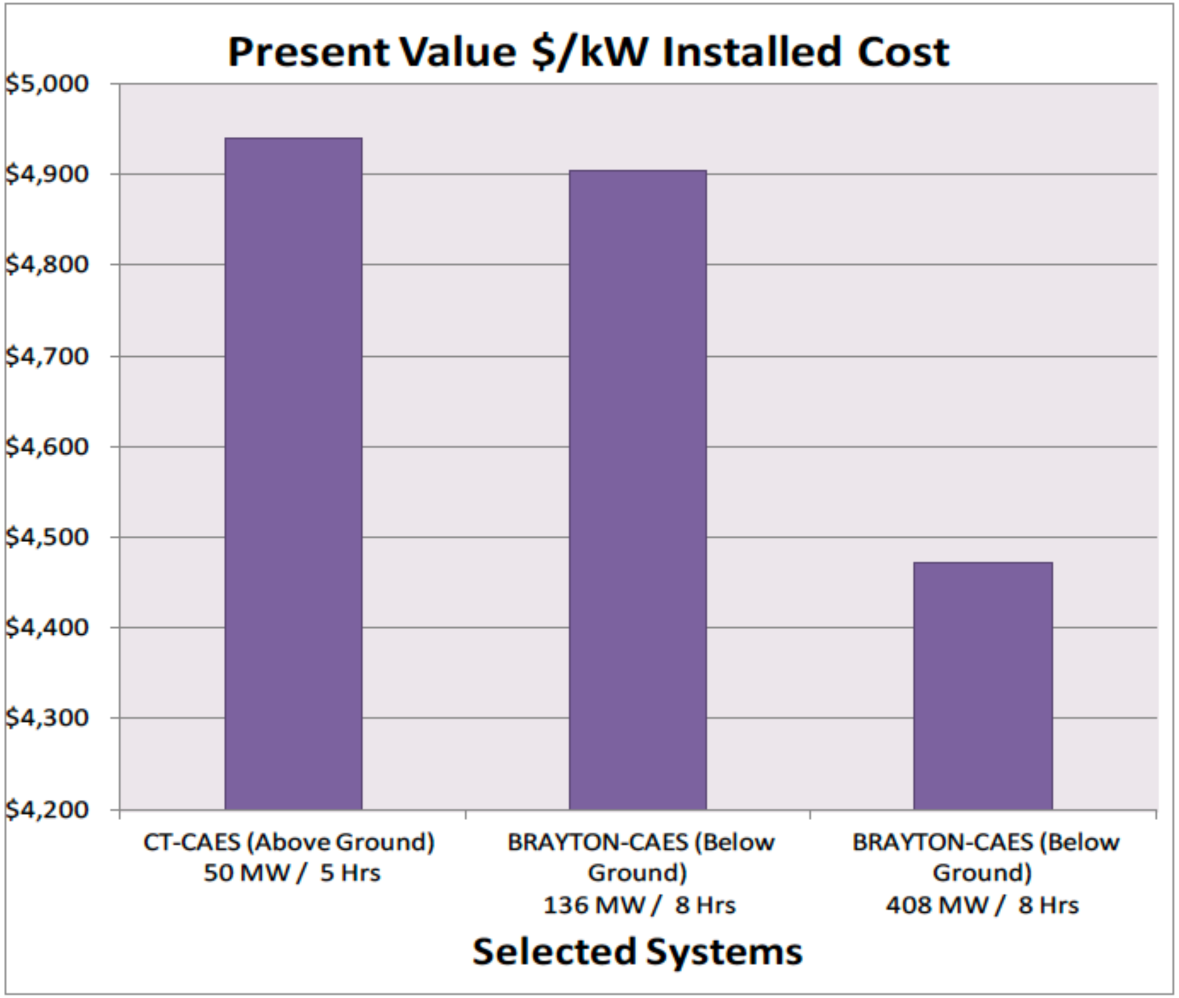
CAES



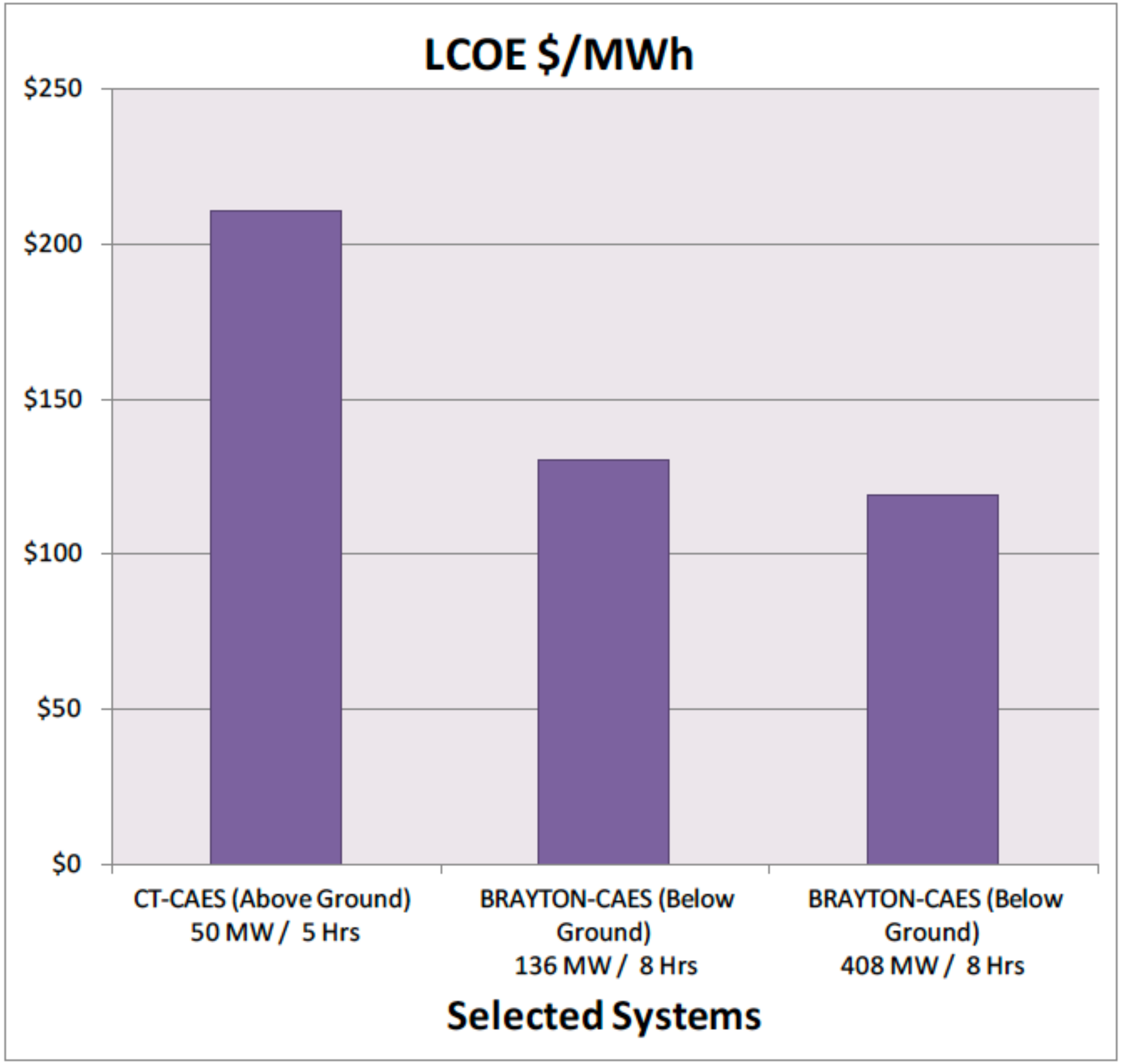
Motor
Compressor
Recuperator
High Pressure Turbine
Low Pressure Turbine
Generator
Fuel (Natural Gas)
Salt Dome
Cavern

CAES

- Underground storage may be as large as 400 MW for 8-24 hours
- Aboveground are between 3 and 50 MW for 2-6 hours



CAES

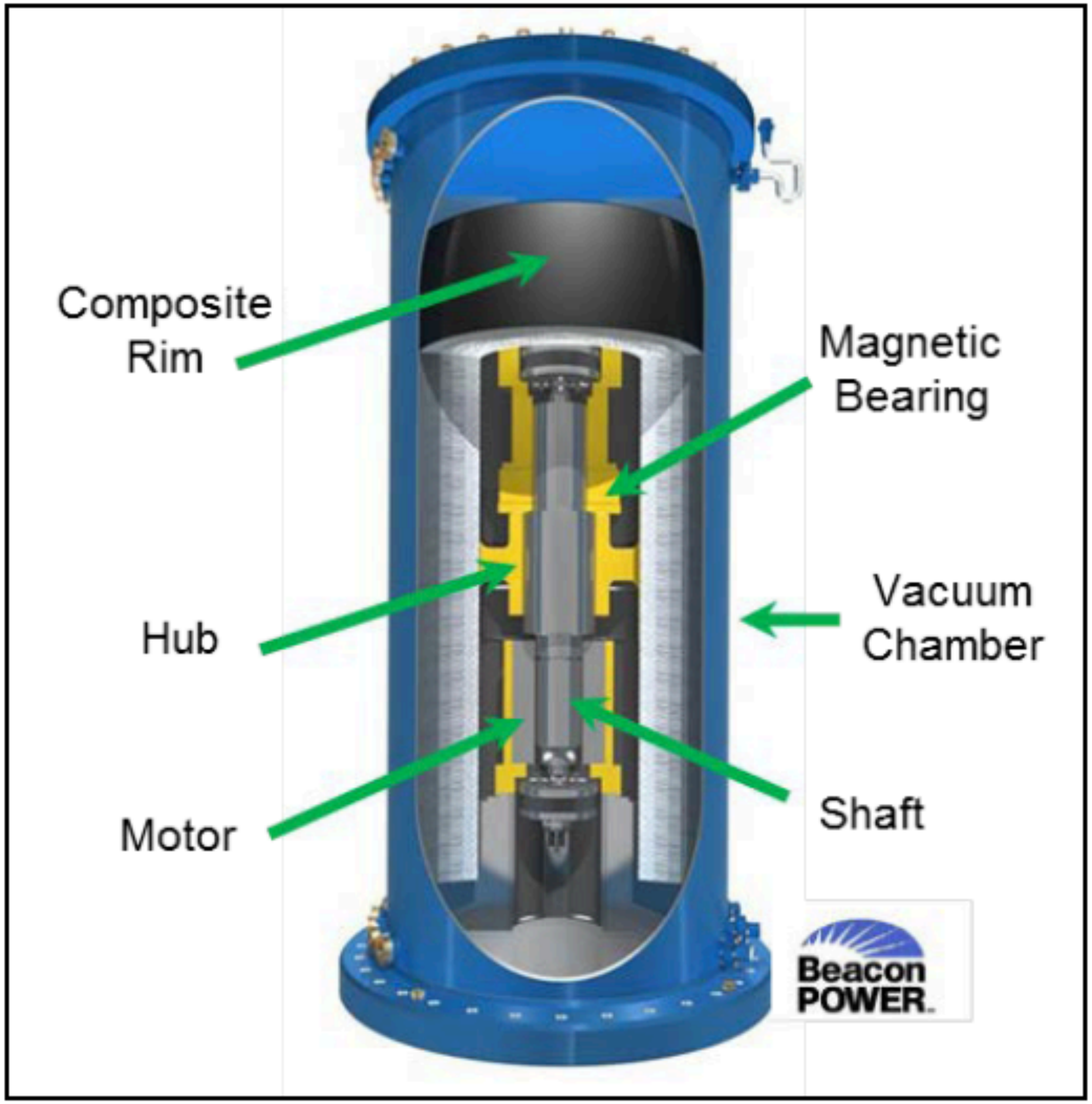


LCOE $/MWh
$250
$200
$150
$100
$50
$0
CT-CAES (Above Ground) 50 MW / 5 Hrs
BRAYTON-CAES (Below Ground) 136 MW / 8 Hrs
BRAYTON-CAES (Below Ground) 408 MW / 8 Hrs
Selected Systems

Flywheel

Technology Development Status	Demonstration status for Frequency Regulation C	Commercial experience in Power Quality UPS applications Pilots in ISO A/S Market applications
Confidence of Cost Estimate	B	Vendor quotes and system installation estimates.
Accuracy Range	B	-15% to +15%
Operating Field Units	10 or more	In a 20-MW application. Numerous uses in power quality applications.
Process Contingency	1-5%	Uncertain long-term life and performance of the flywheel subsystem
Project Contingency	5-10%	

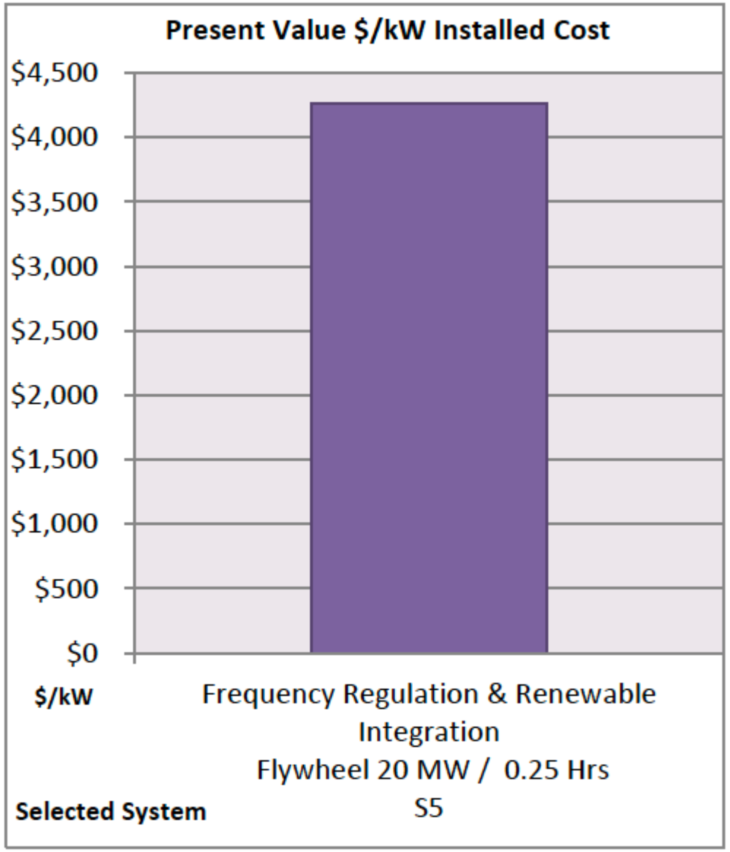
Flywheel

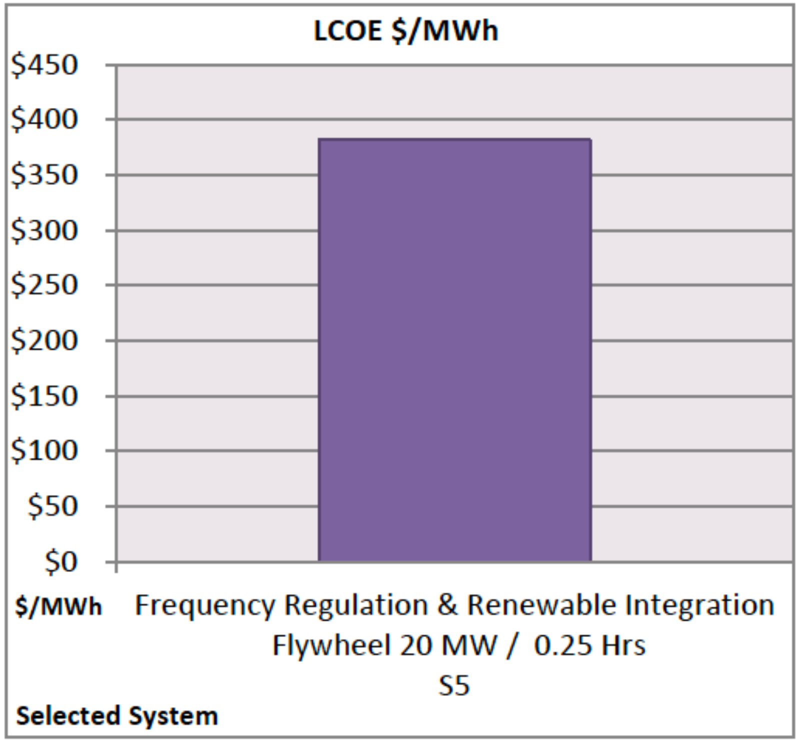


Composite Rim
Magnetic Bearing
Vacuum Chamber
Hub
Motor
Shaft
Beacon POWER

Flywheel

- Size: between 0.6 and 10 kWh and 100 to 1500 kW
- Direct current with response times in milliseconds
- Roundtrip efficiency: 70-80%
- Duration: 100000 cycles
- Power density 5-10 times that of batteries





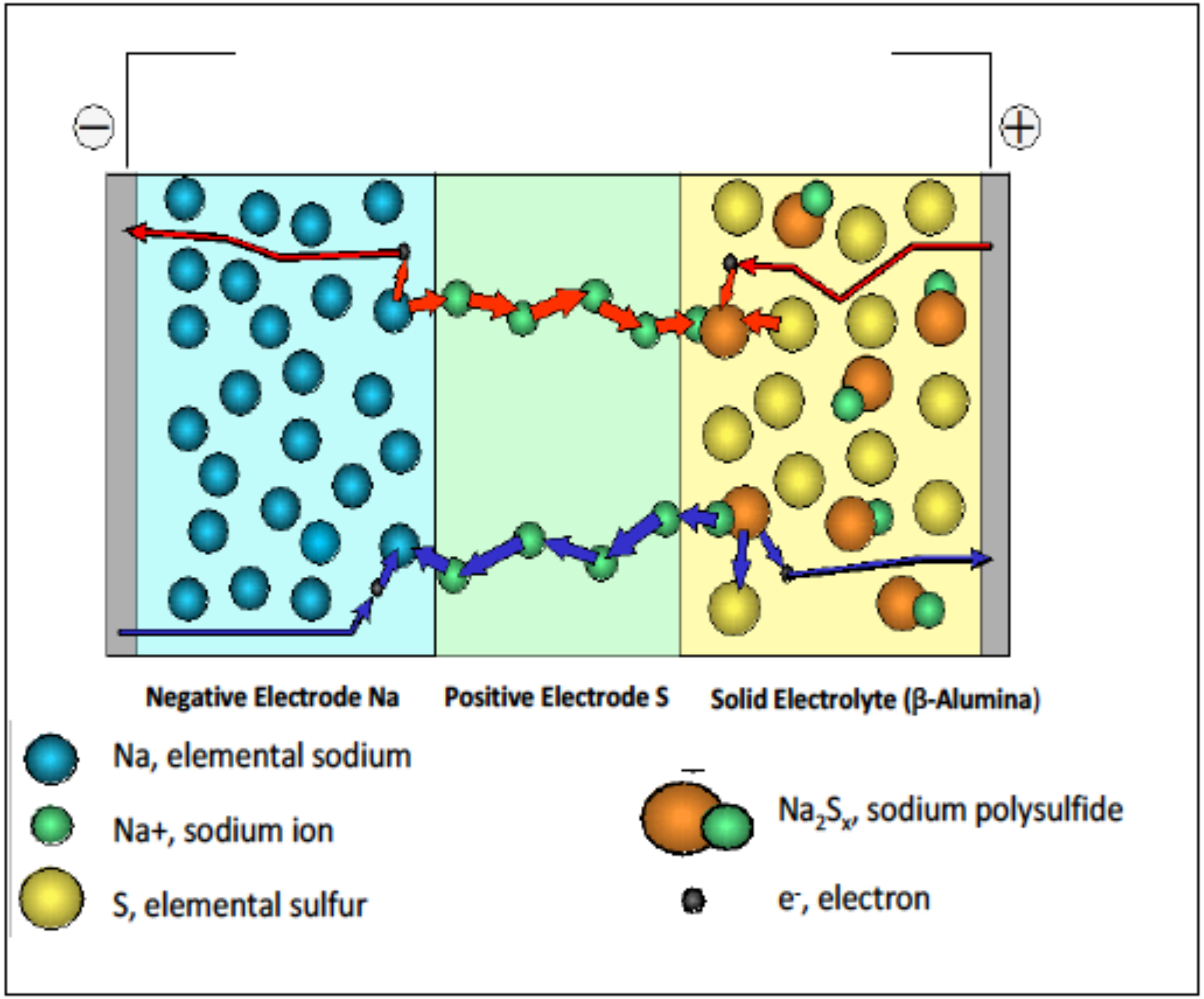
Batteries

- Sodium-sulfur
- Sodium-Nickel-Chloride
- Vanadium redox
- Iron-chromium
- Zinc-bromine
- Zinc-Air
- Lead-Acid
- Lithium-Ion

Sodium-sulfur batteries

Technology Development Status	A	Significant recent commercial experience.
Confidence of Cost Estimate	A	Data based on installed systems.
Accuracy Range	B	-5% to +8%
Operating Field Units	221 sites	306 MW installed.
Process Contingency	0%	Proven battery performance.
Project Contingency	1-5%	Depending on site conditions.

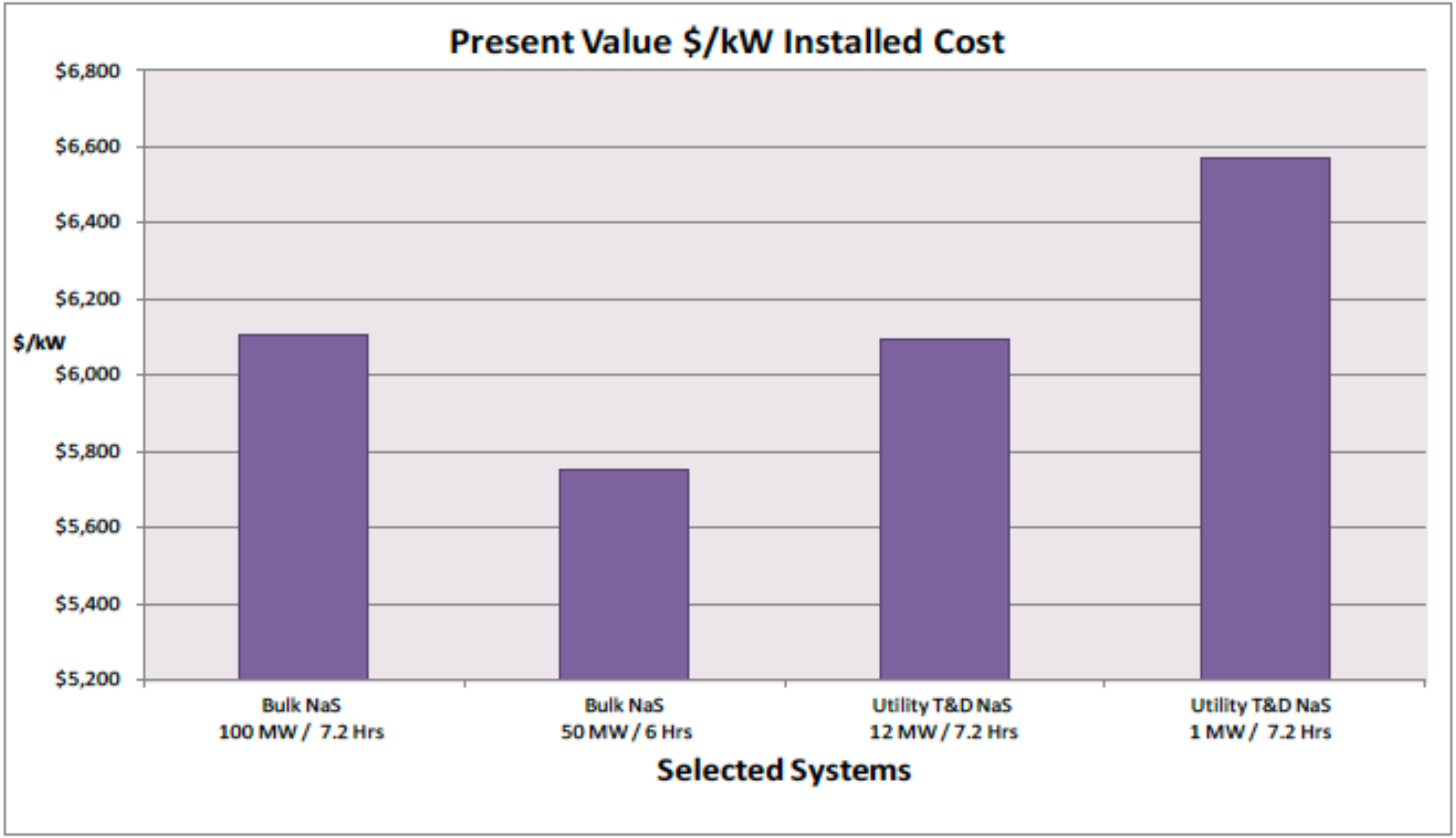
Sodium-sulfur batteries



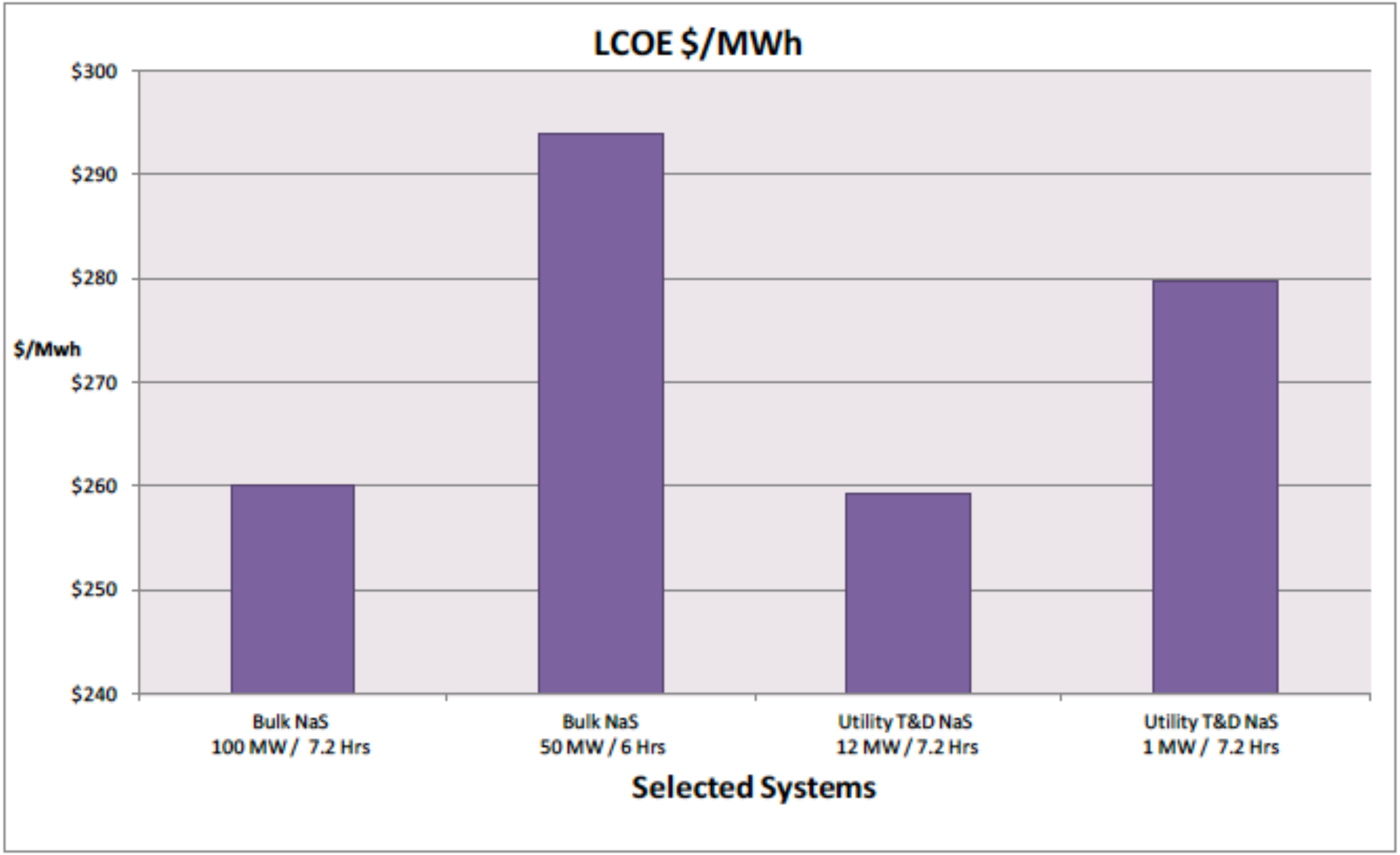
Sodium-sulfur batteries

Energy Density (Volume)	170 kWh/m3
Energy Density (Weight)	117 kWh/ton
Charge/Discharge Efficiency – Batteries (DC Base)	> 86 percent
Charge/Discharge Efficiency – System (AC Base)	≥ 74 percent
Maintenance	Low
Cycle Life	4,500 cycles at rated capacity
Calendar Life	15 yr

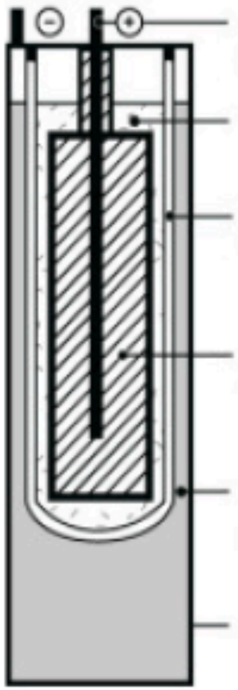
Sodium-sulfur batteries



Sodium-sulfur batteries



Sodium-nickel-chloride batteries



The active materials are:

in the discharged state (when manufacturing):

<u>sodium chloride</u> and <u>metal powders (mainly nickel)</u>

in the charged state (after first charge) they are converted to:

<u>sodium</u> and <u>metal chlorides</u>

$$2NaCl + Ni \rightleftharpoons NiCl_2 + 2Na$$

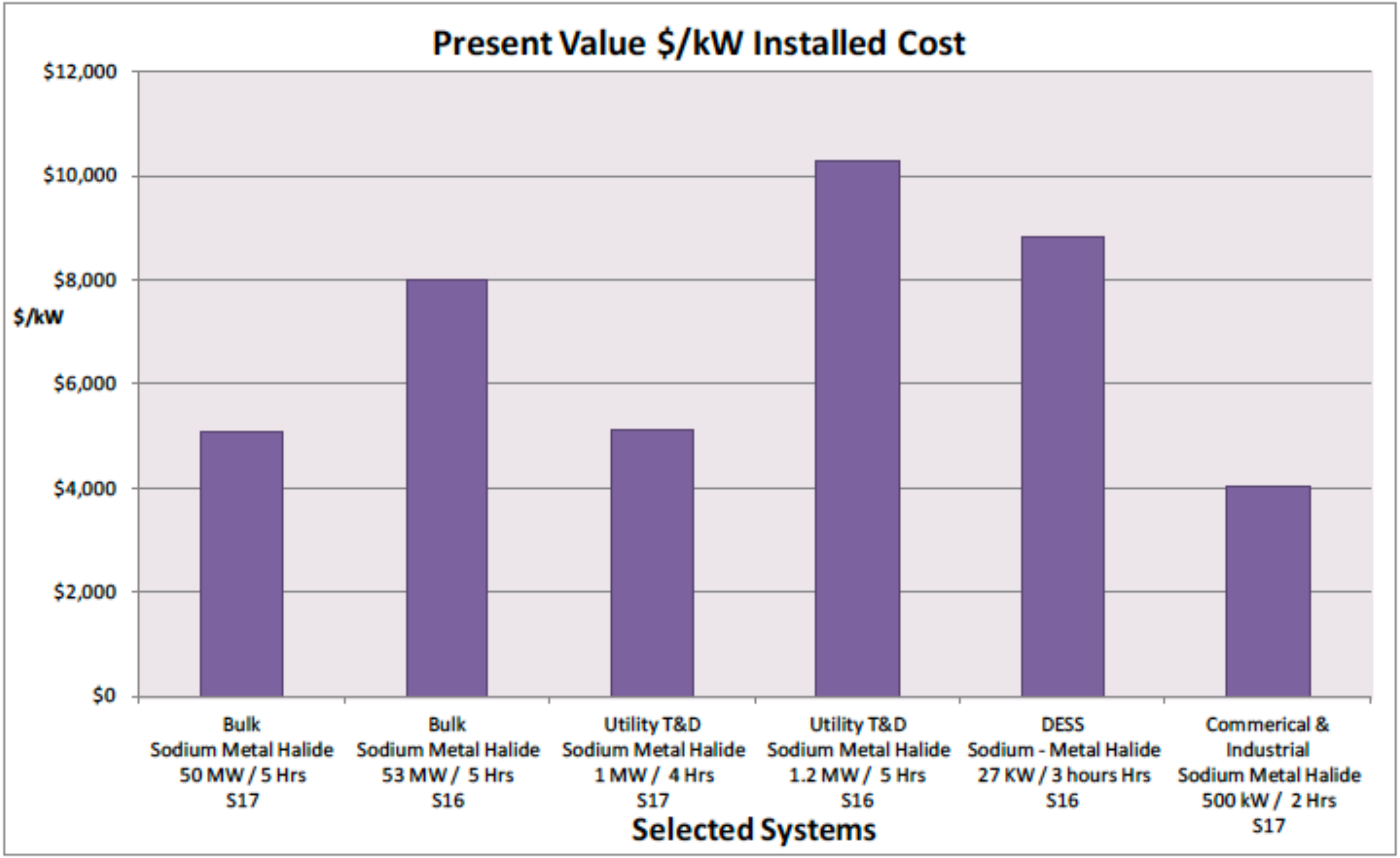
discharged cell **charged cell**

The operating temperature of the cell is around 260ºC

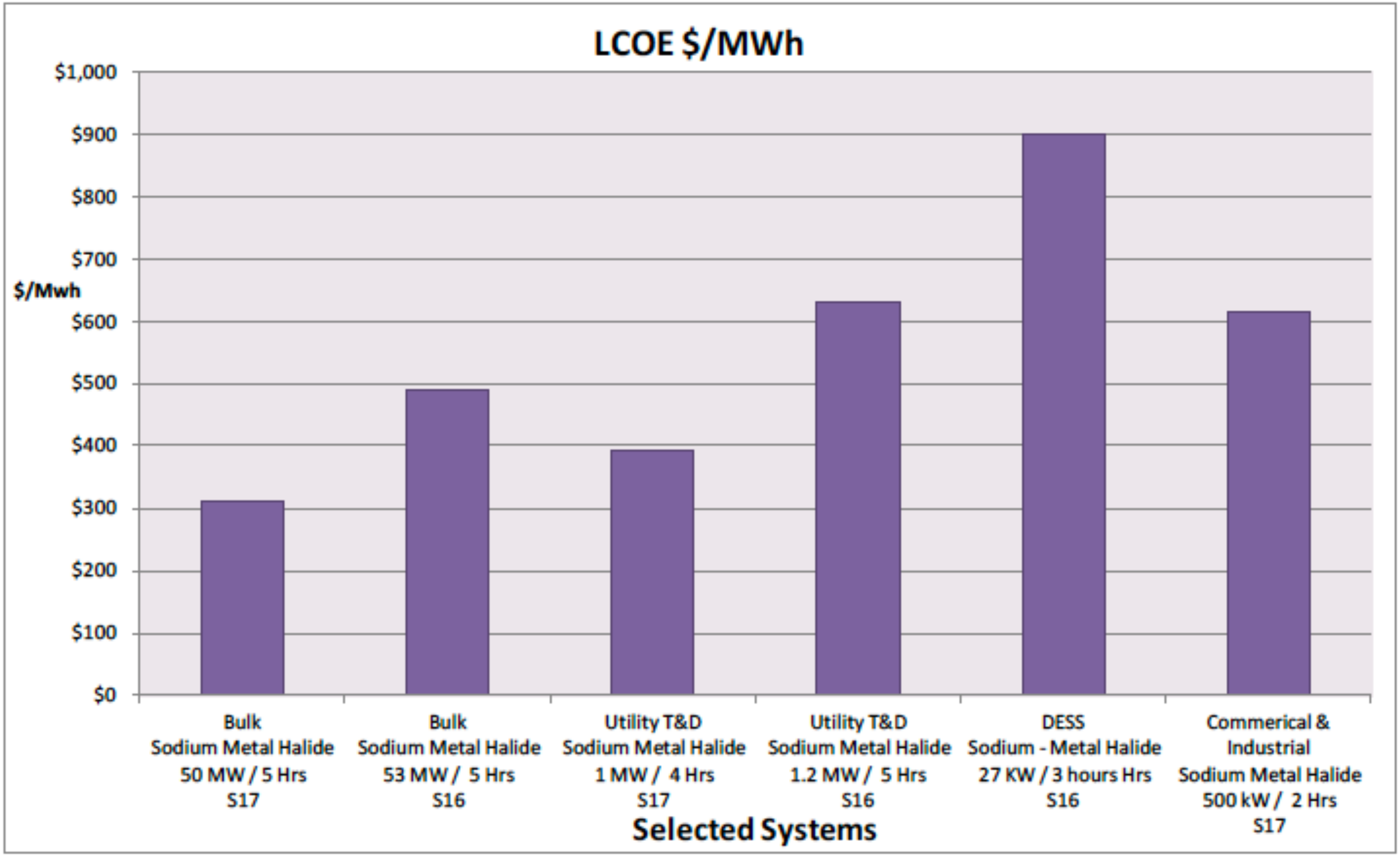
The electrolyte is a fully dense ceramic material, ß"alumina, which provides fast transport of sodium ions and ensures the electrical insulation between anode and cathode.

Technology Development Status	Demonstration C	Limited field demonstrations
Confidence of Cost Estimate	D	Vendor quotes and system installation estimates
Accuracy Range	C	-10% to +15%
Operating Field Units	2 or more	Several photovoltaic and distributed storage installations by 2012
Process Contingency	5-10%	Limited testing and filed experience
Project Contingency	5-10%	Limited data on life-cycle costs; limited operation and maintenance cost data

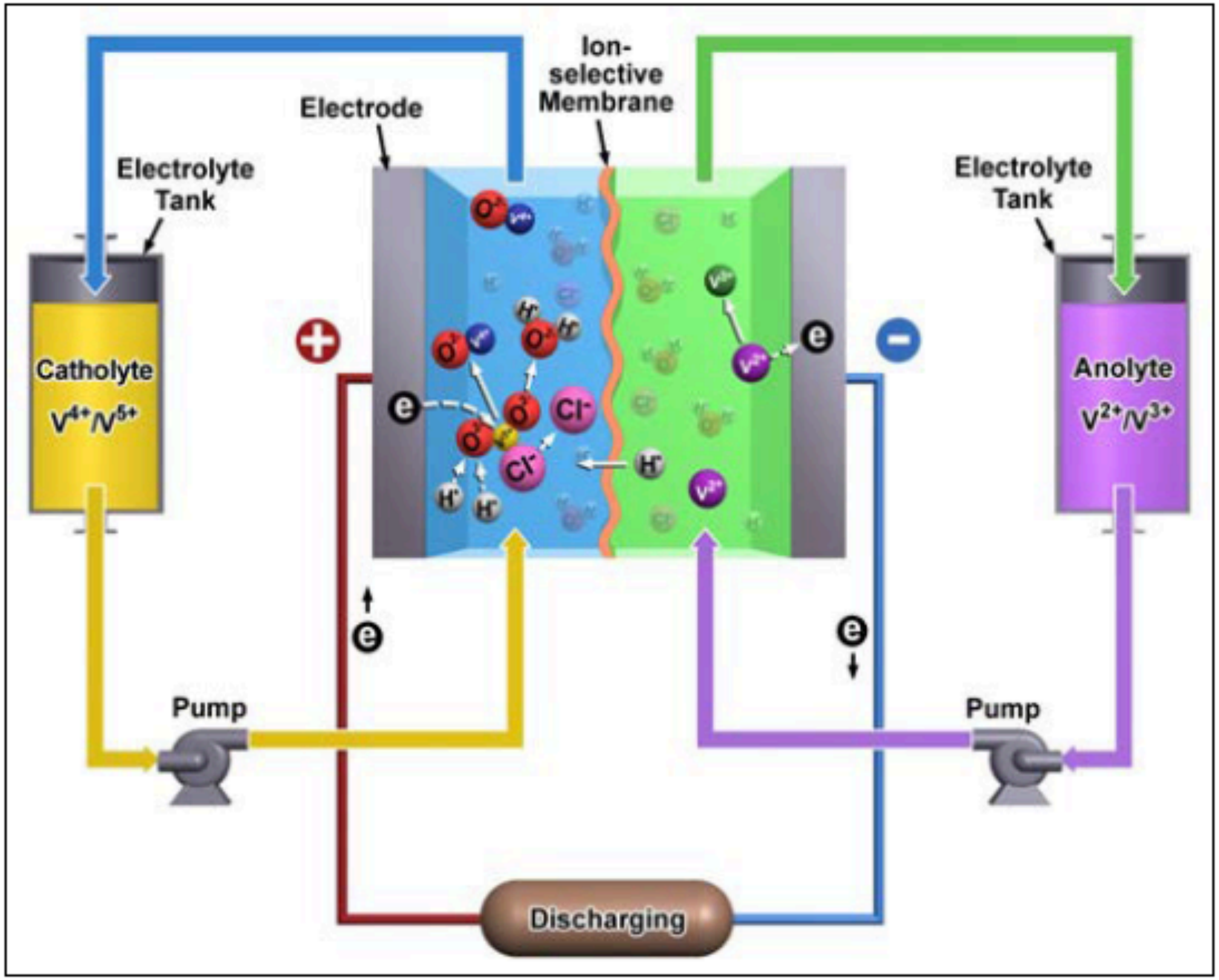
Sodium-nickel-chloride batteries



Sodium-nickel-chloride batteries



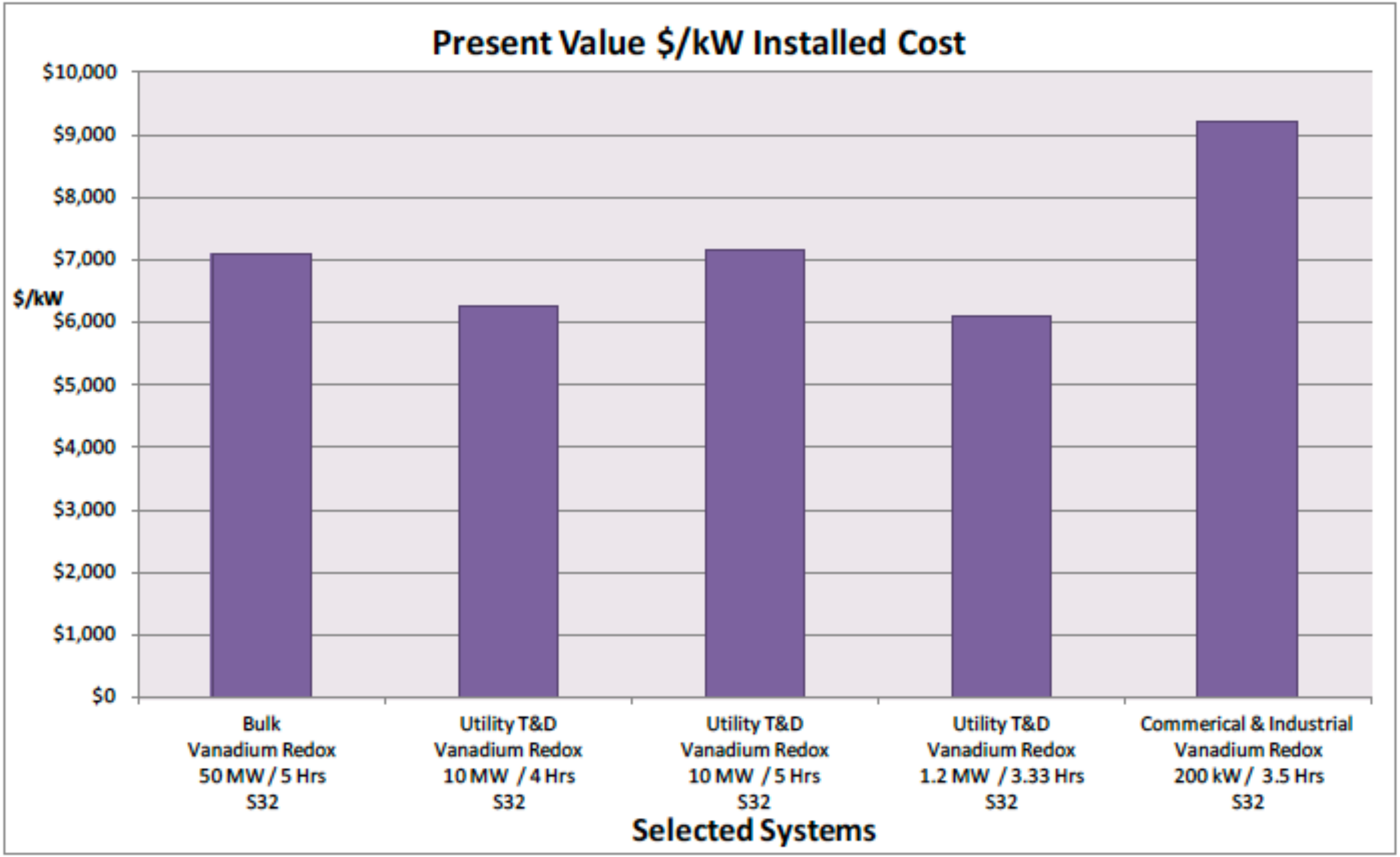
Vanadium redox batteries



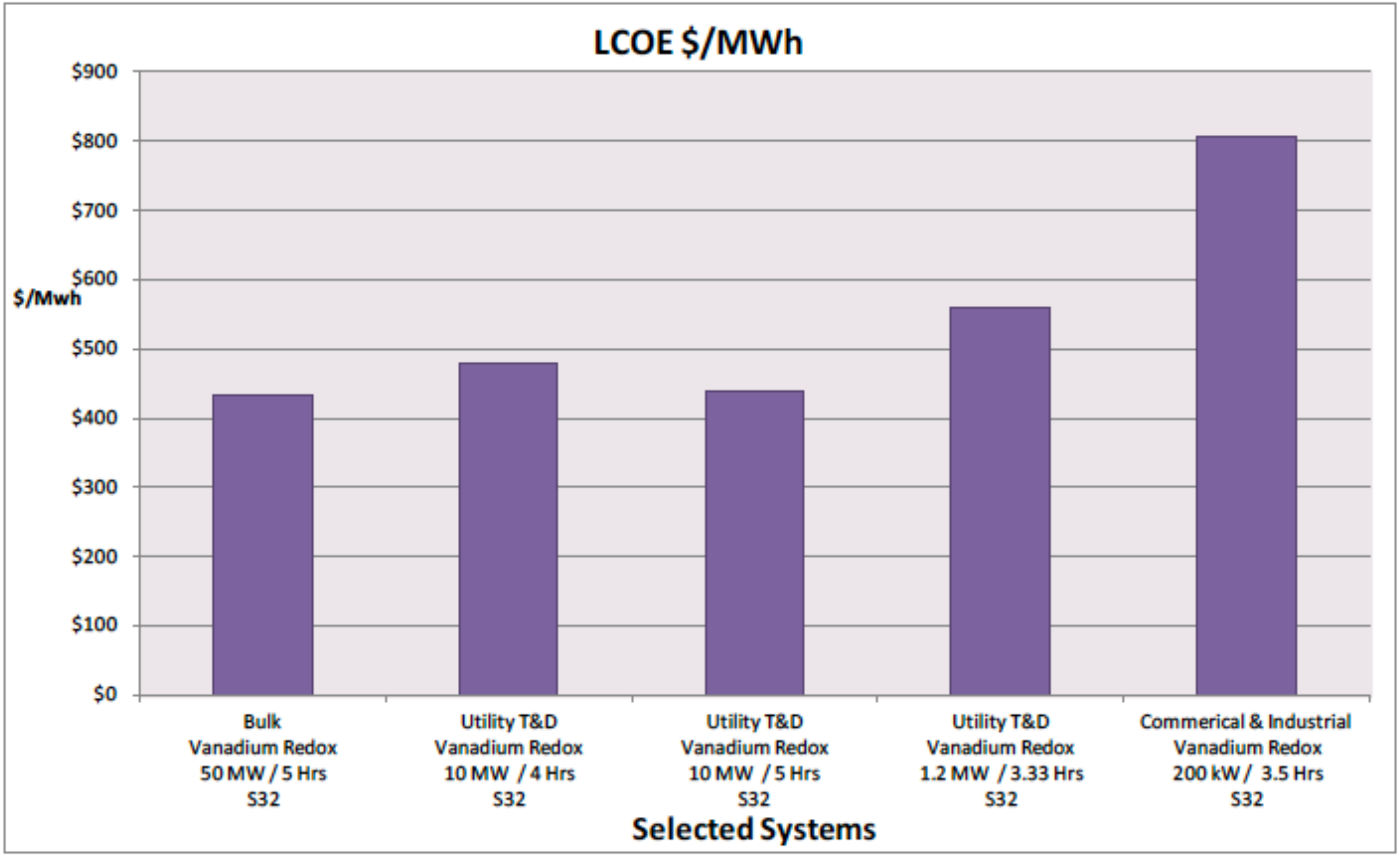
Vanadium redox batteries

Technology Development Status	Pre-Commercial C	Systems Verified in Limited Field Demonstrations
Confidence of Cost Estimate	C	Vendor quotes and system installation estimates.
Accuracy Range	C	-10% to +15%
Operating Field Units	Units operating in renewable integration, end-user energy management, and telecom applications	Currently 50-kW, 100-kW, 500-kW, 600-kW, and 1000-kW systems in operation. The largest in the U.S. is a 600-kW/3600-kWh system in a customer energy-management application. A 1-MW/5-MWh system is in operation in Japan.
Process Contingency	5-8%	For MW-scale applications
Project Contingency	5-7%	For MW-scale applications Contingency will vary by size of the application. Vendors are offering 10-year energy services contracts.

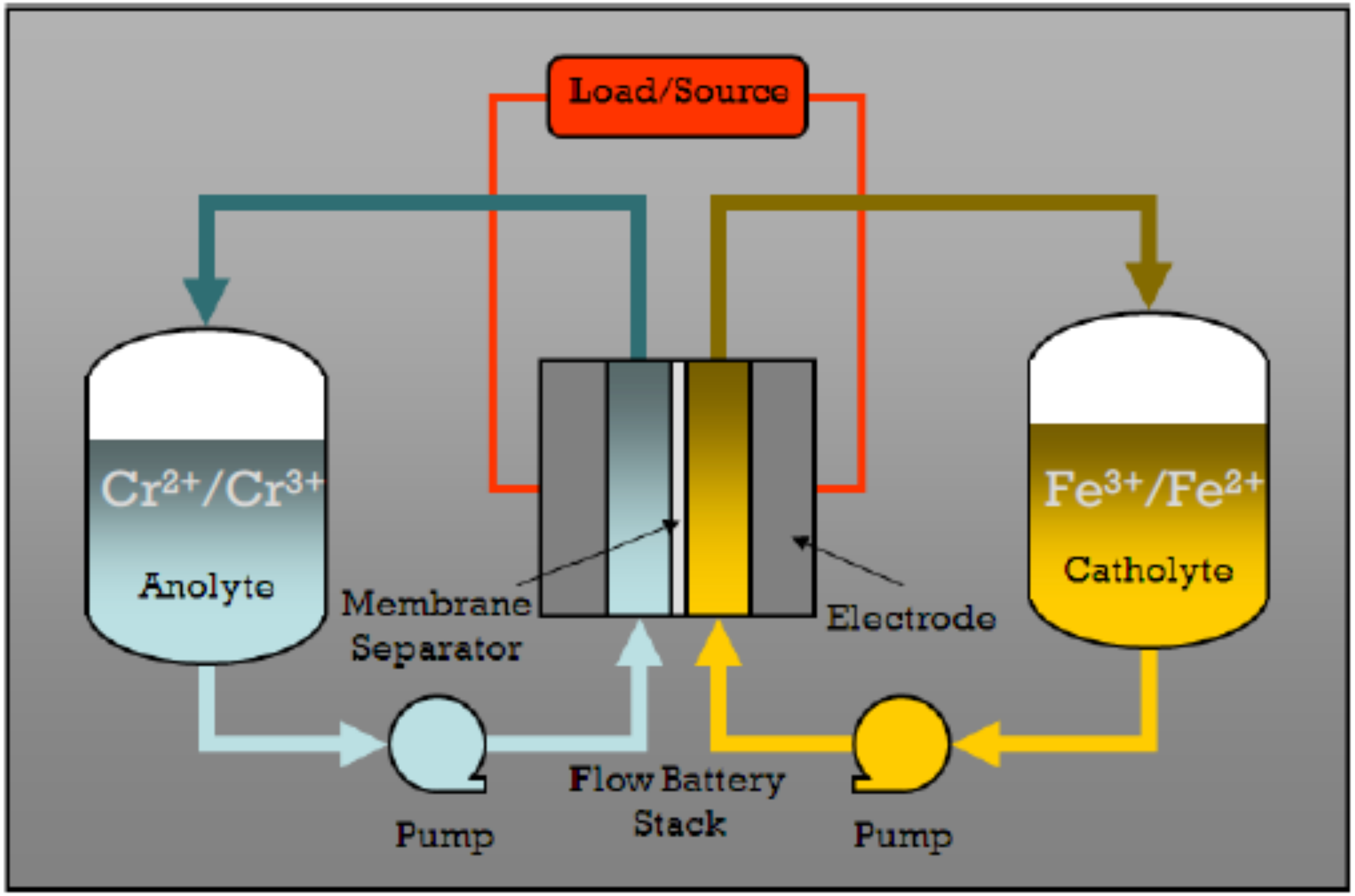
Vanadium redox batteries



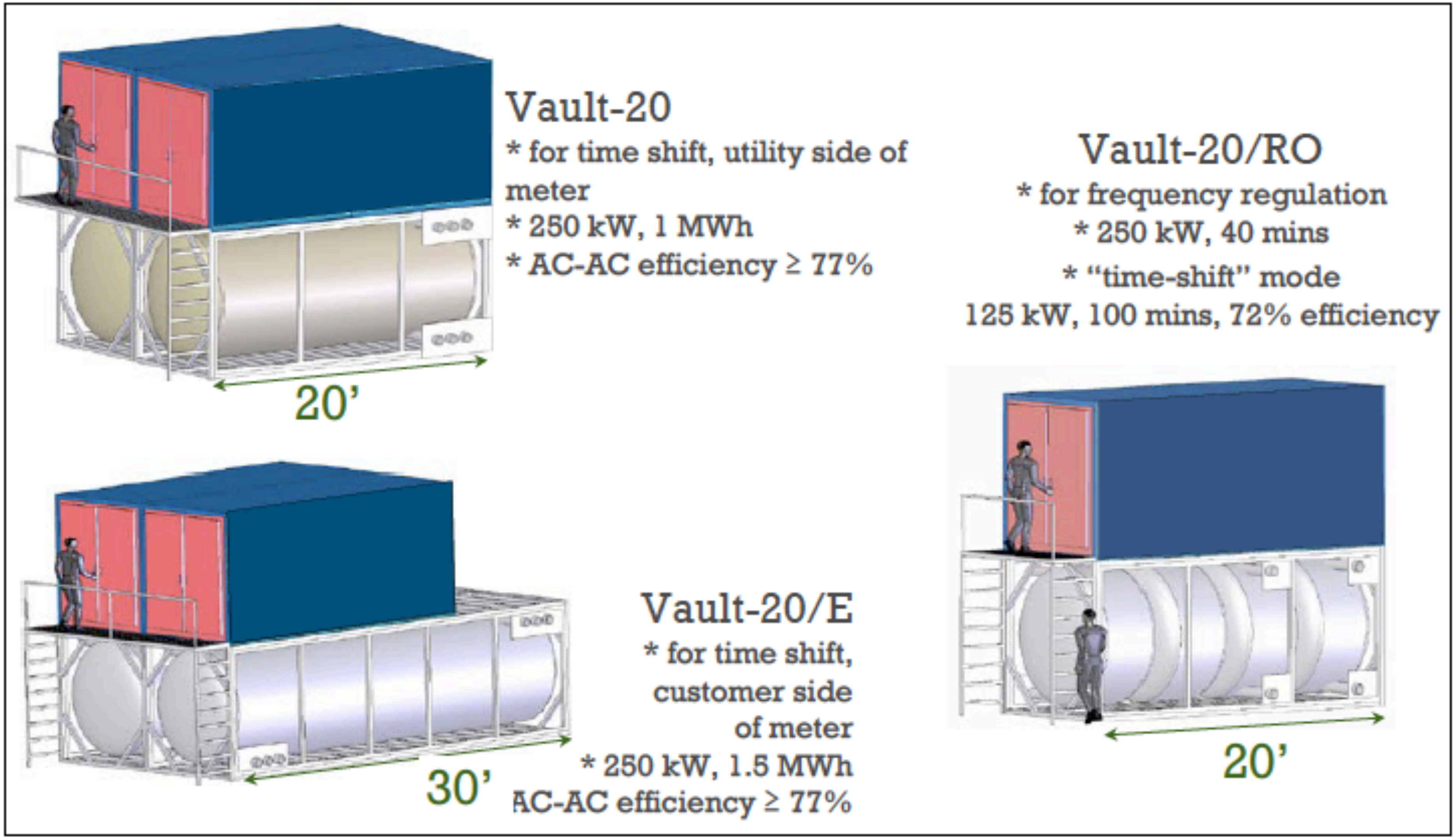
Vanadium redox batteries



Iron Chromium batteries



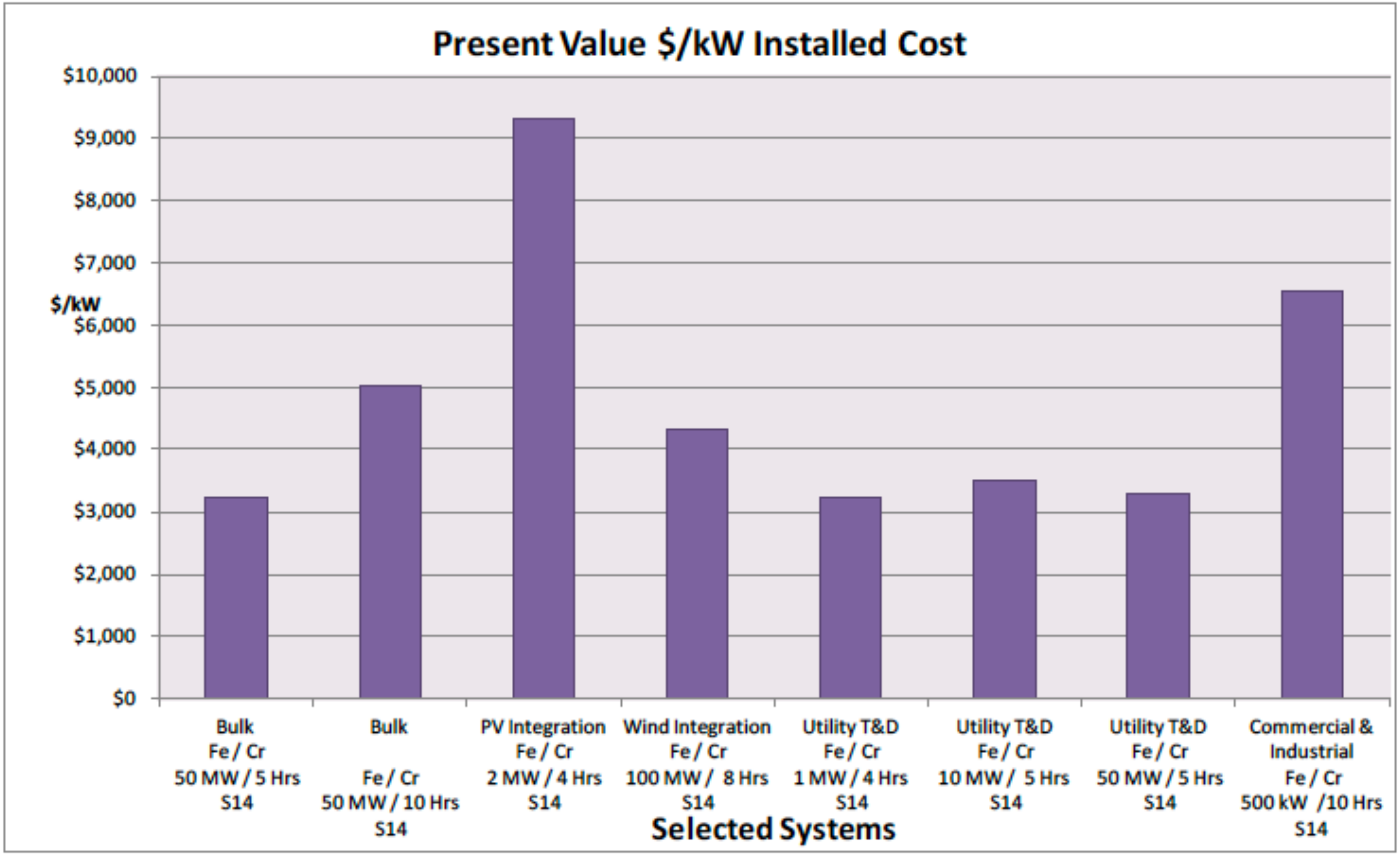
Iron Chromium batteries



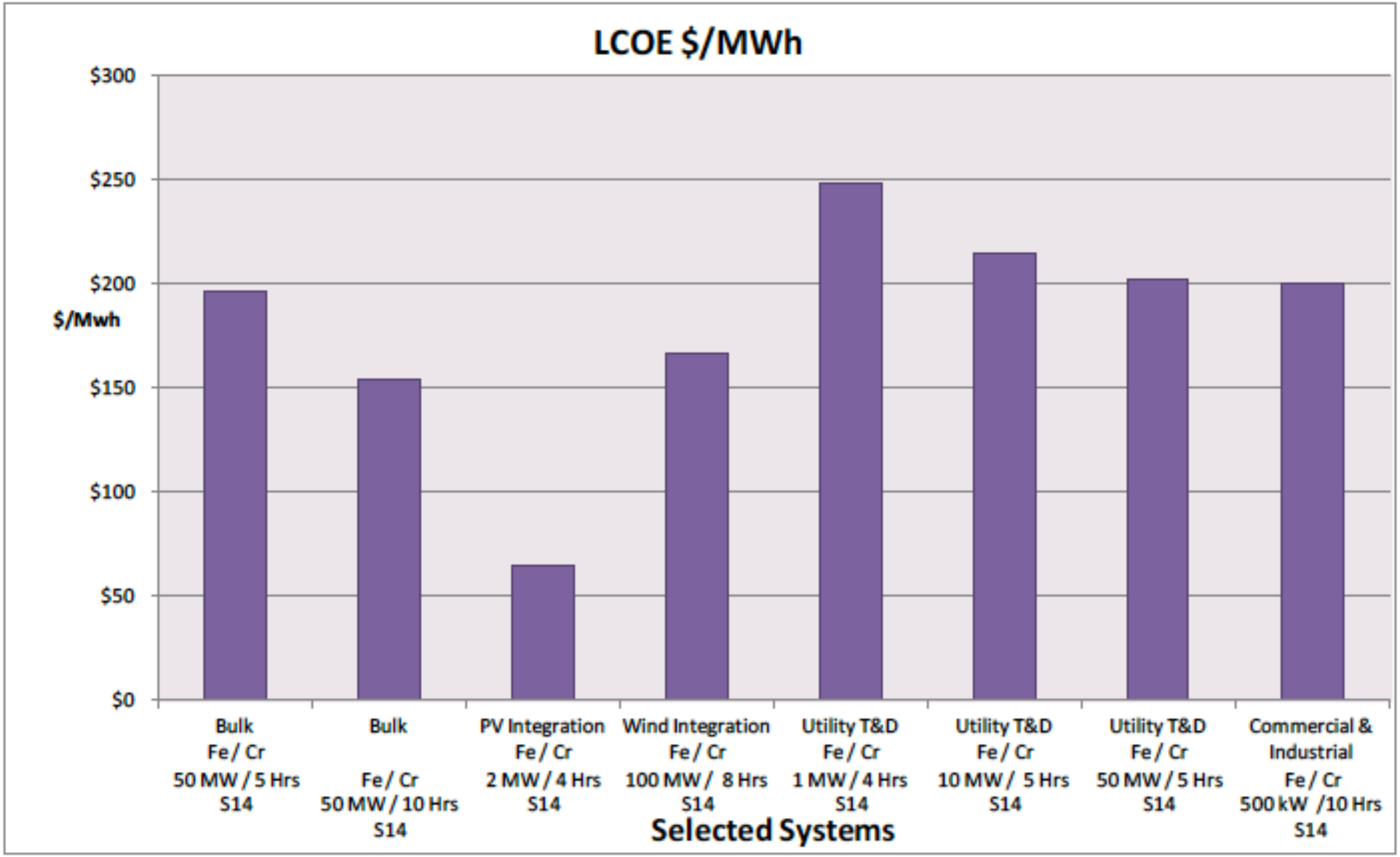
Iron Chromium batteries

Technology Development Status	Laboratory E	Small cells and stack in a lab setting
Confidence of Cost Estimate	C	Vendor quotes and system installation estimates.
Accuracy Range	E	-15% to +15%
Operating Field Units	None	None in utility-scale demonstrations Fe-Cr in niche telecom applications
Process Contingency	15-20%	Efficiency and cycle-life uncertain. Scale-up uncertainties
Project Contingency	10-15%	Limited definition of product designs

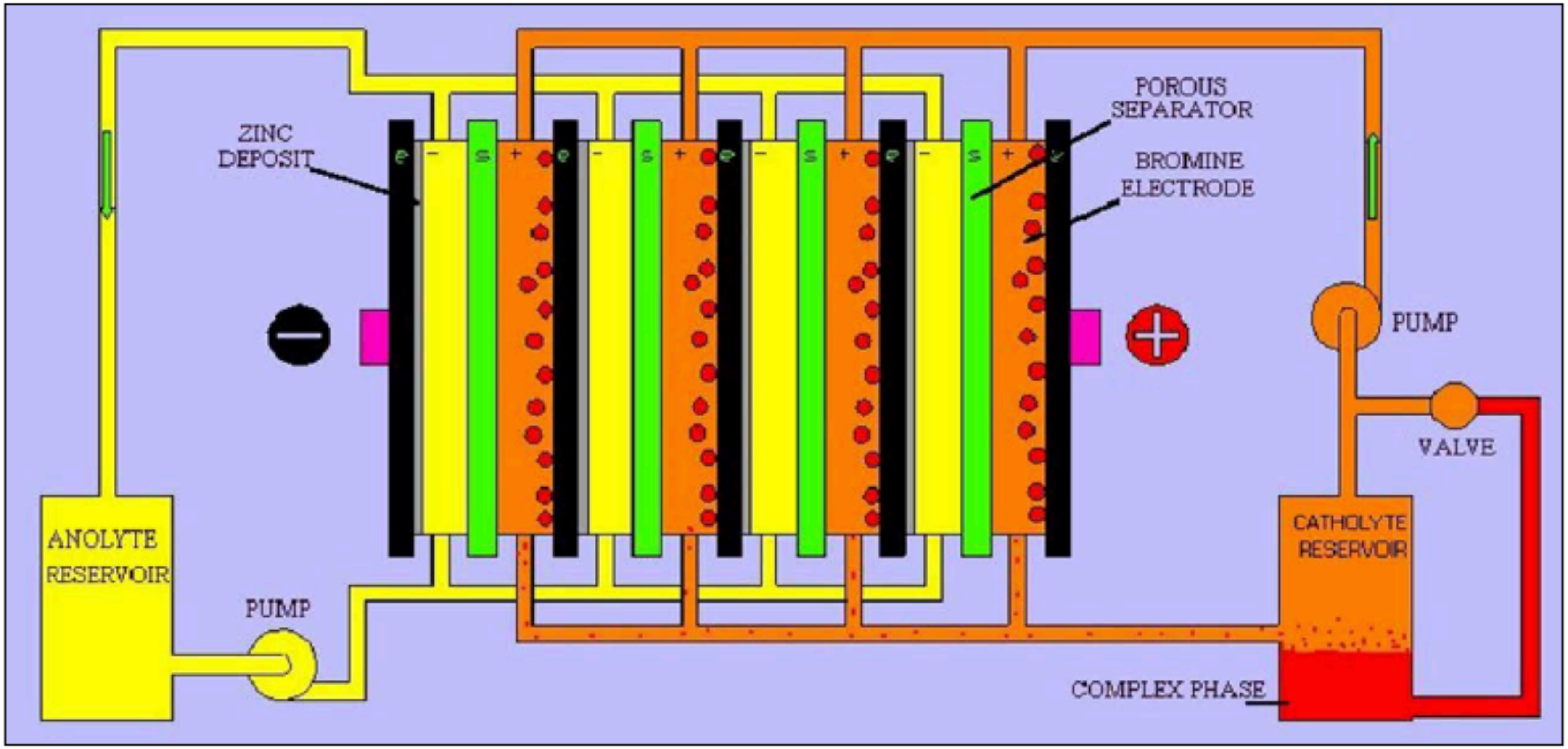
Iron Chromium batteries



Iron Chromium batteries



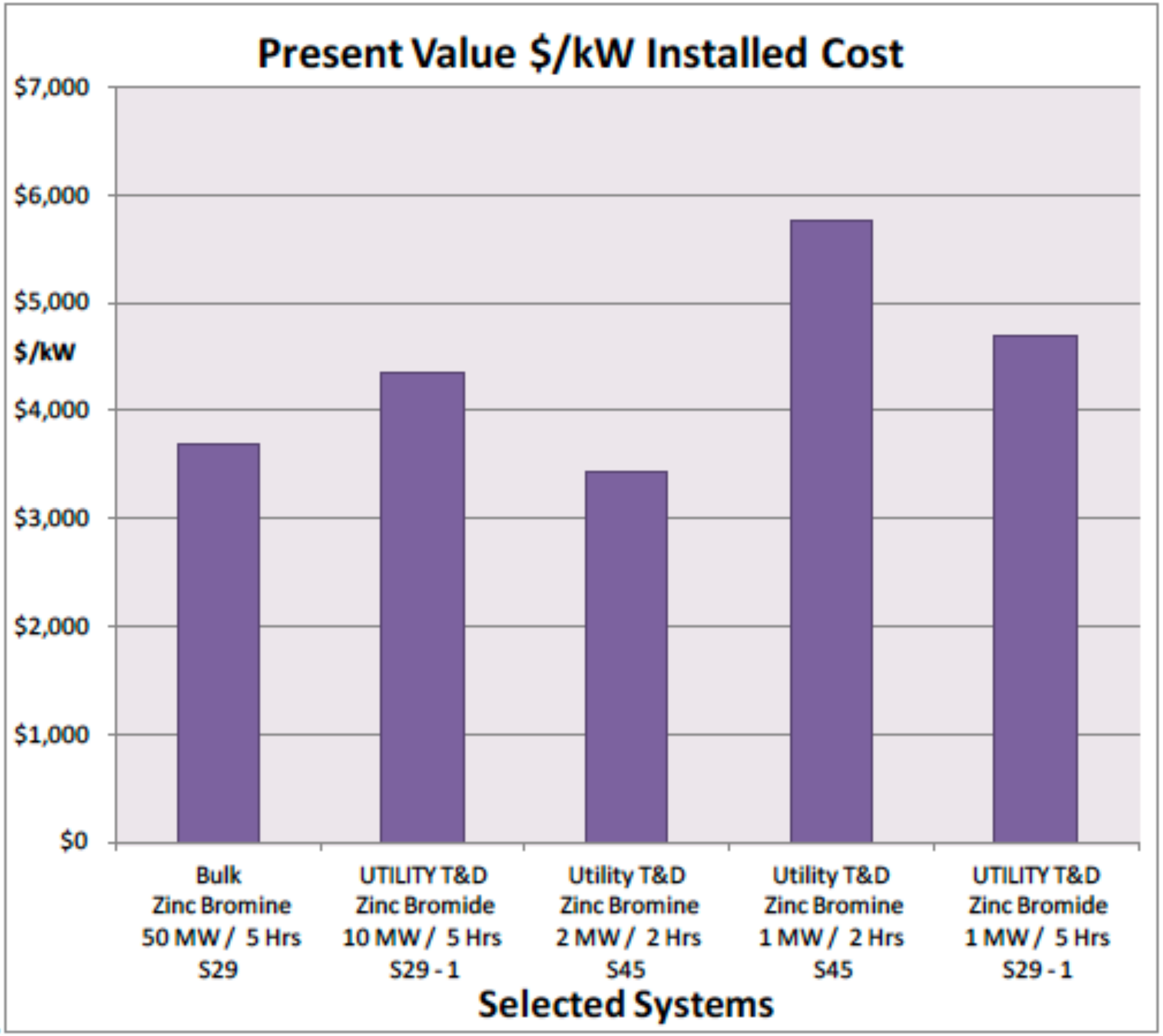
Zinc-bromine batteries



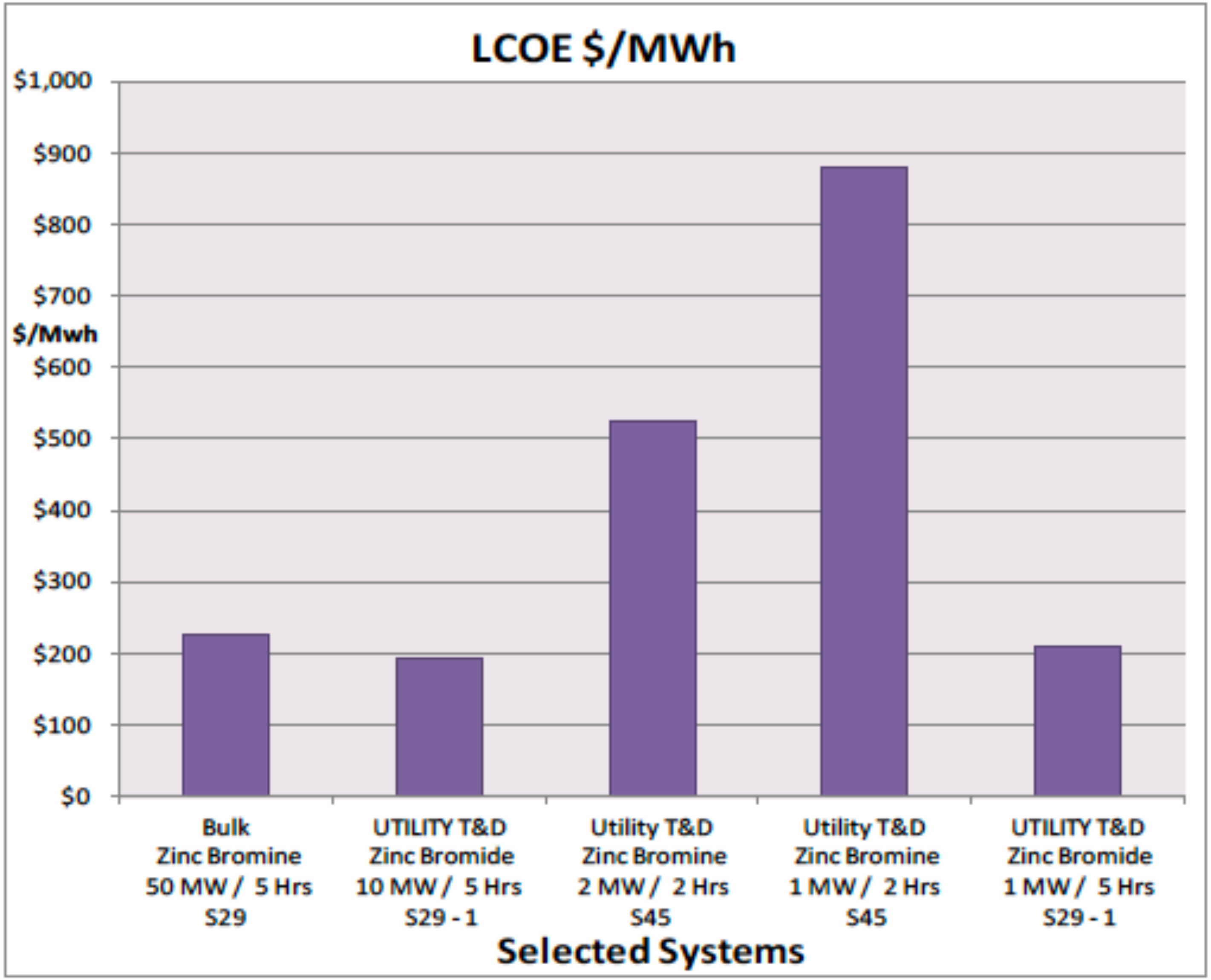
Zinc-bromine batteries

Technology Development Status	Demonstration trials	Small systems deployed in limited field demonstrations.
Confidence of Cost Estimate	C	Vendor quotes and system installation estimates.
Accuracy Range	C	-10% to +15%
Operating Field Units	3 or more	None in utility-scale demonstrations of 500 kW or larger.
Process Contingency	10%	Efficiency uncertain. Limited life and operating experience at greater than 100 kW.
Project Contingency	10- 15%	Transportable and small systems have lower construction and installation issues.

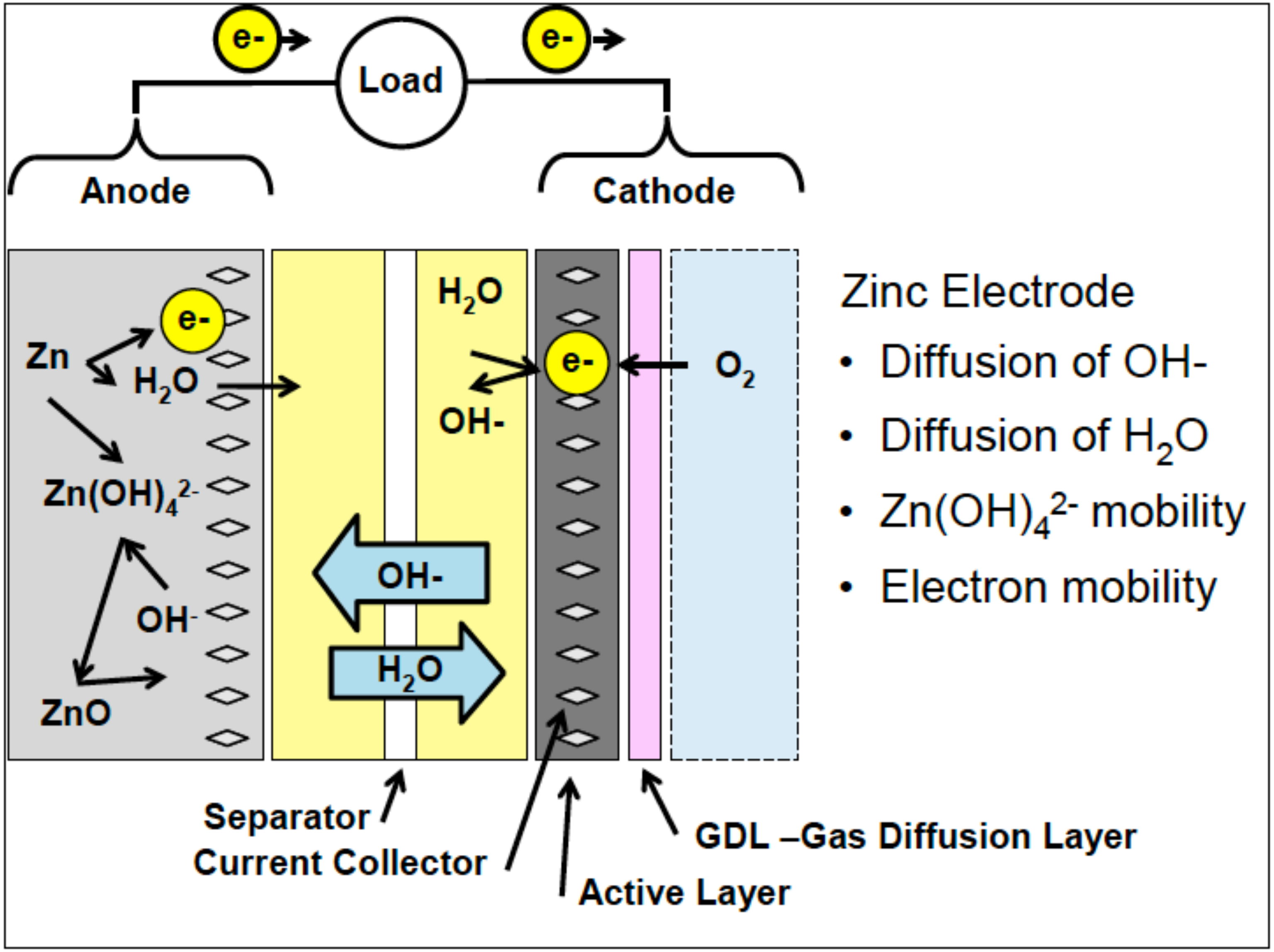
Zinc-bromine batteries



Zinc-bromine batteries



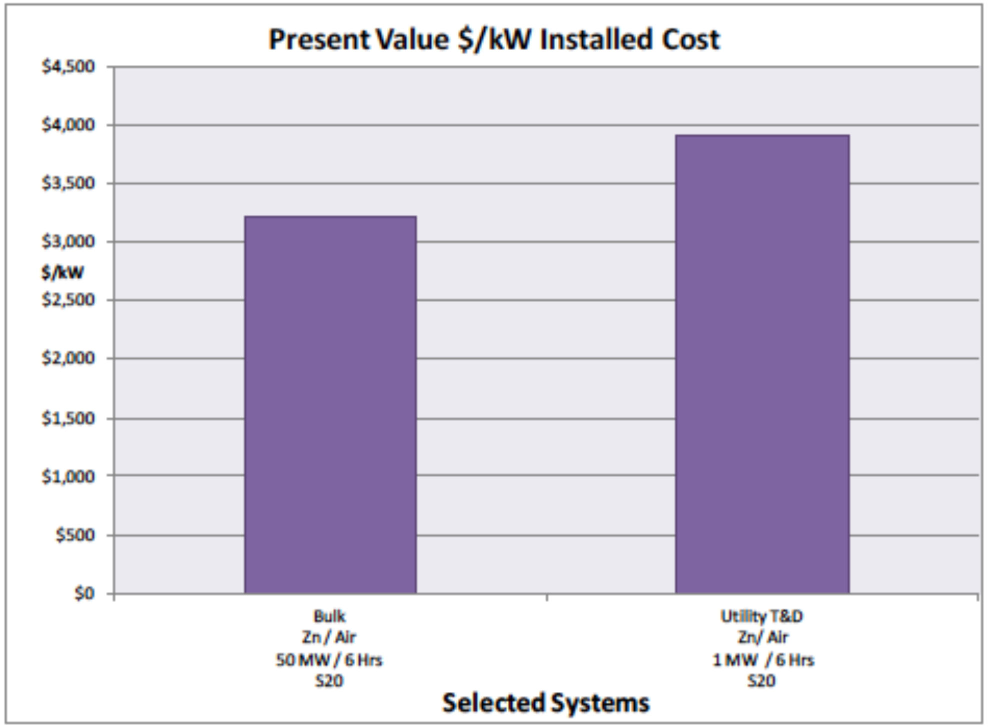
Zinc-Air batteries

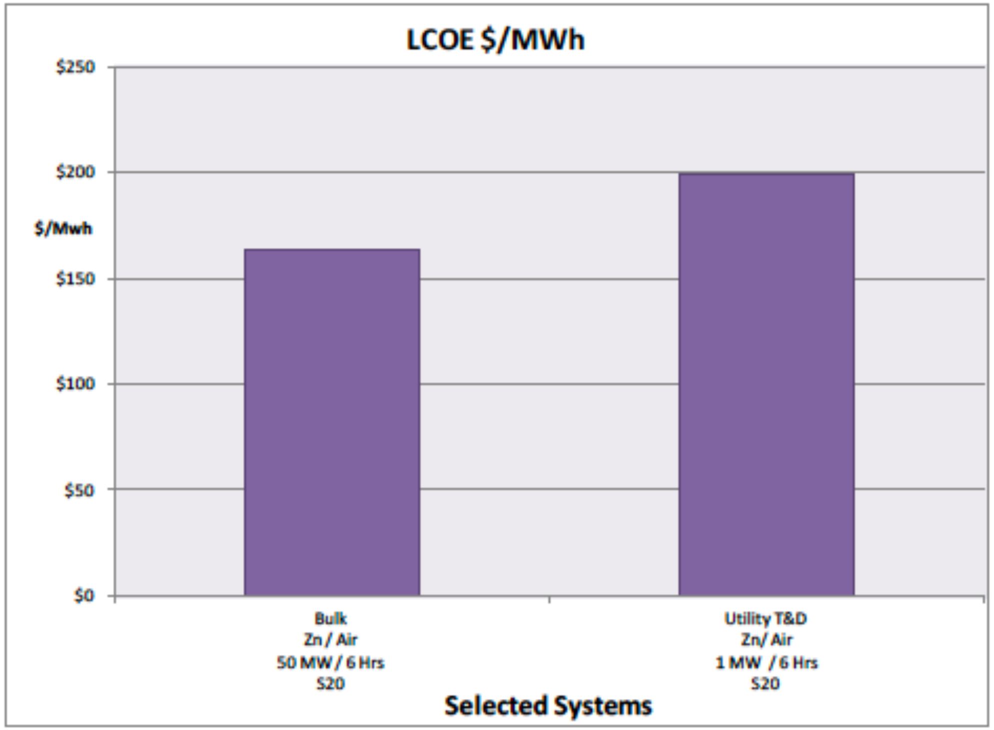


Zinc-Air batteries

Technology Development Status	Laboratory E	Small cells and stacks in a lab setting some bench scale system tests
Confidence of Cost Estimate	C	Vendor quotes and system installation estimates.
Accuracy Range	E	-15% to +15%
Operating Field Units	None	None in utility-scale demonstrations
Process Contingency	15-20%	Efficiency and cycle life uncertain. Scale-up uncertainties
Project Contingency	10-15%	Limited definition of product designs.

Zinc-Air batteries



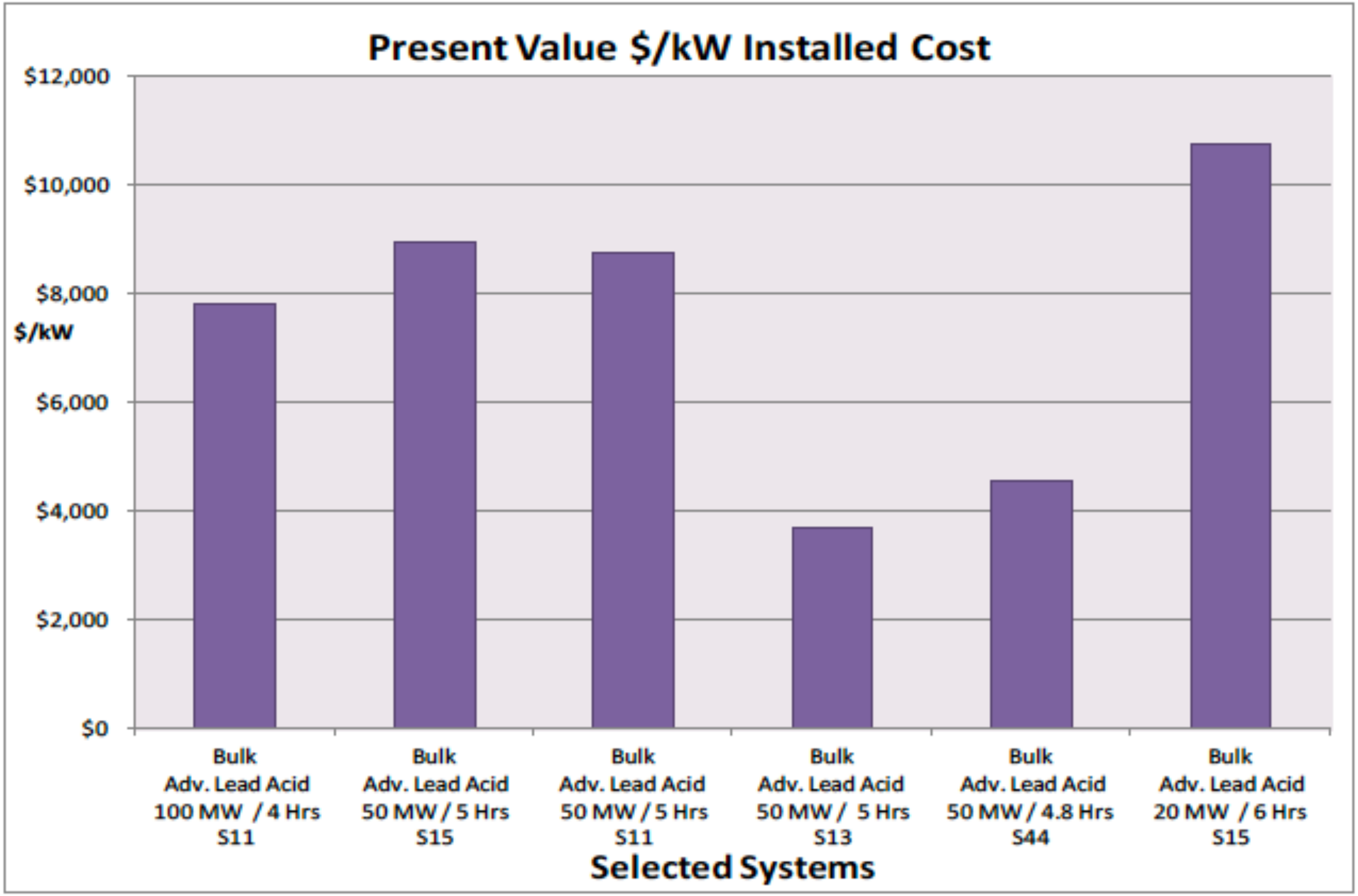


Lead acid batteries

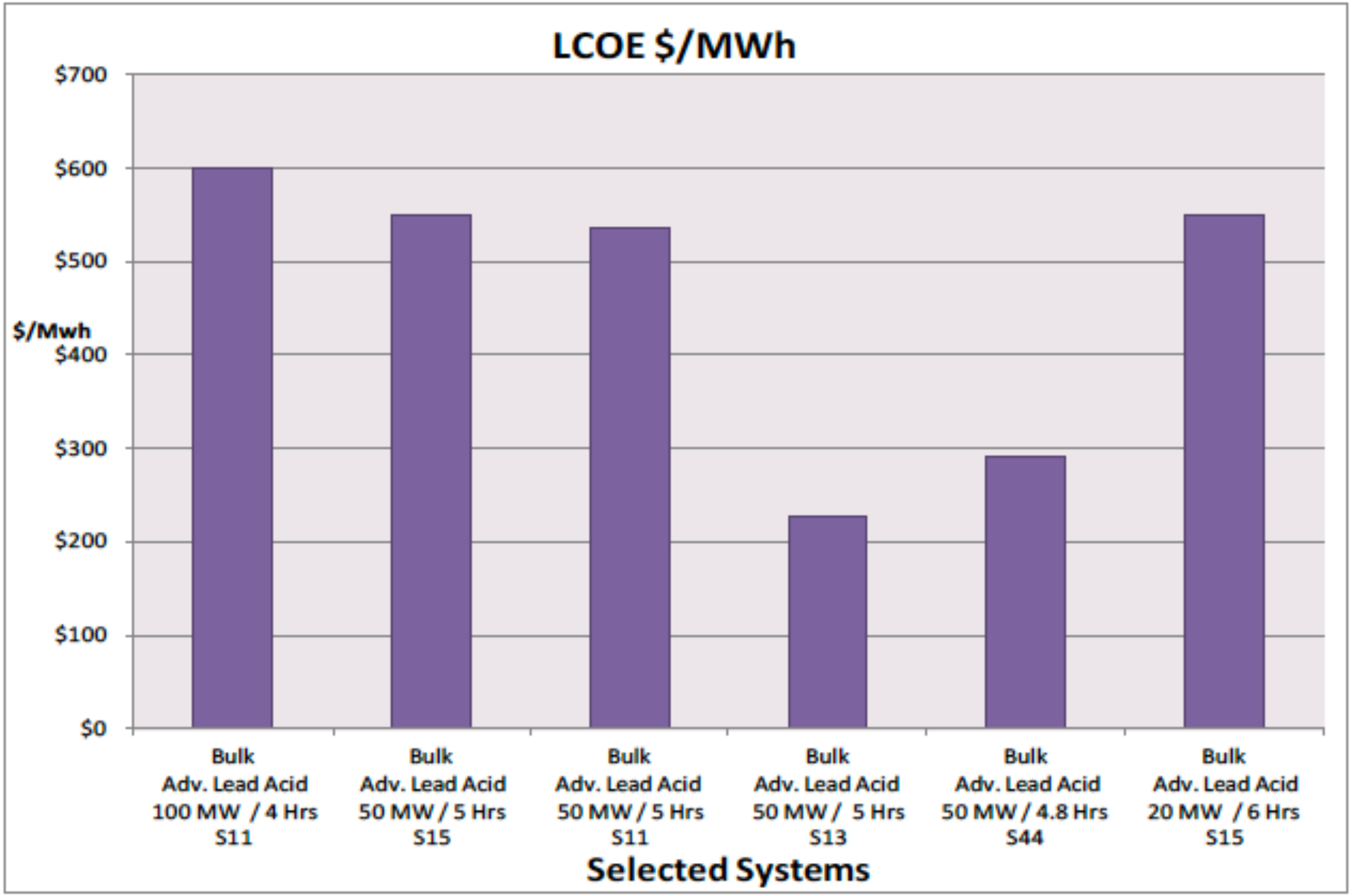
- Problems with deep discharge

Technology Development Status	Demonstration C	Limited field demonstrations Some advanced systems can be classified as commercial
Confidence of Cost Estimate	D	Vendor quotes and system installation estimates
Accuracy Range	C	-10% to +15%
Operating Field Units	5 or more	Several wind and photovoltaic applications expected by 2013
Process Contingency	10-15%	Limited testing and field experience
Project Contingency	5-10%	Cycle life and depth of discharge for application needs careful evaluation; limited operation and maintenance cost data.

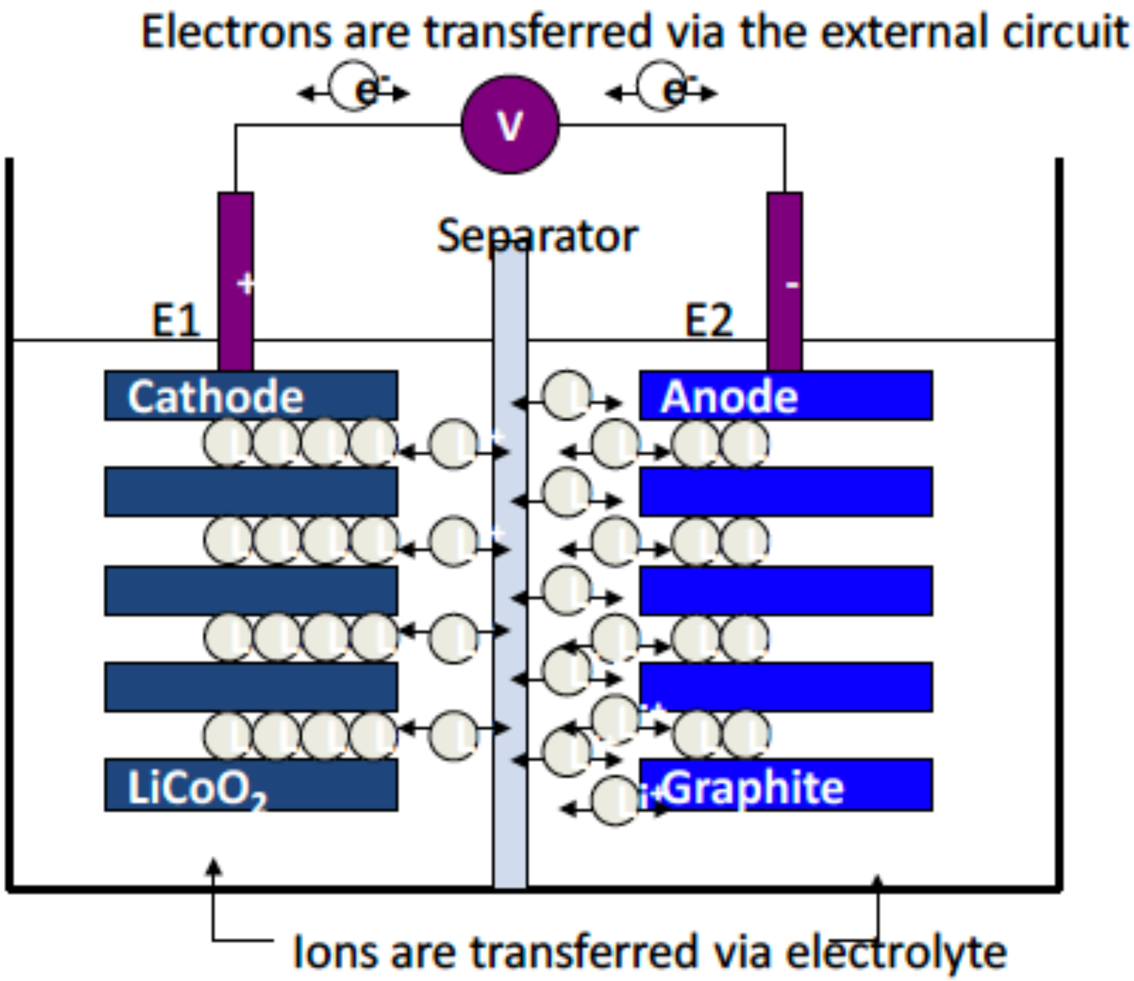
Lead acid batteries



Lead acid batteries



Li-ion batteries

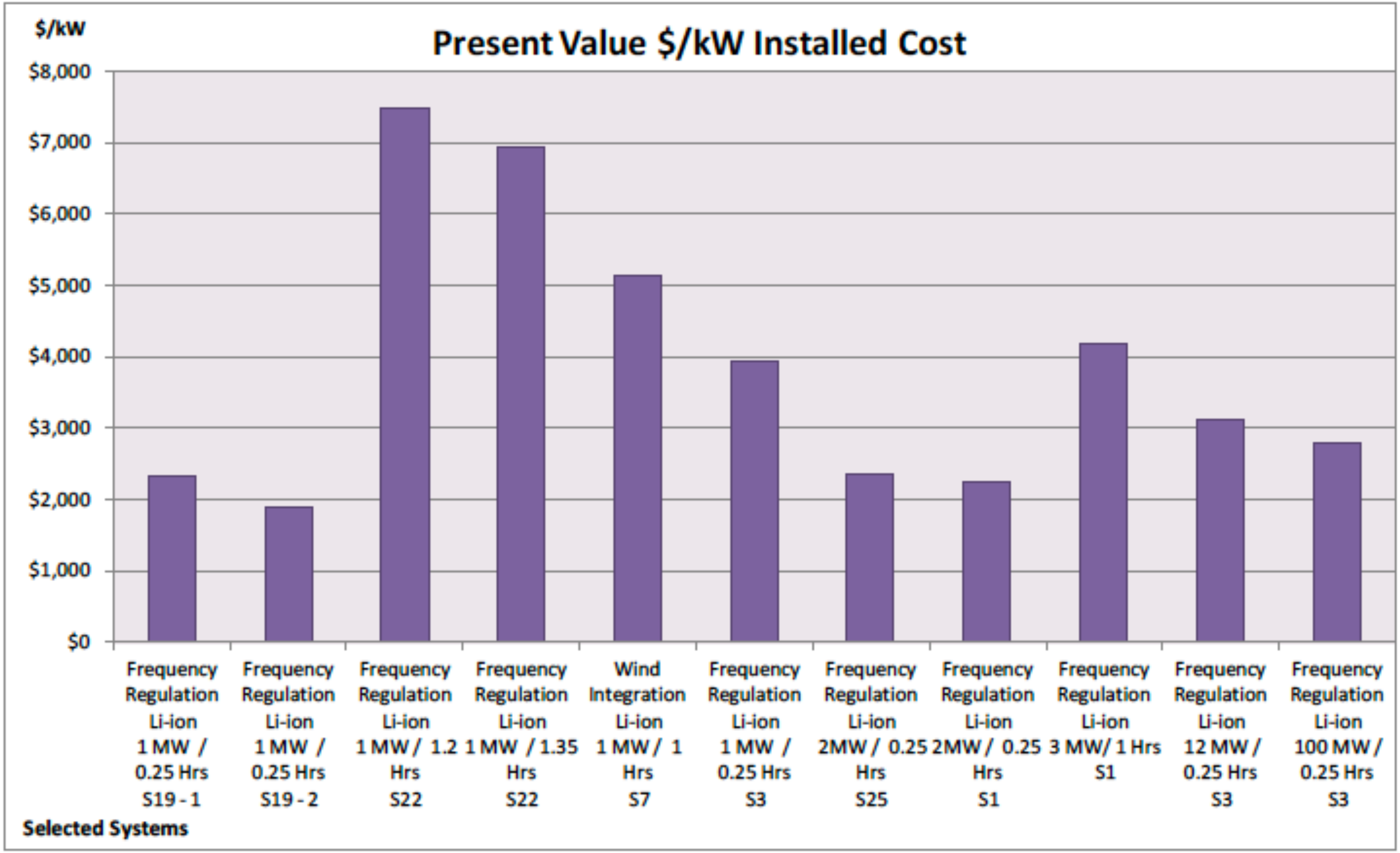


- Chemical reactions involve exchanges of charge between chemical species
- In electrochemical reactions, electric current (charge) is carried by the flow of electrons in the external circuit and by the flow of ions in the electrolyte.
- The flow of ions must be equal to the flow of electrons to maintain local charge balance.

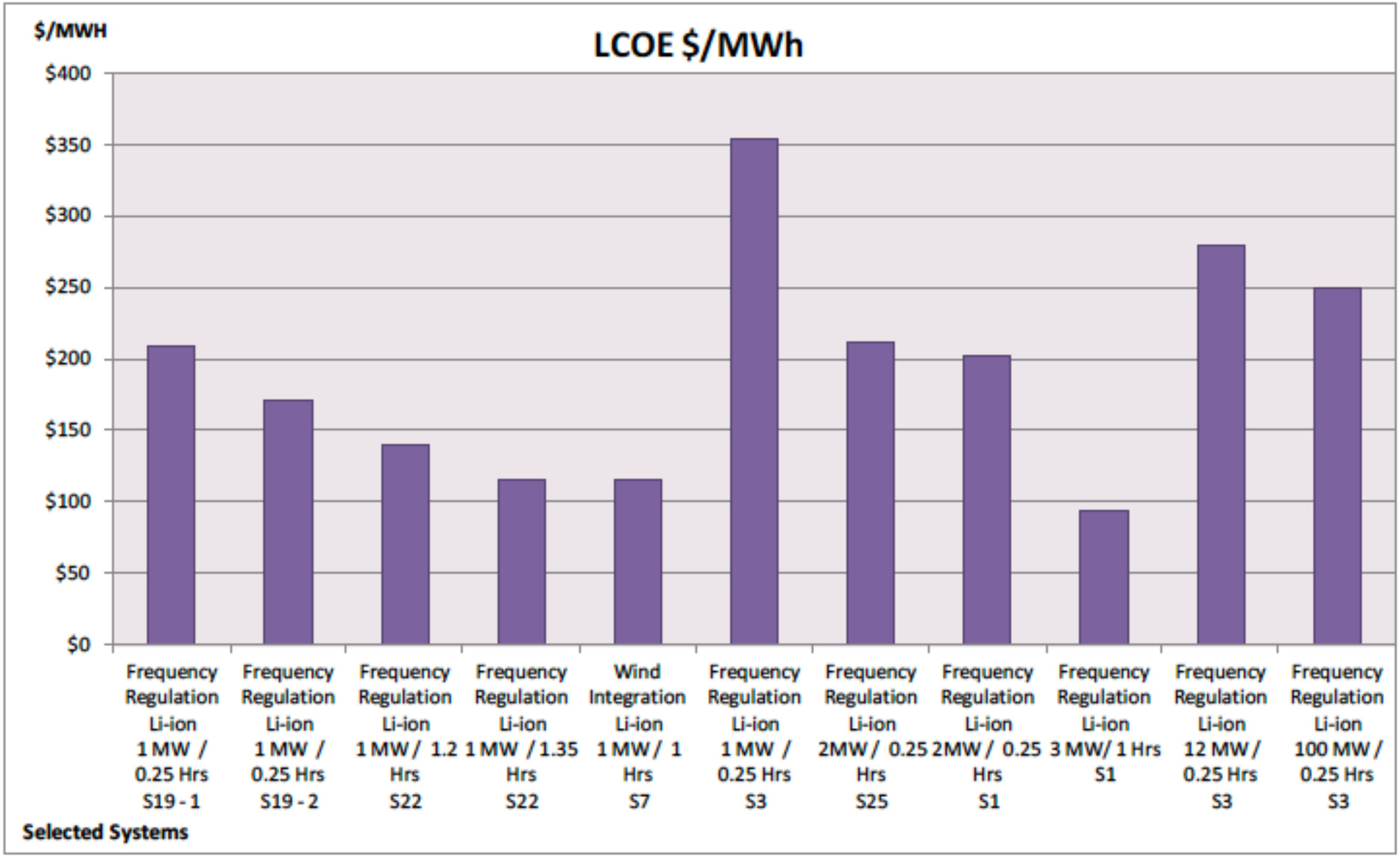
Li-ion batteries

Technology Development Status	Demonstration C	Systems verified in several field demonstrations in a variety of use cases.
Confidence of Cost Estimate	C	Vendor quotes and system installation estimates.
Accuracy Range	C	-20% to +10%
Operating Field Units	32 MW in frequency regulation service 0.5 MW/1 MWh 25-50 kW/2 hr	Numerous small demonstrations in the 5-kW to 25-kW sizes are currently underway. MW-scale short-energy-duration systems are being operated in frequency regulation applications. MW class for grid support and PV smoothing being introduced 2-MW/4-MWh system installed in an end-use customer peak shaving application
Process Contingency	10-15% Depends on chemistry	Battery management system, system integration, and cooling need to be addressed. Performance in cold climate zones needs to be verified.
Project Contingency	5-10%	Limited experience in grid-support applications, including systems with utility grid interface. Uncertain cycle life for frequency regulation applications.

Li-ion batteries



Li-ion batteries



Let us look at some applications and storage systems

Emerging technologies

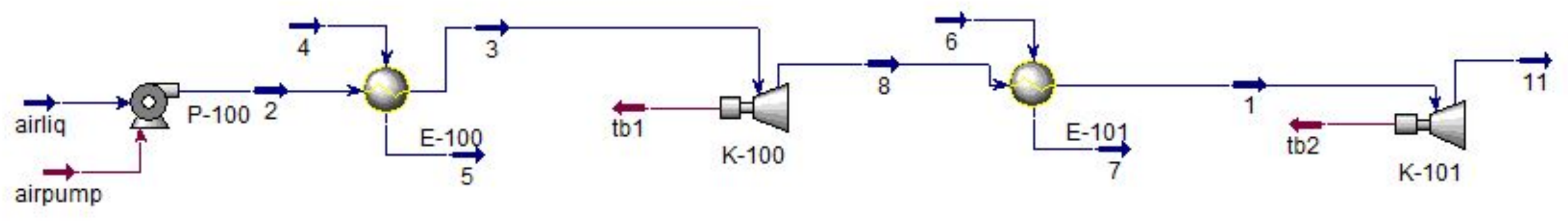
Storage Type	Status/Innovation	Estimated Deployment Timing
Liquid Air Energy Storage Systems	System studies. Low-cost bulk storage. Small demos underway.	2013-2014 first +MW-scale demo.
Non/Low-Fuel CAES	System studies underway to optimize cycle and thermal storage system. Low-fuel and non-fuel CAES for bulk storage.	2015 pilot demonstration of 5-MW system
Underground Pumped Hydro	System studies. New concepts under development.	Under study.
Nano-Supercapacitors	Laboratory testing. High power and energy density; very low cost.	2013-2015
Advanced Flywheels	System studies. Higher energy density.	Under development. 2015.
H_2/Br Flow	Bench-scale testing. Low-cost storage.	2013-2014 pilot demo.

Emerging technologies

Storage Type	Status/Innovation	Estimated Deployment Timing
Advanced Lead-Acid Battery	Modules under test. Low cost; high-cycle life.	2013-2015 early field trials.
Novel Chemistries	Bench-scale testing. Very low cost; long-cycle life.	2013-2015 modules for test.
Isothermal CAES	2 MW and 1 MW System Development and Demonstration effort. Non-fuel CAES for distributed storage.	2013 pilot system tests.
Advanced Li-ion Li-air and others	Laboratory/basic science. Lower costs; high energy density.	2015-2020

The Highview project

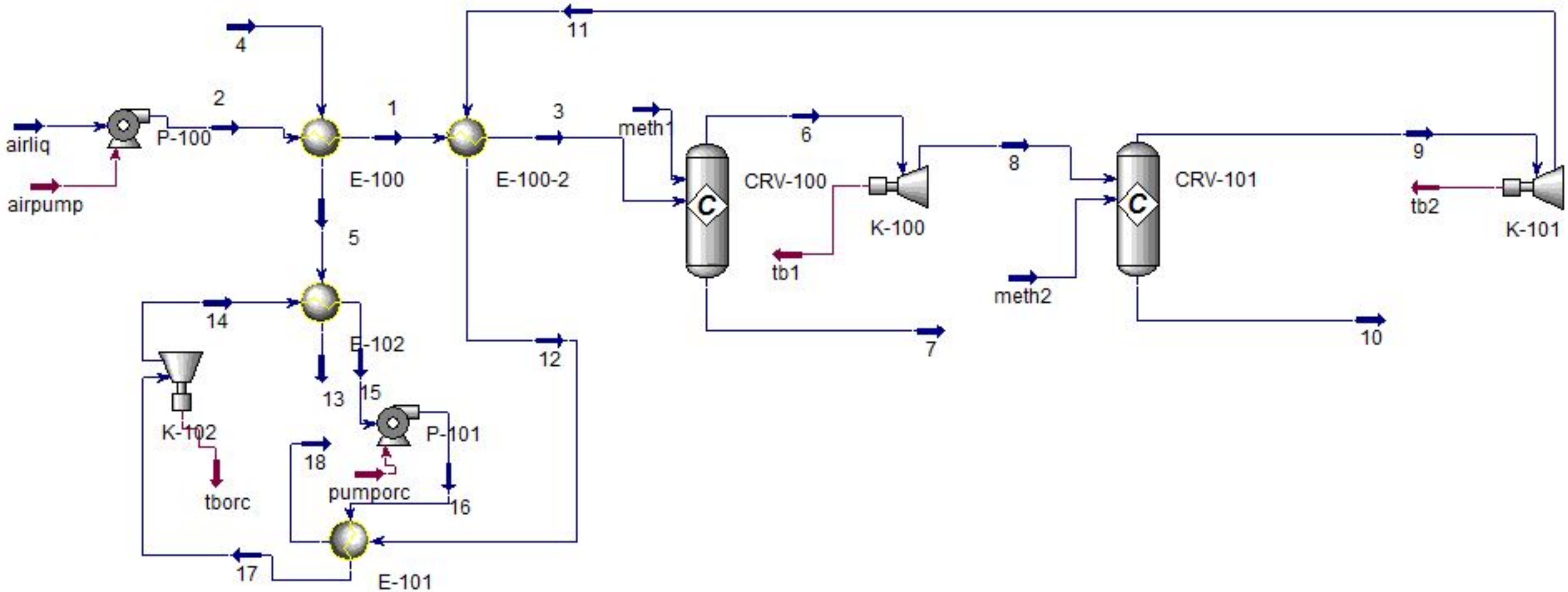
LAES



- 200 bar maximum pressure, ambient air as hot source, without combustion

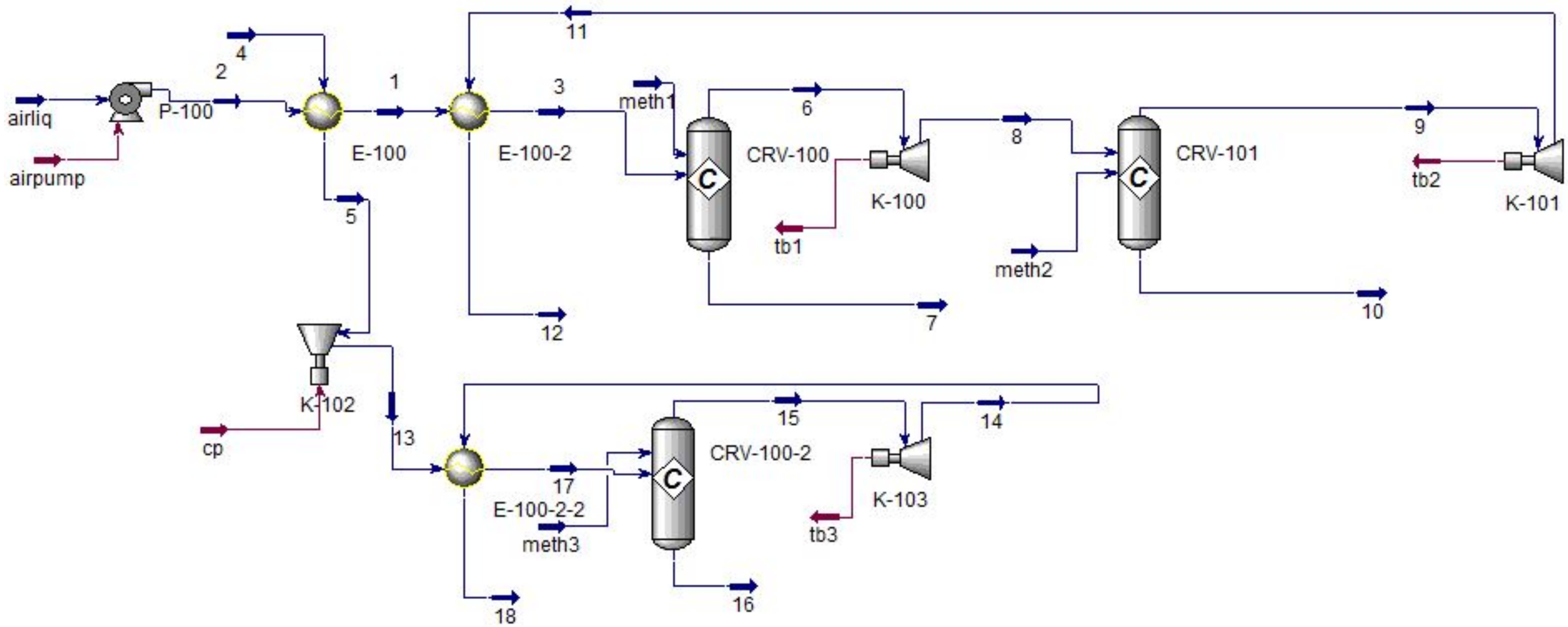
- Round-trip efficiency $\eta_{rt} = 0.10$

LAES



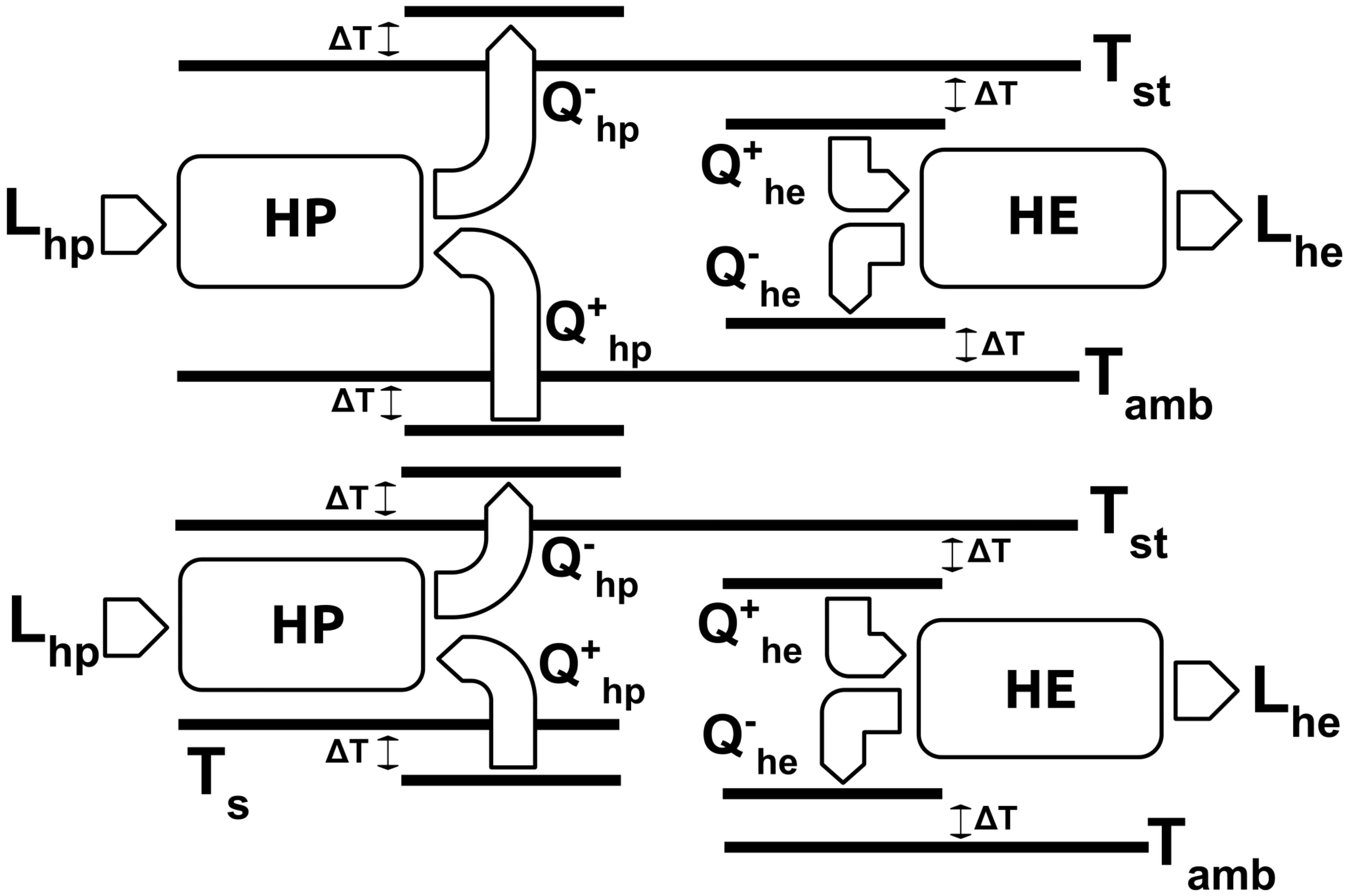
- 200 bar, double methane combustion, 1400K of maximum temperature at turbine inlet, recuperation of exhaust gases, cryogenic Organic Rankine Cycle
- Round-trip efficiency $\eta_{rt}=0.44$
- Fuel efficiency $\eta_{fuel}=0.94$

LAES



- 200 bar, double methane combustion, 1400K of maximum temperature at turbine inlet, recuperation of exhaust gases, cold Brayton Cycle
- Round-trip efficiency $\eta_{rt} = 0.50$
- Fuel efficiency $\eta_{fuel} = 0.79$

PTES



ΔT
T st
Q- hp
ΔT
Q+ he
L hp
HP
HE
L he
Q- he
Q+ hp
ΔT
T amb
ΔT
ΔT
T st
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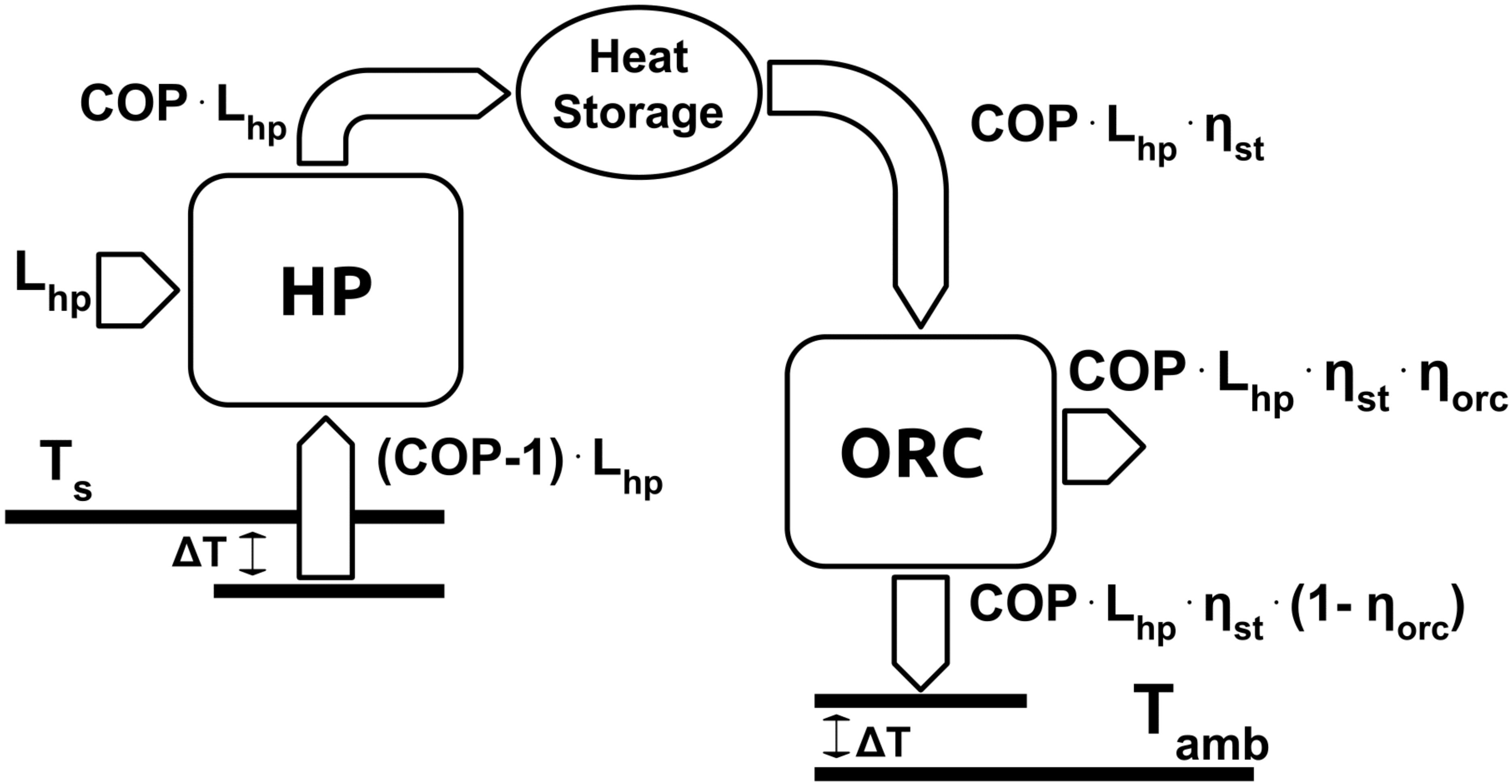
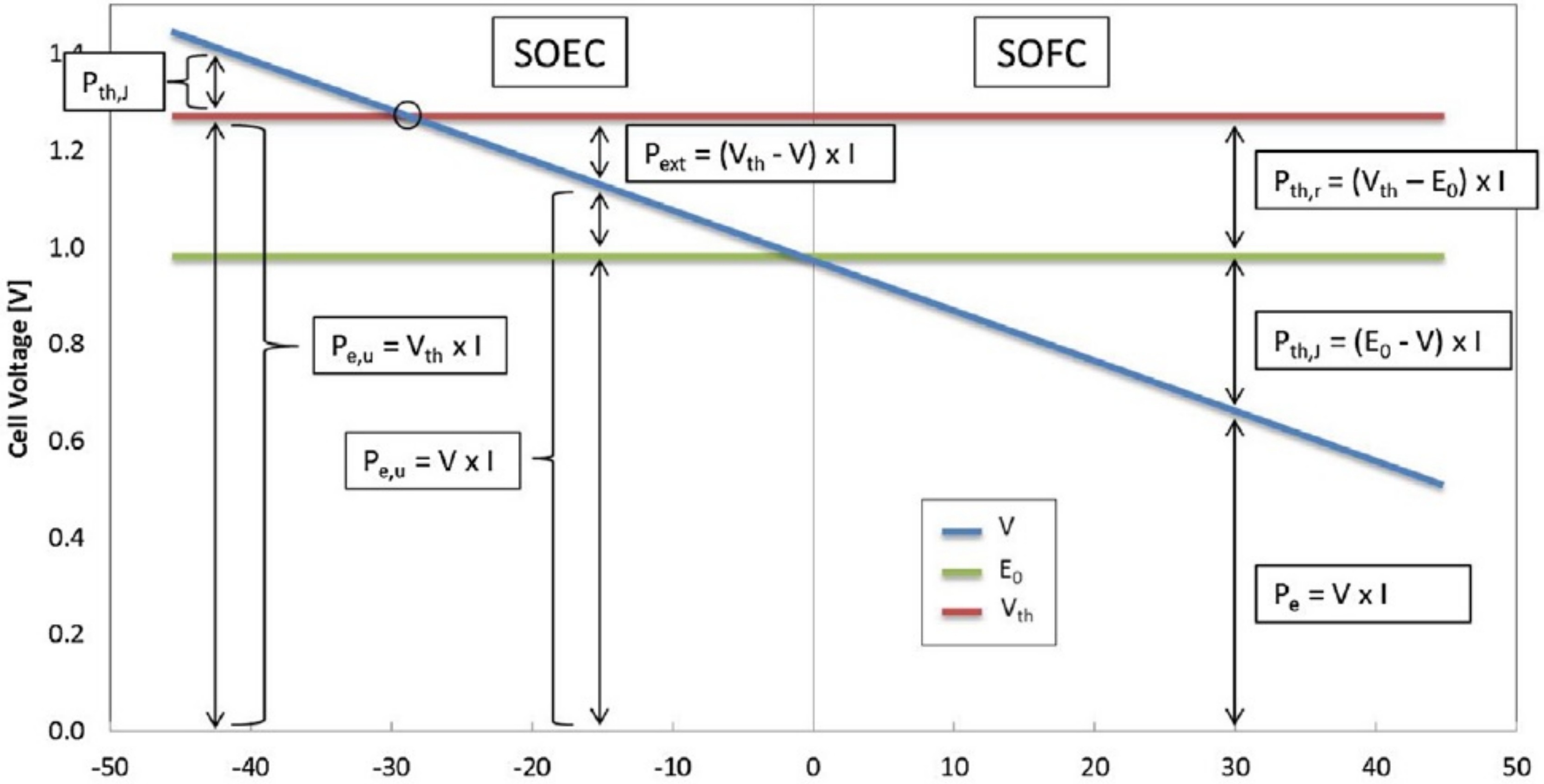
ΔT
T amb

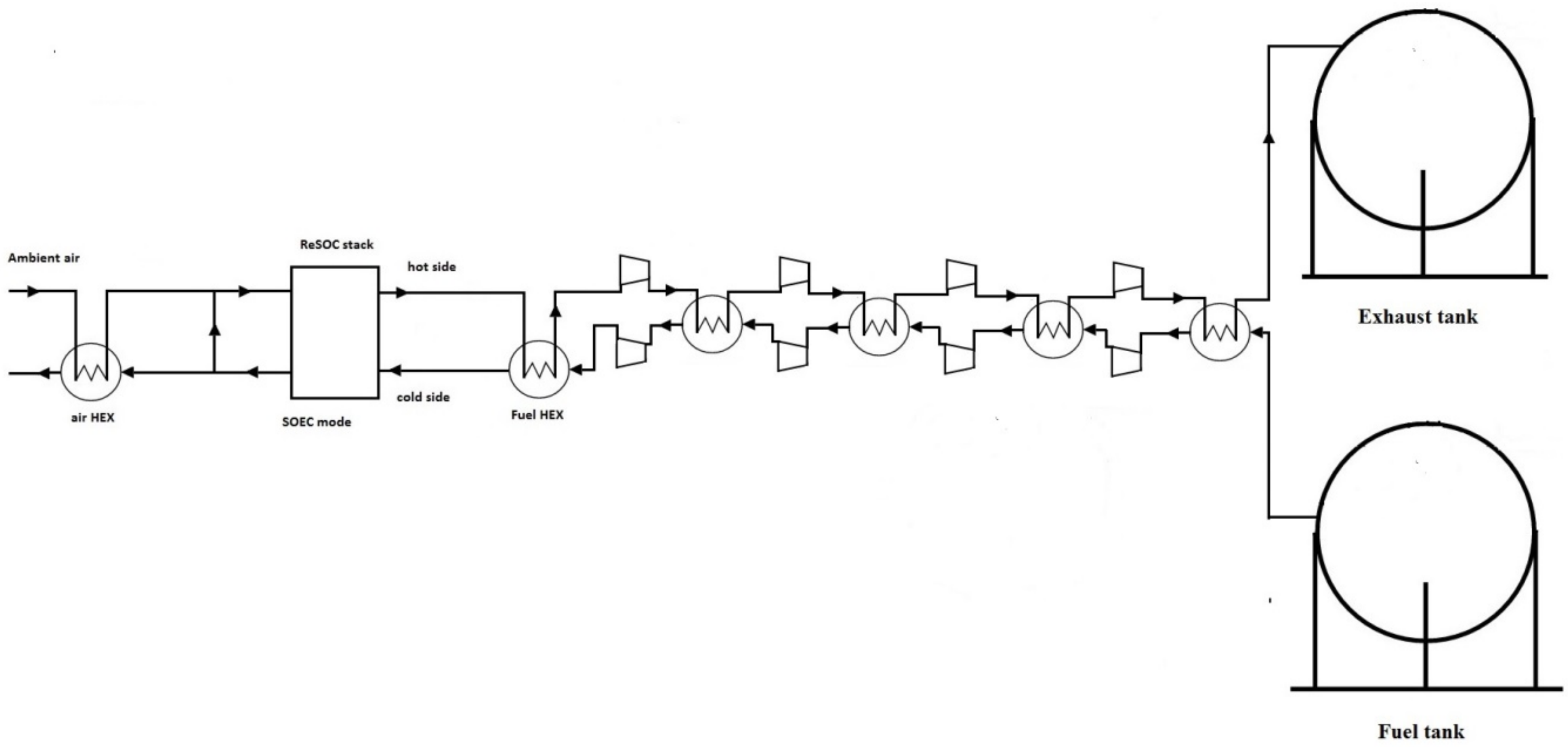


Heat Storage
COP · L_hp
COP · L_hp · η_st
L_hp
HP
ORC
COP · L_hp · η_st · η_orc
T_s
(COP-1) · L_hp
ΔT
COP · L_hp · η_st · (1- η_orc)
ΔT
T_amb

- The same stack can generate power and hydrogen by using it in reverse mode

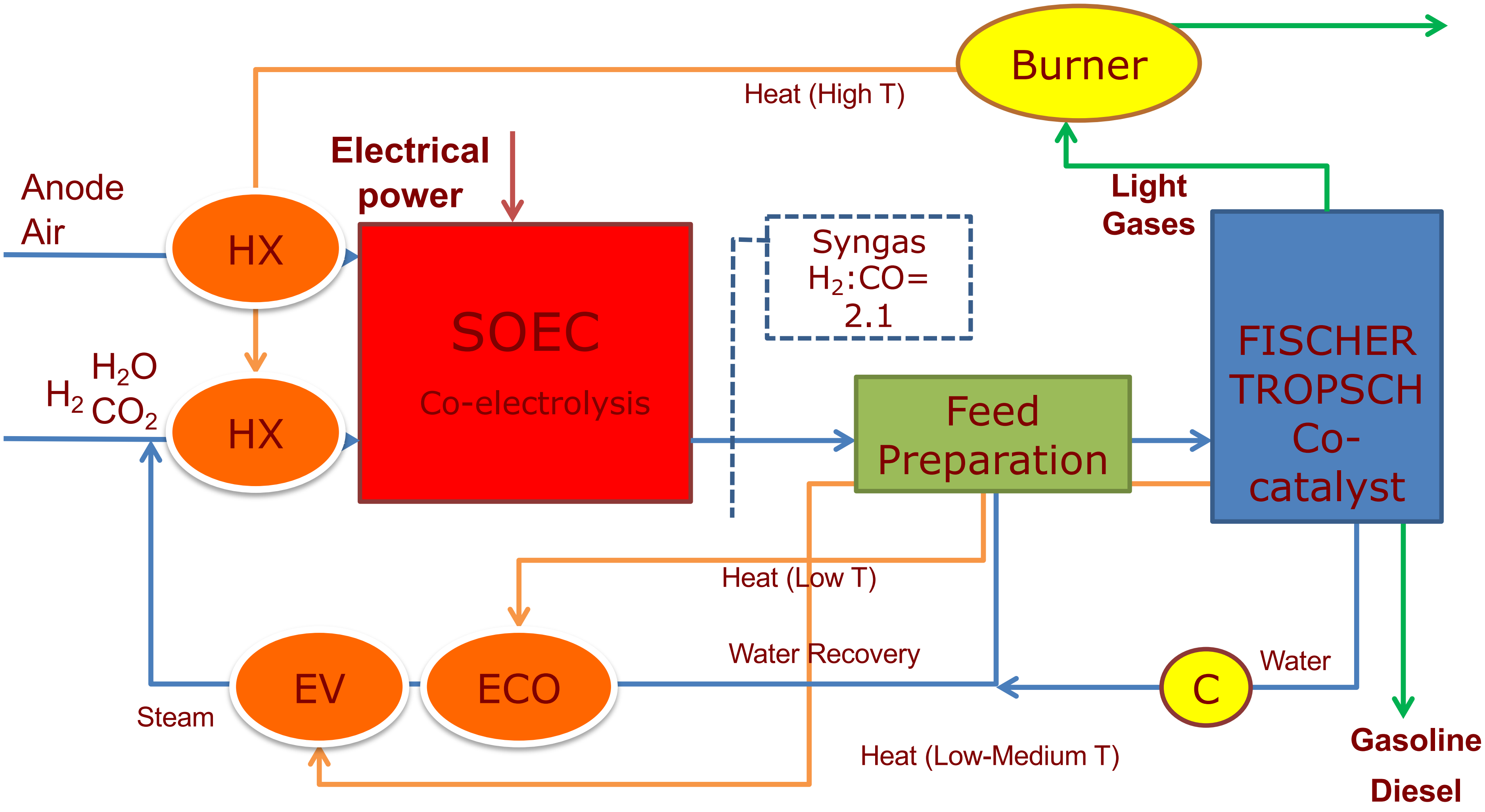


SOFC/SOEC



Ambient air
ReSOC stack
hot side
cold side
air HEX
SOEC mode
Fuel HEX
Exhaust tank
Fuel tank

Power to gas


Burner
Heat (High T)
Electrical power
Anode Air
HX
SOEC
Co-electrolysis
Syngas H_2:CO= 2.1
Light Gases
FISCHER TROPSCH Co-catalyst
H_2O
H_2 CO_2
HX
Feed Preparation
Heat (Low T)
Water Recovery
Water
EV
ECO
C
Steam
Heat (Low-Medium T)
Gasoline
Diesel

- There is no leading technology
- Different systems are suitable for different energy storage applications
- No further development in renewable energy is possible without energy storage
- No sure path is clear for the future

Conclusions

- Challenges
  - Energy supply mix
  - Energy demand mix
  - Infrastructure development
  - Costs
  - Energy storage mix