SunShot U.S. Department of Energy

Sandia National Laboratories

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Dish Storage

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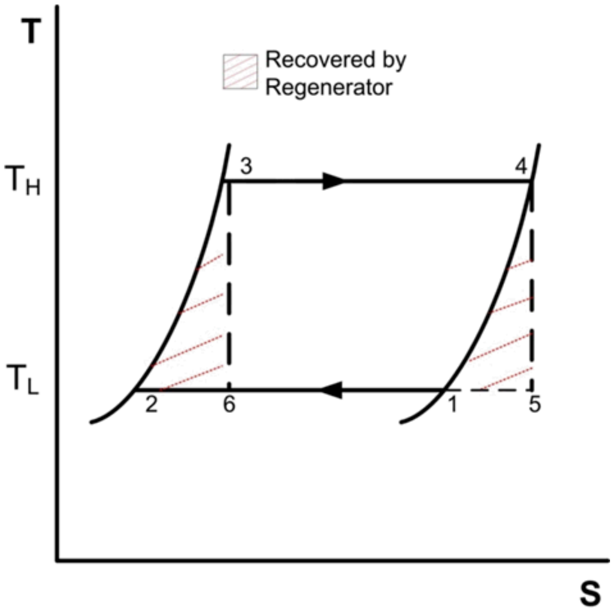
Dish Stirling Technology

- High performance systems
  - Over 31% sunlight to grid efficiency
  - Over 26% annual efficiency
  - High temperature
  - High concentration
- Typically 3-30kWe
  - Potentially off-grid
  - Large power parks proposed for low cost
- Best technology to meet SunShot goal
  - $0.06/kWh attainable
    - Deployment
    - Supply chain development
    - Design for manufacture
- Needs storage
  - Match demand curves
  - Utilities/PUC's need to "value" evening generation
  - Differentiation

Dish Stirling Technology

- Dish
  - High percentage of system cost
  - High concentration ratio, typically over 3000:1
    - Peak 12000:1
  - Typically “balanced” design
    - Requires pedestal slot
    - Allows low drive loads
  - High annual optical efficiency due to 2-axis tracking
- Engine
  - Ideal Stirling identical area to Carnot
  - Highest potential system efficiency
  - Isothermal energy input
- Deployment
  - Large fields
    - Reduce cost
    - Allow consolidated maintenance
    - Avoids insurance issues
  - Shading → 5-6% annual energy production loss
  - Good match to current TOD pricing
    - Very little “inertia”



Finances of Dish Stirling

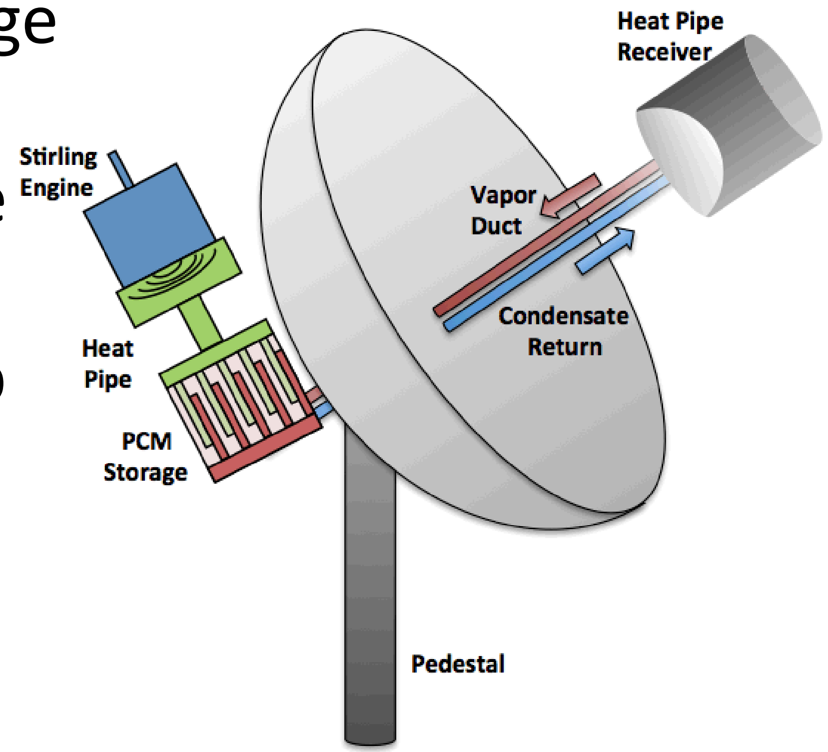
- SES systems
  - 25kW system generates 56MWh/year (Barstow)
  - Estimated at $2/W installed
    - LCOE $0.085/kWh
      - FCR 7.42%
      - O&M $0.045/W/year
  - First plant at $3/W
  - Value of electricity
    - SCE TOD, December 2011
    - "Base" of $0.10/kWh from market price referent
    - $0.14/kWh dish-solar-weighted
  - White paper indicates $0.06/kWh with offshore manufacture, supply chain development, and design for manufacture
    - $0.015 to $0.02/kWh adjustment for offshore

Season	Period	Definition	Factor
Summer June 1 - September 30	On-Peak	WDxH[1], noon-6 pm	3.13
	Mid-Peak	WDxH, 8-noon, 6-11 pm	1.35
	Off-Peak	All other times	0.75
Winter October 1 - May 31	Mid-Peak	WDxH, 8 am-9 pm	1.00
	Off-Peak	WDxH, 6-8 am, 9 pm-midnight; WE/H[2] 6 am-midnight	0.83
	Super-Off-Peak	Midnight-6 am	0.61

1/ WDxH is defined as weekdays except holidays
2/ WE/H is defined as weekends and holidays

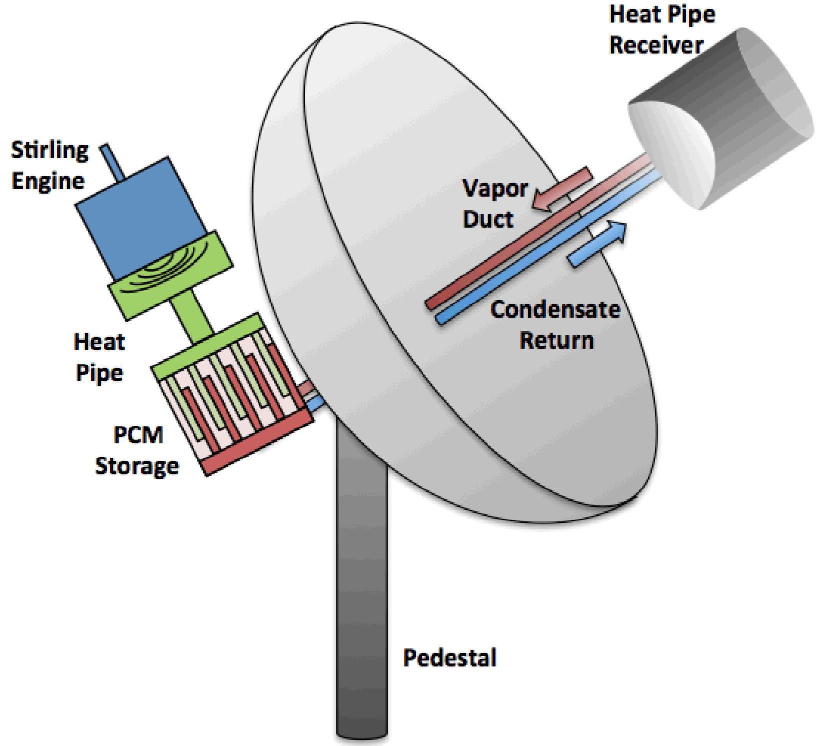
Dish Storage Concept

- PCM storage
  - Heat pipe transport to storage and to engine
  - Latent transport and storage ideal for Stirling input
  - Condensate return via pump
- Rear dish mount
  - Rebalances system
  - Allows heavy storage
  - Closes pedestal gap



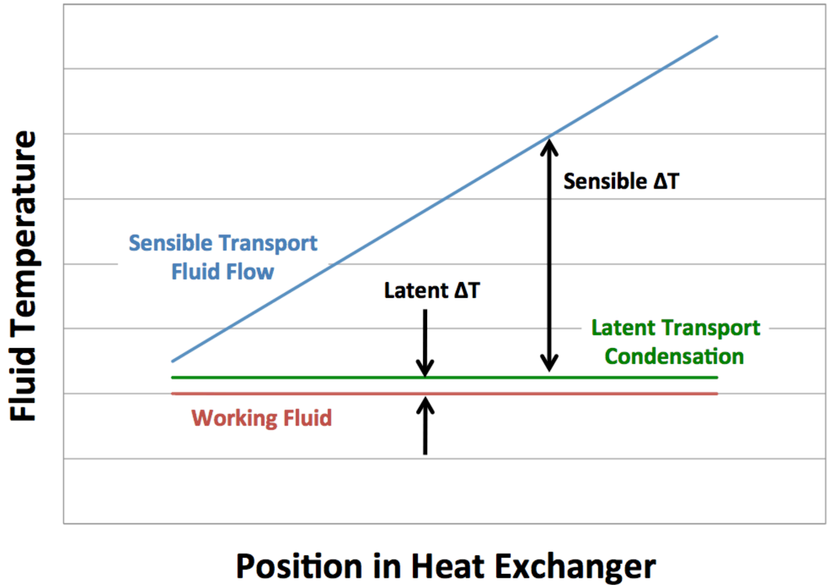
Interfaces

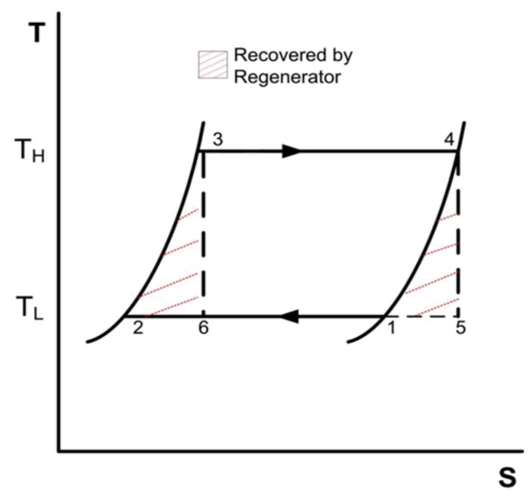
- Solar-to-Transport
  - Heat pipe solar receiver
  - High flux
  - High power
- Transport-to-PCM
  - Two-phase heat transfer
  - Melt/freeze cycles
- PCM-to-Transport
- Transport-to-engine
  - Engine specific
  - Thermal expansion issues



Latent Heat Input

- Isothermal input to engine
  - Sensible heat input results in large exergy loss
  - Latent input matches engine needs
- Performance boost
  - Up to 20% performance improvement demonstrated
  - Fixed peak temp, increased average temp
  - Dead volume reduction
  - Improved receiver absorption
  - First and second law improvements over DIR





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Innovations

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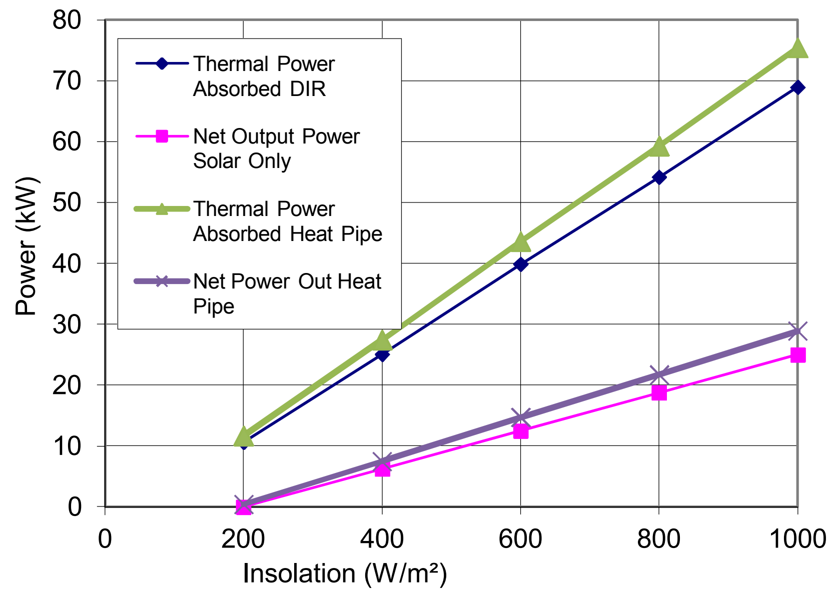
- High operating temperature CSP system
  - 650°C or higher cycle temperature
  - High Carnot fraction
- Isothermal storage and transport minimize exergy losses
- High exergy efficiency
  - System level improves over DIR
- Balanced concentrator reduces cost
- Thermal diode effect reduces losses
- Spherical receiver optimizes cavity performance
- Heat pipe input to engine demonstrated performance enhancement
- Thermal transformer adapts solar flux to engine requirements

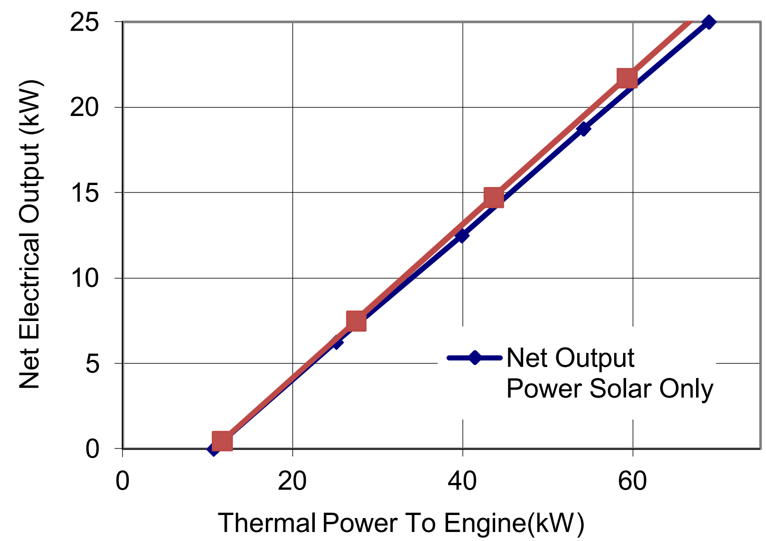
Systems Study Overview

- Simple model
  - Block characterization of storage
  - Empirical engine data
  - Field level model
- Vary storage parameters
  - Capacity
  - Solar multiple
  - Operating Algorithms
- Economics “Lite”

Systems Study Inputs

- Barstow 1977 Solergy 15-minute weather data
  - Calculate thermal input at each interval
- Separate thermal and engine performance
  - Actual system performance data
  - Modeled optical and receiver performance
  - Residual is engine performance
- Performance changes
  - Receiver 85% to 93% (measured)
  - System enhanced from 18 to 21kWe (measured, single point)
  - Change from hydrogen to helium
  - $25kW_e$ from 68.88 to $66.65kW_{th}$





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Storage Model

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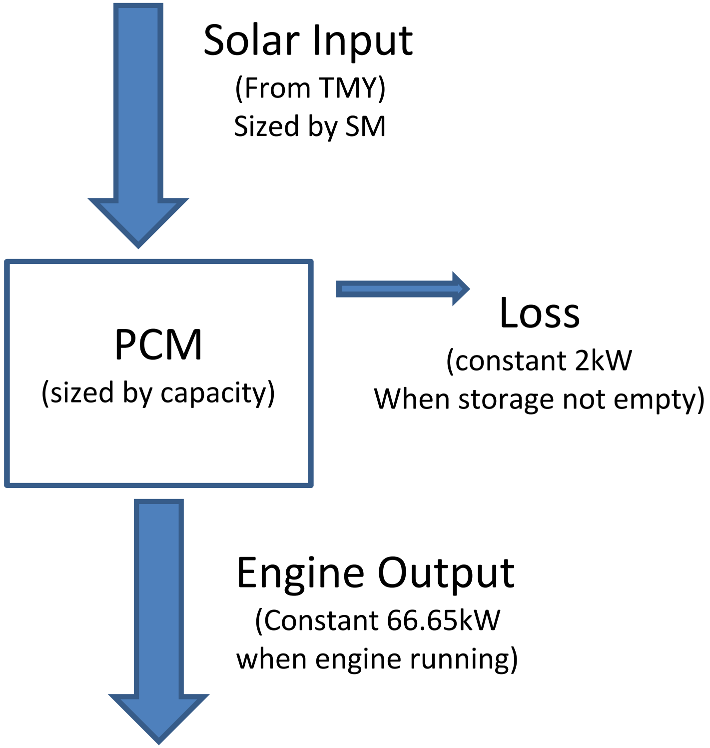
- Simple accumulator
  - Size set by hours of storage
  - Solar input increases accumulator
  - Engine operation decreases accumulator
  - 2kW_{th} loss continuous
- Startup conditions
  - Time of day (noon typical)
  - “Fullness” of accumulator
    - Minimum 10% required to start
    - Must start at 80%
- Engine operation
  - Run until accumulator depleted
  - Shed energy if accumulator is full
  - Run engine at full rated power (25kW_e)
  - Ignore sensible heat
- Solar multiple
  - Did not account for closing dish gap
  - Scaled dish spacing by dish diameter (shading is constant)
  - Did not reduce dish size for improved performance (i.e., S.M. figures are low)



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Financial Model

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- TOD multiplier from SCE Dec. 2011
  - Ignored weekends and holidays
- $0.10/kWh from market price referent
- Fixed price (not escalated over life of system)
- Revenue stream calculated each 15 minutes for entire year of data
- Profit = Revenue-LCOE
- No capacity payments or penalties
- No short-term dropout penalties

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LCOE

$$LCOE = \frac{(CC * FCR + OM_y) * RatedPower}{AE}$$

- LCOE=Levelized Cost of Energy, $/kW-hr
- CC = Capital Cost, $/W, set to $2/W for non-storage system
- FCR = Fixed Charge Rate, set to 7.42%
- OM_y = O&M costs in $/W/yr, set to $0.045/W/yr
- Rated Power = Entire plant size in W, set to 500MW
- AE = Annual Energy produced in kW-h, as calculated

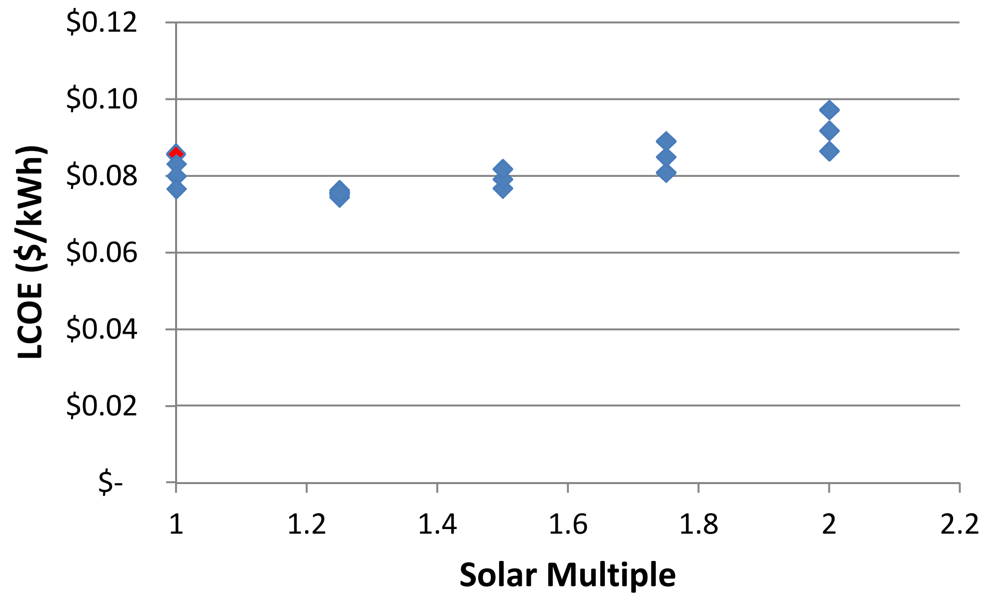
Capital Cost with Storage

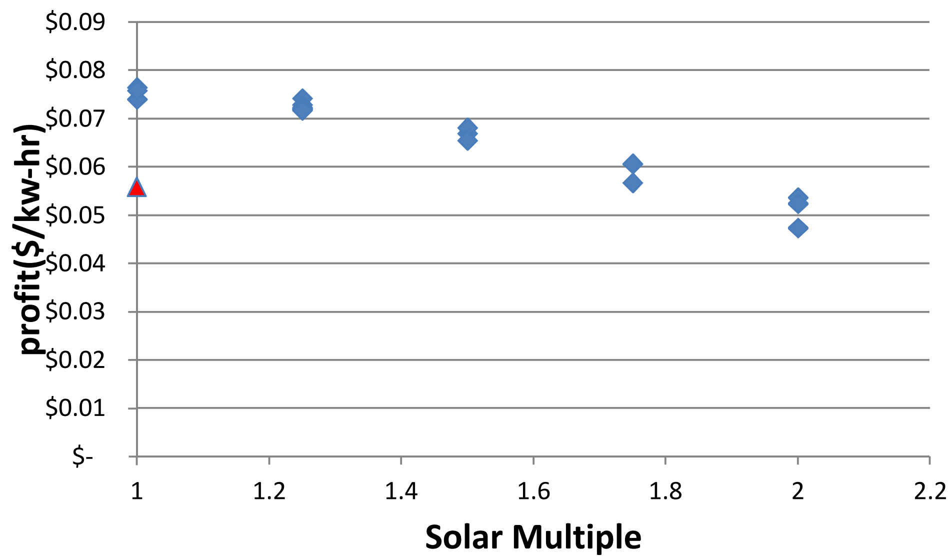
$$CCWS = \frac{(SFC + SVC * SC)}{RPPD} + CC * (1 - SF + SF * SM^{1.5})$$

- CCWS = Capital Cost With Storage, \$/W
- SFC = Storage Fixed Cost, \$/dish, set to \$3000/dish
- SVC = Storage Variable Cost, \$/kWh$_{th}$, set to \$20/ kWh$_{th}$
- SC = Storage Capacity, kWh$_{th}$, user setting
- CC = Basic system Capital Cost, \$/W, set to \$2/W
- SF = Scaled fraction of dish, set to 50%
- SM = Solar multiple
- RPPD = Rated Power Per Dish (W)

Results: Solar multiple

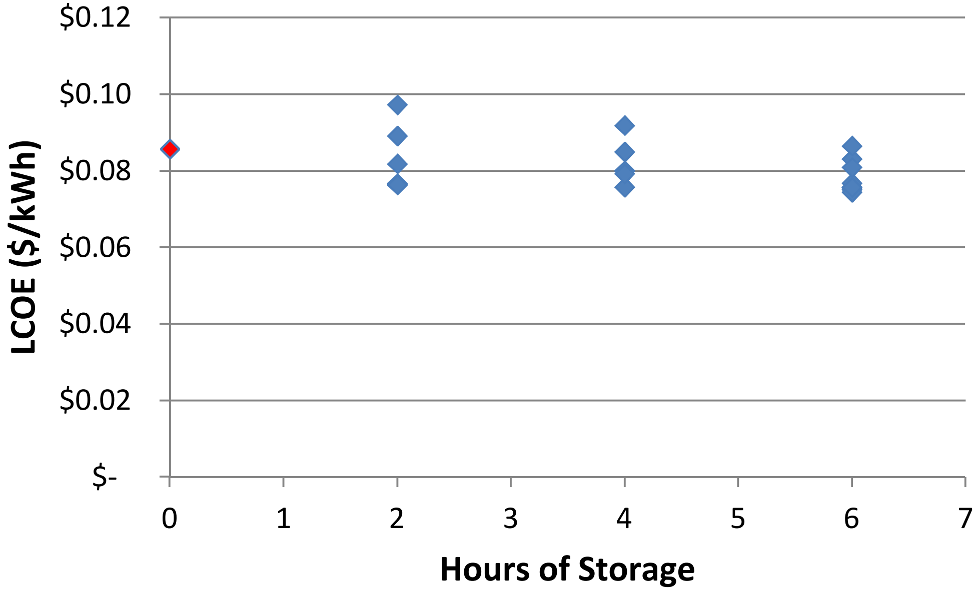
- Clear minimum in LCOE
  - Regardless of storage size
  - 1.25
  - Reasonable from heat pipe standpoint
  - Higher SM has more shedding
  - Shallow slope with higher capacity
  - Small net impact on LCOE
- Large impact on profit
  - Shift morning generation to high value in summer
  - Full generation through 6pm
- Storage can be a net benefit

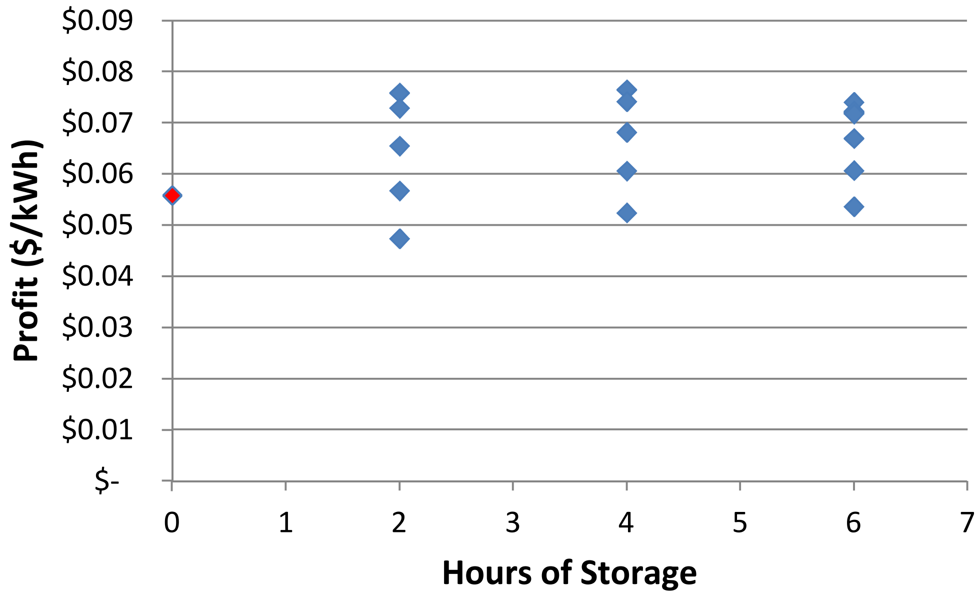




Results: Storage Capacity

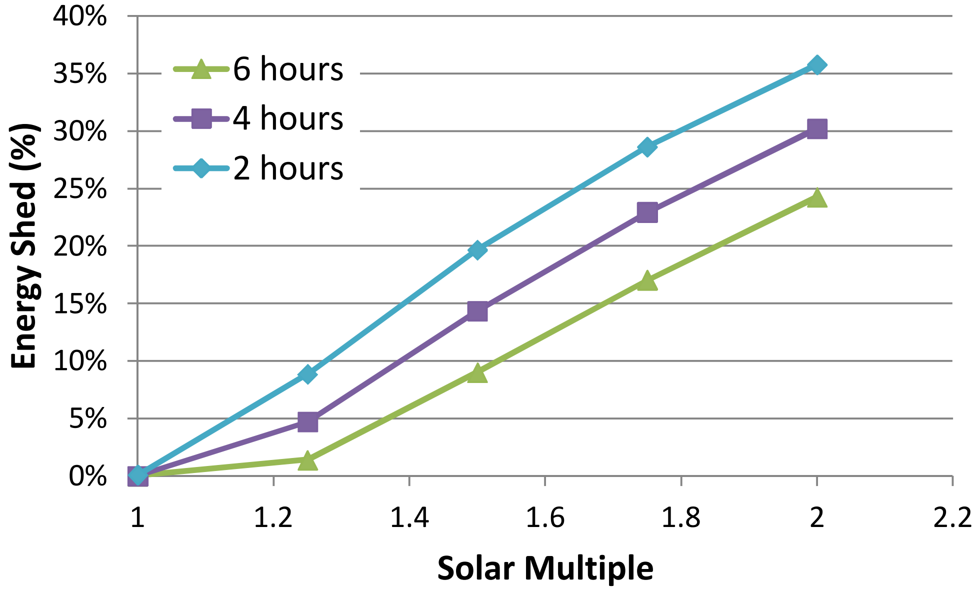
- LCOE and Profit are rather flat for given SM
- Slight peak in profit at 4-6 hours storage

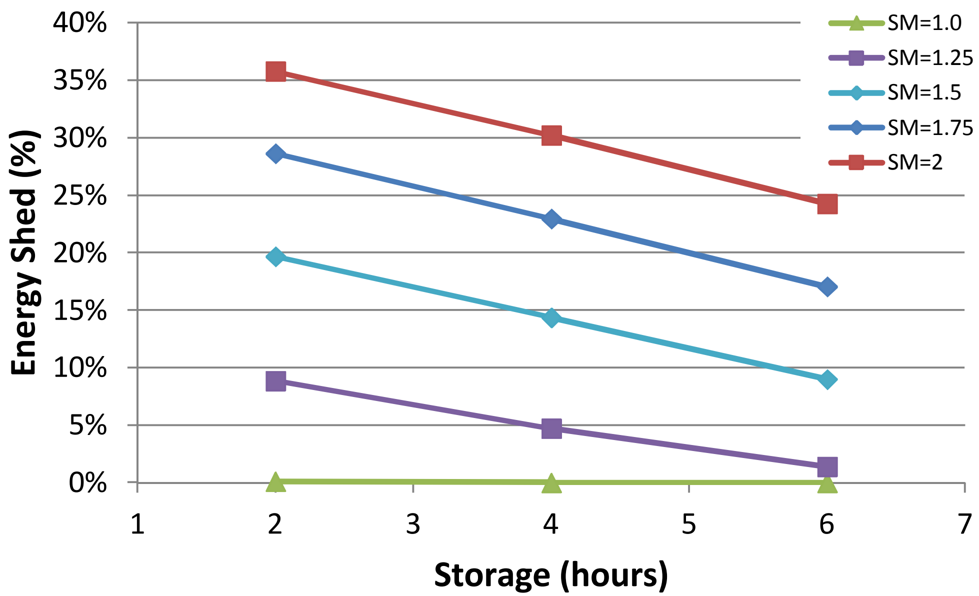




Results: Shedding

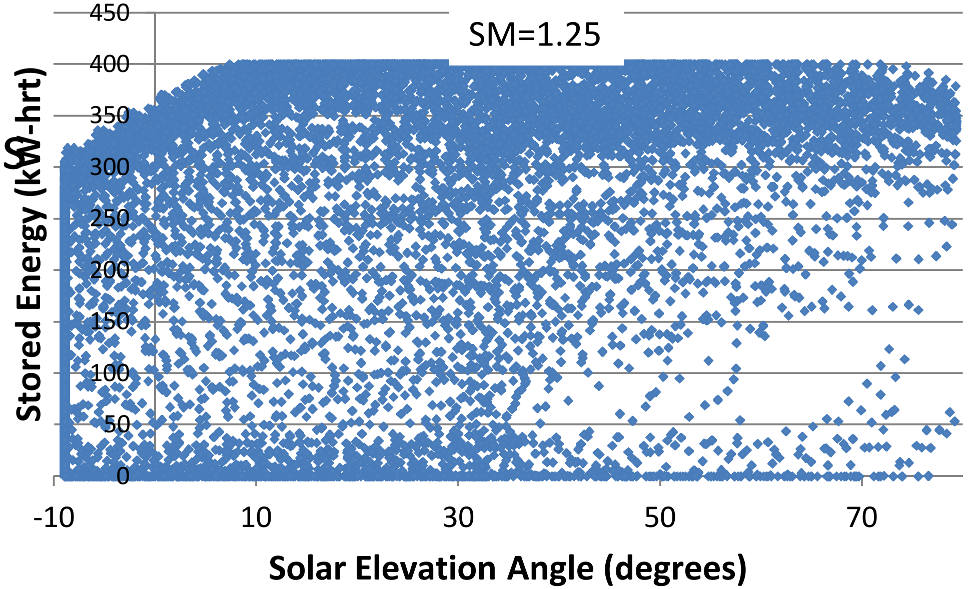
- Trends are as expected
  - More shedding as SM increases
  - Less shedding with more storage
- Some shedding desirable
  - No shedding: Ineffective use of storage capacity
  - Much shedding: Ineffective use of collector area
  - Based on finances, 2-5% shedding looks ideal

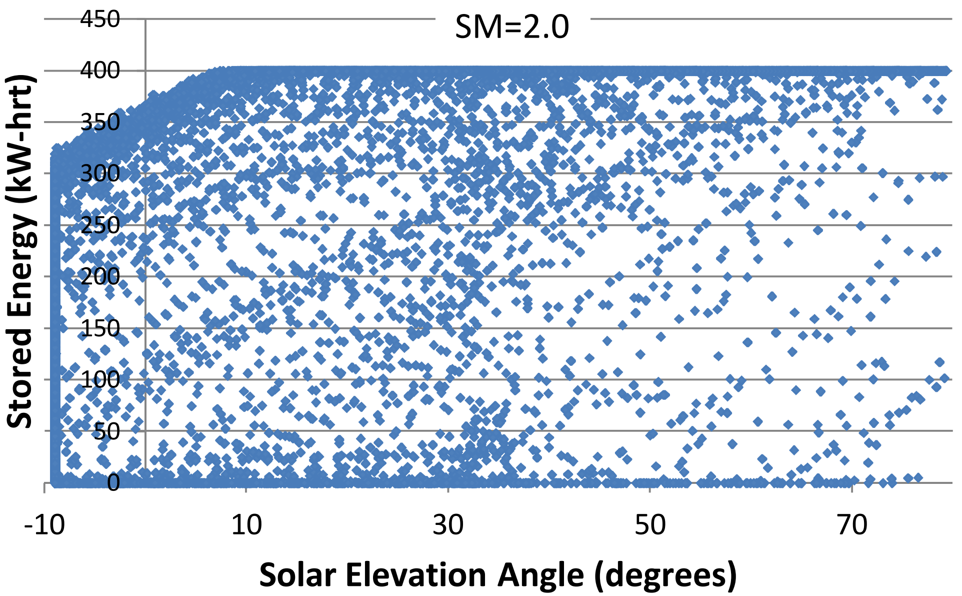




Results: Evening Generation

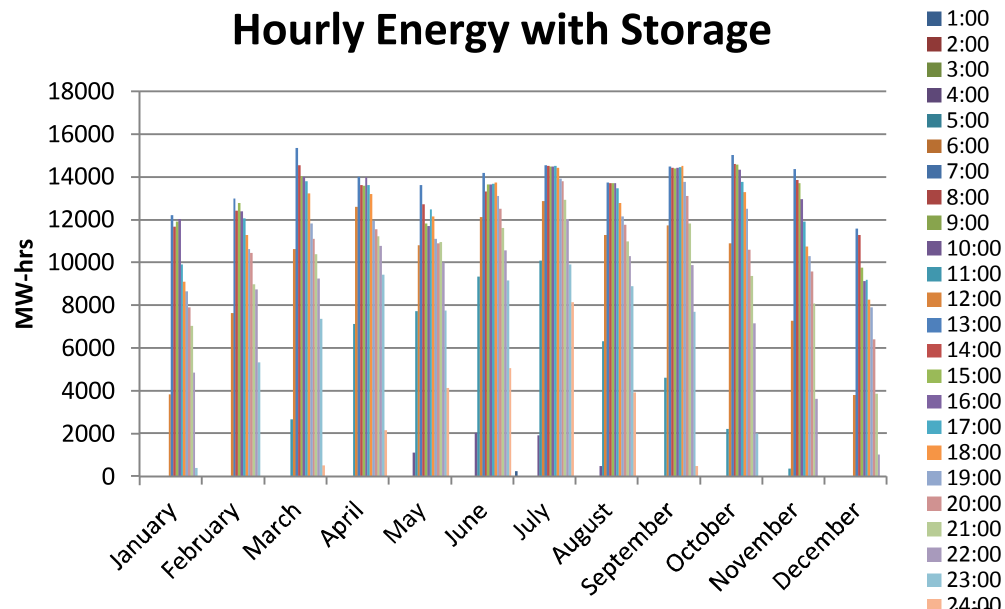
- Extraction from storage begins around 8-10 degrees sun elevation
- Even high SM does not guarantee evening generation
- Majority of days have full storage with 1.25 SM
- SM 2.0 shedding is obvious
- Even with storage, "baseload" is not reached, but predictability is enhanced

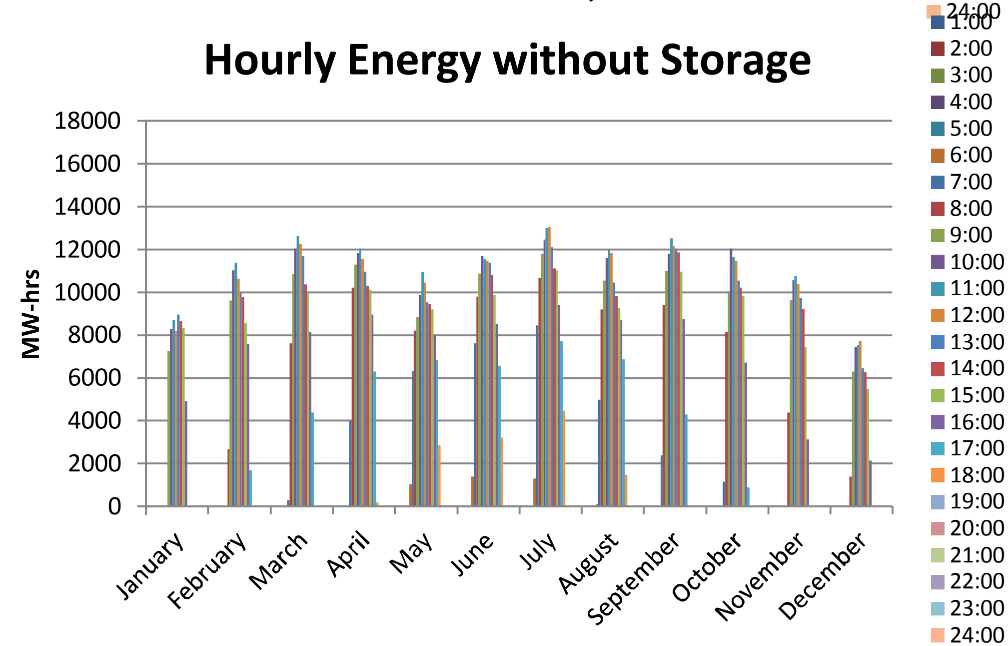




TOD Results

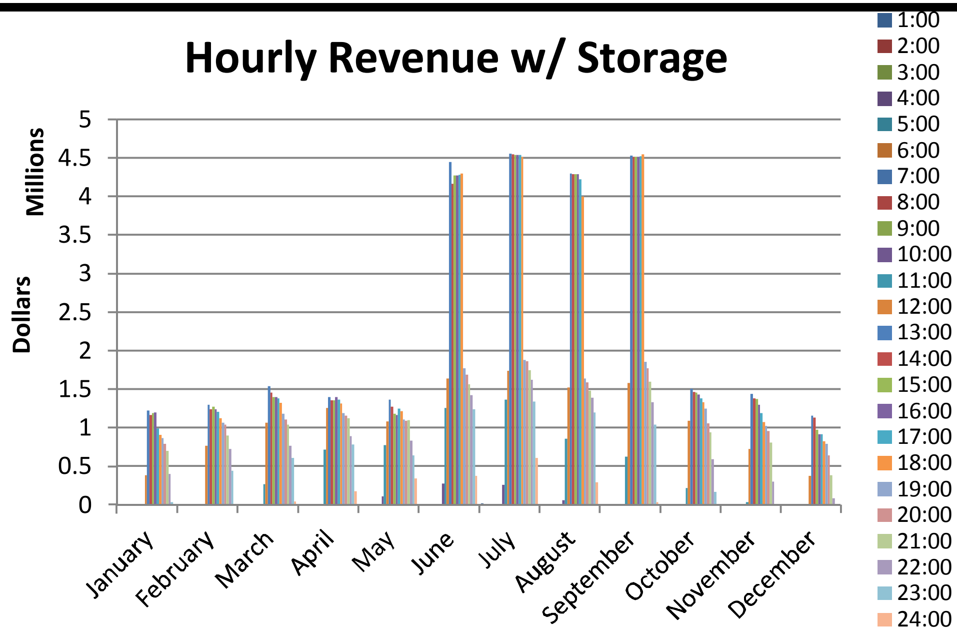
- Storage shows a substantial shift into evening hours
  - Generation to midnight hour in summer
  - Non-storage stops in 6pm hour at best
- Total energy generated increased
  - Due to SM and performance

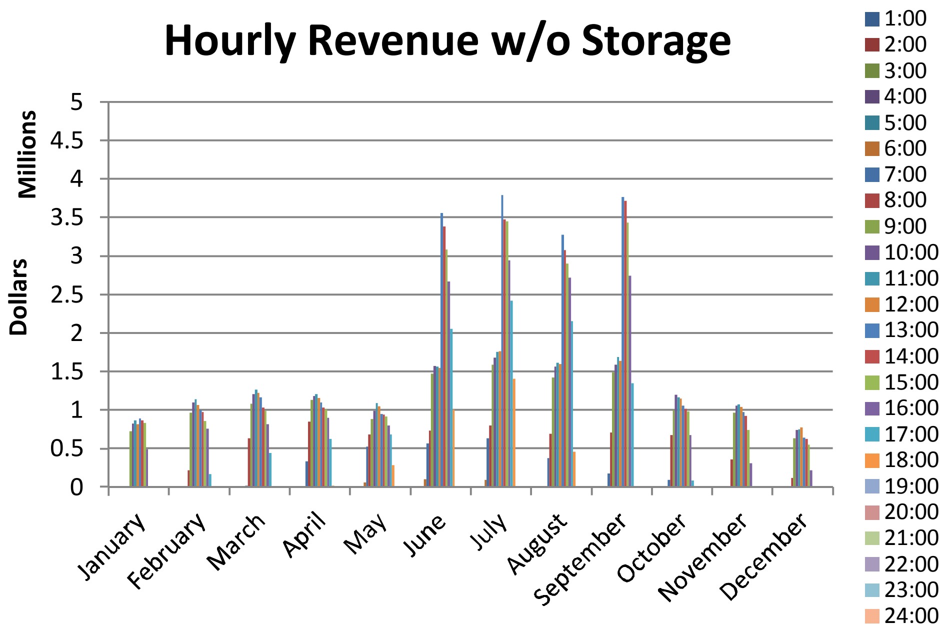




TOD Revenue

- Storage takes full advantage of summer afternoon revenue
  - Critical to plant financial success
  - Evening hours are better than morning





Cost of Storage Results

Case	LCOE ($/kWh)	Profit ($/kWh)	Cost ($k/dish)	Cost ($/kWh$_{th}$)
No Storage	0.086	0.056	0	0
Base	0.076	0.072	21	52
Level LCOE	0.086	0.062	33	82
Level Profit	0.092	0.056	40	99
SunShot	0.06	--	6.5	16

- Storage system improves LCOE and profit
- Base case storage has higher cost than SunShot goals
  - SunShot component cost goals are specific to configuration (tower)
  - Rough guess as to cost of a system
- Dish system can afford relatively expensive storage
  - High performance cycle
  - Different cost balance

System Model Summary

- Storage can improve system LCOE and profit
  - Receiver and engine performance improved
  - Engine always runs at design
  - Full utilization of summer afternoon bonus
  - Amortization of system costs over more energy
- Storage costs can be far greater than SunShot tower goals
- Solar multiple of 1.25 is optimal for cases studied
- Duration of storage depends on TOD pricing, but 6 hours appears acceptable
- Cloudy days are not overcome by storage
- Design and control strategies must take into account profit
  - TOD pricing
  - Capacity payments or penalties
  - Transmission requirements

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Exergy Analysis

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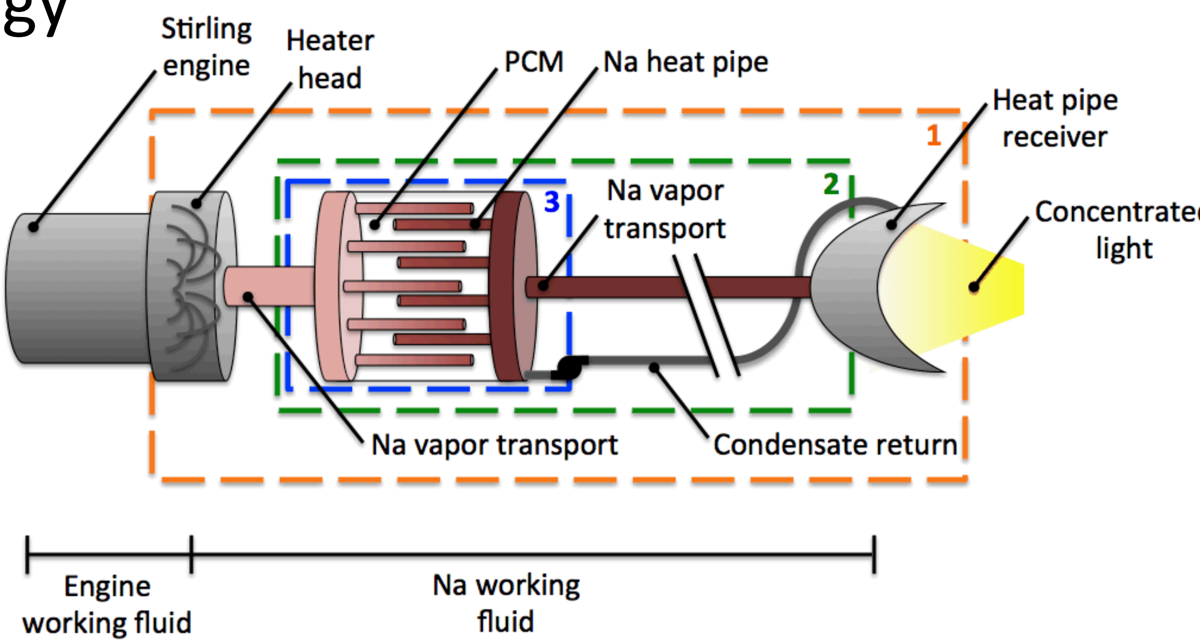
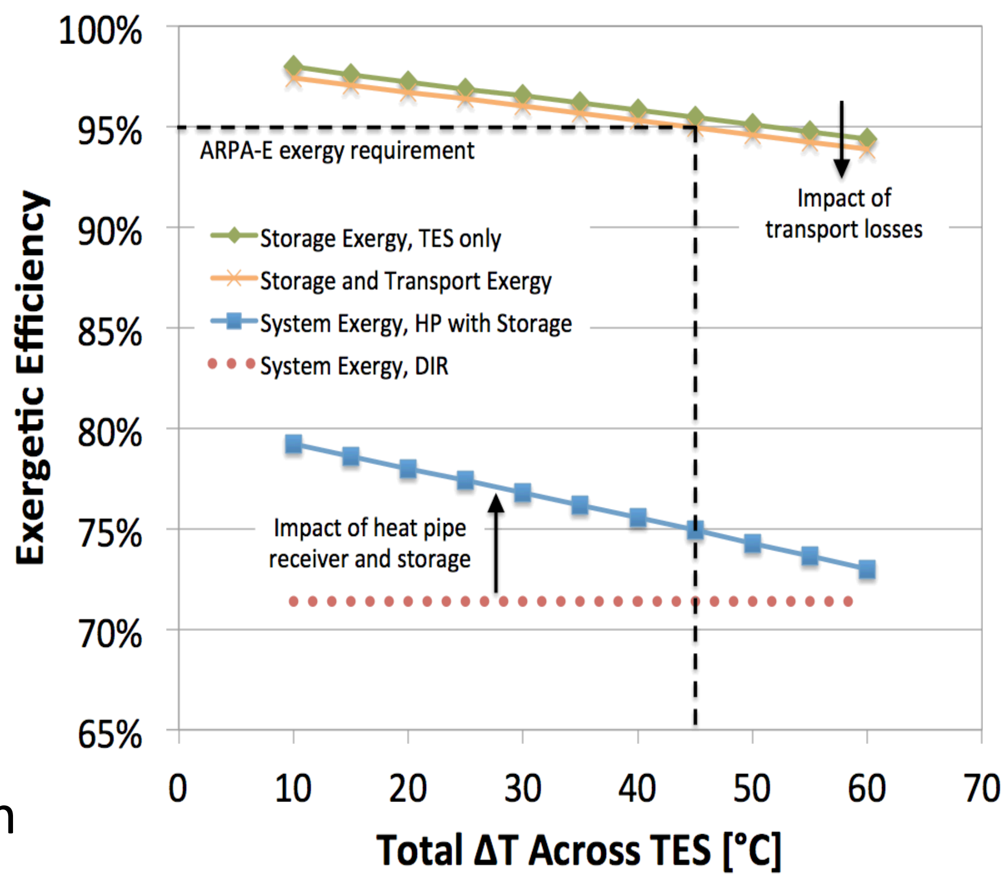
- Multiple control volumes considered
  - Storage device only
  - Storage and transport
  - Entire thermal system
- Goal of 95% exergy efficiency for “storage”
- Evaluate system exergy impact



Exergy Results

- 95% Exergy Storage *and* transport
  - 45°C across TES
  - High performance latent transport has minimal ΔT
- System exergy
  - Substantial improvement with storage
  - Seen in system performance
  - Reflects fist and second law improvements of receiver
  - Reflects improved input to engine
- Net exergy improvement with storage!
  - Marked difference from sensible heat systems



Feasibility Conclusions

- It appears a 6-hour dish storage system is technically feasible
- Significant performance and value benefits are derived from storage
- A Sandia felt wick receiver should have sufficient capability for SM=1.25
- A metallic PCM has clear advantages, but must be proven
- The dish structure can take significant advantage of rebalancing

Key Development Needs

- Demonstrate durability and performance of a suitable solar receiver wick
- PCM selection and data development
- PCM compatibility
- PCM system thermal performance models and tests
- System demonstration of key features
- System modeling of optimization and value guidance

Secondary Development

The following areas are not immediately called out for research, but are significant engineering issues that potential customers must tackle. Any "show stoppers" that crop up from these areas must be considered.

- Engine/Heat Pipe Interface
- Liquid Metal Pump
- Thermal expansion issues
- Freezing and startup
- Ratcheting (thermo-mechanical)
- Management of full storage (shedding)
- Safety
- Dish redesign
- Deployment issues