RHEOMEGA

HARNESSING THE POWER OF HEAT

Foam Turbine

TECHNICAL - JUNE 2016

Today's Goals

How can RheOmega help you?

Intro to RheOmega

Evaluate RheOmega's Isothermal Compression in Brayton cycles

- Applicable?
- Practically Achievable?
- Wanted?

Discuss Microturbines vs. Turbines – markets & technologies

Identify Minimum Viable Product for 1st market segment

Review proposed R&D Path

RheOmega's Future

Who is RheOmega?

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Alex Bell – Founder

"Foam Guy" Senior Research Engineer, R&D Manager – key developer of SustainX's isothermal compression/expansion foam technology – 4 patents

Thayer - MEM

UNH, BS Chemical Engineering

David Perkins – Adviser

CTO – General Compression (Isothermal Compressed Air Energy Storage)

CTO - Active Power (Flywheel & Compressed Air UPSs)

10 patents

University of Texas - BS, MSME

What is RheOmega?

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Our Vision:

- Powering 1 MW of clean energy enabled by Foam Technology within 5 years

Our Convictions:

- **Isothermal compression & expansion** are applicable to many industries
  - Save power on compressors in oil & gas, chemical production, shop air, chillers/AC/refrigerators
  - Increase power output from expanders in organic Rankine cycles, other power cycles
- **Foam** – a stabilized mixture of a gas & a cooling liquid – is a practical means to achieve near-isothermal compression and expansion

- We have the technical know-how to bring Foam Technology to new applications

What is RheOmega?

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Strategy:

- Start with one, most promising application to get business off the ground
- Branch out to other applications

RheOmega's **Foam Turbine** is the best foot forward

Foam Turbine vision:

- Displace diesel recip engines as #1 choice for power gen in 0.5MW-10MW markets

- Leverage RO's efficiency gain for efficiency parity
- Leverage RO's specific work increase for significant $/kW savings
- Maintain reliability & emission advantage

Foam Turbine

Modified Microturbine/Turbine

The Innovation:

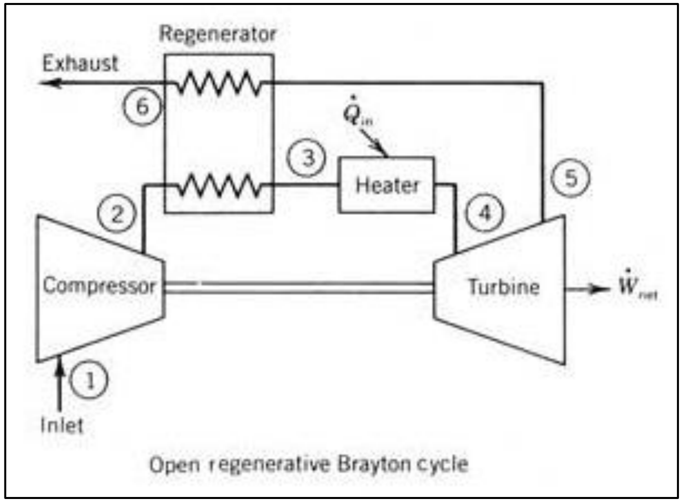
- Up to an additional 4% efficiency
- 50% more specific power

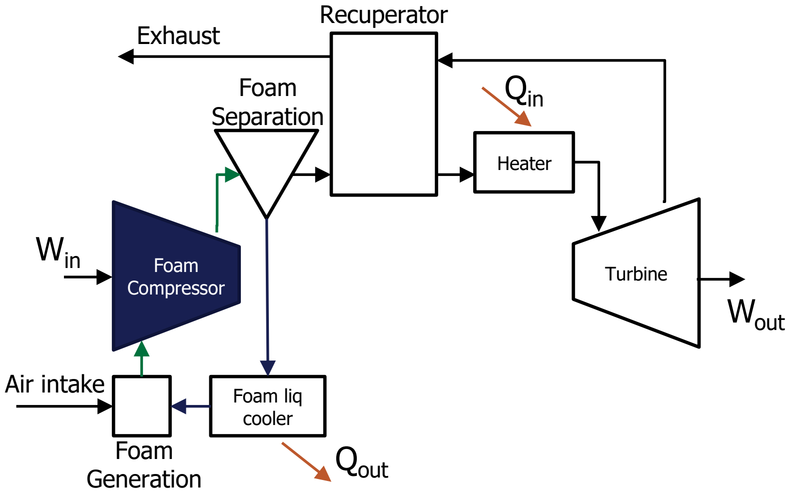
Microturbines use a recuperated/regenerated Brayton cycle to generate power

Turbines don't use a recuperator but sometimes use a combined cycle

How does the Foam Turbine do it?

- The Foam compressor (near-isothermal) instead of the adiabatic compressor
- Adiabatic compressor consumes 40-50% of the turbine's output
- Isothermal compressor consumes 20-30% less power
- Specific power is increased by 40-50% means reduced size on all hot equipment → cost savings

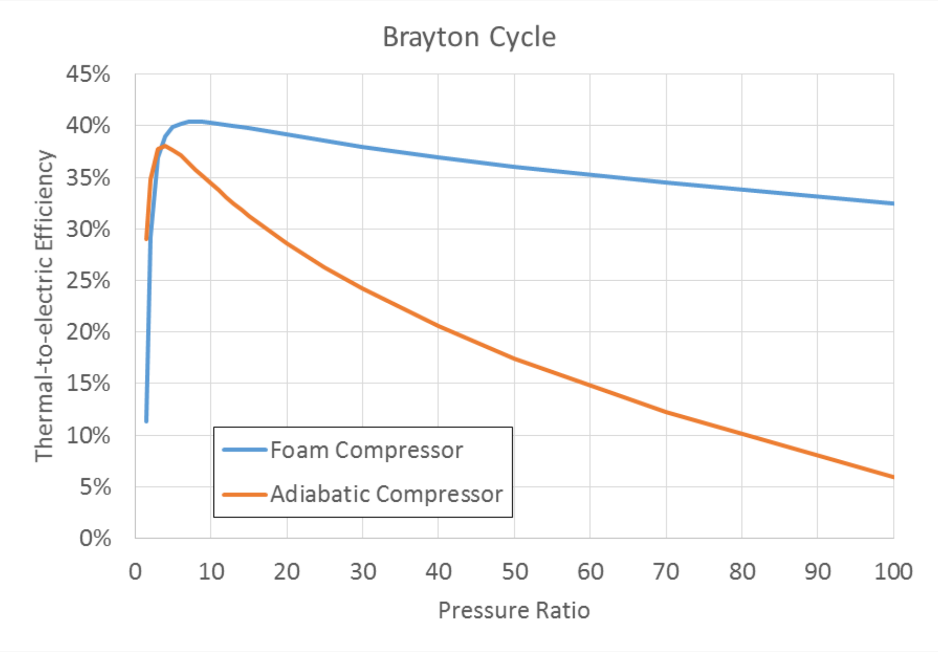


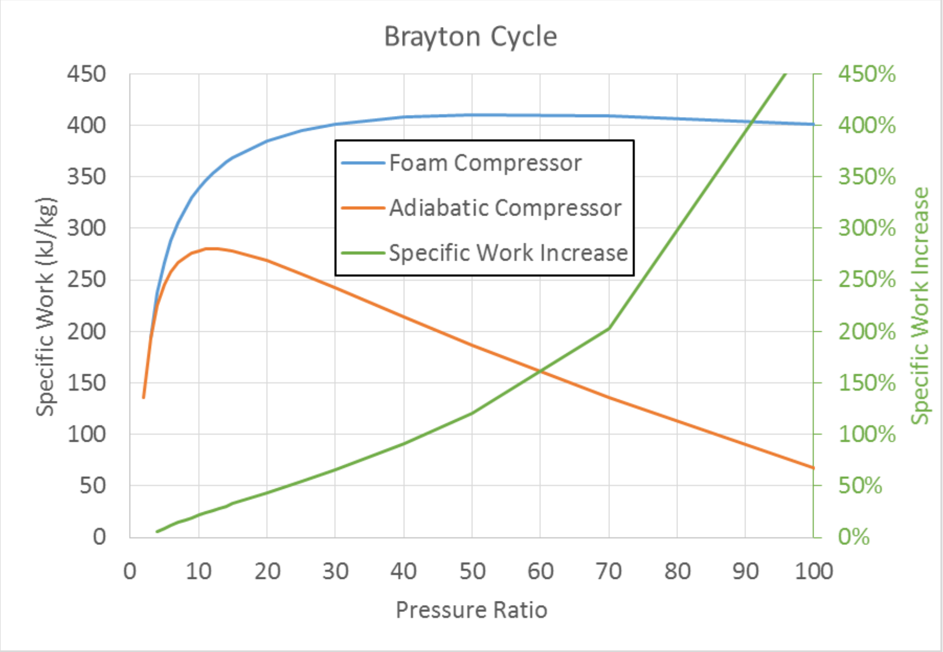


Foam Turbine Cycle

Foam Turbine

Modified Microturbine - Recuperated





Equipment Efficiencies	
85%	Adiabatic Compressor
85%	Foam Compressor
90%	Turbine
85%	Net
90%	Recuperator
80%	Combustor
1150ºC	Turbine Inlet

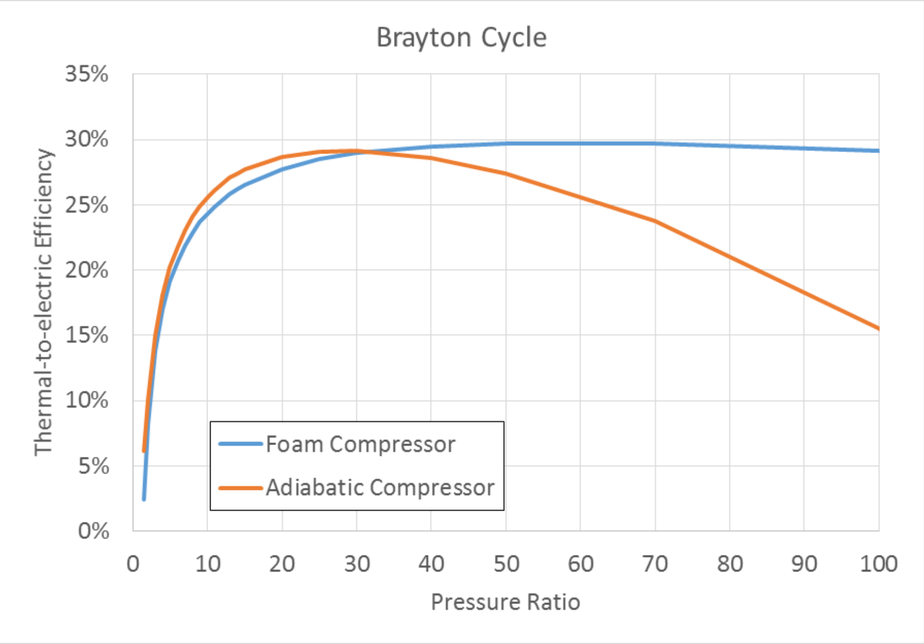
Peak efficiency: +2%

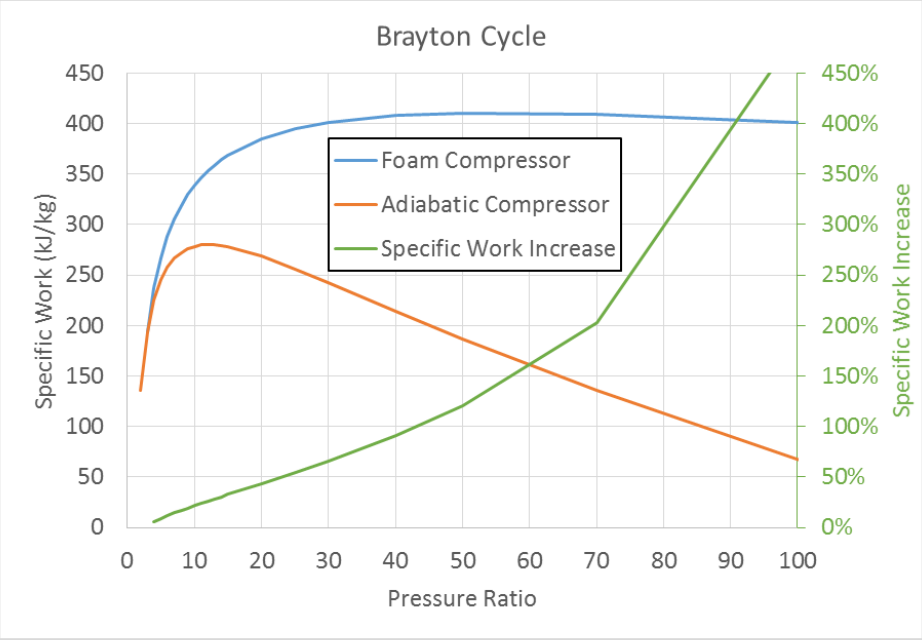
- Standard cycle peaks @ pressure ratio ~4
- Foam cycle plateaus ~7-9 pressure ratio
- 41% more specific work

Peak specific work: +47% more work, +2.5% efficiency

Foam Turbines

Turbines – No Recuperation





Equipment Efficiencies	
85%	Adiabatic Compressor
85%	Foam Compressor
90%	Turbine
85%	Net
0%	Recuperator
80%	Combustor
1150ºC	Turbine Inlet

No recuperation

Peak efficiency: +0.5%

- Standard cycle peaks @ pressure ratio ~30
- Foam cycle plateaus ~55 pressure ratio
- 70% more specific work

Peak specific work: 47% more work, +3% efficiency

Foam Turbines

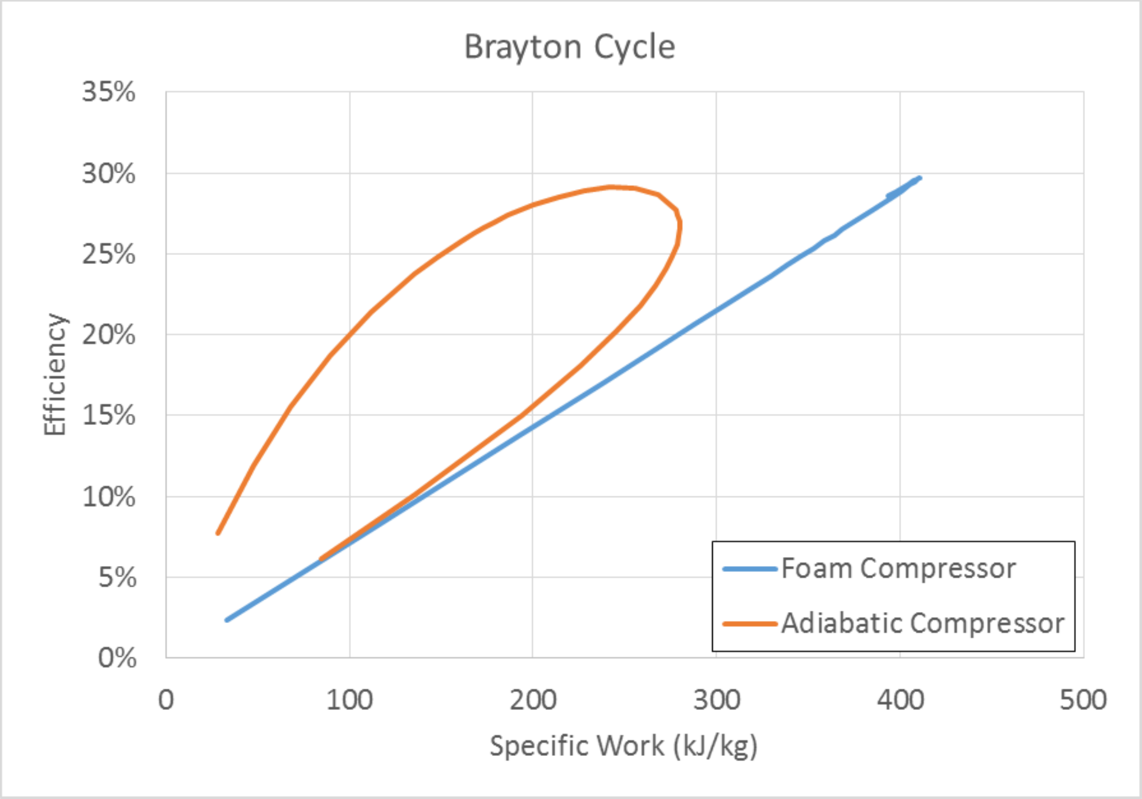
Turbines – No Recuperation

Without recuperation,

The Foam Turbine hits peak efficiency and peak specific work at the same pressure ratio

In this example, PR ~ 55

Equipment Efficiencies	
85%	Adiabatic Compressor
85%	Foam Compressor
90%	Turbine
85%	Net
0%	Recuperator
80%	Combustor
1150°C	Turbine Inlet



Minimum Viable Product

For whom?

- What market segment cares the most about the benefits? Cares the least about the foam tech disadvantages?
- Data centers, hotels, hospitals, oil fields?

What size?

- Trends seem to be upwards: FlexEnergy 250kW → 333kW, Capstone 200kW → 370kW
- 1-2MW?
- 10MW?

What features?

- CHP?
- Maintenance schedule

What are the trends?

The Foam Hardware

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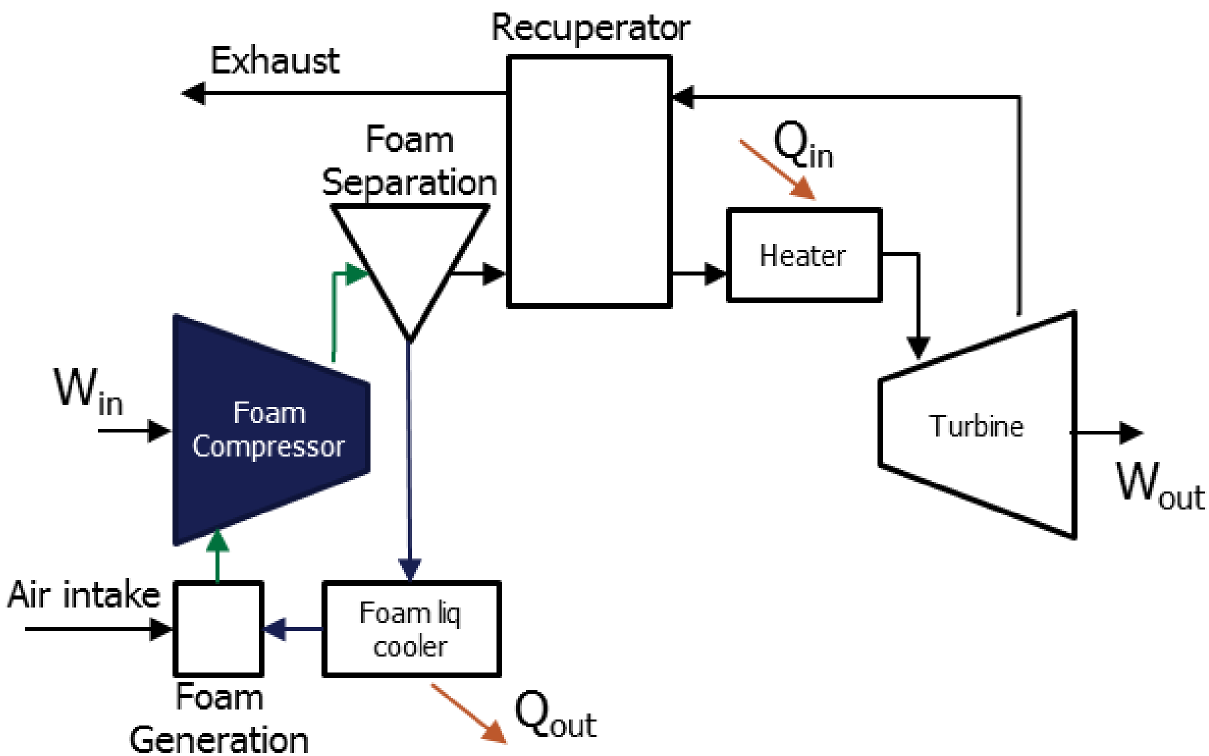

Foam Turbine Cycle

The following slides will describe the Foam Hardware:

- Foam Compressor, Foam Separation, Foam Liquid Cooler, Foam Generation

Foam Compressor

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Foam Compression requires

- Positive displacement
- Low dP/dt ~ <100 bar/s
- Low inlet shear ~ <2000 1/s
- → RPMs in 100s

Positive Displacement compressors

- Vane
- Screw
- Scroll
- Reciprocating piston

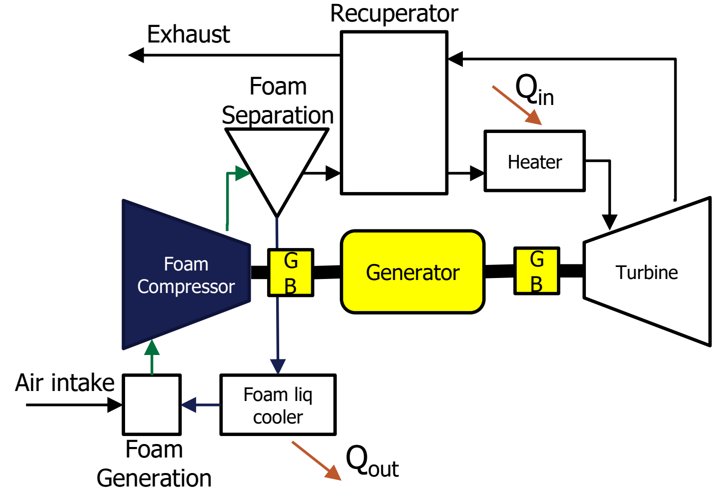
Maintenance & Lubrication?

- Running with water & air
- Corrosion resistant materials needed

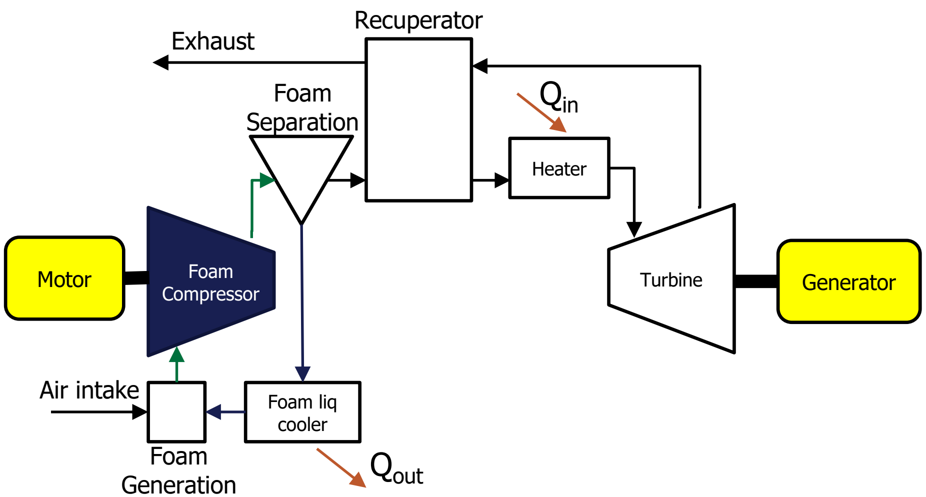
Vane: *275-640rpm, up to 10 barg, 150psi. 8" inlet, 4" outlet, 3.5" shaft*
For dP/dt limit, run at 400rpm ~1250scfm, 0.708kg/s
180kW compressor input – 200kW cycle output

Foam Compressor

Gearbox(es)?
- Capstone – turbo alternator (~5% loss)
- FlexEnergy – gearbox (~2% loss) & synchronous generator



Single shaft? Dual shaft?



Foam Separation

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Cyclonic foam breakers

- DP ~0.2 - 1 bar ~ 1-2% loss
- 1-10 needed

Vessel

- Minutes of residence time
- 100s of gallons

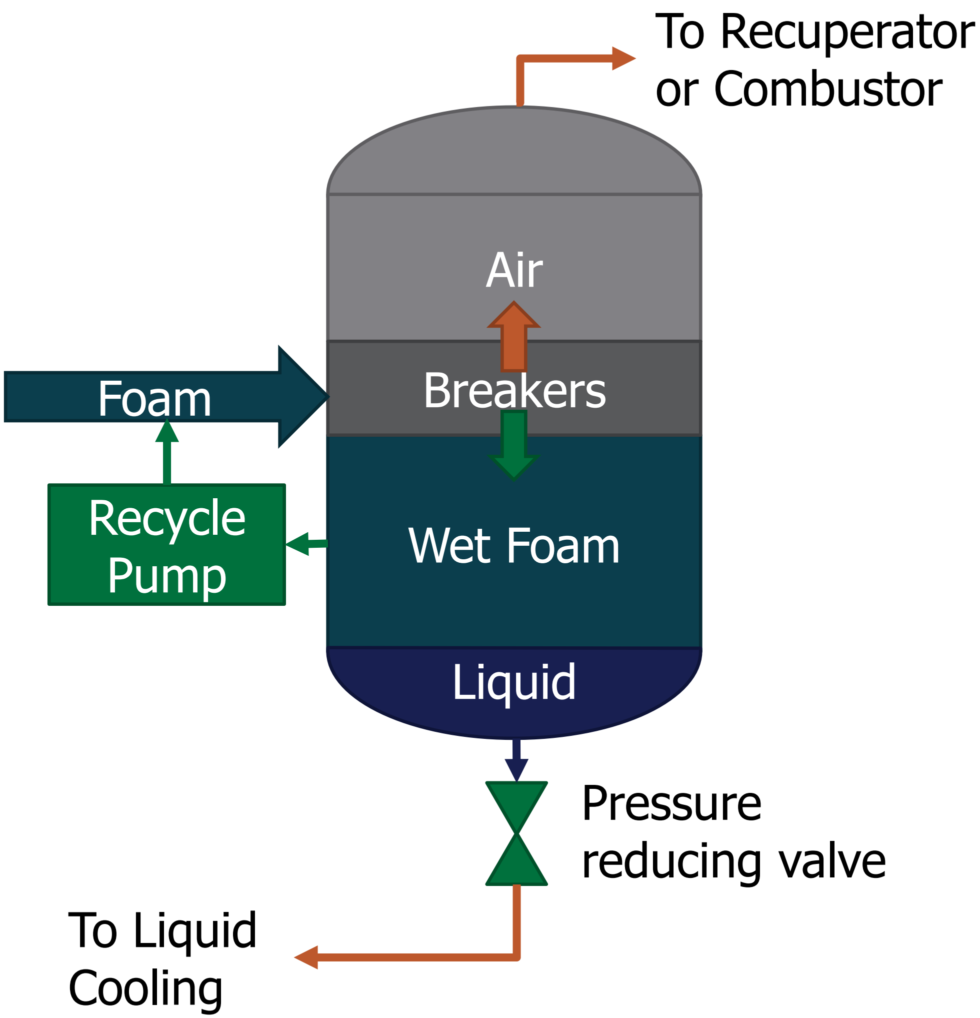
Recycling

- Fraction of foam flow

Pressure Reducing valve

- Down to ~2 barg

*Assumed 200kWe output



CHP & Foam Liquid Cooling

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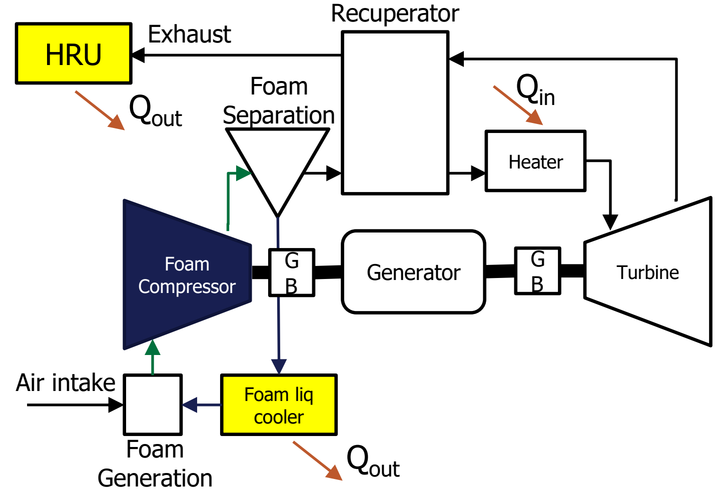
For Foam Turbine CHP,
- 2/3 heat from compressor liquid (Cooler)
- 1/3 heat from exhaust gas (HRU)
- Both lower quality than typical – liquid ~50oC, gas ~100oC

Cool foam liquid is critical
- Liquid sets compression temperature and therefore work

Good fit for warming cold water (15-20ºC)
- Domestic hot water CHP?

Poor fit for keeping warm water hot (50-80ºC in)
- Heating systems targeting 50-80ºC

Air heat exchanger is needed to cool when cool water is unavailable

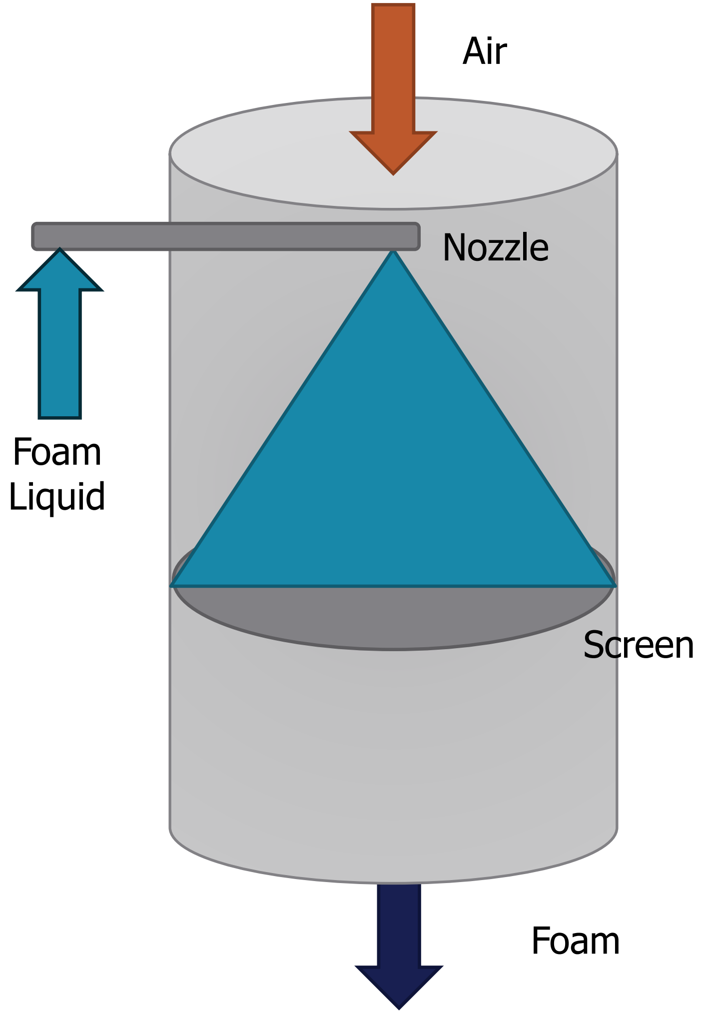


Air: 15ºC	Efficiency Gain
Adiabatic compression	-
Foam liquid: 15ºC	3.9%
Foam liquid: 30ºC	2.7%
Foam liquid: 45ºC	1.6%

Foam Generation

Air Intake – simple pieces

- Circular, vertical, down flow
- <1 m/s
- Screen: layers of stainless steel mesh, sintered together
- Liquid chemistry needs maintenance
  - Atmospheric humidity collected over time



Research & Development

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Feasibility Study & Test Stands

- Addressing components & process risks
- Est. 12 months, 3 people, $500K

- Major components performance & costs
- Test stands data
  - Foam Compressor
  - Foam Separation

Prototype System

- Addressing Integration Risk
- 12 months, 6 people, $1 million

- Phase 1: Detailed design
- Phase 2: Build & Test

Alpha System

- Address Performance Risk
- 18 months, 9 people, $2 million

- Phase 1: Design for pre-production
- Phase 2: Build & test with 1st customers

R&D Partners → Commercial Partners

Proposal

RheOmega needs Funding, a Home, Partners

RheOmega focuses on foam components – Turbine Partner focuses on combustor, turbine, recuperator

Jointly develop a new turbine system using foam compression – Raise funding (likely grants) together

RheOmega pursuing:

- NH TechOut competition: $20k - $50k potential investment – gets Feasibility Study underway
- ARPA-e IDEAS (Innovative Development in Energy-Related Applied Science)
- NSF SBIR
- DoE unsolicited grant proposal?

And/or Strategic investment – develop RheOmega's compressor into new turbine product line

- In-kind engineering, office, lab space contribution
- Cash for equipment (test stand, proof of concept), salaries

RheOmega open to providing alternative/consulting services as well

The Story of Foam

Discovered accidentally

Can't beat it, use it!

- Spray 95% isothermal efficiency @ 3 secs stroke
- Foam 98% isothermal efficiency @ ¼ sec stroke

Developed in 18 months – concept to implementation in full-scale prototype

SustainX's Isothermal Compressor/Expander

- 2.2 MW compressor, 1.5 MW expander, 1 MWhr energy storage
- Atm to 207 bar/3000 psi, 90-120 rpm
- Reciprocating piston, 2-stage, vertical inline 6 cylinder

Intellectual Property

General Compression acquired SustainX's IP and hardware

GC is using a broker to try to sell the IP

- Opportunity to buy now, or license from eventual buyer
- Or avoid altogether

Existing patents claims avoided through use of non-reciprocating machines, e.g.

US Patent 8539763 claim 1

A method of recovering energy, the method comprising:

transferring a first foam to a **first cylinder** assembly, the first foam having a first foam expansion ratio;

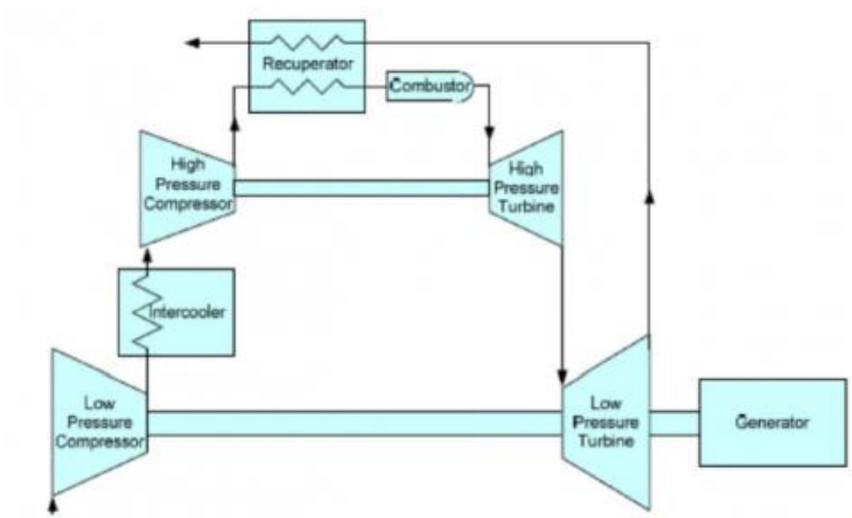
expanding the first foam in the first cylinder assembly, thereby recovering energy therefrom;

thereafter, transferring a second foam to a **second cylinder** assembly different from the first cylinder assembly, the second foam having a second foam expansion ratio larger than the first foam expansion ratio; and

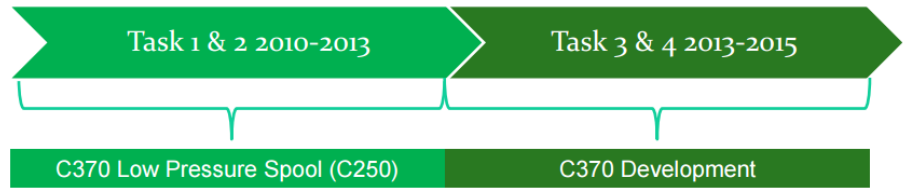
expanding the second foam in the second cylinder assembly, thereby recovering energy therefrom.

Capstone's DoE Project

Project Management & Budget



Schematic of the thermodynamic cycle for the C370.
Illustration courtesy of Capstone Turbine Corporation



Total Project Budget	
DOE Investment	**$5,000,000**
Capstone Cost Share	**$10,025,310**
Project Total	**$15,025,310**

On Budget & Schedule

With ORNL / NASA

The technology and practices learned during the project will be utilized in Capstone's current and future product lines, including scaling up to larger engine systems. The C370 microturbine CHP system is expected to be available on the market within 12 months of the project's completion, and Capstone has projected that 2,700 units will be installed by 2020, representing 1 gigawatt (GW) of electric generating capacity.

Appendix

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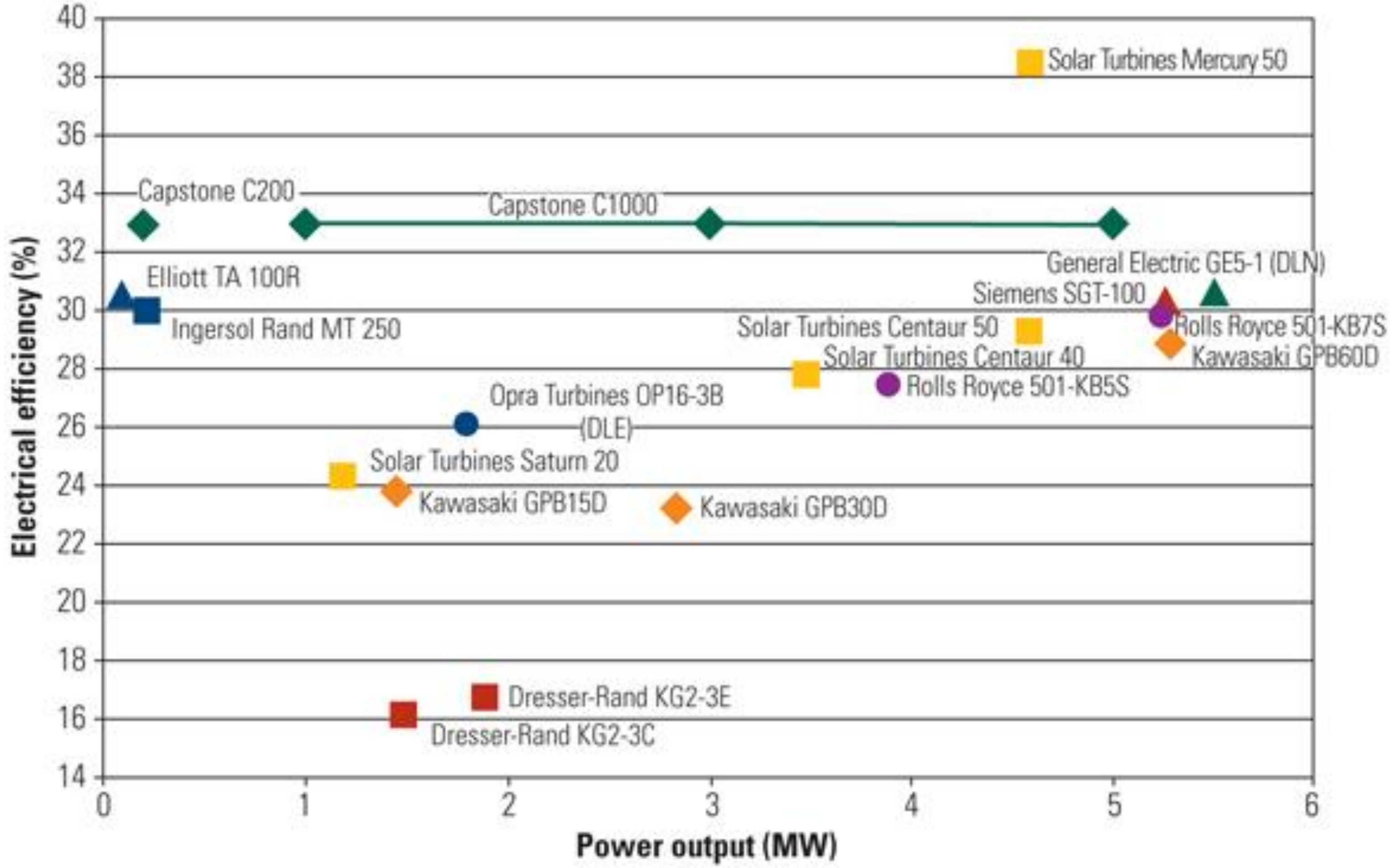
Competitive Landscape
Microturbines & Turbines



Competitive Landscape
Distributed Generation

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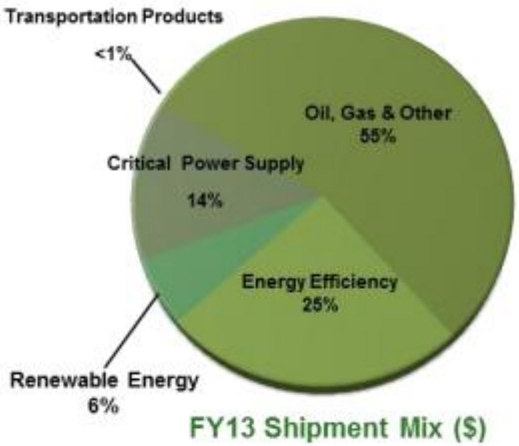
Technology	Size range	Electrical efficiency LHV (%)	Waste-heat quality	Current equipment cost ($/kW)
Reciprocating engine	1–5,000+ kW	25–45	High	500–1,000
Industrial gas turbine	500 kW–multi MW	15–35	High	400–650
Microturbine	30–1,000 kW	25–30	High	500–1,000
Fuel cell	Several watts to 3,000+ kW	30–60	MCFC, SOFC-high, PAFC-medium, PEM-low	1,000–5,000[a]
Stirling engine	Hundreds of watts and up	10–30	Medium	1,200–7,000[b]
Photovoltaics	1 kW and up	10–20	NA	6,000

Notes: kW = kilowatt; LHV = lower heating value; MCFC = molten carbonate fuel cell;
MW = megawatt; NA = not applicable; PAFC = phosphoric acid fuel cell;
PEM = proton exchange membrane; SOFC = solid oxide fuel cell.
a. Variance in price difference comes from the multiple fuel cell types as well as the various applications.
b. Variance in price comes primarily from the application; stationary Stirling engines are on the lower end of the range, whereas solar dish setups represent the high end of the range.

https://ouc.bizenergyadvisor.com/BEA1/PA/PA_DistributedEnergy/PA-44

Competitive Landscape
Microturbines

Capstone Turbine – Los Angeles, CA
- 85% market share – microturbines 30-200kW
- $85 million revenue 2015-2016
  - $115 million revenue 2014-2015



Their market segments
- Oil & gas: 50-70% of their business
- Commercial & Industrial CHP: 40%
- Renewables: 8-9%
- Other: 1-2%
  - Hybrid electric vehicles, the marine sector, and newer markets

Intermittency issues in relation to wind and solar power have proved to be drivers for the adoption of microturbine-based systems, he says, as power producers 'have to invest in other assets to maintain grid stability.` -Jim Crouse, Executive Vice-President of Sales and Marketing

Other player: FlexEnergy – Portsmouth, NH

Foam Turbine
Microturbine Markets

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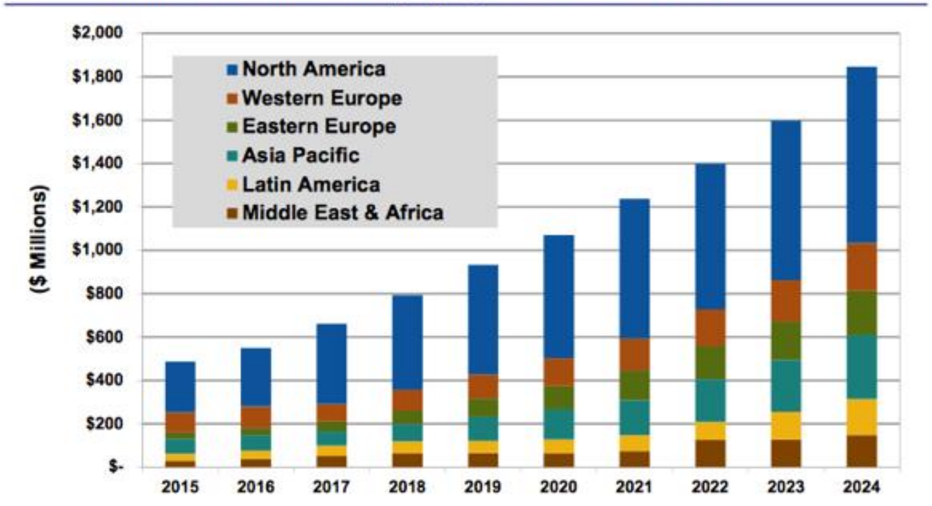
Microturbines offer two major advantages in the DG market: low emissions and low maintenance.

Fueled primarily by natural gas (low pressure or high pressure) – but also compatible with landfill gas, biogas, digester gas, associated gas, propane, and diesel

In general, there are four primary drivers for microturbine adoption:

- High cost of grid electricity and low cost of gas or availability of a free fuel source.
- Demand for onsite power generation
- Environmental standards (whether personal or mandated) that may incentivize the use of microturbines as one of the cleanest fossil fuel-burning technology options.
- Demand or need for continuous power generation in backup applications.

Chart 1.1 Annual Microturbine Revenue by Region, World Markets: 2015-2024



(Source: Navigant Research)

Foam Turbine

CHP Markets

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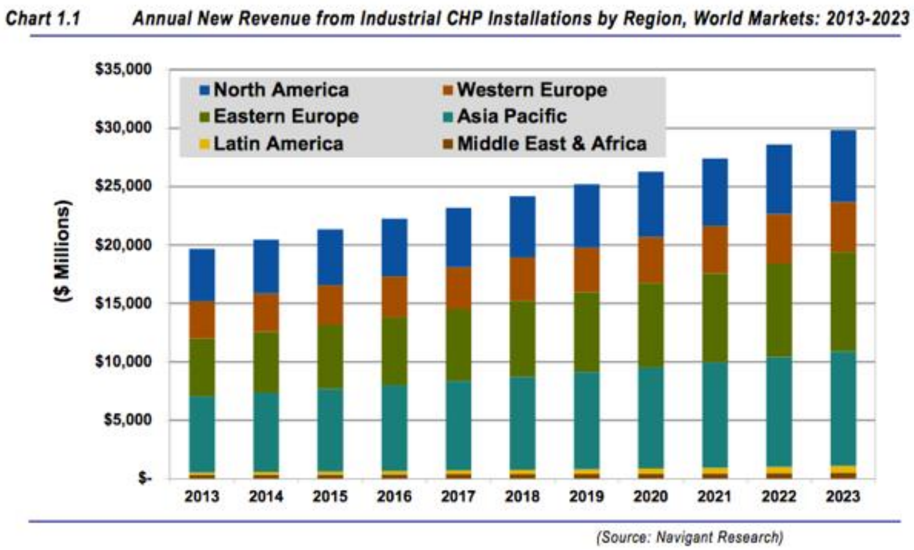
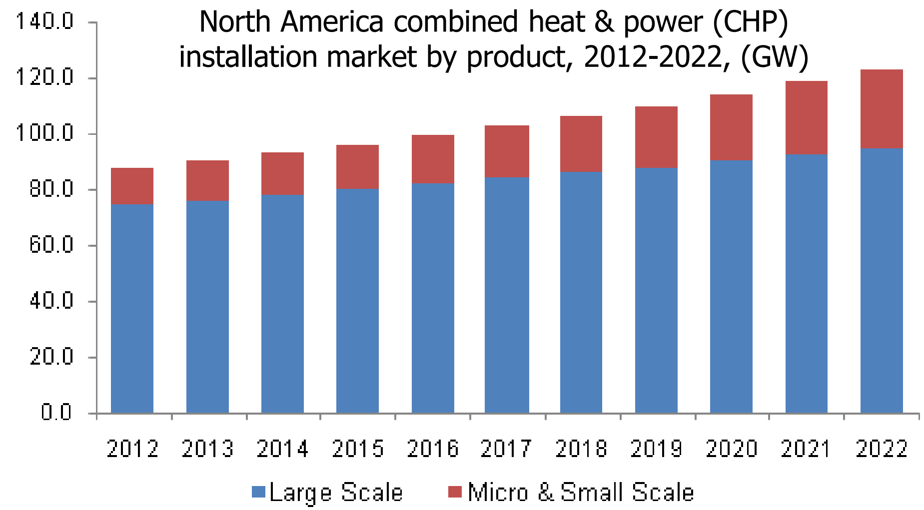




The industrial CHP market is expected to realize moderate to strong growth during the next decade, with high growth anticipated in the United States and Russia, as well as in emerging economies throughout Asia Pacific, Latin America, and the Middle East & Africa

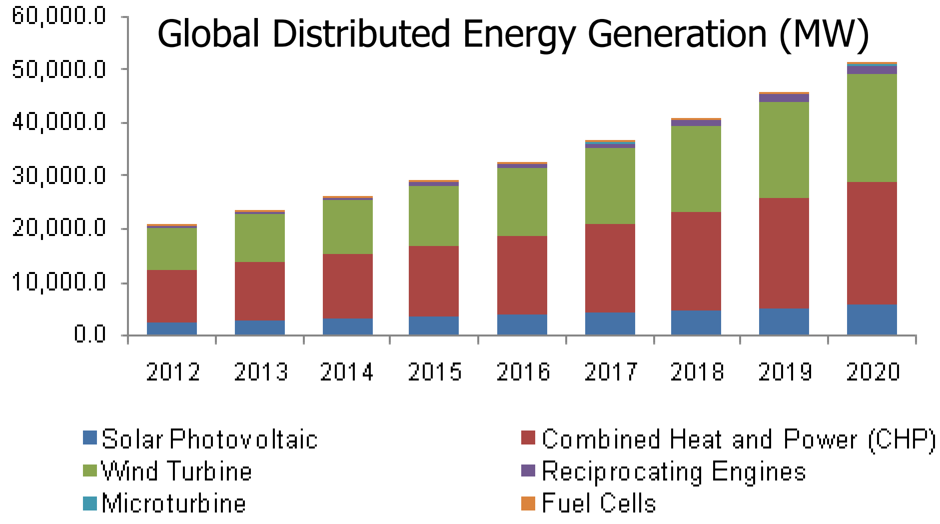
Total installed industrial CHP is expected to reach 483.7 GW in 2023. New deployments will generate $29.8 billion in new revenue that same year, representing a compound annual growth rate (CAGR) of 4.3 percent between 2013 and 2023. New capacity additions during the forecast period are expected to average 16.3 GW per year.

Large scale prototypes accounted for over USD 6 billion in 2014

Micro & small scale systems accounted for over 15% in 2014 and are expected to witness significant growth rates of over 8% from 2015 to 2022.

Foam Turbine

Distributed Energy Markets



Global distributed energy generation market size was estimated at USD 113.53 billion in 2013

Combined heat and power (CHP) technology dominated the global industry, accounting for over 40% of the overall DEG capacity 2013

Commercial & industrial dominated the global industry, accounting for over 70% of the volume in 2013

Turbines

Pressure Ratios
- Can small turbines be designed for higher pressure ratios? i.e. moving from 4 to 10
- Are microturbines too small for ratio?
- Multiple stages?

Modular systems - at what scale?
- Any decoupled compressor & turbine advantages?

Axial vs radial turbines?

What happened to Wilson TurboPower?

THE BASIS FOR THE PREDICTION OF HIGH THERMAL EFFICIENCY IN W.T.P.I. GAS-TURBINE ENGINES
Friday, November 22, 2002

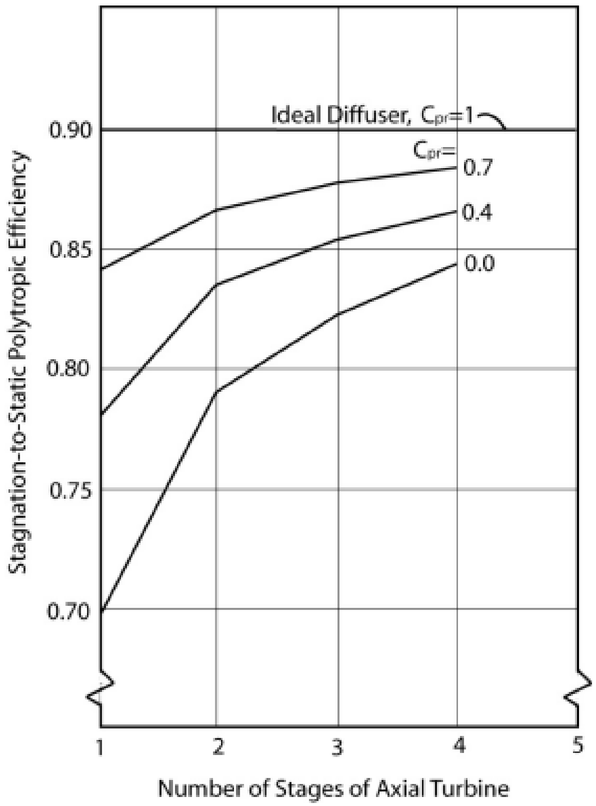
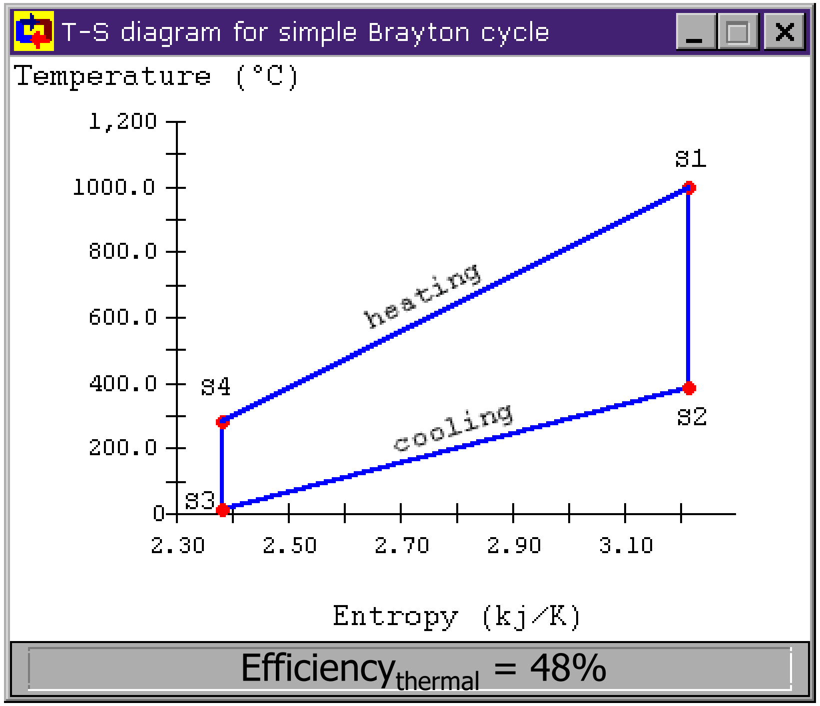
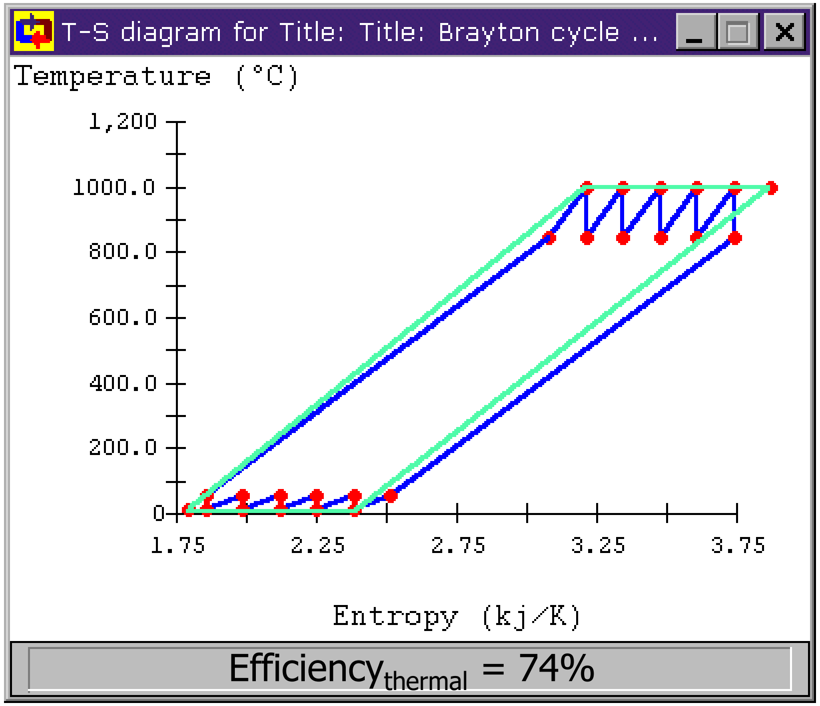


Figure 6: Effect of number of stages and diffuser quality on the useful efficiency of an axial turbine (having an efficiency with a "perfect" diffuser of 0.90).

Brayton → Ericsson





$\text{Efficiency}_{\text{thermal, max}}$ = 77%

The Brayton cycle can approximate the Ericsson cycle through recuperation and multiple reheat & intercooling stages – this achieves near maximum thermal efficiency

The Foam Engine can approximate the Ericsson cycle using recuperation, a single heating and a single cooling stage

http://www.qrg.northwestern.edu/thermo/design-library/airstd/brayton.html

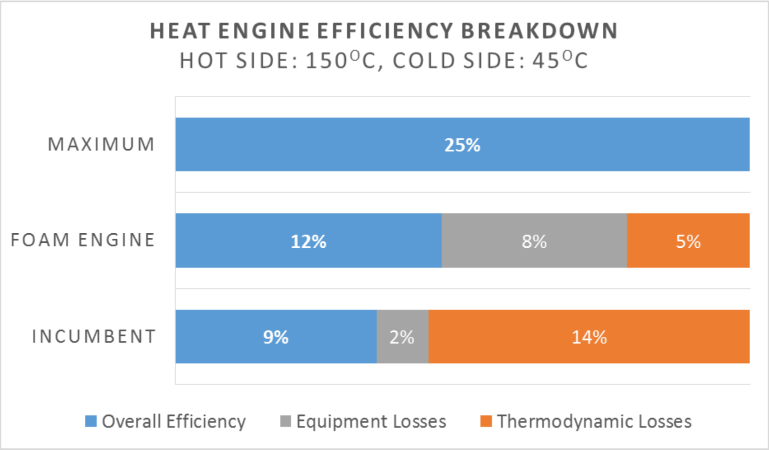
Foam Engine

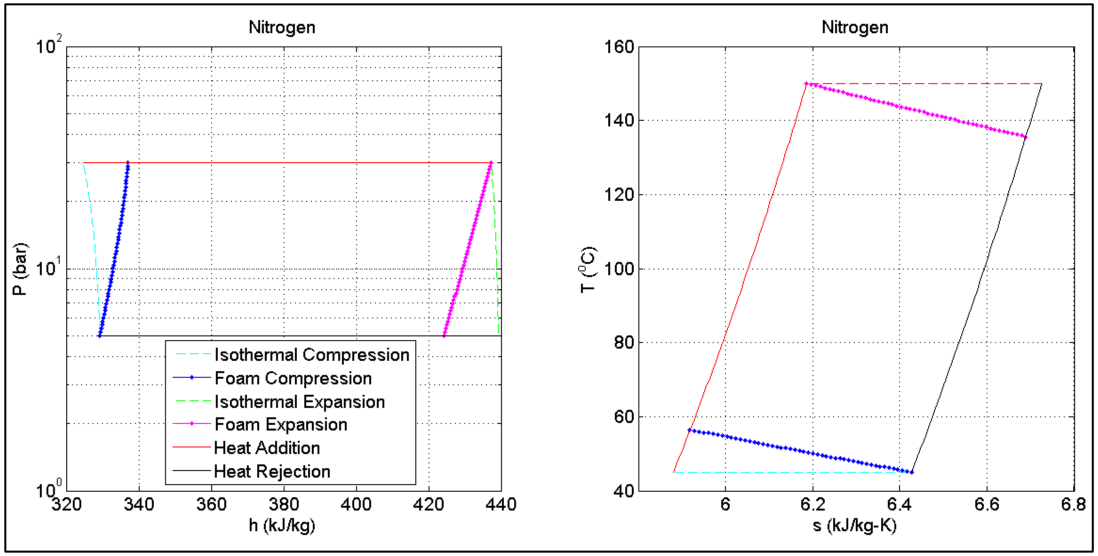
Approximates the Ericsson Cycle – approaching maximum efficiency

On low-quality/low-temperature heat sources

- Industrial waste heat, geothermal, biomass, solar thermal

Generating power at 200kW or less from low-quality heat (under 150°C) poses scaling difficulty for the incumbent heat engine technology, the Organic Rankine Cycle (ORC)





Foam Compressor

Energy consumption is 75% of a compressor's lifetime cost

Typical compressors waste 85% of the electricity they consume

The Foam Compressor can save up to 30% on the energy consumed

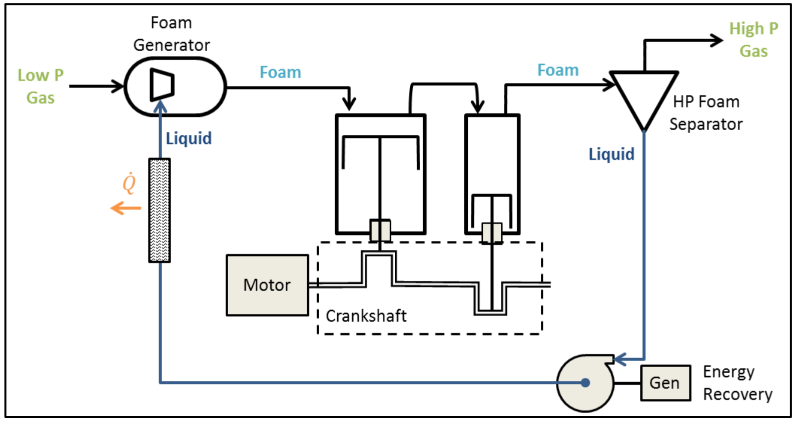


Figure 1 –Near-Isothermal Compression Process Diagram

Example: Compressing air, atm to 200 bara (2900 psia), 30 m^3/hr (1060 cfm)		
	Conventional	Near-Isothermal
Number of Stages	4	2
Pressure Ratio per stage	3.7	14.0
Temperature Rise per stage	137 °C 246 °F	25 °C 46 °F
Intercoolers	3	None
Aftercooler	1 (HP gas cooler)	1 (LP liquid cooler)
Power	404 kW 536 HP	341 kW 452 HP
Power Savings	-	16%
Energy Savings, kWh per year	-	498,718
Demand Charge Savings per year	-	$7,612
Consumption Savings per year	-	$49,872

Table 1 –Near-Isothermal Compression Benefits Example

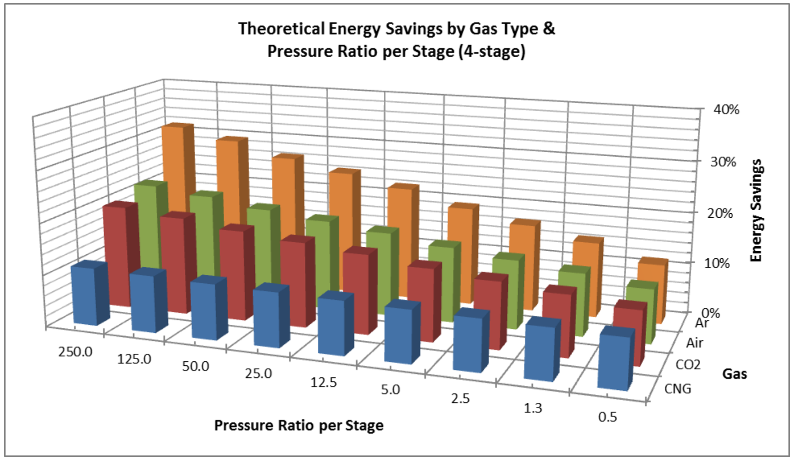


Figure 2 – Near-Isothermal Compression Energy Savings

Proposal

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Letter of support

- Indicate technical traction – this idea seems technically sound
- Indicate market traction – if executed, the technology would see success the market

Market data – what's +1% efficiency worth? -10% $/kW?

Cost data – how does it vary with pressure ratio, specific work

What is RheOmega?

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Our Mission:

- To create an abundance of clean energy through technological innovation.
- To achieve true impact on industry and the environment though both technical and commercial success. We measure our impact by exponentially growing clean megawatt-hours, reducing emissions, and transforming heat into dollars.
- We are obsessed with solving our customers' energy needs with cost-effective clean energy solutions. We are driven by curiosity, the thrill of invention, and the desire to leave a legacy of good.

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