Report back:

Technology specific:

Stirling Engines

June 2, 2011

General Observations – Stirling Engines

- Why aren't Stirlings everywhere?
  - Poor specific power – poor for transport
  - Load following lag – poor for transport
  - Poor torque ramps – poor for transport
  - Transport has driven prime mover requirements for a century – ICEs best
  - Specific power main driver (power to weight) for transportation
  - Stirlings are great for power generation

General Observations – Stirling Engines

- Stirling advantages
  - Good efficiency
  - Easily scaled down
  - Fuel flexible
  - High turndown ratios (90%)
  - High reliability
  - Modular
- Stirling challenges
  - Cost, reliability data

Stirling Engines Cost Drivers

- Stirling cost drivers
  - Pressure vessel
  - Hot heat exchanger/hot head
  - Linear alternator (free piston)
  - Regenerator (high temp engines)

ARPA-E strawman for single family systems

- This is the current sweet spot for Stirlings
  - 2-3kW size (use 3 for 7kW in single package)
  - For 10% adoption, modular approach allows fitting multiple scales
  - Lowers up-front cost for many people
  - Modules could cost <$1000/kW by 10,000/year
  - Direct grid-tie preferred over inverter
  - Other home architectures:
    - Cogeneration as Baxi and others
    - Low-temperature engine for Cogen and Heat Pump during winter and summer

ARPA-E strawman for single family systems

Category	ARPA-E's proposed
System rating	7 kWe – 2-3kWe preferred for Stirling
Electrical efficiency (@ ≥50% kW rating)	≥ 50% - big stretch for Stirling
Cost	$10k CAPEX @ 10,000 EASY with component dev
Lifetime	>7yrs - EASY

- Within each technology platform, what are the technology pathways towards these targets?

- Carnot Efficiency - @800C hot, 20C cold : 73% (endoreversible = 48%)
- - @1000C hot, 20C cold: 77% (endoreversible = 52%
  - @1200C hot, 20C cold: 80% (endoreversible = 55%)
  - NOT TRANSFORMATIVE TO CHASE EFFICIENCY
  - TRANSFORMATIVE TO CHASE COST

- Where is the ARPA-E play? Architecture and components

ARPA-E strawman for community, apartment, small commercial systems

Category	ARPA-E's proposed
System rating	350 kWe – Required architecture design – Hybrid design likely
Electrical efficiency (@ ≥50% kW rating)	≥60% - Unlikely under >1200C
Cost	$1500/kW CAPEX @ 2,500 units/yr Challenging but possible
Lifetime	>7yrs - Likely

- Within each technology platform, what are the technology pathways towards these targets?

- Carnot Efficiency - @800C hot, 20C cold : 73% (endoreversible = 48%)
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- Where is the ARPA-E play? Architecture (hybrid system) and components

ARPA-E strawman for community, apartment, small commercial systems

- Design study for Bechtel Bettis - 4.2MW scale, conceptual design
  - Large scale could involve separate bottoming cycle (Stirling) regardless of topping
  - Multi-stage systems have technical advantages (components can be designed for best performance in different temp ranges)

  - Other large-scale waste recapture architectures:
    - Low-temperature opportunities (geo, WHR, non-tracking solar, biomass)
    - Co-located at LNG facility for massive efficiency while re-gasifying
    - Expansion of NG in pipelines

Impact Areas

- Reviewing the “knobs”, rank them in order of potential highest impact and highest risk relative to ARPA-E’s 3-yr program horizon? (Please add categories if necessary).

Potential “knobs”	Impact rank	Risk rank (1-5)
Engine architecture	1	3
Combustion approach	4	5
Component design	2	3
Materials	3	2
Working fluid	5	3

- What can be done in Stirling engines with a 3yr $30M program? Enough to “move the needle”?

- Cost Reduction in Small Engine (component design and architecture improvement)
- Demo and Reliability in Small Engine

- Architecture Design for Large Engine (Hybrid System Design and Development)
- Proof of Concept Demo for Large Hybrid System (<50kW)
- Seedling – thermo-acoustic transduction

Is this an ARPA-E play? - ABSOLUTELY

Application Bookeeping

- What do you think is the minimum set of calculations/modeling results/test data that should be required for consideration for ARPA-E funding (For example: thermodynamic cycle analysis? FEA/CFD system analysis? energy calculations, reliability data, cost-modeling, emission data, …)?

- Large ($3M):
  - Cycle analysis
  - Energy calculations
  - Emissions analysis
  - Cost Modeling
  - Reliability modeling
- Small – seedling
  - Cycle analysis
  - Energy Modeling
  - Cost modeling