“Carnot Batteries” for electricity storage

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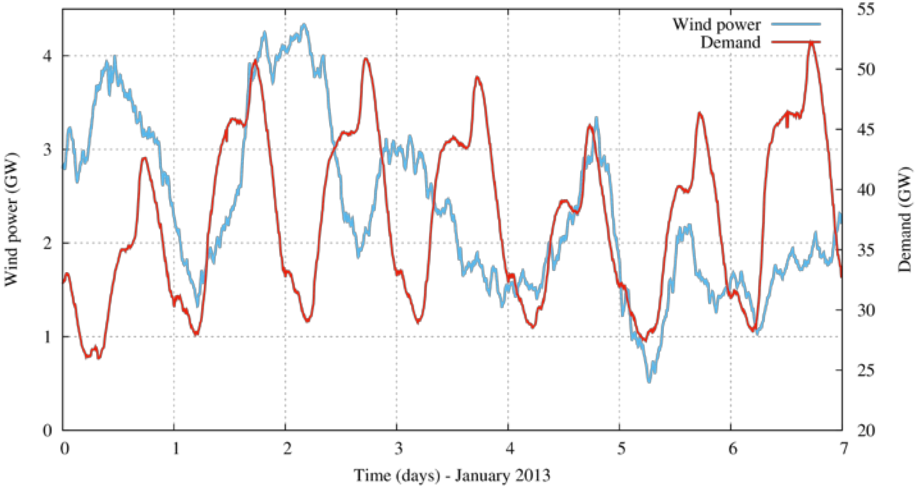
Yale Blueprint Webinars: The Next Step? NREL and Malta discuss Thermal Energy Storage Solutions

December 4, 2019

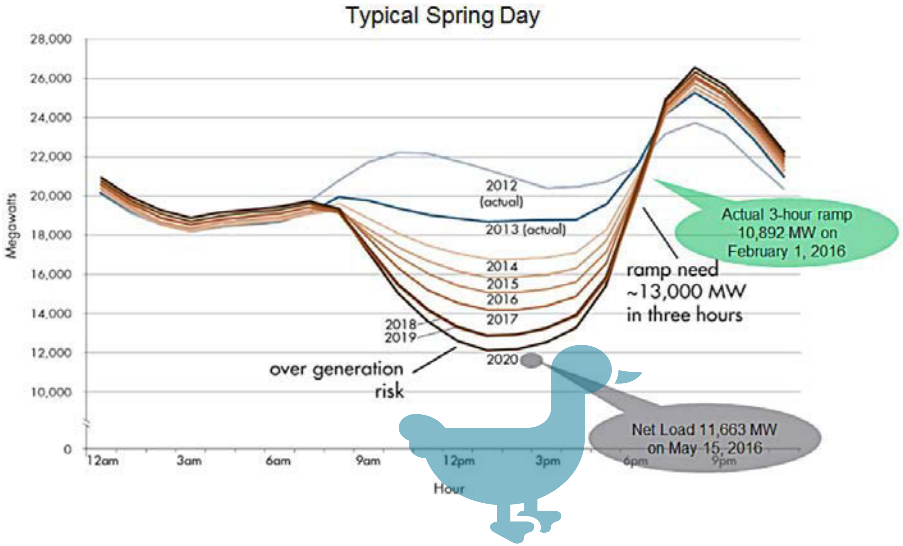
Crescent Dunes Solar Energy Facility, USA

1. Grid Energy Storage: requirements and technologies
2. Carnot Batteries: concept and history
3. Advantages of Carnot Batteries
4. Commercial interest
5. Research projects
6. Summary

Why?: Slews and Lulls



Variable wind and demand (UK January 2013)

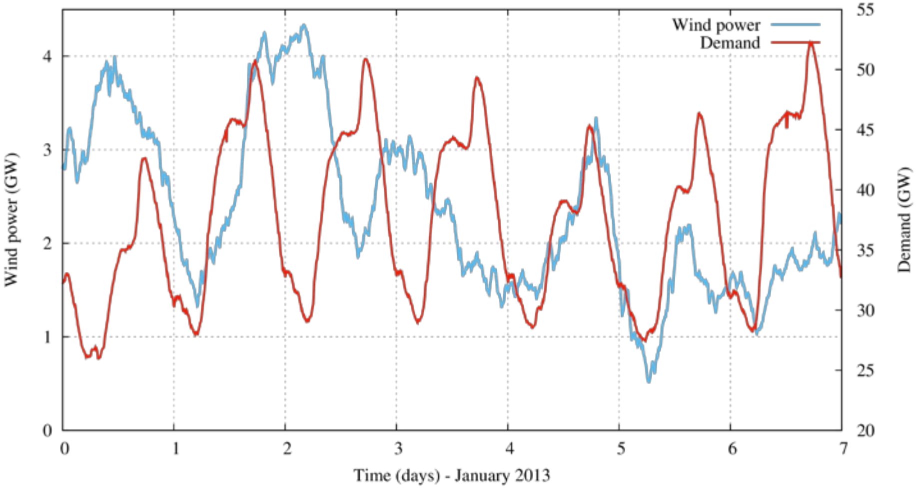


The Duck Curve (California)
Net load = Total demand – variable renewables

https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

Ramps/slews demonstrate required power capacity

Why?: Slews and Lulls



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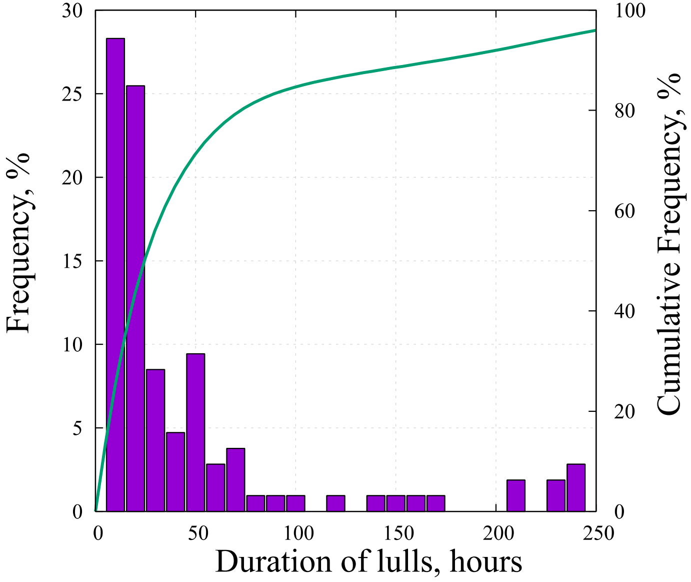
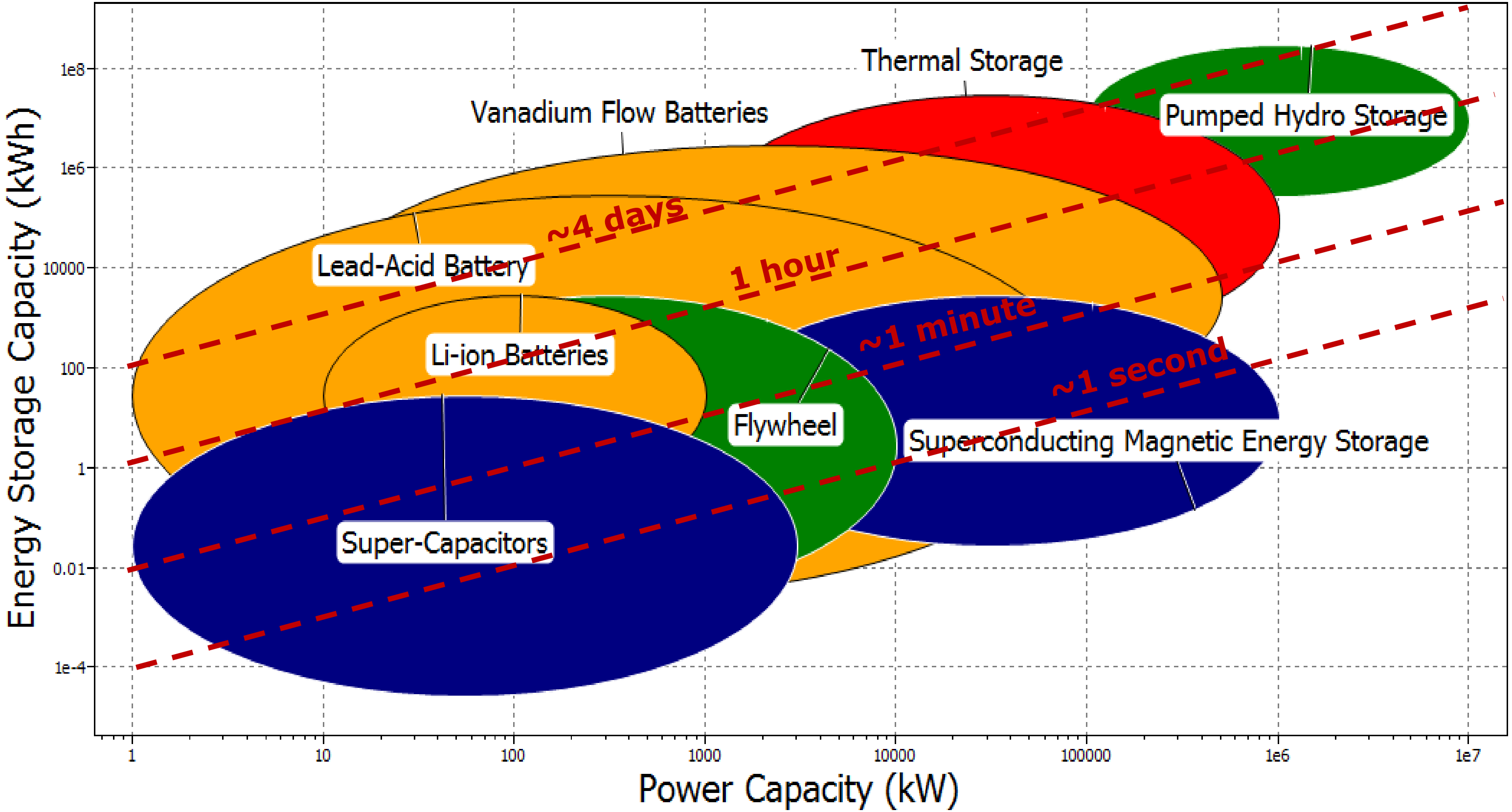


Lulls in renewable supply can indicate the required energy capacity

Existing Storage Technologies



Existing Storage Technologies

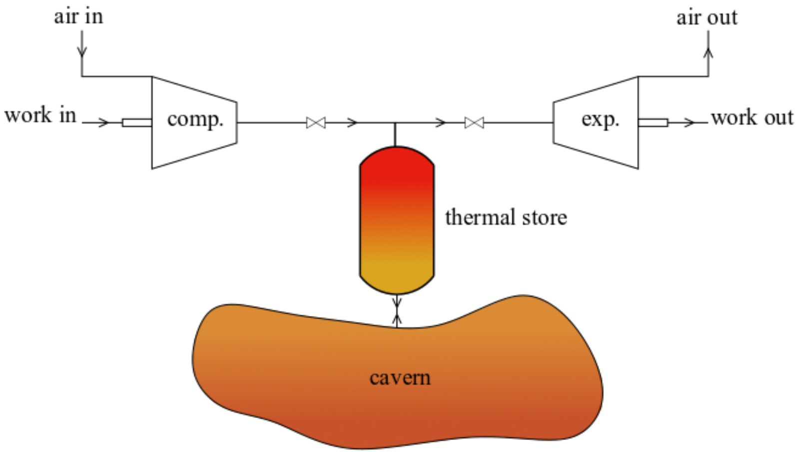
Pumped Hydro-Electric Storage

- 184 GW installed globally
- Fast response
- Most US and UK plants installed 40-60 years ago
- Create underground reservoir?

The upper reservoir of the Ffestiniog power station, Wales (taken by Adrian Pingstone in 1988)

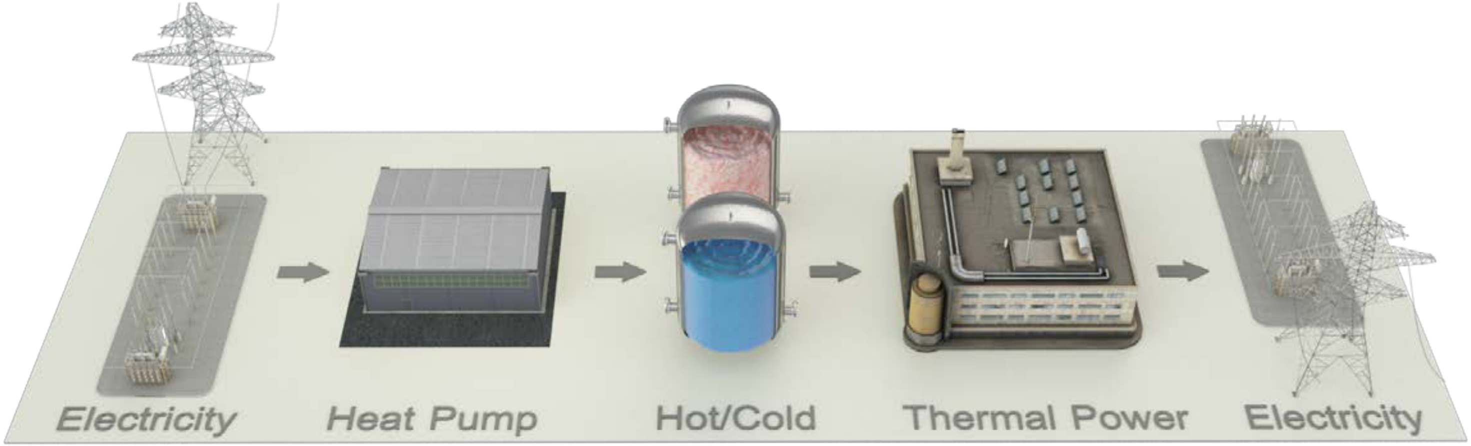
Compressed Air Energy Storage

- Two existing plants (1978 and 1991)
- Huntorf (Germany) = 290 MW_e
- McIntosh (Alabama) = 110 MW_e
- 1 GW_e plant to be developed in Utah?



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

Carnot Battery advantages

- No geographical constraints
- Can use cheap, abundant, sustainable, non-toxic storage materials
- Can use existing technologies – e.g. from CSP industry
- Modular
- Integrates with other systems

Carnot Battery History

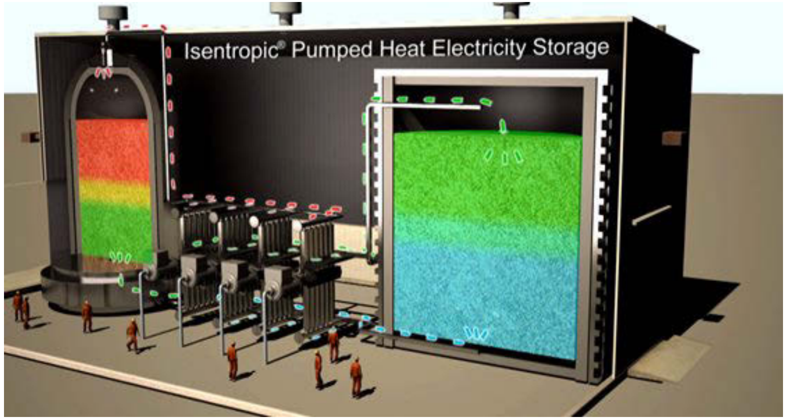
1924 – first patents to Maguerre

1970s – patents to Cahn, Smith (LAES), Babcock

2000s – concept revived in UK (Isentropic Ltd. + Cambridge) and France (CEA+Saipem) and Switzerland (ABB) simultaneously

2010s – Active research globally. Isentropic Ltd. builds prototype, sells to Newcastle University, UK. Various DOE funding awarded.

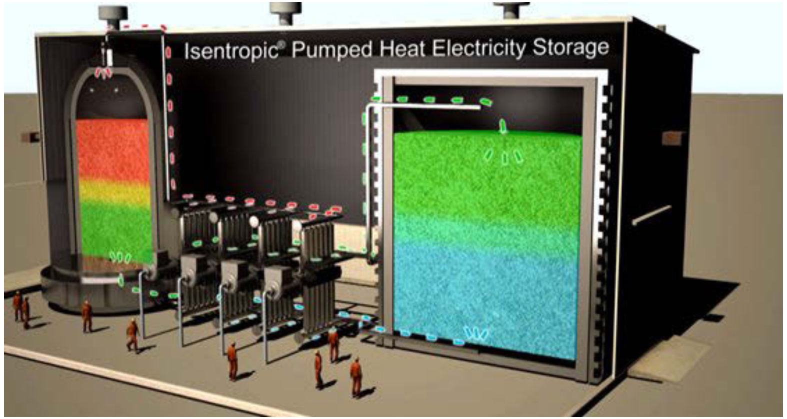
Commercial interest: Siemens Gamesa/Stiesdal Storage Technologies, Malta Inc (Google X), Highview Power, Isentropic Ltd., ABB, WindTP, Echogen, Brayton Energy



Carnot Battery History

Proliferation of names:

- Pumped heat electricity storage
- Pumped thermal electricity storage
- Electro-thermal electricity storage
- Thermo-electric energy storage
- Thermal Batteries
- Carnot Batteries
- …
- Liquid Air Energy Storage



The Carnot Battery

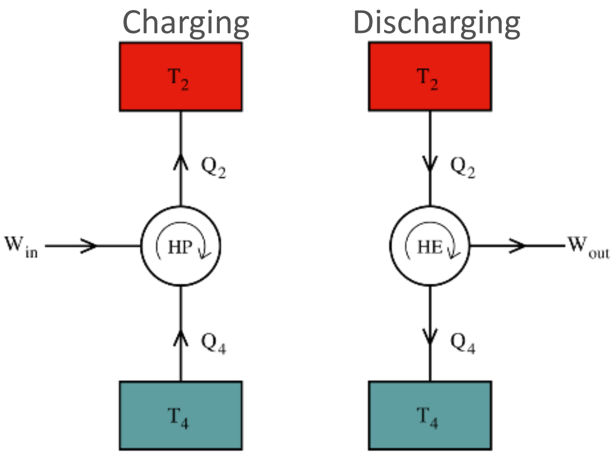
- Carnot cycles are:
  - Reversible
  - Isentropic (no entropy generation)

Thermodynamic jargon

Maximum Carnot Battery round-trip efficiency = 100 %

- However ….
- A Carnot efficient engine has never been demonstrated
- A "non-Carnot" Battery has a round-trip efficiency of 40 – 70 %

Sadi Carnot (1796 – 1832)



HEAT PUMP

HEAT ENGINE

Grid Electricity Storage

		Carnot Batteries	PHS	CAES	Li-ion
Round-trip efficiency	%	40 – 70	60 – 80	50 – 70	80 – 90
Energy density	kWh / m^3	50	1.4	10	250 – 750
Cost (energy)	$ / kWh	25 – 250	5 – 100	2 – 50	200 – 800
Cost (power)	$ / kW	300 – 2800	600 – 2000	400 – 800	1000 – 1700

Are these believable?

Data from:

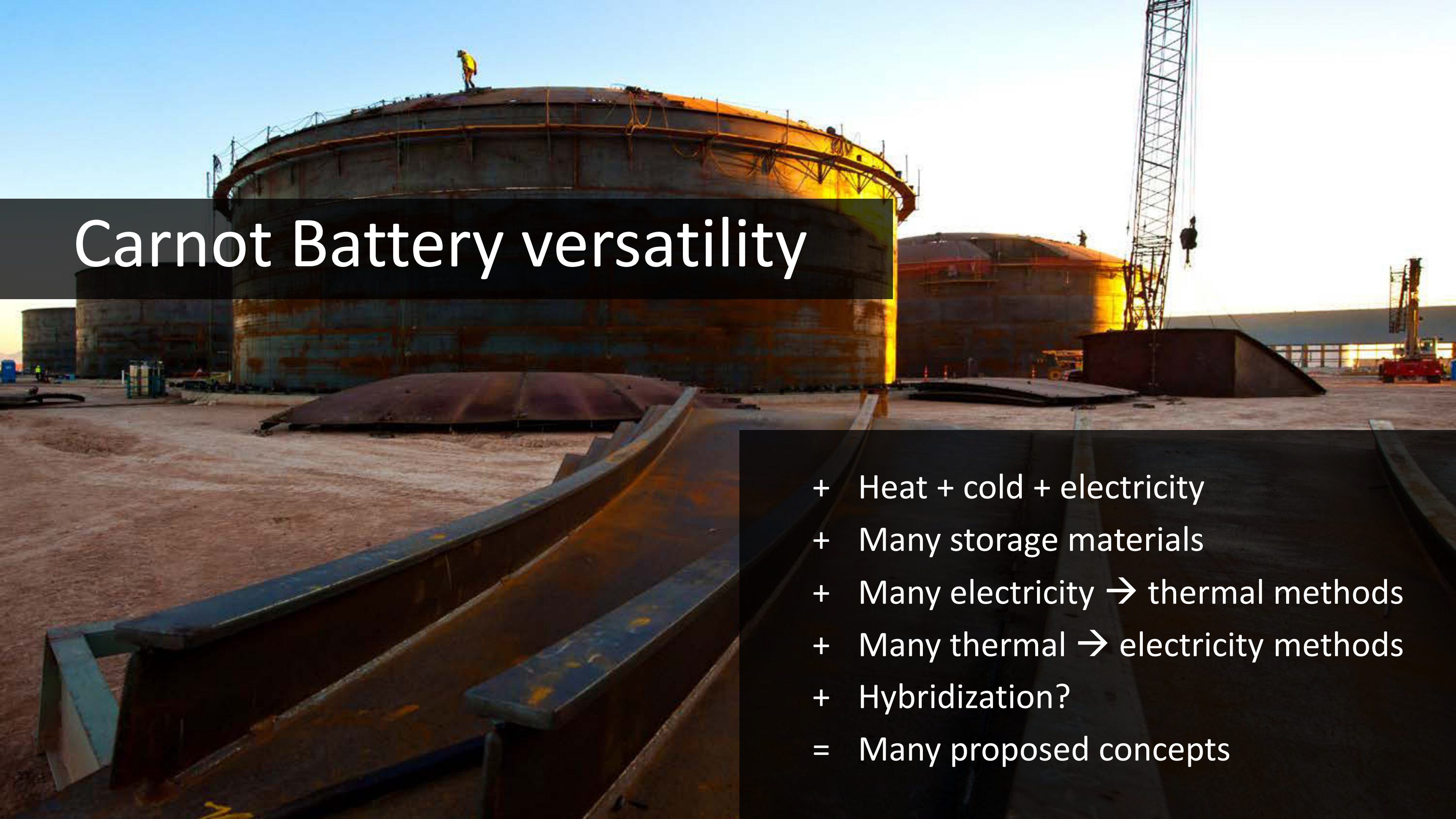
A. White, G. Parks, C.N. Markides, Thermodynamic analysis of pumped thermal electricity storage, Appl. Therm. Eng. 53 (2013) 291–298. doi:10.1016/j.applthermaleng.2012.03.030.

H. Chen, T.N. Cong, W. Yang, C. Tan, Y. Li, Y. Ding, Progress in electrical energy storage system: A critical review, Prog. Nat. Sci. 19 (2009) 291–312. doi:10.1016/j.pnsc.2008.07.014.

P. Farrés-Antúnez, Modelling and development of thermo-mechanical energy storage, University of Cambridge PhD Thesis, 2018. doi:https://doi.org/10.17863/CAM.38056.

J. McTigue, Analysis and optimisation of thermal energy storage, University of Cambridge PhD Thesis, 2016. https://doi.org/10.17863/CAM.7084.

Carnot Battery versatility



- \+ Heat + cold + electricity
- \+ Many storage materials
- \+ Many electricity → thermal methods
- \+ Many thermal → electricity methods
- \+ Hybridization?
- = Many proposed concepts

Commercial interest

Isentropic Ltd.

Sir Joseph Swan Centre for energy research

Newcastle University

Joule-Brayton Cycle

Storage:

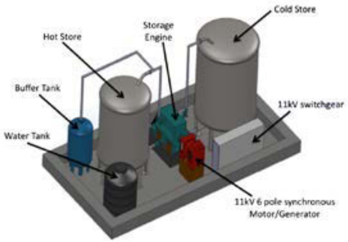
- Segmented packed beds of rocks between 500°C and -150°C.

Power cycle:

- Argon-based Brayton cycle
- Not recuperated
- Two reversible reciprocating engines (expensive)

Key Facts:

- Received GBP 15 million funding from Energy Technology Institute
- Ran out of funds in 2015
- Partially-built prototype completed by Newcastle University



Malta Inc.

Joule-Brayton Cycle

Storage:

- Molten salts at 565°C
- Glycol/water mixture at -60°C

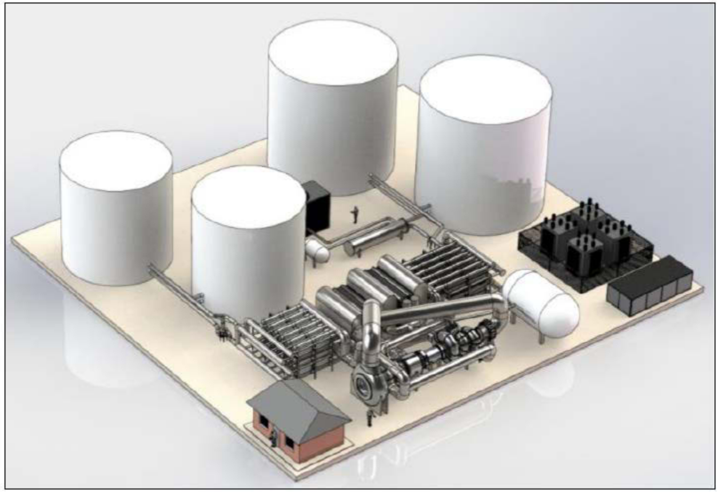
Power cycle:

- Air-based Brayton cycle
- Recuperated
- Four turbomachines

Key Facts:

- Received $30 million funding from Breakthrough Energy Ventures
- Raising further funds
- Looking to build 10 MW_e plant with 10 h storage

MALTA



Highview Power

Liquid Air Energy Storage

Storage:

- Liquified air at -196°C
- Packed beds of rocks for hot storage

Power cycle:

- Air-based Brayton cycle

Key Facts:

- Founded in 2005, and received GBP 12 million from the UK government
- Have built two pilot plants in the UK
- Demonstrated system concept with off-the-shelf components
- Began operation of a 5 MW_e plant in 2018 in the UK
- Opened a US office in 2018

Highview Power®

Siemens Gamesa

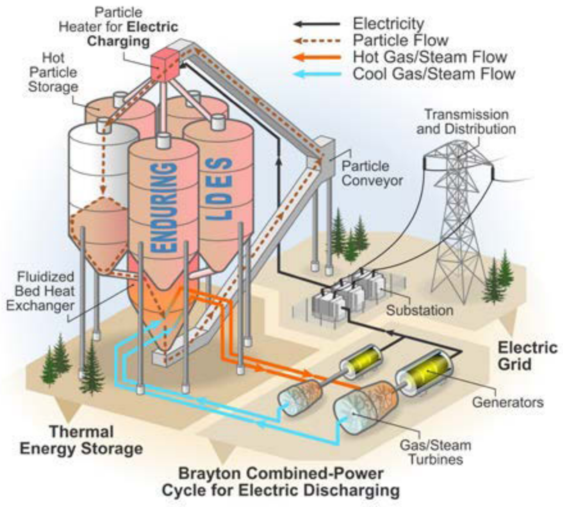
SIEMENS Gamesa
RENEWABLE ENERGY

Storage:
- Air as the HTF
- Volcanic rock at 700°C

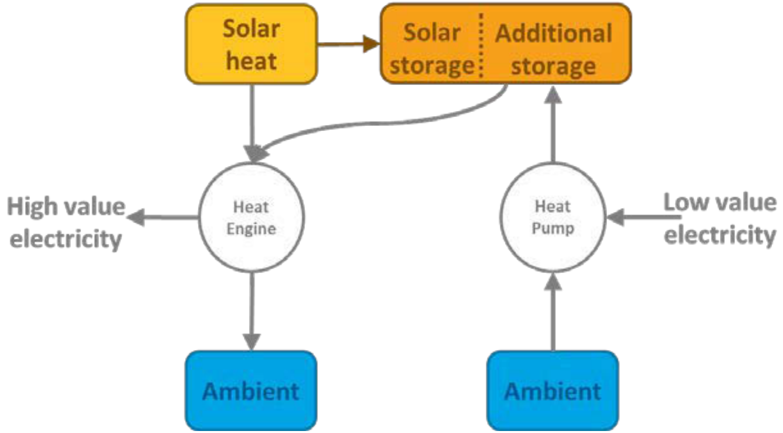
Power cycle:
- Steam turbine

Key facts:
- Pilot plant June 2019: 130 MWh (thermal?) for up to a week. 1000 tonnes of rock.
- Collaboration with Hamburg University of Technology and local utility Hamburg Energie
- Funded by German Federal Ministry of Economics and Energy

NREL Projects



- Electrical heating
- High-temperature storage in particles
- Drive a CCGT or other power cycle
- ARPA-E funded



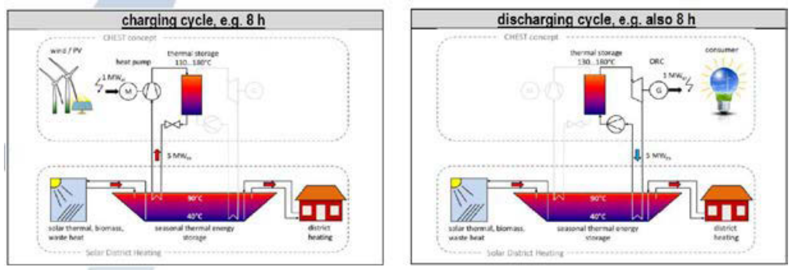
- Can we use knowledge from the solar industry?
- Integration with a CSP plant
- Make use of thermal storage year-round, regardless of solar availability
- Create a cold storage to reduce impact of ambient temperatures
- Combined CSP-PTES system provides
  - Electricity generation
  - Energy storage services

Integration with other industries

CHESTER
Compressed Heat Energy Storage for Energy from Renewable sources

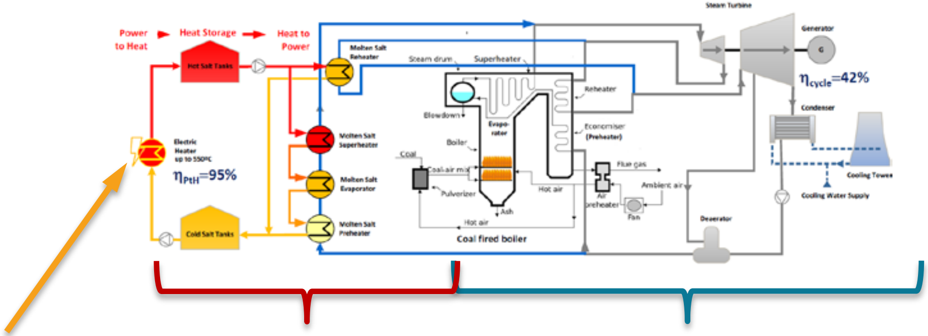
CHESTER European collaboration

- Intended for both electricity *and* district heating.
- Uses waste heat.



DLR

- Retrofit existing coal plants
- Use to manage peak demand



Convert electricity to heat

New thermal storage system

Existing coal plant

German Aerospace Center DLR

Summary

- Electricity storage can combat slews and lulls due to variable renewable generation (and demand)
- Carnot Batteries:
  - Electricity storage that uses thermal stores
  - Promising in terms of cost, efficiency, sustainability
  - A variety of configurations are being researched and commercialized

Thanks!

www.nrel.gov

https://www.nrel.gov/csp/pumped-thermal-electricity-storage.html

NREL/PR-5500-75559

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NREL Transforming ENERGY