A better steam engine: Designing a distributed concentrating solar combined heat and power (DCS-CHP) system

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Research objective

It is my objective to advance the technical and socioenviroeconomic understanding of solar combined heat and power.

This work will investigate the potential of a small scale solar Rankine thermodynamic cycle.

- establish the economic and environmental parameters that will guide the design and analysis
- Determine value through water, energy, GHG and economic analysis
- simulate and test expanders for such a system

A small and efficient expander is key new enabling technology, yet as a single component collector costs dominate.

Distributed generation options

- Biomass - methane, alcohol, dung, syngas, hydrogen, etc.
- Hydro
- Wind
- Solar - PV, Thermal
  - 5.4 GW of PV, 20 GW of solar thermal added globally in 2008
- Geothermal heat pump
- Fossil fuels - diesel, natural gas, propane, gasoline, coal

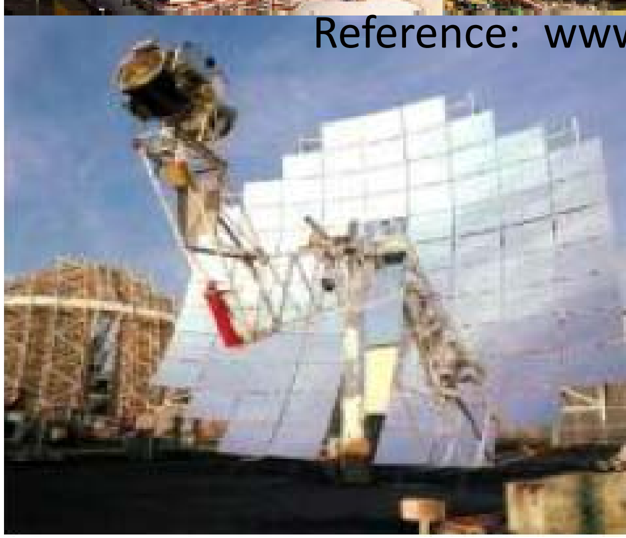
A few potential benefits of DCS-CHP

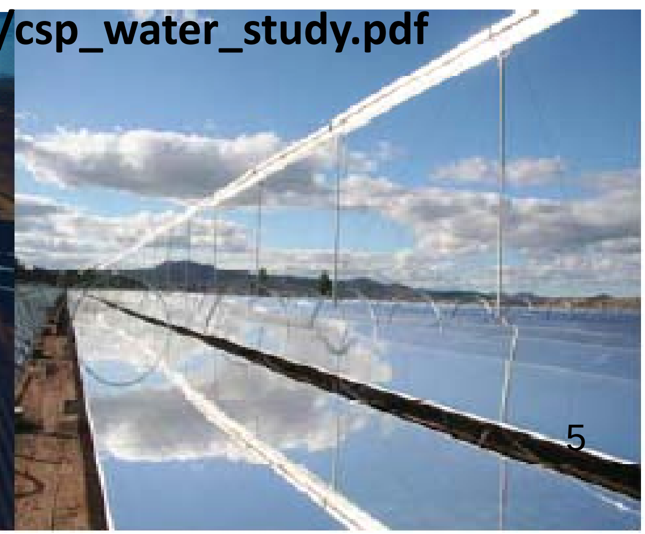
- Higher reliability of grids/microgrids esp. in developing world.
- Decreased transmission constraints
  - Quick permitting, less new transmission, etc.
- Decreased cost of heat and electricity compared to other distributed renewables (<$4/W electric, $0.25/W thermal)
- Large capital fundraising on a project by project basis not required
- Increased overall solar utilization with CHP
- Thermal storage is cheaper than electric
- Developed world: Mass production, like a refrigerator not a nuclear power plant
- Developingworld: Local production, ease of manufacturing without specialized equipment and materials
- Water use greatly reduced compared to centralized generation
- More jobs for skilled technicians in repair and installation
- Distributed power is owned and operated locally vs. the centralized power paradigm of corporate and government control

Sources: Casten and Ayres (2007); Norwood et al. (2010); Concentrating solar power commercial application study: Reducing water consumption of concentrating solar power electricity generation, Tech. rep., United States Department of Energy.

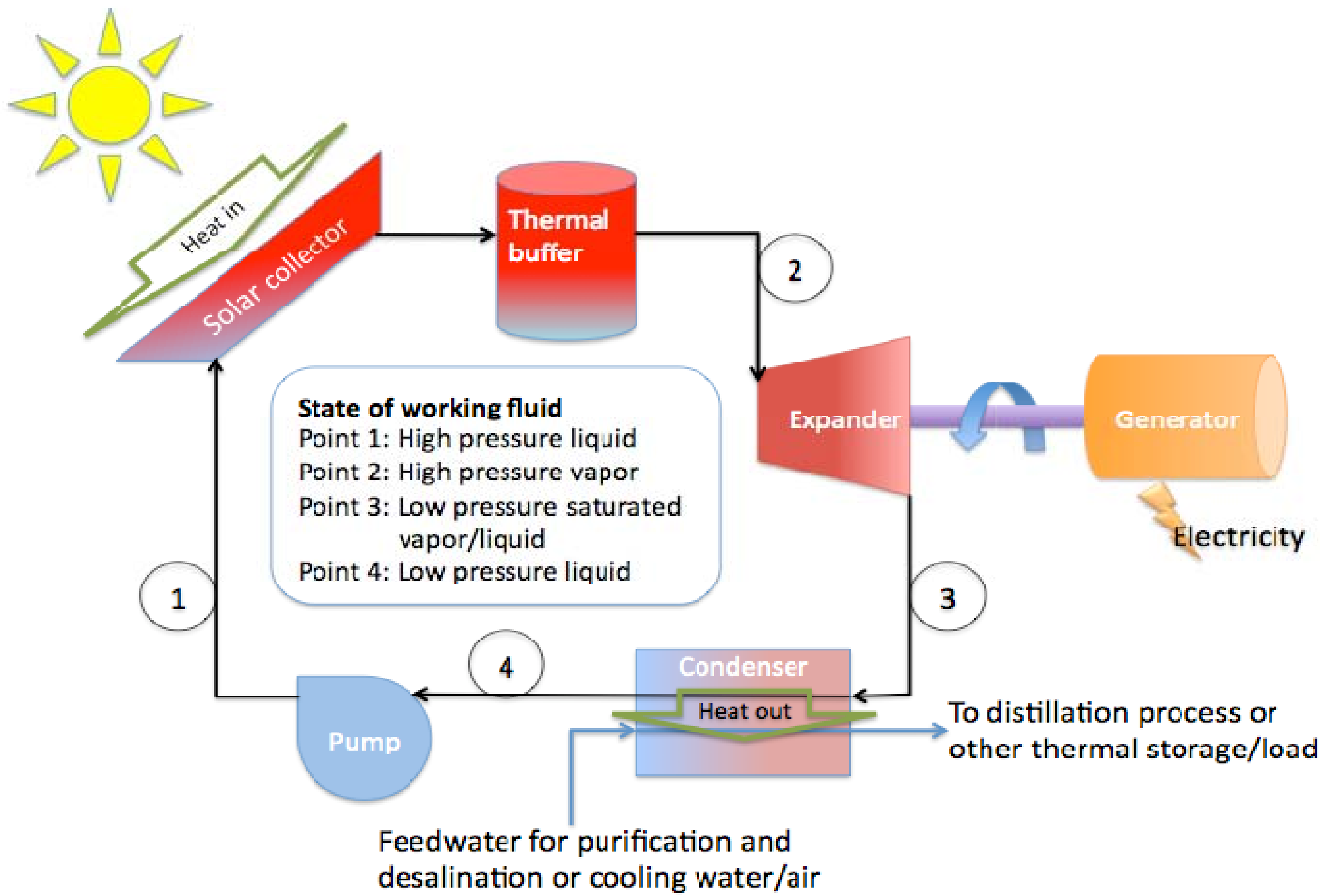
Figure 1: Above, power tower pilot project, pioneered in the U.S. (Barstow, CA) and (left) commercial unit under development by Abengoa called PS10, an 11 MW plant in Sevilla Spain (photo credit: Abengoa Solar). Bottom left, Stirling Dish/Engine, Center SEGS trough plants, Right, Compact Linear Fresnel Reflector.

Reference: www1.eere.energy.gov/**solar/pdfs/csp_water_study.pdf**





Distributed concentrating solar combined heat and power



Rankine cycle and fluids

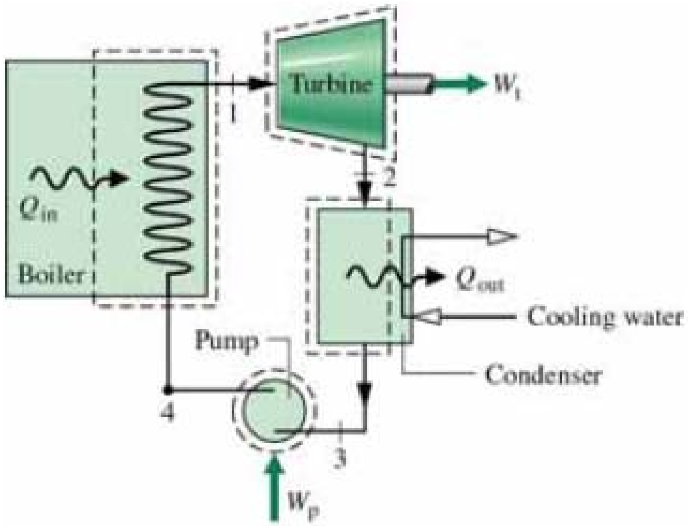


Figure 1.14 – Rankine cycle Layout.

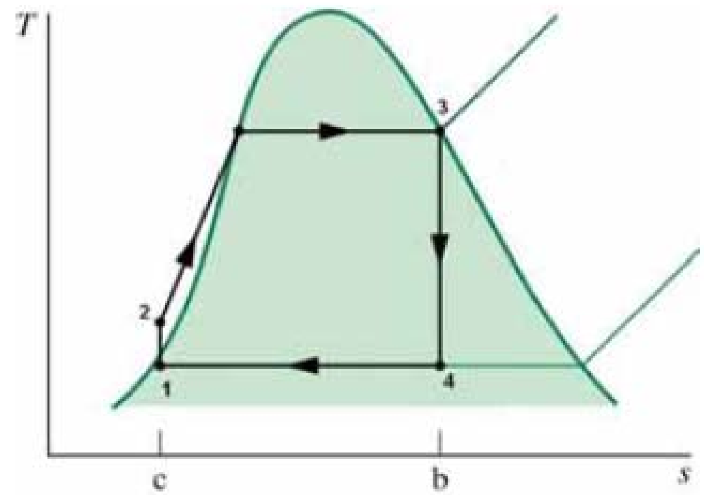
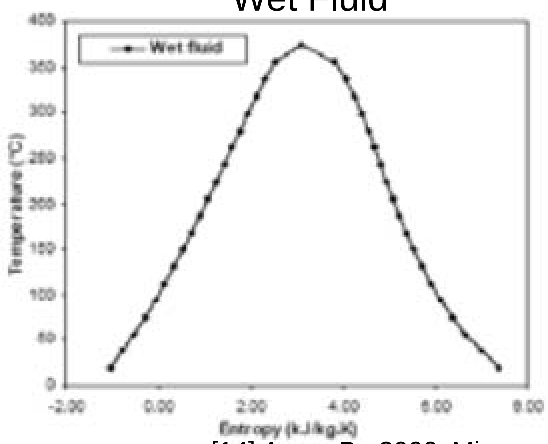
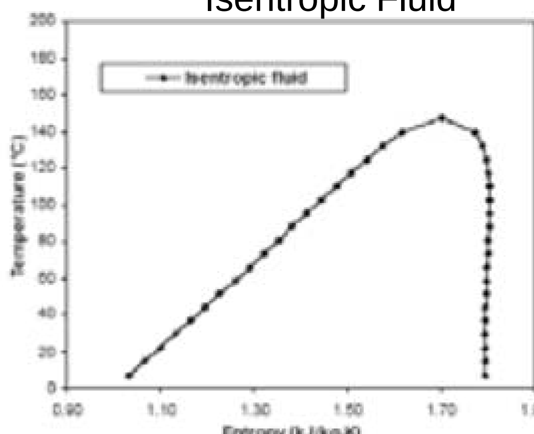


Figure 1.15 – T–S Diagram of an ideal Rankine cycle.

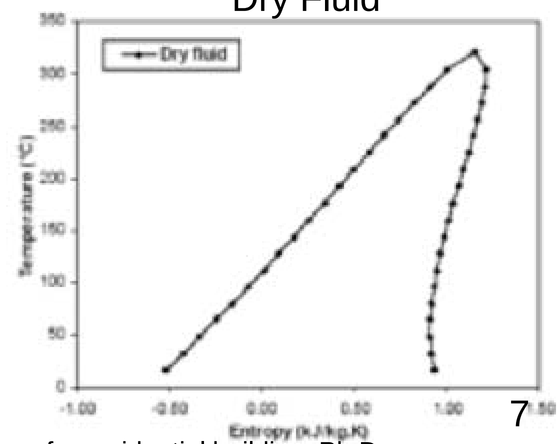
Wet Fluid



Isentropic Fluid



Dry Fluid



[14] Aoun, B., 2009, Micro combined heat and power operating on renewable energy for residential building, Ph.D. thesis, Ecole Doctorale 432 Sciences des Métiers de l'Ingénieur.

Developing tools for design and optimization:
Demand modeling

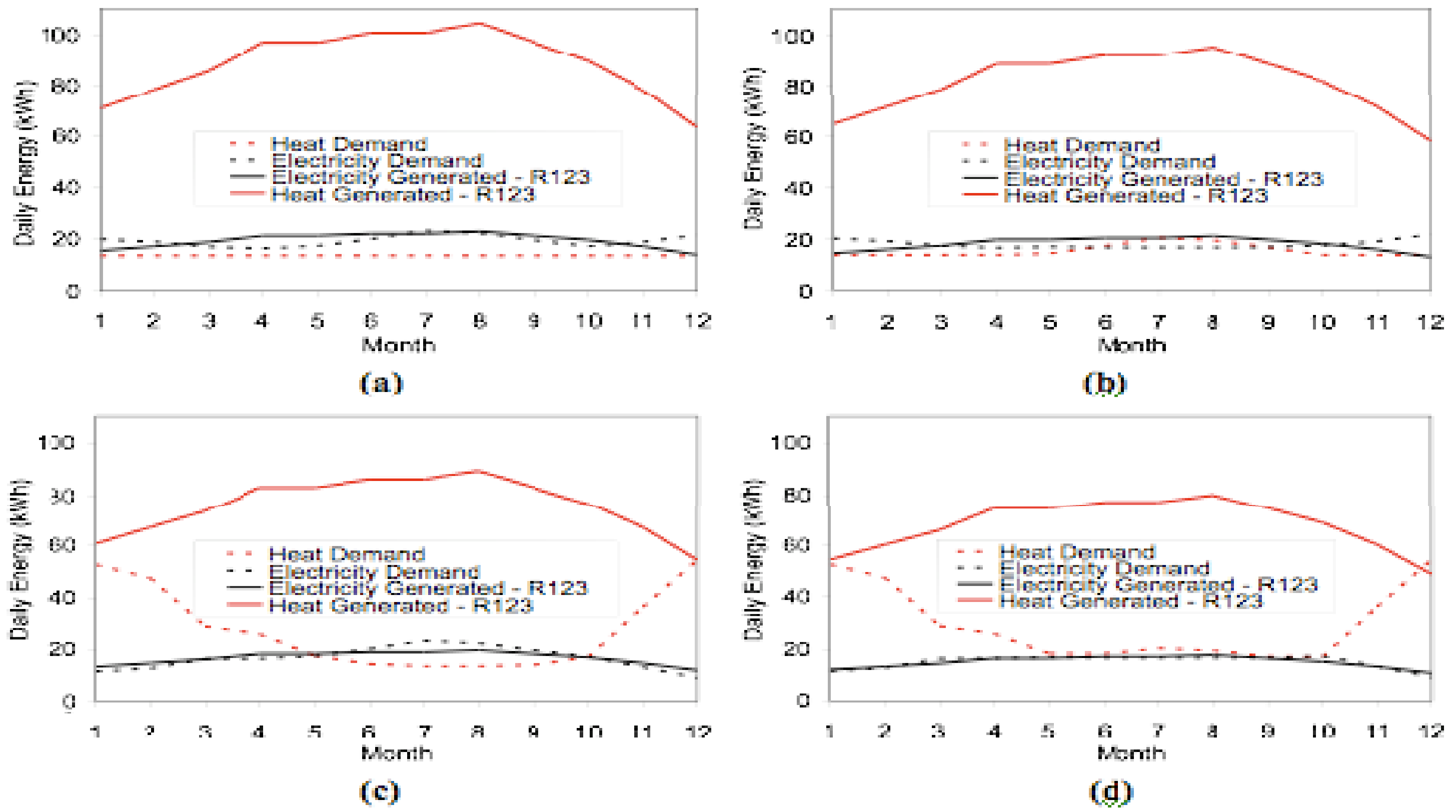
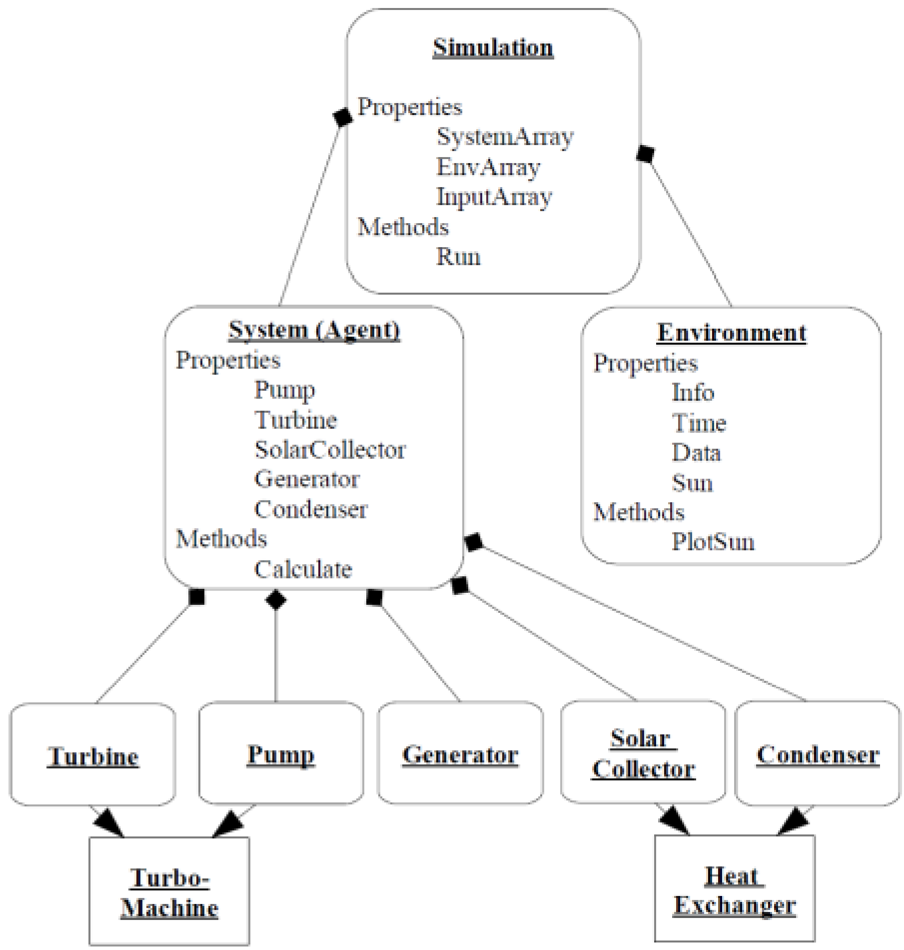


Figure 2. Average California residential daily demand compared with the R123 solar-thermal system's expected output of electricity and (a) hot water (b) hot water and air-conditioning (c) hot water and space-heating (d) hot water, air-conditioning, and space heating. System is sized to meet electrical demand in each figure. Notice the trend from a) to d) towards less heat generation and correspondingly smaller system size. Case d) requires just under $30 m^2$ of panels to produce all the electricity, hot water, a/c (using absorption chillers) and space heating for an average California residence. (Norwood, 2006)

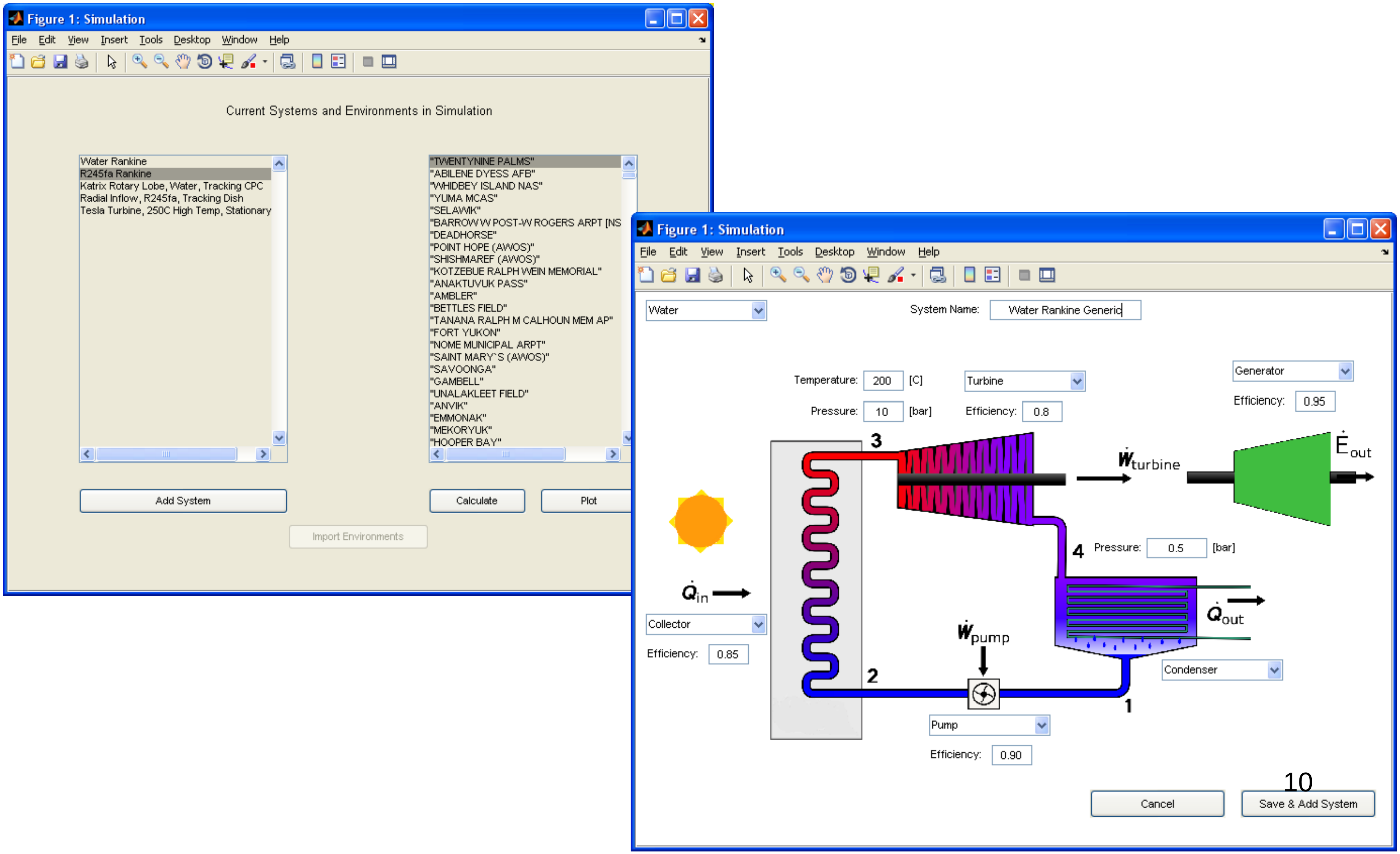
Developing tools for design and optimization:
Simulation framework (in MATLAB)

Simulation-Environment-Agent

- Simulation
  - Calculate and compare performance (e.g. heat and electricity output) of many systems at many geographic sites.
- Environment
  - Using NREL Solar Data for 1020 US Sites
- Agent
  - Ability to integrate detailed component models to create a variety of system configurations

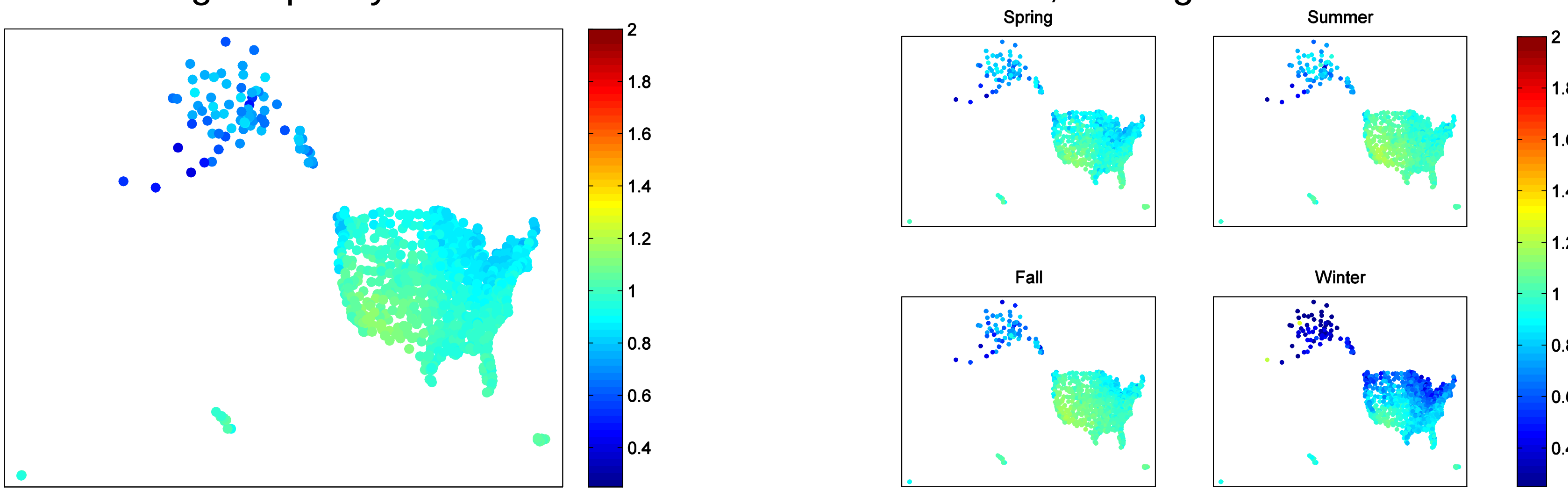


Developing tools for design and optimization:
Simulation and optimization

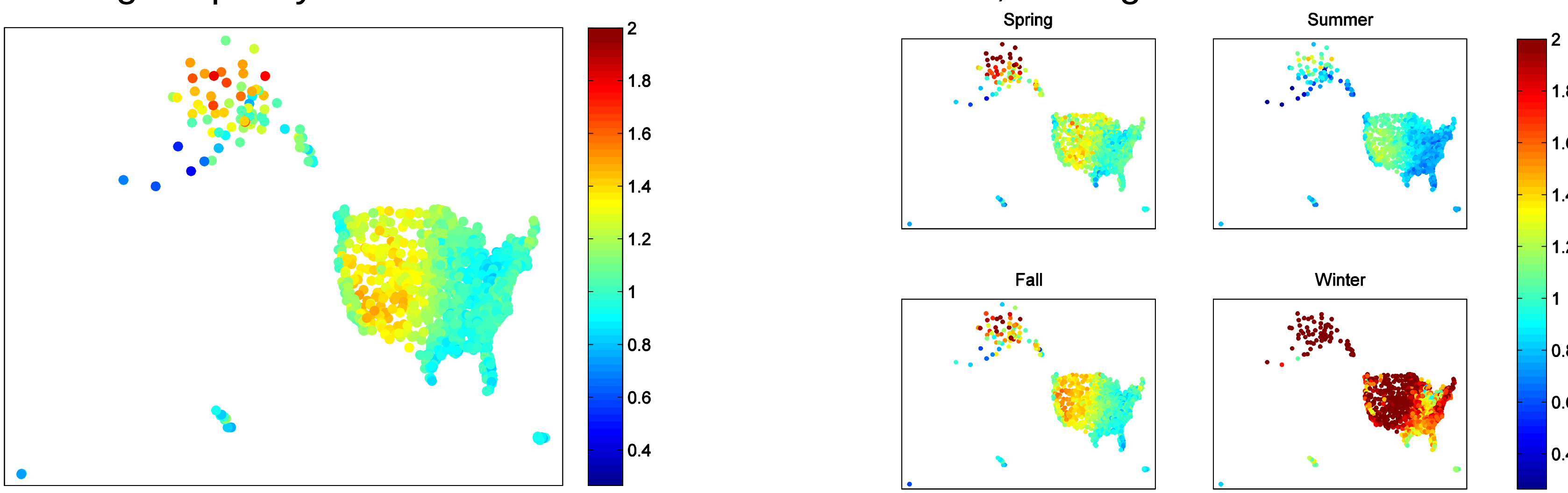


Developing tools for design and optimization:
Simulation and optimization

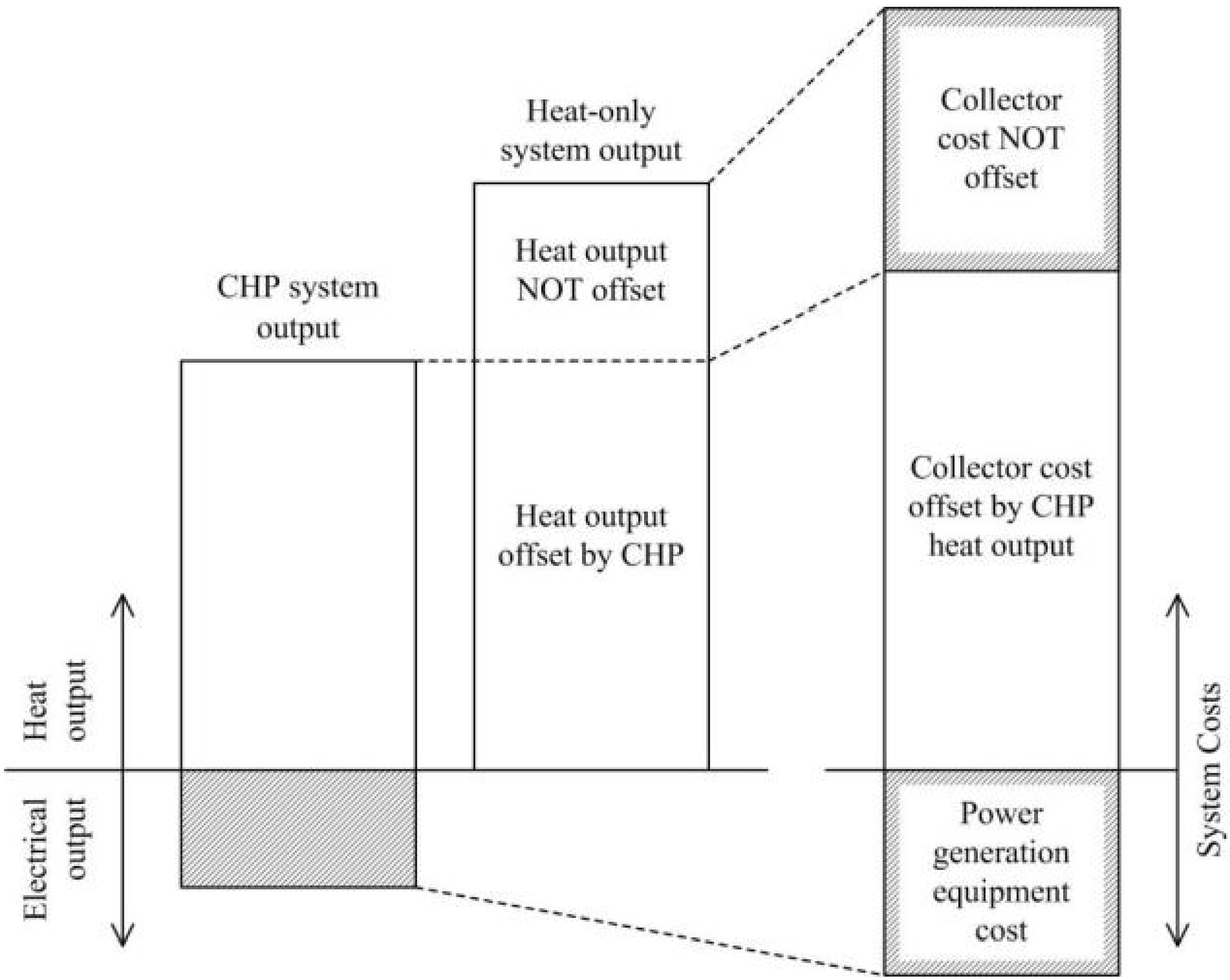
Non-tracking: Capacity Factor vs. Flat Panel PV is .4 to 1.15, Average of .93



Tracking: Capacity Factor vs. Flat Panel PV is 0.48 to 1.8, Average of 1.1

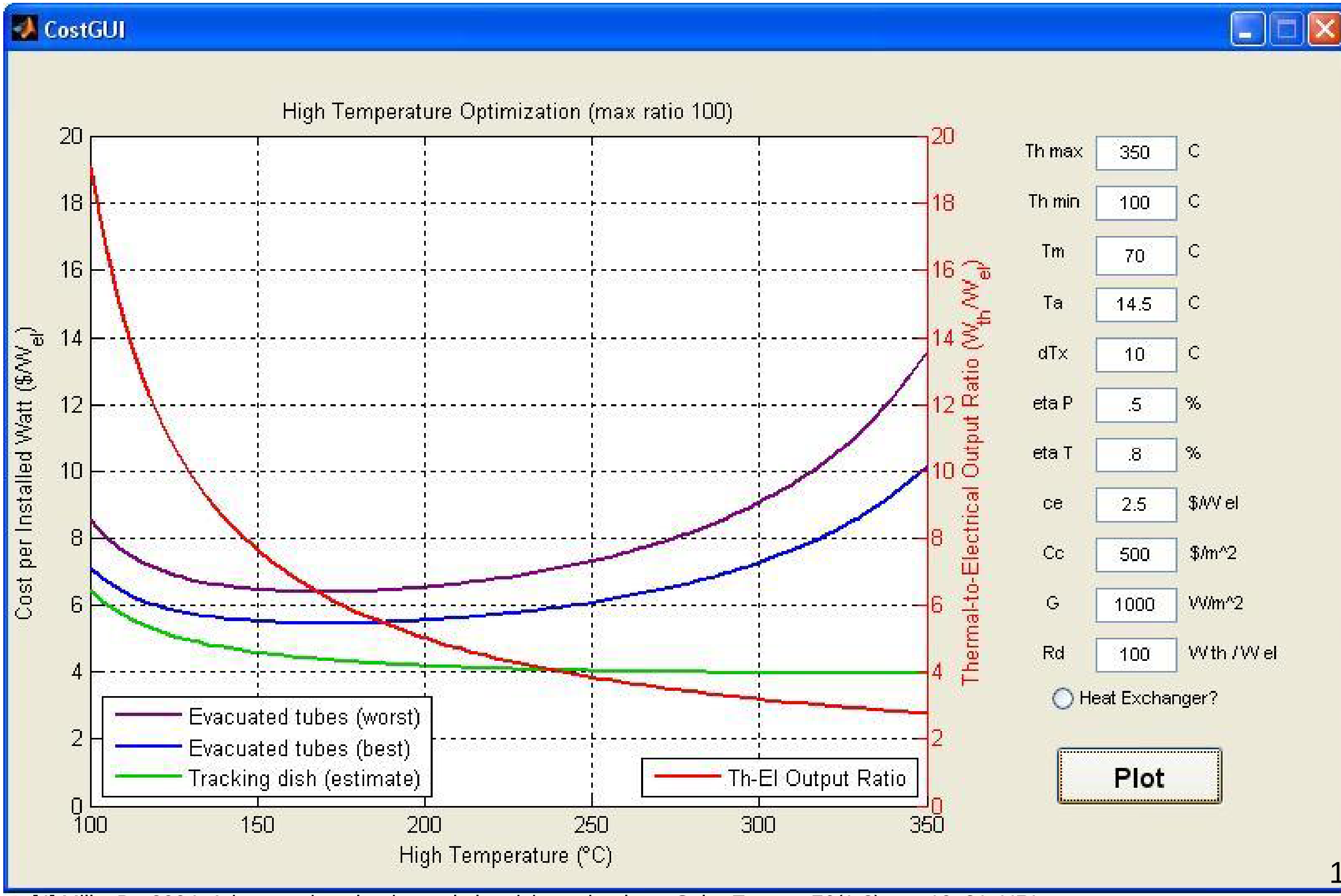


Developing tools for design and optimization:
Calculating cost of solar CHP



[26] Wade, N. M., 1999, Energy and cost allocation in dual-purpose power and desalination plants, Desalination, 123(2-3), pp. 115 125, URL http://www.sciencedirect.com/science/article/B6TFX-3YGTMKK-3/2/2c8fe7888aa4e57ba47782 selected papers presented at The WSTA Fourth Gulf Water Conference.

Developing tools for design and optimization:
Calculating cost of solar Rankine CHP



[4] Mills, D., 2004, Advances in solar thermal electricity technology, Solar Energy, 76(1-3), pp. 19 31, URL http://www.sciencedirect.com/science/article/B6V50-48FC6SP-2/2/c5a22010c116577d693296 Solar World Congress 2001.

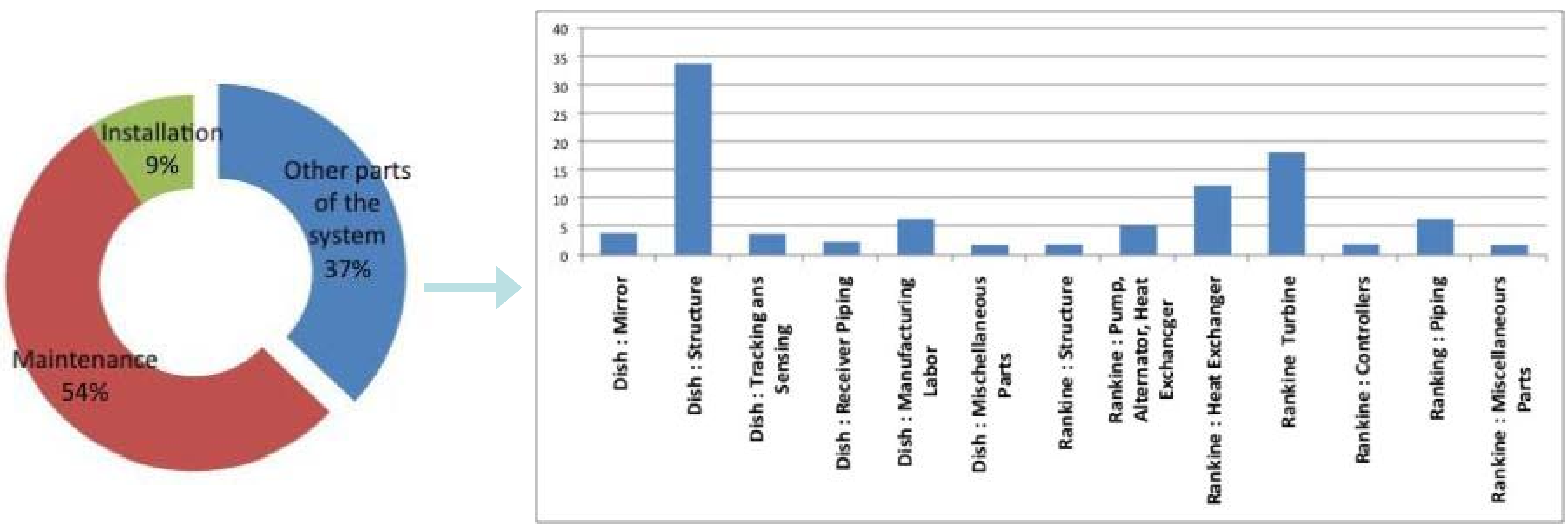
Developing tools for design and optimization:
Life cycle analysis of solar Rankine CHP

- Using Raw Solar data for the dishes
- Lifetime of the system : 25 years
- Location: San Francisco
- EPBT: ~1 year, GWP 50/50 Collector/Rankine

Comparisons:

- ~800g CO2eq/kWhe for coal-fired electricity
- ~320g CO2eq/kWhe for California electricity

GWP/kWhe (g CO2 eq)	52
g CO2/kWhe	44.51
g NOx/kWhe	0.12
g SO2/kWhe	0.12
g VOC/kWhe	0.11
Embodied MJ/kWhe	0.64



Greenhouse gas emissions over the system lifetime

[23] Reich-Weiser, C., Horne, S., and Dornfeld, D. A., 2008, Environmental metrics for solar energy, Tech. rep., University of California at Berkeley, Laboratory for Manufacturing and Sustainability.

Developing tools for design and optimization:
Water analysis: DCS-CHP with desalination

- What is the range of values of potable water specifically from for communities in the global south?
- Can distributed concentrating solar provide water cost competitively through desalination of salt and brackish water as a co-product of electricity generation?
  - www.suntrough.com

- What is the Life-cycle analysis for water in these distributed systems and how does dry cooling vs. wet cooling impact water use compared to competing technologies (for instance solar PV)?

Table 2: Comparison of consumptive water use of various power plant technologies using various cooling methods

Technology	Cooling	Gallons / MWhr	Perform. Penalty*	Cost Penalty**	Reference
Coal / Nuclear	Once-Through	23,000 – 27,000***			1, 3
	Recirculating	400 - 750			1, 3
	Air Cooling	50 - 65			1, 3
Natural Gas	Recirculating	200			4
Power Tower	Recirculating	500 - 750			(estm.)
	Combination Hybrid Parallel	90-250	1-3%	5%	10, 11
	Air Cooling	90	1.3%		9
Parabolic Trough	Recirculating	800			5
	Combination Hybrid Parallel	100-450	1-4%	8%	7, Appx. A
	Air Cooling	78	4.5-5%	2-9%	6, 9
Dish / Engine	Mirror Washing	20			5
Fresnel	Recirculating	1000			(estm.)

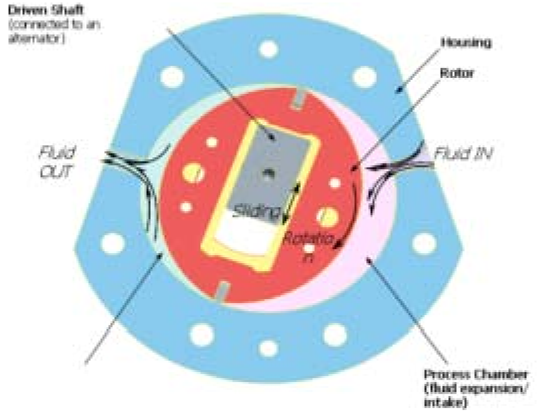
Source: www1.eere.energy.gov/**solar/pdfs/csp_water_study.pdf**

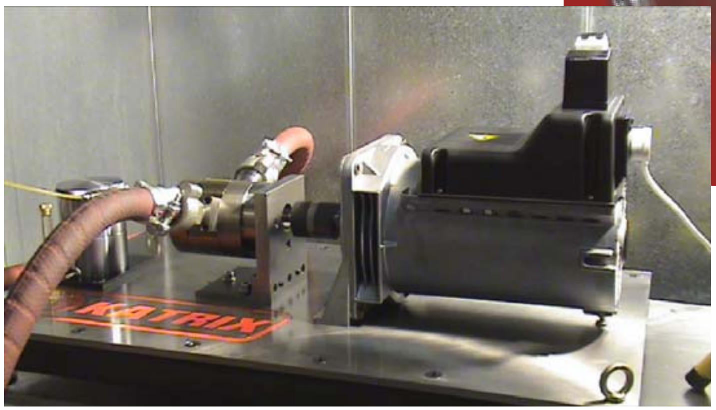
Developing tools for design and optimization:
Water analysis: DCS-CHP with desalination

- DCS-CHP water used in operation should be comparable or less to parabolic trough solar CSP.
  - Dry cooling not a significant cost barrier
- Value of water questionable/variable in developing world
  - (e.g. \$0.02 - \$15.00 / m^3 in Asia)
- Yet cost of solar desalination as co-product of electricity generation adds real cost of \$2.30/m^3
- Desalination/Flash only appropriate in developing world coastal regions or where water distillation can clean up contaminated sources
- Economically viable only where water is primarily provided by the informal sector
- Developed world prices for water are less than \$1.30/m^3 so water end-use efficiency is the economic answer here, not desal.

Water prices: *Second Water Utilities Data Book, Asian Development Bank, 1997.*

Developing tools for design and optimization:
Performance testing: Rotary lobe expander

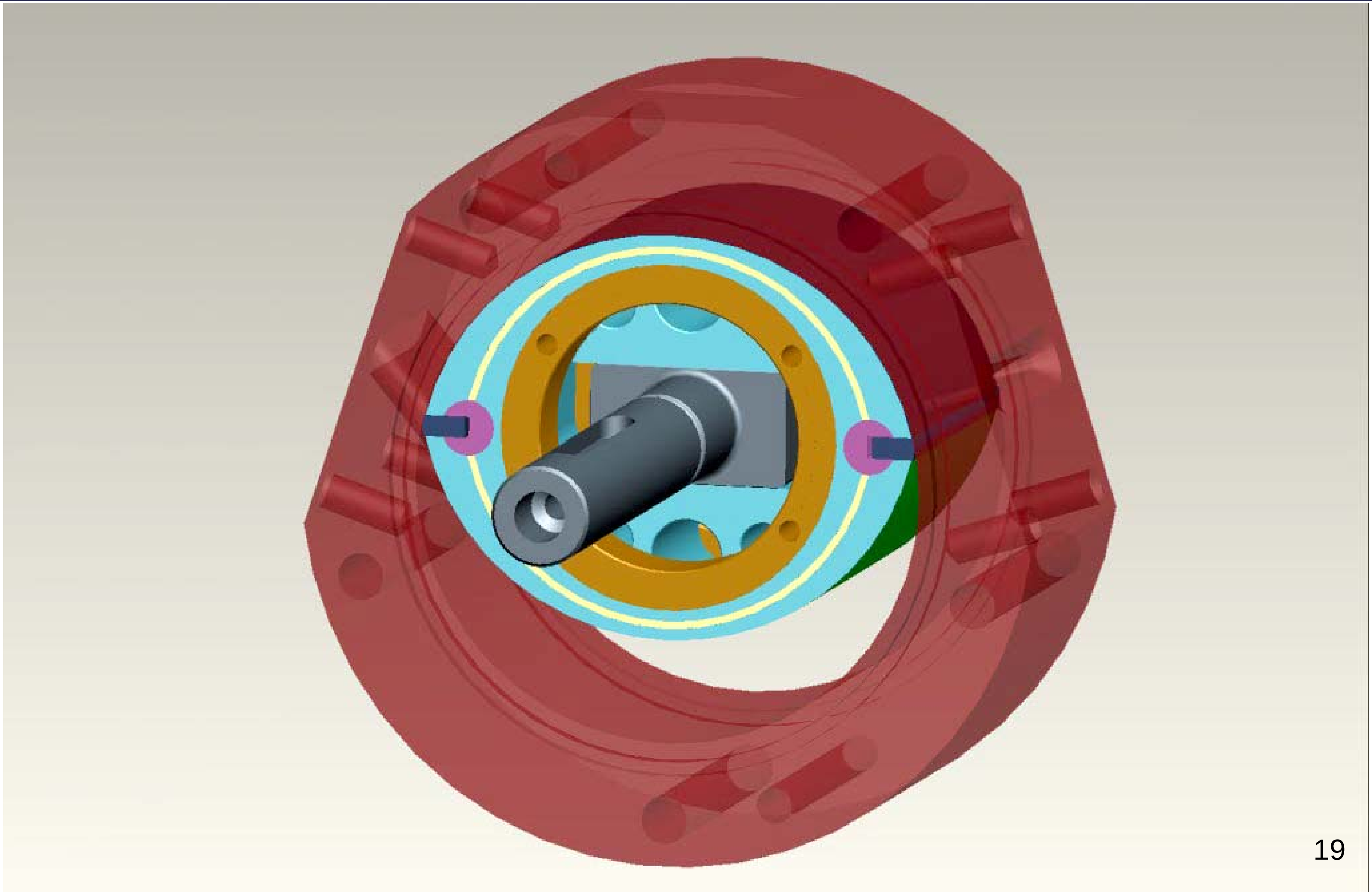




- Testing at UCB with air
- Rotary lobe expander performance is expected to be better than:
  - Radial inflow turbine: bad performance at this power output
  - Screw: Volume (power) to surface area (losses) ratio low at this scale
  - Tesla turbine: further development possible, low pressure ratios (<2), low efficiency

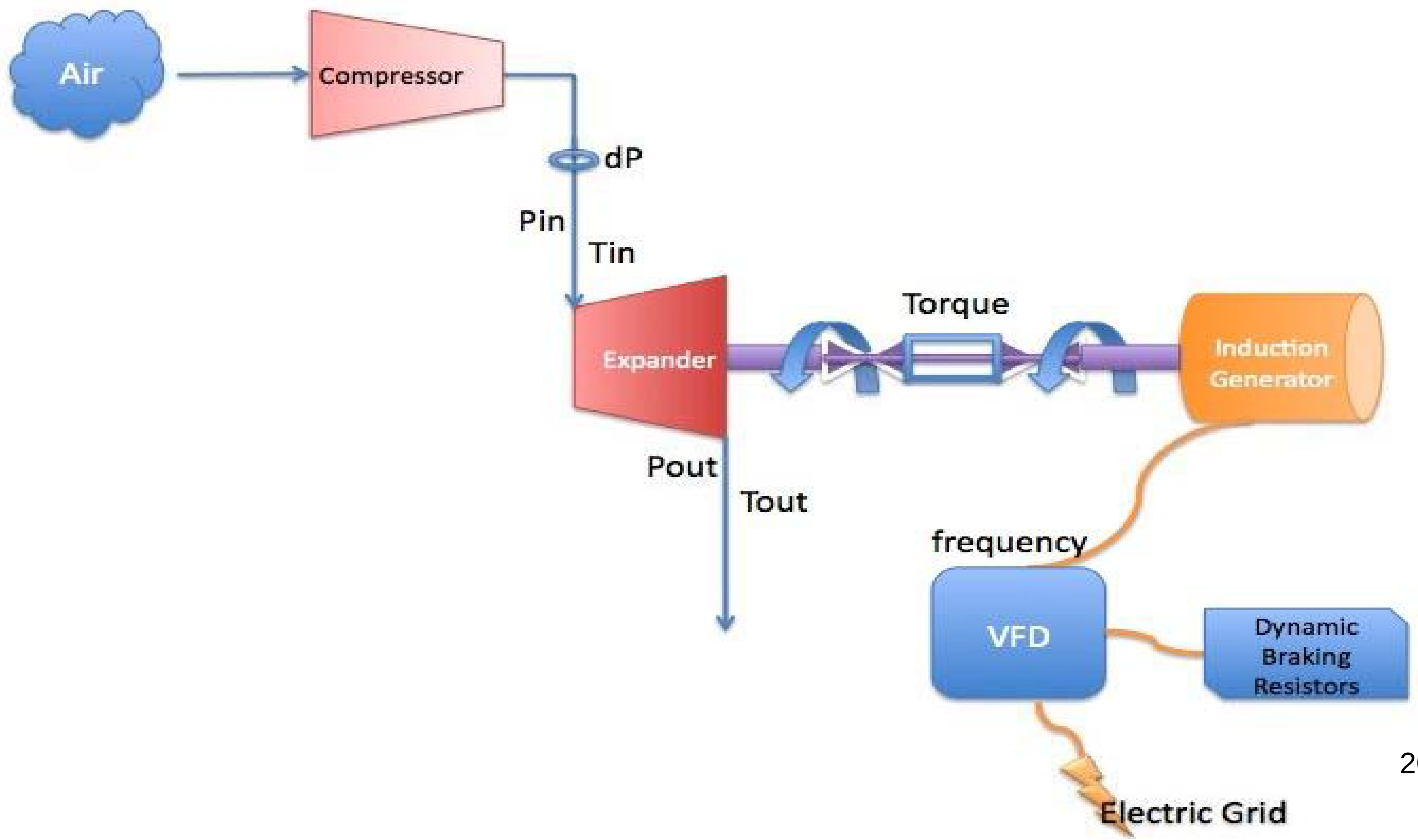
[15] Sultan, I., 2005, The limaçon of pascal: Mechanical generation and utilization for fluid processing, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 219(8), pp. 813822

Developing tools for design and optimization:
Performancetesting: Rotary lobe expander

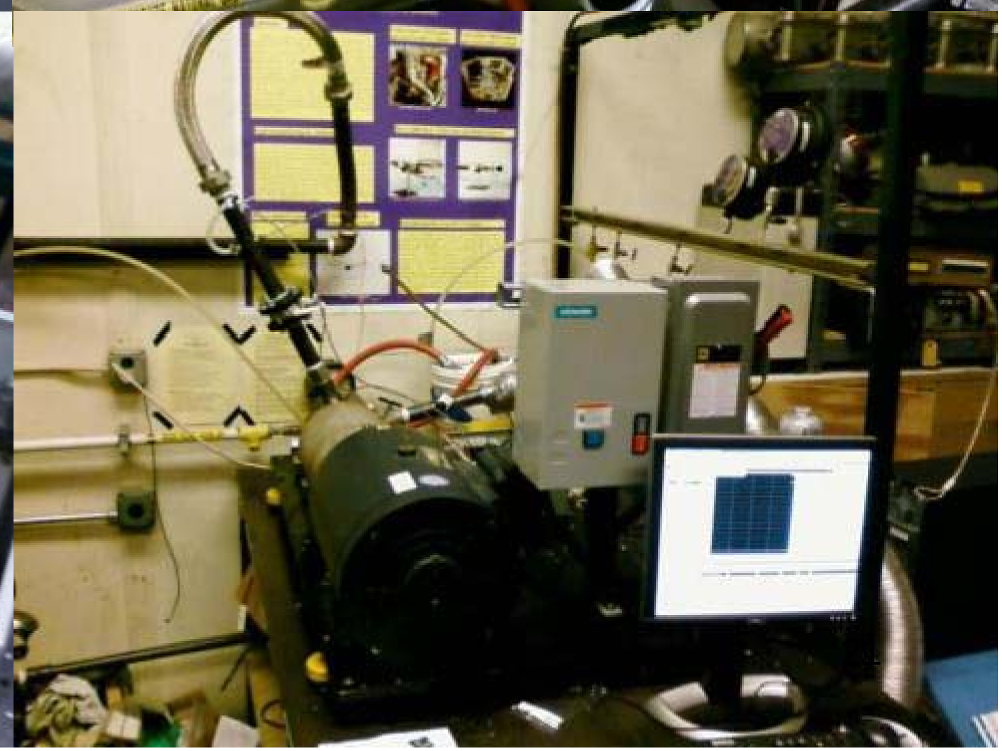


Source: Katrix, Inc. Australia

Developing tools for design and optimization:
Performance testing: Rotary lobe expander




Societal benefits of an HCCI Engine

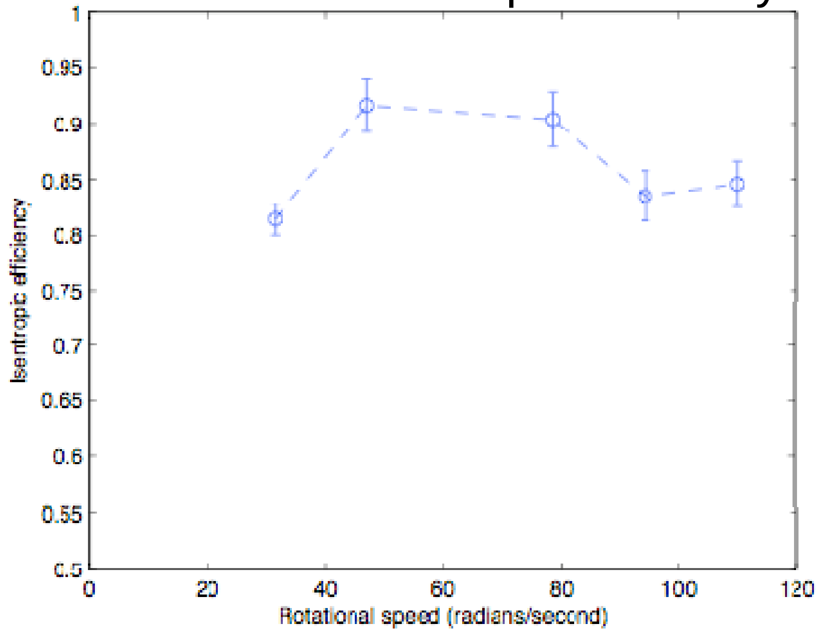


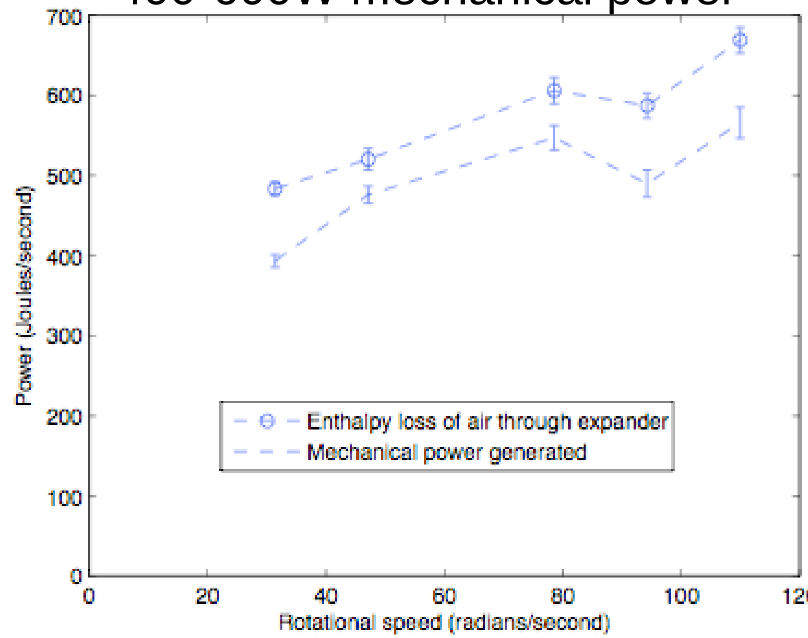
Developing tools for design and optimization:
Performance testing: Rotary lobe expander

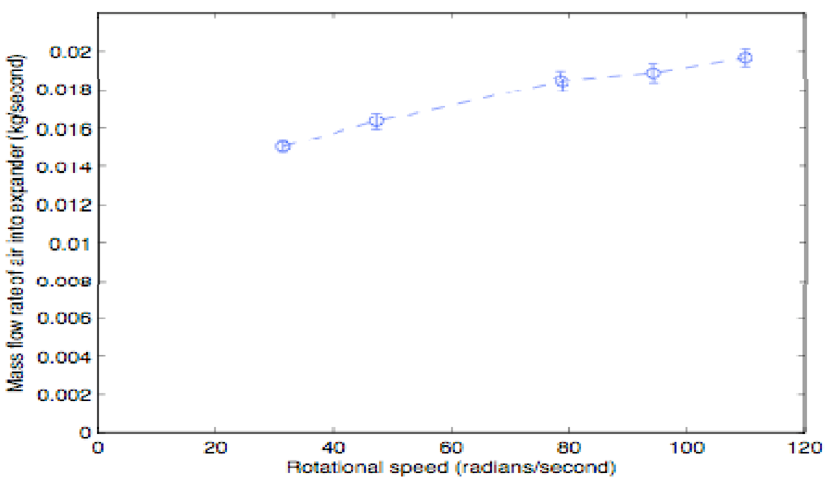
- Test Procedure
  1. First the VFD is turned on and the electric motor spins the expander up to the set frequency starting at 300 rpm (with no load).
  2. Then the compressed air supply is turned on allowing the expander to begin providing power through the shaft to the electric motor where it is converted to AC, then dissipated in a resistor bank connected to the VFD.
  3. After the system runs for 15 minutes to “warm up” (i.e. reach steady state) several data acquistion boards powered by LabView will begin recording the upstream and downstream pressure and temperature of the working. Torque, and differential pressure across the orifice plate flow meter are also recorded during the 10-20 minutes of data collection.
  4. Data collection stops and the VFD frequency is adjusted up by 100 rpm.
  5. Repeat steps 3 and 4 until the VFD frequency reaches the limit of the motor (1800 rpm) being sure to wait for steady state operation before doing data acquisition at each speed.
  6. The apparatus is shut down by first shutting off the compressed air and then turning off the VFD.
  7. Find 5 minutes of data with fairly steady characteristics of upstream pressure and temperature to calculate efficiency.

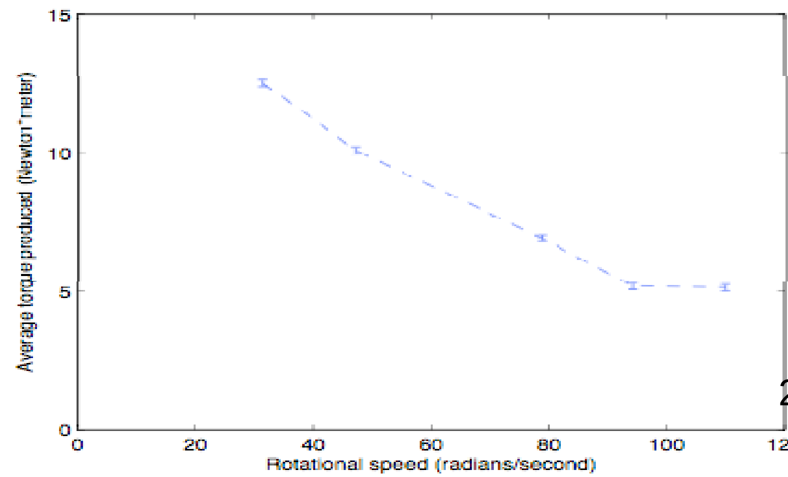
Developing tools for design and optimization:
Performance testing: Rotary lobe expander

Results: 80-95% isentropic efficiency 400-600W mechanical power

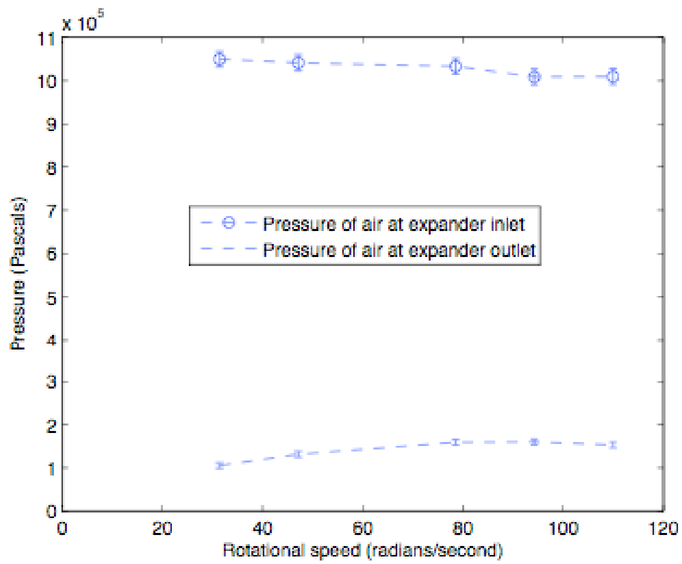




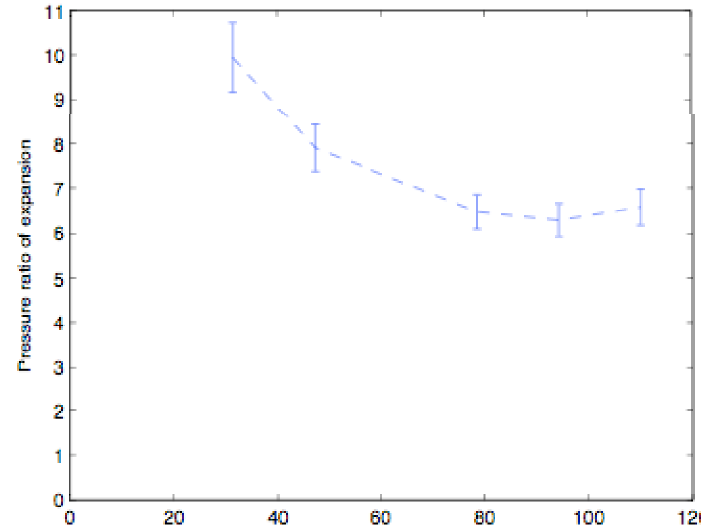


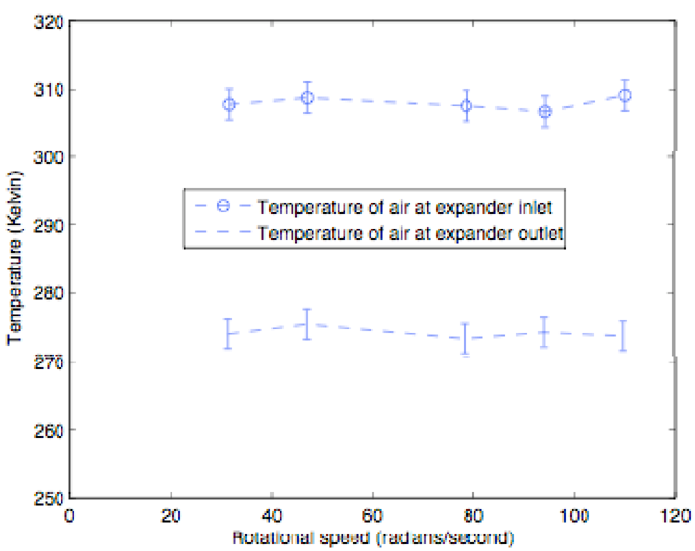


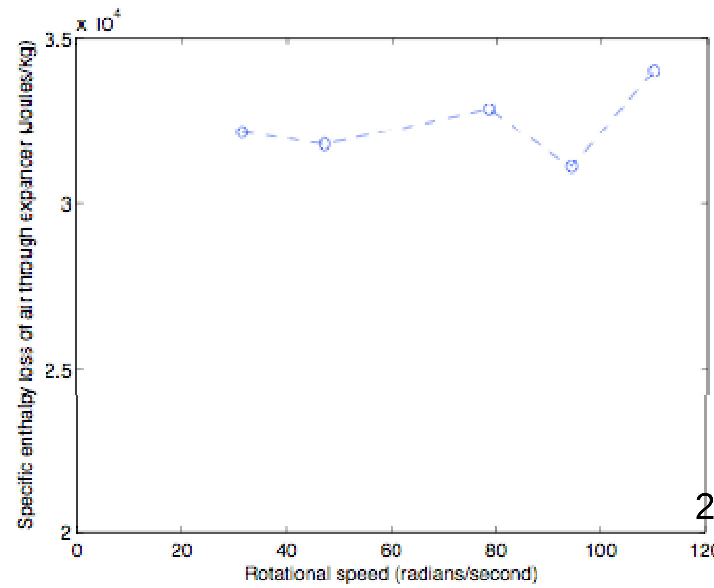
Developing tools for design and optimization:
Performance testing: Rotary lobe expander



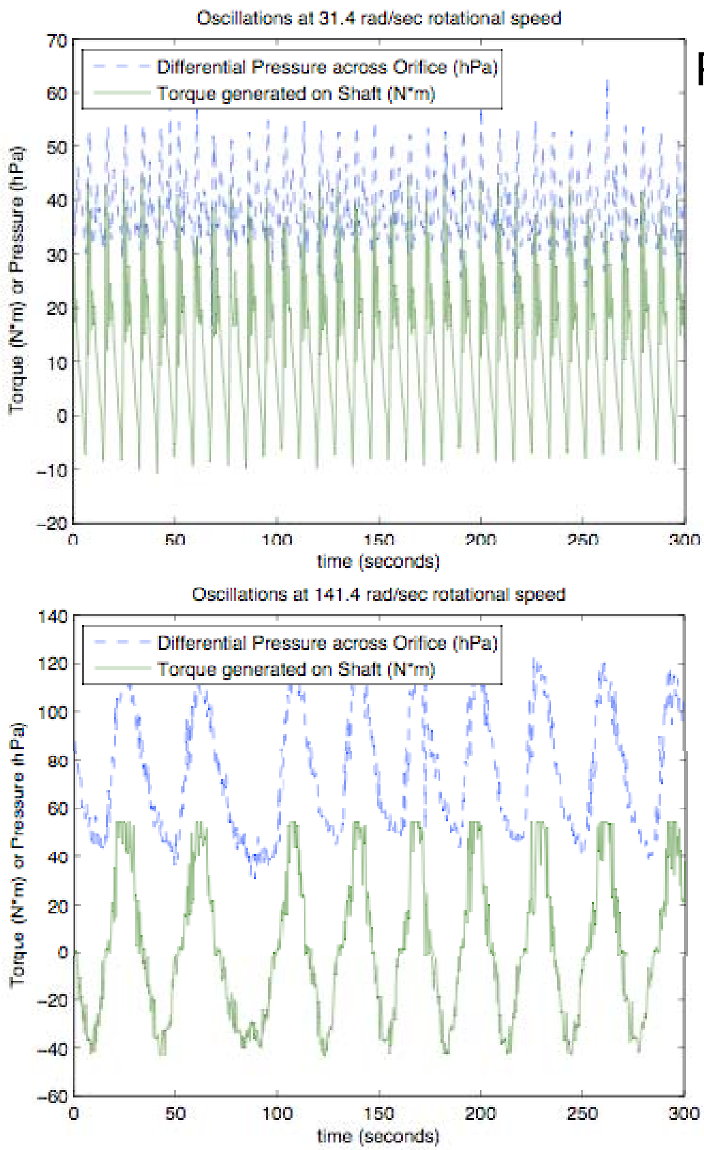
Results: 6-11 Pressure Ratio



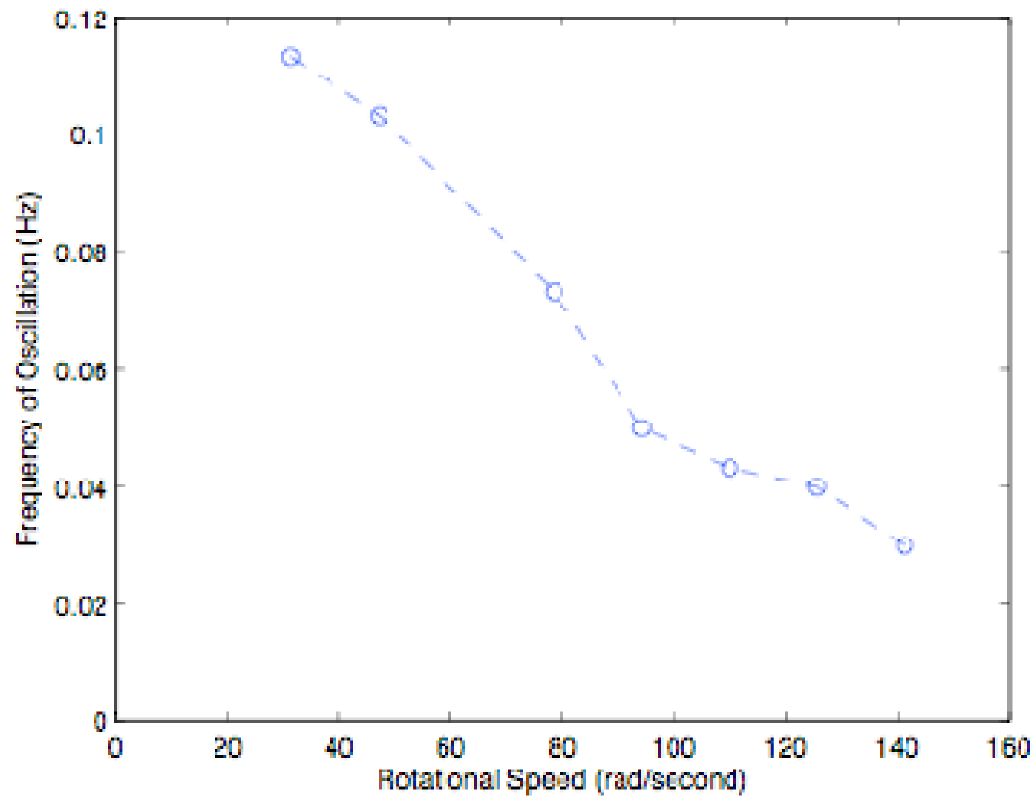




Developing tools for design and optimization:
Performance testing: Rotary lobe expander



Results: Unexplained oscillating torque & mass flowrate



thanks

- The Combustion Laboratory and Laboratory for Manufacturing and Sustainability, Mechanical Engineering faculty/students for the use of facilities, advice.
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