DESTINATION 2050

POWERGEN INTERNATIONAL®

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ORANGE COUNTY CONVENTION CENTER
ORLANDO, FLORIDA, USA
POWERGEN.COM

ORGANIZED BY: CLARION ENERGY

CO_2 as Energy Storage

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VP Sales (USA), Energy Dome
February 22, 2023

ENERGYDOME
Making the Energy Transition happen

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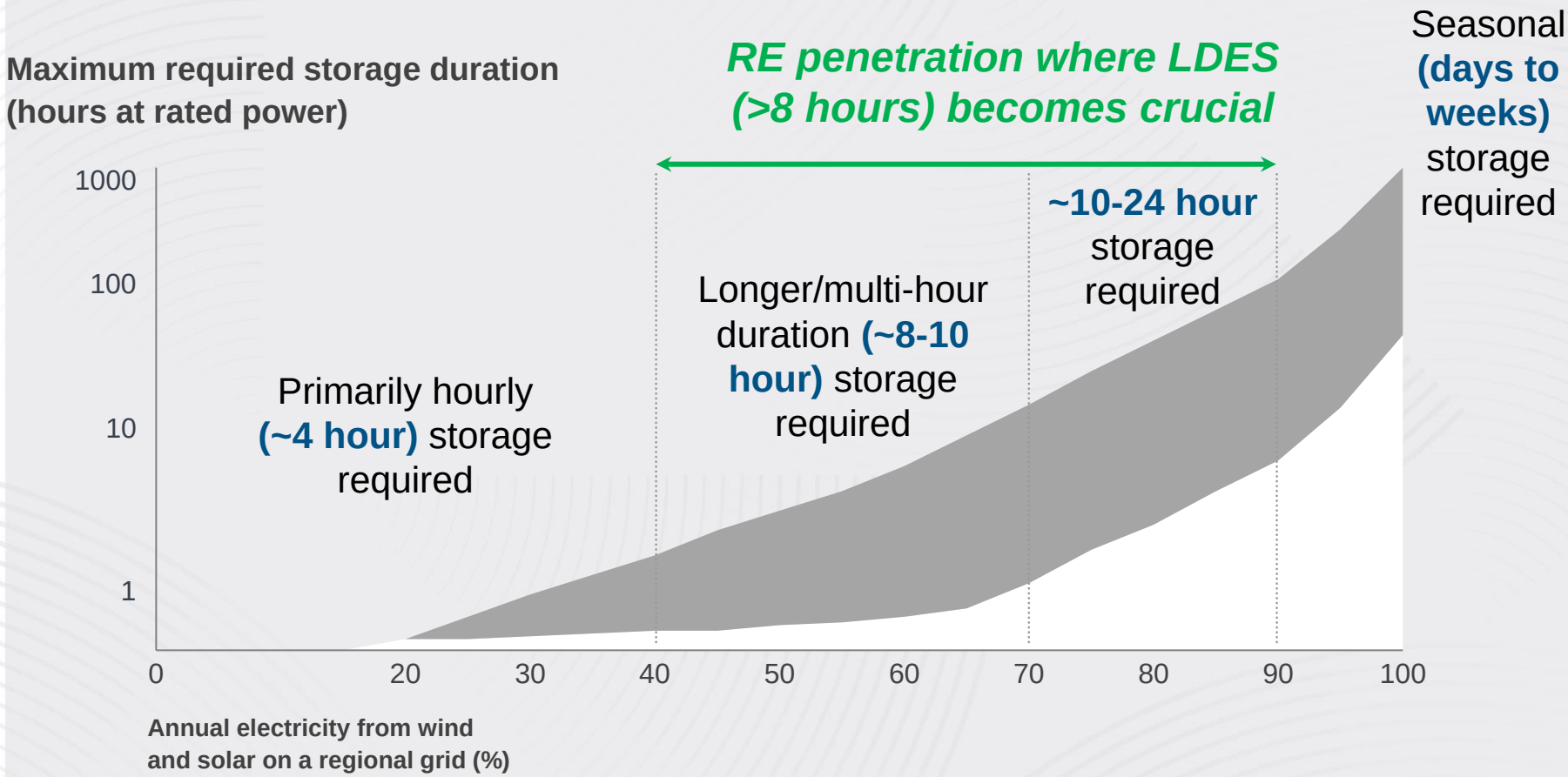
Energy Storage Needs for Reaching Net-Zero

Long Duration Energy Storage



Long Duration Energy Storage (LDES) becomes a crucial enabler at ~40% renewable energy (RE) penetration

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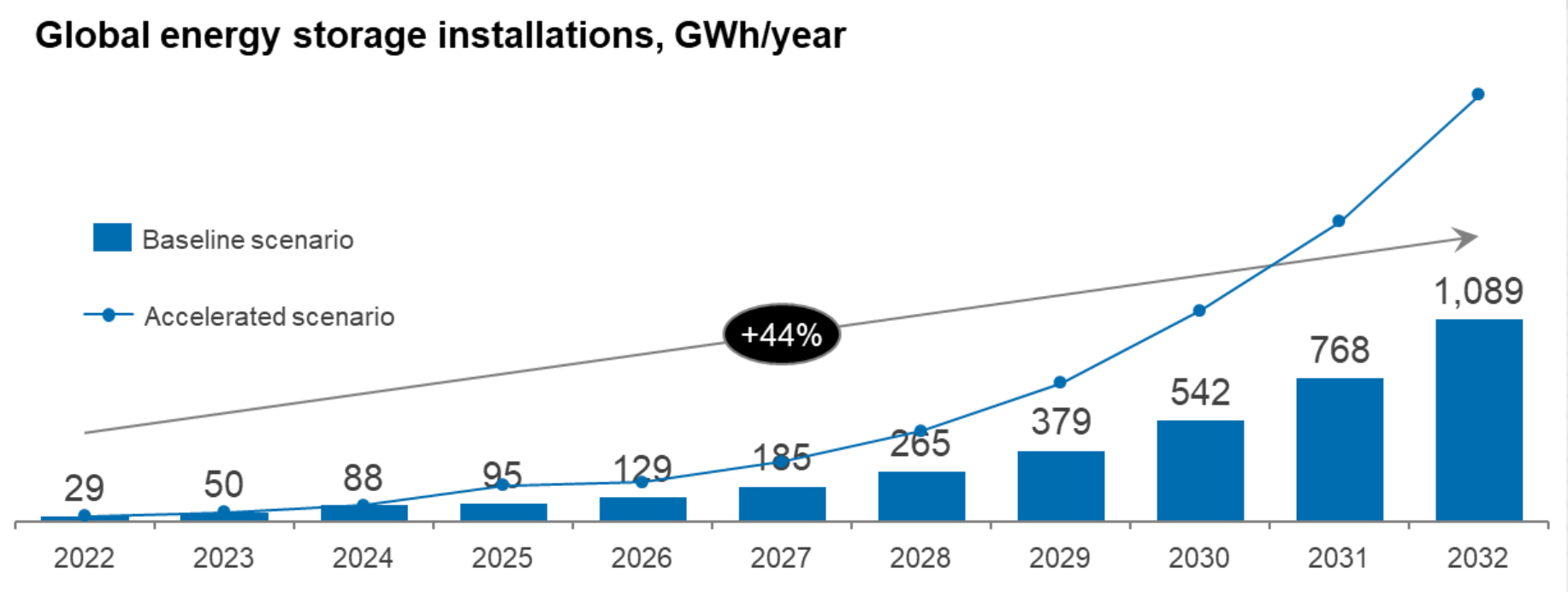
Source: Albertus et al Joule (2020); Sepulveda et al Nature Energy (2021)

LDES Market – Massive Growth Expected



- Consensus across leading sources on **massive LDES market potential**[1]
- Expecting **strong uptake of demand for longer duration systems**
- Positive signals of **LDES market mechanisms shaping up** (e.g., USA)

Market constrained by lack of technology that's proven & available today; does not account for breakthrough tech

First Mover Advantage to be gained by the fastest proven & lowest cost player

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1. E.g., LDES Council, BNEF
Source: LDES Council, triangulation with other relevant sources

Energy Storage, all based on deltas in Potential Energy

Mechanism	Sample Technologies	Potential Energy leveraged
Electrochemical	Li-ion, flow batteries	Voltage differences
Gravity	Pumped Hydro, gravity systems	Height differences
Thermal	Molten Salt, thermal oils	Temperature differences
Pressure	Compressed air, liquid air, **liquid CO2**	Pressure differences

Properties of CO_2 that make it an Ideal Gas for Energy Storage (relative to air)

- CO_2 can be stored as a liquid at ambient temperatures in carbon-steel pressure vessels, no cryogenics or chillers needed
- CO_2 is a clean fluid. In comparison, air needs to be filtered/managed for pollutants (e.g. dust) and needs moisture control, CO2 in closed loop doesn't need such conditioning
- CO_2 has a high molar mass (44 kg/mol) relative to air (29 kg/mol). This translates to smaller turbomachinery for same power output. Fewer compressor stages, and smaller turbines (less $$)
- CO_2 has a higher specific heat than air, allows for higher enthalpy difference for the same temperatures, more efficient heat transfer
- CO_2 is not corrosive or erosive. Ideal for turbomachinery, less maintenance needed relative to operating similar machinery with air.

Advantage of CO_2 for Pressure-Based Storage

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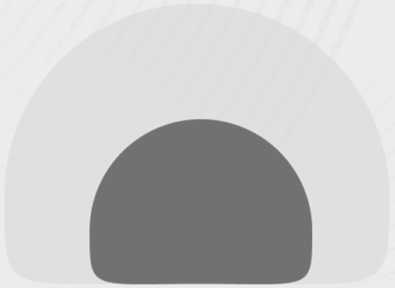
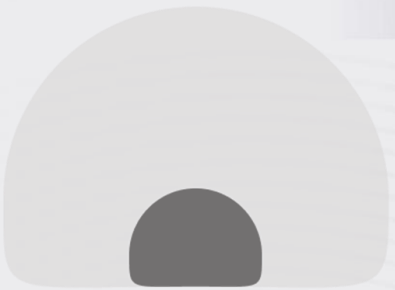
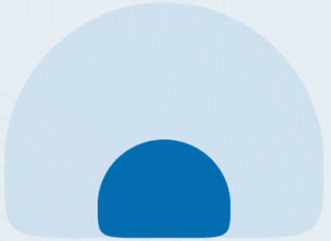


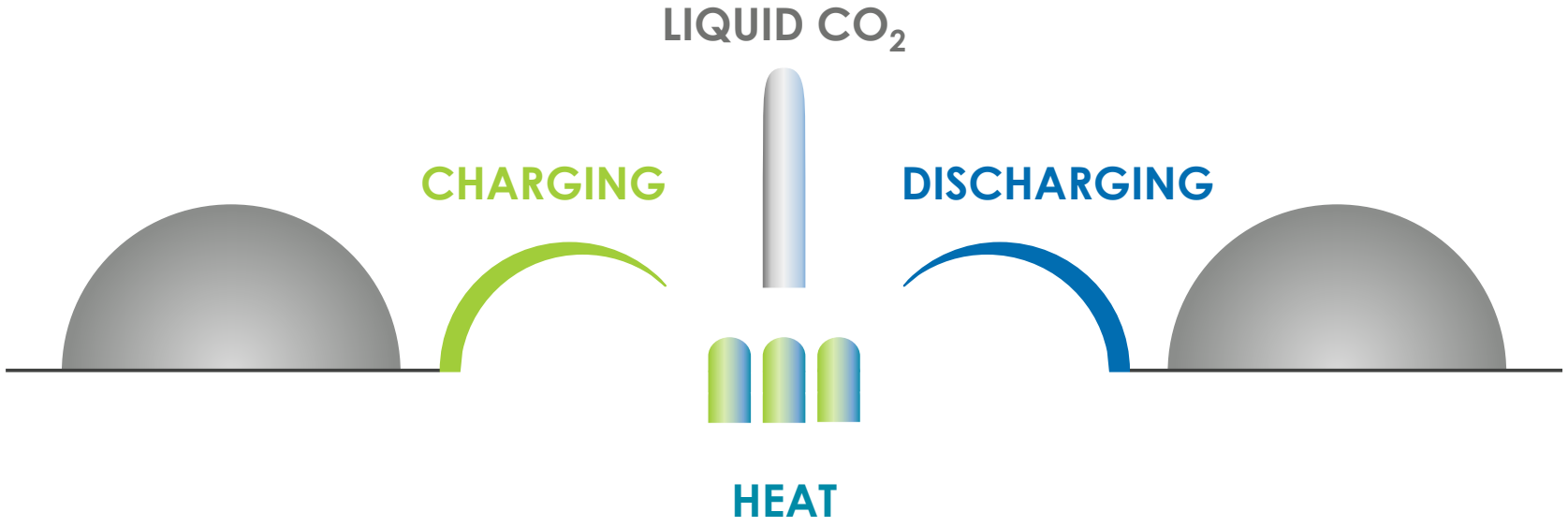




	AA-CAES	LAES	C02 BATTERY
Starting	1 kg of Air	1 kg of Air	1 kg of CO2
Volume at ambient conditions	0.82 m3	0.82 m3	0.55m3
Pressure in Storage conditions	High Pressure (70 bar)	15 bar	High Pressure (<70 bar)
Temperature in storage conditions	Ambient temperature	-190°C	Ambient temperature
Volume in Storage conditions	12 liters	1.1 liters	1.3 liters
Energy Storage density	2-6 kWh/m3	107 kWh/m3	66.7 kWh/m3

SMALL STORING VOLUME AT AMBIENT TEMPERATURE LEAD TO LOW CAPEX

Principle of a CO_2 Battery



The **CO2 Battery...**

- an **innnovative utility scale long duration energy storage** solution
- Novel **industrial process** that integrates **off-the-shelf** components from existing **supply chains**
- **No special materials needed- Steel, Water, Concrete, CO2**
- **Low Capex and High Efficiency**

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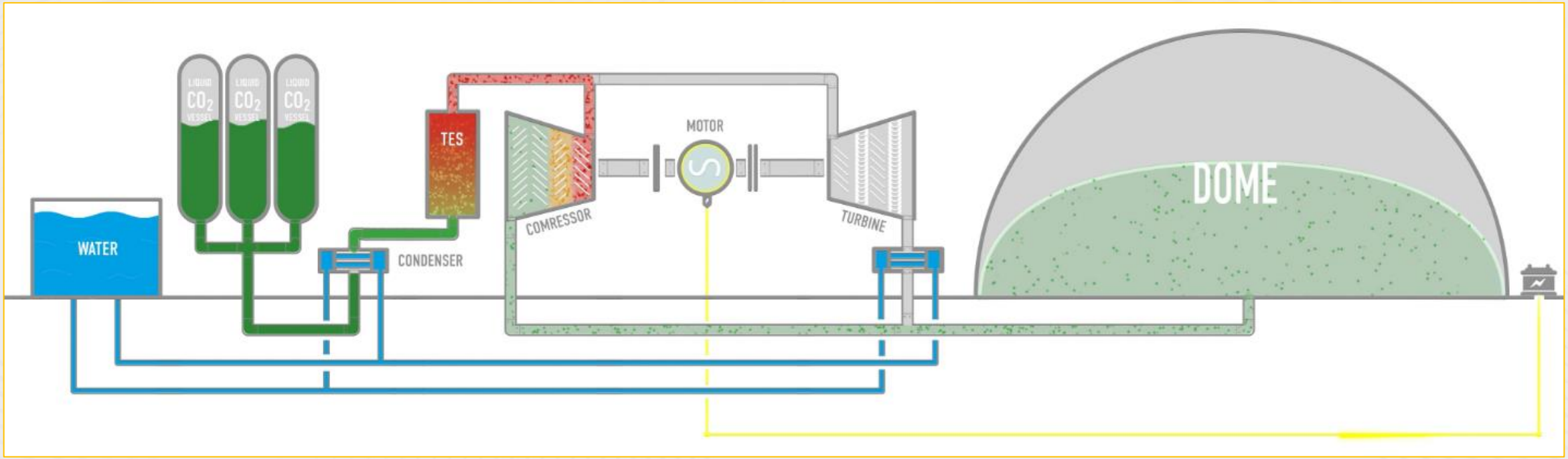
- Innovation in **process**, not components
- **CO_2** is the **perfect working fluid**: Critical temperature 33°C
- Multiple patents family filed & patent strategy in place: **1st patent in Feb '19, 6 others filed** and pending approval

Major Components of a CO_2 Battery



https://www.youtube.com/watch?v=LXSSH6ZuOWk

Major Components from Tier 1 suppliers

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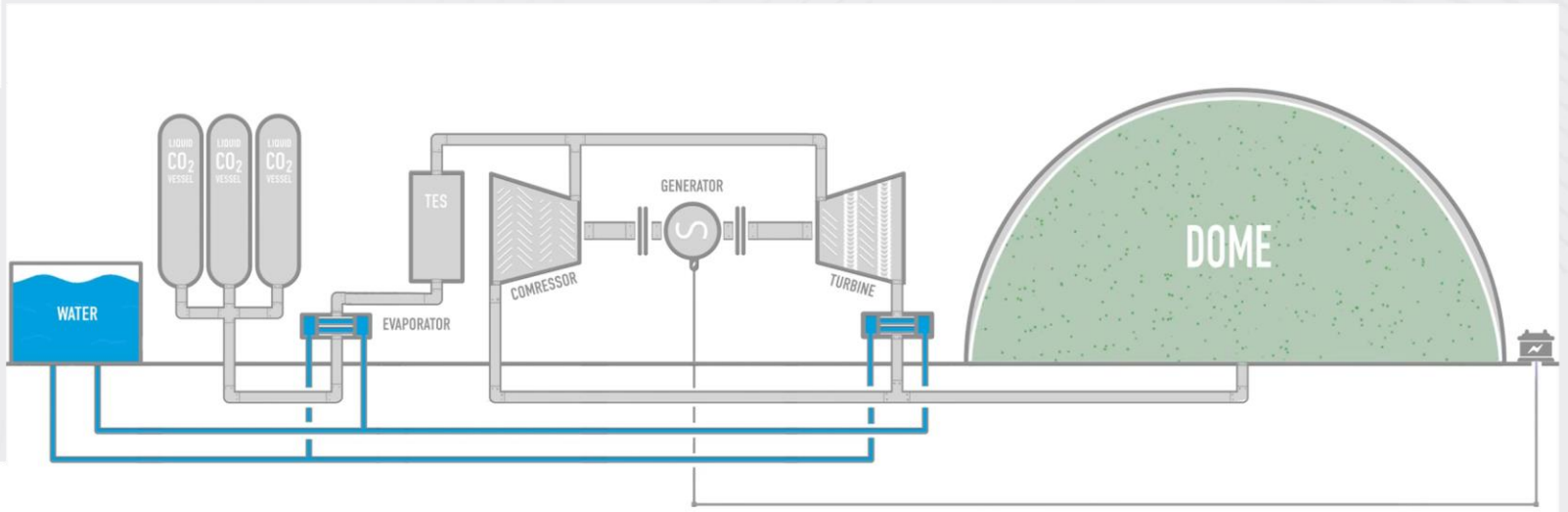
SSS® Clutch Company, Inc.

Nidec All for dreams

Geometrica®

ECOMEMBRANE ENVIRONMENTAL TECHNOLOGY

Atlas Copco



ARIZON® BUILDING SYSTEMS

ZC-SPACE 中成空间

KOBELCO

FRANCO TOSI MECCANICA

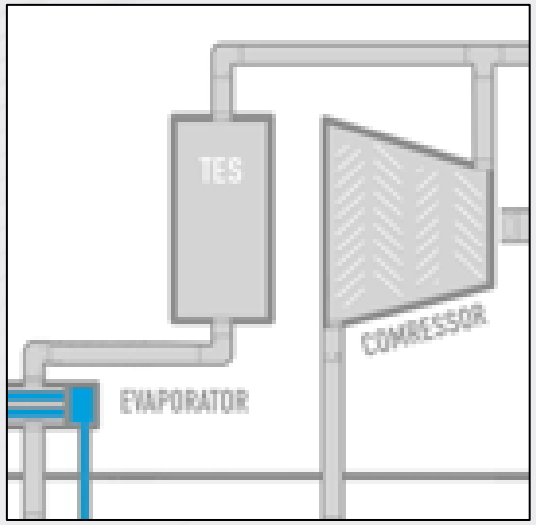
MITSUBISHI HEAVY INDUSTRIES

MAN Energy Solutions

SIEMENS

TGM KANIS TURBINEN

Thermal Energy Storage (TES) System



Efficiency/Performance maximized via recovery of heat of compression in the TES system

Many options for TES, from molten salt to thermal oil systems (toxicity and safety concerns)

Alternative = Packed Particle Bed using inert material

- No moving parts, completely recyclable
- Highly efficient, on expansion CO_2 after the TES is only 5^{o}C less than the original inflow from the compressor!

Space Requirements

CO2 Battery Module (20 MW x 10h) needs 10-12 acres

Relative to solar facilities it could be paired with, there's plenty of real estate to do this.

Comparison with Mainstream Storage Technology

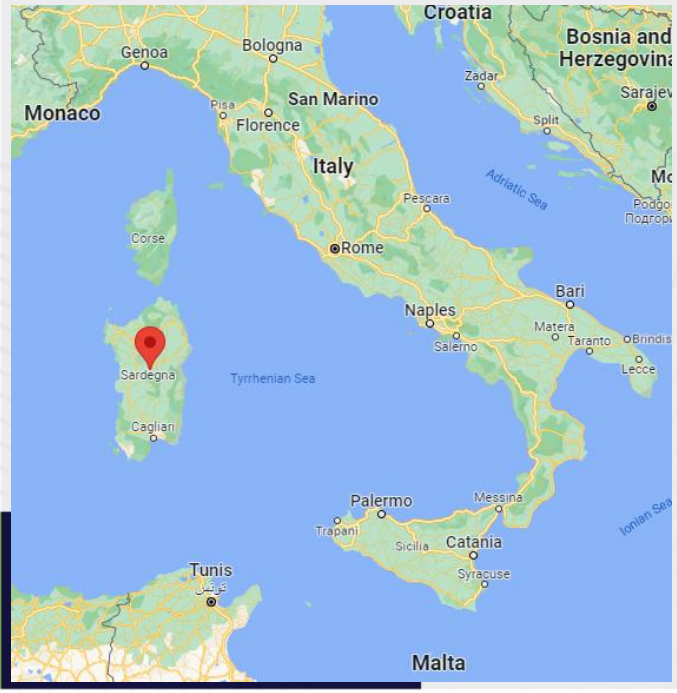
	Lithium-Ion Battery (4 hour)	CO2 battery (today) 2022 (10 hour)	CO2 Battery (future) With economies of scale and design improvements (10 hour)
RTE	85-90% RTE Degrades over time, augmentation	75% No degradation over time	80+% No degradation over time
CAPEX	300+ $/kWh	225-250 $/kWh	100-150 $/kWh
LIFETIME	10 y	30 y	30 y
OTHER	Depth of discharge limitations End of life disposal issue Fire hazards High dependance on battery metals prices (Li, Co, Ni , etc.)	0%-100% (full depth of discharge) No disposal issue/recyclable No fire hazard Low cost common material (only Carbon Steel, concrete, water)	

Commercial Demonstration Plant

Commissioned May 2022

Grid connected, responding to Price Signals

2.5 MW / 4MWh



Expected Performance of CO2 Battery in US Markets

CAISO
NP 15
Procurement Mandate

PJM
DOM Zone
VCEA Storage Mandate

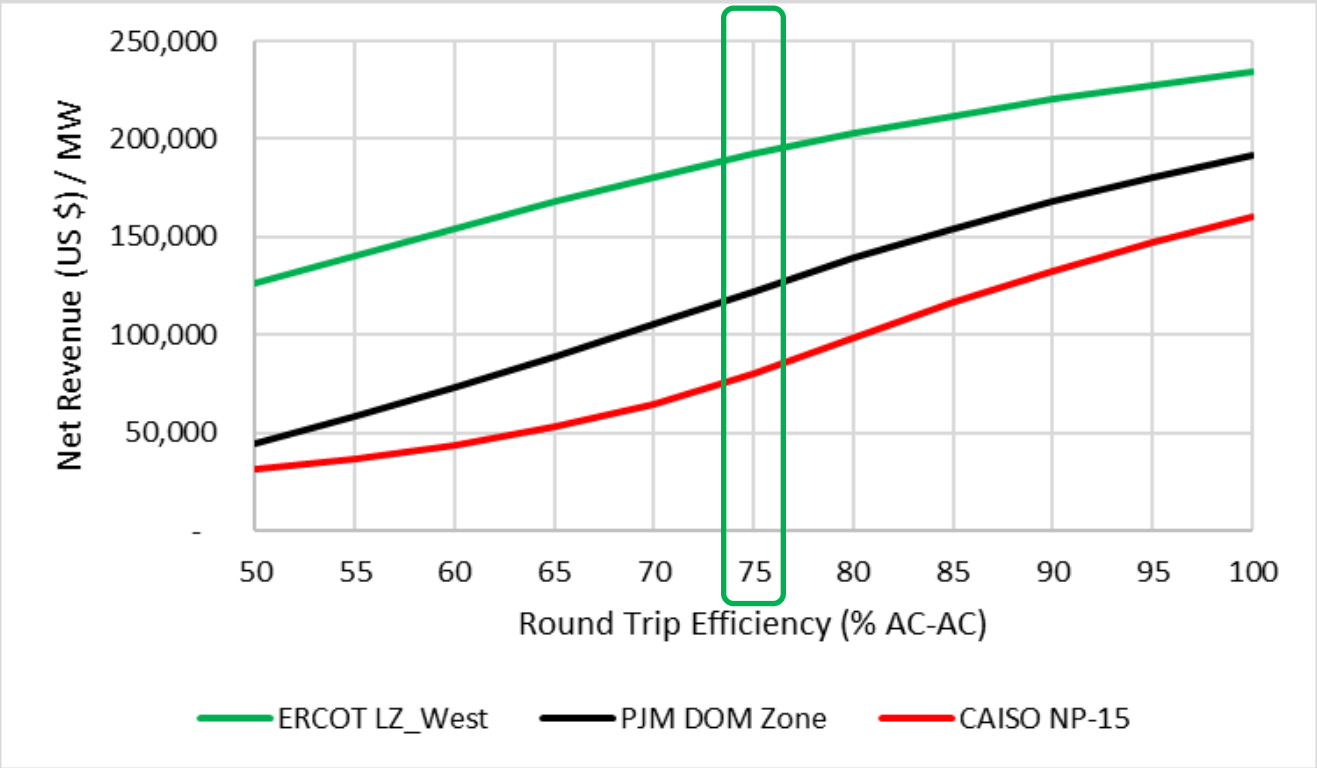
ERCOT
LZ_West
Curtailment

Calculations….

- **2022 Day Ahead LMPs**
- **Pure Energy Shifting**
- **10 hours duration**
  - **Charge during 10 lowest price hours each day**
  - **Discharge during 10 highest price hours**
- **For 3 round trip efficiency (RTE) classes:**
  - **50%**
  - **65%**
  - **75%**
- **Determine: Annual Revenue ($) per MW installed**

Market View (representative)

CO_2 Battery
Capex @ 150 - 250 $/kWh



- High Efficiency (75% RTE)
- High Net Revenue Expectations
- Low Capex, limited geographic constraints
- ***High Revenue coupled with low Capex***
  - ***Highest IRR for developers***
  - ***Lowest cost impact for ratepayers***

(Net Revenues based on representative 2022 Zonal LMPs and for LDES systems with 10h duration)

Efficient, cost-effective, anywhere

Energy Dome's CO2 Battery is based on the principle of manipulating and storing CO2 in different state conditions

HOW IT WORKS?

In charging mode, CO2 is drawn from an inflatable atmospheric gas holder (the 'Dome'), compressed, and then stored in liquid CO2 vessels at ambient temperature.

When discharged, the liquid CO2 is evaporated back into a gas and expanded into a turbine, and then returned back to the atmospheric gas dome, ready for the next charging cycle.
The physics of CO2 as a working fluid drives a crucial benefit: **occupying low volume at medium pressure, with high energy density at ambient temperature.**

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Making the Energy Transition happen

CO2 BATTERY

EFFICIENT
Round-Trip Efficiency (75%+) AC-AC MV-MV

PROVEN
The first CO2 Battery plant (2.5MW-4MWh) currently operational and grid connected

COST-EFFECTIVE
Highly competitive CAPEX and OPEX

DURABLE
No degradation of capacity or performance over 30+ years

RELIABLE
Off-the-shelf components based on sustainable materials

SITE INDEPENDENT
The plant can be installed anywhere in the world

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Thank You!

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