Megawatt Scale, Multi-Source Heat Recovery System with a Flexible Grid Interconnect

DE-EE0009423

(October 2021 – September 2024)

Randy Collins, Clemson University
Dean Sarandria, TECO Westinghouse

July 7-9, 2022
DOE AMO CHP Workshop

Dean Sarandria, Enrique Ledezma
TECO Westinghouse
Round Rock, TX

Randy Collins, Ramtin Hadidi, Jay Ochterbeck
Clemson University
North Charleston, SC

Julian Osorio, Rob Hovsapian
National Renewable Energy Laboratory
Golden, CO

U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
Advanced Manufacturing Office

DE-EE0009423: Megawatt Scale, Multi-Source Heat Recovery System with a Flexible Grid Interconnect

Project Partners: Clemson University, TECO Westinghouse, NREL
Project Duration: 36 months
Project Start Date: October 1, 2021

Project Goals:

- Create a model-based Use Case analysis tool for the multi-source heat recovery system
- Implement a scalable, distributed control architecture for complete system dynamic control
- Enable a TRL 6 demonstration of megawatt scale, multi-source heat recovery system suitable for applications in the 1 – 20 MWe range requiring IEEE 2030.8 and IEEE 1547.1 compliance
- Realize a system cost of less than $1,800/kWe considering the complete balance of plant and deferred costs

Project Summary

- Use an ORC in a multi-source heat recovery application with a single turbo expander, leveraging technological developments of high-speed induction machines and high frequency power conversion to streamline grid integration and increase overall efficiency.
- The heat recovery system will aggregate multiple heat sources into a single collection heat stream that can then be controllably proportioned between electrical generation and district heating and cooling requirements.
- The system will be able to ramp electrical output power based upon the ramp rate of any one of the heat sources, momentarily the energy for grid event ride-through, and assist in stabilization of the grid.
- Apply advanced sensing and controls to manage multi-source heat flow into a central ORC and generation system.
- Manage heat exchange from individual heat sources and the heat inconsistency through adaptable control of the working fluid to each heat source to enable the overall system optimization for electrical generation and combined heat and power applications.

Key attributes and technologies

- Able to concentrate multiple heat resources to a single stream
- Centralized ORC and generation systems provide economies of scale in the 1 – 20 MWe range
- Directly application to geothermal energy harvesting and geothermal energy storage systems
- High speed generator and turbo expander simplify mechanical designs and maintenance
- Power electronics grid interface improves flexibility in dynamic power flow control
- Asynchronous, variable speed connection from the electrical grid and the turbo expander allow wider operating range efficiency than fixed-speed ORC designs
- SiC enabled medium voltage, multi-level power converter and induction generator directly scalable to 20 MWe

Heat Recovery System Concept

- Recovering waste heat to generate electricity
  - Heat of compression
  - Biomass fired boilers
  - Geothermal sources
  - Hydrogen electrolyzers
- Improves the overall system efficiency
  - Electricity generated can be directly used locally or integrated to the grid as a distributed energy resource (DER)
- Reduces CO2 emissions
  - 1 MW of heat recovery is equivalent to 8,672,400 lbs. of CO2 annually according to the U.S. Energy Information Administration
- Combining multiple heat sources reduces total system components and cost

Significant opportunities for reciprocal gas compression applications either engine or motor driven greater than 1,500 HP in gathering plants, cryogenic plants and gas pipelines

Acknowledgements

This work is supported under the following Department of Energy, Advanced Manufacturing Office Awards:

- DE-EE0009423 - Megawatt Scale, Multi-Source Heat Recovery System with a Flexible Grid Interconnect

Prior related awards:

- DE-EE0008409 - High Speed Medium Voltage CHP with Advanced Grid Support
- DE-EE0007254 - Fully Integrated High Speed Megawatt Class Motor and High Frequency Variable Speed Drive System

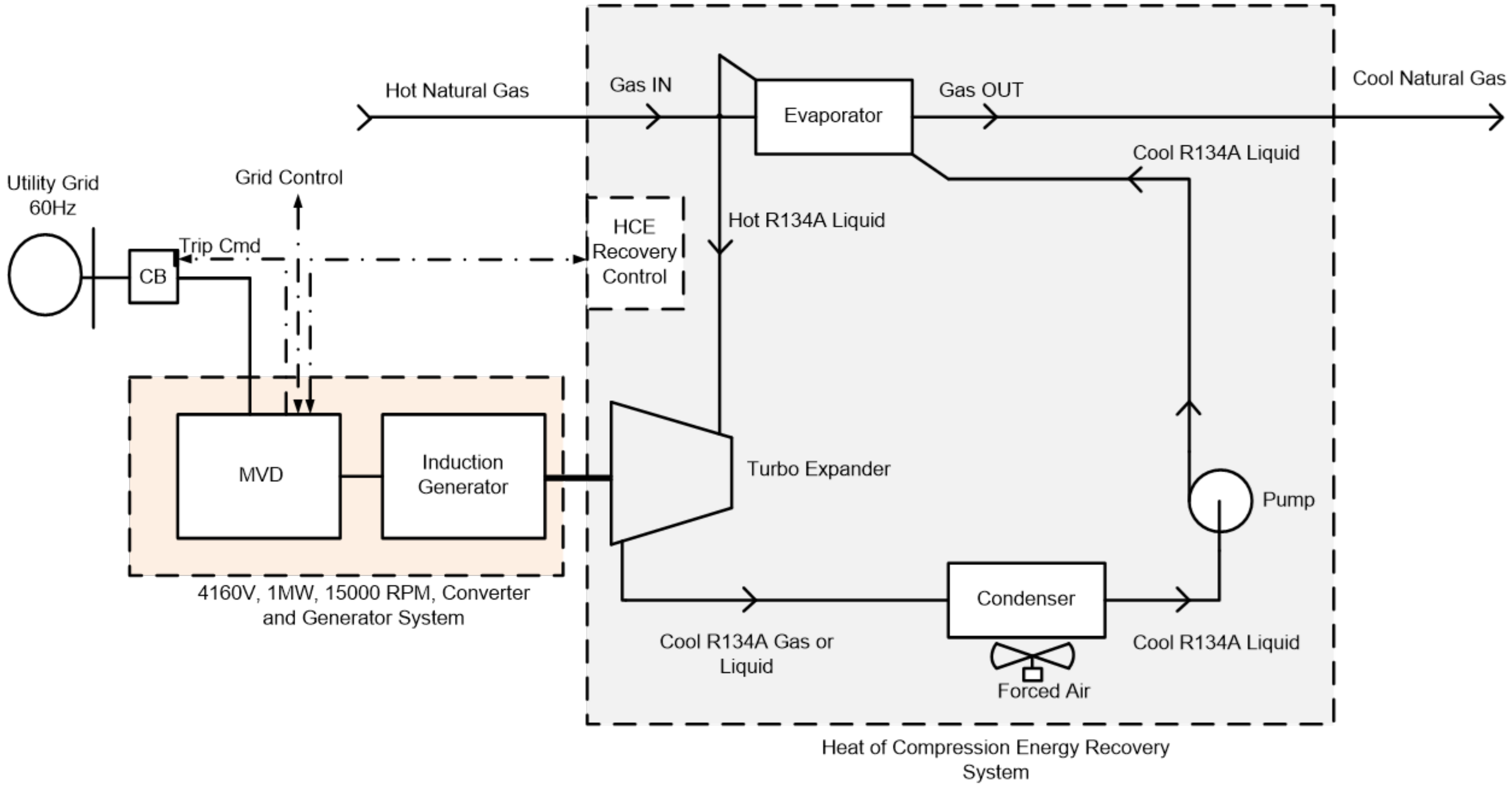
TECO Westinghouse CLEMSON UNIVERSITY NREL Transforming ENERGY

Organic Rankine Cycle (ORC) Heat Recovery System

- Organic Rankine Cycles have been used since the 1950's where lower grade heat is available

- ORC Key Components
  - Working fluid
  - Turbo expander
  - Evaporators
  - Condensers
  - Pumps

- Research Opportunity
  - System monitoring and control for multiple heat sources



Example ORC Heat Recovery System

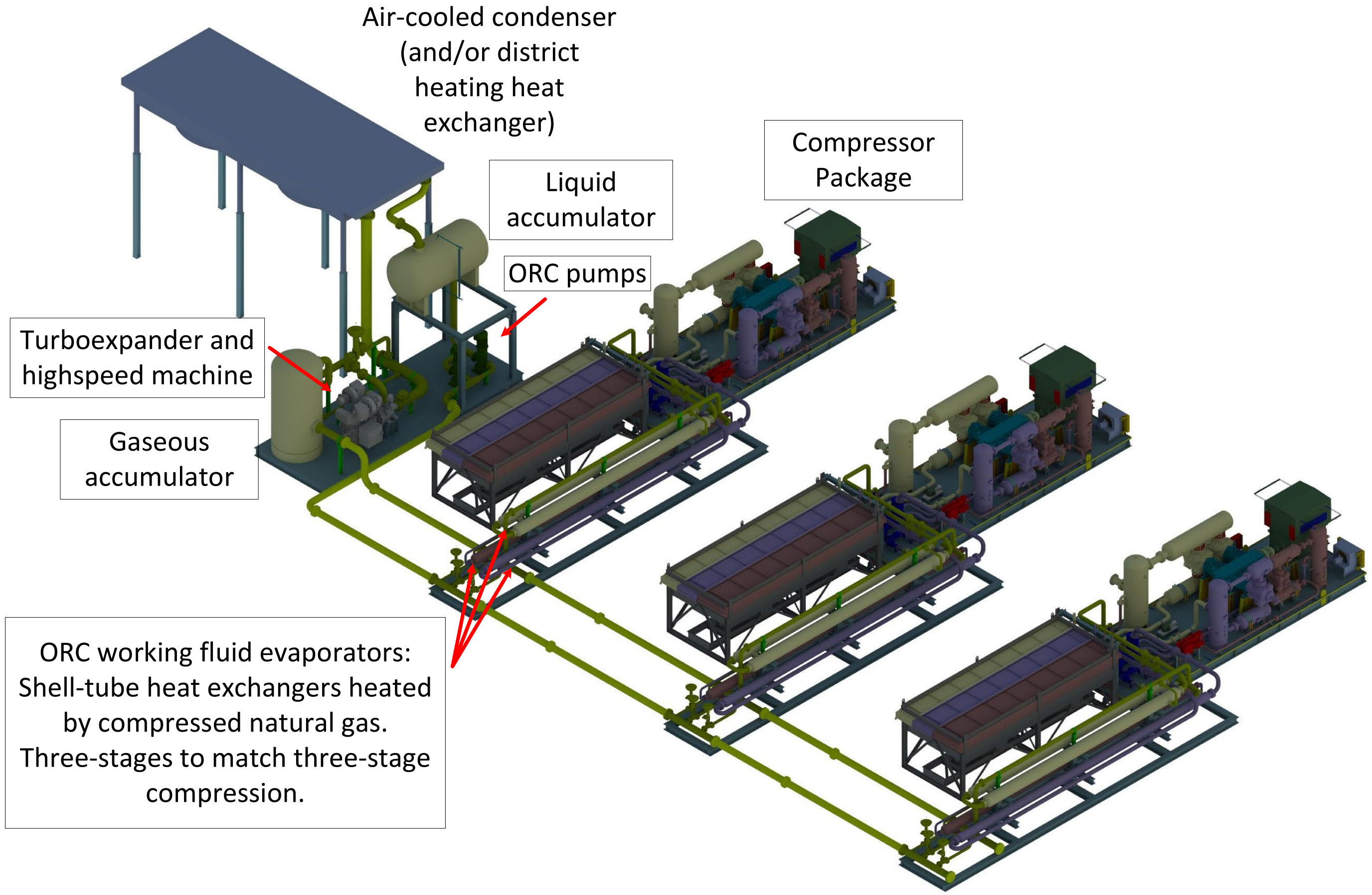
Multi-Resource ORC Heat Recovery System

Applications	Thermal Unit Type(s)	District Heat
Municipality owned natural gas generation site	LM6000 Gas Turbine: (2) exhaust evaporators (2) fuel conditioning compressor package waste heat	Industrial port district
Municipality owned development	(2-3) wood-biomass boilers	Heat intensive commercial businesses: brewery, dry cleaner
Municipality owned development	(3) natural/methane gas boilers	Heat intensive commercial businesses: Plastic molding
Mid-Stream Natural Gas Compression Site	(6) gas compressor package waste heat	Well wastewater treatment

Example Application: Natural Gas Compression Site

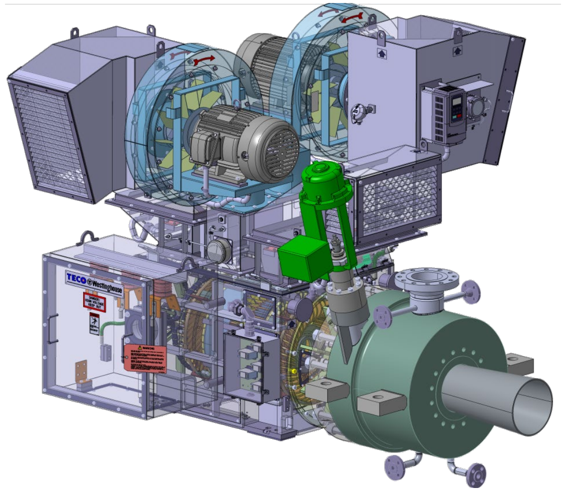
Example Heat of Compression Recovery System

- 1 MW reference design
- Six natural gas reciprocating compressors (only 3 shown)
- Multi-stage evaporators to match compressors
- Gas and liquid accumulators
- Working fluid pumps
- Air-cooled condenser



Enabling Technology

- High Frequency Medium Voltage Variable Frequency Drive
    - Multi-level design suitable for many applications
    - Modular design for simplified O&M requirements
    - Using state-of-the-art Silicon Carbide power electronics to increase efficiency



- High Speed Medium Voltage Induction Machine
    - Robust machine design building off decades of experience
    - Low maintenance squirrel cage design with no permanent magnets
    - Open or totally enclosed designs available
    - Can be designed for hazardous environments

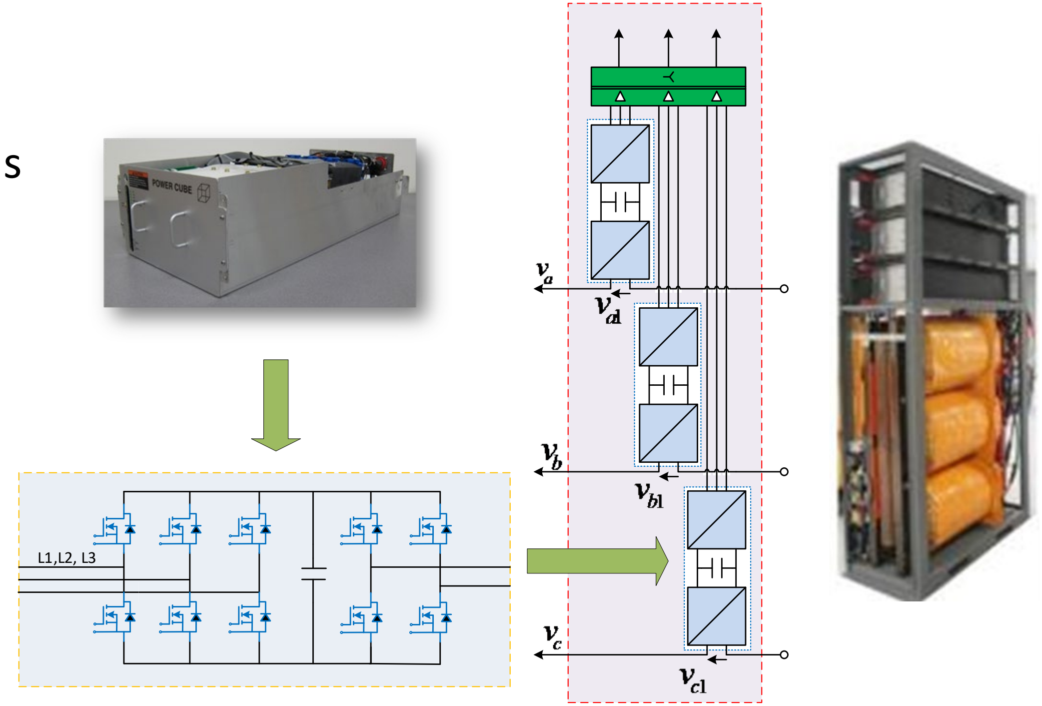
TECO Westinghouse   CLEMSON UNIVERSITY   NREL Transforming ENERGY

High Frequency Medium Voltage Variable Frequency Drive

- Modular, multi-level system architecture
    - Scalable in voltage by adding slices in series
    - Scalable in power by adding units in parallel
- Suitable for high speed motoring and generation applications
- Able to use low voltage SiC MOSFETs, leveraging cost reductions from other industries
- Low input and output distortion reducing grid and induction machine requirements

1 MW Reference System Specifications

(sensitive data removed)

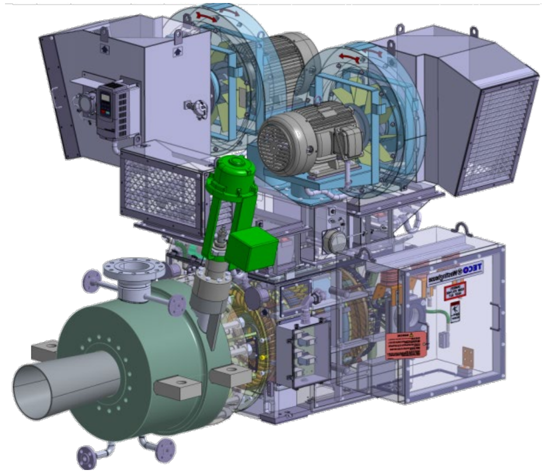


Modular, multi-level, medium voltage VFD architecture scalable in the 1 to 20 MWe range

High Speed Medium Voltage Induction Machine

- Considered a squirrel-cage induction motor topology for the high speed application because of its robustness
- Selected commercially available materials with low losses and high strengths
- Optimized the geometry for the application to achieve the required performance with lowest cost
- Designed the stator coils using type 8 Litz conductors to minimize losses

Prototype 1 MW, 15,000 RPM Induction Machine



3D rendering with the turbo expander attached

1 MW Reference System Specifications

(sensitive data removed)

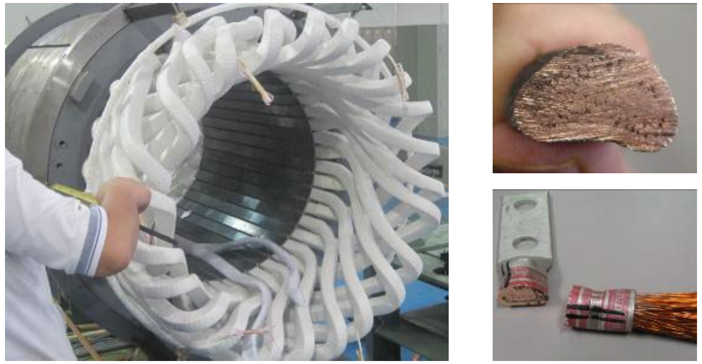
TECO Westinghouse

CLEMSON UNIVERSITY

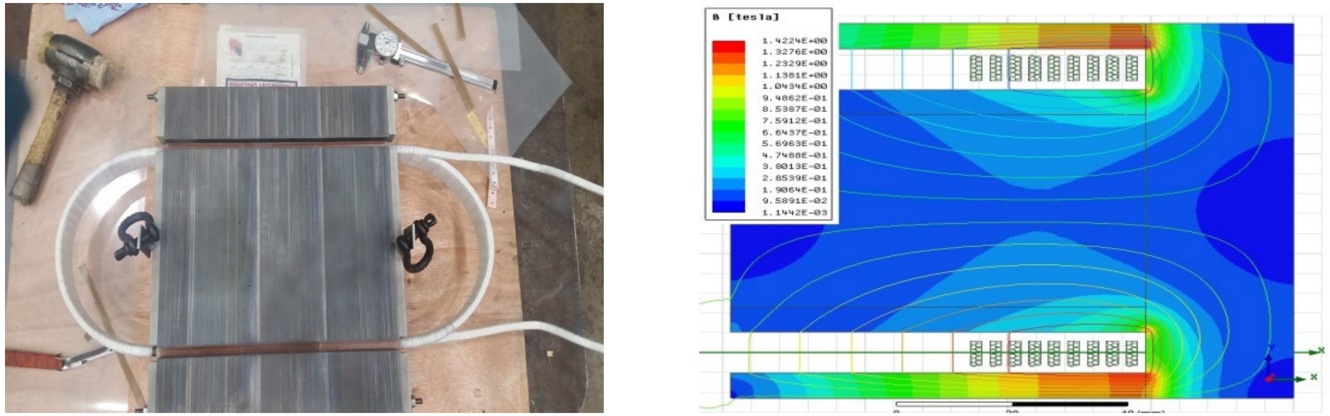
NREL Transforming ENERGY

High Speed Induction Machine

- Electromagnetic design using 2D and 3D simulations
  - Performance evaluated using sinusoidal and PWM voltage waveforms
- Frequency domain steel-embedded slot model developed and validated
  - Used to calculate AC impedance, a key driver in stator efficiency



Litz wire stator coils for high frequency operation



Benchtop test and electromagnetic FEA simulation for Litz wire model validation

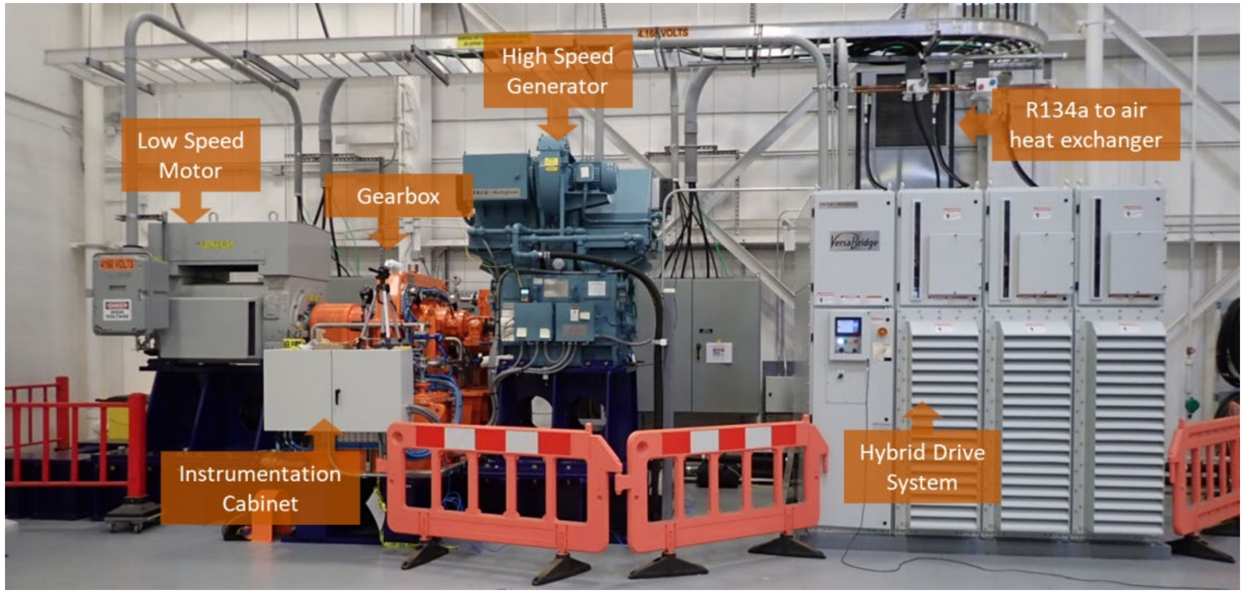
(sensitive data removed)

Litz wire ratio of AC to DC resistance versus frequency

TECO Westinghouse   CLEMSON UNIVERSITY   NREL Transforming ENERGY

1 MW Prototype System Validation

- Initial full power heat runs completed demonstrating successful results
  - Total system efficiency, shaft to grid > 92%
- Comprehensive test plan developed and validation testing underway

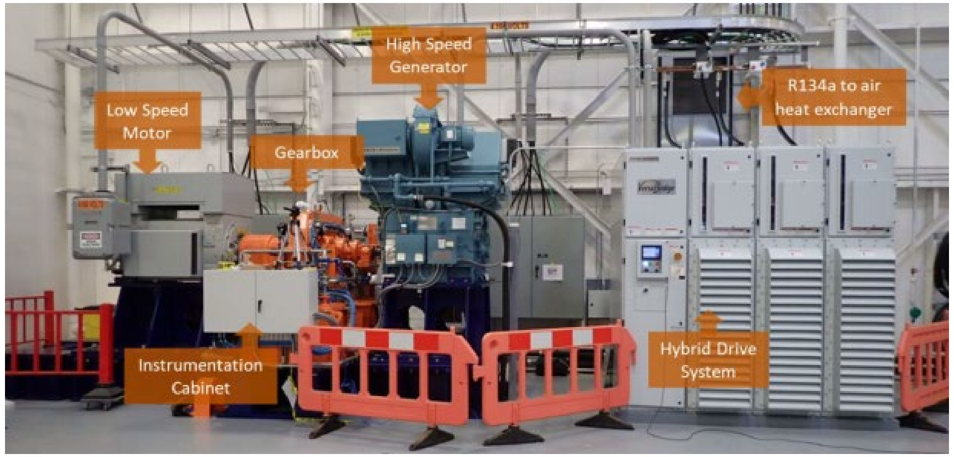


1 MW reference design undergoing validation testing at the Clemson University eGRID Center

Protocol Reference	Title
IEEE Std 1566™-2005	IEEE standard for performance of adjustable speed ac drives rated 375 kW and larger
UL 347A-2015, 1st Ed.	Medium voltage power converter equipment, standard for safety
IEC 61800-4:2002	Adjustable speed electrical power drive systems-general requirements-rating specifications for ac power drive systems above 1000 VAC and not exceeding 35 kV
IEEE Std 519™-1992	IEEE recommended practices and requirements for harmonic control in electrical power systems
IEC 61000-3-6:2008	Harmonic Emission Limits for Customers Connected to MV, HV and EHV
IEEE Std 112™-2017	IEEE standard test procedure for polyphase induction motors and generators
NEMA MG1-2014	Motors and generators
IEEE Std 85-1973	IEEE Test Procedure for Airborne Sound Measurements on Rotating Electric Machinery
IEEE Std 1547.1-2020	IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces
UL 1741 SA, 2nd Ed.	Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources

TECO Westinghouse CLEMSON UNIVERSITY NREL Transforming ENERGY

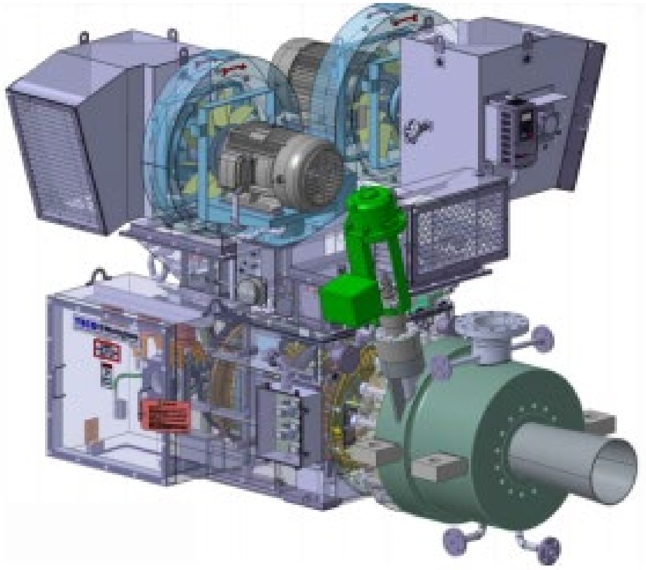
Electrical/Generator System Design Update



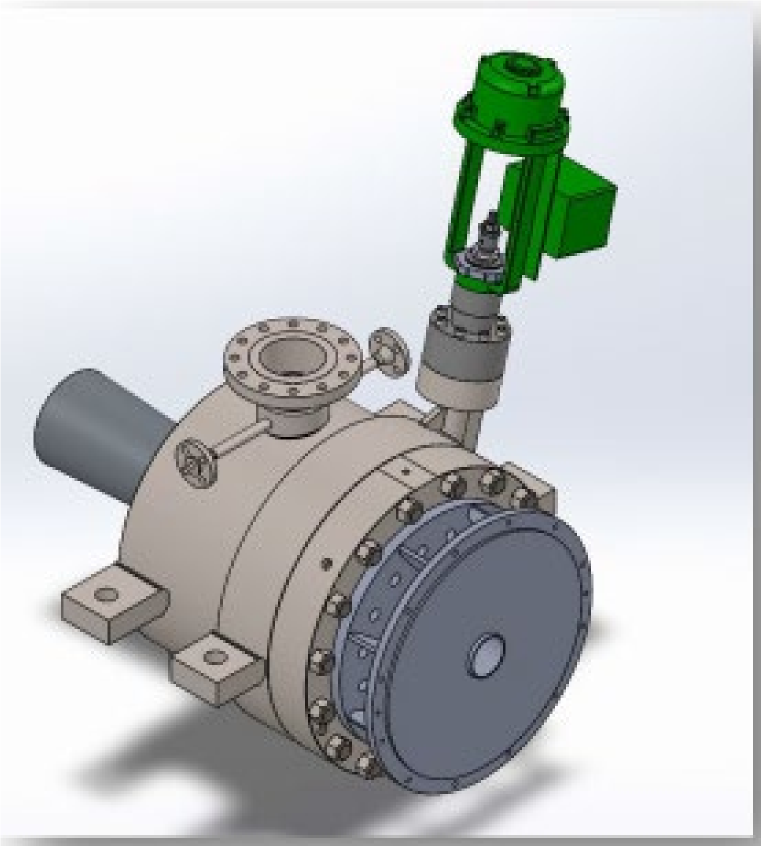
1 MW reference design undergoing validation testing at the Clemson University eGRID Center

The high-speed water-cooled generator was tested at Clemson without the Turbo Expander. It was done to validate the motor and SiC MVD design. The SiC MVD can be used for field testing with upgraded power cubes. The generator is not usable for field testing due to design interface with the turbo expander.

The commercial generator design will be air cooled and has modifications to the shaft and end frame for mounting the turbo expander housing with its purged shaft seals and shaft mounted wheel. LA Turbine will machine the shaft to mount the expander wheel. TWMC anticipates testing at high-speed near the end of 2022.



Thermal/ORC System Design Details



The Turbo Expander has been built with its titanium wheel for the designed flow conditions. Variable inlet vanes are included to fine tune the wheel performance for flow

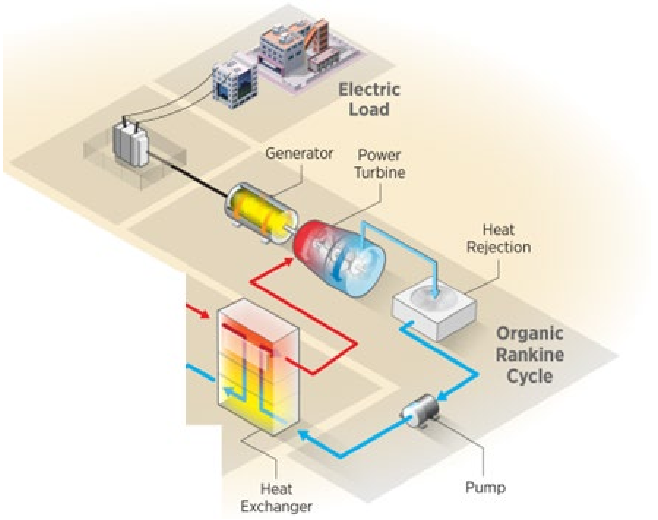
The lead time for the air-cooled generator with the turbo expander is 42 weeks. Since the expander manufacture is complete for expected Rankin cycle flow conditions, we are working on the schedule shorten the TRL 6 field testing. The closed-loop propane system design by NREL to match the required flow conditions.

Turbo Expander and Wheel Design

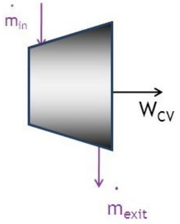
(sensitive data removed)

Model formulation and Integration into Real Time Simulation Environment

Organic Rankine Cycle



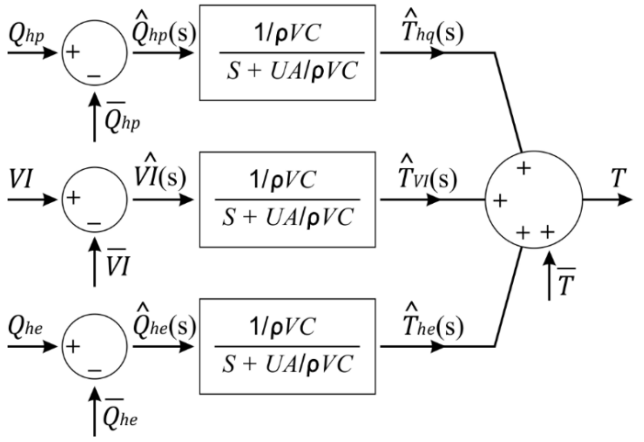
Physics-based model



$$\frac{dm}{dt} = \dot{m}_i - \dot{m}_e$$

$$\frac{dE_{cv}}{dt} = \dot{E}_i - \dot{E}_e$$

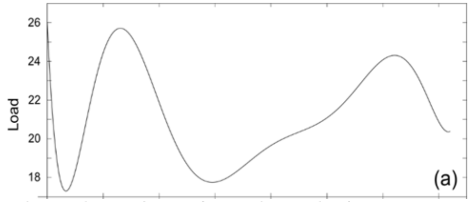
Block diagram model

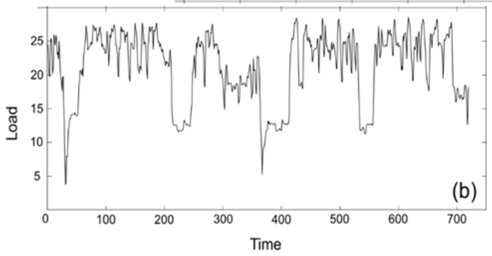


Transfer functions

$$\Delta P_{ORC}(s) = \frac{n_{\omega 1}s + n_{\omega 0}}{s^2 + d_{\omega 1}s + d_{\omega 0}} \Delta\omega(s)$$

Digital Real Time Simulation





Variable load

Budget Period 1: Research and Development

Task 1: Multi-Source Heat Recovery System Use Case Analysis – Create Use Cases and analysis tools for the evaluation of the requirements for the proposed sites and other potential applications of the technology to enable a scalable and flexible system for dynamic heat sources and electrical generation capabilities.

Task 2: Physics-based Organic Rankine Cycle Modeling and Simulation – Develop and validate a physics-based model of the Organic Rankine Cycle to analyze its behavior under full and partial load operations as well as the dynamic behavior of the system in response to specific grid conditions.

Task 3: Dynamic Multi-Source Heat Recovery Control Development – Develop algorithms, cost functions and hardware that will manage the dynamic performance of the system from the heat entering the evaporators to the electrons leaving the power converter such that the overall system requirements are reliably maintained under varying heat input, heat output, electrical generation and grid conditions.

Task 4: Multi-Source Heat Recovery System Component Design – Detailed engineering design and analysis for system components to be utilized in the demonstration, including: heat exchangers for district heating, evaporators for each heat source and condensers, the working fluid characteristics and pumping requirements, expansion tank sizing, turbo expander design and operating envelopes, and control valving and sensing.

Budget Period 2: Design and Testing

Task 5: Controller Hardware-In-the-Loop Validation – Advance the modeling and simulation of Task 2 to enable real-time thermal, mechanical and electrical co-simulation that captures the system dynamic behavior and merging these simulation models with the physical control hardware from Task 3 to create a Controller Hardware-In-the-Loop environment for validation of the multi-source heat recovery system.

Task 6: Installation and Commissioning – Installation of both the heat recovery system as well as the controllable laboratory equipment required to create the dynamic multi-source heat environment needed to demonstrate the efficacy and viability of this technology across a broad range of applications.

Budget Period 3: Installation and Demonstration

Task 7: Full Scale Laboratory Demonstration – A 1 MWe, multi-source heat recovery system demonstration in a controllable laboratory environment utilizing the requirements and constraints of the Use Cases, including: district heating, renewable energy integration, microgrid applications and dispatchable generation.

Questions