GTEN 2023 Symposium

CELEBRATING 50 YEARS

October 16 - 18, 2023 I Banff, Alberta

Decarbonization of Gas Turbines and Brayton Cycles Through Indirect Heat Addition

Tim Allison, Ph.D.
Southwest Research Institute (SwRI)

Presented at the Gas Turbines Energy Network (GTEN) 2023 Symposium
Banff, Alberta, Canada - October 2023

Net-Zero Pathways: United States

- All pathways decrease overall energy supply through increased efficiency
- All pathways expand renewable significantly
- Carbon capture part of most pathways

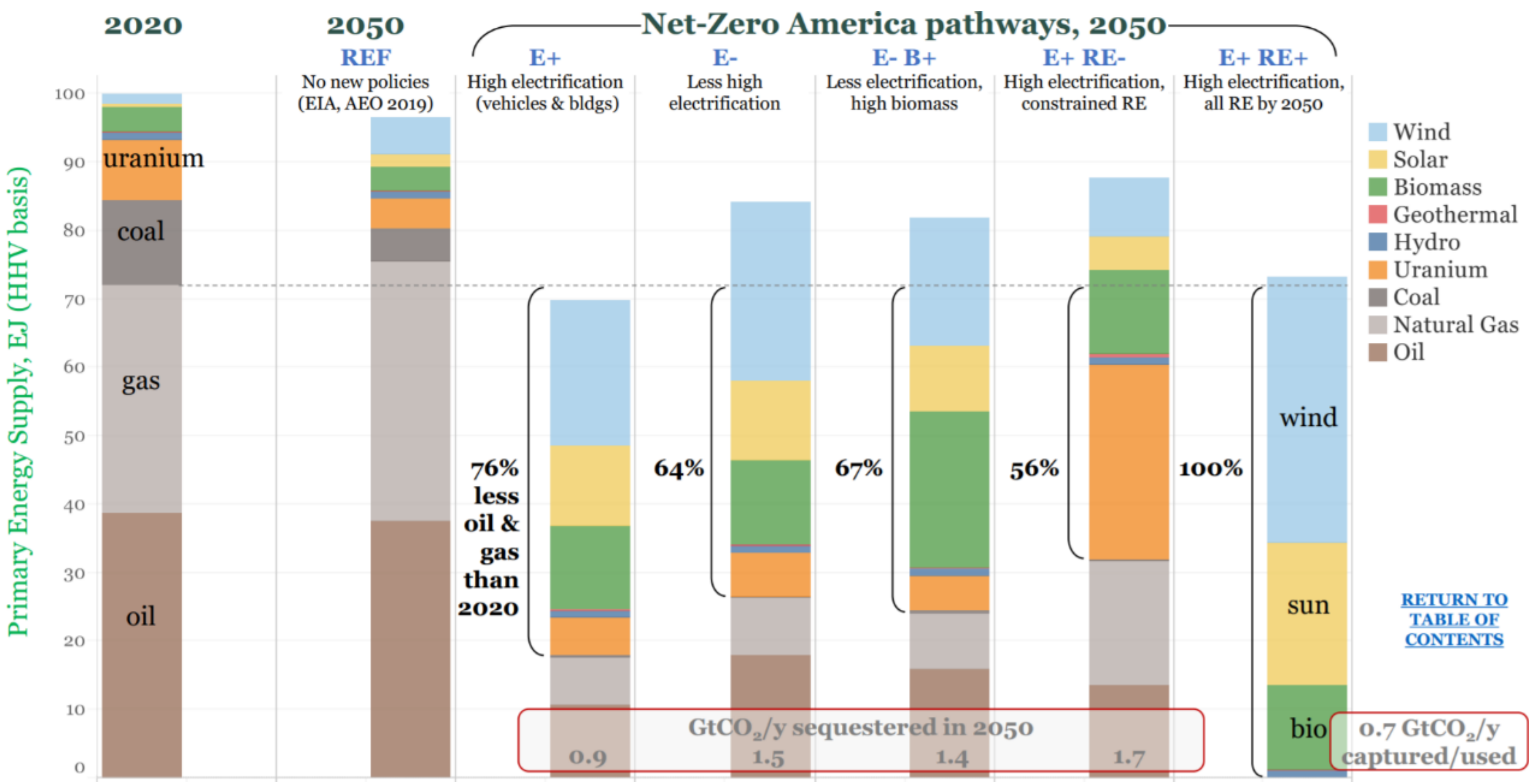
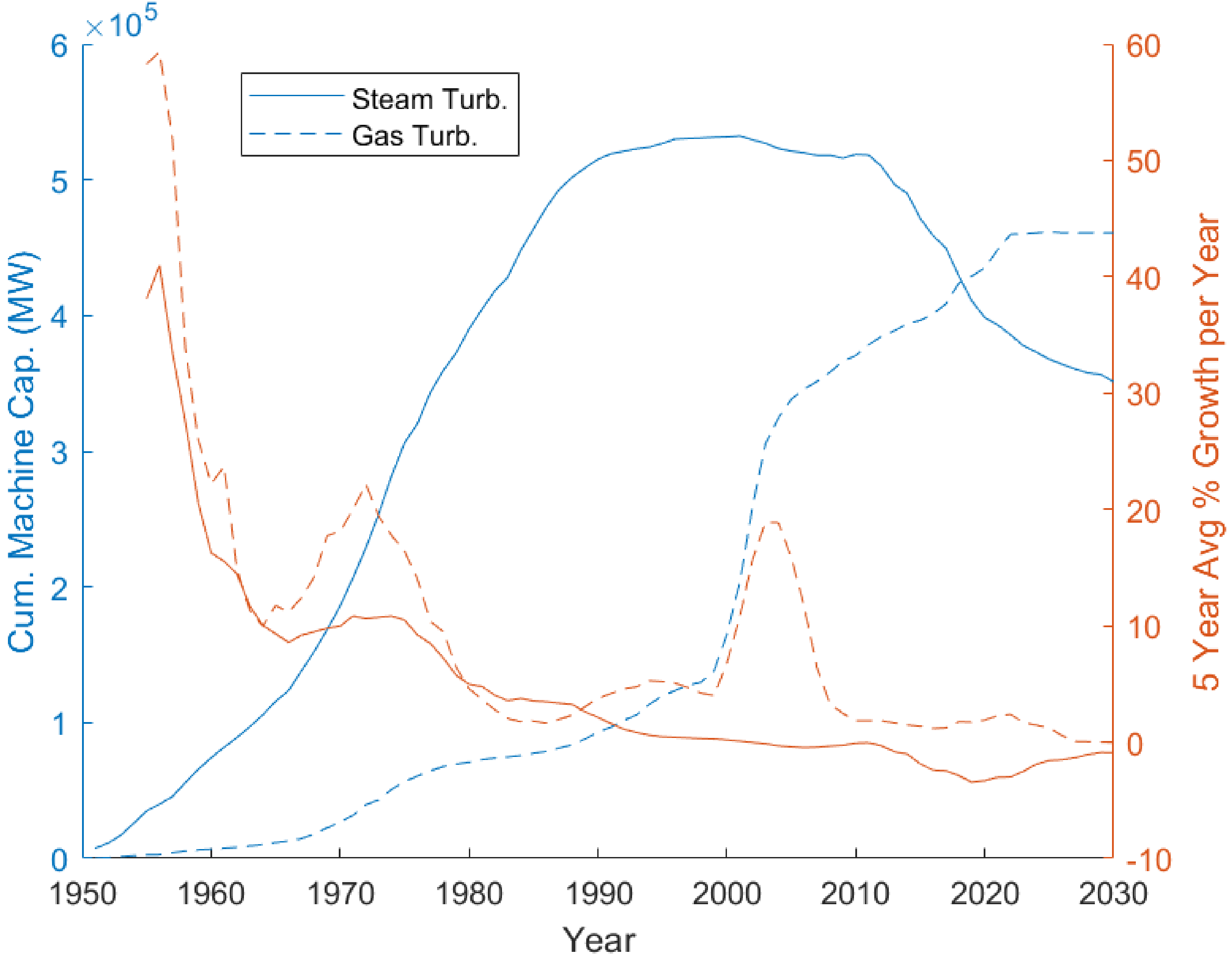


Image Source: Princeton University

History of Turbine-Based Power Generation

- The modern steam turbine was invented in **1884** by Charles Parsons, whose first model was connected to a dynamo that generated **7.5** kilowatts.
- The first successful gas turbine was demonstrated in Paris in **1903**, recip compressor and impulse turbine
- The start of this graph is **65 years after** the first steam turbine was demonstrated and 50 years after the gas turbine was demonstrated
- Average growth of power generation gas turbines and steam turbines has been approximately 5-10% of the installed capacity per year
  - Transition in the 70's to nuclear power that involved a large number of steam turbines
  - Shale boom in the early 2000's that resulted in increases of 20-30% per year
- ~800 GW in ~70 years



Data from U.S. Energy Information Administration, 2023; Image from Wilkes *et al*, 2023

Energy "Evolution" Takeaways

- Efficiency increases anticipated to reduce demand
- Significant wind/solar buildout anticipated in most scenarios
  - Will require matching large-scale energy storage for long durations
- Most scenarios still anticipate oil & gas with carbon capture
- It's going to take time
  - >1000 GW of capacity to decarbonize in U.S. just for power generation
  - Currently have ~800 GW of installed steam and gas turbine power gen capacity in U.S., which took steady growth since 1960 to achieve
  - Only 13.6% of energy came from wind/solar as of February 2023.

Rapid, Cost-Feasible Energy Evolution Requires Adaptation of Existing Machinery and Supply Chains

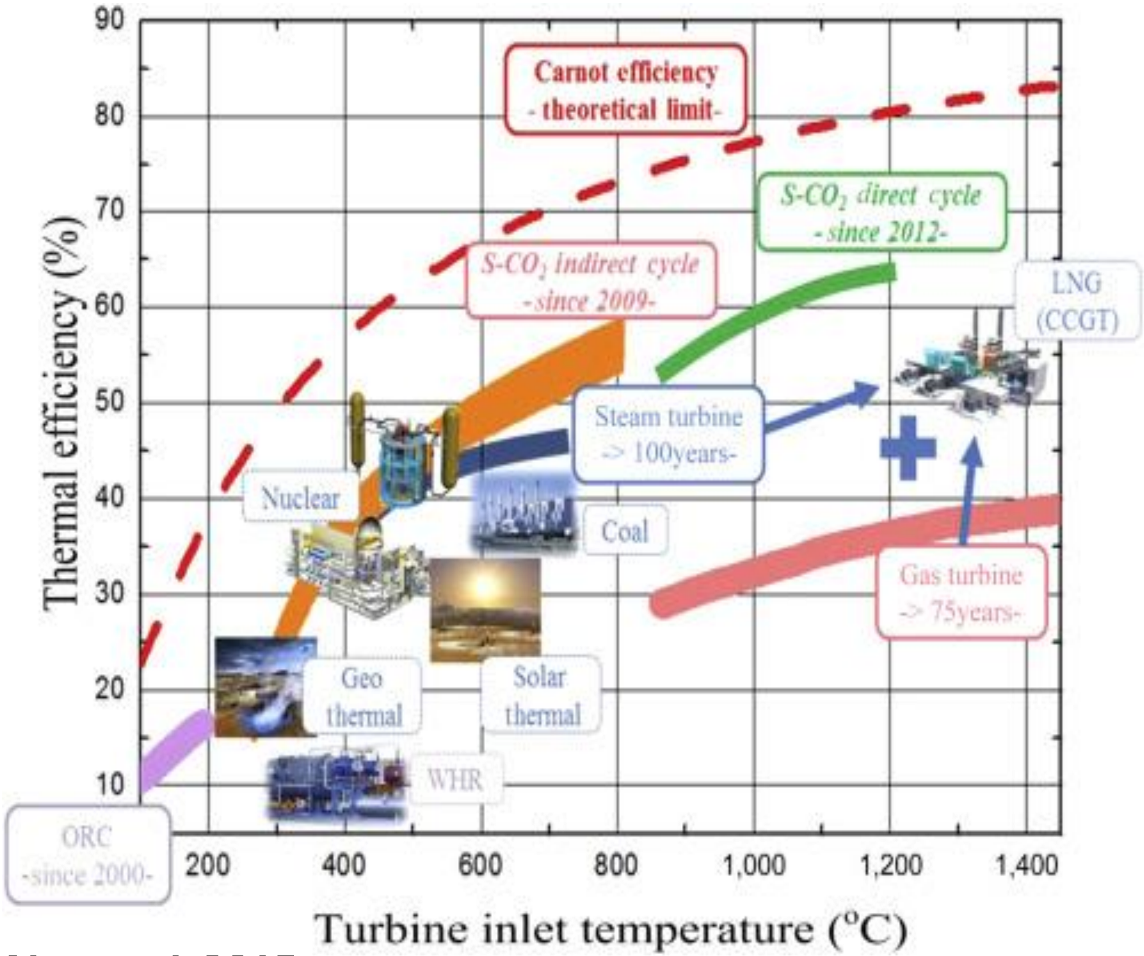
Gas Turbine Decarbonization Pathways

	Amine-Based Carbon Capture	Decarbonized Fuels	Indirect Heat Addition
Technology gaps for gas turbine system	Exhaust gas recirculation (optional)	Combustion system	Thermal integration; new cycles / fluids (optional)
Efficiency penalty	16-19% net power reduction	Electricity to fuel is ~45% for renewable natural gas, 51% for ammonia, 62% for "blue" hydrogen	Zero to Negative. Increases thermal efficiency through WHR; energy storage can have same efficiency or better with heat pump.
Cost penalty	~40% increase in cost of electricity to ~$95 USD/MWh	$90-$705 USD/MWh (energy content) for fuel production	$2000-15000 USD/MWh for thermal storage (one-time cost), $1900-8900 USD/kW (waste heat to power)
Other pros		Potential for fuel blending; current customer demand	Technology crossover for waste heat recovery and EGR/fuels; potential for co-firing with thermal storage
Other cons	Continued use of fossil fuels; needs space and CO2 infrastructure	Require new or de-rated fuel transport pipelines (H2, NH3) and storage	Can't transport stored thermal energy

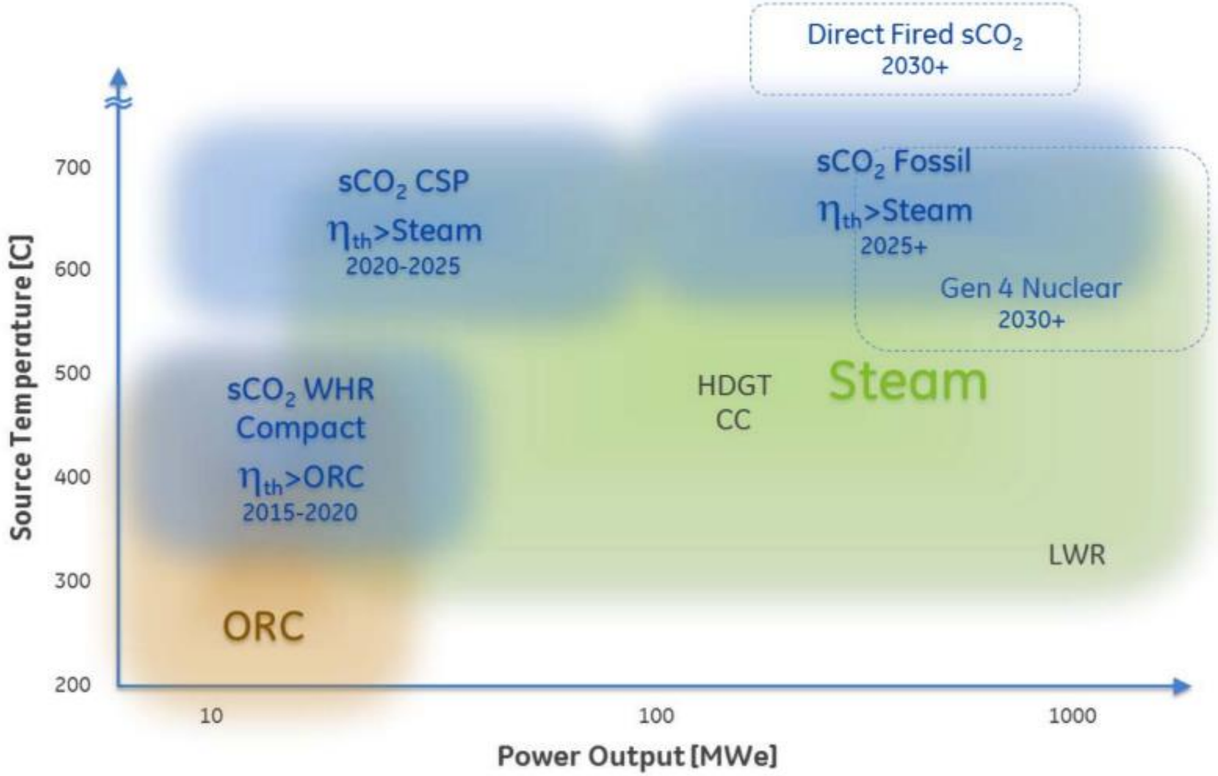
Data from Oh *et al* (2021), Allison *et al* (2021), and Bellotti *et al* (2022)

Indirectly Heated Bottoming Cycles for Gas Turbines

Bottoming Cycle Comparisons



Ahn *et al*, 2015



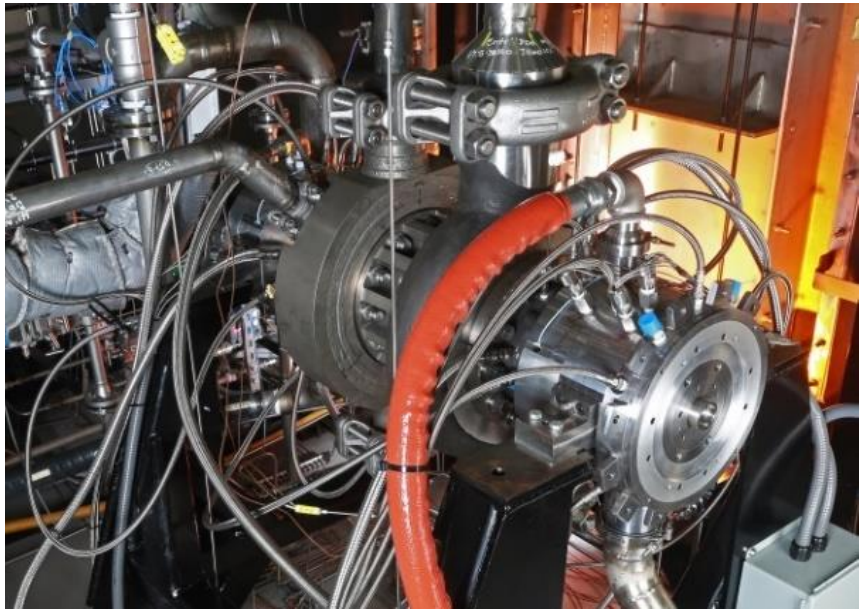
Hofer, 2016

Technoeconomic Comparison for Titan 130 Pipeline Gas Turbine WHR Case Study

	sCO_2 Preheat SR	Recuperated ORC with Direct Heating (Cyclopentane)
Bottoming Cycle Power Output at 35°C Cold Temp	5.660 MW	5.066 MW
Combined Cycle Efficiency at ISO Gas Turbine Conditions, 35°C Bottoming Cycle Cold Temp	45.9%	44.6%
Nominal Capital Cost Estimate (and Range)	$2,900/kW ($1,900/kW – $4,000/kW)	$3,000/kW ($2,400/kW – $8,900/kW)

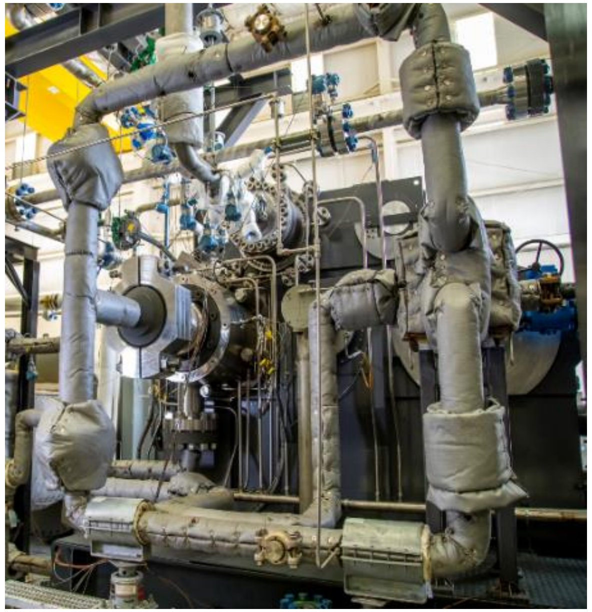
Data from Allison *et al*, 2021

sCO_2 MW-scale Machinery Development



SunShot 10 MWe Axial Turbine
715 °C, 255 bar, reduced-flow tests completed in 2019

APOLLO 10 MW Centrifugal Compressor
255 bar discharge, full flow test completed in 2021



APOLLO 10 MW Integrally-Geared Compander
720 °C, 280 bar, reduced-flow test completed in 2021

Supercritical Transformational Electric Power (STEP) Pilot Plant Test Facility

Objective:

- Advance the state of the art for high temperature sCO_2 systems
- Design, construct, and operate a *reconfigurable* 10 MWe sCO_2 Pilot Plant Test Facility

Key Advances:

- Turbomachinery for 715C
- 740H Primary HX & Piping @ 250 bar, 715C,
- Recuperator scale up at 600C design temperatures
- Plant Controls and Operability

Project Team & Timeline:

- $156M Project and Building Budget with $112M Federal Funding
- Mechanical assembly complete; System commissioning in progress
- Project Team includes: U.S. Department of Energy (DOE NETL), GTI Energy, Southwest Research Institute (SwRI), and General Electric Global Research (GE-GR)

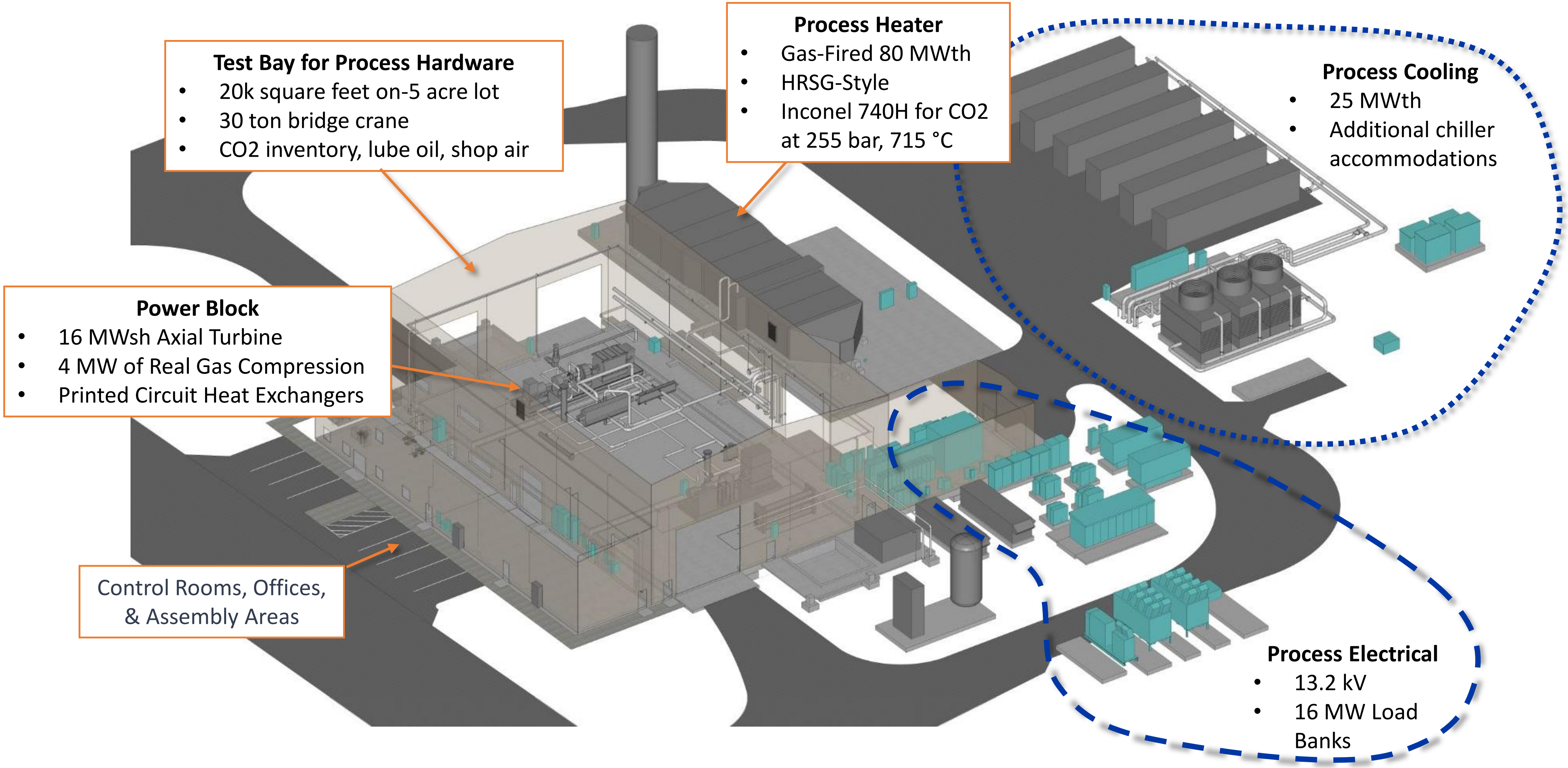
Joint Industry Partners Include:

Project Publications:

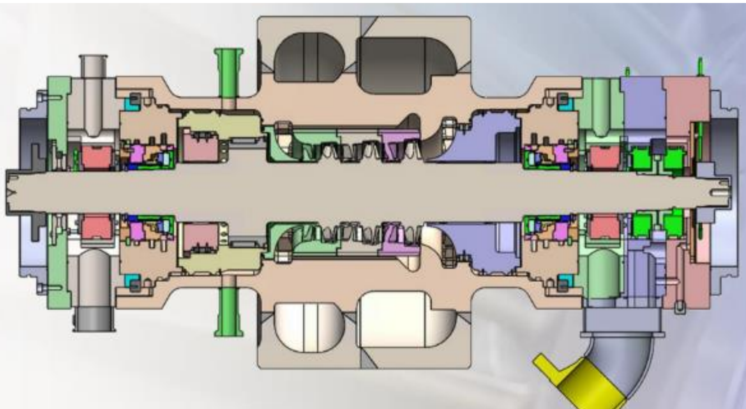
1. Marion, Kutin, McClung, Mortzheim, Ames, 2019, "The STEP 10 Mwe sCO2 Pilot Plant Demonstration," Proc. of ASME Turbo Expo 2019, Paper GT2019-91917, June 17–21, 2019, Phoenix, AZ, USA.
2. Tang, McClung, Hofer, Huang, 2019, "transient Modeling of 10 MW supercritical CO2 Brayton Power Cycles using Numerical Propulsion System Simulation (NPSS)," Proc. of ASME Turbo Expo 2019, Paper GT2019-91443, June 17–21, 2019, Phoenix, AZ, USA.
3. Huang, Tang, McClung, 2018, "Steady State and Transient Modeling for the 10 MWe SCO2 Test Facility Program," Proc. 6th Intl. Symp. – Supercritical CO2 Power Cycles, March 27-29, Pittsburgh, PA.

STEP Facility Layout & Specs

STEP DEMO SwRI



STEP Equipment



Marion, J., Macadam, S., McClung, A., Mortzheim, J., 2022, "The STEP 10 MWe sCO2 Pilot Demonstration Status Update," GT2022-83588, Proceedings of the ASME Turbo Expo 2022, Rotterdam, The Netherlands, June 13-17, 2022

STEP 10 MW Axial Turbine (SwRI, GE Research)

STEP Main Compressor Skid (Baker Hughes)

STEP Process Heater (Optimus)

Brayton Cycle-Based Energy Storage

Comparing Battery and Thermal Storage

- Case study of behind-the-meter solar PV
- Hourly dispatch model against historical solar and load data for a sample year
- Cost reduction until ~40% PV energy, 50% limit
- Thermal storage (composite model) extends to >90% and offers cost savings over Li-Ion batteries

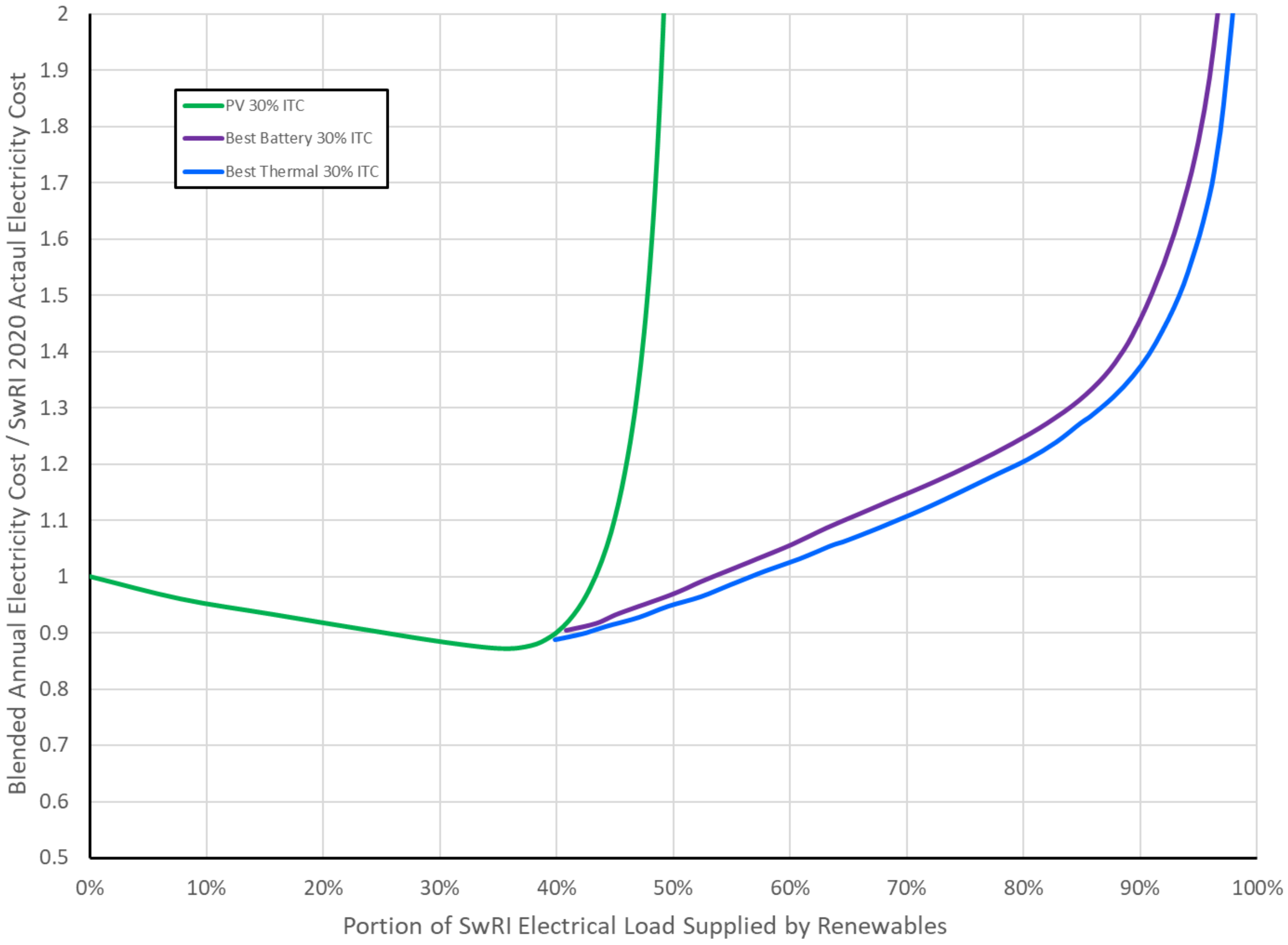
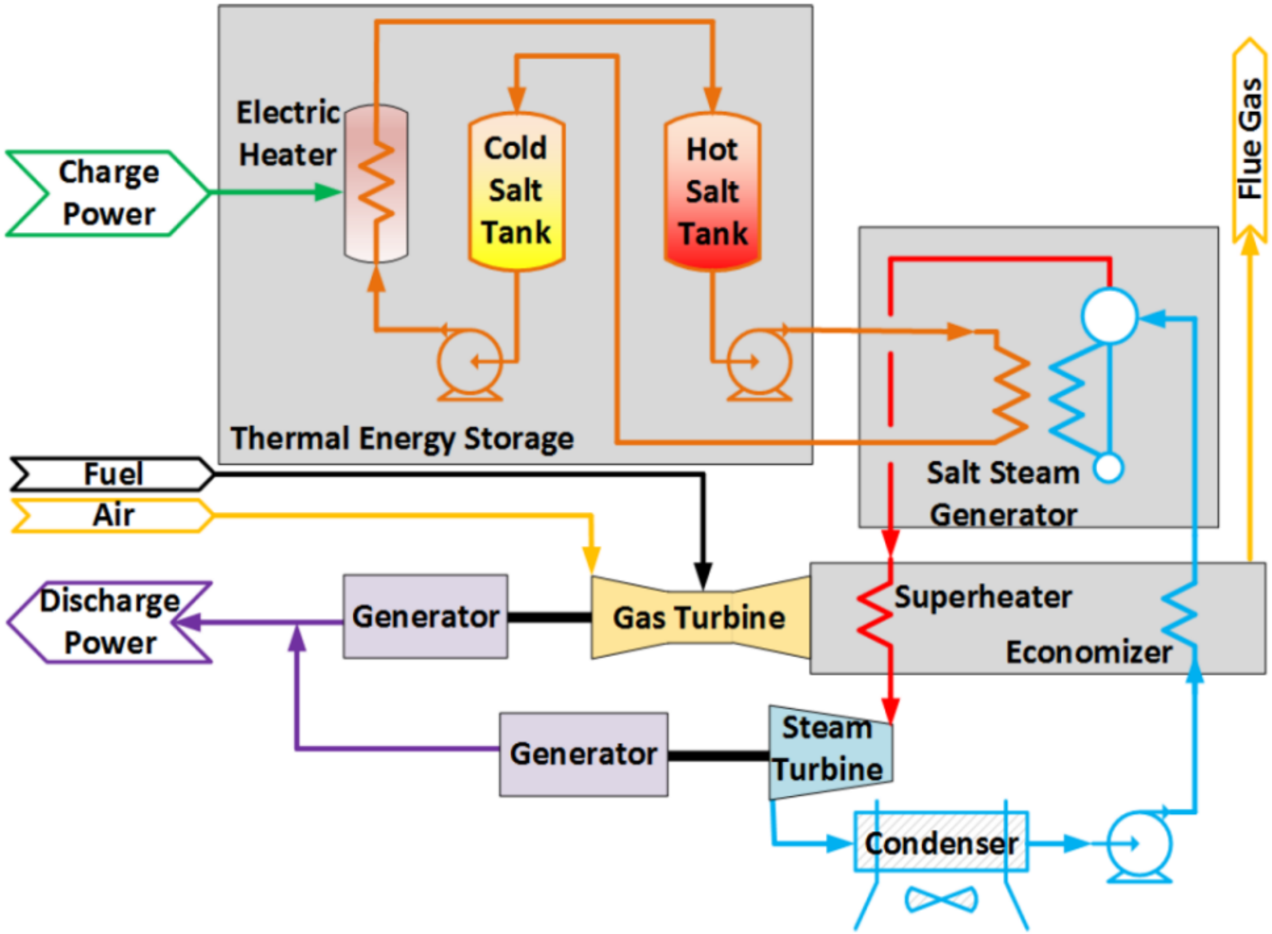


Image Courtesy Hofer *et al* [2023]

Gas Turbine with Molten Salt Thermal Energy Storage

Liquid Salt Combined Cycle

- Hybridizes with existing open cycle gas turbine
- Renewable heating of molten salt
- Bottoming steam cycle leverages molten salt and gas turbine waste heat
- >3x typical combined cycle steam flow
- Targeting 5+ hours diurnal storage

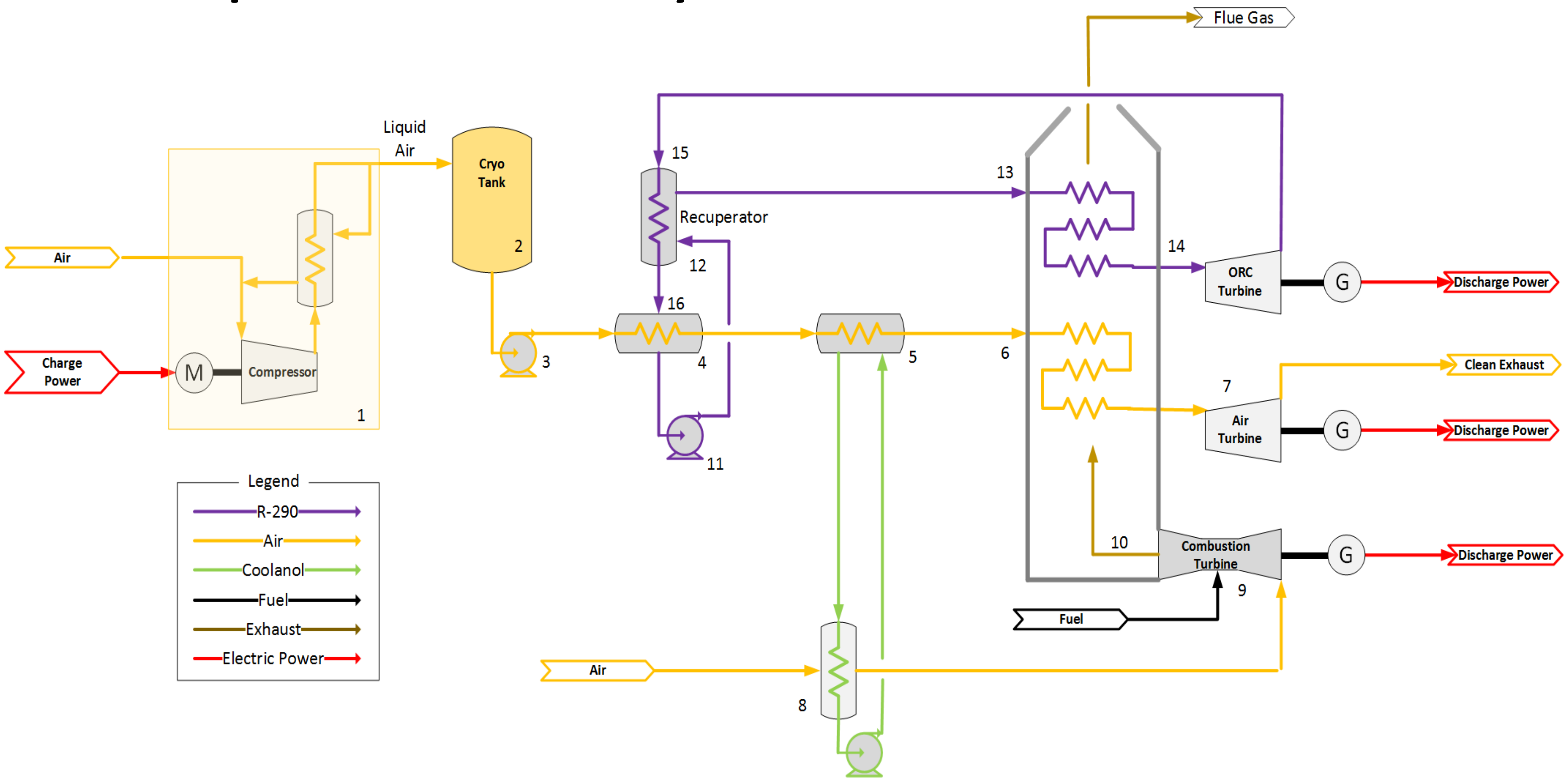


Data and Image Sources: Pintail Power (2020), Hume *et al* (2021)

Gas Turbine with Liquid Air Energy Storage

- Hybridizes with existing open cycle gas turbine
- Incorporates liquid air for energy storage
- Requires bottoming cycle component development
- System optimization for different cycles, fuel cost scenarios, hardware/permitting constraints
- Best at multi-day durations

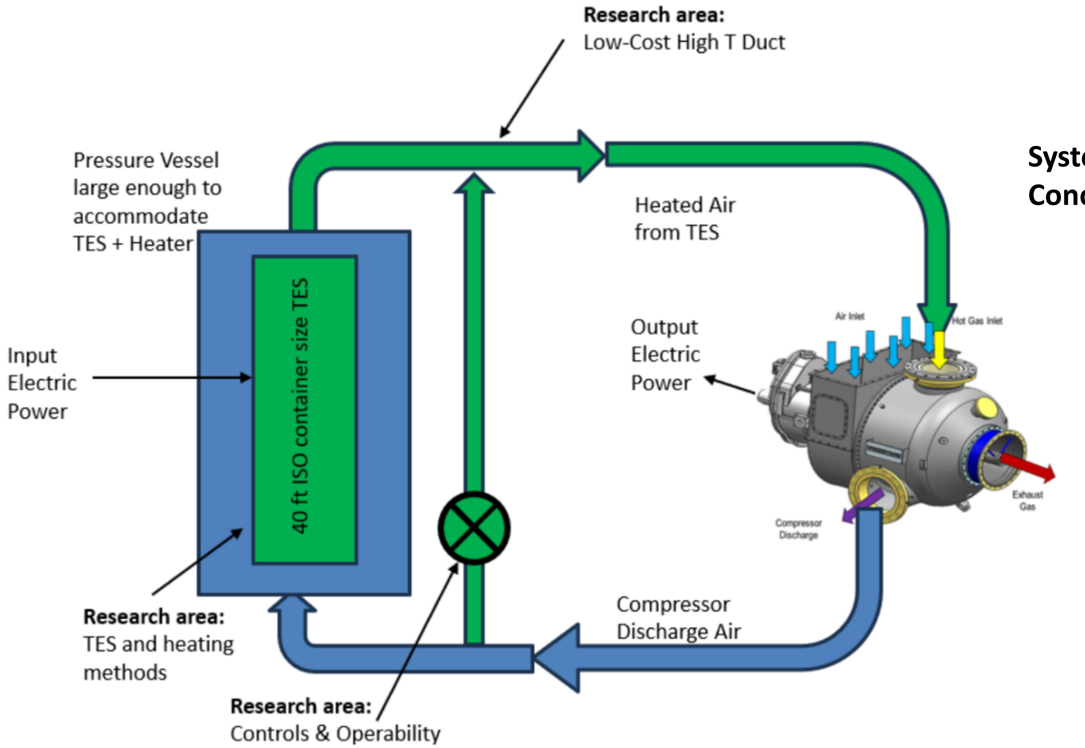
Liquid Air Combined Cycle



Data and Image Sources: Pintail Power (2020)

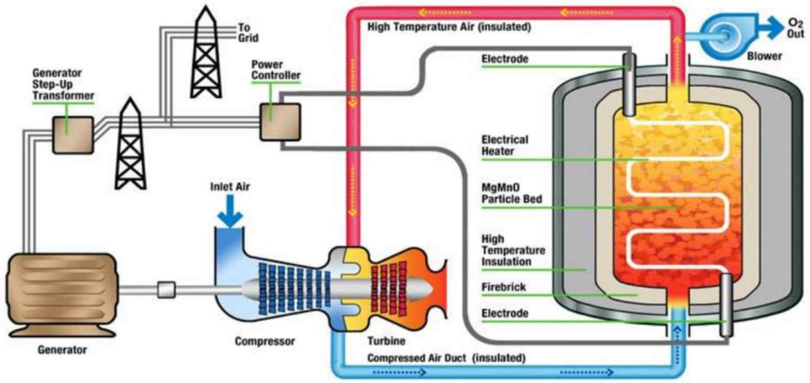
Gas Turbine with Electrified Thermal Energy Storage

- Electric heat addition and storage displaces or hybridizes with combustion
- Many potential energy storage media including up to 1500 °C
- R&D elements include transition piece, combustor integration, dynamics & controls
- System demonstration partnership opportunity



System and Test Facility Concept

Images Courtesy Electrified Thermal Solutions



Images Courtesy RedoxBlox

Image Sources: Electrified Thermal Solutions (2021)

Pumped Thermal Energy Storage (PTES)

Working Principles

- Electricity in drives heat pump to charge system
- Heat engine discharges system to produce energy

Technology Benefits

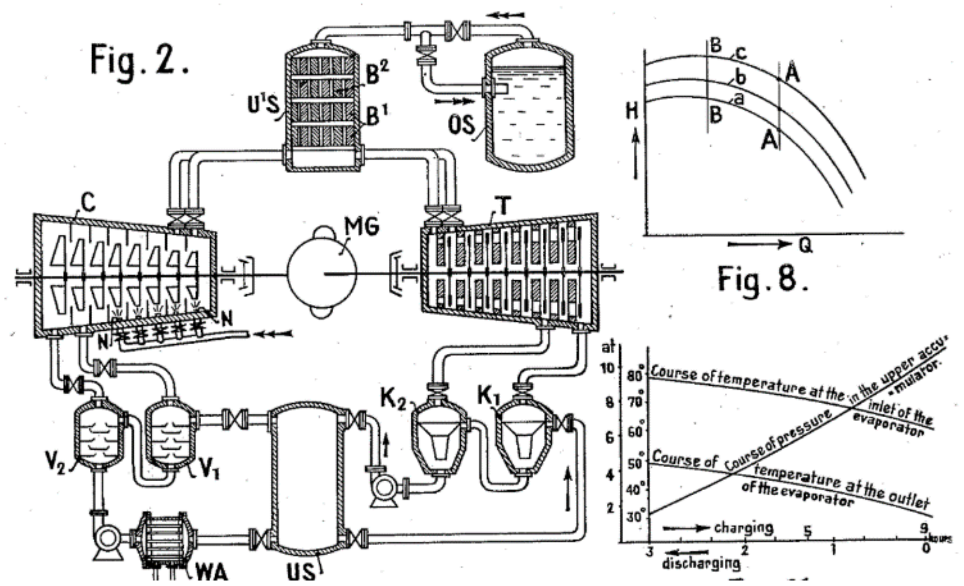
- Up to 50-70% RTE
- No geographical constraints
- Leverages many existing technologies

Technology Gaps

- Multiple cycles/fluids
- Large-scale closed-cycle machines
- Reversible turbomachines?

Turbomachinery Integration

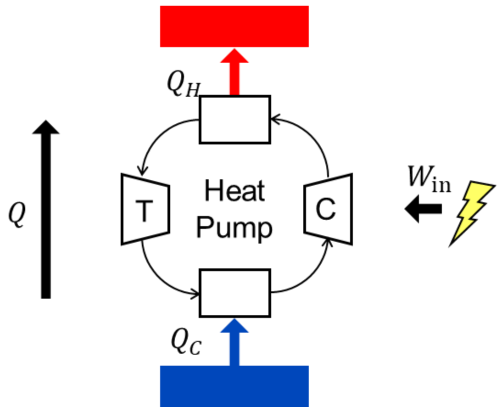
- Development for high efficiency turbomachinery capable of required temperatures
- Designs for high component ramp rates (rapid response)
- Axial or radial machines



Maguerre, 1924

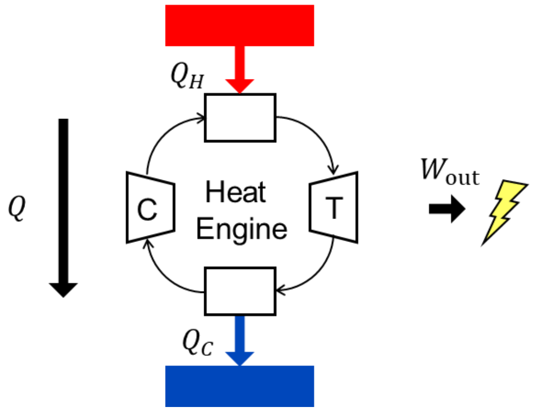
Charge Mode

Use excess energy to run heat pump and store energy in hot and cold reservoirs

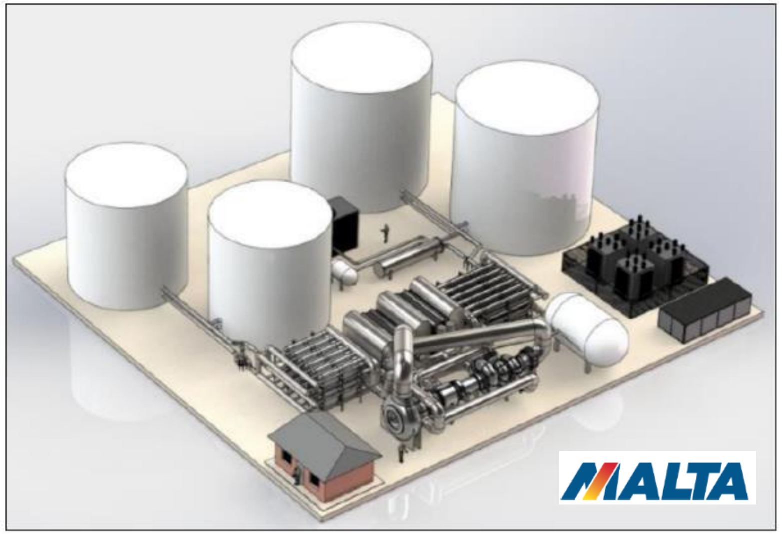


Discharge Mode

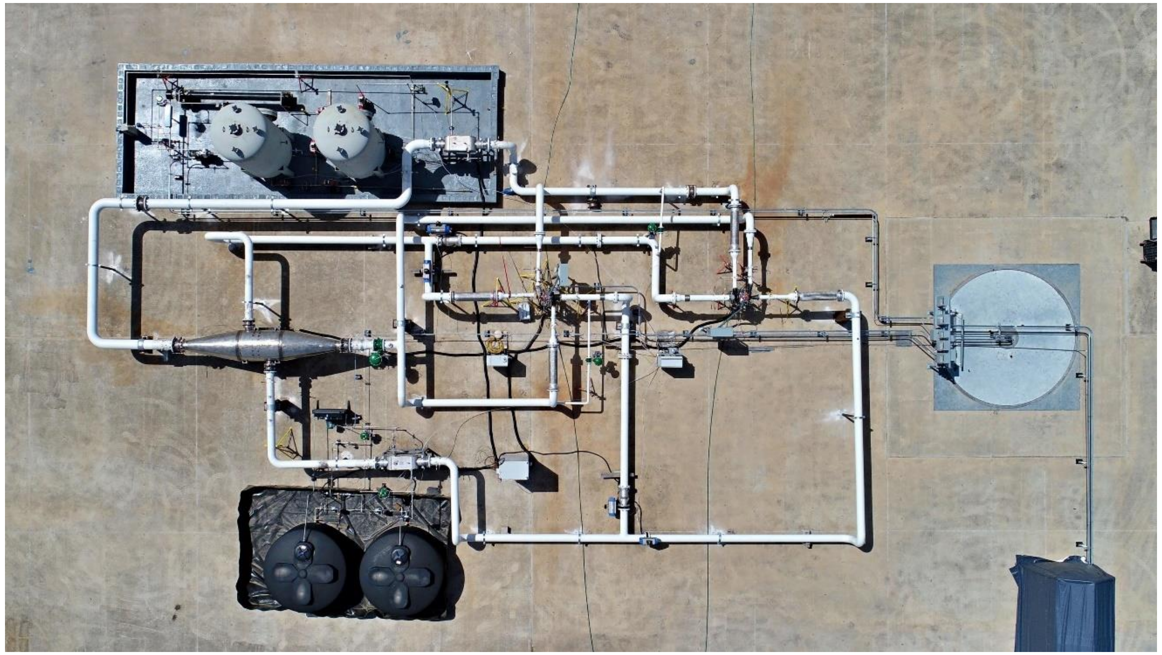
Use thermal reservoirs to run heat engine and generate power



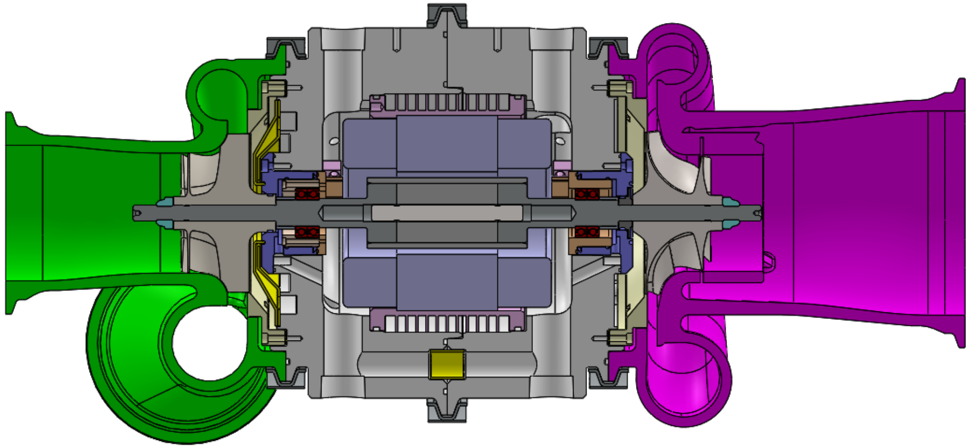
Air PTES Development



- Molten salts at 565°C
- Anti-freeze like fluid at -60°C
- Two separate drivetrains for charge and discharge mode
- Up to 60% RTE
- Targeting ~100 MWe system



- Two new turbine aero designs
- Integrated a motor-generator between the impellers
- New bearing and seal layout
- Thrust balance mechanism
- Incorporated multiple cooling features



- SwRI-led kW-scale PTES demonstration system focusing on system integration and controls, transients
- 400 °C Thermal oil and 12 °C water glycol
- Two separate drivetrains
- Funded by ARPA-E OPEN18 (DAYS)

Questions?

Tim Allison, Ph.D.
Southwest Research Institute
(210) 522-3561
tim.allison@swri.org