Clean energy investments: Lessons from the 2009 Recovery Act

&

Energy storage requirements for deep renewable energy penetration

Global Energy Dialogues

23 June 2020

Lessons from the 2009 Recovery Act

A RETROSPECTIVE ASSESSMENT OF CLEAN ENERGY INVESTMENTS IN THE RECOVERY ACT

February 2016

EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES
COUNCIL OF ECONOMIC ADVISERS

- 2005 ARPA-E recommended in “Rising Above the Gathering Storm”
- ARPA-E was authorized (allows a program to be established) in 2007
- Recovery Act of 2009, which provided $400 M/2 years.
- First Budget request in 2011 was for $ 300M

Since 2009 ARPA-E has provided

$2.3 billion

in R&D funding to more than **850 projects**

82 companies

formed by **ARPA-E projects**

219 projects

have **partnered with other government agencies** for further development

161 Projects have attracted more than

$3.2 billion

in private-sector follow-on funding

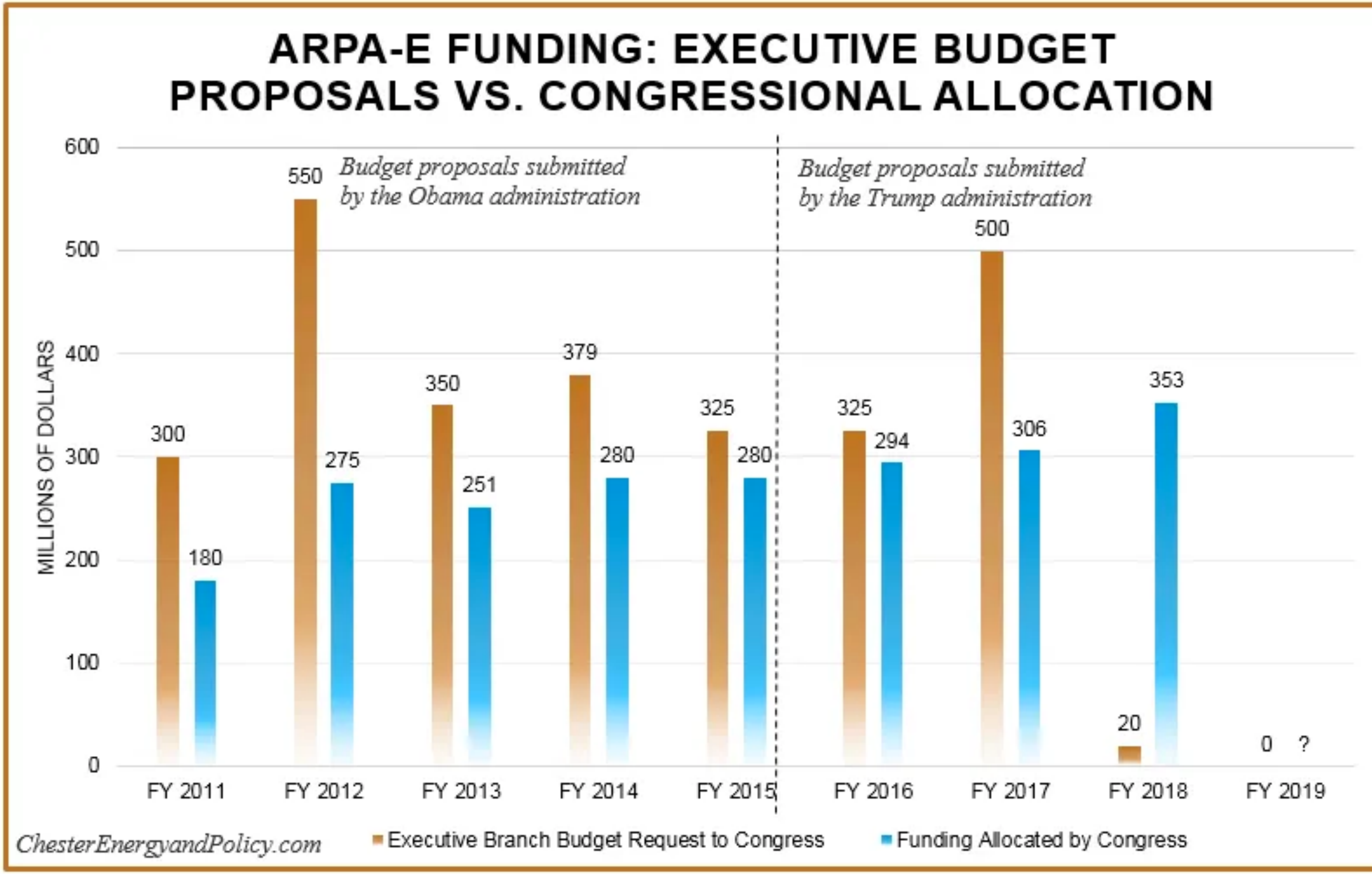
3,658

peer-reviewed **journal articles** from ARPA-E projects

385 patents

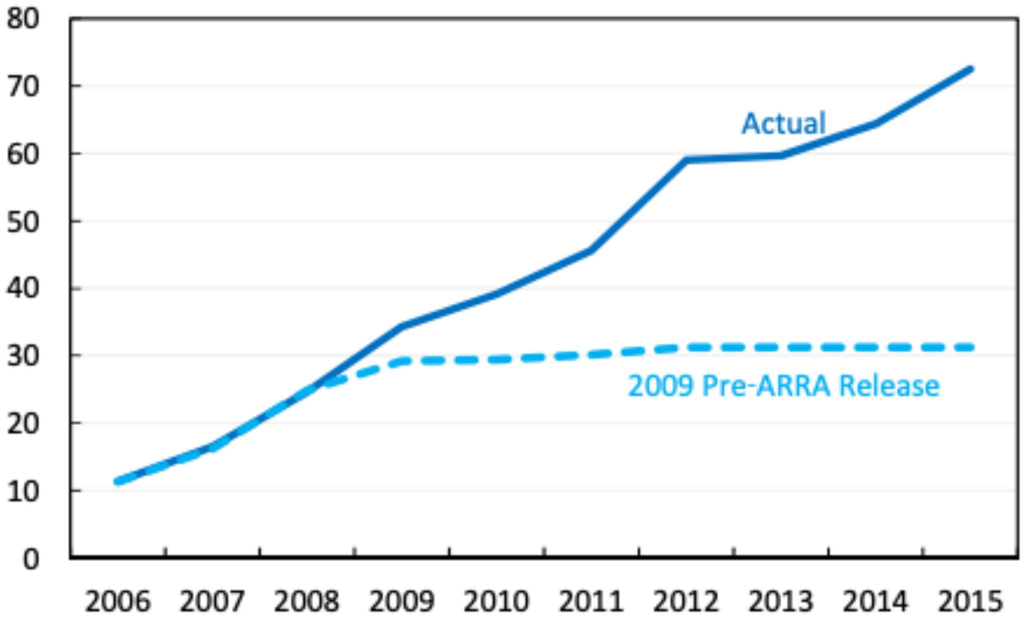
issued by U.S. Patent and Trademark Office

As of February 2020

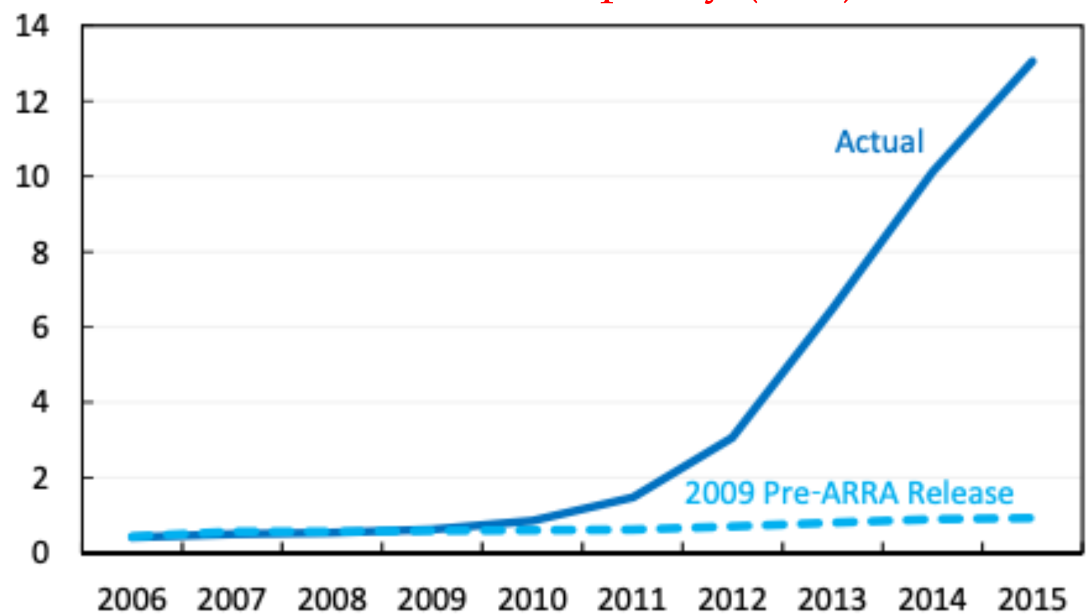


ARPA-E FUNDING: EXECUTIVE BUDGET PROPOSALS VS. CONGRESSIONAL ALLOCATION
Budget proposals submitted by the Obama administration
Budget proposals submitted by the Trump administration
MILLIONS OF DOLLARS
600
500
400
300
200
100
0
300
180
550
275
350
251
379
280
325
280
325
294
500
306
20
353
0
?
FY 2011
FY 2012
FY 2013
FY 2014
FY 2015
FY 2016
FY 2017
FY 2018
FY 2019
ChesterEnergyandPolicy.com
Executive Branch Budget Request to Congress
Funding Allocated by Congress

Installed wind capacity (GW)

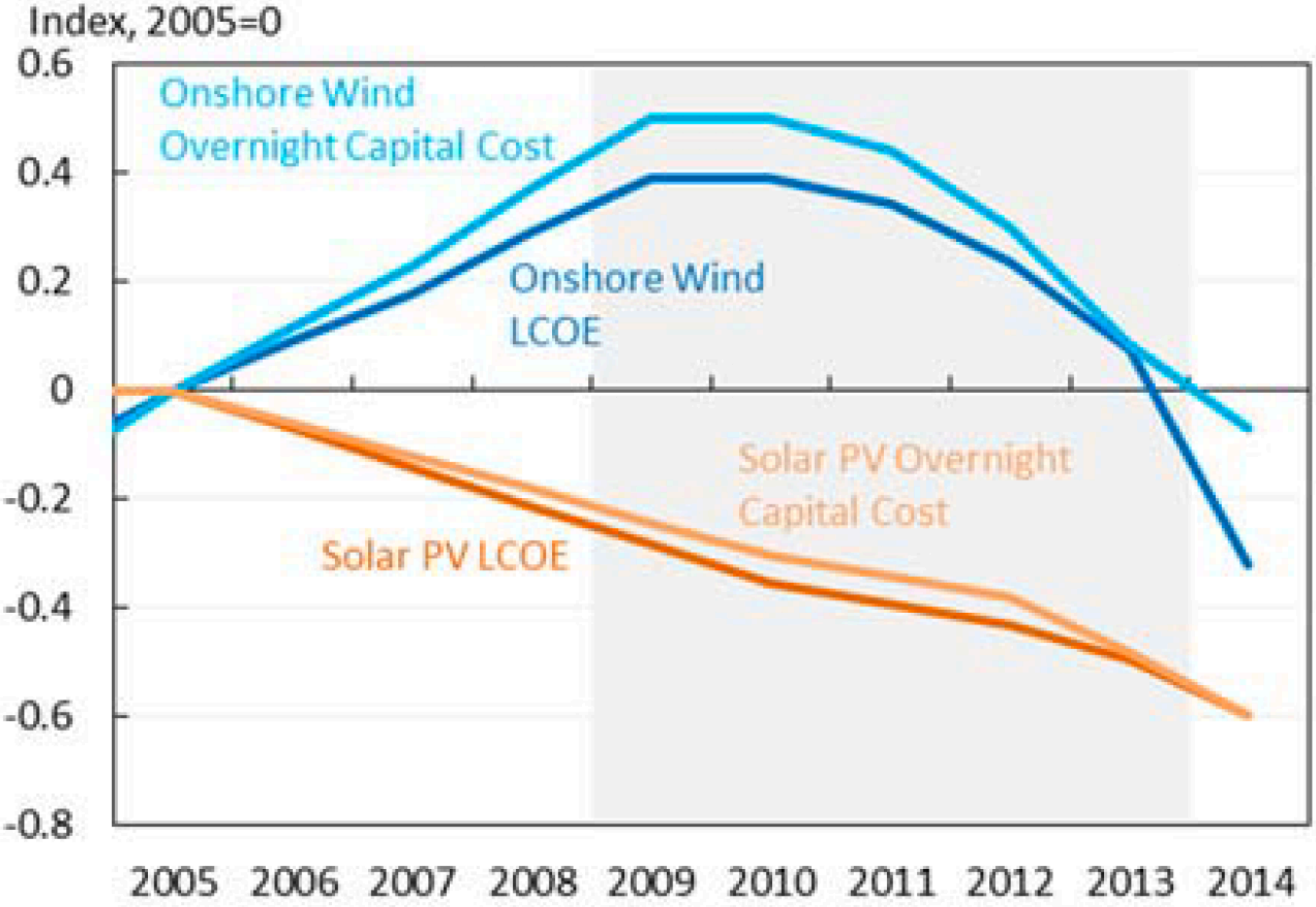


Installed solar capacity (GW)



Source: Energy Information Administration

Figure 8: Change in Costs for Onshore Wind and Solar PV



Source: NREL; Wiser, Bollinger et al. 2013; Lazard 2014.

- ARPA-E

- The Smart Grid Investment Grant. (Authorized in 2007.)

- Loan Program (authorized in 2005)
  Many successful wind and solar installations
  Solyndra ($535M loss), Abound ($68M loss)

- ATVTM (Advanced Technology Vehicle Manufacturing)

  Ford ($6B),
  Nissan ($1.45B Leaf and battery manufacturing in the U.S.)
  Tesla ($465 M),
  Fisker went bankrupt ($138 M loss)

OMB assigns a credit risk of default. (e.g. If the risk is 20%, that fraction of the loan is set aside as allocated (spent) funds. “self-pay” means the loan applicant pays for the “loan insurance.” All of fossil, nuclear and

Table 2. Estimates of LPO Credit Authority ($billions)				
Programs	Current Remaining Authority	Pending conditional commitments	Net amount available	Credit subsidy appropriations support
Title XVII Volume Caps (self-pay authority)				
Advanced fossil energy	$8.5B	$2.0B	$6.5B	None (self-pay)
Advanced nuclear energy	$12.7B	$3.7B	$9.0B	None (self-pay)
Nuclear – Front End	$2.0B	-	$2.0 B	None (self-pay)
Renewable energy and energy efficiency (self-pay)	$2.5B	–	$2.5B	None (self- pay)
Subtotal (Title XVII self-pay)	**$ 25.7B**	**$5.7 B**	**$20.0 B**	
Estimated Renewable Energy and Energy Efficiency (supported by credit subsidy appropriation)	$1.1B	-	$1.1 B	$160 million
Subtotal (Title XVII) (self-pay and credit subsidy appropriation)	**$26.8B**		**$21.1B**	**$160 million**
ATVM (supported by credit subsidy appropriation)	$17.7B	–	$17.7B	$4,333 million
Estimated Tribal Energy Loan Guarantee Volume (supported by credit subsidy appropriation)	$0.1B		$0.1 B	$8.5 million
TOTAL	**$44.6B**	**$5.7B**	**$38.9B**	

Smart Grid Investment
Grant Program
(Authorized in 2007.)

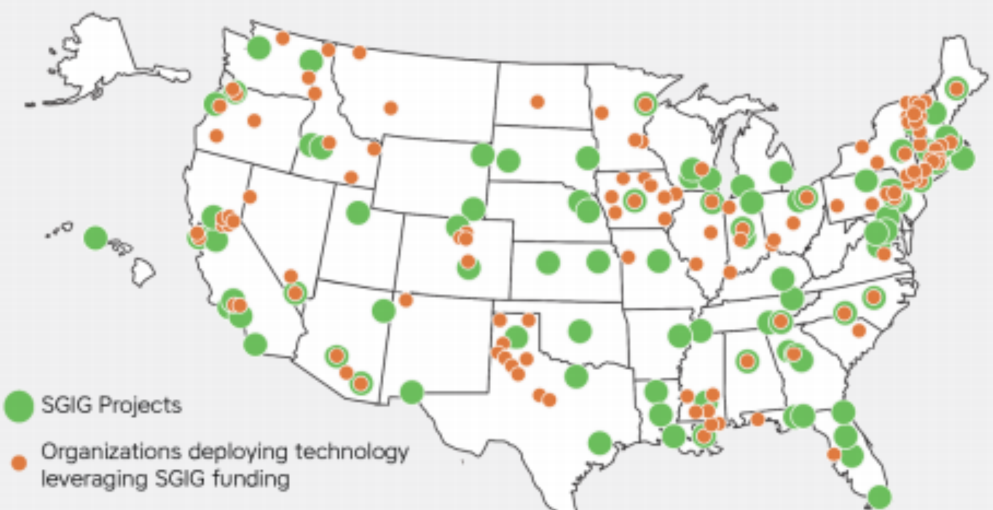
SMART GRID INVESTMENT GRANT (SGIG) PROGRAM OVERVIEW

SGIG PROGRAMS AND FUNDING

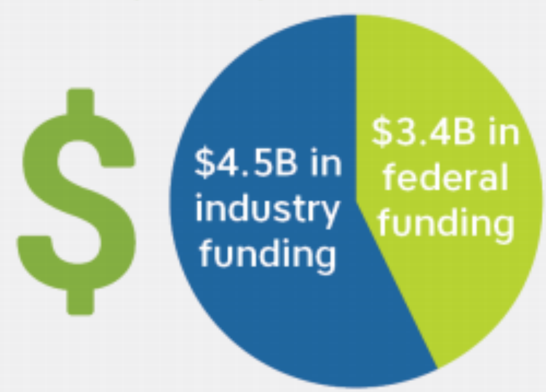
99 competitively selected projects

228 participating utilities and organizations

6 years (2010-2015)



$7.9B public/private investment



ARRA funding was matched or exceeded dollar for dollar by recipients.

SGIG TECHNOLOGY DEPLOYMENTS

ELECTRIC TRANSMISSION SYSTEM

1,380 networked synchrophasors contributed to a more than **10** fold increase in North American synchrophasors from 2007 to 2015.

CUSTOMER SYSTEMS

Nearly **700,000** customer devices

ELECTRIC DISTRIBUTION SYSTEM

82,000 intelligent, automated devices

ADVANCED METERING INFRASTRUCTURE

16M SGIG smart meters about **33%** of the **49M** total smart meters installed in the U.S. from 2010 – 2014

U.S. DEPARTMENT OF
ENERGY

Electricity Delivery
& Energy Reliability

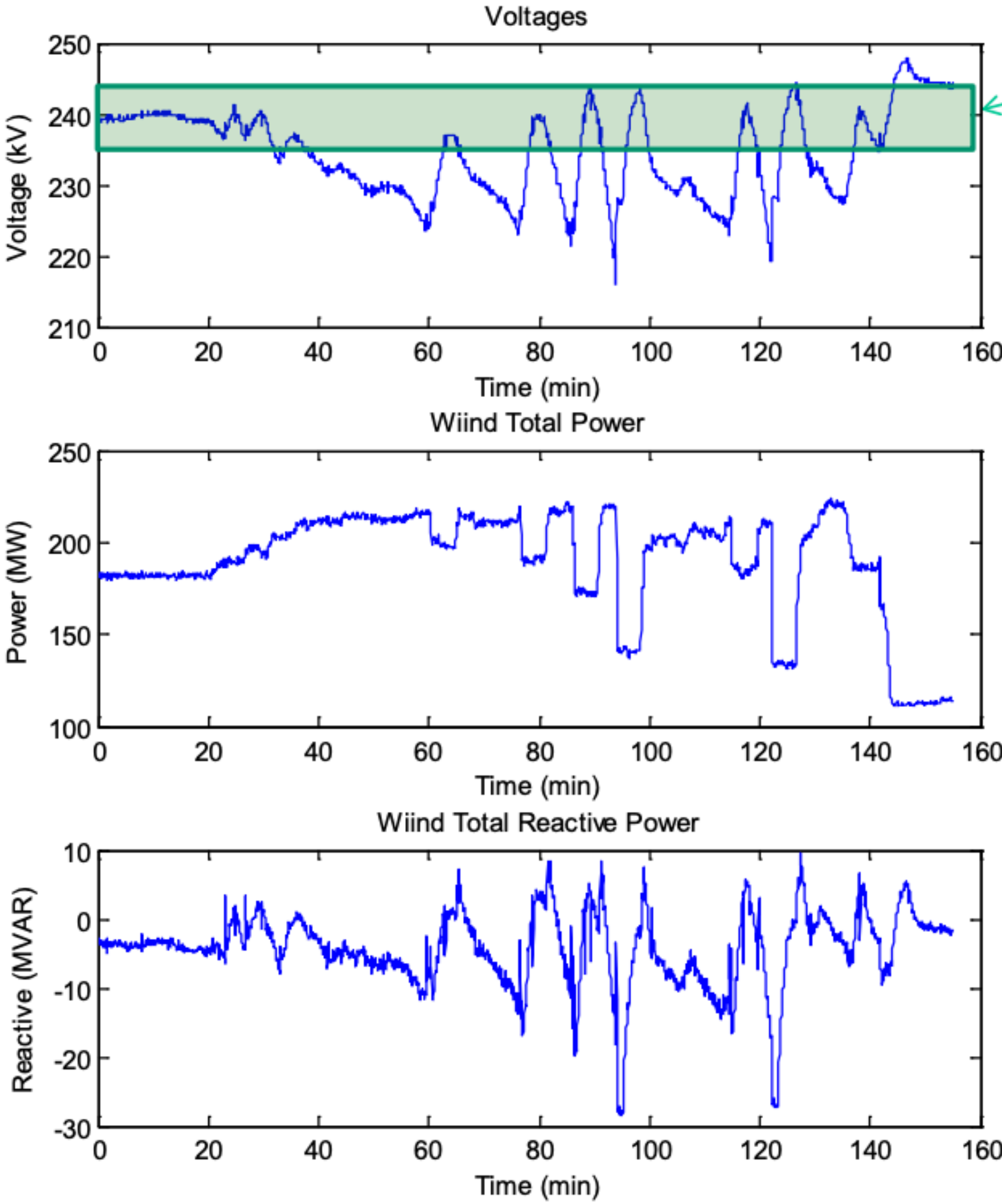
NASPI North American SynchroPhasor Initiative

American Recovery and
Reinvestment Act of 2009

Synchrophasor Technology and Renewables Integration

NASPI Technical Workshop
June 7, 2014

NASPI Synchrophasor Technical Report

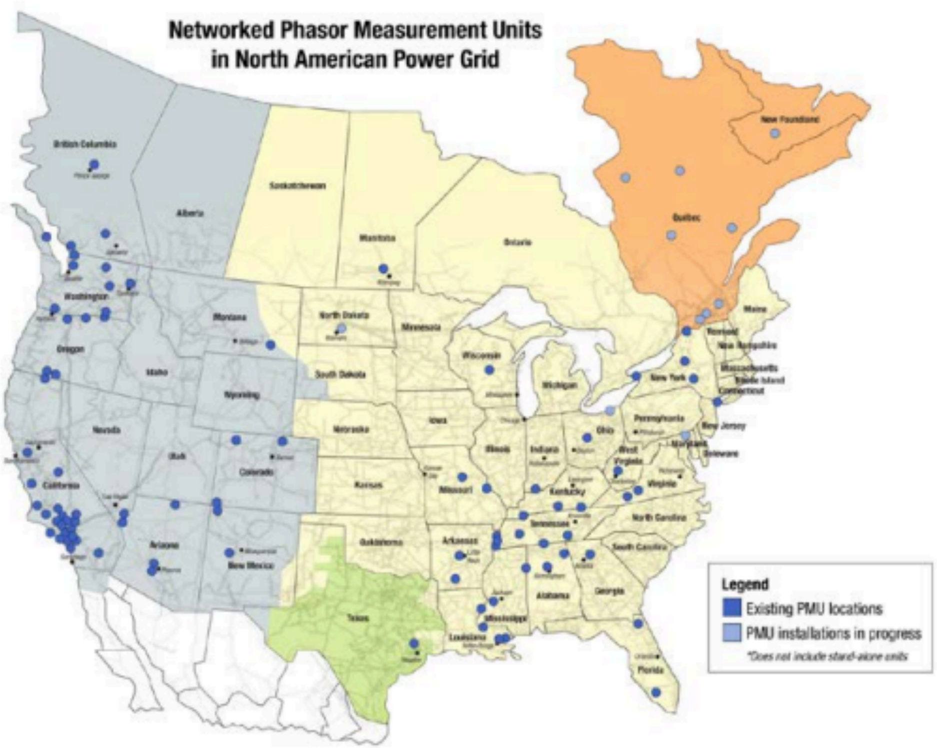


Normal operating range

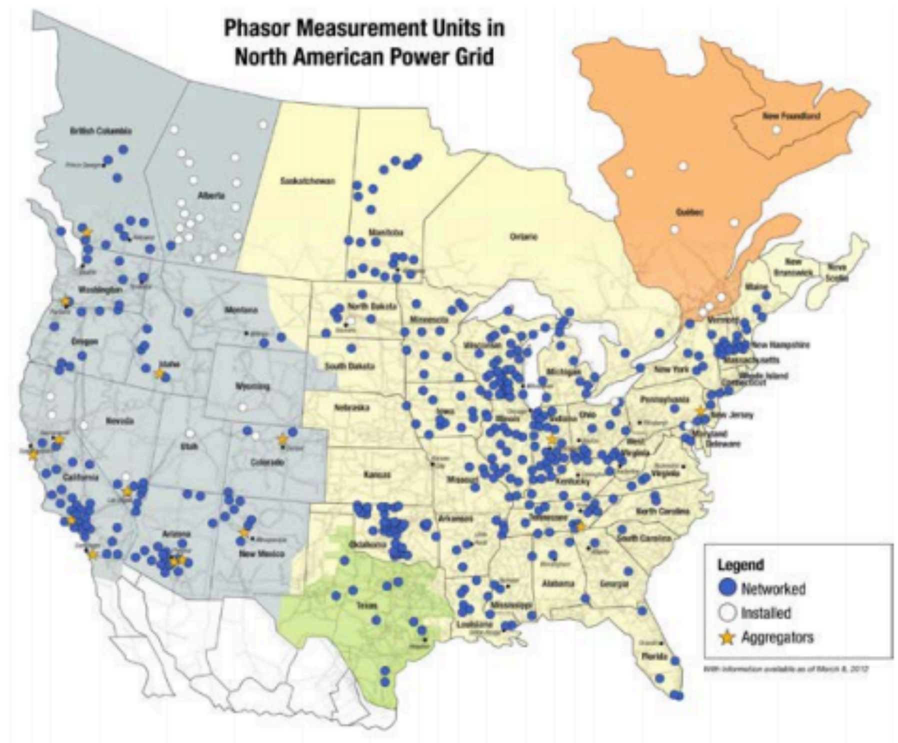
Voltage and power oscillations at a wind hub with type 2 wind power plants and a type 3 plant in power factor mode, December 2010

Phasor Measurement Units added by the Recovery Act

April 2007



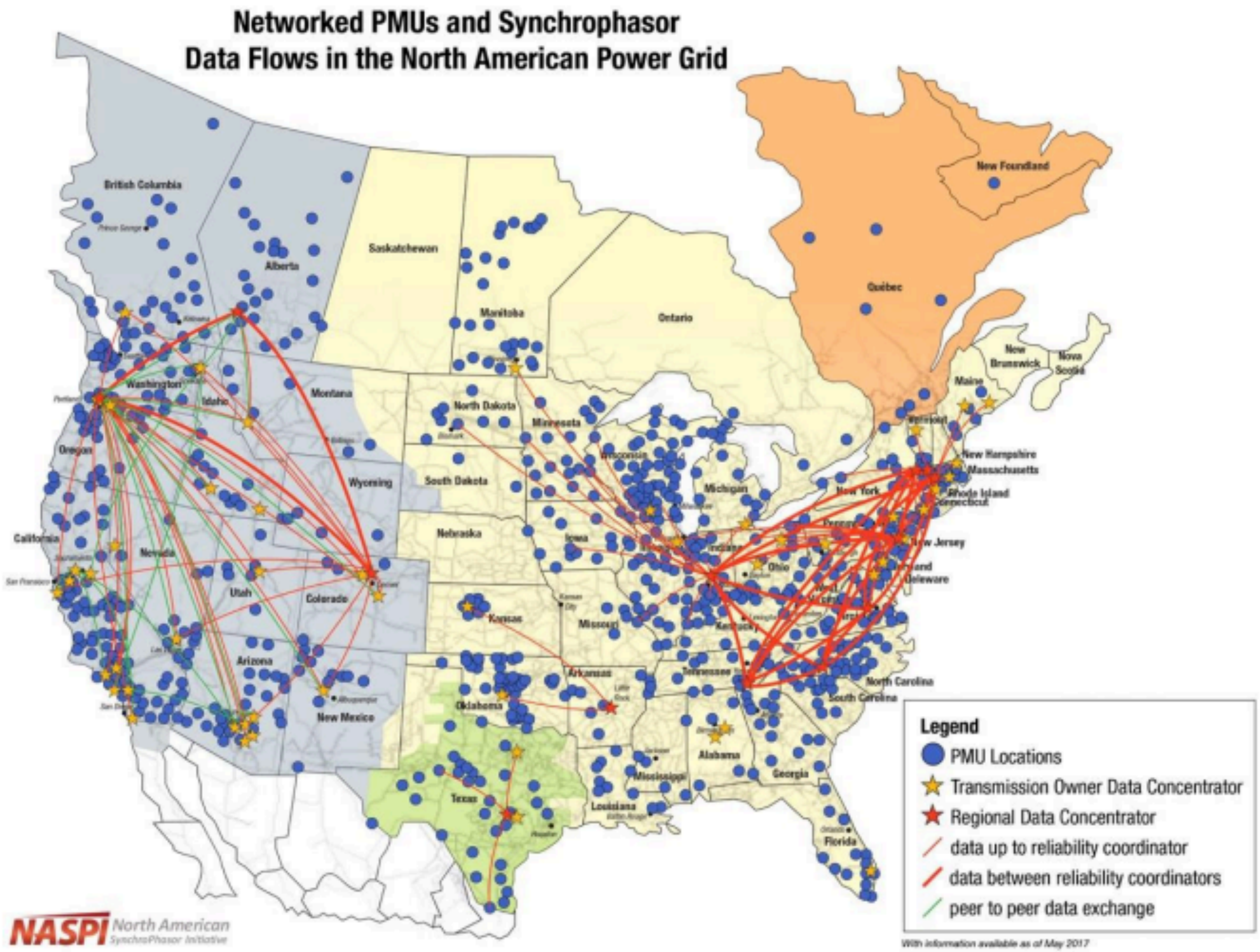
March 2012



Networked PMUs across North America

2017 North America Synchrophasor networks

- Over 2,500 networked PMUS
- Most RCs are receiving and sharing PMU data for real-time wide-area situational awareness



Synchrophasor technology improves grid reliability

- 30-60 samples/second (100 times faster than SCADA) & time-synced, provides real-time situational awareness
- High volumes of highly granular data enable insight into grid conditions
  - Early warning of grid events & dynamic behavior
  - Fast identification of failing equipment and asset problems
  - Better models of equipment, generators and power system
- Redundant, secure operator tools and automated system protection

Current uses for synchrophasor technology

Situational awareness

- Wide-area visualization
- Oscillation detection
- Phase angle monitoring
- Voltage stability monitoring
- Trending
- Event replay
- Alarms and alerts
- Linear state estimation
- Fault location

Off-line analysis

- NERC standard compliance
- Forensic event analysis
- Model validation (equipment, generation, power system)
- Identify equipment problems & mis-operation
- Field equipment commissioning

Loan Guarantee Program (authorized in 2005)

The U.S. government assumes the risk of loan default. The default risk is mostly determined by OMB, and "credit subsidy (loan insurance) is paid to the U.S. Treasury. In the original bill, the loan applicant pays the credit subsidy, and all fossil and nuclear loans are paid by the applicant. In the Recovery Act, $6B of credit subsidy funds was appropriated to cover up to $60 B in loan guaranteees. The insurance against assigned risk of the loan is paid to Treasury. All fossil and nuclear loan "credit subsides" were paid by the loan applicant.

Many successful wind and solar installations were financed by the DOE loan program. In 2011, LPO > $4.6 B to support the first 5 utility-scale solar PV facilities larger than 100 MW. A Financial Institution Partnership Program (FIPP) worked with the DOE and commercial banks (John Hancock, Bank of America, Citigroup).

By 2015 there were over 12,000 MW of solar PV capacity installed at utility scale.

Loan program success

- Ford ($5.9B, final payment due by June, 2022)
- Nissan ($1.45B Leaf manufactured in the U.S.)
- Tesla ($465 M)

Loan program failures

- Solyndra ($535M loss), Abound ($68M loss)
- Fisker ($138 M), VPG ($45 M)

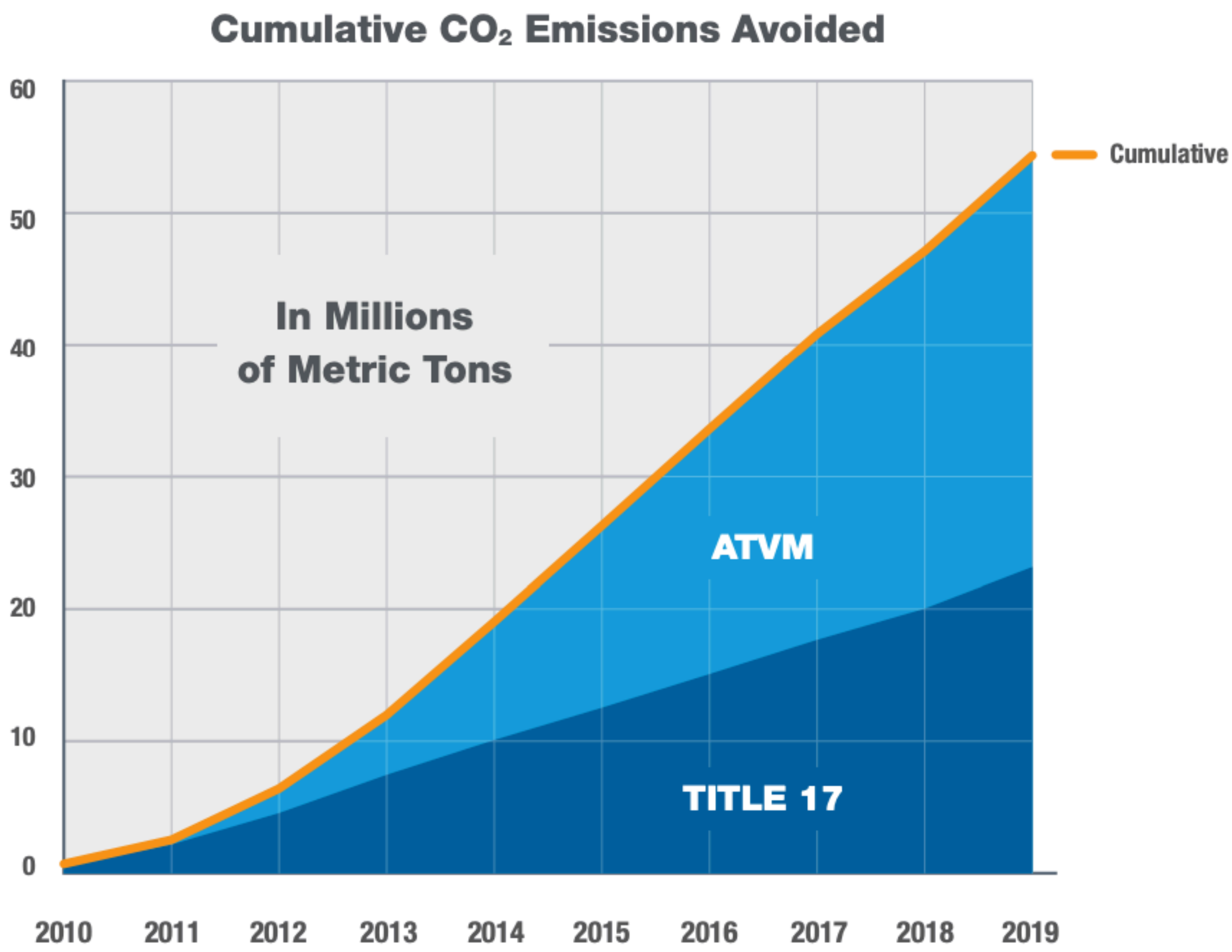
LPO Portfolio Performance Summary as of March 31, 2020

Loan and Loan Guarantees Issued	$35.69 billion
Conditional Commitments	$2.00 billion
Amount Disbursed	$28.66 billion
Principal Repaid	$10.90 billion
Interest Paid*	$3.01 billion
Actual and Estimated Losses	$0.79 billion
Losses as % of Total Disbursement	2.74%

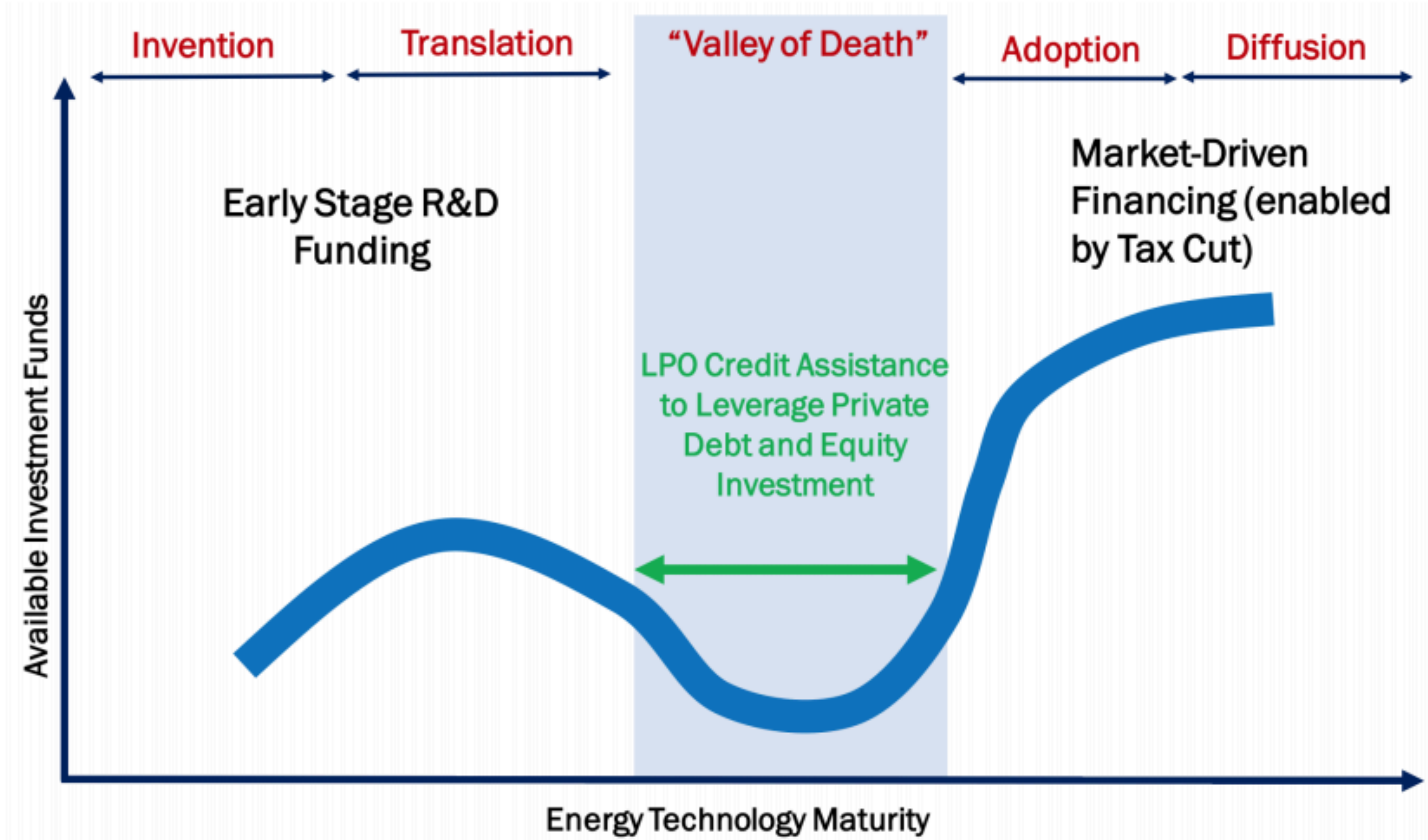
* Calculated without respect to Treasury's borrowing cost.

Biggest current risk: Off-take agreements of wind and solar projects with Pacific Gas & Electric (PG&E) and Southern California Edison (SCE).

LPO Portfolio Climate Impact



LPO Bridges the Financing Gap in the Technology Innovation Process



Source: "Leveraging the DOE Loan Program." ENERGY FUTURES INITIATIVE

Table 2.

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TABLE 1. OVERVIEW OF BENEFITS FROM THE WEATHERIZATION PROGRAM		
SUMMARY OF BENEFITS	**RETROSPECTIVE (2008)**	**RECOVERY ACT (2010)**
Program Wide Benefits for All Housing Types		
Total Homes Weatherized	97,965	340,158
Average Cost per Weatherized Home	Total Cost: $4,695/DOE Investment: $2,301	Total Cost: $6,812/DOE Investment: $5,926
Average Energy Measure Costs	$2,899	$3,545
Savings Per Household (Present Value)	$4,243	$3,190
Energy Savings (Present Value)	$340 million	$1.1 billion
Total Benefits including Health & Safety (Present Value)	$13,550	$13,167
Savings-to-Investment Ratio (SIR)	1.4[i] Energy Benefits	0.9[i] Energy Benefits
Jobs Supported	8,500	28,000
Carbon Reduction	2,246,000 metric tons	7,382,000 metric tons

Calculated Savings to Investment Ratio (SIR) in an Oak Ridge National Lab (ORNL) study assumes escalating energy prices, a weighted average lifetime for installed measures of about 20 years, and **a discount rate of 2.7%.**

The ORNL study shows that when you add in the costs and the benefits for the health and safety (or non-energy) measures, that the total SIR increase from 1.4 to 4

“Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program, Meredith L. Fowlie, Michael Greenstone, Catherine Wolfram, Quarterly Journal of Economics (2018), 1597–1644. doi:10.1093/qje/qjy005.

The enrollment phase, which lasted through February 2012.

- 9,000 personal phone calls and 2,720 home visits
- Field staff helped individuals assemble documentation and complete paperwork. In some cases, field staff provided transportation to and from the program agency offices.
- In total, the encouragement and enrollment efforts cost approximately $450,000, which amounts to $50 per targeted household and over $1,000 per weatherized household.

Footnote: “On the one hand, our encouragement costs may have been higher than necessary. To our knowledge, ours was the first encouragement program for WAP, and we learned from our initial experiences how to refine our intervention. On the other hand, the costs in Table I do not reflect the time the research team devoted to overseeing the encouragement effort.”

"Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program, Meredith L. Fowlie, Michael Greenstone, Catherine Wolfram, Quarterly Journal of Economics (2018), 1597–1644. doi:10.1093/qje/qjy005.

TABLE VII

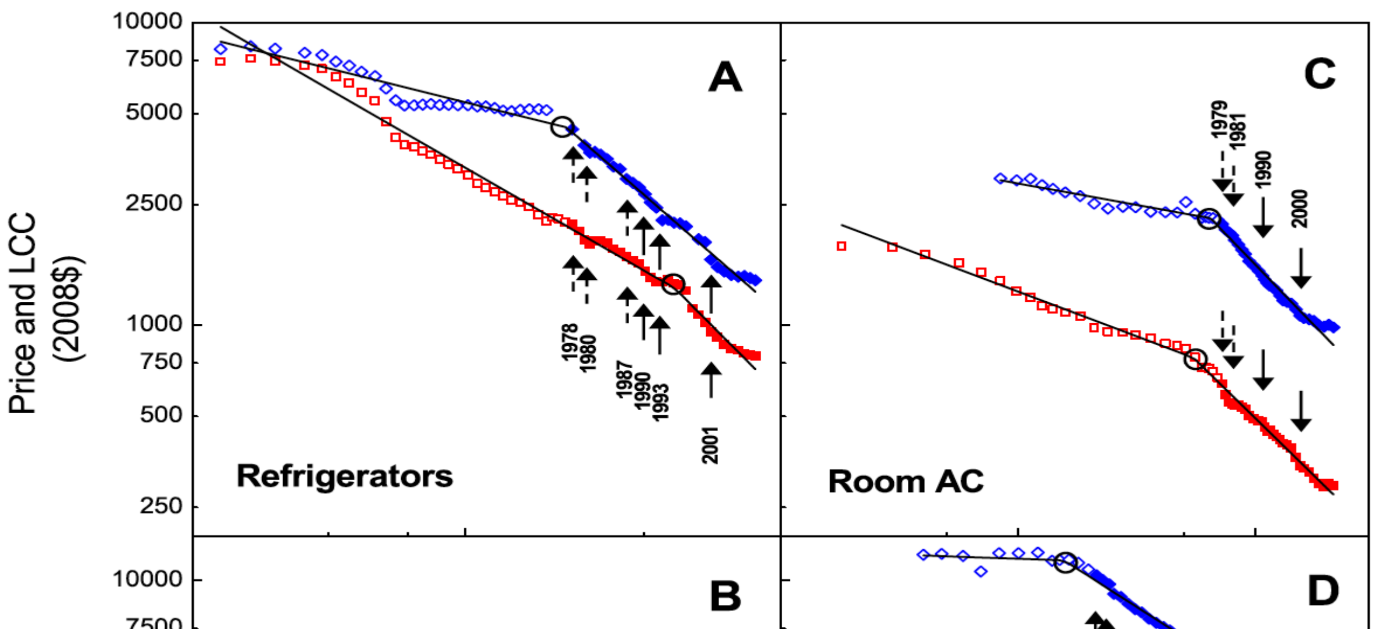
ESTIMATED RETURNS ON INVESTMENTS IN ENERGY EFFICIENCY

Time horizon	Ex ante (NEAT) projections (1)	Empirical estimates (2)
Panel A: Private internal rate of return		
10 years	7.0%	–10.6%
16 years	11.9%	–2.3%
20 years	13.0%	0.21%
Panel B: Private internal rate of return, adding the avoided emissions damages		
10 years	11.4%	–7.6%
16 years	15.5%	0.1%
20 years	16.4%	2.3%
Panel C: Social internal rate of return		
10 years	–3.9%	–17.8%
16 years	3.1%	–7.8%
20 years	5.0%	–4.6%
Panel D: CO_2 abatement cost, 3% discount (\$/ton CO_2)		
10 years	\$85	\$322
16 years	\$38	\$201
20 years	\$22	\$161
Panel E: CO_2 abatement cost, 7% discount (\$/ton CO_2)		
10 years	\$117	\$404
16 years	\$71	\$285
20 years	\$56	\$248

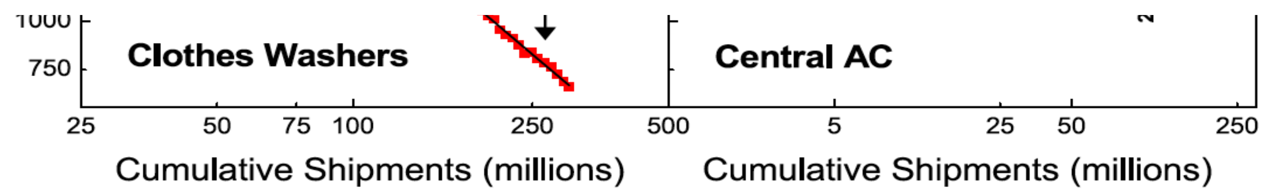
Appliance standards have also been a frequent target of some free-market economists.

The effect of appliance standards on total cost and purchase price

R. van Buskirk, C. Kantner, B. Gerke and S. Chu, Environ. Res. Lett. 9 114010 (2014)



Refrigerator cost declines by 28% for each doubling of production. Energy saved in the U.S. each year is more than 270 TWh = 30 nuclear reactors operating at 1 GW 24 hours a day, 365 days a year.

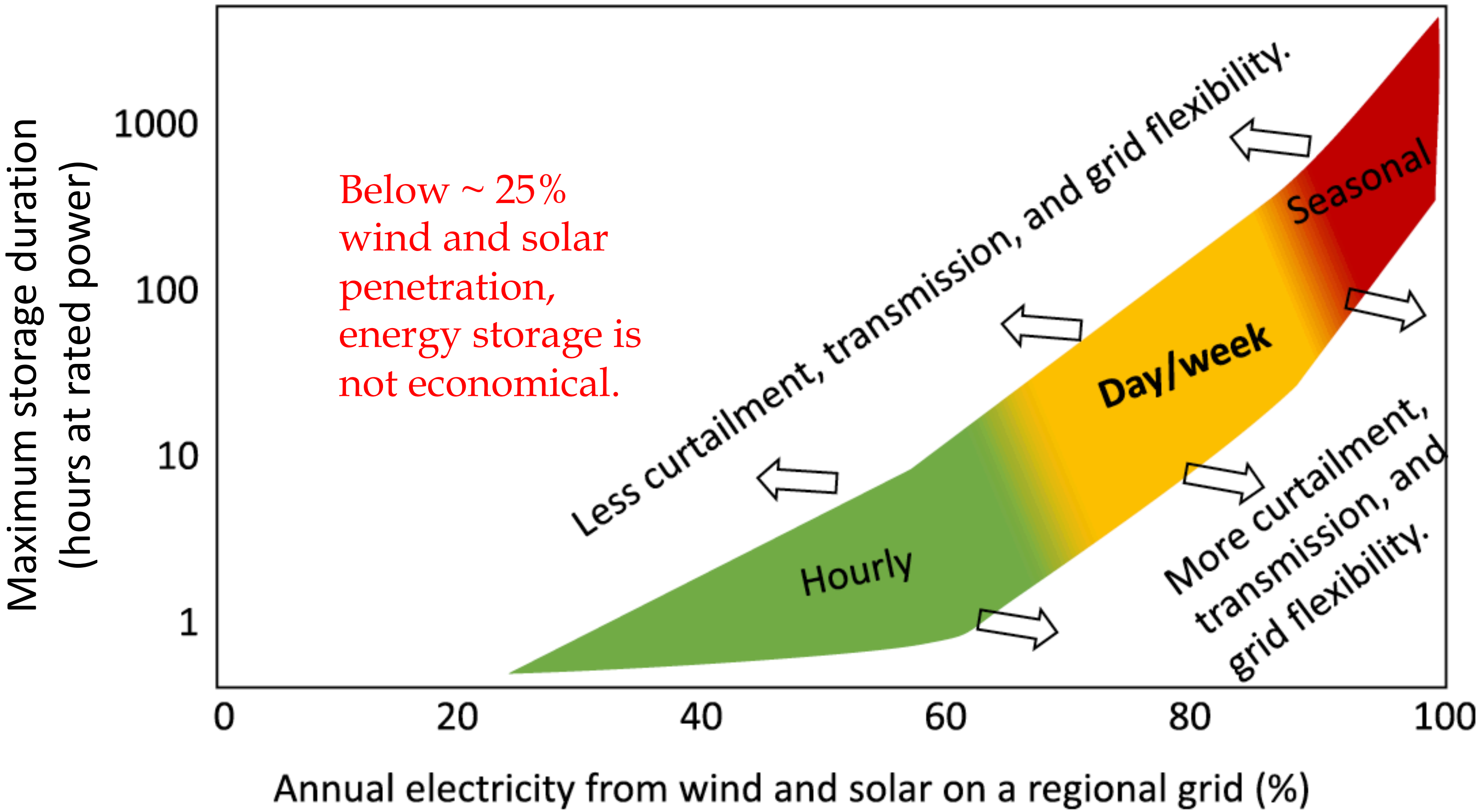


Clean electricity at 1.5¢/kWh may become a reality in 10-20 years at the best sites in the world.

This opens up new opportunities in energy storage and electrochemistry.

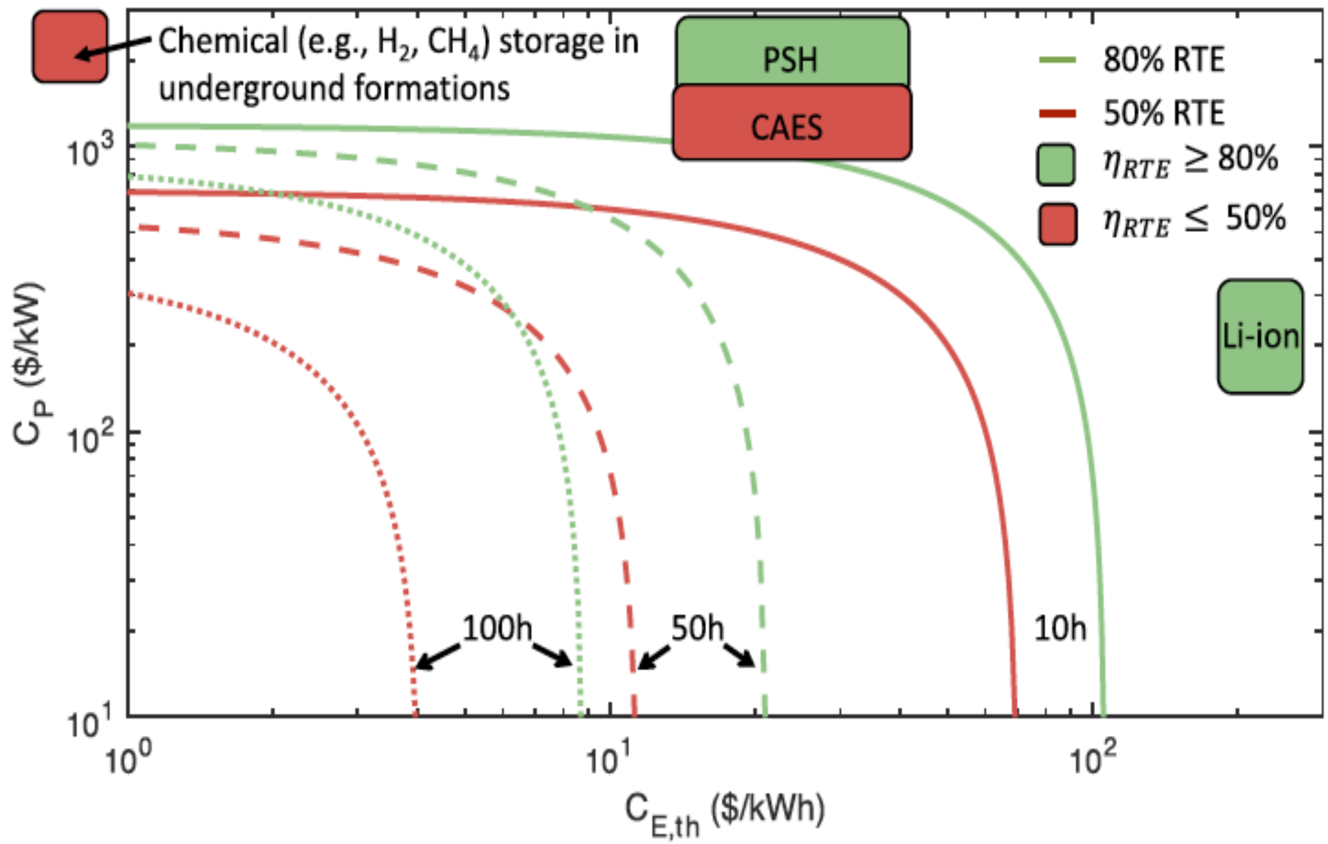
"Semi-quantitative summary of the maximum duration storage vs. fraction of variable renewable energy generation for the U.S."

"Long-Duration Electricity Storage Applications, Economics, and Technologies," Paul Albertus, Joseph Manser, Scott Litzelman, Joule **4**, 21 - 32 (2020)



Former APRA-E program managers for the DAYS program

Power and Energy Capital Costs assuming $R_P = 25\$/kWh$

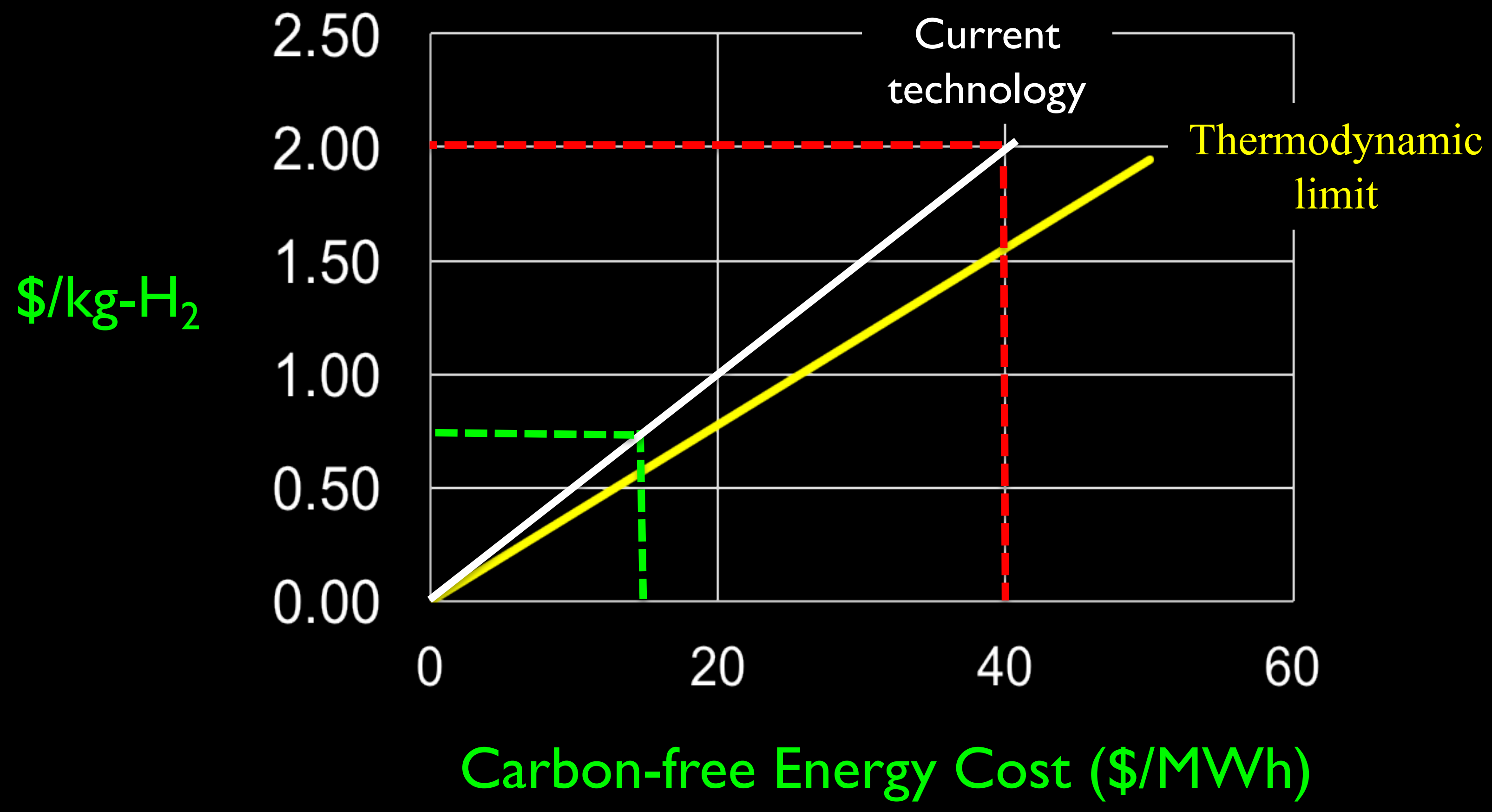


Natural gas stored in the US in below-ground storage and pipelines (4×10^{12} cubic feet = 1,200 TWh = 2-month supply of US electricity)

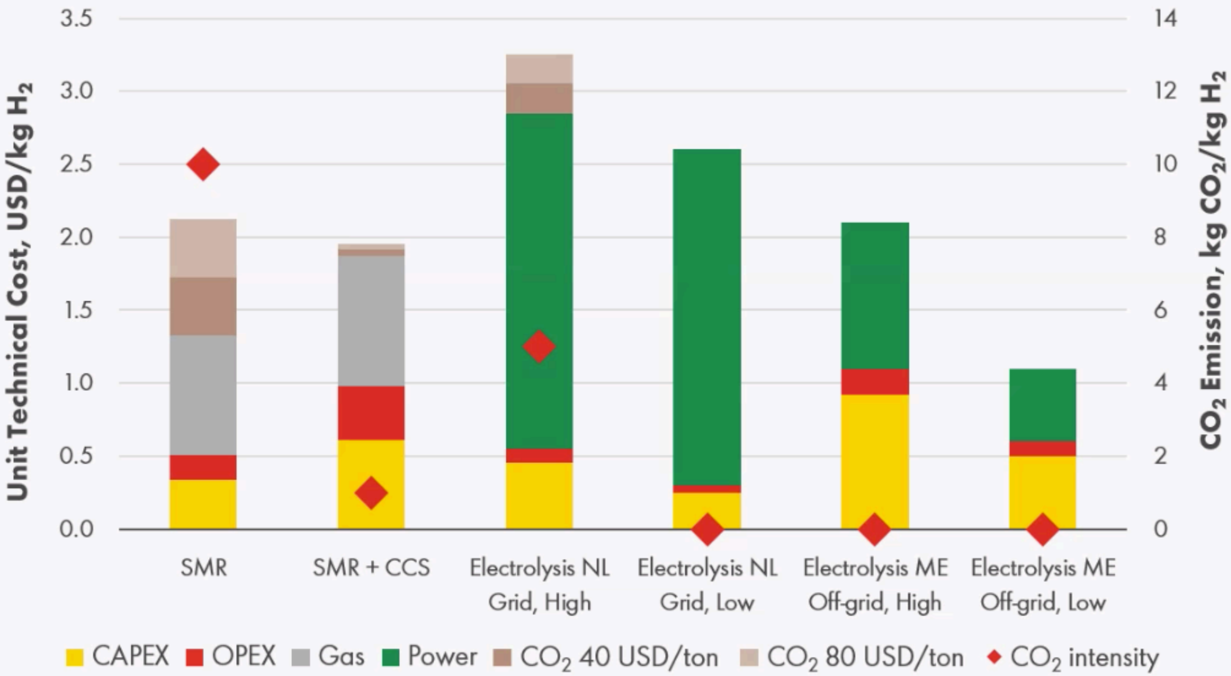
Thermodynamics & Cost Limits

$H_20 = H_2 + ½ O_2$; $\Delta G = 237.2$ kJ/mol = 32.4 kWh/kg-H_2

At 1.5 ¢ / kWh, the energy cost is only half the cost of producing H_2.



Unit Technical Cost of H_2 after 2030



Key assumptions:

- Large scale H_2 production
- Steam Methane Reforming (+CCS):
  - Natural gas price is 5 USD/MMBtu
- Electrolysis the Netherlands Grid:
  - Power price is 5 cent/kWh in both cases
  - Electrolyzer capacity factor = 100%
  - High case: 70% green power (2030 target); Electrolyzer CAPEX 750 USD/kW
  - Low case: 100% green power (2030+ target); Electrolyzer CAPEX 250 USD/kW
- Electrolysis Middle East Off-grid:
  - Powered by solar PV under a PPA
  - Electrolyzer capacity factor = 50%
  - High case: Power price is 2 cent/kWh (2030); Electrolyzer CAPEX 750 USD/kW
  - Low case: Power price is 1 cent/kWh (2050); Electrolyzer CAPEX 250 USD/kW

Source: IEA, McKinsey

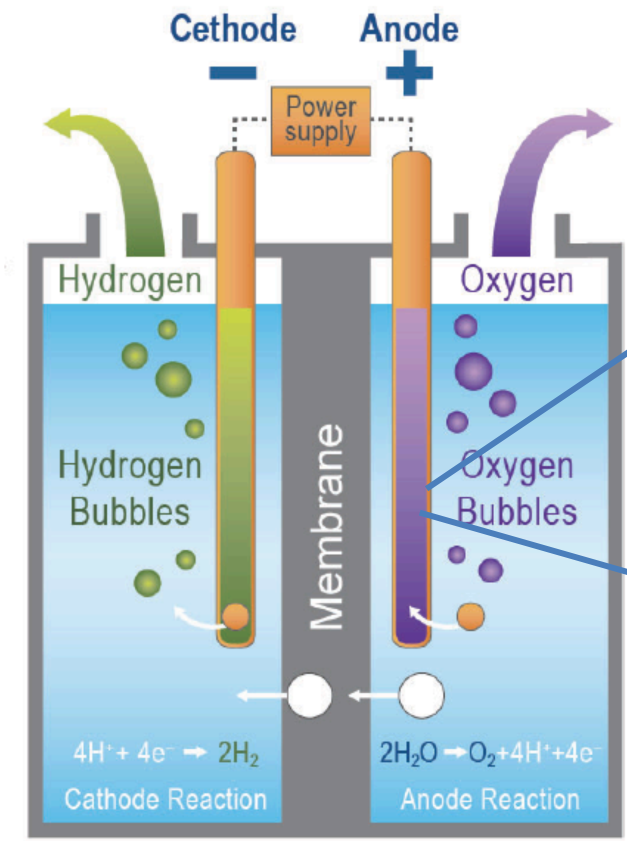
Electrolysis of water

Cathode (reduction): H_2O (liq.) + $2e^- \rightarrow H_2$ (gas)+ 2 OH^-(aq)

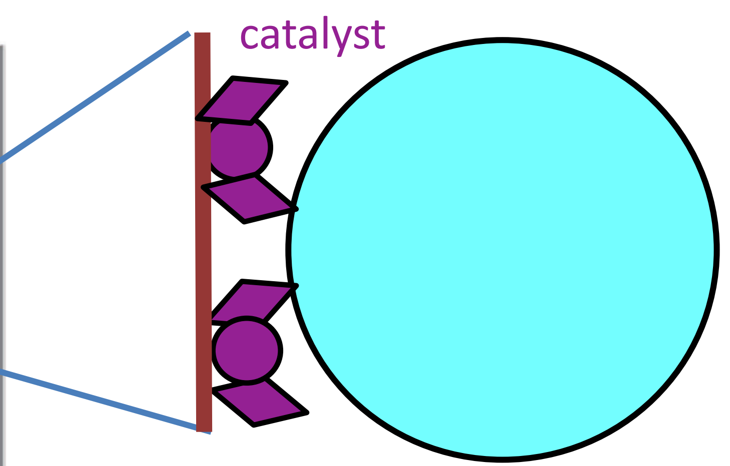
Anode (oxidation): 2 OH^-(aq) $\rightarrow$ ½ O_2 (gas) + H_2O (liq.) +$2e^-$

Anode (oxidation): 2 H_2O (liq.) $\rightarrow O_2$ (gas)+ 4 H^+(aq) + $4e^-$

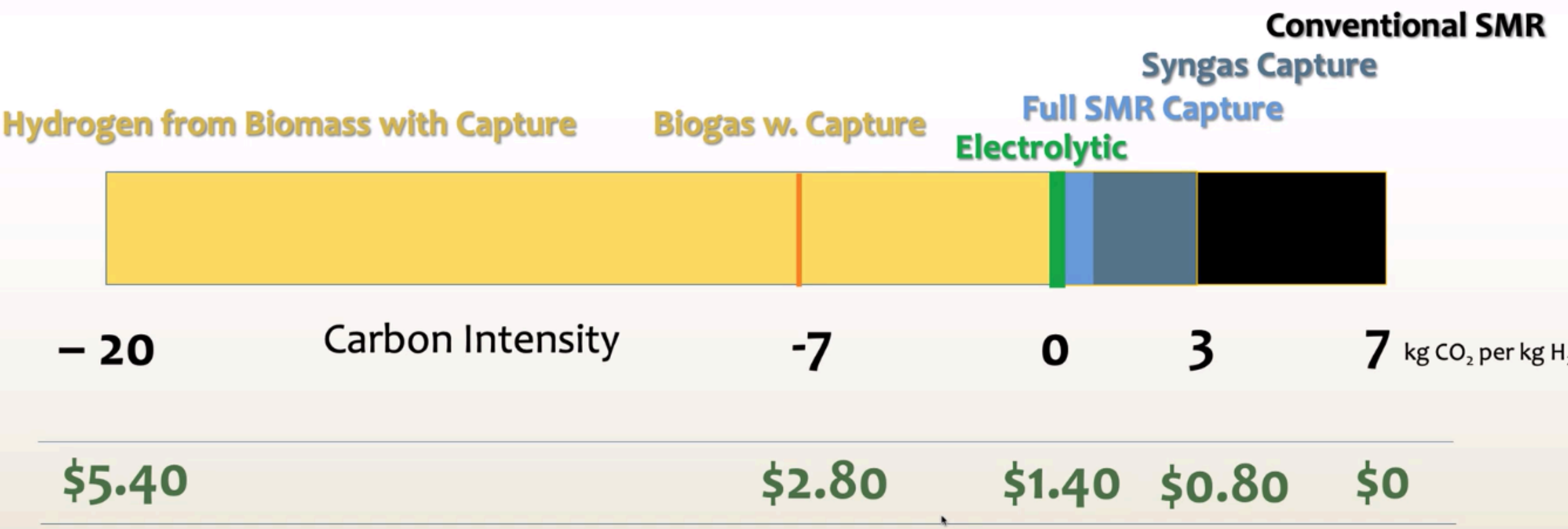
Cathode (reduction): 2 H^+ (liq) + $2e^- \rightarrow H_2$ (gas)



The catalytic threshold ~ 1.4 volts,
Current electrolyzers run at ~ 2.2 volts

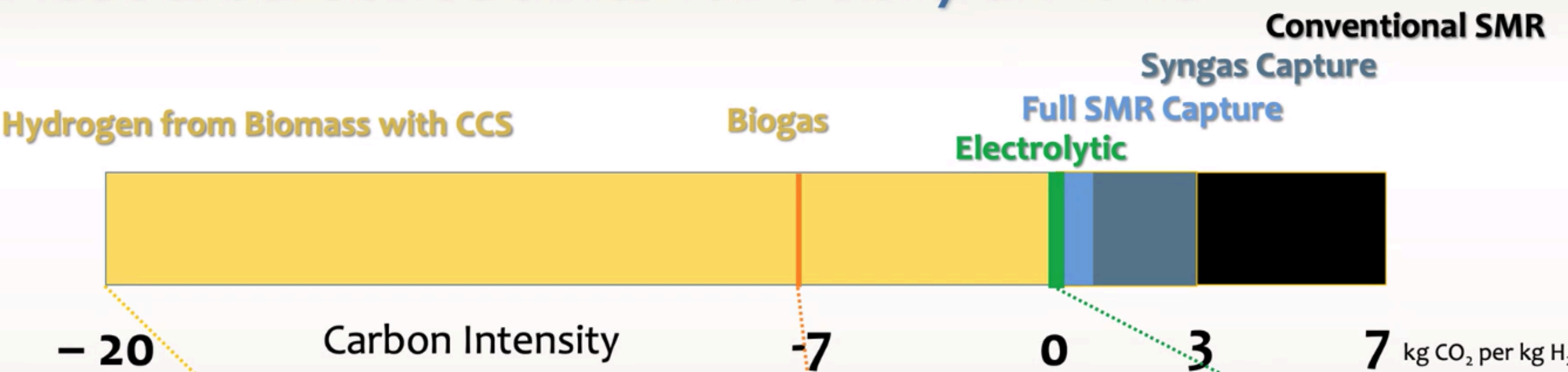


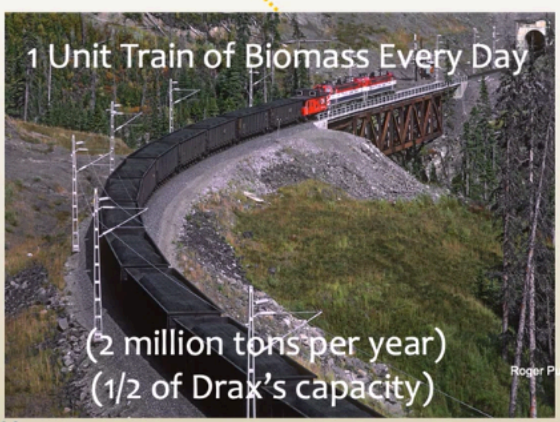
Low Carbon Fuel Standard Value

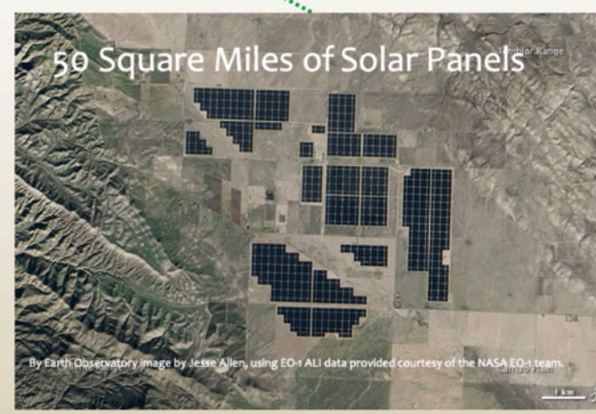


Today's LCFS value
Per kg H_2

Resource Constraints for 500 t/d Plant

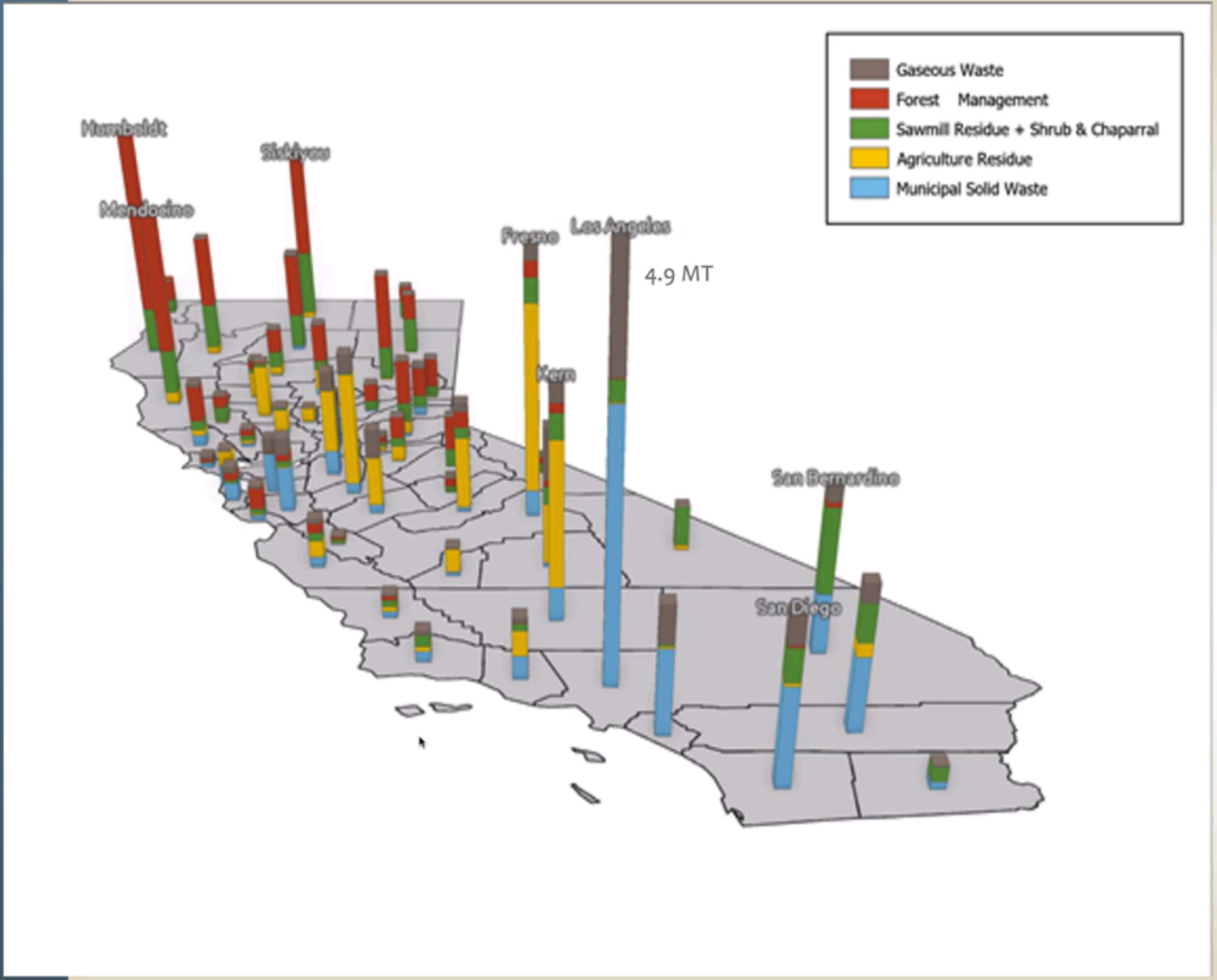




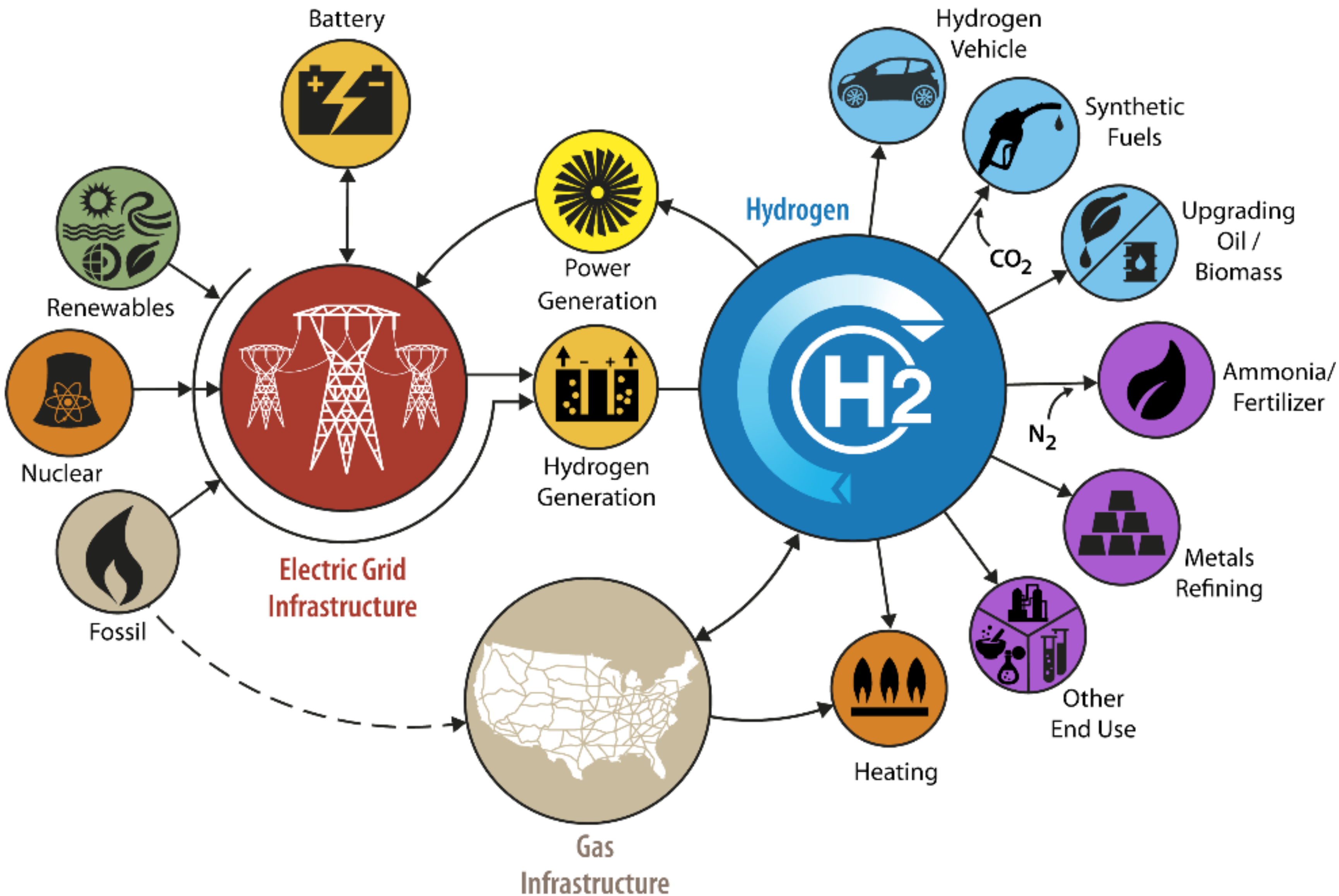


Waste biomass is broadly distributed in California

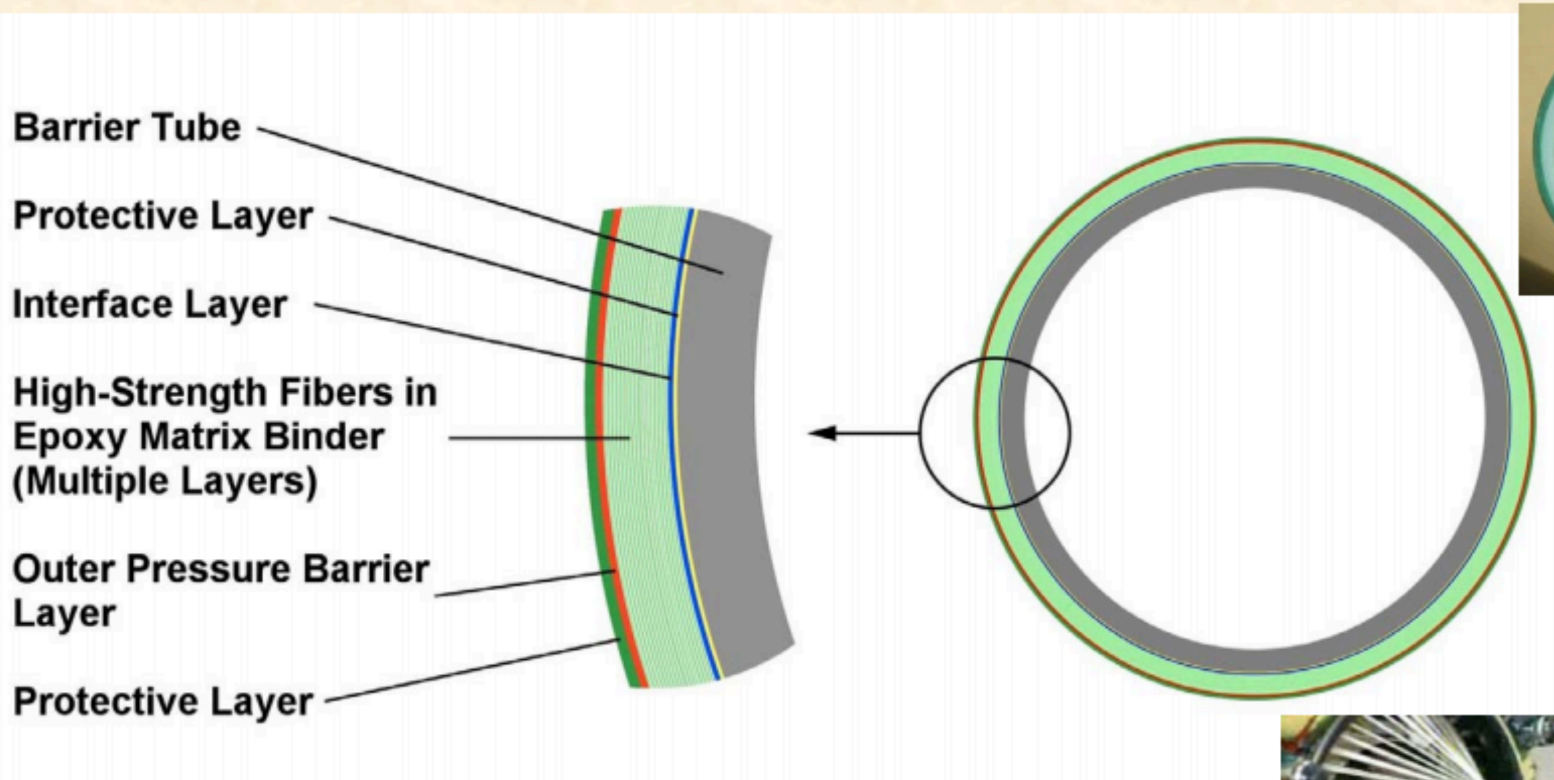
- 58 million bone-dry tons will be available from waste sources
- 25 million tons are wood
- 100% conversion to CO_2 would yield 106 MT CO_2
- Only waste biomass considered – *no energy crops*



For widespread use of hydrogen for transportation or heating a pipeline distribution system will be needed



Fiber-Reinforced Polymer (FRP) Pipeline Architecture



Inner thermoplastic pressure barrier is reinforced by helical windings of high-strength glass fiber yarns embedded in an epoxy thermoset resin matrix.

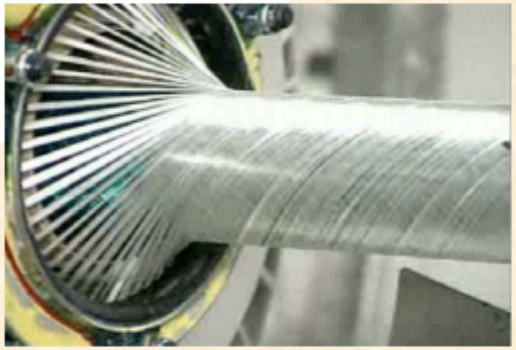


Photo provided by Fiberspar LinePipe, LLC

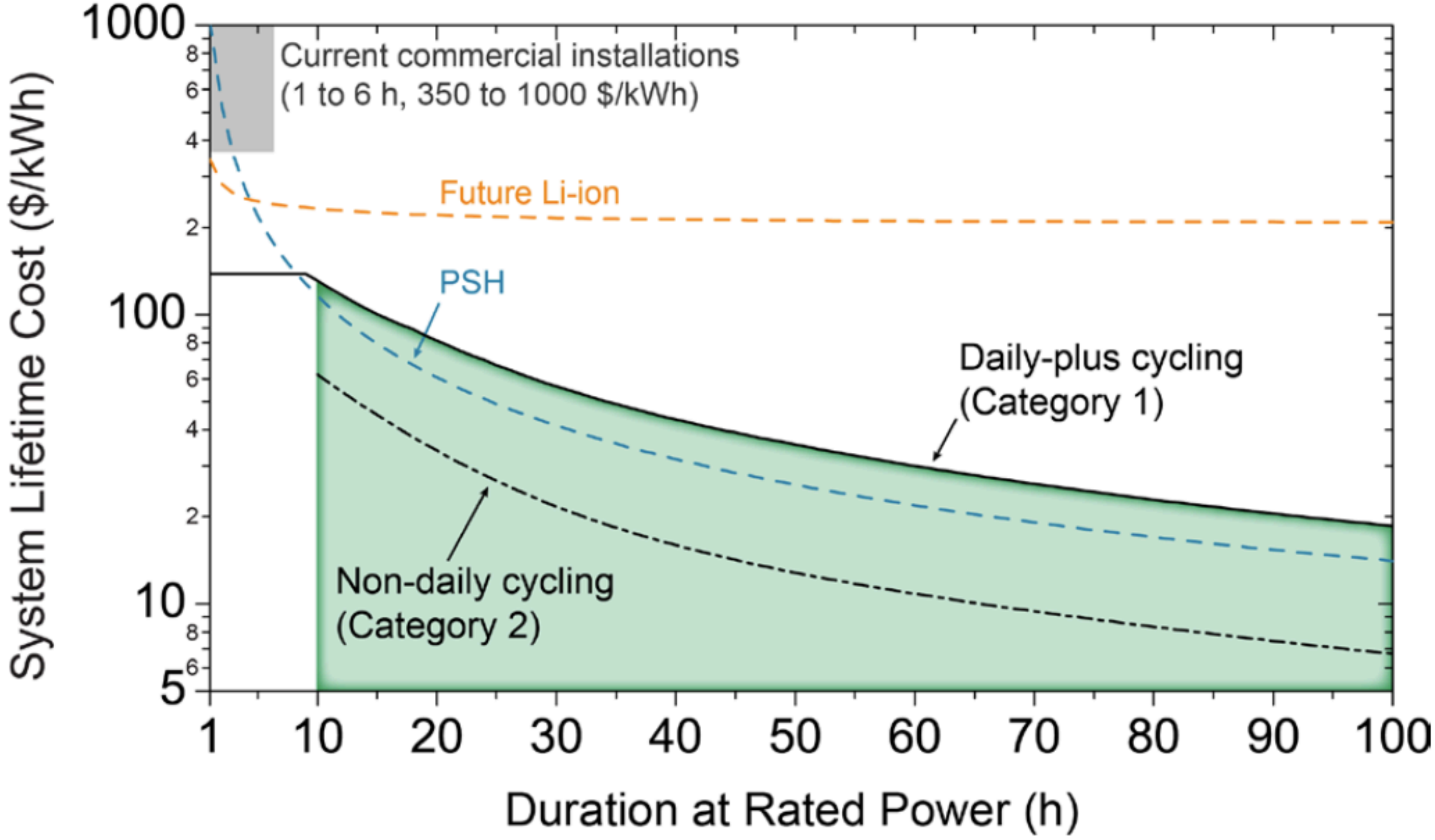
Capital cost estimation for FRP hydrogen transmission pipelines

- Today's cost for 4.5-inch ID, 1500 psi-rated FRP pipeline (pipeline, connectors, transportation, installation) is approximately $80k per mile

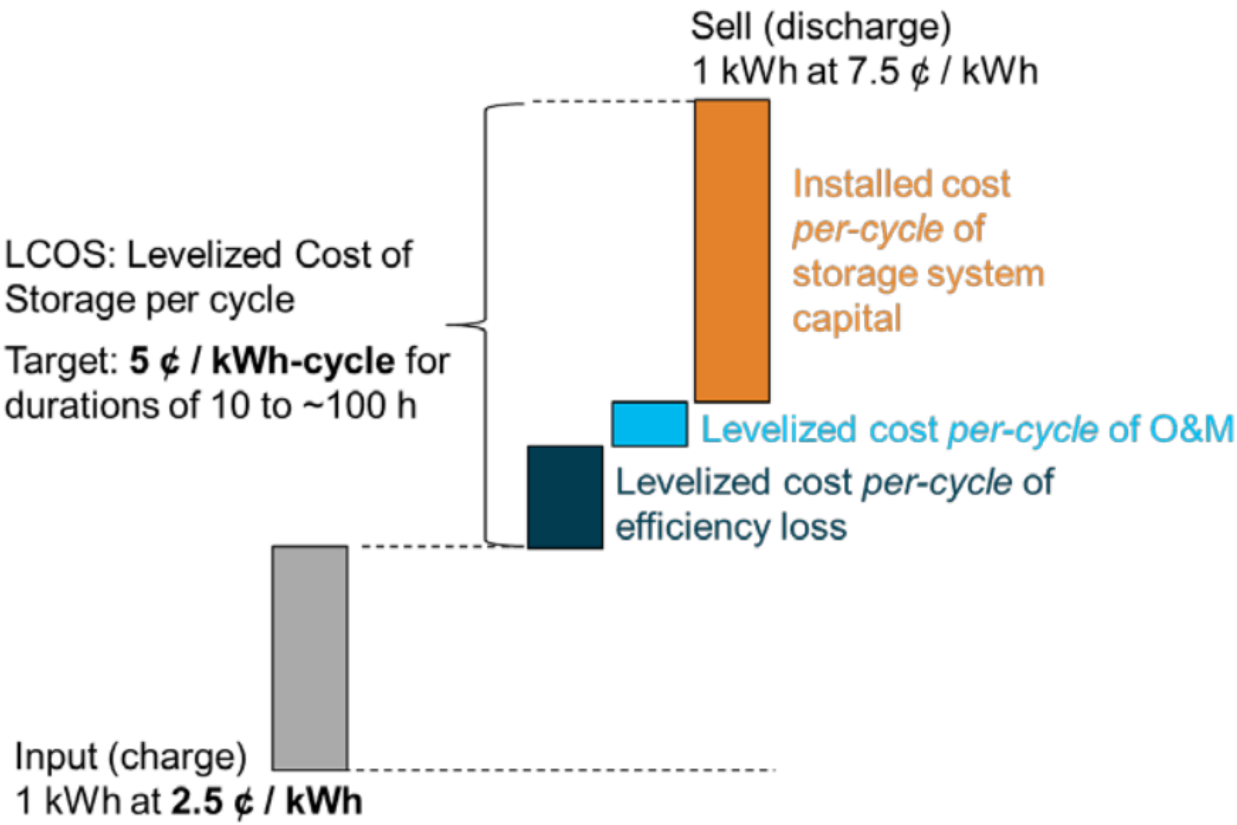
- Installation of four 4.5-inch ID pipelines would require investment of approximately $331k to $346k per mile, excluding ROW and permitting costs.

City Size	FRP Pipelines Installed ($k/mi)	Est'd ROW & Permitting ($k/mi)	Total Capital Investment ($k/mi)	2017 Cost Target ($k/mi)	16-inch ID Steel Pipeline ($k/mi)
200,000	331 – 346	250	581 – 596	490	636

Duration Addition to electricitY Storage (DAYS) Overview



Duration Addition to electricitY Storage (DAYS)

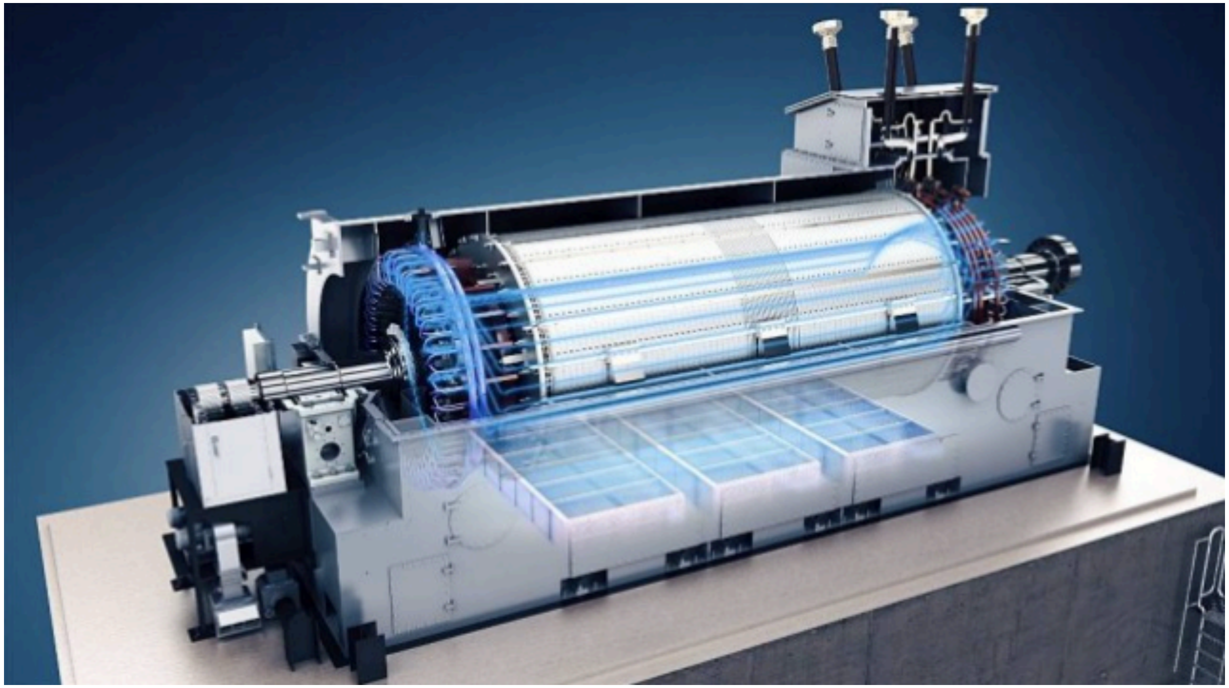


LCOS cost (0.05 $/kWh-cycle) assumed 50% of renewable energy is directly used and 50% is cycled through the storage system. This price is competitive with electricity generated by future combined cycle natural gas plants (which are in the range of 0.041 to 0.074 $/kWh).

With 90% flowing through the storage asset, the combined LCOE would still be competitive at 0.07 $/kWh.

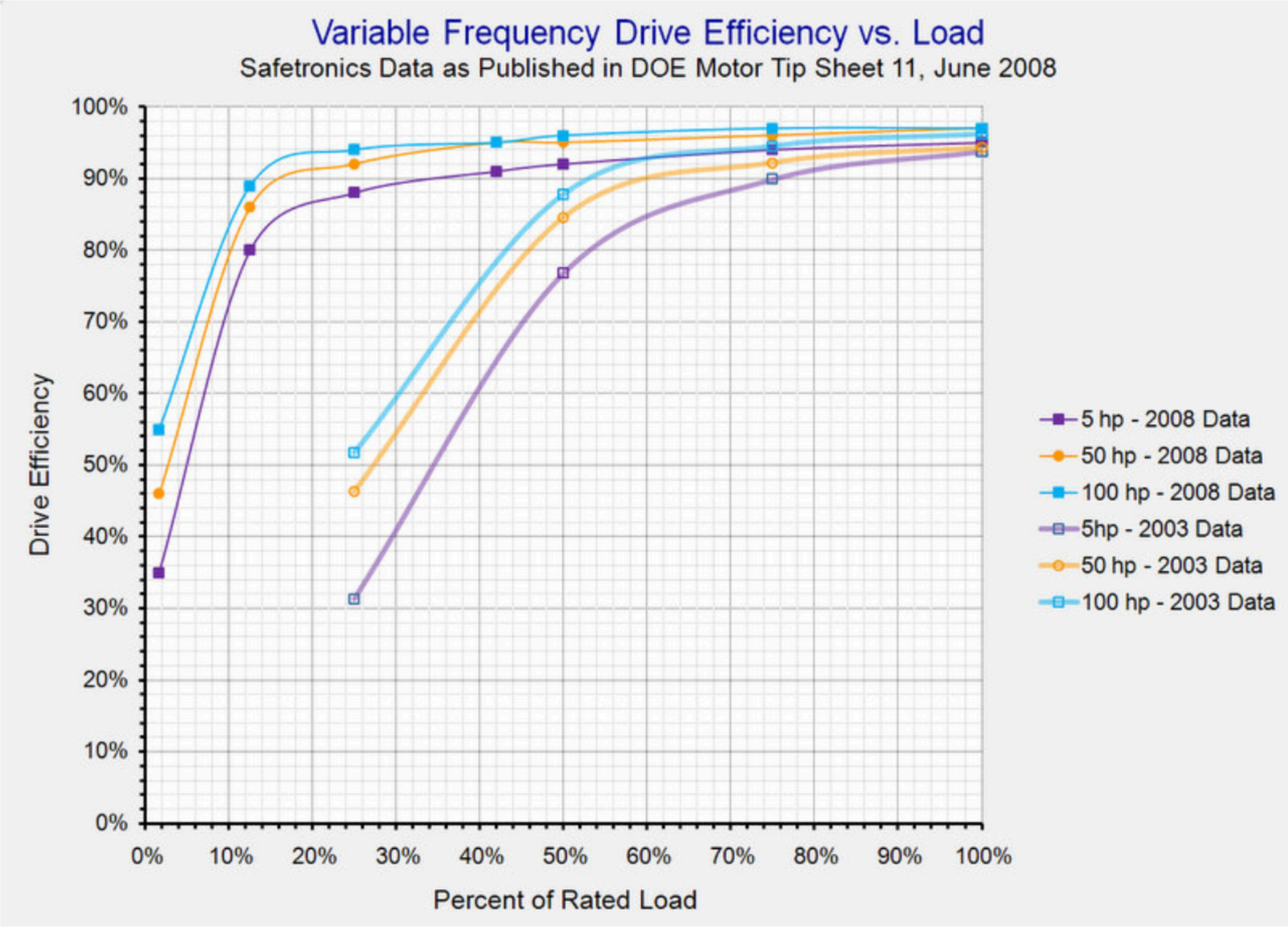
Conversion of electrical energy directly into heat is 100% energy efficient but creates unnecessary entropy. The measure of energy that is useful for conversion into mechanical work is defined by the "exergy" of the thermodynamic system.

The goal is to minimize the creation on unnecessary entropy. The conversion of electricity to mechanical motion/work, $W = \vec{\boldsymbol{F}} \cdot \Delta\vec{x}$, can be ~ 99% efficient.



S-Gen 2000P Air-pressurized cooling replaces hydrogen cooled generators

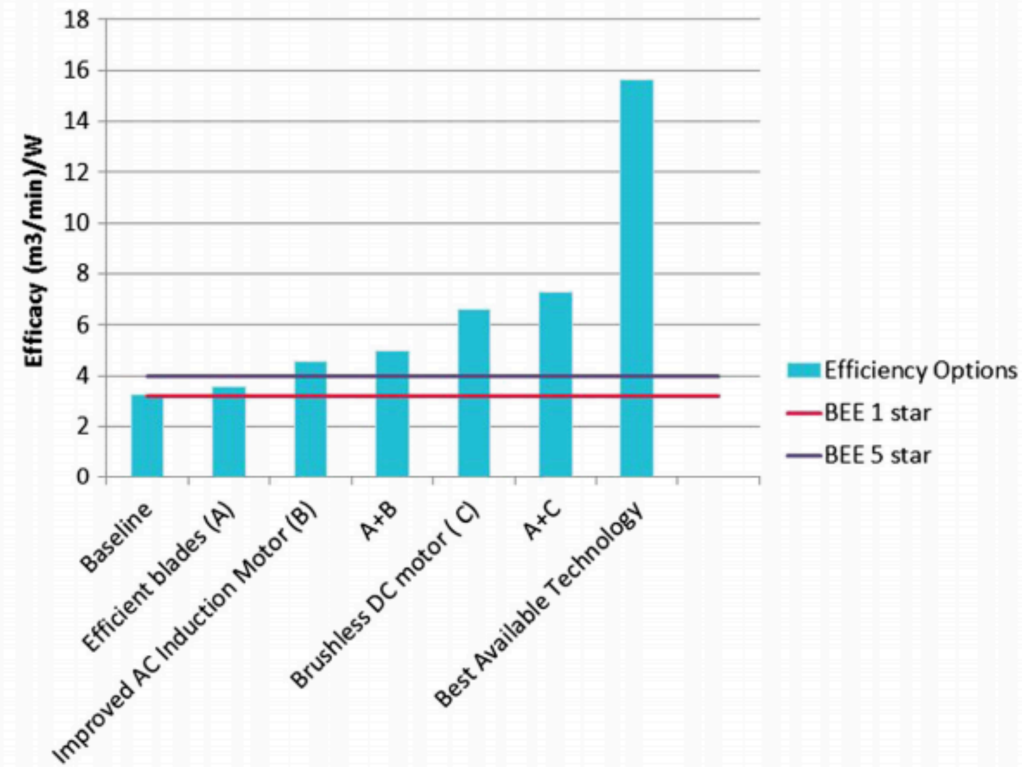
Variable frequency drives increase the range where they are energy efficient. The downside of high-power variable speed motors is the reliability of power electronics



Many inexpensive AC induction motors are < 50% efficient.

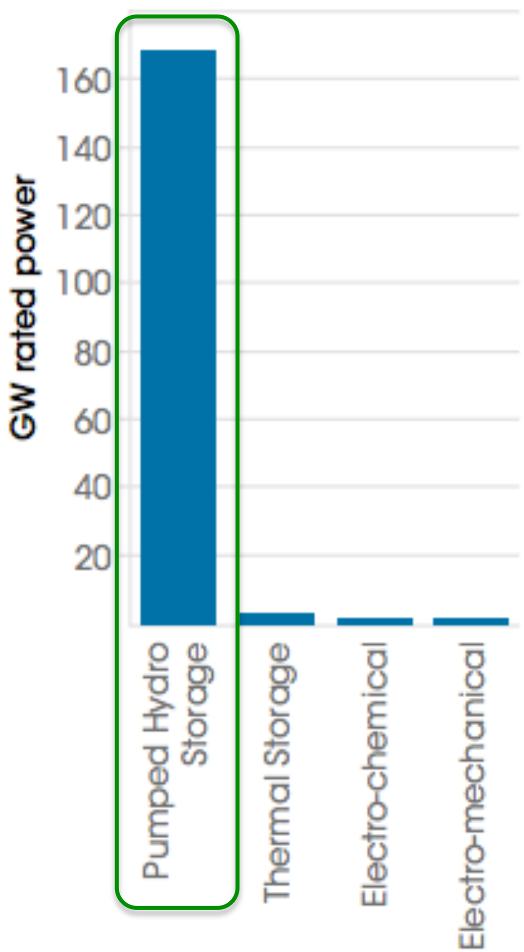
Source: "Efficiency improvement opportunities for ceiling fans," Nihar et al., Energy Efficiency (2015) 8:37–50 DOI 10.1007/s12053-014-9274-6.

While Secretary of Energy, we commissions a study on fan efficiency and worked with India to establish ceiling fan efficiency standards (~ 6% of electricity consumption in India in 2000).



Efficiency Improvement Option	India		USA		Average ($)
	Prayas Energy Group (2012)		Chiang (2010)	Parker and Hibbs (2010)	
	Low	High			
Improved AC induction motor	$1.09	$1.82			$1.5
BLDC motor	$5.45	$10.91	$3.2–$22.5		$10.5
Efficient blades	$1.09			$6.00	$3.5

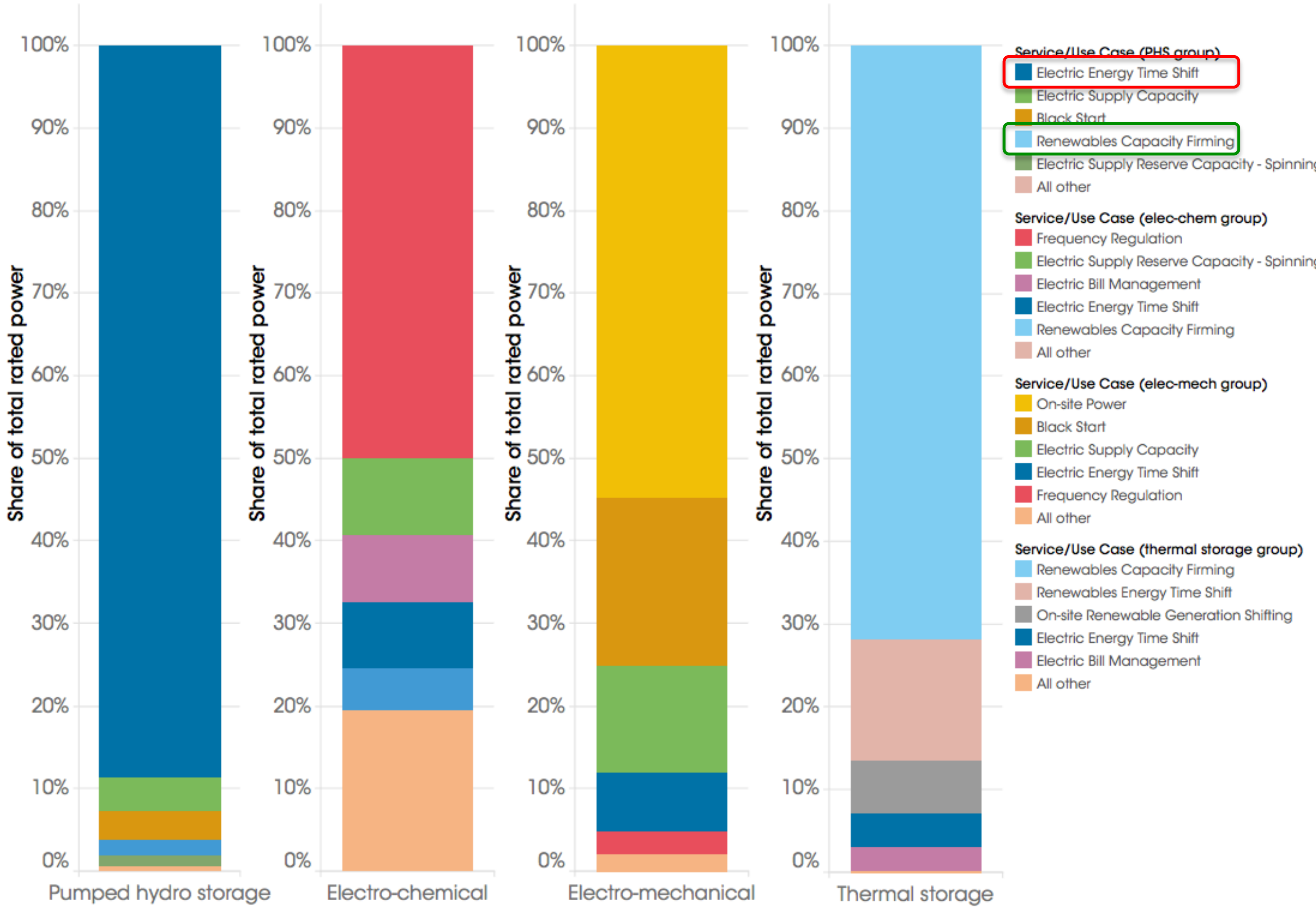
Global operational electricity storage power capacity by technology, mid-2017 (IRENA 2017 Report of Energy Storage)



96% of energy storage world-wide is pumped-storage in 2017. Round-trip efficiencies 70% - 85% efficient.

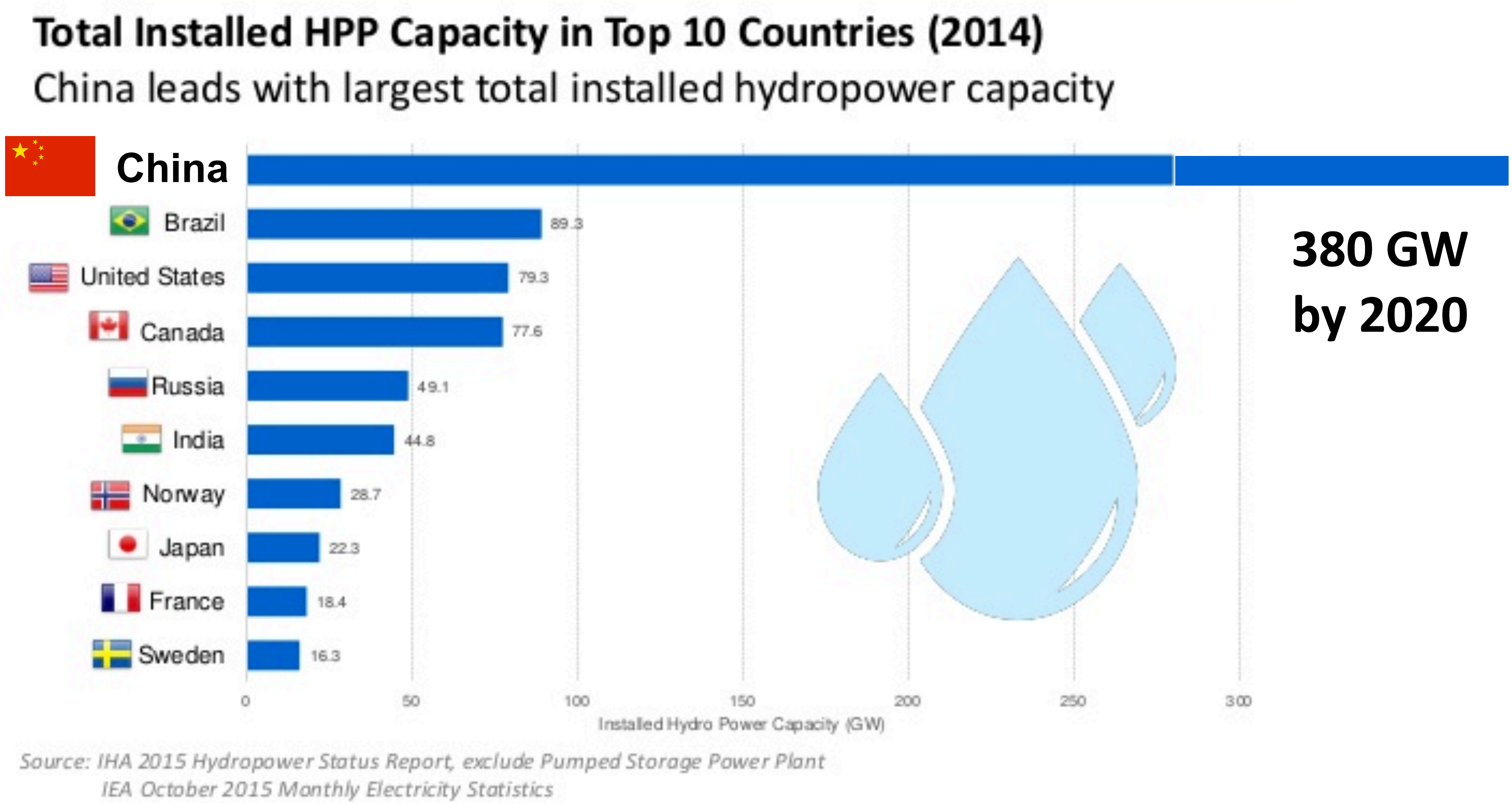
New hydropower projects take twice as long to permit as other energy sources including solar, wind, or natural gas projects, and *time is money*.

Figure 7: Global energy storage power capacity shares by main-use case and technology group, mid-2017

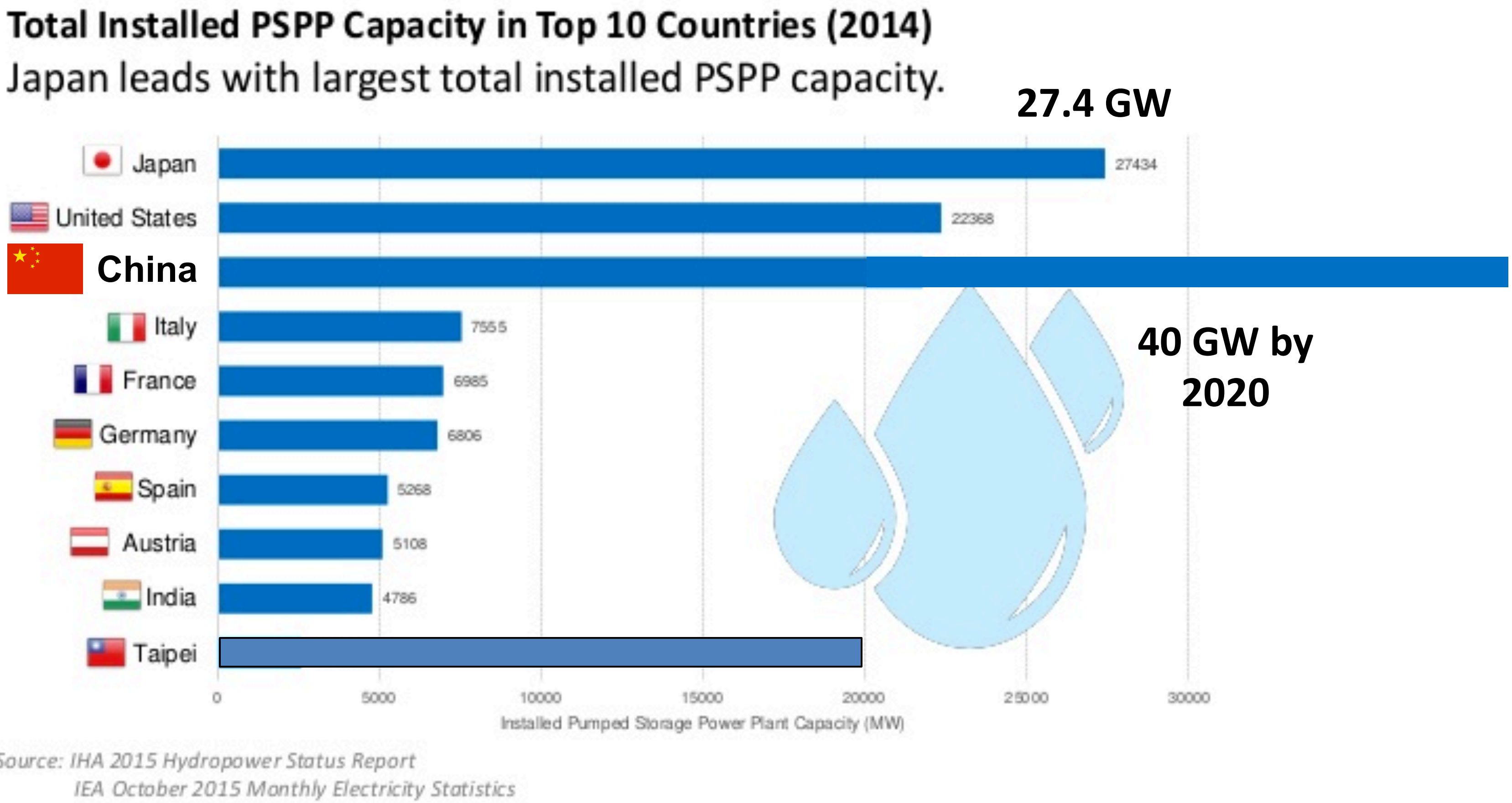


Source: US DOE, 2017.

Hydroelectric in The World

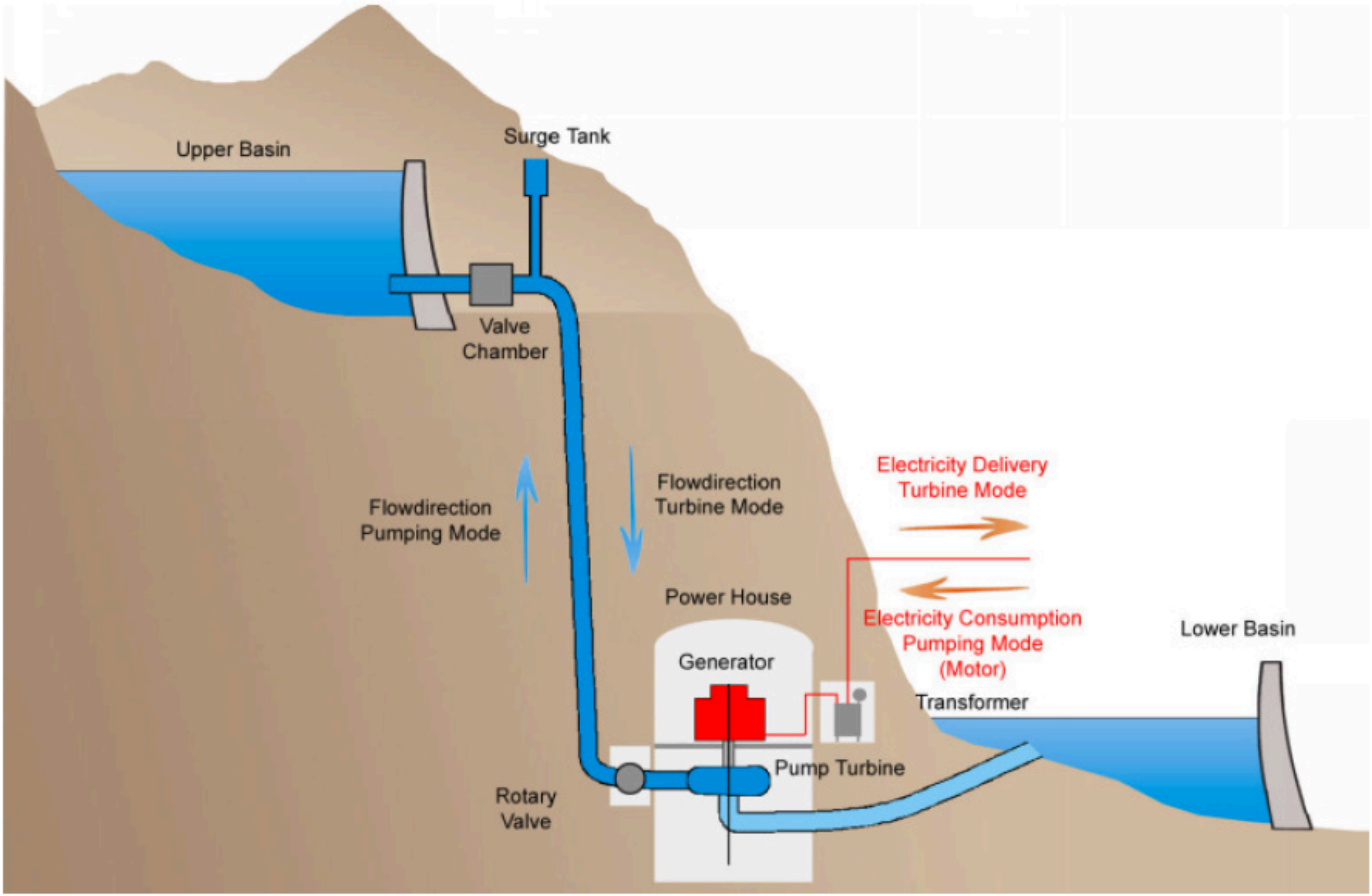


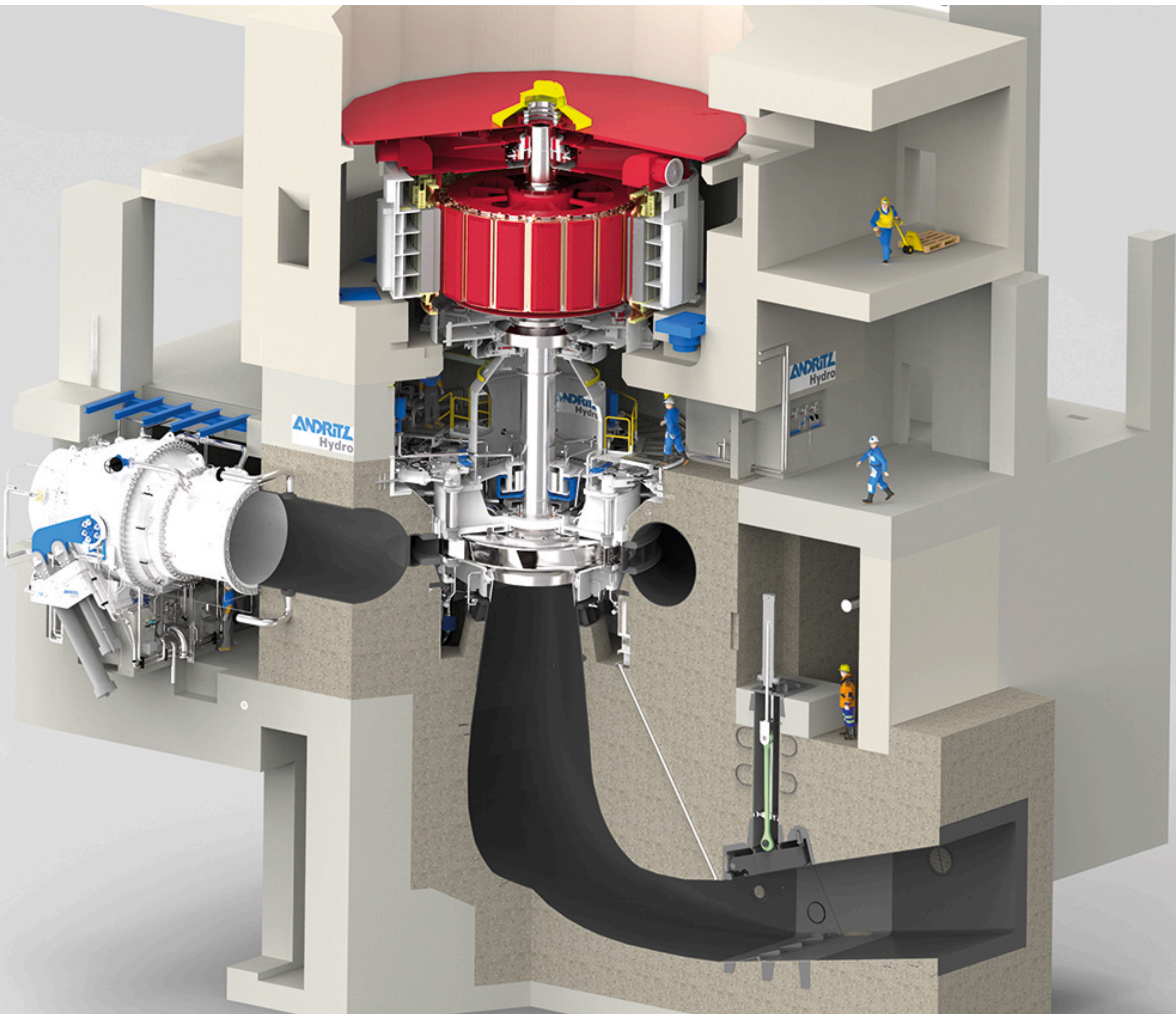
Pumped Storage PP in The World



Adjustable-speed pump-turbines have been used since the early 1990s in Japan and the late 1990s in Europe. Another advantage of adjustable speed units is the increase in overall unit efficiency: the turbine can be operated at its optimum efficiency level under all head conditions and power demand needs.

The size of the machinery of hydro power is *massive*.



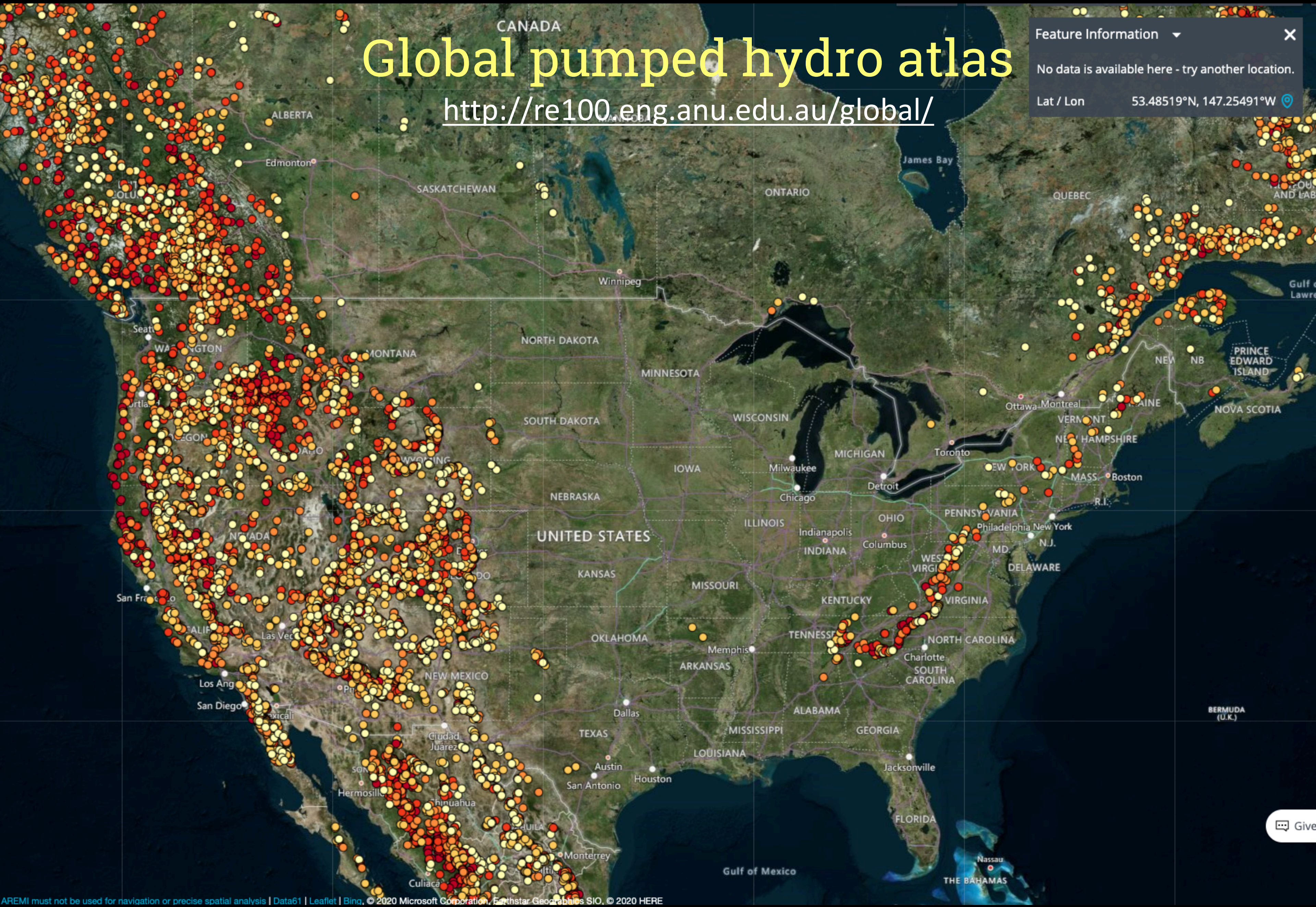

ANDRITZ Hydro
ANDRITZ Hydro
ANDRITZ Hydro

Pump turbine runner

Variable speed generator

Global pumped hydro atlas

http://re100.eng.anu.edu.au/global/



Eagle Mountain Project (Riverside County California)

California Public Utilities Commission approved on March 26, 2020

Calls for 1 gigawatt of “pumped storage, or other long-duration storage with similar attributes” by 2026. Anticipates 11 gigawatts of utility-scale solar by 2030, nearly 3 gigawatts of wind

Table 4.26. Cycles, life years, and round-trip efficiency of pumped storage hydro.

Cycles	Life Years	Round-Trip Efficiency (%)	Source
20,000	20	82	Aquino et al. (2017b)
	50	80	May et al. (2018)
	>20	70-87	Shan and O’Connor (2018)

Assumptions of net present value (discount rate) and lifetime of investment are critical for longer term-projects.

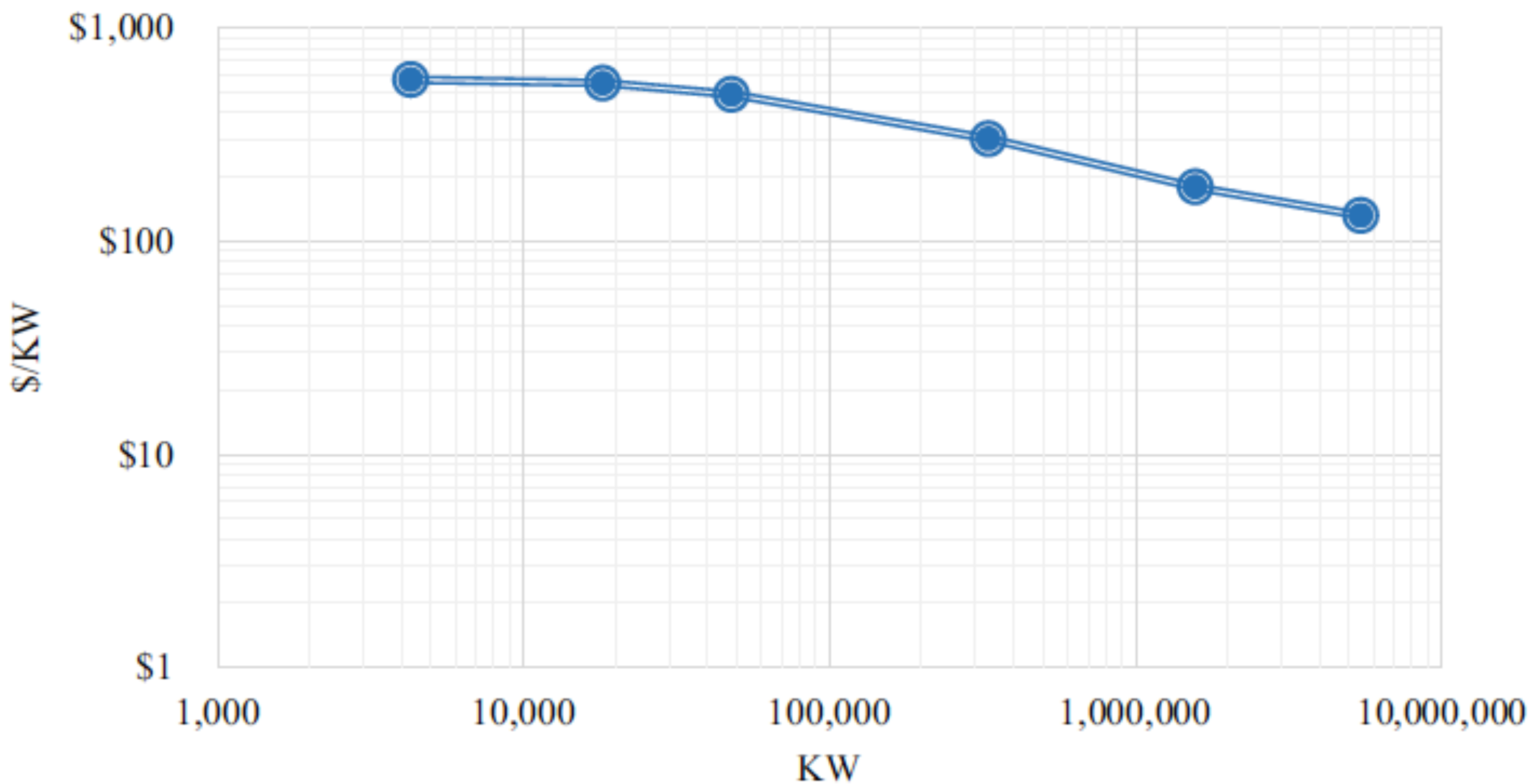


Figure 4.1. Cost of electromechanical equipment for hydro plants.

Storage Cost and Performance Characterization Report. K Mongird et al., PNNL (2019)

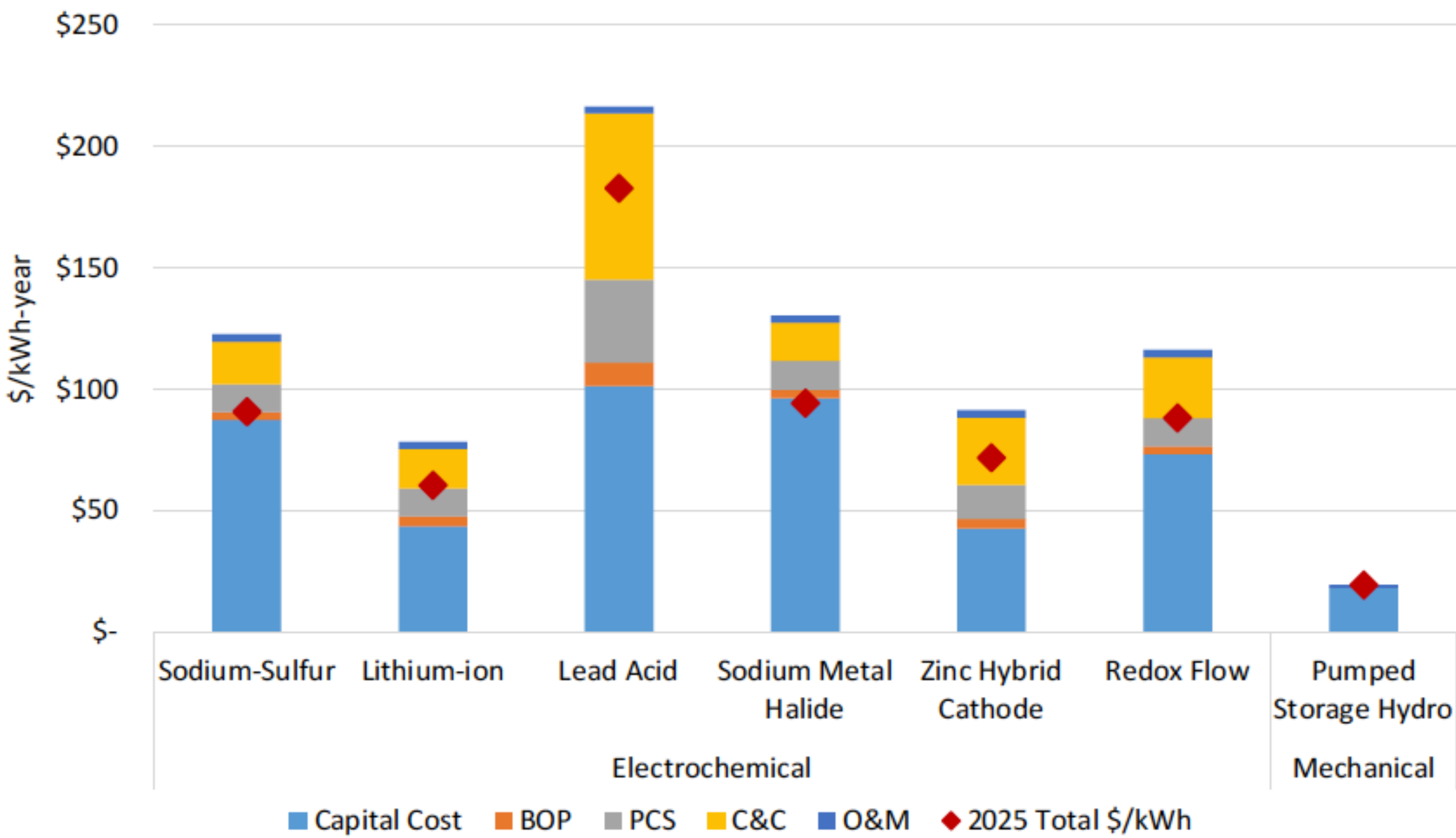


Figure 5.3. Annualized \$/kWh-yr cost of battery storage technologies vs. pumped storage hydro by cost component.

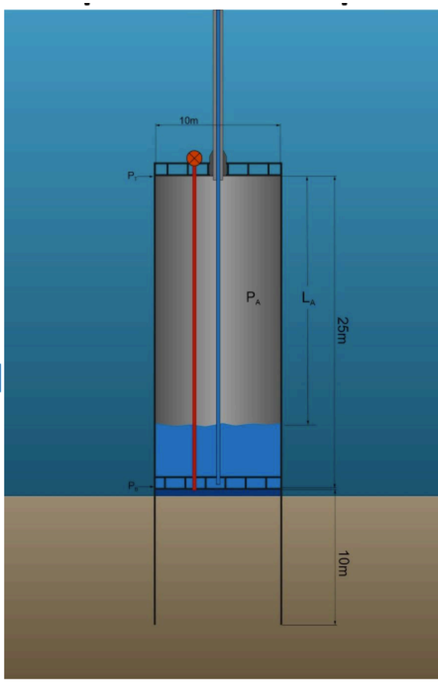
Deep Blue

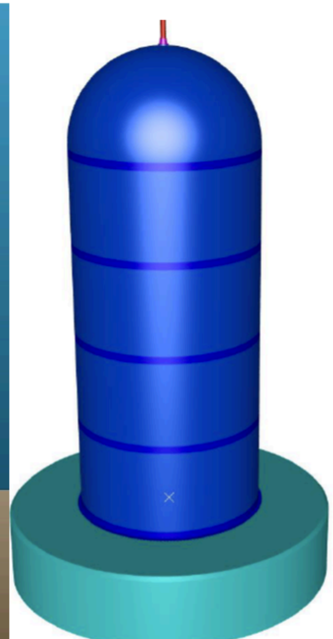
Ocean Assisted Isothermal Energy Storage
Modular Scalable Grid Scale - Unlimited Cycle Life
Just add Air and Water

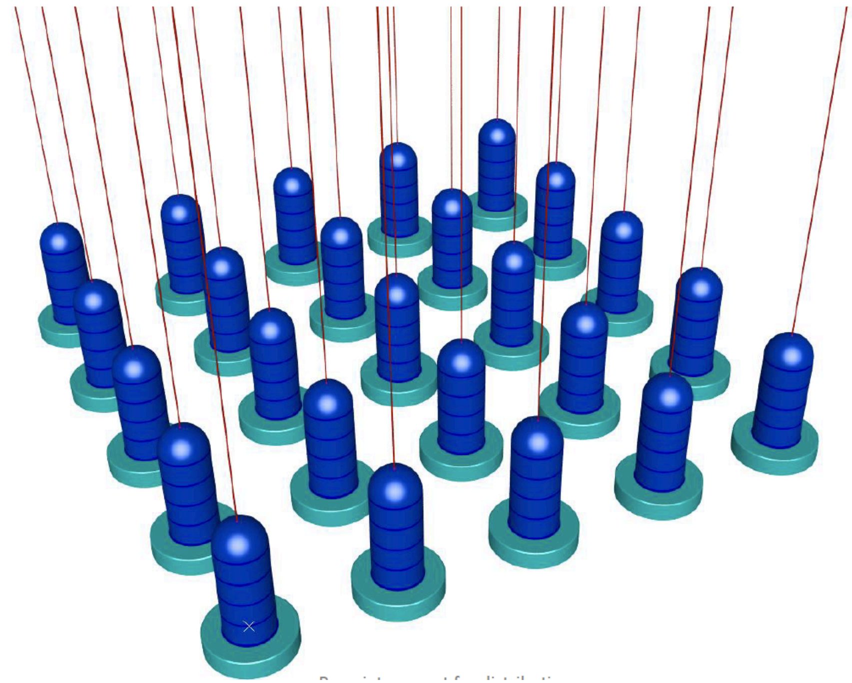
Philip Lubin
Mark Pryor
Directed Energy – Vorticy – UC Santa Barbara

lubin@ucsb.edu

Leverage Existing Deep-Sea Exploration for Oil and Gas







Cylindrical Container -Hemispherical Top –Open Bottom

Compressed Air Energy Storage (CAES)

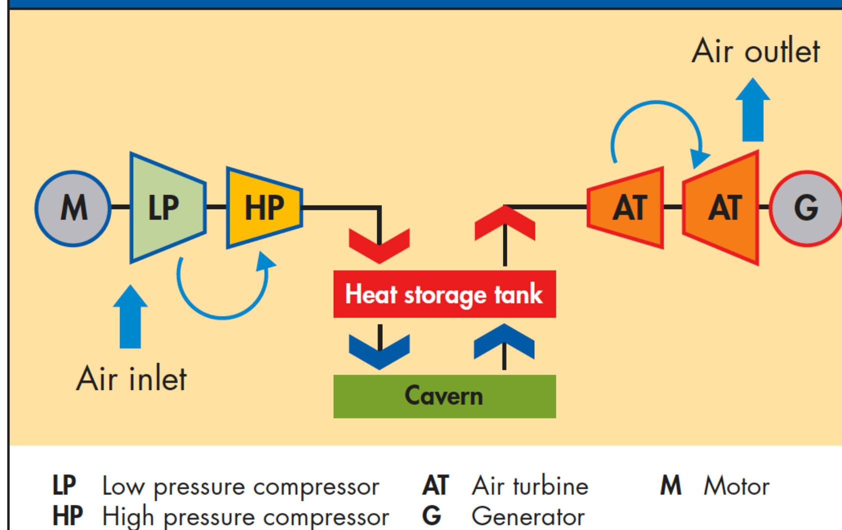
Fig. 2: CAES power plants in existence today

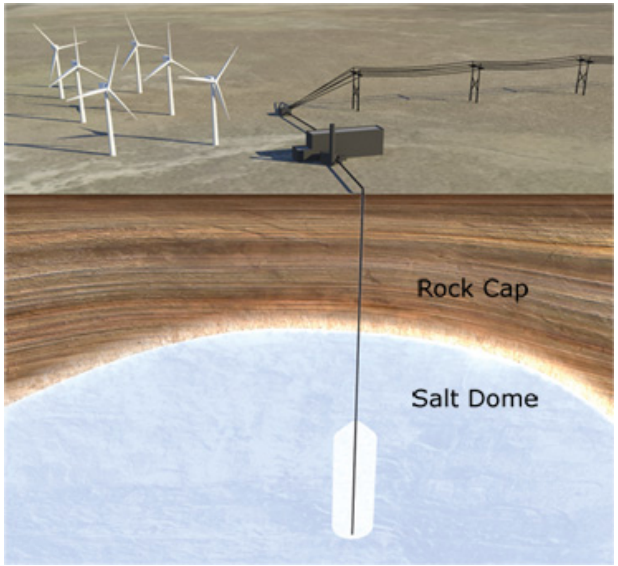
Location	Huntorf, Germany	McIntosh, USA
Commissioned	1978	1991
Store	Two cylindrical salt caverns, each with 150,000 m³ at a depth of 600 m – 800 m (height 200 m, diameter: 30 m)	Salt cavern, 538,000 m³ at a depth of 450 m – 750 m
Output	290 MW over 2 hours	110 MW over 26 hours
Energy required for 1 kWh el	0.8 kWh electricity	0.69 kWh electricity
	1.6 kWh gas	1.17 kWh gas
Pressure tolerance	50 – 70 bar	45 – 76 bar
Remark	World's first CAES plant	First CAES plant with recuperator

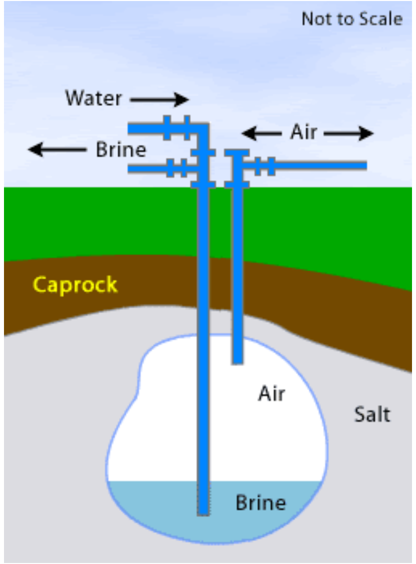
What is "new?" Add adiabatic energy storage: Air compressed to ~70 bar would heat up to around 900K.

Multistage air compressors use inter- and after-coolers to reduce discharge temperatures to 149/177°C and cavern injection air temperature reduced to 43/49°C. T Heat storage used to re-heat expanding gas

Fig. 4: Adiabatic storage power plants







Mitsubishi Hitachi and Magnum Development announced development to store to store ~ 1 GWh of energy. The project will also combine renewable hydrogen, compressed air storage, large-scale flow batteries, and solid oxide fuel cells

Isothermal Compressed Air Energy compression and expansion could improve round-trip efficiency and lower capital costs. *Isothermal CAES requires heat to be removed and added continuously, but in principle it can be 100% efficient.*

Heat transfer is proportional to the $\Delta T \times$(surface area). Large ΔT generates excess entropy. A large surface area adds to capital costs. **Possible solutions have been proposed based upon reciprocating machinery**. One method is to spray fine droplets of water inside the piston during compression. The high heat capacity of water keeps the temperature approximately constant within the piston – the water is removed and either discarded or stored and the cycle repeats.

“Repurposing Mines as Alternative Storage Reservoirs

Recently, the concept of using repurposing abandoned mines as alternative locations for one or both storage reservoirs has been considered. The use of an open pit mine, such as the abandoned iron ore mine pits in Southern California proposed for the Eagle Mountain Pumped project, in concept is a viable alternative, and is similar to using a manmade reservoir. There is no incremental environmental impact and the upper and lower reservoirs (the abandoned open pit quarries) are existing and simply hydraulically connected.

Locating one or both of the reservoirs in underground mines, however, has significant concerns and challenges. Typical underground mining results in small passages looking like an ant farm in cross section and are not suitable as is for a lower reservoir configuration. Quite simply, the pump-turbines would be starved of water in the pump mode. The underground excavation and material costs, construction risk, and time required for underground excavation and construction necessary for the volume of water and elevation difference make the economics of such a project questionable. These underground sites have been evaluated due to the perceived lack of availability of potential surface reservoirs and the potential for reduced environmental impacts. There are no operating pumped storage projects worldwide that utilize an underground reservoir.”

Renewable energy at ~ \$15 /MWh (1.5 ¢/kWh) will be cheaper than natural gas.

1 million (MM) Btu of energy = 293 kWh

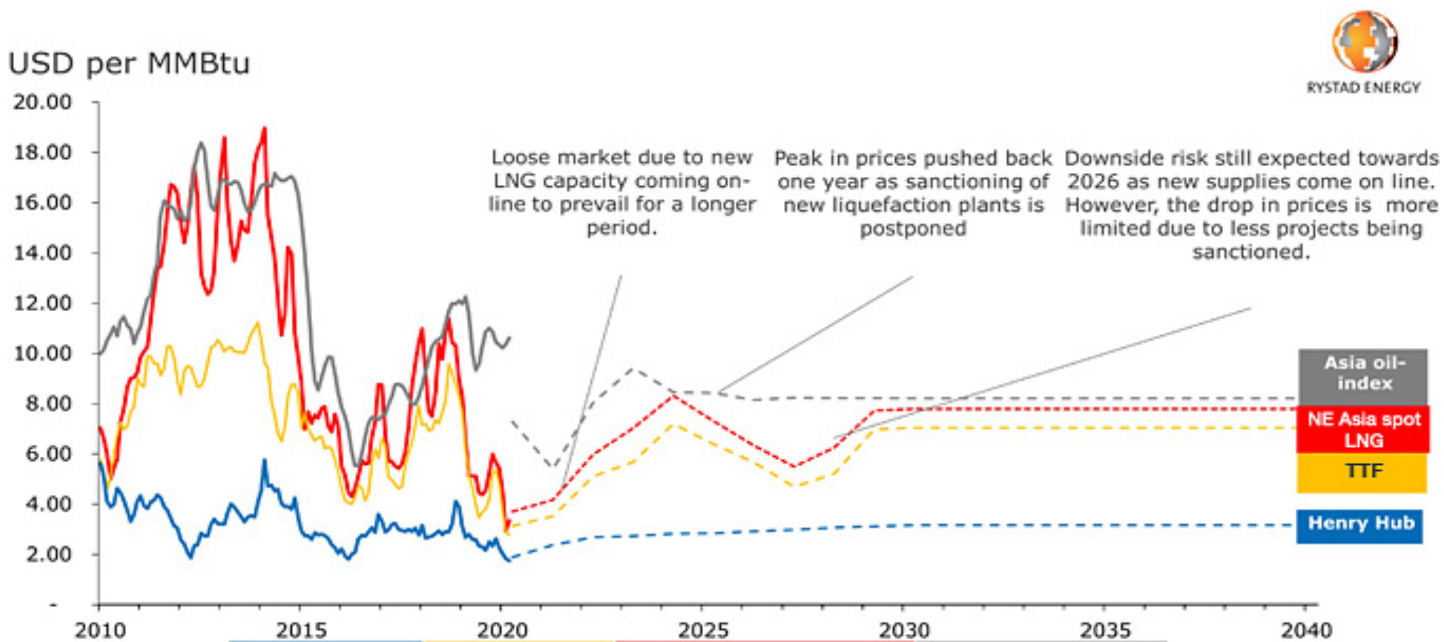
1.5 ¢/kWh = \$4.39/MM Btu.

The cost of natural gas varies between \$2.50 - \$8.00 /MM Btu (See chart below)

Natural gas power plants emit an average of 550 grams CO_2 per kWh

= 0.16 tonnes CO_2/MM Btu

If there is a carbon price of \$60/tonne, the cost of using natural gas and emitting it adds ~ \$9.60/ MM Btu. (High-efficiency plants will still cost > \$7/ MM Btu) The cost of carbon capture, sequestration and monitoring will likely be \$40 - \$60/tonne of CO_2

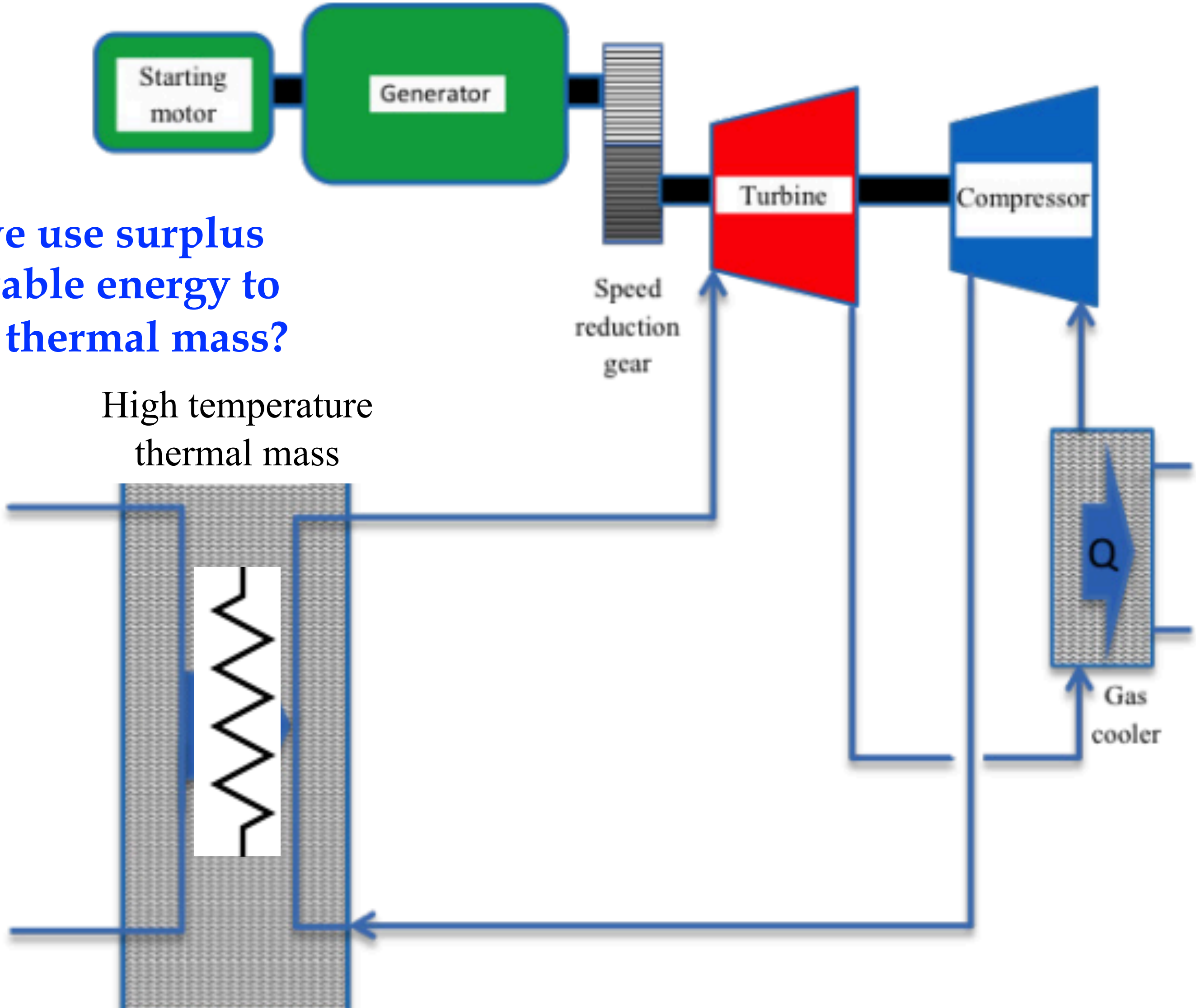


Prices Real	Henry Hub	TTF	NE Asia Spot LNG	Brent Indexed
2020	1.94 (-0.26)	3.20 (-0.62)	3.80 (-0.61)	7.45 (-0.35)
2021	2.43 (-0.07)	3.61 (-1.04)	4.27 (-1.09)	5.54 (-1.02)

Utility-scale thermal energy storage

Figure 4.R.1 Block Flow Diagram for Simple Brayton Cycle

Credit: NETL

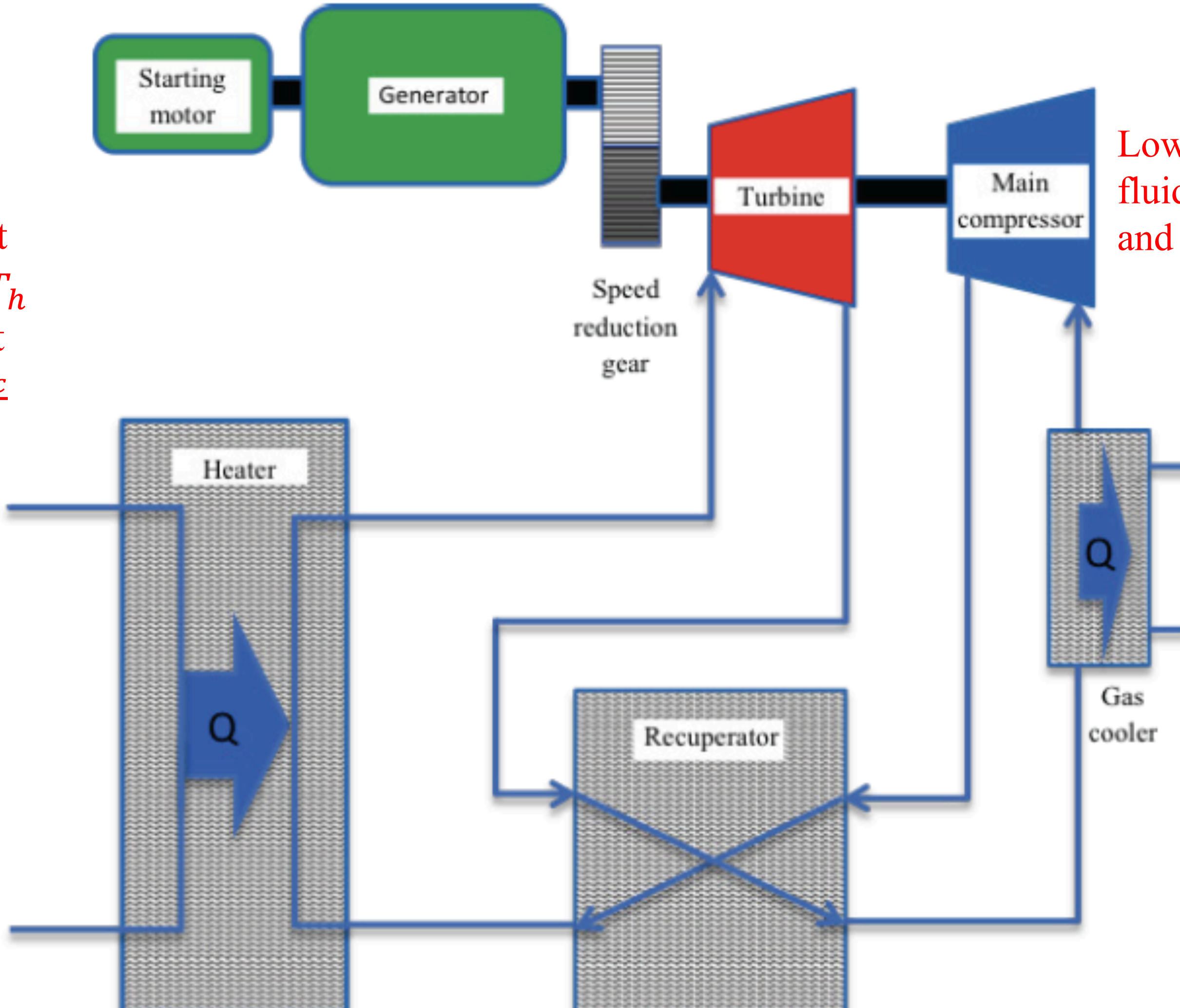


Can we use surplus renewable energy to heat a thermal mass?

https://www.energy.gov/sites/prod/files/2016/06/f32/QTR2015-4R-Supercritical-Carbon-Dioxide-Brayton%20Cycle.pdf

Figure 4.R.5 Block Flow Diagram for Recuperated Brayton Cycle

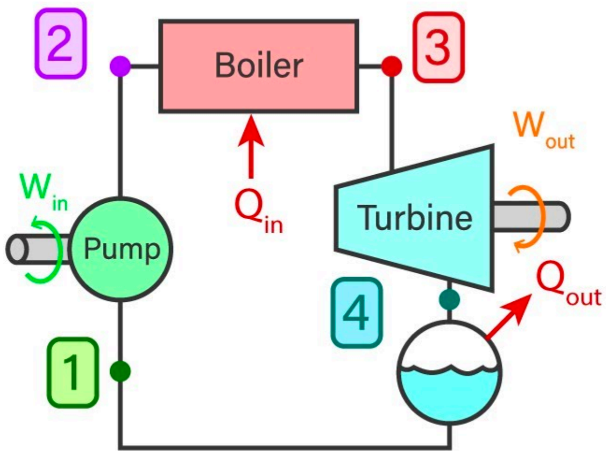
Credit: NETL

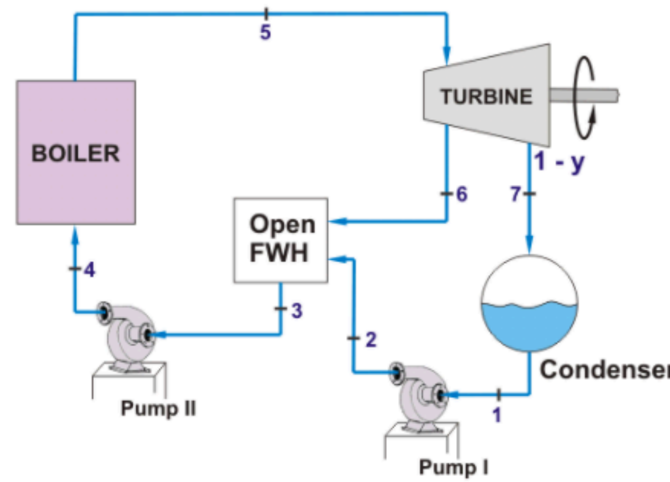


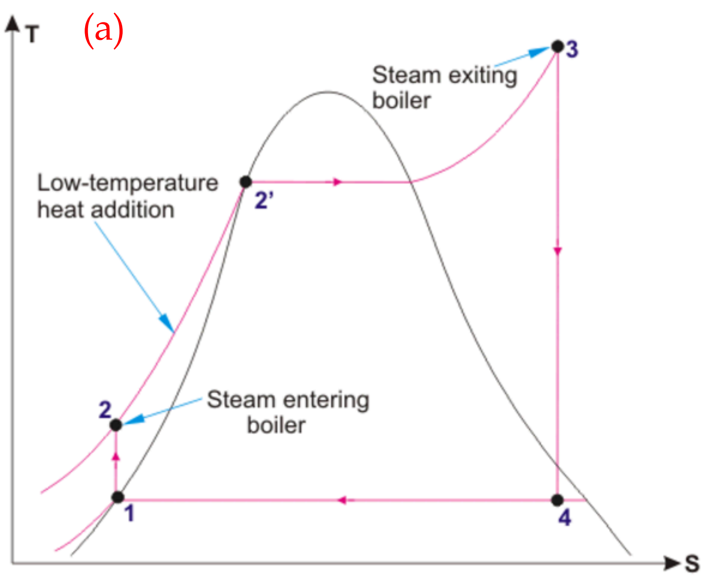
Principle: add heat at the highest average T_h guided by the Carnot efficiency: $\eta = \frac{T_h - T_c}{T_h}$

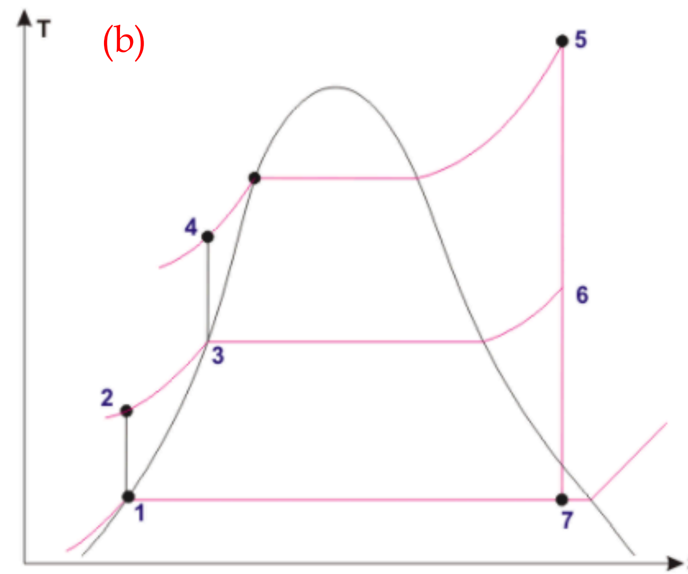
Low-temperature fluid is compressed and re-heated

Exhaust heat from the turbine is used to reheat the compressed turbine

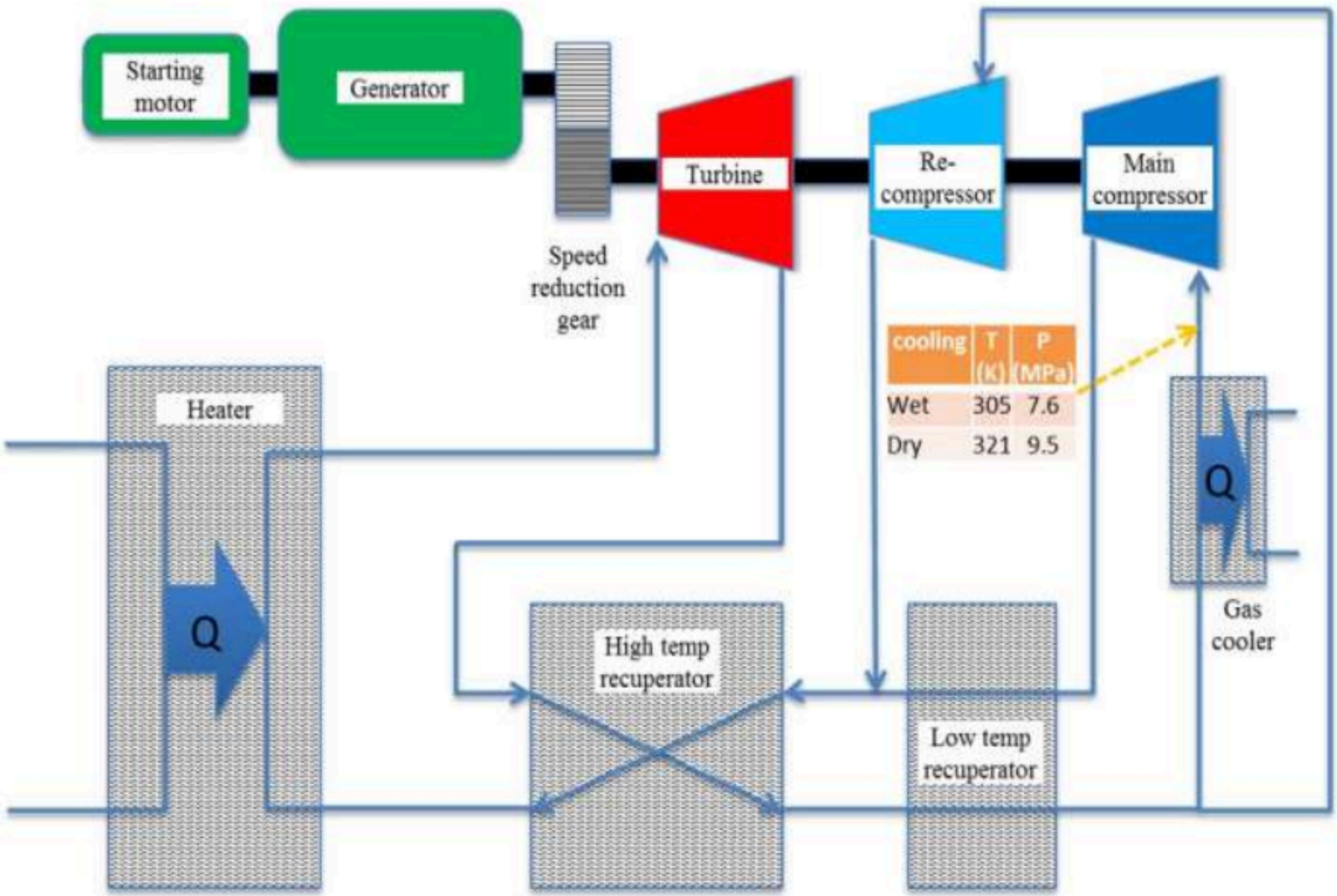

2
Boiler
3
W out
W in
Q in
Turbine
Pump
4
Q out
1


5
TURBINE
BOILER
1 - y
6
7
Open
FWH
4
3
2
Condenser
Pump II
1
Pump I


T
(a)
3
Steam exiting
boiler
Low-temperature
heat addition
2'
2
Steam entering
boiler
1
4
S


T
(b)
5
4
6
3
2
1
7
S

A Brayton generator with high and low temperature recuperators.

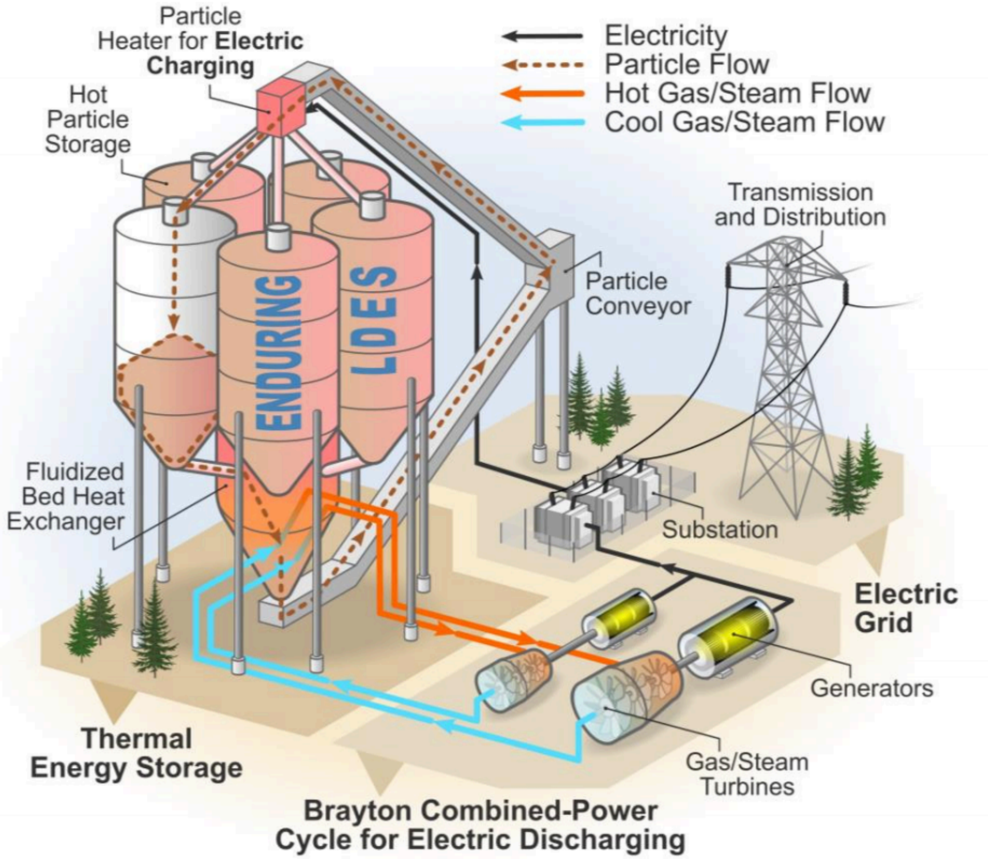


https://www.energy.gov/sites/prod/files/2016/06/f32/QTR2015-4R-Supercritical-Carbon-Dioxide-Brayton%20Cycle.pdf

Table 4.24. Capital costs of pumped storage hydro systems.

Capital Cost ($/kW)	Notes	Source
$1,500-$4,700		Aquino et al. (2017b)
$70-$230/kWh		Kamath (2016)
$2,020	$762/kW in 1985 converted to 2018 dollars using 3% escalation rate	United States Bureau of Reclamation (2018)
$250-$350/kWh		May et al. (2018)
$1,500-$2,000	Target cost for project to be economical. Excludes transmission upgrade cost of $700/kW and civil and infrastructure cost of $460/kW	Manwaring (2018a)
$3,000	For 50 MW system	Manwaring (2018a)
$1,300	Projected cost for Eagle Mountain PSH in Southern California	Manwaring (2018a)

ENDURING Long Duration Energy Storage (LDES)



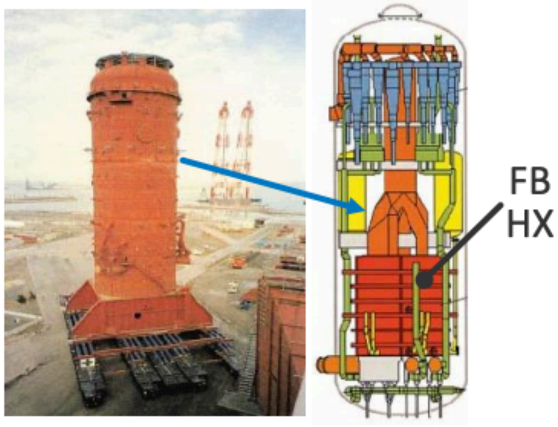
Technology Innovations

- ENDURING LDES operates as a standalone thermal battery for grid-scale electricity storage.
- Inexpensive, stable, abundant solid particles as storage media.
- Novel fluidized bed heat exchanger for cost-effective and efficient power conversion.
- Decoupled power and storage duration.
- Scalable system for wide storage capacity (10 – 100 hours) and power (60 – 300 MWe).

Challenges and Risk Mitigation

1. Particle stability at 1,200°C
   - Knowledge/resources from Allied Mineral, Purdue Center for Particulate Products and Processes, and particle suppliers will be applied.
   - Several particle types will be screened/tested.

Commercial 360-MW FB boiler



2. Fluidized Bed (FB) Heat Exchanger (HX) design
   - Strong team expertise on gas/solid two-phase flow modeling, testing, and scaling up will be tapped.
   - Industry experiences and commercialized technologies will be leveraged.

ENDURING Project Team

NREL is specialized in thermal energy storage in concentrating solar power (CSP):

- Early advocacy of the supercritical carbon dioxide (sCO2) Brayton power cycle.
- SunShot projects using particles as heat transfer fluid and storage media.

GE Global Research (GE-GRC) will lead the power system integration:

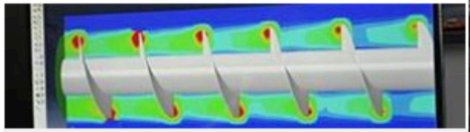
- Global leader in power system equipment and services.
- Record power conversion efficiency of gas-turbine combined cycles.

ENDURING Project Team

Colorado School of Mines (CSM) participated in NREL's SunShot project in TES and particle system.

POWER Engineers (PEI):

- Power system integration
- Power generation engineering



Purdue Center for Particulate Products and Processes has full line of particle characterization equipment, and expertise in MFIX modeling.

Allied is specialized in refractory materials, powder, high-temperature insulation (>1,600°C) material, design and construction.

Project Objectives and Timeline

Private/public partners for commercialization

Technology Transfer & Outreaching (TTO)

- Utility involvement
- EPCs, manufacturing
- Supply chains

Demonstration:
Pilot plant in 2 – 5 MW

- 2–5 MW heater and fluidized bed
- 10–50 MWh pilot storage design
- 1 – 2 MW turbine integration

ARPA-E DAYS

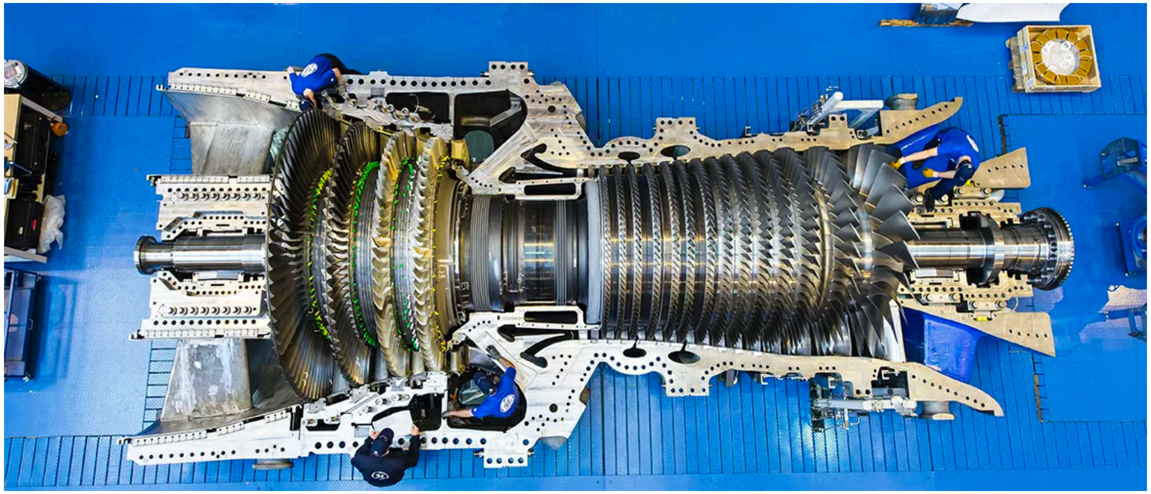
BP2 Development:
Concept verification laboratory prototypes

- 10 kW benchtop particle heater
- 5 kW fluidized bed gas/particle test prototype
- 100 kWh TES material and design verification

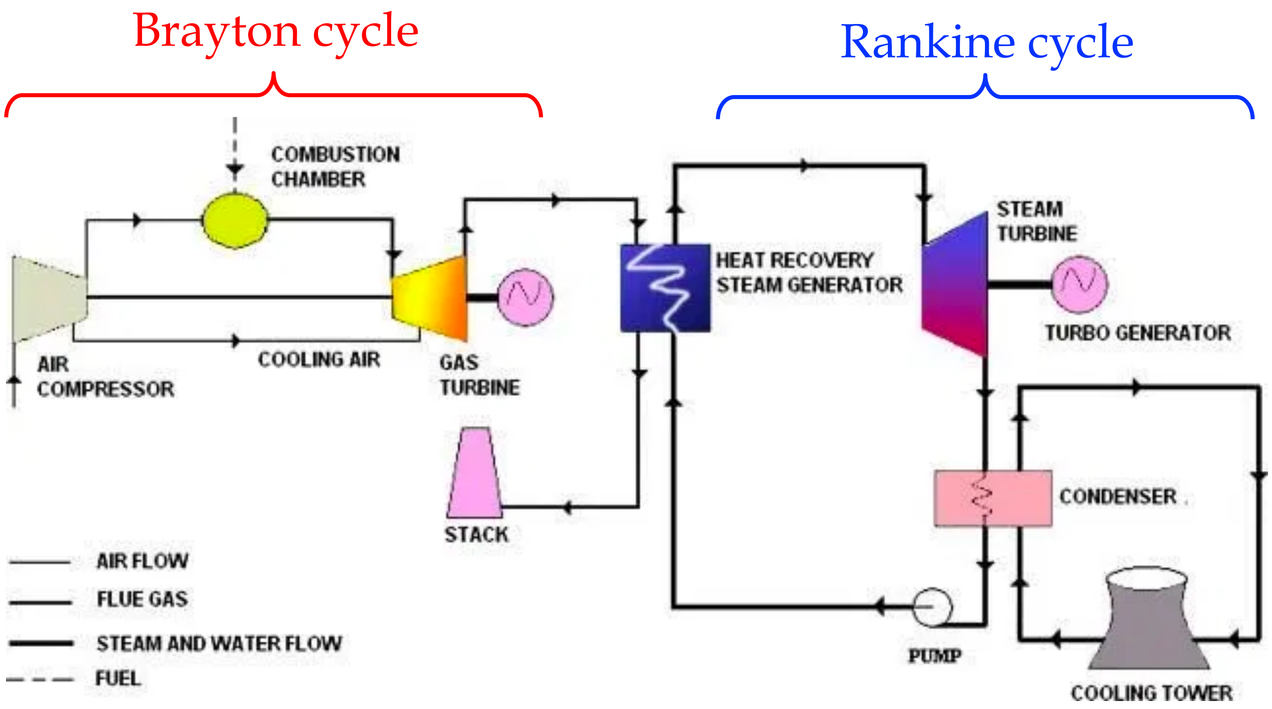
BP1 Research:
Fundamental designs and materials

- Select particles, heater, storage insulation, containment
- Fluidized bed, gas seal, particle feeding and dispensing
- Power system configuration, efficiency, cycle optimization

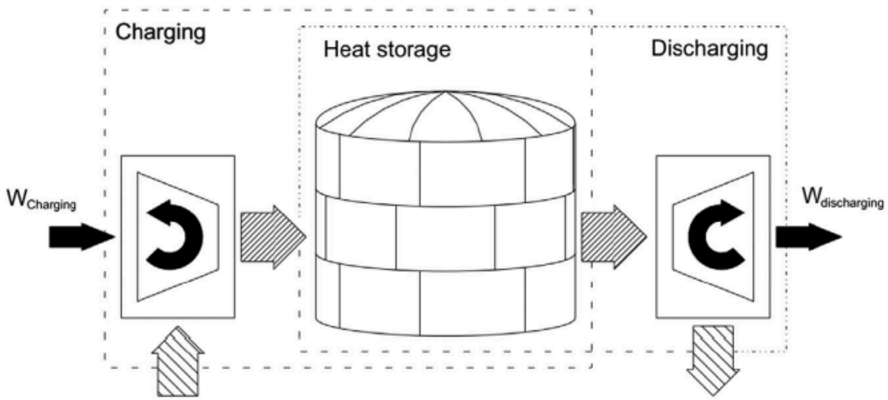
2019 2020 2021 2022 2023 2024



GE H-class turbine (inlet temperature 1600 C and combined cycle efficiency 63%



Thermodynamic Analysis of High-Temperature Carnot Battery Concepts, Wolf-Dieter Steinmann, Henning Jockenhöfer, and Dan Bauer, Energy Technol. 2020, 8, 1900895



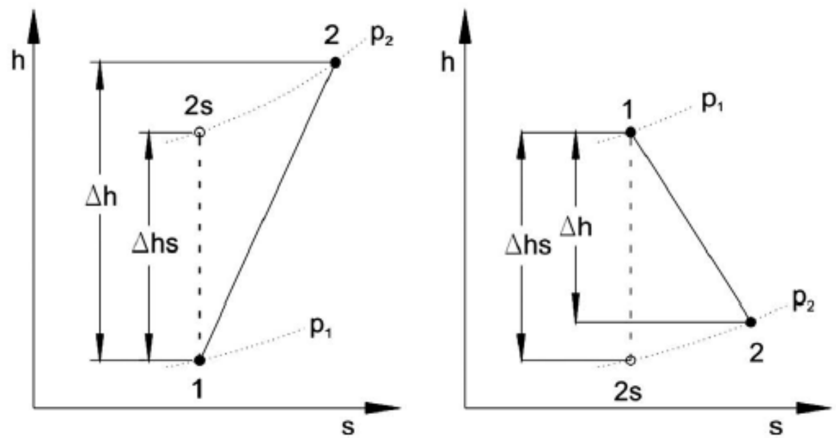


Figure 2. Nonideal compression (left) and expansion (right) as the source for efficiency losses in the hs-diagram.

Carnot Batteries

Basic premise:

- Charge: heat pump or electric heater
- Discharge: some kind of heat engine (Brayton cycle, Rankine cycle etc.)
- Based on established thermodynamic cycles

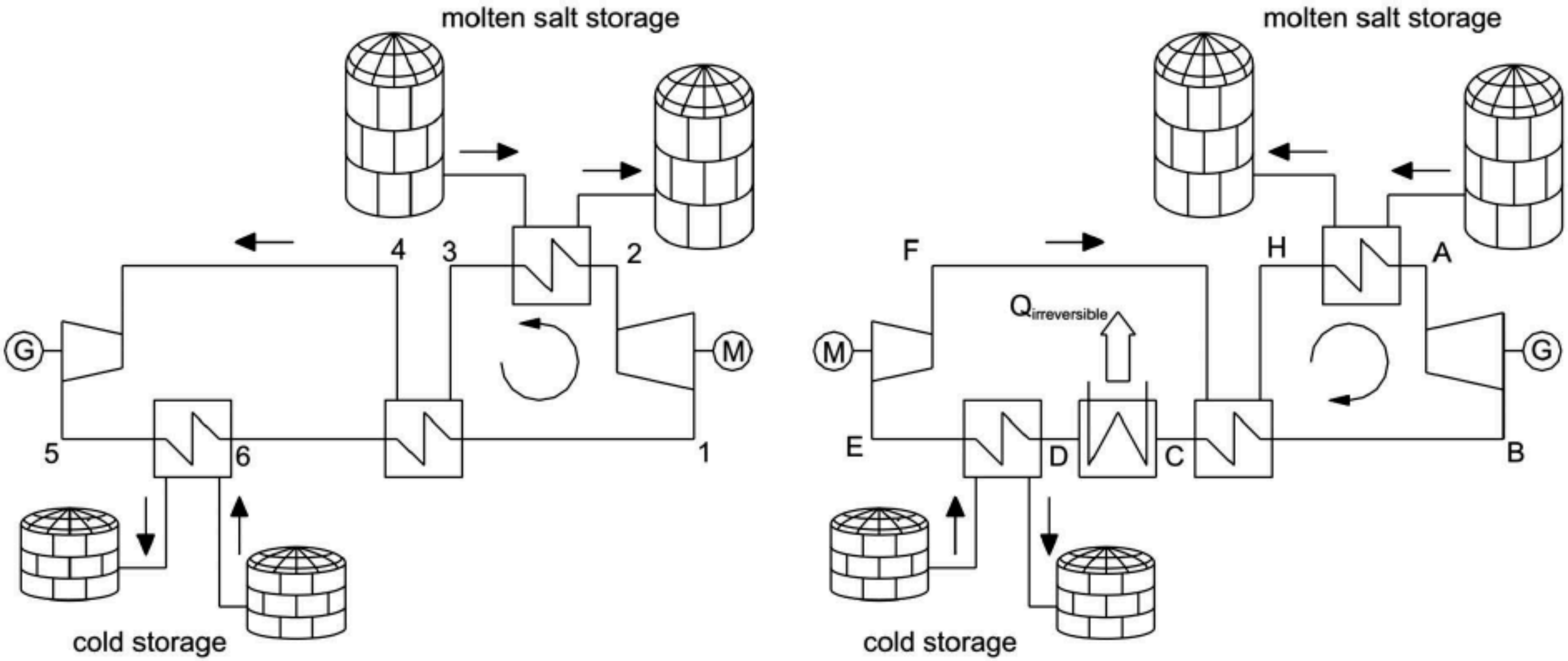
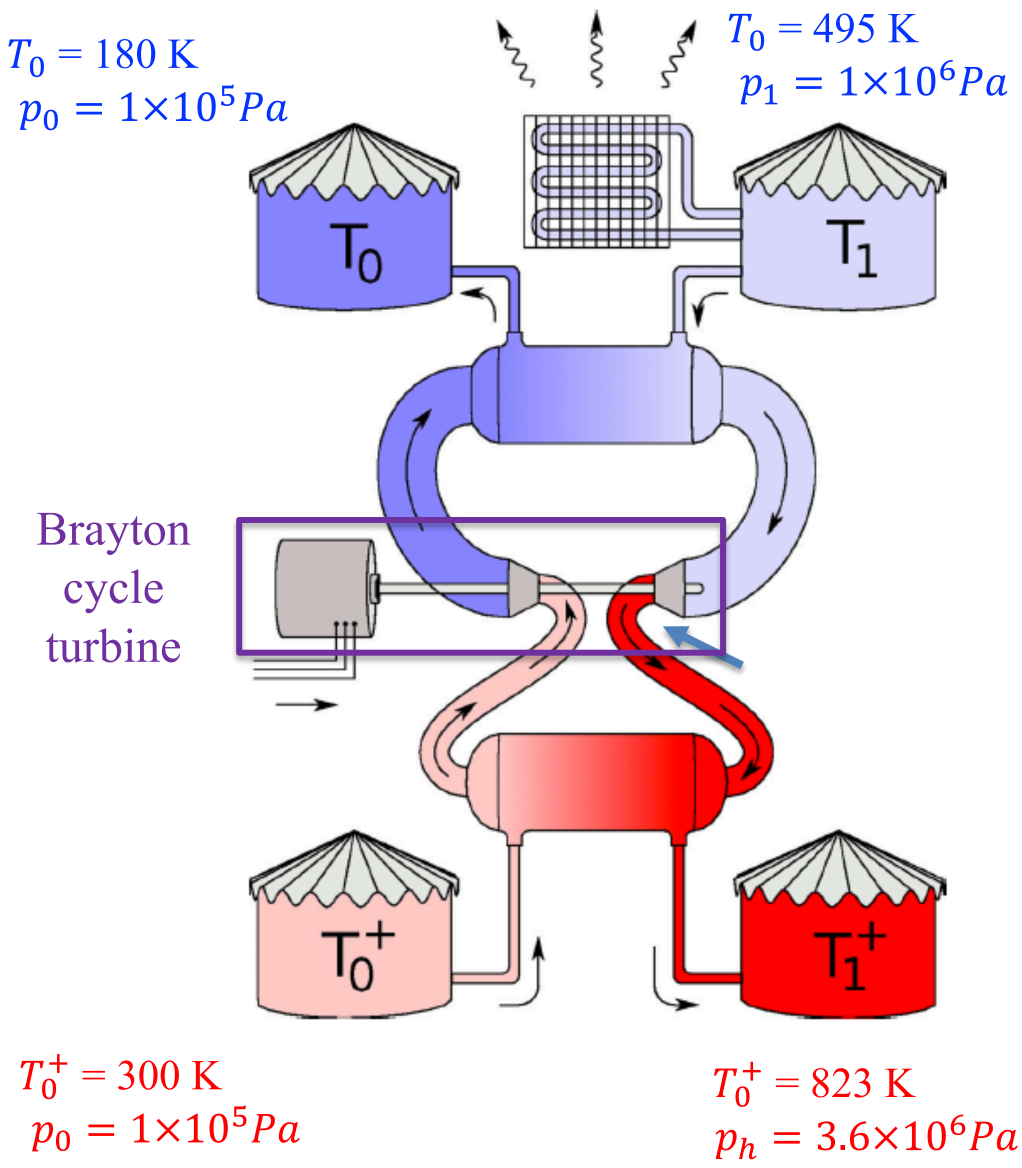


Figure 5. Schematic of the recuperated Brayton PTES variant: charging (left) and discharging (right).

Pumped thermal grid storage with heat exchange

Robert B. Laughlin, J. Renewable Sustainable Energy 9, 044103 (2017);



Laughlin uses 4 thermal storage volumes and the electrical energy is used to move heat analogous to mechanically pumping water.

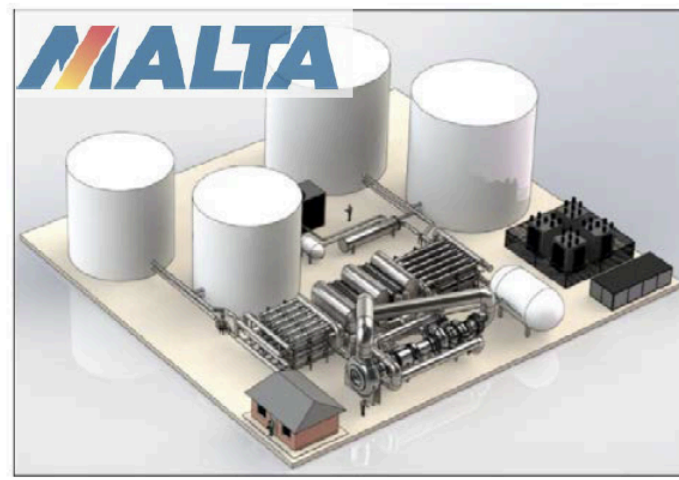
A Brayton turbine uses electrical energy to move energy stored at thermal reservoir T_1 to a reservoir at T_1^+. The same turbine is boosted by allowing heat at T_0^+ flow to T_0. Heat exchangers are used as energy recuperators.

If $T_0^+/T_0 = T_1^+/T_1 = \xi$, and the turbine and compressor is perfectly adiabatic and the heat exchangers are very large, the heat storage engine $\eta_{store} = 1$

For $\eta_c, = 0.9, \eta_t = 0.93$,

$$\eta_{store} = 1 - \frac{2T_{dump}}{T_1 - T_0}\left(\frac{1}{\eta_c} - \eta_t\right)\frac{\ln \xi}{\xi - 1}$$

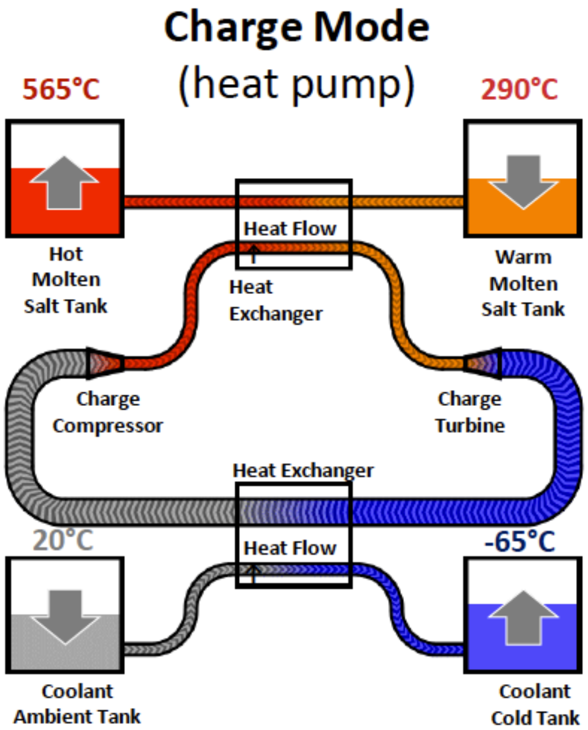
Commercial interest

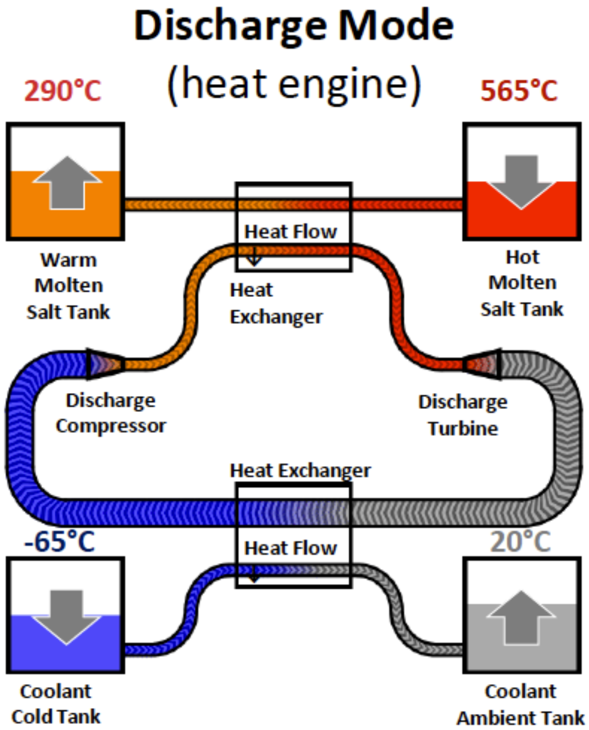


Technology Overview

Unique features:
- **Air working fluid**
- **Liquid storage**
- **Hot & Cold**

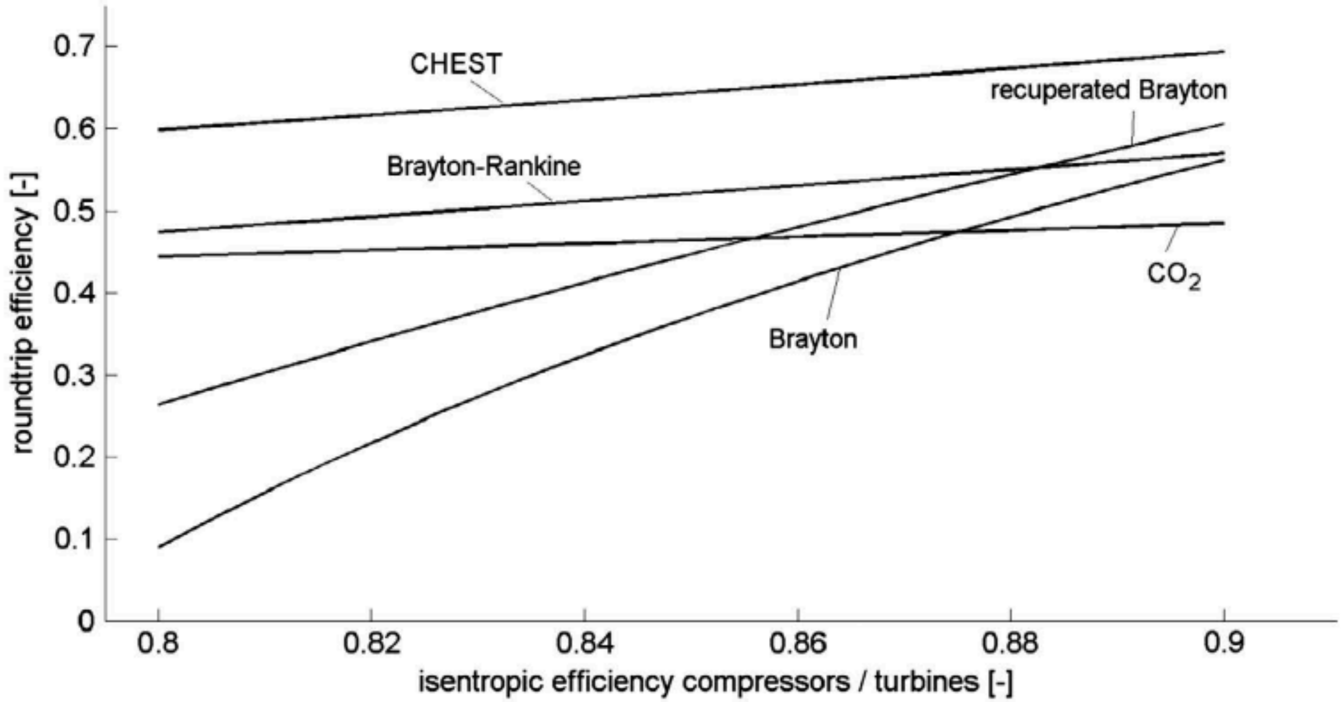
"New" Component Challenges
- **Custom TM**
- **Affordable low-temperature coolant**
- **Affordable large heat exchangers**



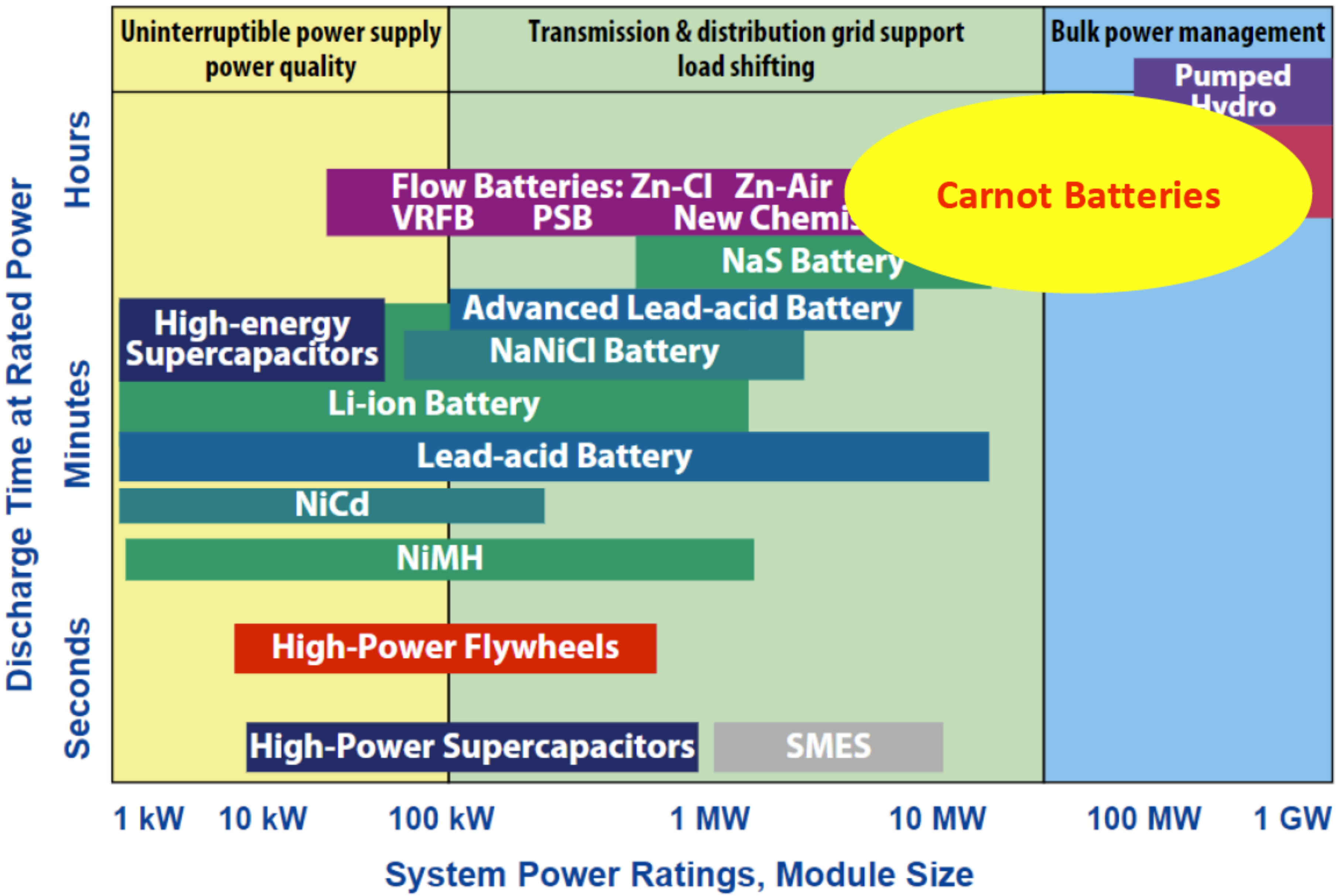


MALTA

CHEST = Compressed Heat Energy Storage



Dependence of the roundtrip efficiency for the PTES variants on the isentropic efficiency of the engines; temperature difference of 10 K assumed for all heat transfer processes.



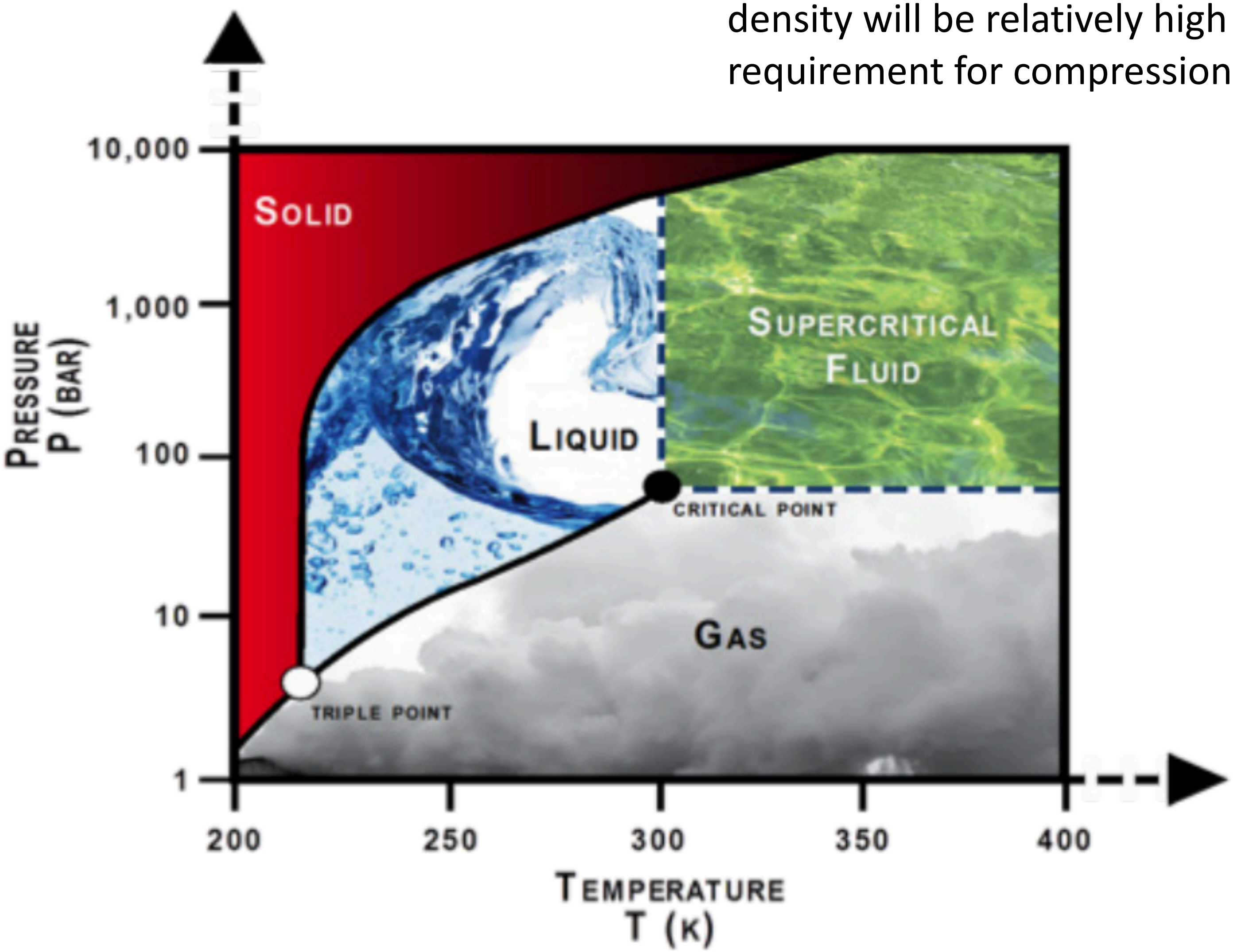
Uninterruptible power supply
power quality
Transmission & distribution grid support
load shifting
Bulk power management
Pumped
Hydro
Carnot Batteries
Flow Batteries: Zn-Cl Zn-Air
VRFB PSB New Chemis
NaS Battery
Advanced Lead-acid Battery
High-energy
Supercapacitors
NaNiCl Battery
Li-ion Battery
Lead-acid 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

Steam has been historically used as the working fluid in a turbine generator.

CO_2 is a better.

Figure 4.R.4 CO_2 Phase Diagram

Credit: Wikimedia Commons



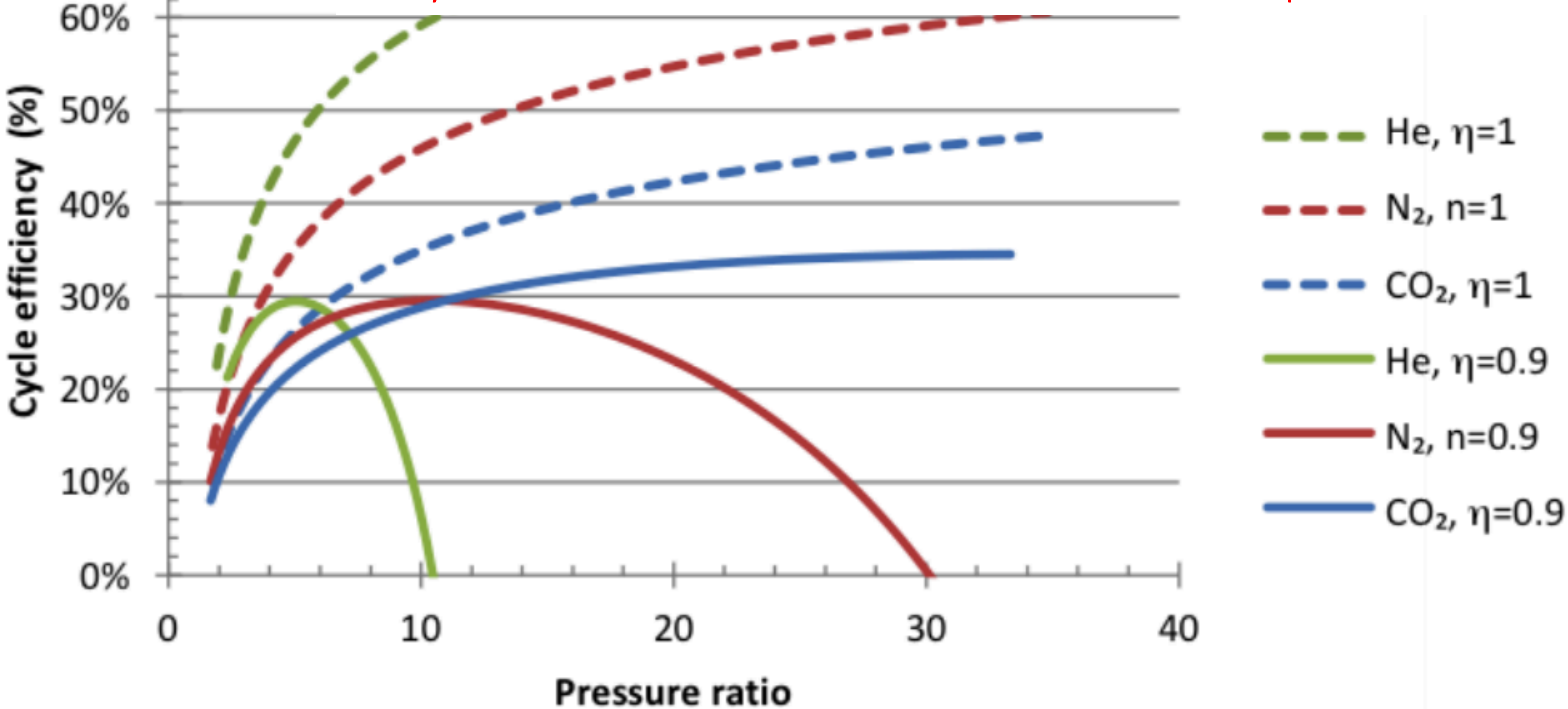
A fluid near its critical point has a density, closer to the density of a liquid than of a gas. With the CO_2 near the critical pressure at the point of entrance to the compressor, its density will be relatively high and the power requirement for compression will be lower.

Turbines work at ~ 90% adiabatic efficiency.

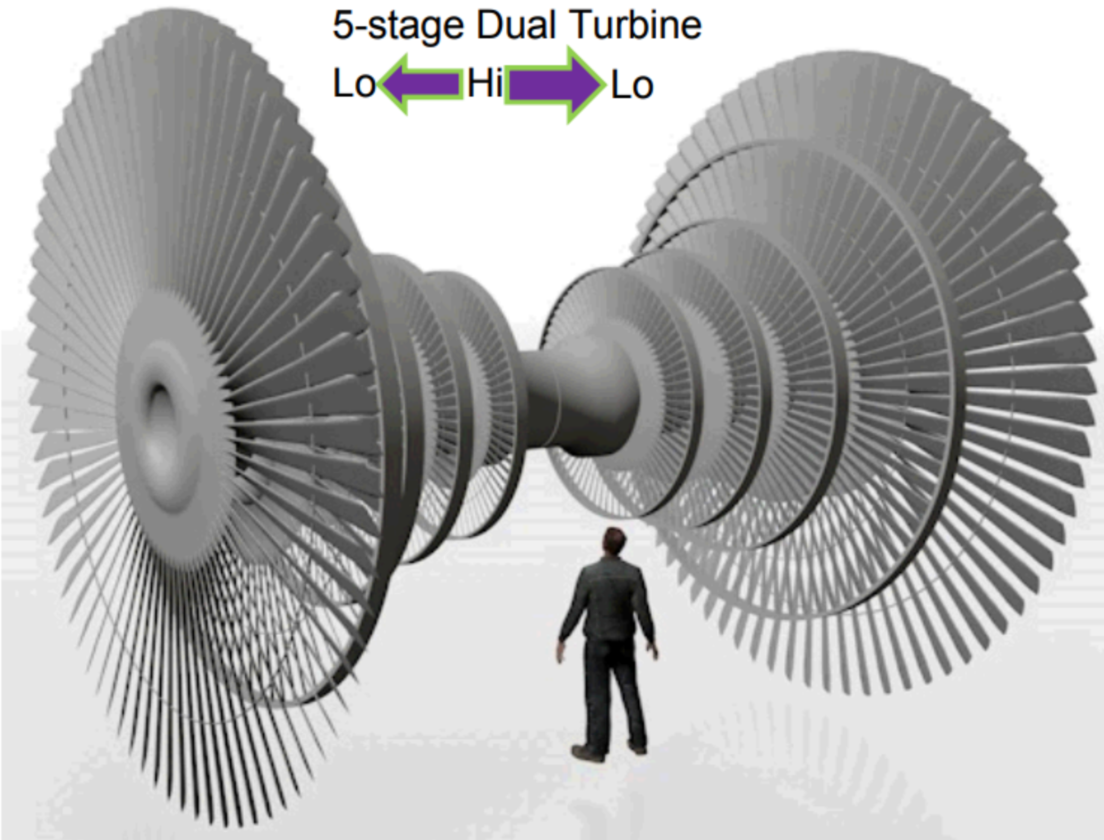
Figure 4.R.2 Simple Brayton Cycle Efficiency. Plot of cycle efficiency versus pressure ratio for three different working fluids with ideal turbomachinery (dashed lines) and non-ideal cycles with turbomachinery isentropic efficiencies (η) of 0.9.[5]

Credit: NETL

CO_2 near its critical point becomes more incompressible than steam and hence, the compression work can be substantially decreased leading to high cycle efficiency. In addition, in its supercritical state, CO_2 is also nearly twice as dense as steam so the turbine can be more compact.

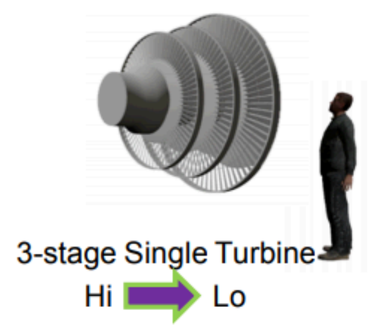


Transformational Energy Systems



20 meter Steam Turbine (300 MWe)
(Rankine Cycle)

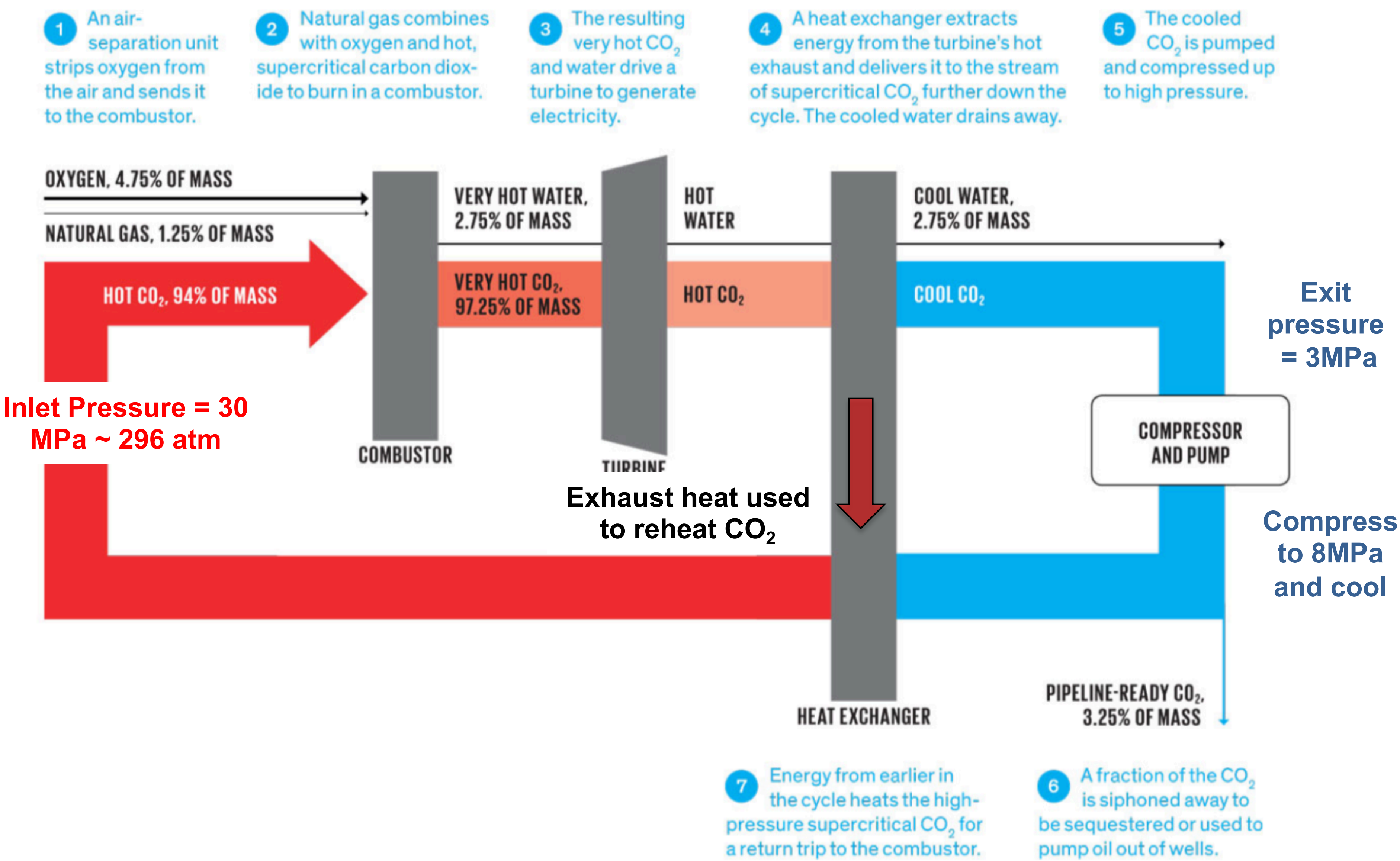
- Comparison
  - Rankine efficiency is 33%
  - Supercritical CO_2 (sCO_2) potential to surpass 40% efficiency
  - Greatly reduced cost for sCO_2 compared to the cost of conventional steam Rankine cycle
  - sCO_2 compact turbo machinery is easily scalable

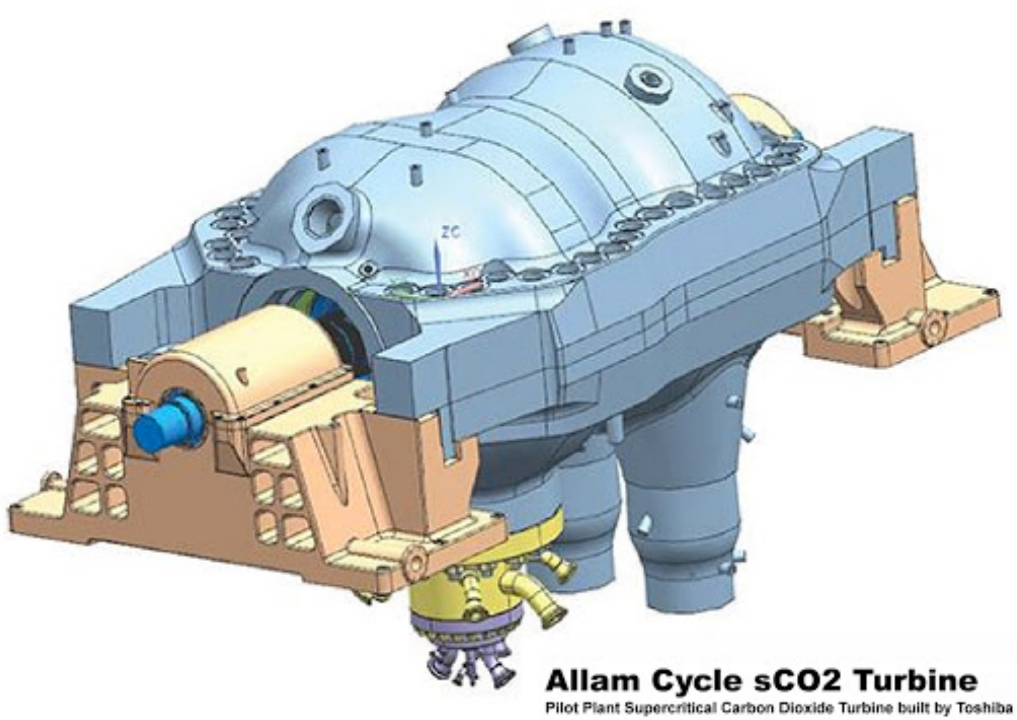


1 meter sCO_2 (300 MWe)
(Brayton Cycle)

Allam Cycle CO_2 + natural gas turbine

https://spectrum.ieee.org/energy/fossil-fuels/this-power-plant-runs-on-co2

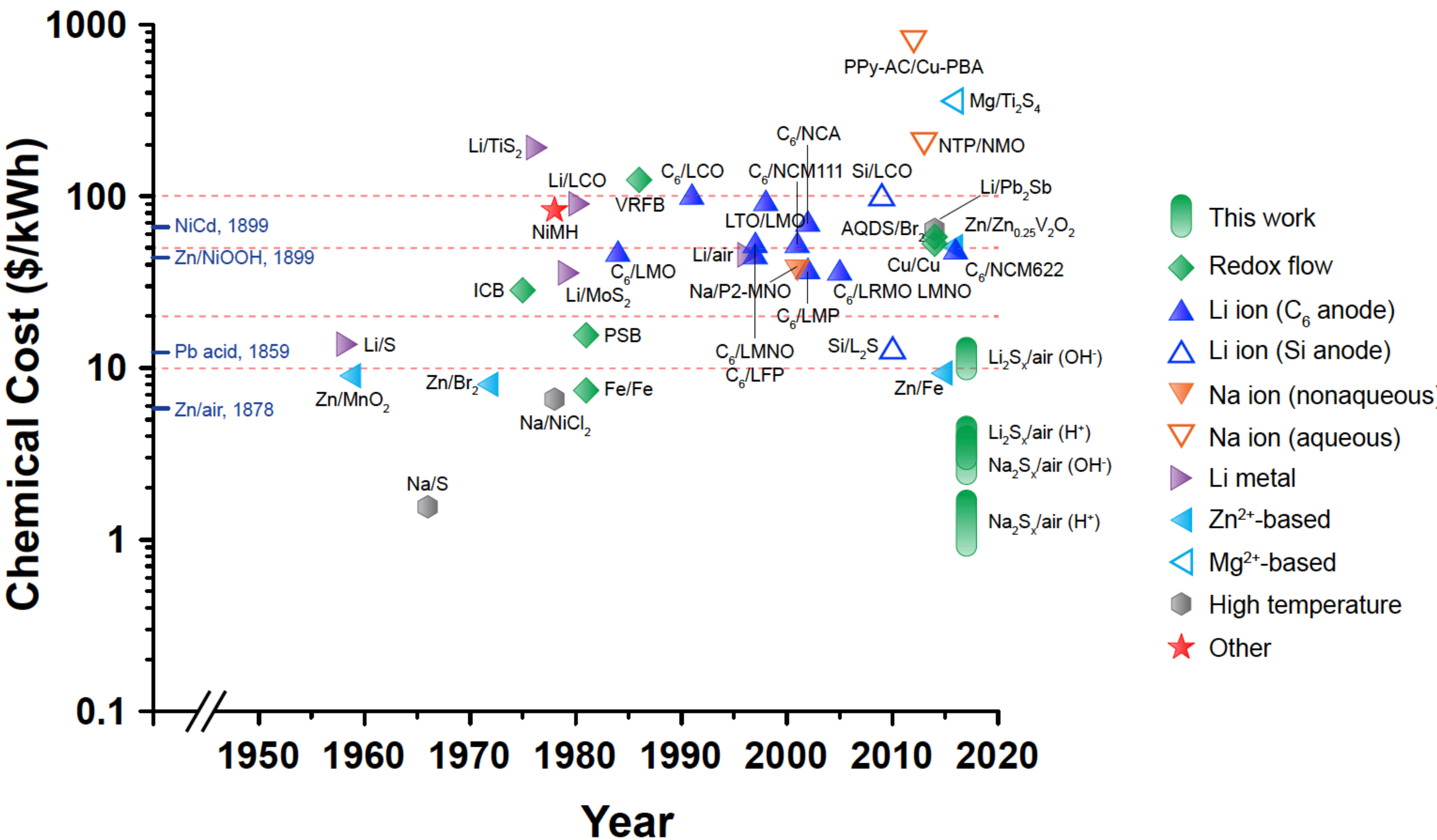




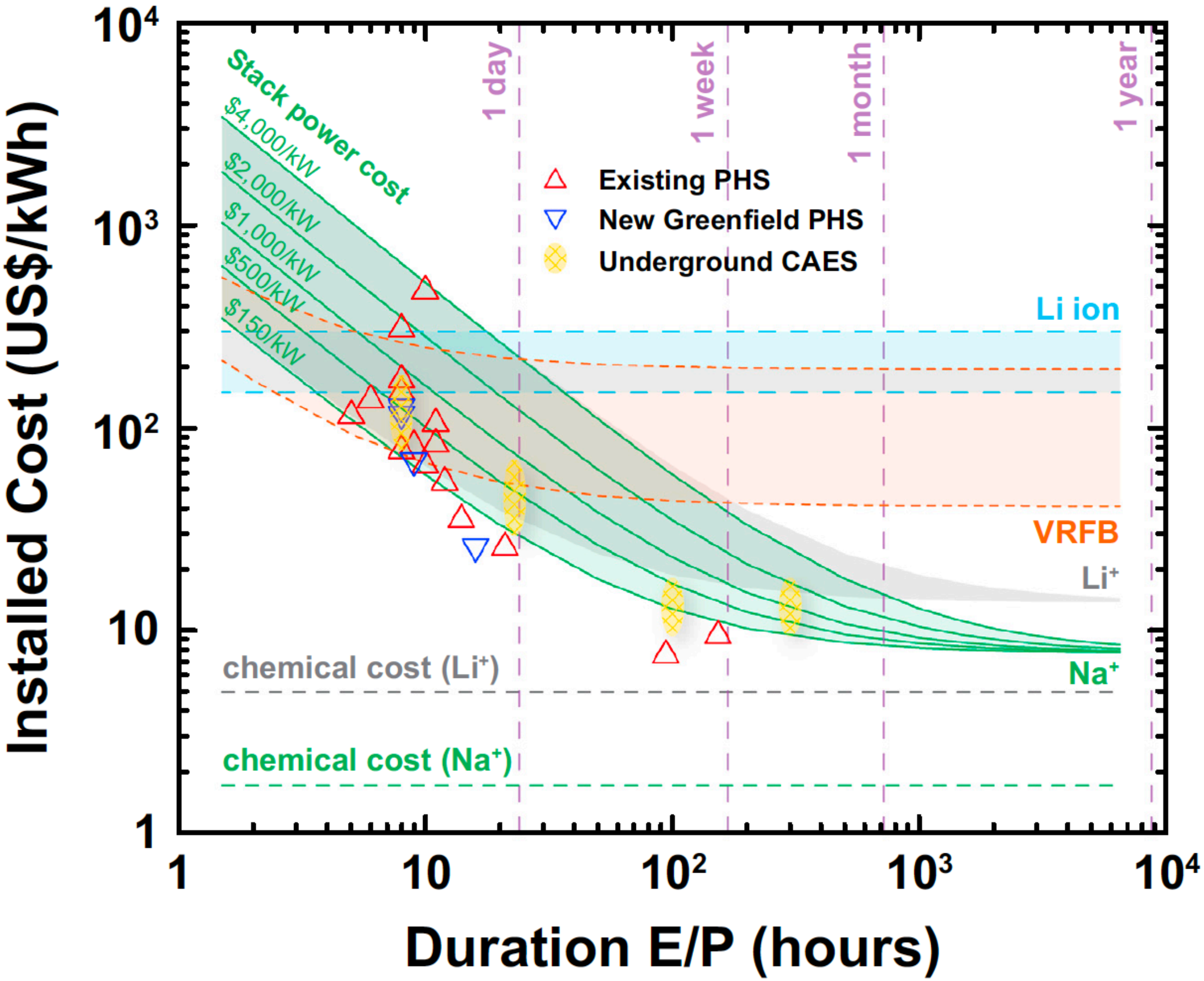
Toshiba 50 MW CO_2
Allam Cycle turbine

New ideas in flow batteries

Air-Breathing Aqueous Sulfur Flow Battery for Ultralow-Cost Long Duration Electrical Storage, Zheng Li … Yet-Ming Chiang, Joule 1, 306–327 (2017)



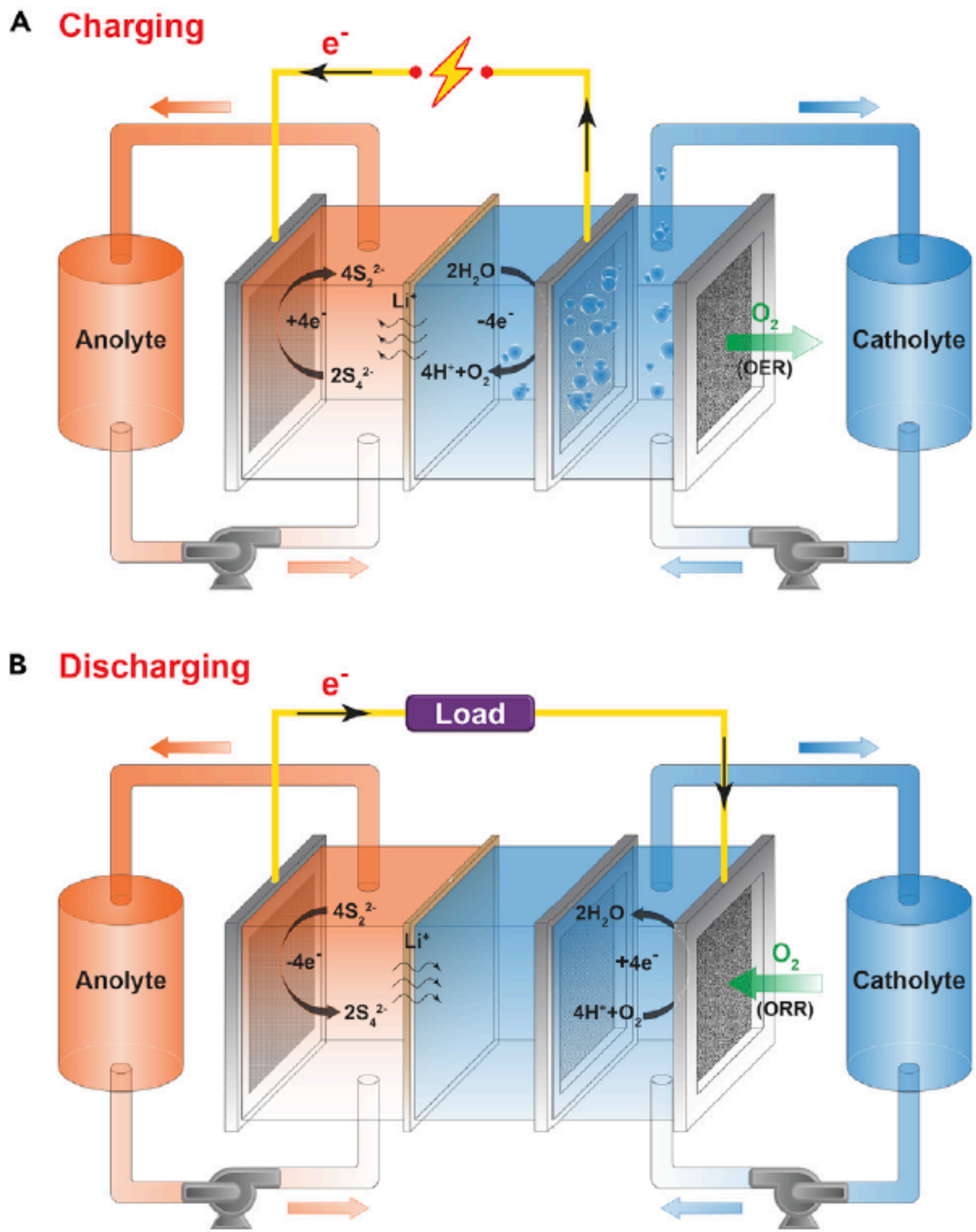
Air-Breathing Aqueous Sulfur Flow Battery for Ultralow-Cost Long Duration Electrical Storage, Zheng Li … Yet-Ming Chiang, Joule 1, 306–327 (2017)



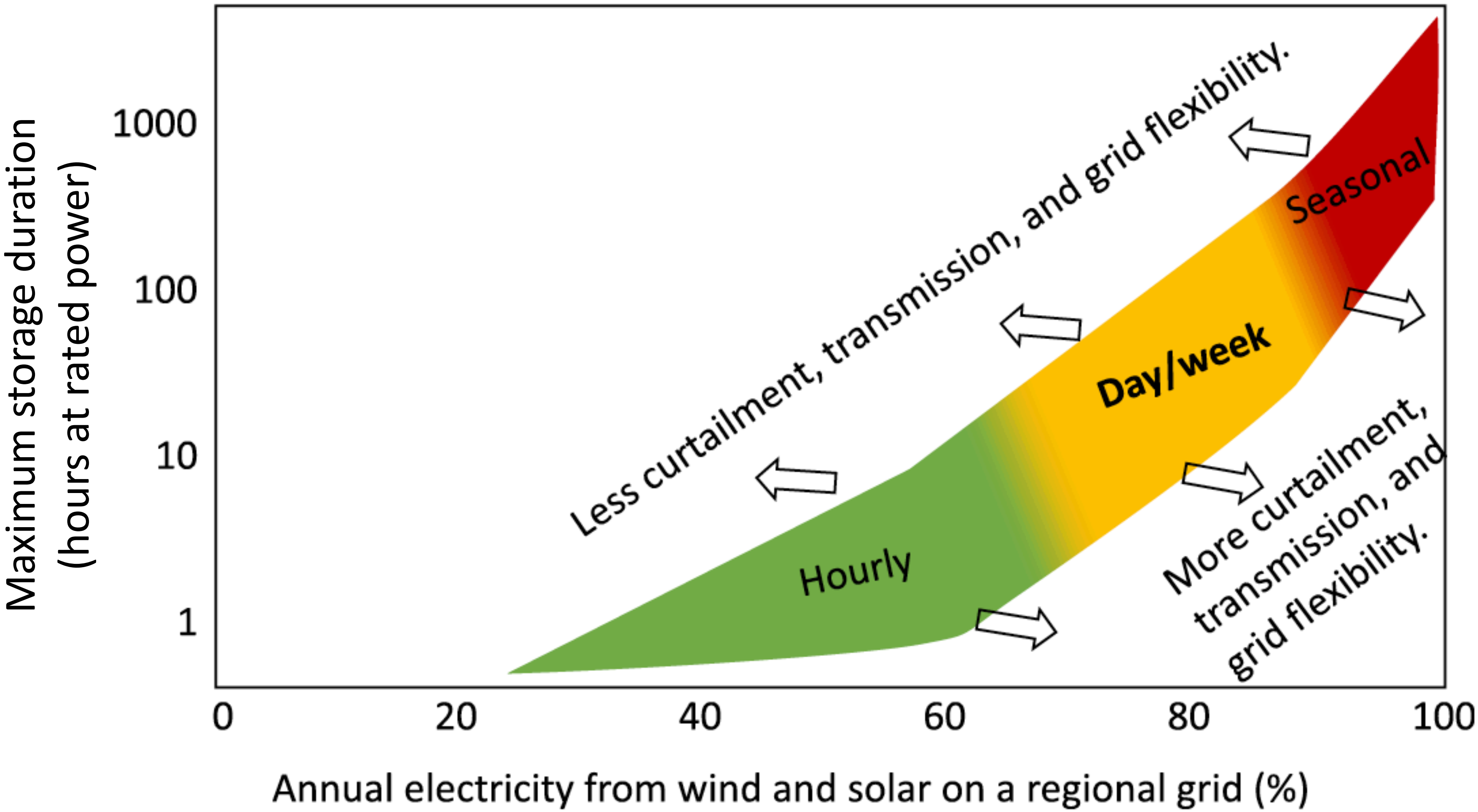
PHS (pumped hydro storage)

CAES (compressed air energy storage)

VRFB (vanadium redox flow battery)


A
Charging
e-
Anolyte
4S22-
+4e-
2S42-
Li+
2H2O
-4e-
4H++O2
O2
(OER)
Catholyte
B
Discharging
e-
Load
Anolyte
4S22-
-4e-
2S42-
Li+
2H2O
+4e-
4H++O2
O2
(ORR)
Catholyte

Summary: There are potentially new energy storage technologies for 100-hour storage (e.g. heat storage). All are focused on minimizing unnecessary entropy generation by mimicking pumped storage



END

Additional slides

Revenue over financial life of project ⟺ total cost of ownership ($/kWh)

$$\sum_{t=1}^{T}(1+r)^{-t}\left[\Delta_{E,t}n_{c,t} + R_{P,t}d^{-1}\right] = \left[C_P d^{-1} + C_{E,th}\eta_D^{-1}\right] + \sum_{t=1}^{T}(1+r)^{-t}\left[n_{c,t}P_{C,t}\left(\eta_{RTE}^{-1} - 1\right) + n_{c,t}VOM_t + d^{-1}FOM_t\right] + C_{Re}(1+r)^{-L/n_c}$$

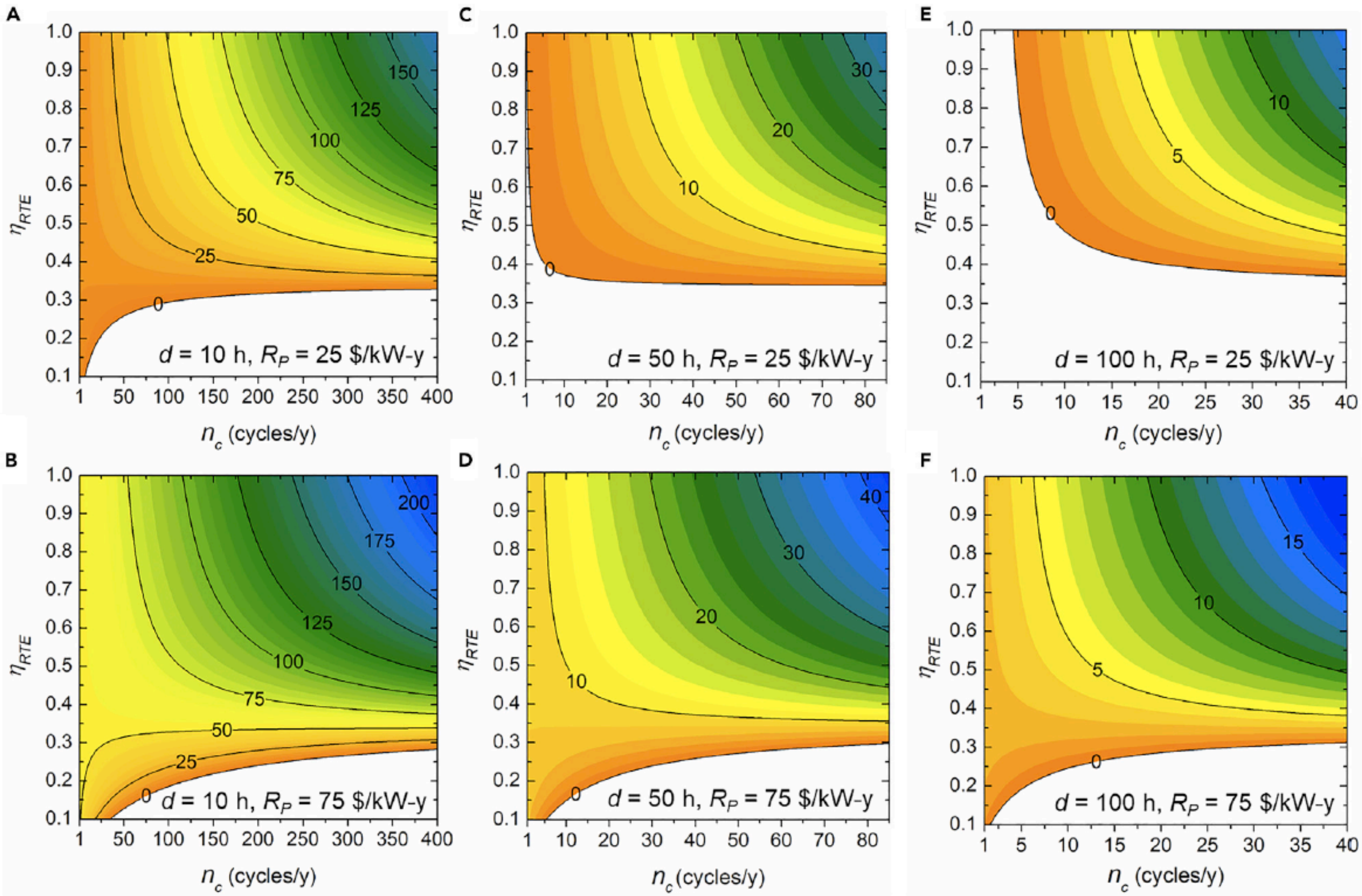
"Long-Duration Electricity Storage Applications, Economics and Technologies," P. Albertus, J. Manser, S. Litzelman, Joule **4**, 21 - 32 (2020)

Abb.	Definition
Δ_E	Price differential of charging/discharging
$C_{E,d}$	Deliverable installed energy cost
$C_{E,th}$	Theoretical installed energy cost (no loss)
C_{eff}	Per-cycle cost of efficiency losses
C_P	Installed power cost
E_r	Rated energy of storage block
n_C	Number of equivalent cycles
P_C	Input charging price
P_r	Rated power capacity
R_P	Revenue from capacity payments
η_D	Discharge efficiency

η_{RTE}	Round trip efficiency
d	Price differential of charging/discharging
DOD	Deliverable installed energy cost
FOM	Theoretical installed energy cost (no loss)
PV_R	Per-cycle cost of efficiency losses
r	Installed power cost
r	Rated energy of storage block
T	Number of equivalent cycles
TCO	Input charging price
VOM	Rated power capacity
C_{Re}	Revenue from capacity payments
L	Discharge efficiency

Revenue from capacity payments at $R_P = \$25/kWh$ and $= \$25/kWh$

"Long-Duration Electricity Storage Applications, Economics and Technologies," P. Albertus, J. Manser, S. Litzelman, Joule **4**, 21 - 32 (2020)



Rated power capacity (*VOM)* = 0.002 \$/kWh-cycle

Installed energy cost (*FOM)* = 1% of installed capital cost (representative of Pumped Storage Hydro)

Input charging price (P_C)= 0.025 \$/kWh-cycle

Δ_E = 0.05 \$/kWh-cycle, no storage medium replacements.

Storage Cost and Performance Characterization Report, K Mongird et al., PNNL (2019)

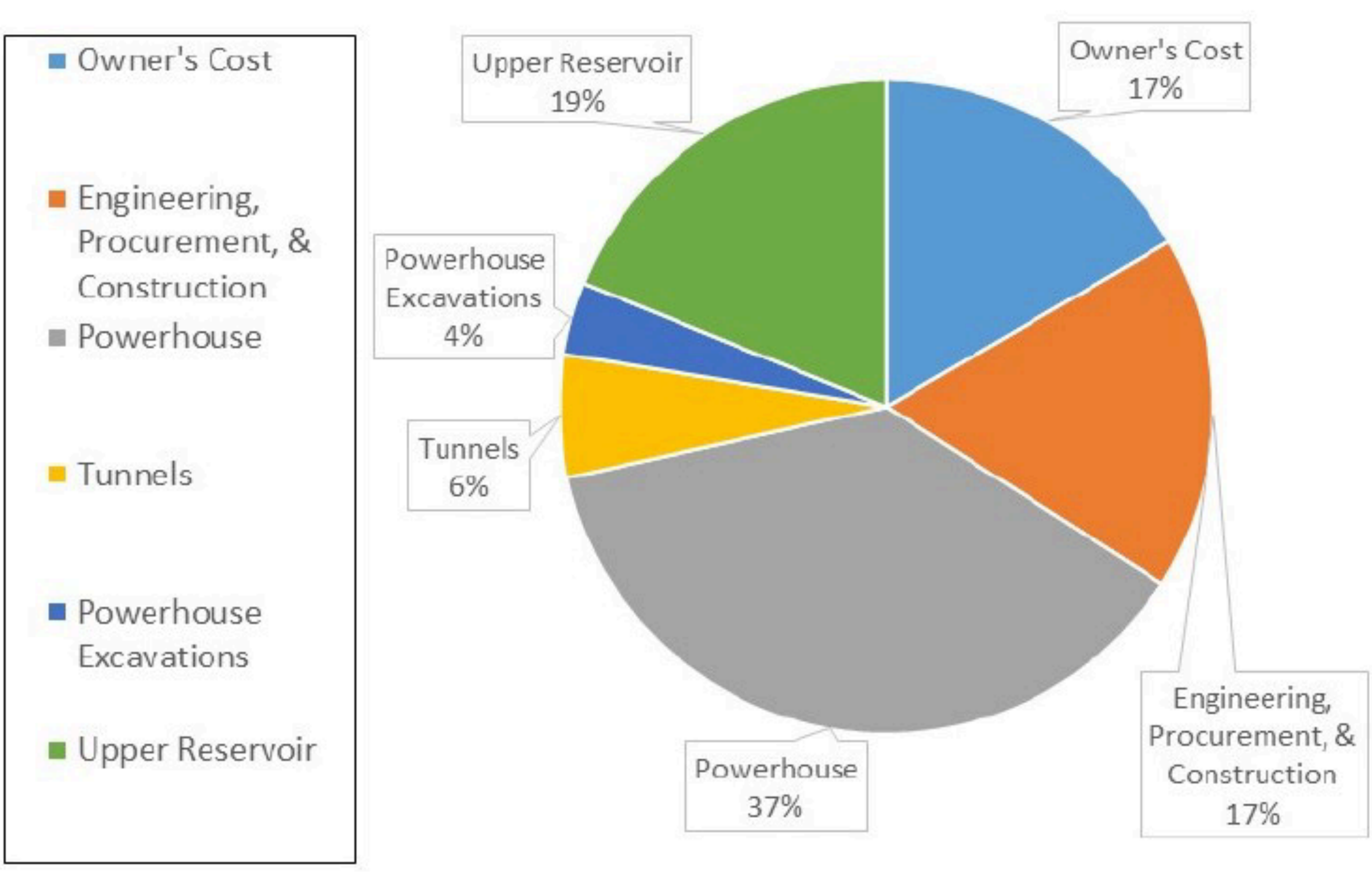
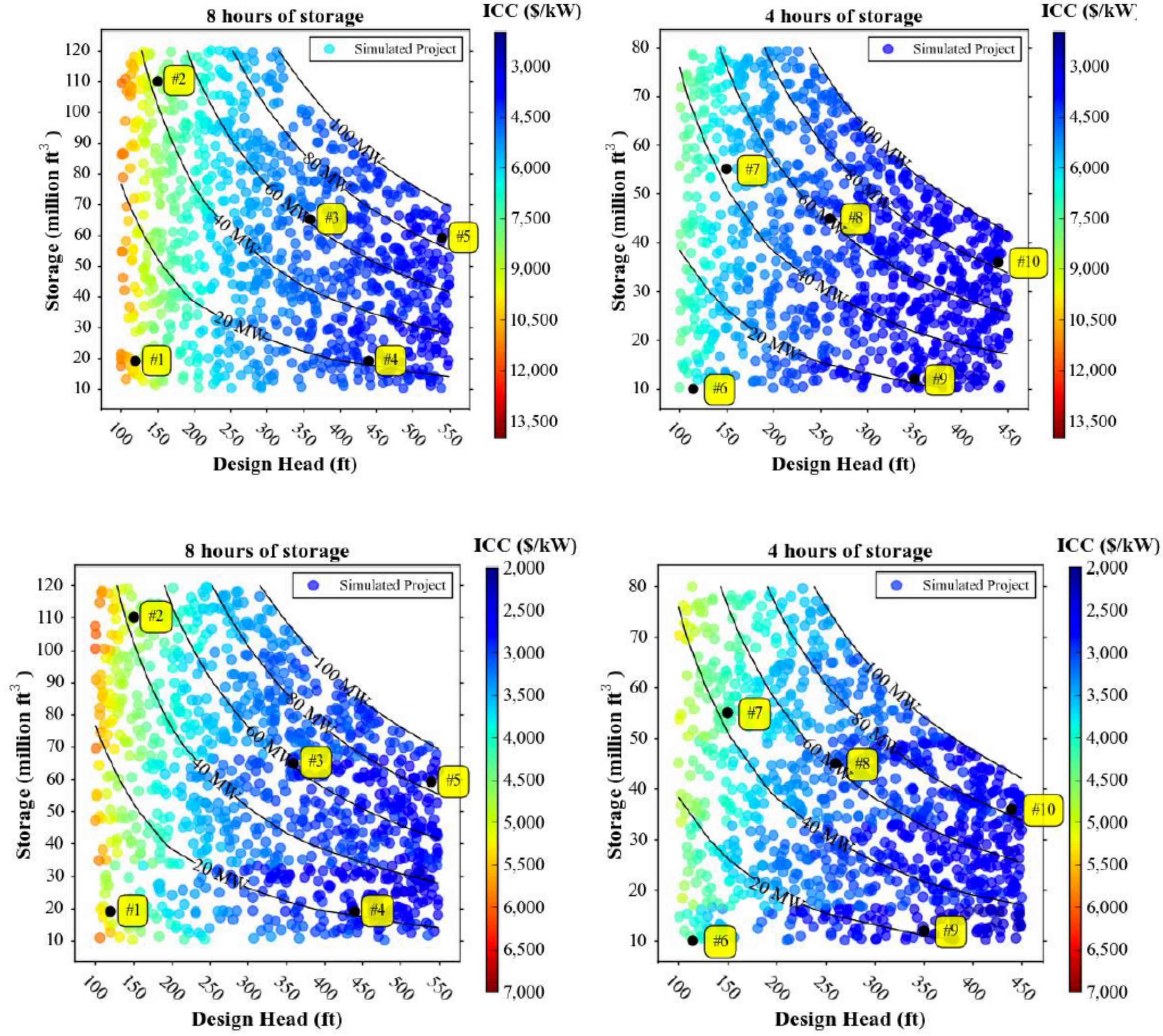


Figure 4.2. Capital cost breakdown for a pumped storage hydro plant.

Test Case 1: Full excavation of two reservoirs is necessary.



DO ENERGY EFFICIENCY INVESTMENTS DELIVER? EVIDENCE FROM THE WEATHERIZATION ASSISTANCE PROGRAM
Meredith Fowlie Michael Greenstone Catherine Wolfram

NATIONAL BUREAU OF ECONOMIC RESEARCH

National Energy Audit Tool (NEAT) produces an estimate of the energy savings and costs associated with different combinations of efficiency measures. The present value of energy savings are calculated using a discount rate of 3% and an engineering estimate of the lifespan of the measures. The WAP program requires that all recommended measures return a minimum of $1.00 in incremental savings for every $1.00 expended in labor and material costs.

WAP is the nation's largest residential energy efficiency program and has provided more than 7 million low-income households with weatherization assistance since its inception in 1976. Recipient households in our study received approximately $5,150 worth of home improvements on average, with zero out-of-pocket costs. The most common measures included fur Nace replacement, attic and wall insulation, and infiltration reduction. Importantly, WAP only pays for energy efficiency measures that pass a cost-benefit test, based on ex ante engineering projections, with the aim of ensuring that only beneficial investments are undertaken.

For Program Year 2010, 65 percent of homes were site-built, 15 percent were mobile family, and 20 percent were large multi-family. Applying the above estimates of savings per unit to the over 800,000 sites ORNL notes are weatherized with ARRA funds over the 2010 to 2013 period implies that there would be an estimated 97 million MMBtu saved as a result of the ARRA funds in the WAP.41 Taking the average of the ORNL savings estimates across site types gives an average savings of 19.63 MMBtu per site per year. Using the EIA (2009b) summary data on household energy consumption and expenditures to estimate average expenditures per MMBtu, the energy savings from WAP lead to an average savings of $444 per year per weatherized site.

ORNL calculates equivalent emissions reductions from PY 2010 energy savings using state specific emissions factors based on state-specific energy portfolios. With this approach they estimate a reduction of 7,382,000 metric tons of carbon. If attributing the MMBtu to a reduction in an energy source with an emissions rate of natural gas, then this energy savings corresponds to a reduction in CO_2 by 403,482 for newly weatherized sites in PY 2010. Applying these estimates to all weatherized sites over the period 2010 to 2015 implies a reduction of over 5 million metric tons of carbon. This calculation is likely an underestimate to the extent that energy savings offset energy use from more carbon-intensive sources (e.g., electricity use from coal-fired generation).

“Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program, Meredith L. Fowlie, Michael Greenstone, Catherine Wolfram, Quarterly Journal of Economics (2018), 1597–1644. doi:10.1093/qje/qjy005.

The study was conducted in southeast Michigan. To select the study sample, we first identified census blocks that had high rates of home ownership, high rates of natural gas heating, and household incomes that would qualify for weatherization assistance… From this group we drew a sample of over 30,000 households. Approximately one-quarter of these were randomly assigned to an encouragement “treatment.” The remaining “control” households were free to apply for WAP but were not contacted or assisted in any way by our team.

Encouragement activities ran from March to May 2011. During the encouragement phase, field staff made almost 7,000 initial in person house visits, and with 23,500 targeted robo-calls to raise awareness of the weatherization program and our encouragement campaign.

Storage Cost and Performance Characterization Report. K Mongird et al., PNNL (2019)

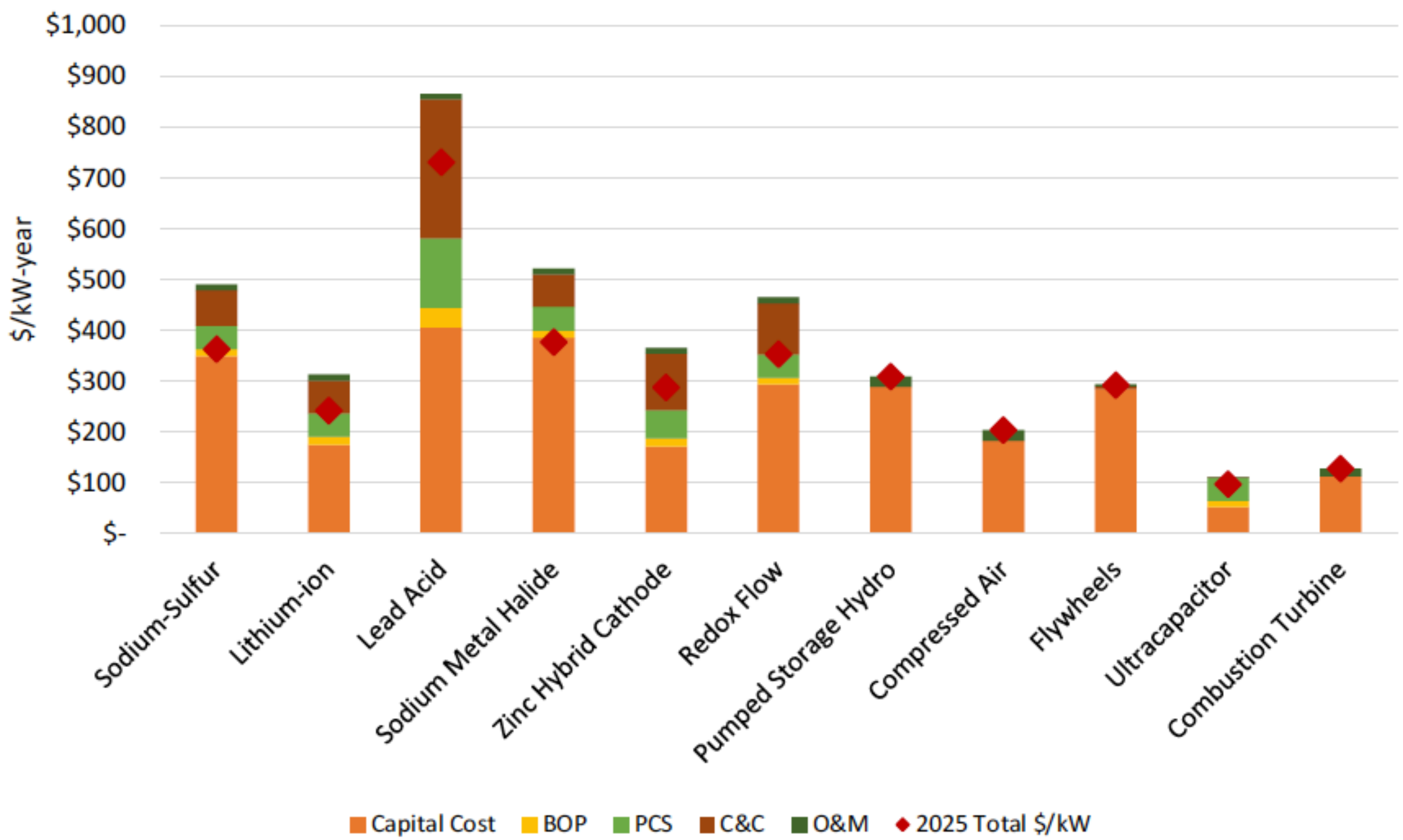


Figure 5.5. Annualized $/kW cost of all technologies.

Table 19. CAES and LAES Comparison

Item	Compressed Air Energy Storage	Liquid Air Energy Storage
General Criteria		
Commercial status (developmental, commercial, mature)	Commercial	No Commercial Operation
Number of plants to date	2 to 3 commercial plants currently operational	1 pilot plant worldwide
Year of first operation	1978	2010
Typical project lead times (months)	24 to 28 months	Not enough data available
Footprint or energy density (ft^2 per MW)	20 acres for 135 MW Block	Not enough data available
Applicability for long-term operation- multiple hour operation (e.g., peak shaving, sustained outages)	Peak shaving and Intermediate Service (8 hours of daytime operation w/ 8 hours of compression at night typical)	Peak shaving and Intermediate Service (8 hours of daytime operation w/ 8 hours of compression at night typical)
Applicability for short-term operation- subhourly operation (e.g., power quality applications)	Similar characterstics to a simple cycle gas turbine, provided compressed air is available.	Similar characterstics to a simple cycle gas turbine, provided compressed air is available.
Potential environmental/regulatory factors	Plant emissons similar to simple cycle gas turbine application. Compressors require cooling water supply (mechanical draft cooling tower required).	Plant emissons similar to simple cycle gas turbine application. Compressors require cooling water supply (mechanical draft cooling tower required).
Electrical transmission considerations	Same as a simple cycle gas turbine.	Same as a simple cycle gas turbine.
Vehicular access and local infrastructure considerations	Same as a simple cycle gas turbine. Natural gas pipeline required.	Same as a simple cycle gas turbine. Natural gas pipeline required.
Geological or topographic factors	Solution mined salt cavern, aquifer, or mined hard rock cavity (limestone mines) required.	No major geological requirements
Required size of interconnection (kV)	230 kV or higher	230 kV or higher
Technology risks	Limited suppliers available, integrity of cavern used for storage of compressed air.	Existing components are mature technology, but the overall system lacks maturity that other energy storage systems have.
Potential fatal flaws to commercial viability	Satisfactory Geology	System lacks maturity that other energy storage processes have
Staffing requirements (# full time staff members for 100 MW Facility)	2 hourly, 6 salaried	2 hourly, 6 salaried
Performance Characteristics		
Range of power capacity (MW)	100 MW +	100 MW +
Range of discharge time (hrs)	8 hours typical	4 hours typical
Range of energy capacity (MWh)	800 MWh +	400 MWh +
Average Annual Availability (% of time)	93%	Not enough data available
Typical Plant Capacity Factor	23.7%	12%
Expected life of equipment (years)	30	30
Gross Plant Output (MW), Average Ambient Day	101.0	100.0
Aux Power (MW), Average Ambient Day	1.01	-
	1.0%	-
Net Plant Output (MW), Average Ambient Day	100.0	-
Net Plant Heat Rate (btu/kWhr), Average Ambient Day	4436	4436
% of Energy Recovered From Compression	83.4%	-
Net Plant On Peak Efficiency (Gas Turbine Efficiency)	76.92%	-
Complete Plant Turn around efficiency (AC-AC efficiency) (%)	64.11%	60%
Basis for Cost Estimates (costs are expressed in 2017 US dollars)		
EPC Cost ($/kW)	$1,200 - $1,400 per kW	-
Total Project Cost including Caverns ($/kW)	$2,000 - $2,300 per kW	$2,000 - $4,000 per kW
Cost to Solution Mine Salt Caverns	$68 MM	Not Applicable
Estimated fixed operations and maintenance cost ($ per kW)	$18.90	-
Estimated variable O&M cost (excluding fuel & electric costs) ($ per MWH)	$2.30	$2.0-$2.50

Table 20. Pumped Hydro Storage Overview

Item		General Pumped Hydro Projects				
		General	Single Speed	Variable Speed	Closed Loop(1)	Open Loop(2)
General Criteria						
1	Commercial status (developmental, commercial, mature)	mature	mature	commercial	mature	mature
2	Number of plants to date (United States)	40	40	0 (10 worldwide)	18	22
3	Year of first operation (United States)	1929	1929	1990 (Japan)	1963	1929
4	Typical project lead times (years)	5 licensing 5 construction	5 licensing 5 construction	5 licensing 5 construction	< 5 licensing 5 construction	> 5 licensing 5 construction
5	Footprint or energy density (MWh/ft^2)	Varies depending upon head and reservoir size, for example, Bath County has 700 acres for 2700 MW				
6	Applicability for long-term operation- multiple hour operation (e.g., peak shaving, sustained outages)	Load shifting and peak shaving (8 hours of daytime operation w/ 12 hours of pumping), with sufficiently sized reservoirs, weekly and seasonal storage available				
7	Applicability for short-term operation- subhourly operation (e.g., power quality applications)	load following, frequency regulation, spinning reserve, for both single and variable speed. variable speed provides faster response times and finer adjustments				
8	Potential environmental/regulatory factors	vary widely from site to site. may include land use, recreation and fisheries issues	vary widely from site to site. may include land use, recreation and fisheries issues	vary widely from site to site. may include land use, recreation and fisheries issues	generally fewer impacts and shorter licensing period than open loop	generally more impacts and longer licensing period than closed loop
9	Electrical transmission considerations	proximity to transmission line can affect project economics				
10	Required size of interconnection (kV)	>230 to 500 kV preferred				
11	Vehicular access and local infrastructure considerations	projects may be in remote locations. roads, additional construction material transportation cost, and electrical transmission may be included in total project cost.				
12	Geological or topographic factors	short length of conveyance and high head create better project economics	short length of conveyance and high head create better project economics	short length of conveyance and high head create better project economics	makeup water for the reservoirs must be considered (but generally easy to overcome)	may have more fisheries and environmental considerations than a closed loop system.
13	Technology risks	tunneling, sedimentation, seismology	generating technology is proven	variable speed not implemented in US, but has been proven internationally	tunneling, seismology, makeup water for reservoirs	tunneling, sedimentation, seismology
14	Potential fatal flaws to commercial viability	environmental fatal flaws, seismology, project financing	environmental fatal flaws, seismology, project financing	environmental fatal flaws, seismology, project financing	environmental fatal flaws, seismology, project financing	environmental fatal flaws, seismology, project financing
15	Staffing requirements (# full time staff members for 1000 MW facility)	15 to 25 depending on asset portfolio in region				
Performance Characteristics						
1	Range of power capacity of plant (MW)	9 - 2800	9 - 2800	85 - 600 (internationally)	28 - 2700	9 - 2000
2	Range of discharge time (hrs)	5 - 100+	5 - 100+	same capacity as single speed (NA in US)	5 - 100+	9 - 100+
3	Range of energy capacity (MWhr)	87-370,000	87-370,000	same capacity as single speed (NA in US)	247-190,000	87-370,000
4	Annual forced outage rate (% of time)	0-3%				
5	Expected life of generating equipment (years)	20+				
6	Expected life of project (years)	50+				
7	Expected life of project (number of cycles)	>10 cycles/day/year for 50 years				
8	Parasitic load (for a 1000 MW plant) (MWhr/year)	5 MW				
9	Turn around efficiency (AC-AC efficiency) (%)	75 - 80%	75 - 80%	80 - 82%	75 - 80%	75 - 80%
Basis for Cost Estimates (costs are expressed in 2017 US dollars)						
1	Range of capital cost ($ per kW)	$1,500-$4,700 per kW				
2	Range of operations and maintenance cost ($ per kW-yr)	$6.2-$43.3				
3	Biannual Outage Costs (for a 1,000 MW project)	$280,000				
4	Major Maintence Costs (for a 1,000 MW project at year 20)	$6,700,000				
5	Replacement frequency (years)	20				

1. Closed loop system- A pumped storage system in which the upper and lower reservoirs are connected by a relatively short water conveyance system and the dams are not on a main-stem river.
2. Open loop system- A pumped storage system in which one or more of the dams are on a main-stem river.
3. O&M Cost/MW based on largest and smallest pumped storage plants in US

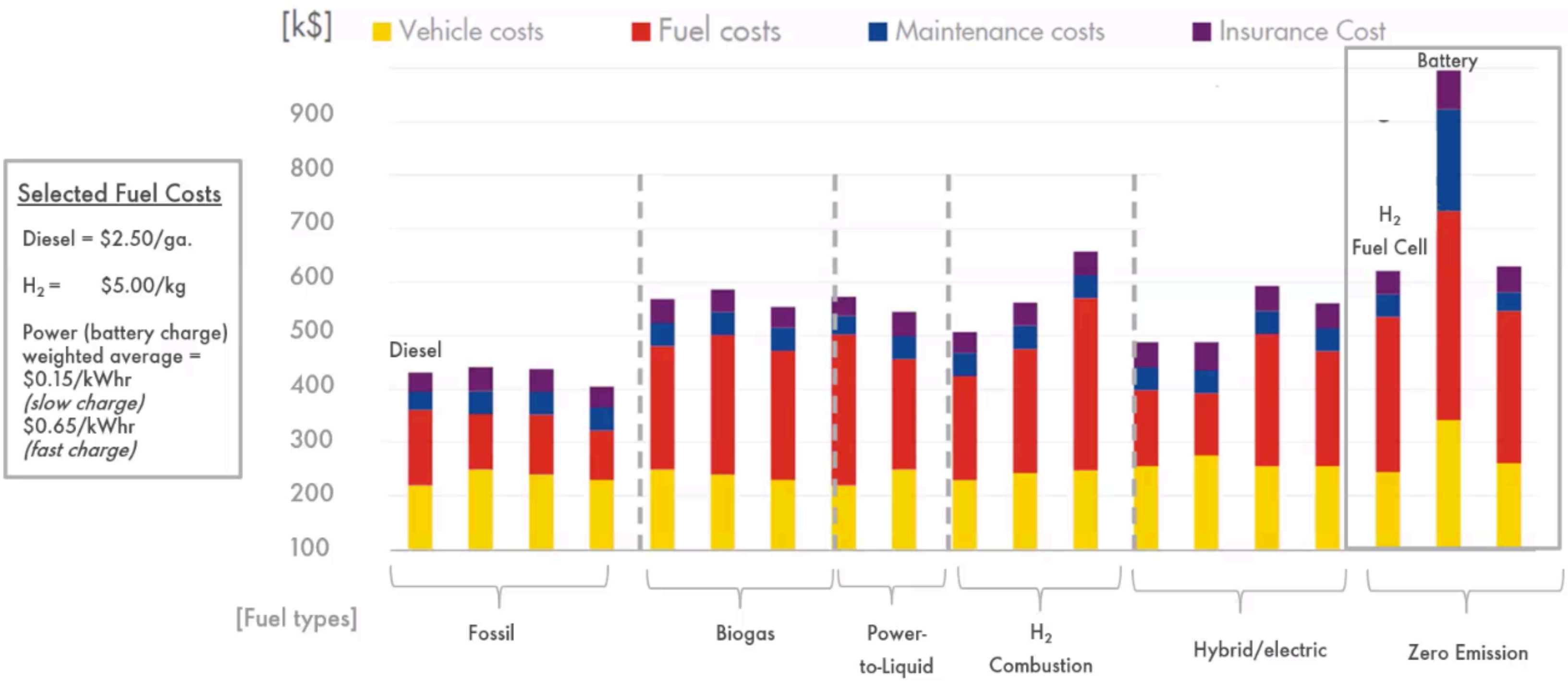
Variable Speed Pump-turbines

Variable speed pump-turbines have been used since the early to mid-1990’s in Japan and late 1990s in Europe. They are being increasing considered during project development in Europe and Asia due to a high percentage of renewable energy penetration. In California, three large pumped storage projects in development are considering variable speed technology almost exclusively due to the growing need for detrimental reserves at night, enabling greater penetration of variable renewable energy resources. Although the technology has been in place since the 1990’s, major equipment vendors are continuously redesigning the equipment to improve performance.

I

n a conventional, single speed pump-turbine, the magnetic field of the stator and the magnetic field of the rotor always rotate with the same speed and the two are coupled. In a variable speed machine, those magnetic fields are decoupled. Either the stator field is be decoupled from the grid frequency using a frequency converter between the grid and the stator winding, or the rotor field is decoupled from the rotor body by a multi-phase rotor winding fed from a frequency converter which is connected to the rotor. Table 15 provides a summary comparing the operational characteristics and advantages/disadvantages of single and variable-speed turbine units for an example project. Actual benefits will vary depending on specific site characteristics. Because of the multiple advantages, variable-speed units have been discussed in this report.

2030 TCO for Class 8 trucks shows Fuel Cell drivetrains are least cost Zero Emission solution, using 100% renewable hydrogen fuel



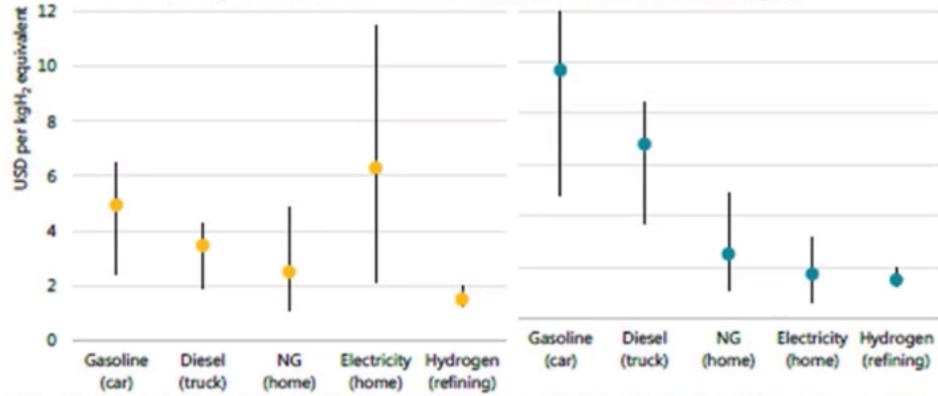
Selected powertrains (diesel, fuel cell and battery) are highlighted. TCO is calculated over 6 years, assuming 130,000 km driven p.a

Source: various, Shell Analysis 2020

Viability of Hydrogen Economy?

Price paid for energy services

Figure 65. Today's fuel prices in hydrogen-equivalent terms on an energy basis (left) and accounting for the relative efficiencies to provide the same service (right)



Notes: Average prices paid in IEA countries plus China. Prices include taxes and tariffs. Fuel cell and motor drivetrain assumed to be 96% more efficient than an internal combustion engine. Heat pump assumed to be 3.6 times more efficient than heating with hydrogen. NG = natural gas.

Source: IEA (2018a), *World Energy Prices 2018*.

After accounting for the efficiency of converting hydrogen to motive power, the price paid by car drivers for gasoline is equivalent to nearly USD 10/kgH₂, which is achievable for delivered hydrogen costs in many regions by 2030.

IEA (2019). https://www.iea.org/reports/the-future-of-hydrogen

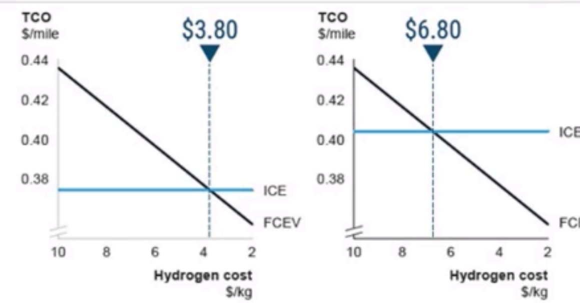
H2 Mobility Comparative Analysis of Infrastructures: Hydrogen Fueling and Electric Charging of Vehicles, Martin Robinius, Jochen Linßen, Thomas Grube, Markus Reuß, Peter Stenzel, Konstantinos Syranidis, Patrick Kuckertz and Detlef Stolten, Energie & Umwelt / Energy & Environment Band / Volume 408 ISBN 978-3-95806-295-5: **Forschungszentrum Jülich Research Centre and the H2 Mobility**

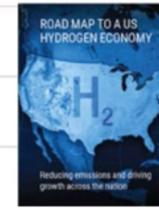
Total cost of ownership SUV

http://www.fchea.org/us-hydrogen-study (2020)

Exhibit 38
SUV TCO analysis
TCO per mile ($/mile) in 2030

	Assumption 1 ICE efficiency of 39 mpg	Assumption 2 ICE efficiency of 29 mpg
Capex[1,2]	FCEV: Hyundai Nexo – 39K ICE: Honda Pilot – 32K	FCEV: Hyundai Nexo – 39K ICE: Honda Pilot – 32K
Lifetime	200,000 miles ~35 miles/day	200,000 miles ~35 miles/day
Efficiency	FCEV: 5 kWh battery 0.015 H_2 kg/mile (67 GGE[3]) ICE: 39 mpg[4]	FCEV: 5 kWh battery 0.015 H_2 kg/mi. (67 GGE[3]) ICE: 29 mpg[5]
Break-even price of hydrogen at the pump	$3.80	$6.80





Infrastructure

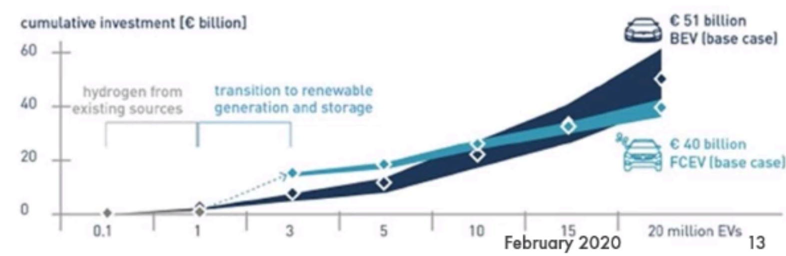
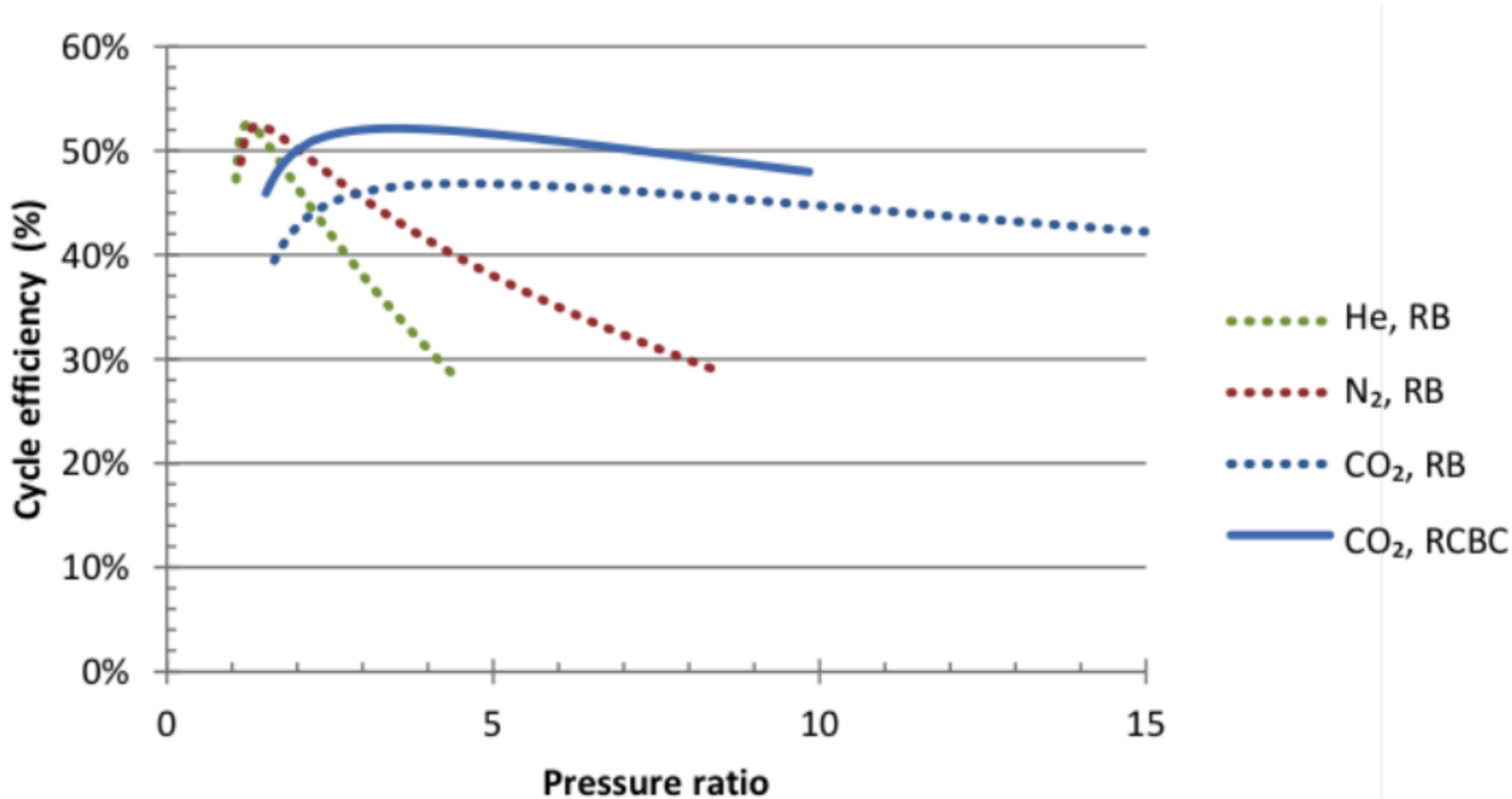


Figure 0-2: Comparison of the cumulative investment of supply infrastructures.

Figure 4.R.9 Recompression Brayton Cycle Efficiency.[17] Plot shows cycle efficiency versus pressure ratio for RCBC (solid line) and Recuperated Brayton Cycle (dashed lines, RB).

Credit: NETL



High exit pressures require stronger materials while higher working densities dramatically decrease the size of the turbine

Figure 4.R.3 Maximum Simple Brayton Cycle Efficiency varies strongly with turbine exit pressure for CO_2. Plot of cycle efficiency versus turbine exit pressure ratio for three different working fluids and turbomachinery isentropic efficiencies of 0.9.[9]

Credit: NETL

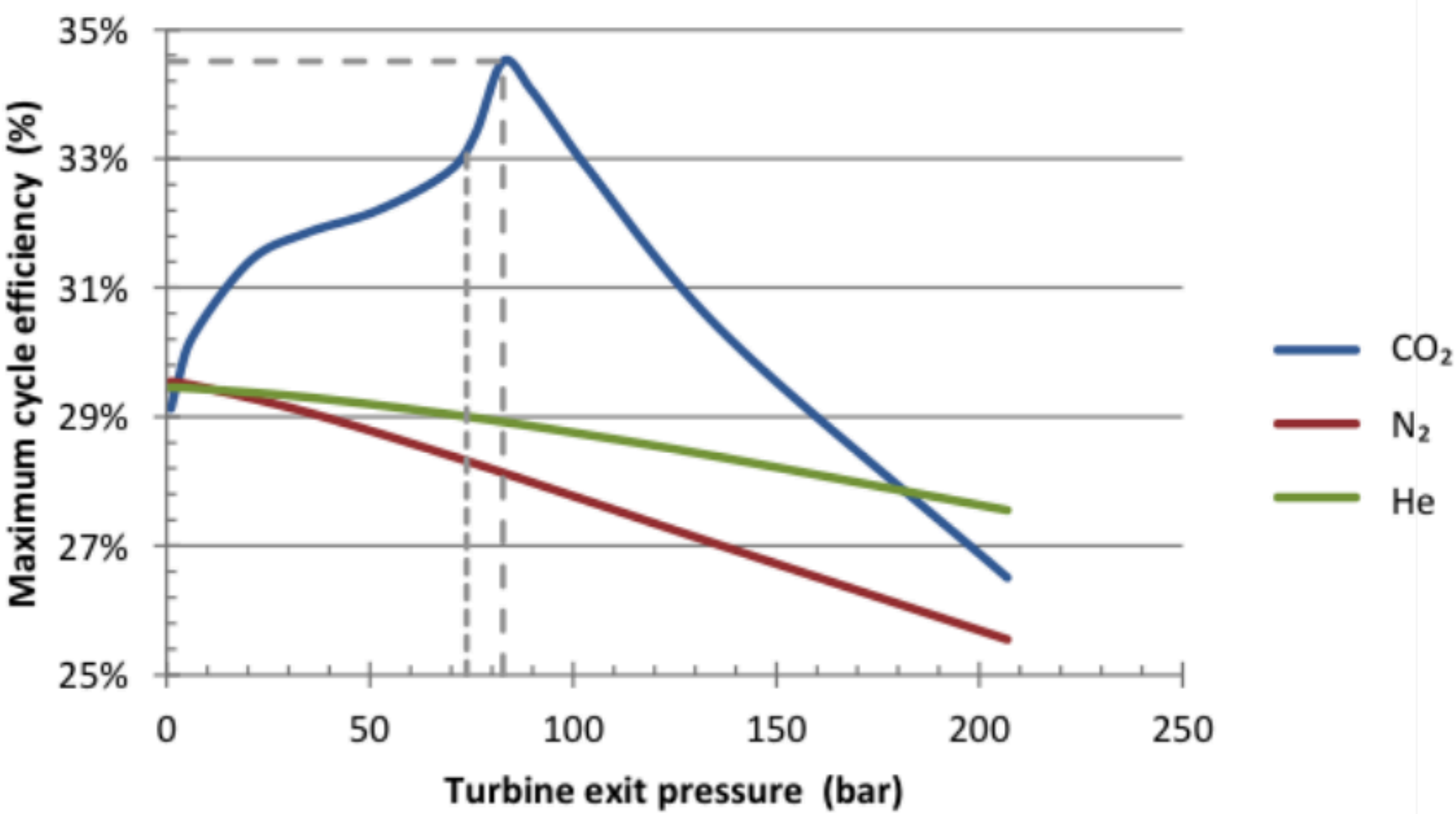
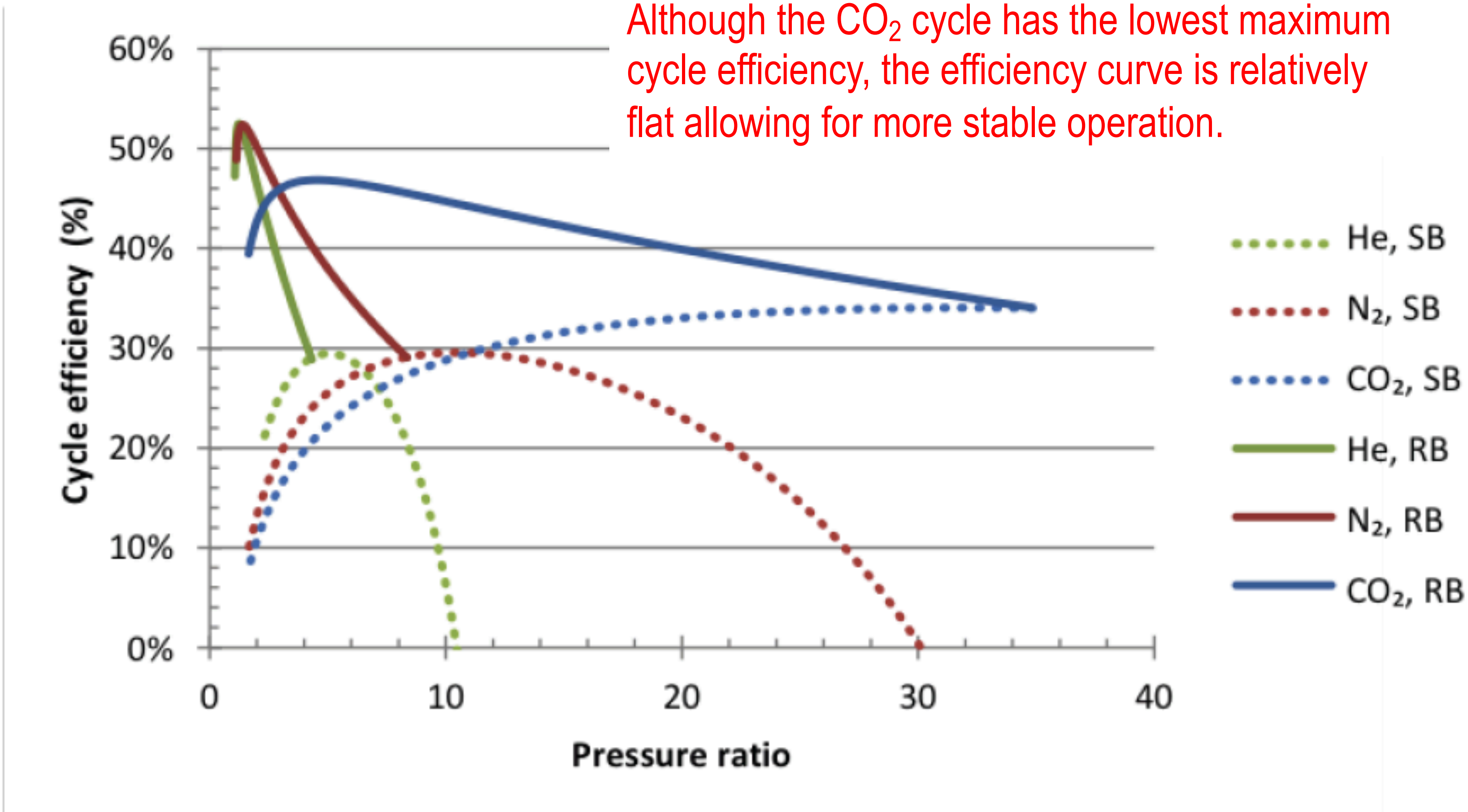


Figure 4.R.6 Recuperated Brayton Cycle Efficiency. Plot of cycle efficiency versus pressure ratio for recuperated Brayton cycle (solid lines, RB) with three working fluids compared to the simple Brayton cycle (dashed lines, SB).[12]

Credit: NETL



Although the CO_2 cycle has the lowest maximum cycle efficiency, the efficiency curve is relatively flat allowing for more stable operation.