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SAND2019-2152PE

sCO2 Brayton Cycle Economics Modeling and Optimization

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Sandia National Laboratories

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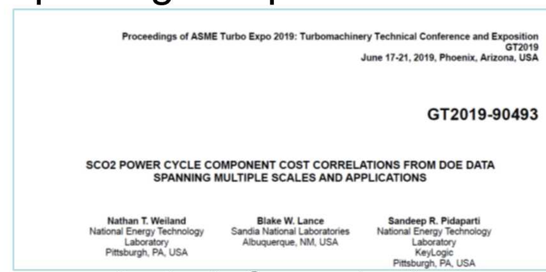
Project Overview

Scope

1) Continue development of economics model by updating component models with collaboration across DOE national labs


Proceedings of ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition
GT2019
June 17-21, 2019, Phoenix, Arizona, USA

GT2019-90493

SCO2 POWER CYCLE COMPONENT COST CORRELATIONS FROM DOE DATA SPANNING MULTIPLE SCALES AND APPLICATIONS

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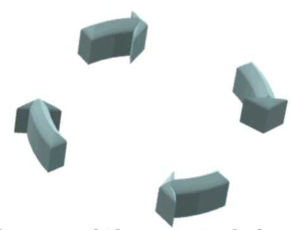
2) Perform LCOE optimization of the sCO2 Brayton cycle to inform design parameters while considering cross-cutting heat sources



3) Perform market analysis for sCO2 Brayton cycles with outside contractor

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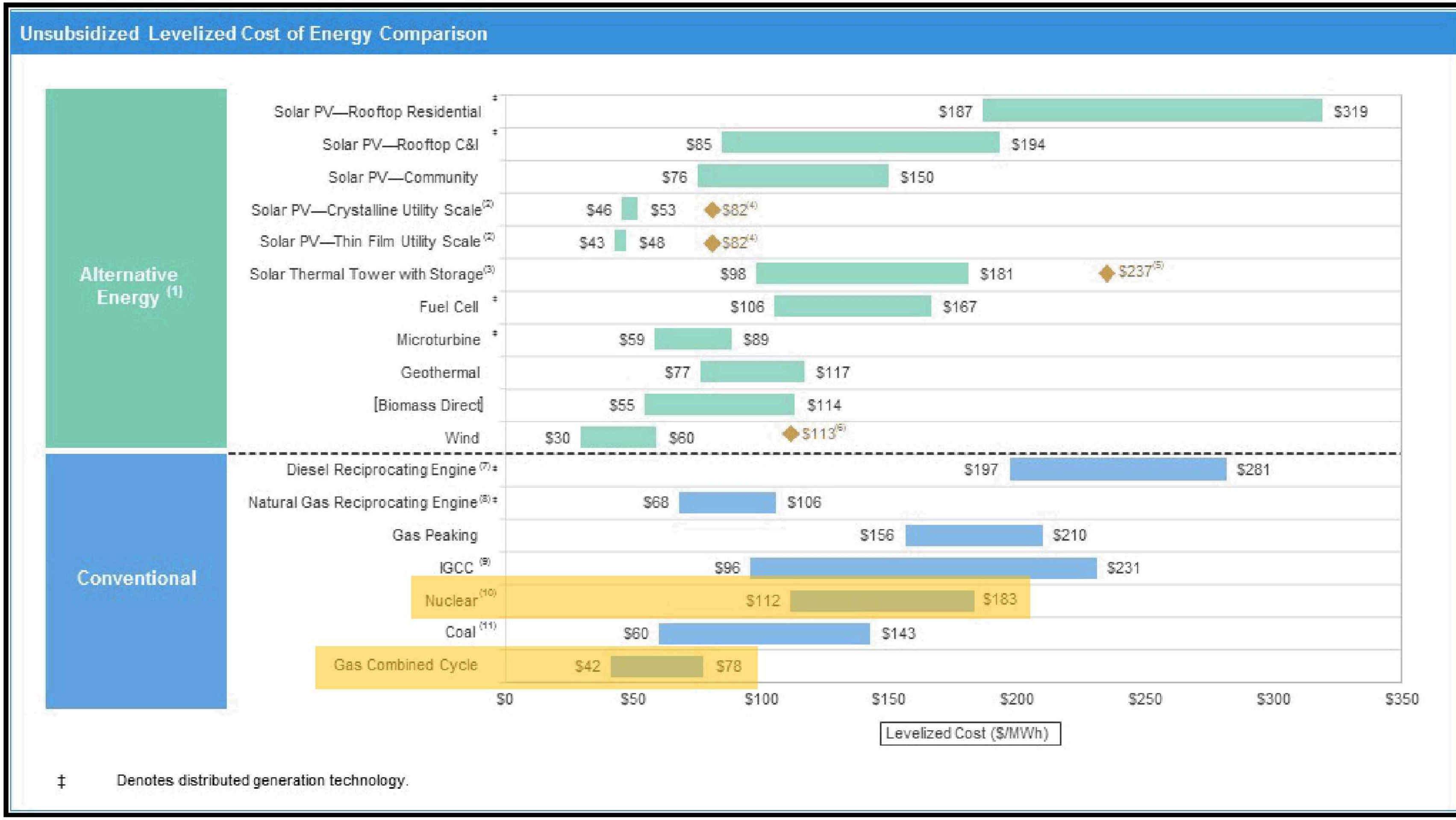
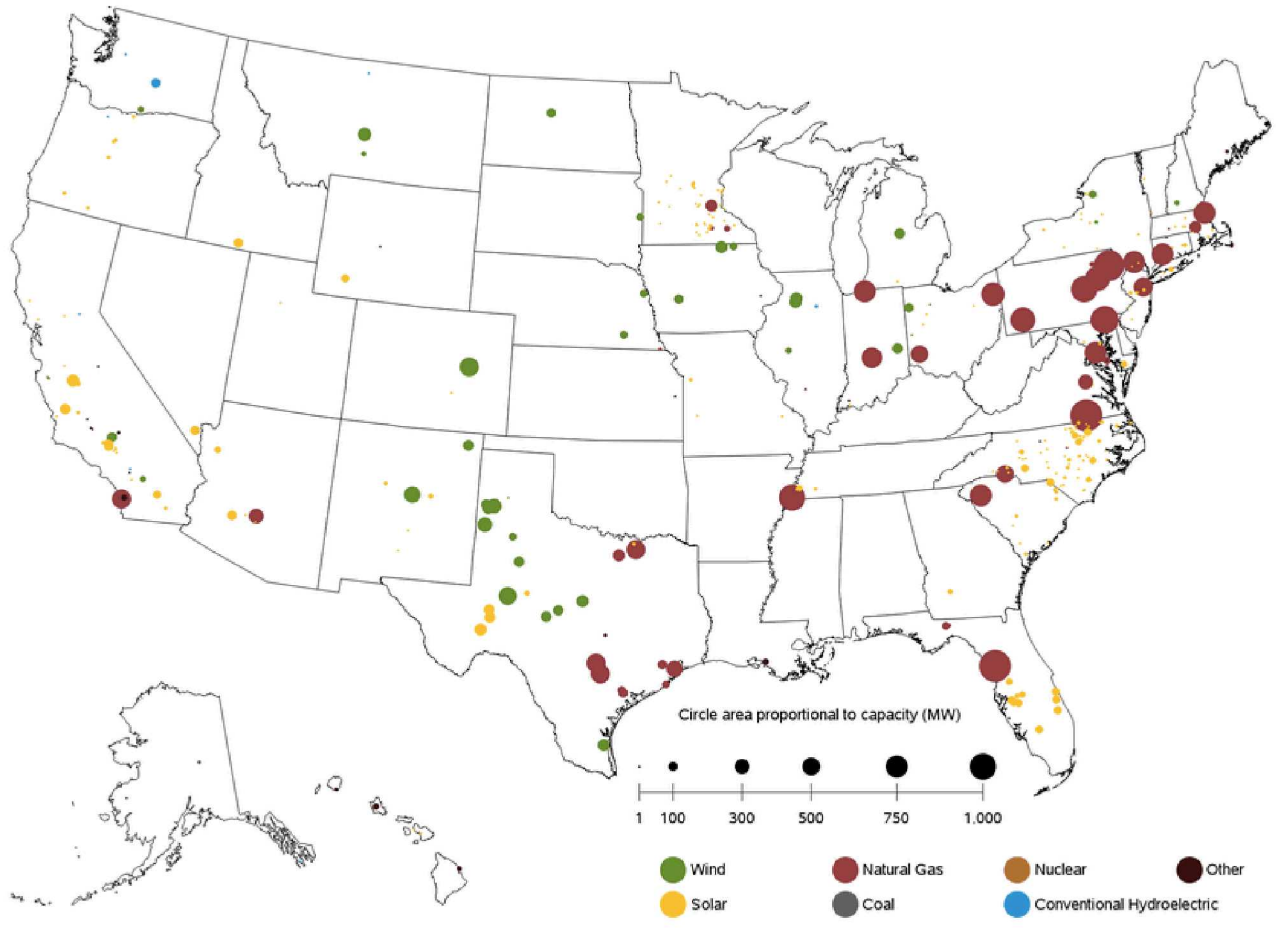
Projected LCOE (¢/kWh)



Source: Lazard, 2018.

Planned Capacity Additions, 2018-2019

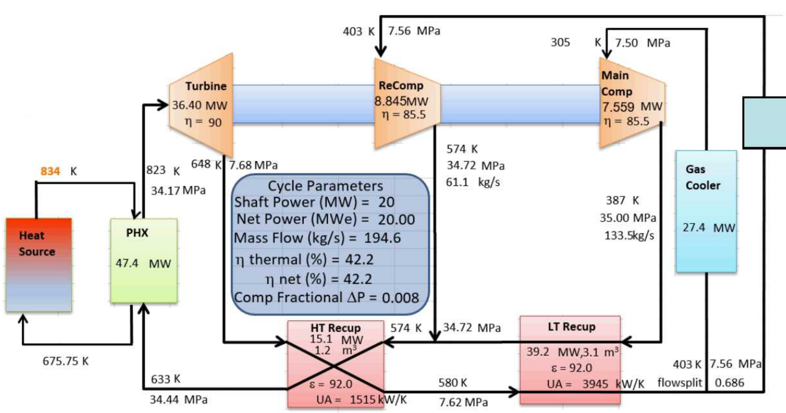


Sources: U.S. Energy Information Administration, Form EIA-860, 'Annual Electric Generator Report' and Form EIA-860M, 'Monthly Update to the Annual Electric Generator Report.'

EIA, *Electric Power Monthly,* February 2018

Integrated Techno-Economic Modeling Tool for sCO_2 Power Cycles

- Estimates the levelized cost of energy (LCOE) for recompression closed Brayton cycle (RCBC) systems. **LCOE is often used as an economic measure of energy costs as it allows for comparison of technologies with different capital and operating costs, construction times, and plant load factors.**



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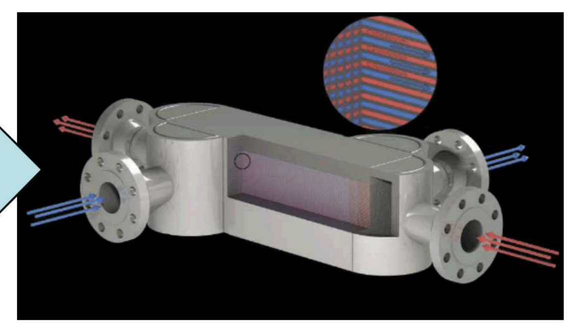

Component Costs

O&M Fuel Financing

LCOE

sCO2 Component Costing

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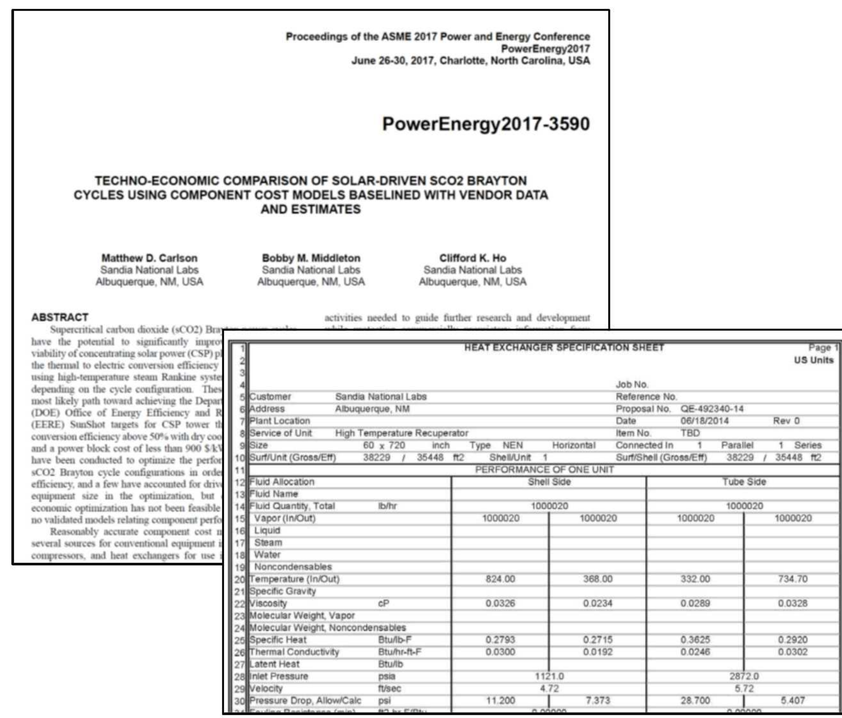
Component costing for
- Heat Source
- Heat Exchangers
  - Primary Heat Exchanger
  - High Temperature Recuperator (HTR)
  - Low Temperature Recuperator (LTR)
  - Cooling
- Turbomachinery
  - Turbine
  - Compressors
  - Control Valves
  - Generator
- Piping

Source information includes
- Publications
- Reports
- Vendor cost estimates/quotes



Proceedings of the ASME 2017 Power and Energy Conference
PowerEnergy2017
June 26-30, 2017, Charlotte, North Carolina, USA

PowerEnergy2017-3590

TECHNO-ECONOMIC COMPARISON OF SOLAR-DRIVEN SCO2 BRAYTON CYCLES USING COMPONENT COST MODELS BASELINED WITH VENDOR DATA AND ESTIMATES

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ABSTRACT

activities needed to guide further research and development

HEAT EXCHANGER SPECIFICATION SHEET — Page 1 — US Units

1				
2				
3				
4			Job No.	
5	Customer	Sandia National Labs	Reference No.	
6	Address	Albuquerque, NM	Proposal No.	QE-492340-14
7	Plant Location		Date	06/18/2014 Rev 0
8	Service of Unit	High Temperature Recuperator	Item No.	TBD
9	Size	60 x 720 inch Type NEN Horizontal	Connected In	1 Parallel 1 Series
10	Surf/Unit (Gross/Eff)	38229 / 35448 ft2 Shell/Unit 1	Surf/Shell (Gross/Eff)	38229 / 35448 ft2

			Shell Side		Tube Side	
11	PERFORMANCE OF ONE UNIT					
12	Fluid Allocation		Shell Side		Tube Side	
13	Fluid Name					
14	Fluid Quantity, Total	lb/hr	1000020		1000020	
15	Vapor (In/Out)		1000020	1000020	1000020	1000020
16	Liquid					
17	Steam					
18	Water					
19	Noncondensables					
20	Temperature (In/Out)		824.00	368.00	332.00	734.70
21	Specific Gravity					
22	Viscosity	cP	0.0326	0.0234	0.0289	0.0328
23	Molecular Weight, Vapor					
24	Molecular Weight, Noncondensables					
25	Specific Heat	Btu/lb-F	0.2793	0.2715	0.3625	0.2920
26	Thermal Conductivity	Btu/hr-ft-F	0.0300	0.0192	0.0246	0.0302
27	Latent Heat	Btu/lb				
28	Inlet Pressure	psia	1121.0		2872.0	
29	Velocity	ft/sec	4.72		5.72	
30	Pressure Drop, Allow/Calc	psi	11.200	7.373	28.700	5.407

Non-Component Costs

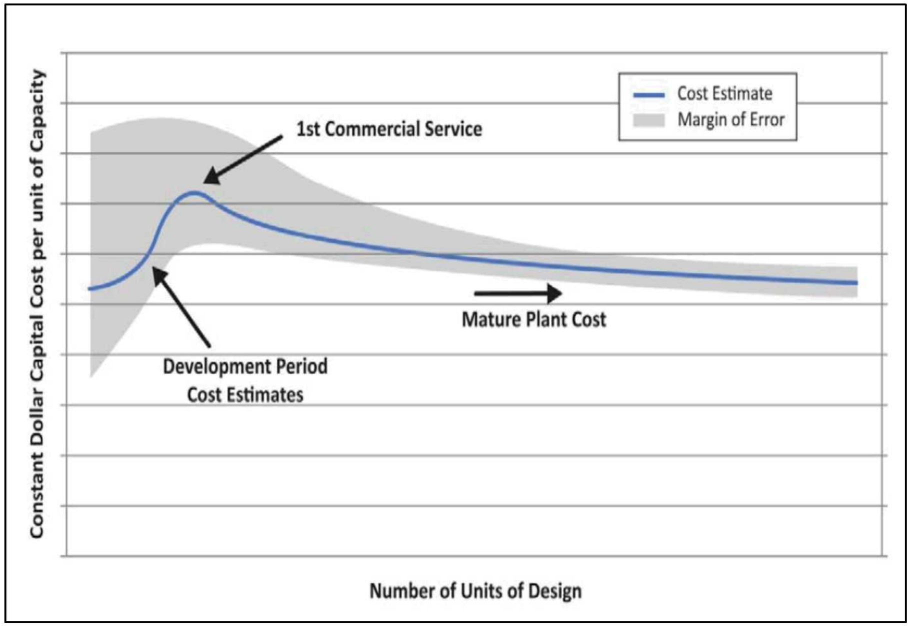
- Tool incorporates methodology outlined by the EIA (2013) for estimating total cost estimates for utility scale electricity generating plants.

- This methodology includes the following categories:
  - Component costs
  - Electrical and instrumentation and control (transformers, switch gear, etc.)
  - Civil and structural costs (site preparation, underground utilities, structural steel supply, and on-site building construction)
  - Project indirect costs (engineering, labor, construction management)
  - Fees and contingency
  - Owners costs (development costs, feasibility and engineering studies, legal fees, insurance, electrical interconnection

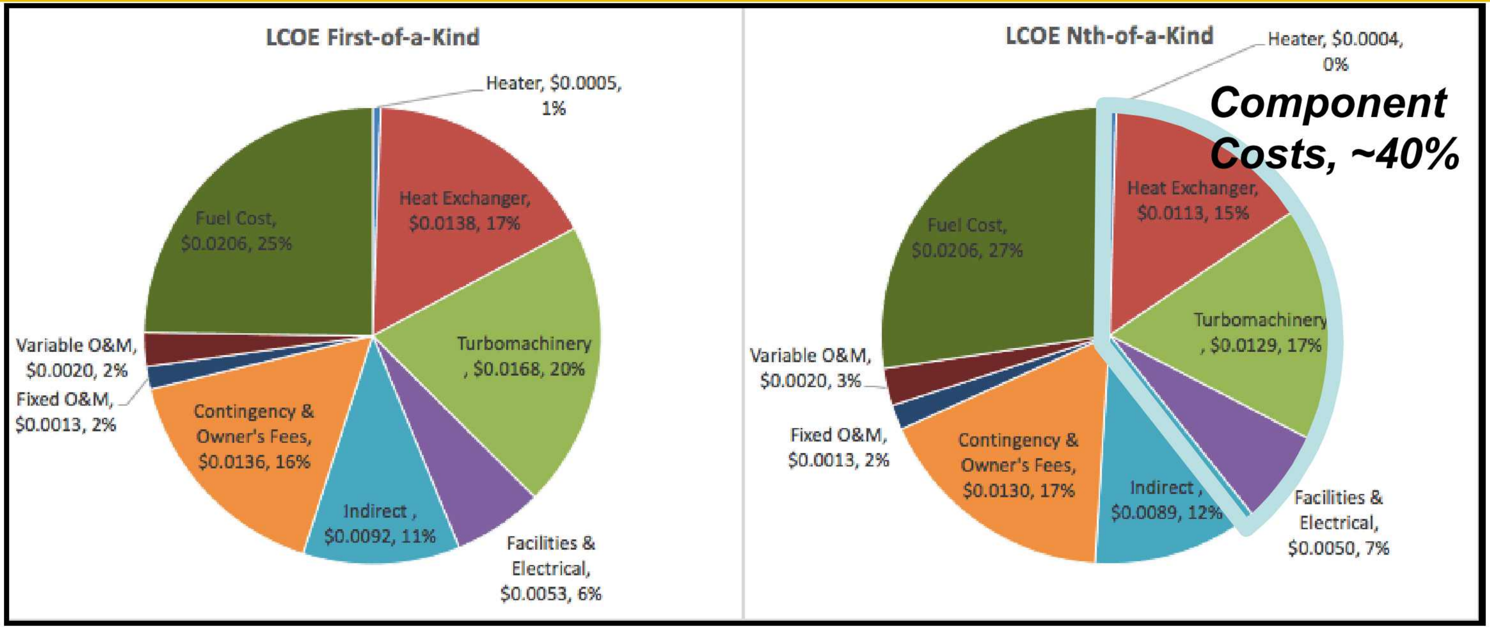
Capturing Costs as Technology Develops

First-of-a-Kind vs. Nth-of-a-Kind Methodology

- Uses approach documented by NETL (2013)
- History has shown that new technology costs initial rise as details are refined until the 1st commercial unit.
- Costs decrease as lessons are learned and processes refined.
- We are using conservative scaling for Nth-of-a-Kind scaling.

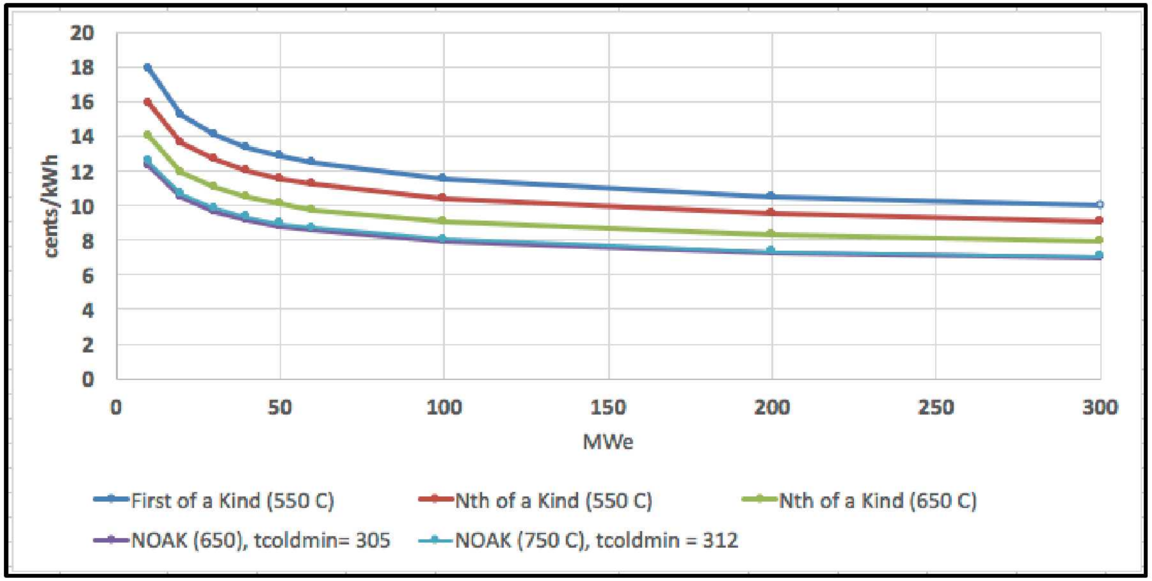


Nominal LCOE Results



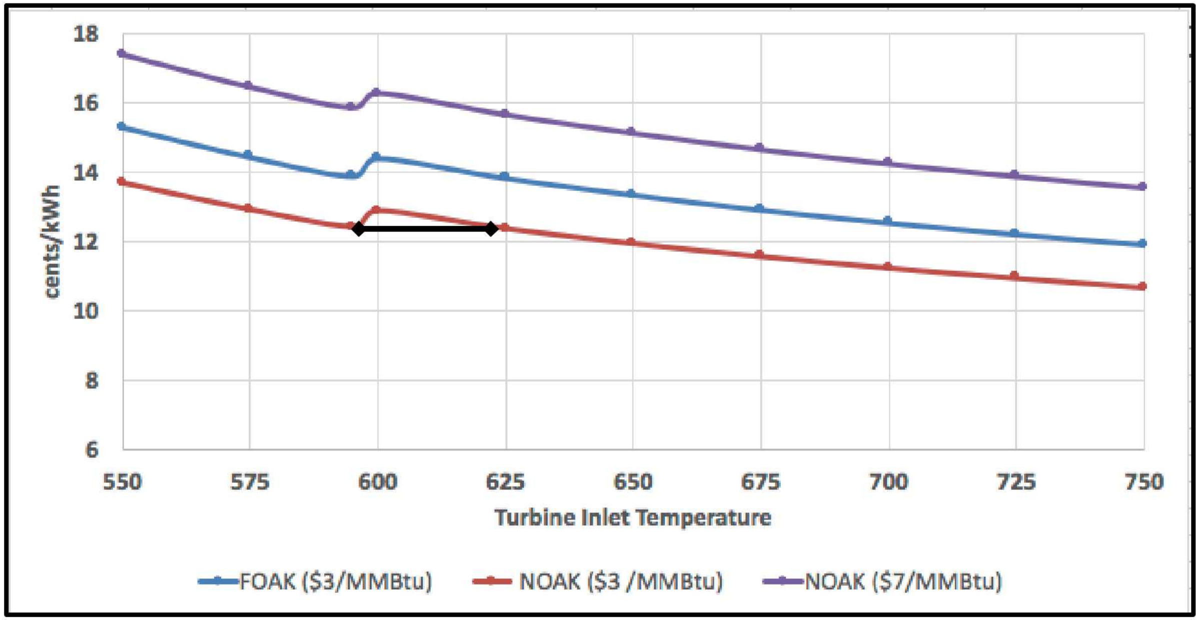
- The estimated LCOE for a 100 MWe Brayton system operating with an inlet turbine temperature of 700°C with dry cooling are **8.32 ¢/kWh and 7.54 ¢/kWh for a first-of-a-kind and Nth-of-a-kind plant**, respectively.
- For the 100 MWe facility, the various heat exchangers and turbomachinery account for 15% and 17% of the total costs for the nth-of-a-kind plant, respectively.
- The Nth-of-a-kind total mechanical costs for are
  - $1320/kWe for 100 MWe
  - $2000/kWe for 20 MWe

Plant Size and Turbine Inlet Temperature Parameter Study



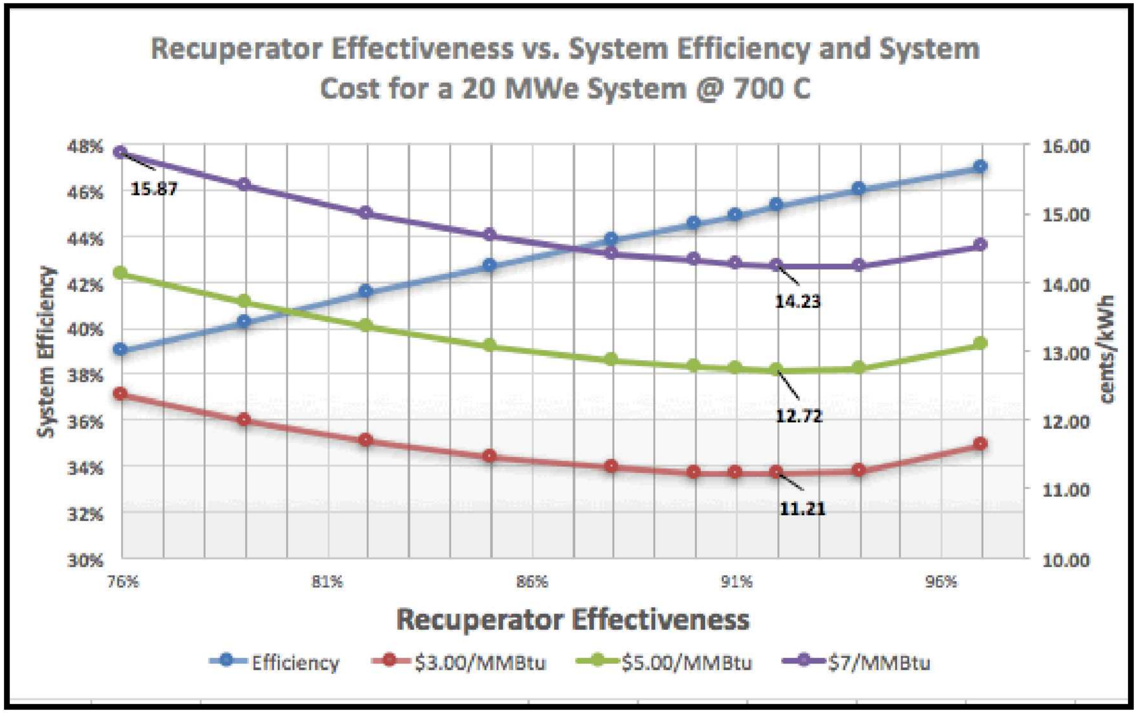
- Costs decline rapidly as size increases from 10 to 50 MWe, before slowly leveling off.
- Plants under 50 MWe, typically used for distributed or remote generation, are expected to have higher costs but higher value.
- This result demonstrates a benefit of these parameter studies, that a **relatively small decrease in cycle minimum temperature of 7°C has as much benefit as increasing the turbine inlet temperature by 100°C.**

Turbine Inlet Temperature Parameter Study



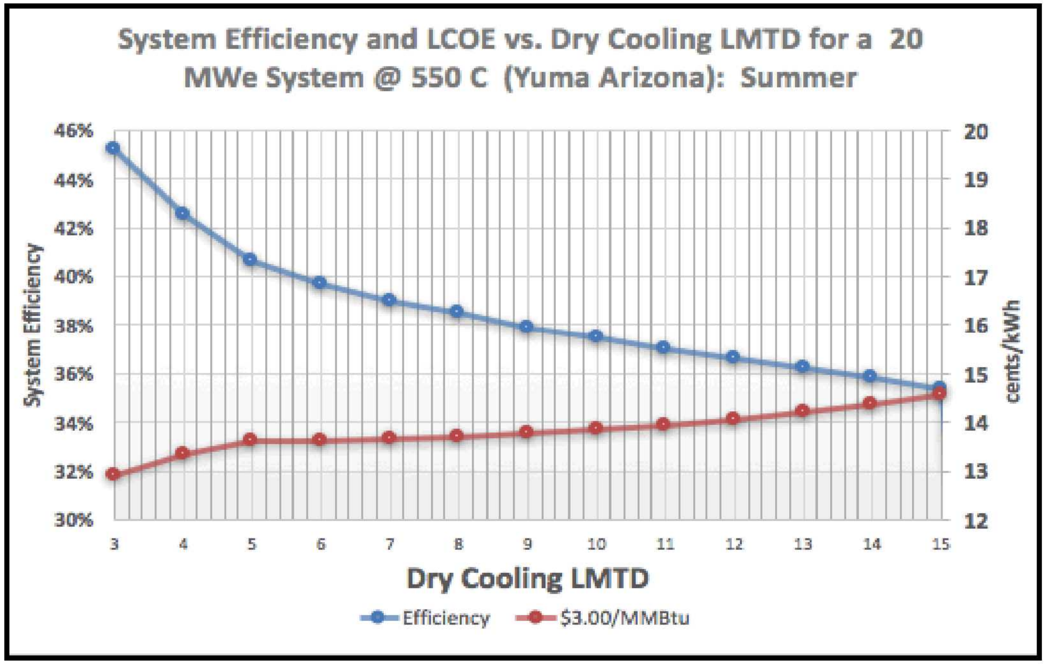
- 20 MWe system with dry cooling
- As turbine inlet temperature increases above 600°C, certain individual system components (primary heat exchanger, turbine, and high temperature recuperator) will require higher-quality alloys. The higher component costs are quickly offset by the increased overall system efficiency.

Recuperator Effectiveness Parameter Study



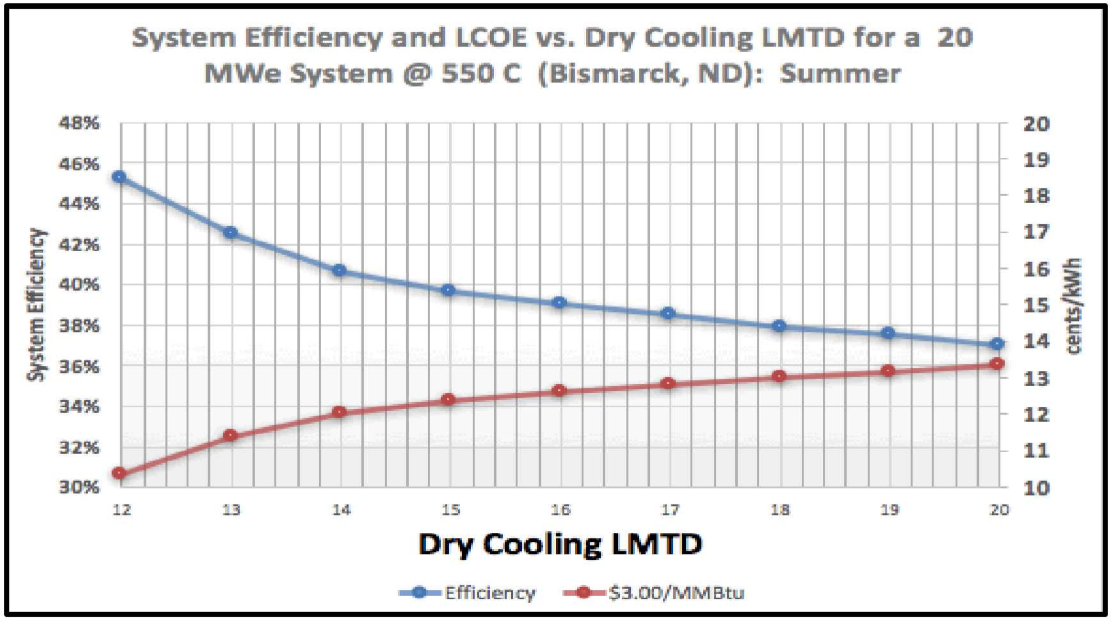
- Demonstrates the impact of recuperator effectiveness on system efficiency and LCOE. As recuperator effectiveness increases, system efficiency increases. The present analysis shows that the **optimal recuperator effectiveness, regardless of fuel price, is 92%.**

Dry Cooling Approach Temperature Parameter Study



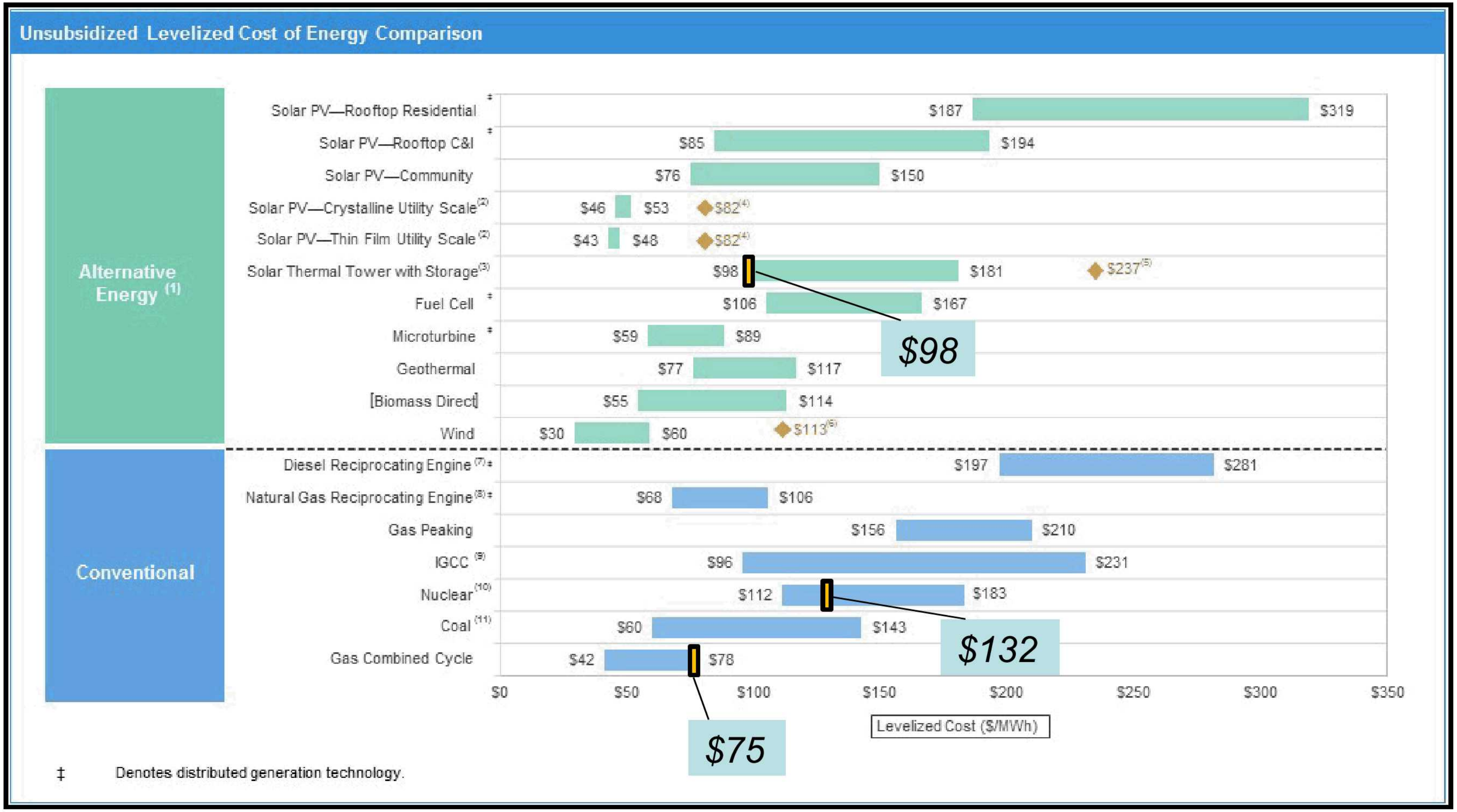
- Illustrates the sensitivity of the results to the technical assumptions regarding the approach temperatures for dry cooling in a hot, dry climate (Yuma, AZ).
- The overall system efficiency drops sharply 10% as the LMTD increases from 3 to 15°C in Yuma. **The increased system costs associated with lower LMTD translate into lower LCOE due to the increased system efficiencies.**
- sCO2 properties were assumed constant for this analysis. A discretized heat exchanger model will be developed to account for property variations.

Dry Cooling Approach Temperature Parameter Study



- This same relationship holds for Bismarck, ND in the summer, although the overall LCOE is lower that was the case in Yuma, AZ as the ambient air temperatures are lower, allowing for a smaller cooling heat exchanger.
- **The location change from AZ to ND reduces LCOE by 25%.**

Projected LCOE (¢/kWh)



Current estimates are for Nth-of-a-kind at 700°C and 100 MWe

Source: Lazard, 2018.

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The current model is cumbersome for parameter studies

- Running the current model
  - Manual manipulation of a text input file

DCBCSFRin.txt

```
base                  ! output filename, 4 characters long
1 1                   ! units flag: 1 = Metric, 2 = English.  te
0.008 0.008 0.001     ! dpFractMin,dpFractMax,dpFractInc
973. 973. 5.          ! tHotMin,tHotMax,tHotInc [K]
305. 305. 0.2         ! tColdMin,tColdMax,tColdInc [K]
7.5d6 7.5d6  0.1d6    ! pLowMin,pLowMax,pLowInc [MPa]
35.d6 35.d6 1.0d6     ! pHighMin,pHighMax,pHighInc [MPa]
2                     ! RecupFlag: recuperator approach temp or
.92 .92 .01           ! fLTR_Min,fLTR_Max,fLTR_Inc
.92 .92 .01           ! fHTR_Min,fHTR_Max,fHTR_Inc
0.90 0.90 0.01        ! effTurbMin,effTurbMax,effTurbInc
0.855 0.855 0.01      ! effCompA_Min,effCompA_Max,effCompA_Inc
0.855 0.855 0.01      ! effCompB_Min,effCompB_Max,effCompB_Inc
100.                  ! power  [MW]
```

  - Running RETS from command line

```
Z:\sCO2\RETPeT-2016-10-04>"split flow recup prediction.exe"
 Copyright 2013 Sandia Corporation.
 Under the terms of Contract DE-AC04-94AL85000,
 there is a non-exclusive license for use of this
 work by or on behalf of the U.S. Government. Export of
 this data may require a license from the
 United States Government.
 CO2.FLD


 Iteration      1  complete.
 Iterations complete.

Z:\sCO2\RETPeT-2016-10-04>
```

  - Opening output .csv file

dcbcsfrout.csv

  - Opening Excel file

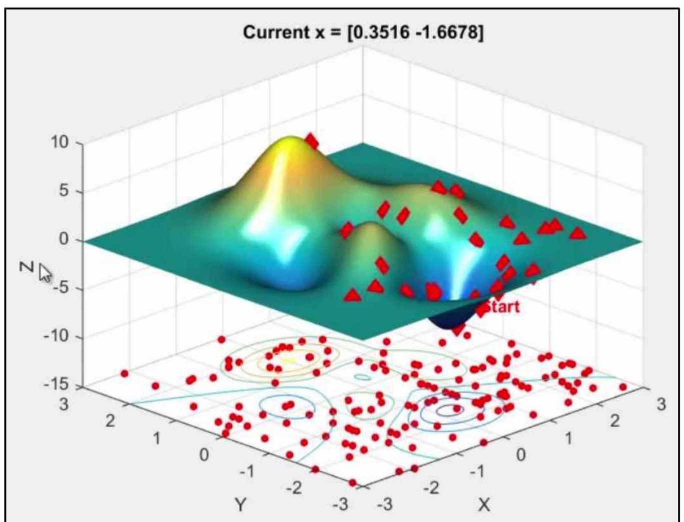
DCBCSFRmap2018-03-13.xlsx

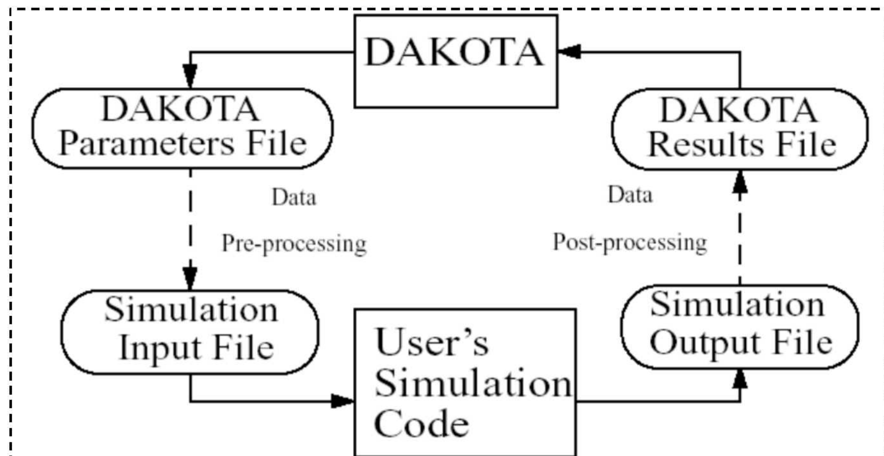
  - Recording Results, closing .csv file
- This process has to be repeated for each set of conditions, so parameters studies take some time

Economics Optimization

- RETS is written in FORTRAN
- Cost Models will be translated from Excel into FORTRAN
- Sandia's DAKOTA will be used as an optimization wrapper that will also enable sensitivity studies

DAKOTA
Explore and predict with confidence.





RETS ⟹ sCO_2 Economics

A Genetic Algorithm is the best approach for this application*,*
https://www.youtube.com/watch?v=1i8muvzZkPw

Collaboration with DOE National Labs

- The DOE national labs that have interest in sCO_2 power cycles are starting a collaboration for component cost information sharing.
- Vendor identification will be protected.
- This collaboration is expected to improve understanding and accuracy for economics modeling.
- Nathan Weiland at NETL initiated a monthly teleconference.
- Sandia is planning to facilitate information sharing, similar to the 2017 sCO_2 Summit Site.

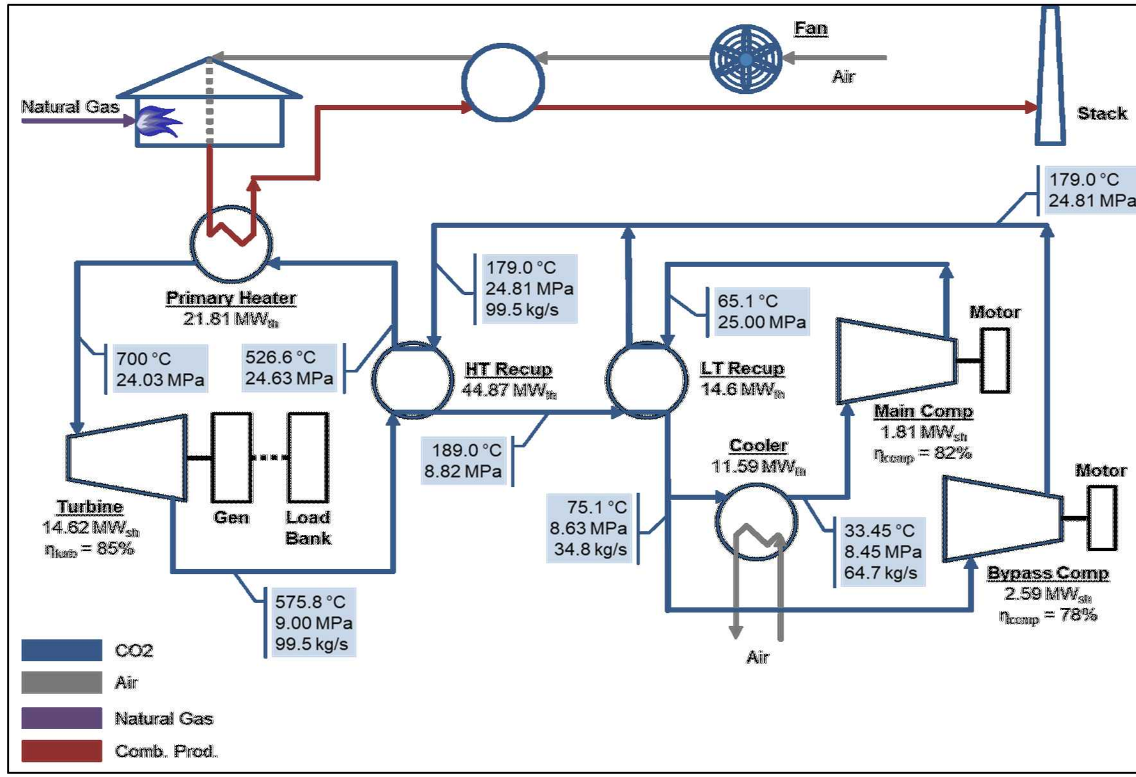
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sandia National Laboratories

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Component Cost Estimates of 10 MWe STEP Pilot Plant

Component	10 MW_e Plant	
	(2017 $1,000)	% of total cost
NG-fired heater	$8,909	38.21%
PC-fired heater	-	
LTR	$2,056	8.82%
HTR	$3,324	14.25%
Direct dry cooler	$1,617	6.93%
Main compressor	$1,558	6.68%
Recompressor	$1,798	7.71%
Motors	$407	1.74%
Turbine	$2,831	12.14%
Generator	$471	2.02%
Gearbox	$340	1.46%
Total equipment cost (2017 $1,000)	$23,310	
Uncertainty range of total equipment cost	-28% to +35%	



S. E. Zitney and E. A. Liese, "Dynamic Modeling and Simulation of a 10 MWe Supercritical CO2 Recompression Closed Brayton Power Cycle for Off-Design, Part-Load, and Control Analysis," in The 6th International Supercritical CO2 Power Cycles Symposium, Pittsburgh, 2018.

Conclusions and Future Plans

Conclusions

- A DOE National Lab sCO_2 Power Cycle Economics Consortium was organized
- The sCO_2 Brayton Economics Tool has been updated with component cost information
- Economics optimization has begun with software selection, algorithm planning

Future Plans

- Current cost models will be updated with collaborative work from Consortium
- Economics optimization will be performed

Backup

Pathways to Commercialization

- Initial market opportunities
  - waste heat
  - distributed generation
- Strong market opportunities in water-stressed regions as Brayton cycles achieve high efficiencies with dry cooling
- Key challenges:
  - *Customers not willing/able to invest in unproven technologies*
  - *Need demonstrable evidence that Brayton technology can operate for extended periods of time in a real-world environment*
- Main competitors (Next slide):
  - Renewable technologies, such as onshore wind (3.0 – 6.0 ¢/kWh)
  - Natural Gas Combined Cycle (NGCC) plants (4.2 – 7.8 ¢/kWh)
  - Bottom line: Must be able to compete on an economic basis with existing options or will be difficult to break into the market (subsequent slide)

Basic LCOE Methodology

- The levelized cost of energy is given by:

$$LCOE = \frac{I * FCR}{E} + \frac{O\&M}{E} + \frac{F}{E}$$

where:

I	= total financed capital costs
FCR	= fixed charge rate
E	= annual plant output (i.e. kWh)
$O\&M$	= fixed and variable operating and maintenance costs
F	= feedstock costs (i.e. natural gas, biomass)

Non-sCO2 Component Costs

- Tool incorporates methodology outlined by the EIA (2013) for estimating total cost estimates for utility scale electricity generating plants.

- This methodology includes the following categories:
  - Mechanical equipment supply (major equipment)
  - Electrical and instrumentation and control (transformers, switch gear, etc.)
  - Civil and structural costs (site preparation, underground utilities, structural steel supply, and on-site building construction)
  - Project indirect costs (engineering, labor, construction management)
  - Fees and contingency
  - Owners costs (development costs, feasibility and engineering studies, legal fees, insurance, electrical interconnection

- Adding all of these costs obviously increases the estimated LCOE estimates, but are more realistic than studies which ignore such costs. For example, the **project indirect costs add an additional 28.8% to the mechanical and electrical costs**.

Capturing Costs as Technology Develops

First-of-a-Kind vs. Nth-of-a-Kind Methodology

- Uses approach documented by NETL (2013) where costs are:

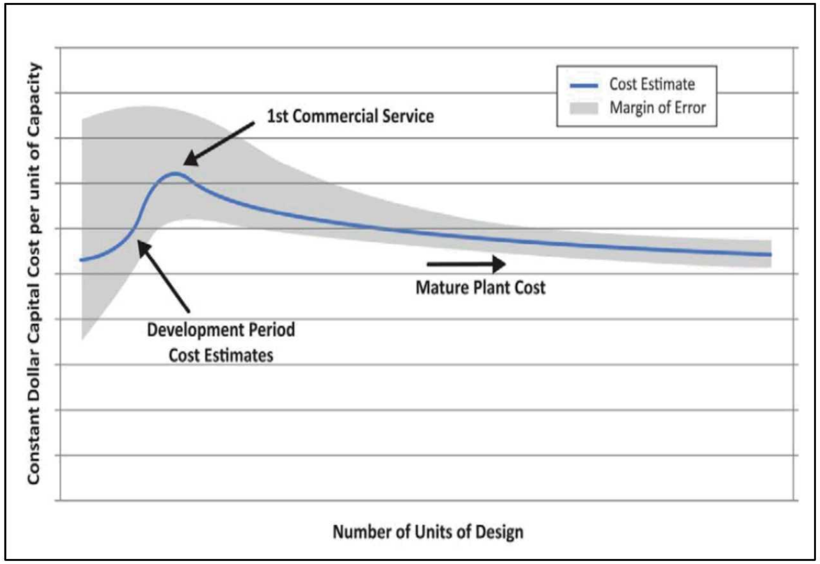
$$\text{Cost}_{\text{NOAK}} = \text{Cost}_{\text{FOAK}} * X^{-b}$$

Where X is the cumulative number of units and b is the learning rate exponent, which is further defined as:

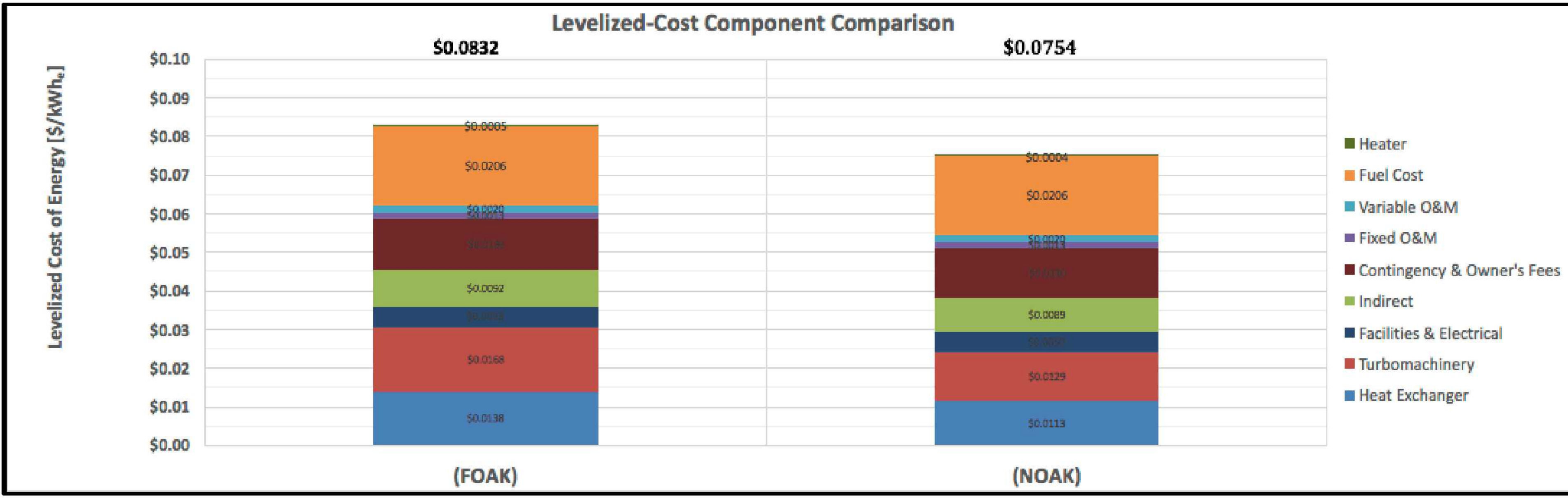
$$b = \frac{\log(1 - R)}{\log(2)}$$

where R is a technology-specific learning rate.

- Suggested R values as high as 0.06 for experimental technologies (e.g., fuel cells) and in the range of 0.01 for mature technologies (e.g., buildings, steam turbines, instrumentation).



Nominal LCOE Results



- *The estimated LCOE for a 100 MWe Brayton system operating with an inlet turbine temperature of 700°C with dry cooling are **0.832 $/kWh and 0.754 $/kWh for a first-of-a-kind and Nth-of-a-kind plant, respectively.***
- *For the 100 MWe facility, the various heat exchangers and turbomachinery account for 15% and 17% of the total costs for the nth-of-a-kind plant, respectively.*
- *The Nth-of-a-kind total mechanical costs for are*
    - *$1320/kWe for 100 MWe*
    - *$2000/kWe for 20 MWe*