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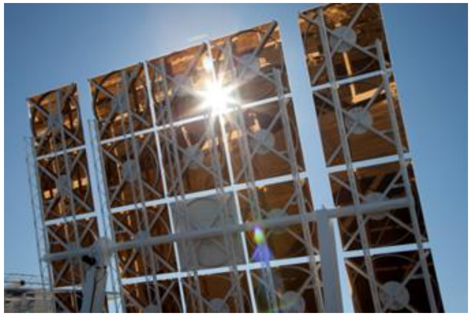

Dish Stirling Advanced Latent Storage Feasibility

Solar PACES 2013
Chuck Andraka
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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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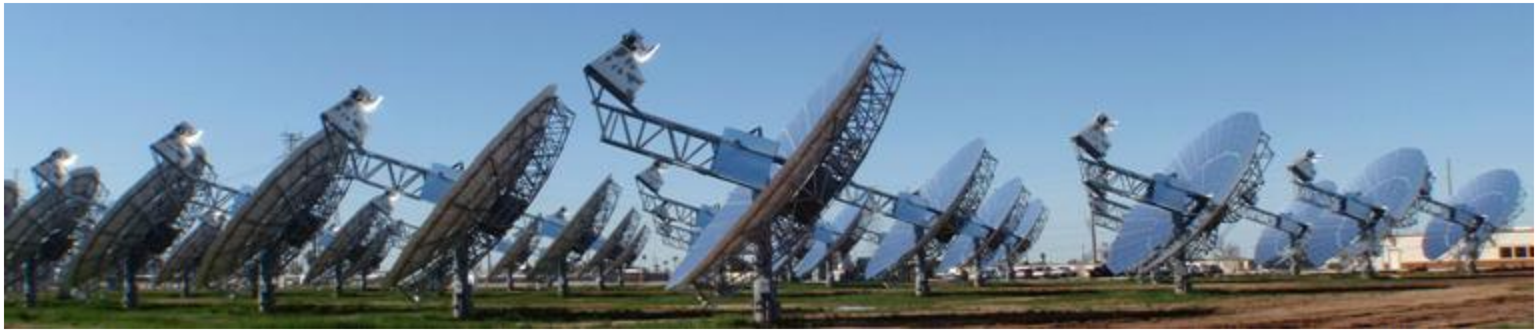
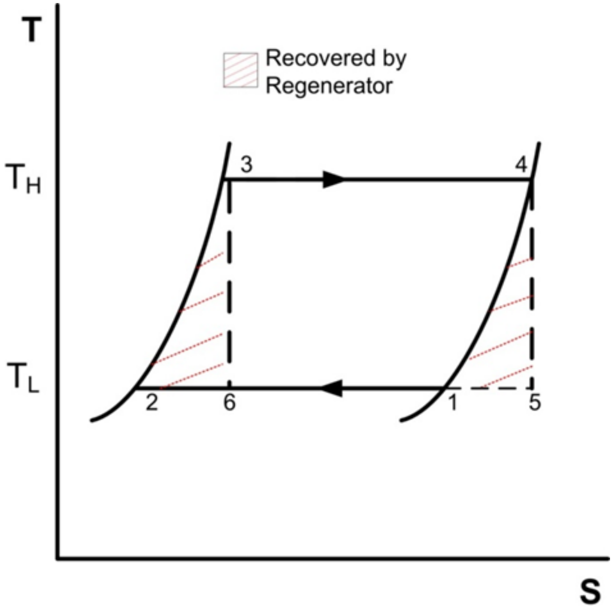
Dish Stirling Technology

- 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



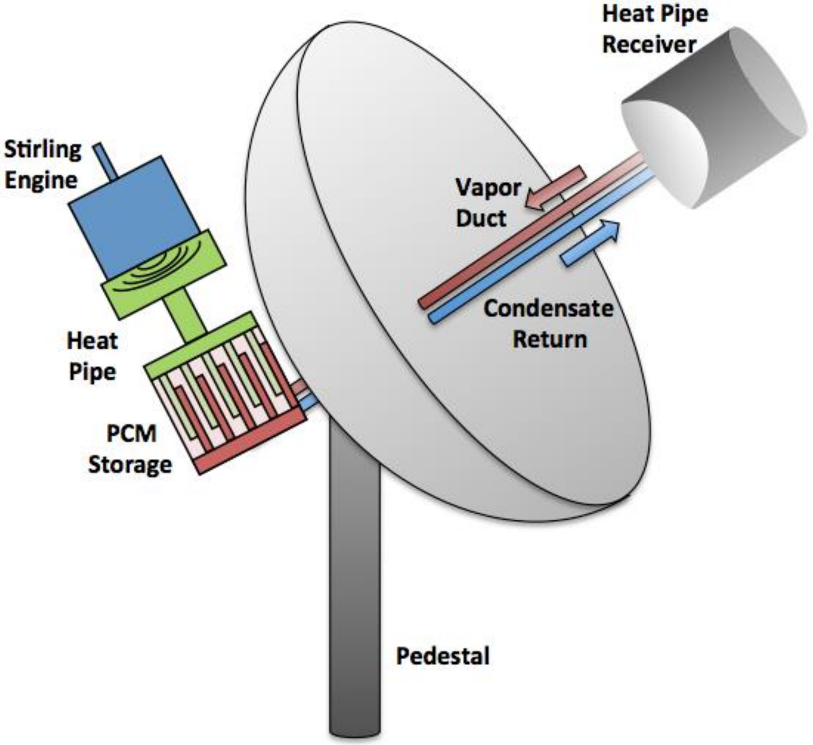
Dish Stirling Technology

- Dish
  - Higher percentage of cost than heliostats
  - High concentration ratio, typically over 3000:1
  - Typically “balanced” design
    - Requires pedestal slot
    - Allows low drive loads
- 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”



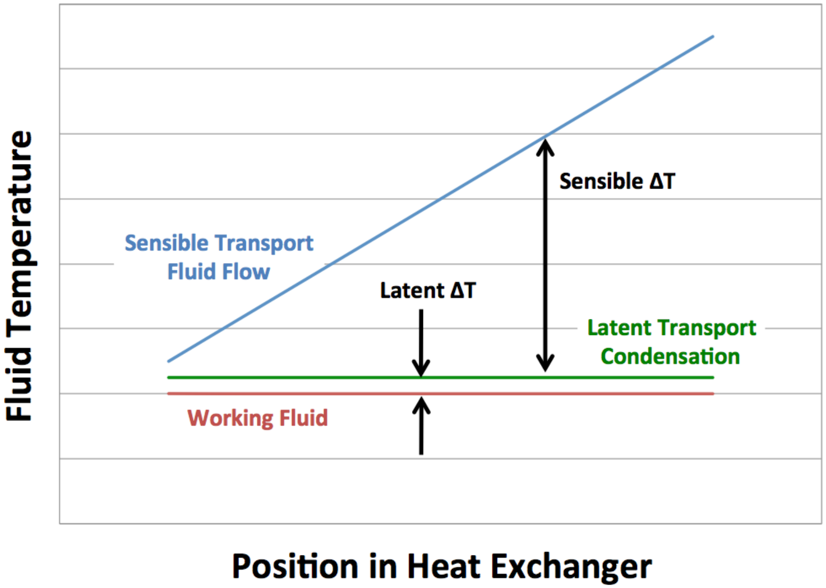
Dish Storage Concept

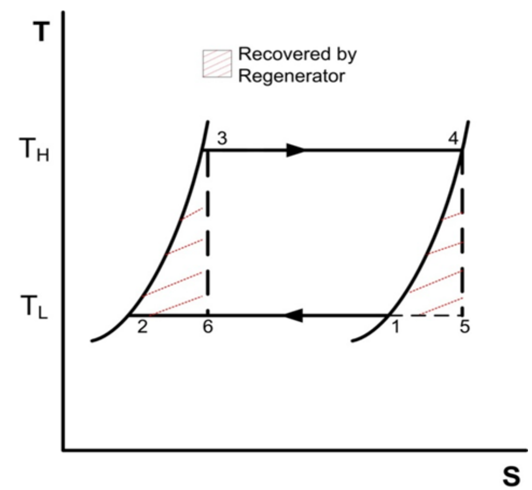
- PCM storage
  - Heat pipe transport to storage and to engine
  - Latent transport and storage ideal for Stirling input
  - Condensate return via pump
- Rear dish mount
  - Rebalances system
  - Allows heavy storage
  - Closes pedestal gap



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% solar-only performance improvement demonstrated
  - Fixed peak temp, increased average temp
  - Dead volume reduction
  - Improved receiver absorption
  - First and second law improvements over DIR



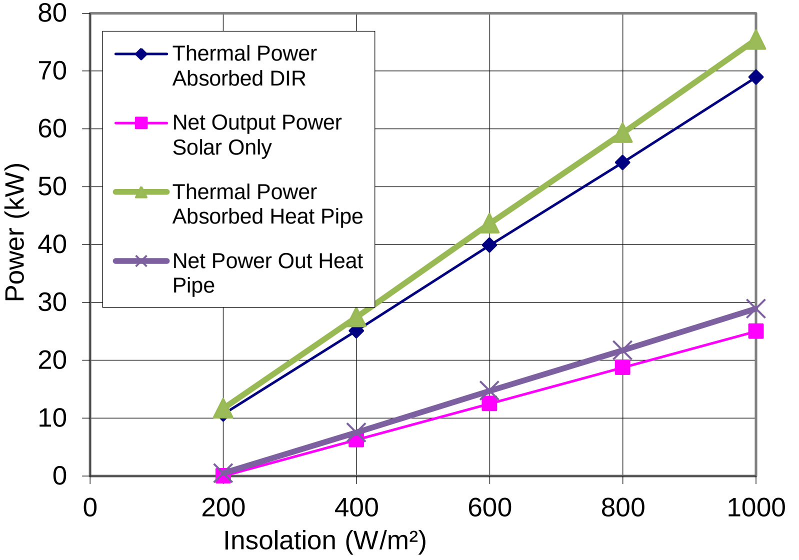


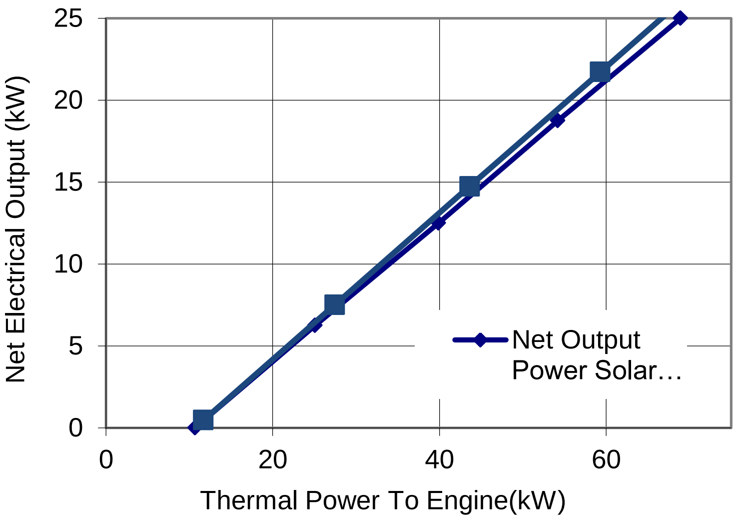
Systems Study Overview

- 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

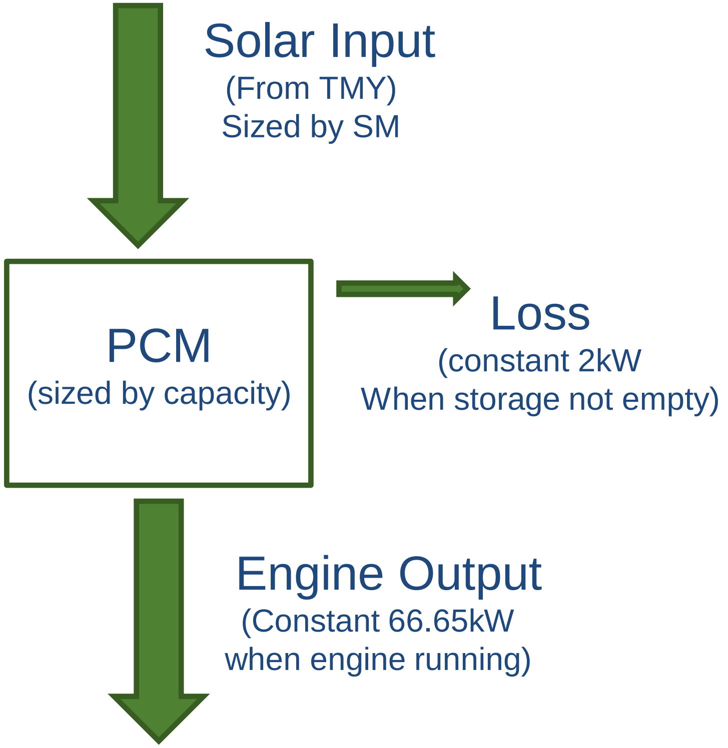
- Barstow 1977 Solergy 15-minute weather data
  - Calculate thermal input at each interval
- Separate thermal and engine performance
  - Actual system performance data
  - Modeled optical and receiver performance
  - Residual is engine performance
- Performance changes
  - Receiver 85% to 93% (measured)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





Storage Model

- 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)



Financial Model

- 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

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

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

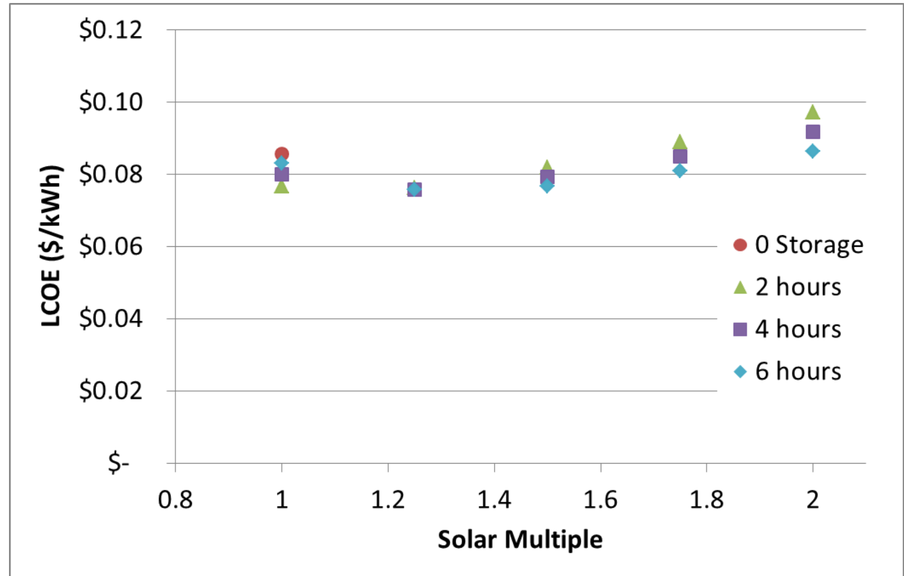
Capital Cost with Storage

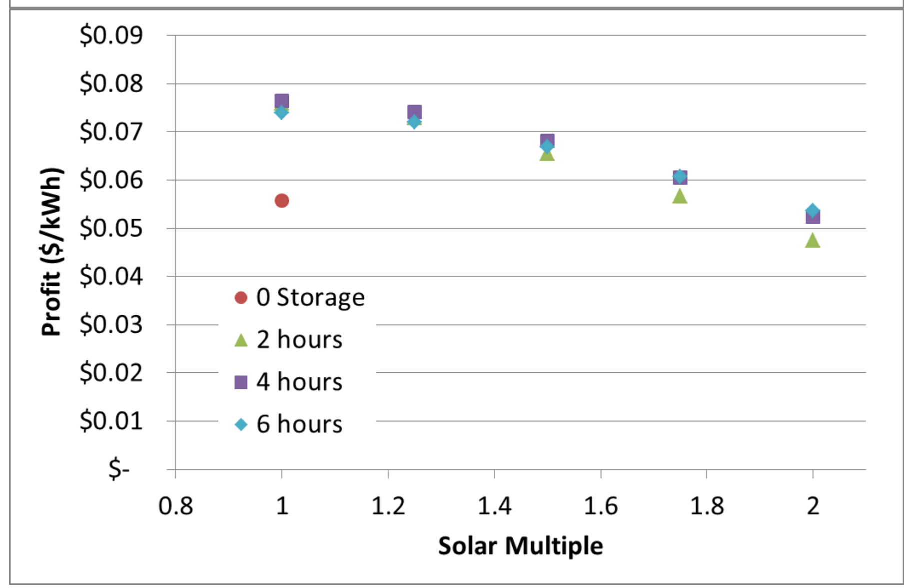
$$CCWS = \frac{(SFC + SVC * SC)}{RPPD} + CC * (1 - SF + SF * SM^{1.5})$$

- 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

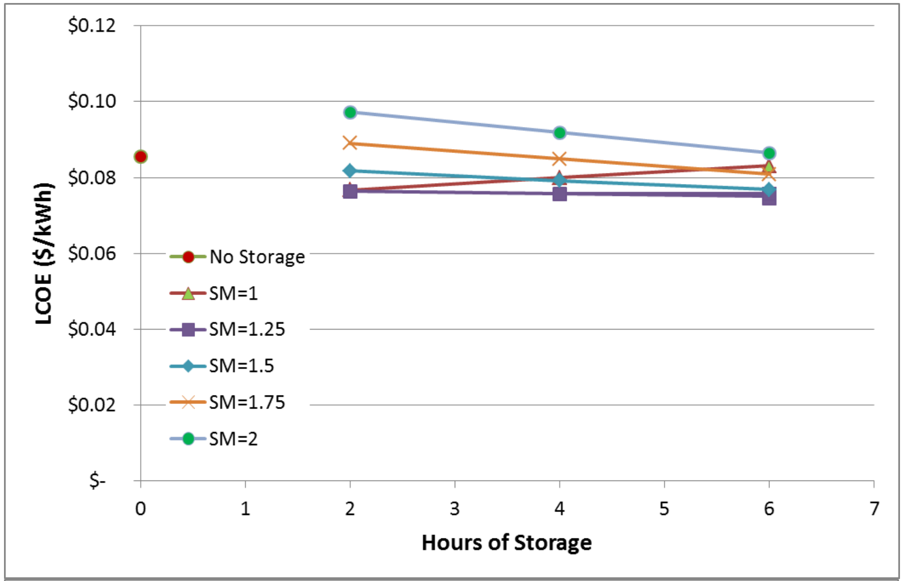
- Clear minimum in LCOE
  - Regardless of storage size
  - 1.25
  - Reasonable from heat pipe standpoint
  - Higher SM has more shedding
  - Shallow slope with higher capacity
  - Small net impact on LCOE
- Large impact on profit
  - Shift morning generation to high value in summer
  - Full generation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

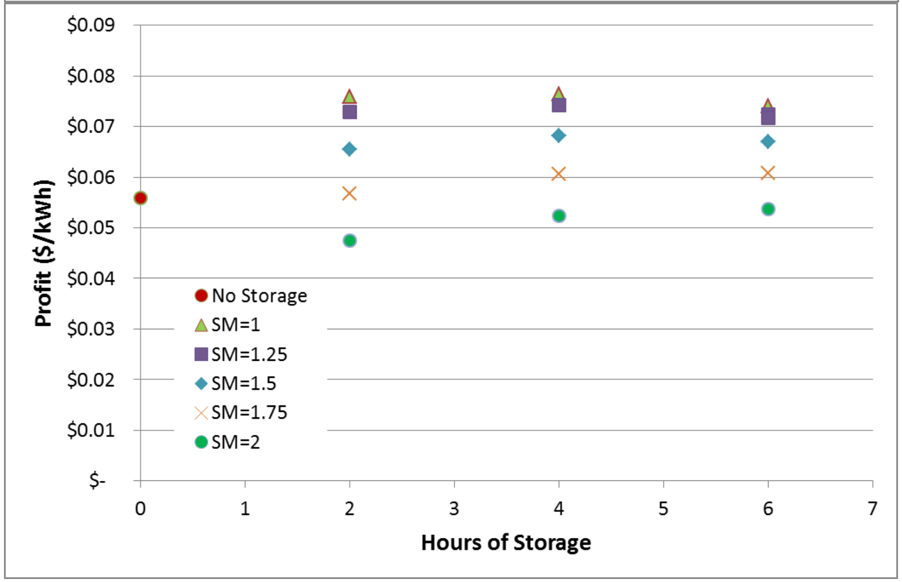




Results: Storage Capacity

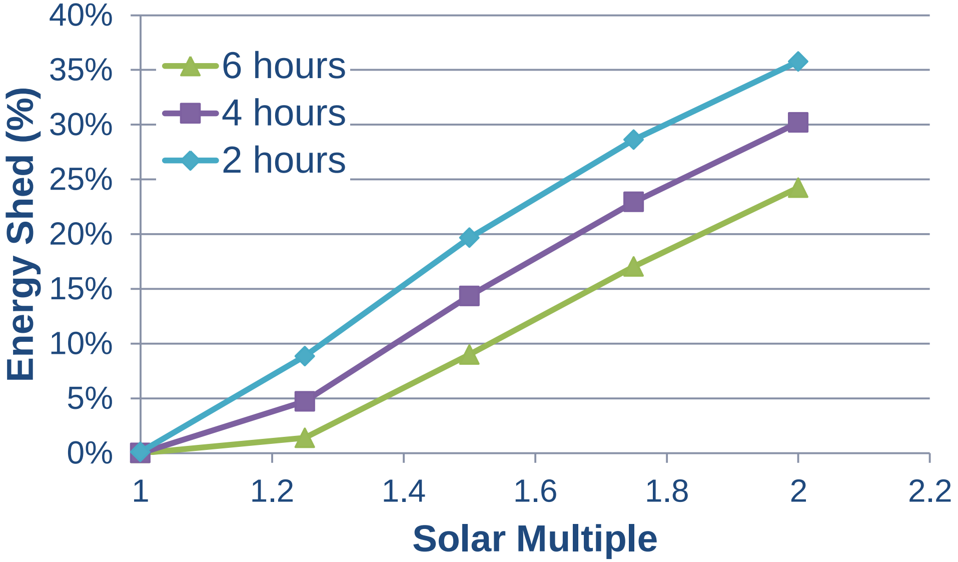
- LCOE and Profit are rather flat for given SM
- Slight peak in profit at 4-6 hours storage

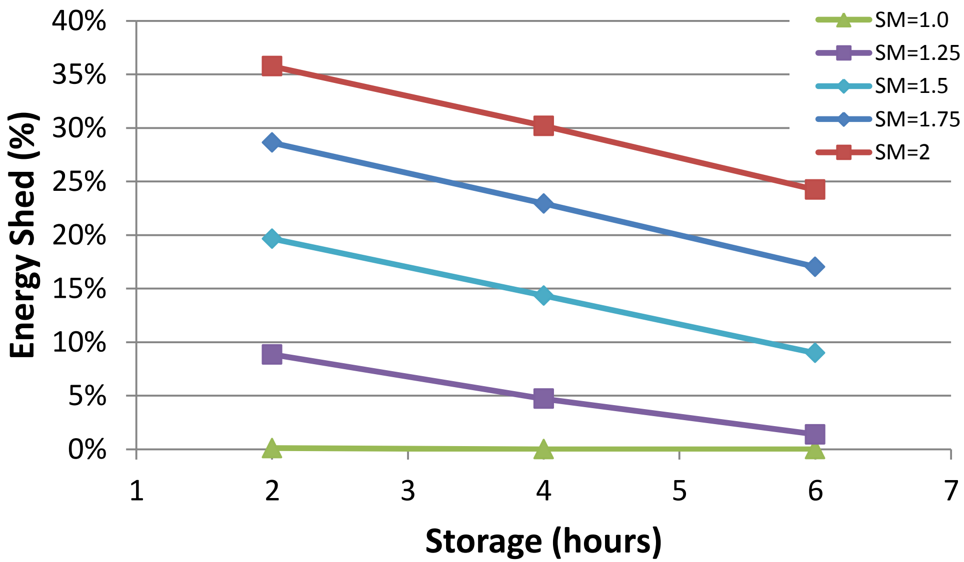




Results: Shedding

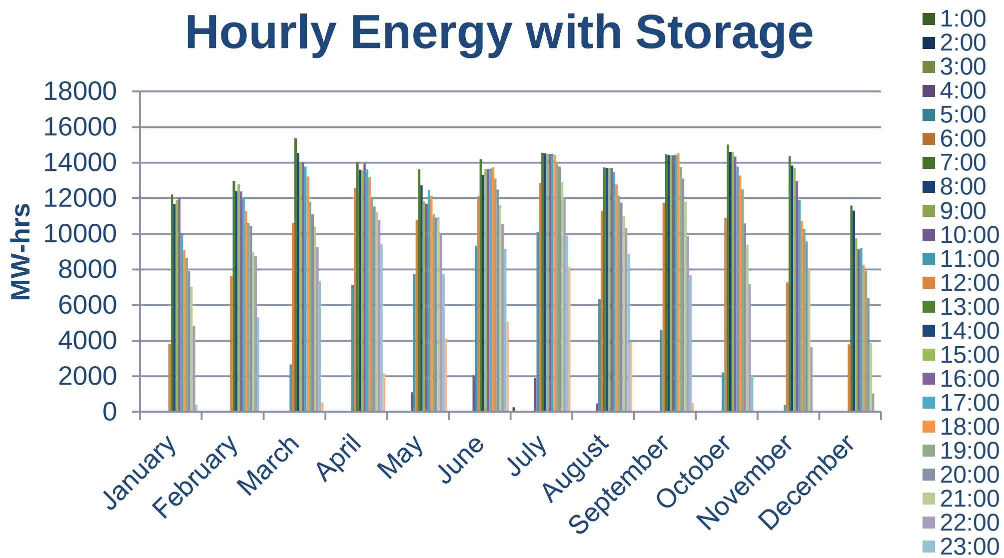
- Trends are as expected
  - More shedding as SM increases
  - Less shedding with more storage
- Some shedding desirable
  - No shedding: Ineffective use of storage capacity
  - Much shedding: Ineffective use of collector area
  - Based on finances, 2-5% shedding looks ideal

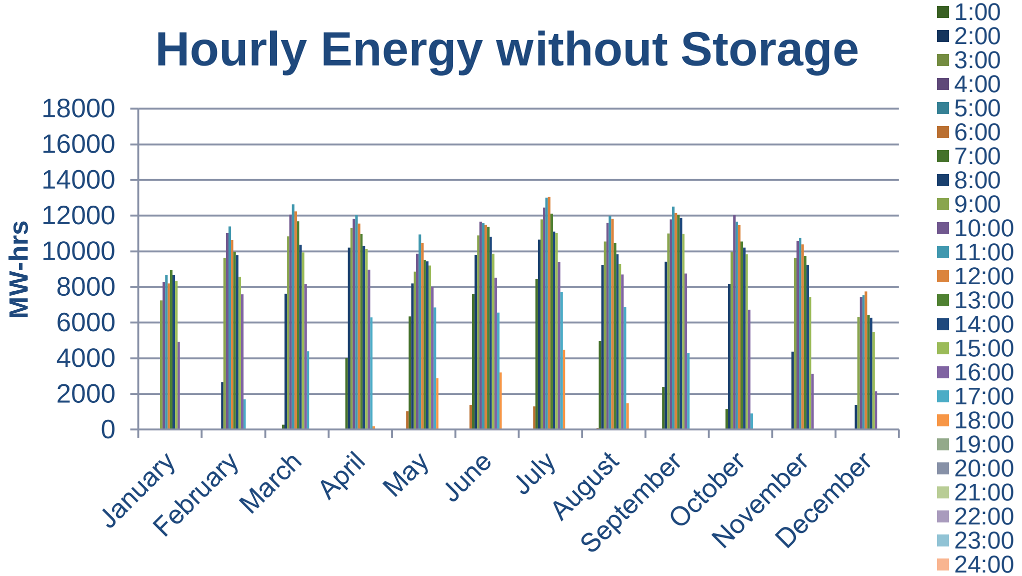




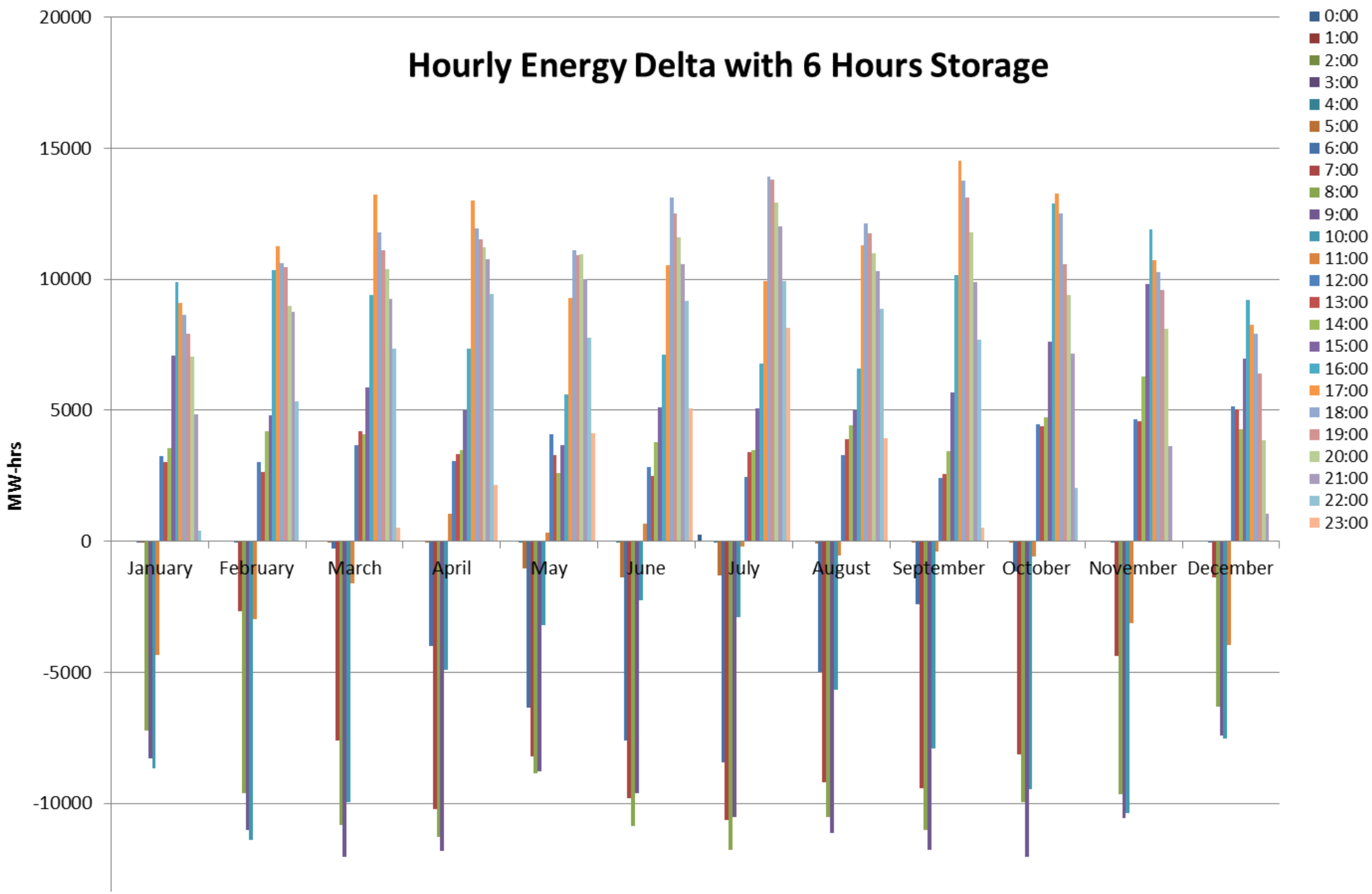
TOD Results

- 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





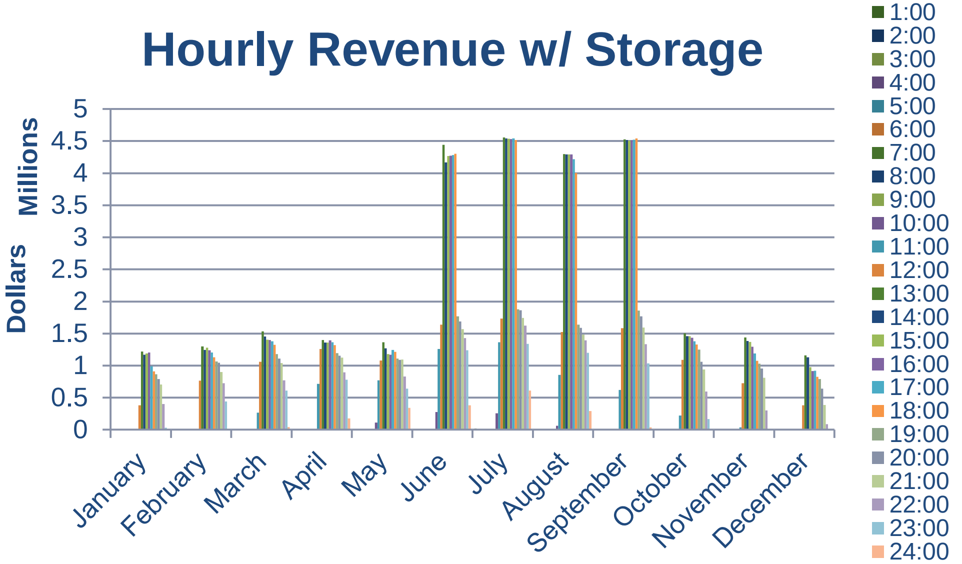
TOD Results

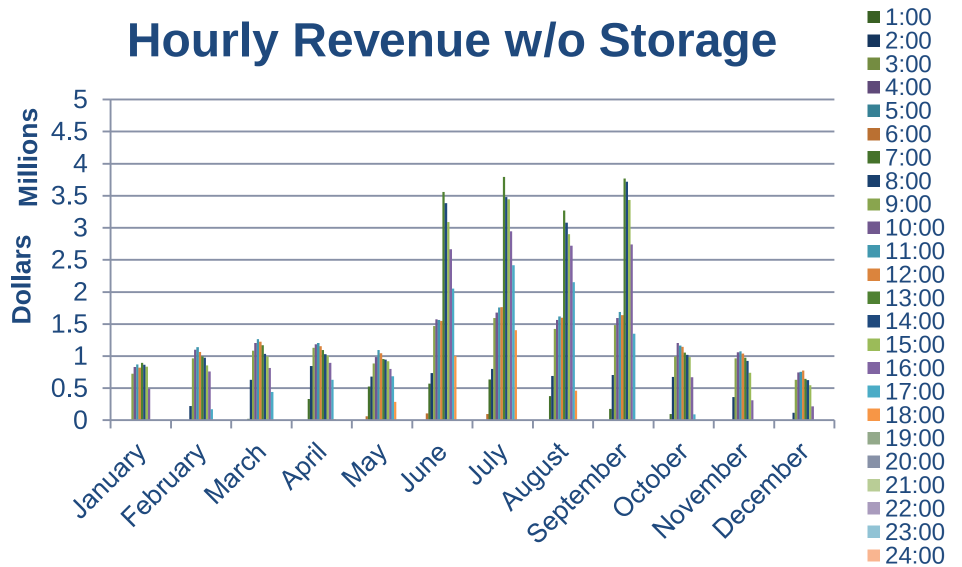


Hourly Energy Delta with 6 Hours Storage
MW-hrs
20000
15000
10000
5000
0
-5000
-10000
January
February
March
April
May
June
July
August
September
October
November
December
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00

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-based 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

PCM Selection

Criterion	Implications
Melting Point	Needs to match Stirling cycle. Ideally between 750 °C and 800 °C.
Heat of Fusion	Equal to the gravimetric density, determines the mass of the storage media needed to meet the storage requirements. Implications of system support structure and system balance.
Volumetric Storage Density	Gravimetric storage density times the mass density of the material. This impacts the size of the storage media, and therefore the quantity of containment material as well as the thermal losses by conduction.
Thermal Conductivity	Low conductivity leads to higher temperature drops on charge and discharge, impacting exergetic efficiency. Can be mitigated with a higher density of heat pipe condensers and evaporators, but at a system monetary cost.
Material Compatibility	The PCM must have compatibility at temperature with reasonable containment materials over long periods.
Stability	The PCM must not break down over time at temperature. This includes major changes such as separation of components and changes in composition, as well as minor issues such as outgassing and changes in melting point.
Coefficient of Thermal Expansion	This can impact the design of the containment and may require volumetric accommodation of size changes with temperature.
Phase Change Volumetric Expansion	This can lead to voids, increasing thermal resistance through the solid phase, and can potentially cause damage to the heat pipe tubes.
Vapor pressure	Related to stability, a high vapor pressure can lead to containment issues and/or higher cost for containment.
Cost	The cost of the PCM directly impacts the LCOE of the system.

PCM Candidates

PCM	Melting Point (°C)	Mass(kg for 6 hr)	Vol (m^3 for 6 hr)	Conductivity (solid, W/mK)
NaCl	801	2980	1.1	1.59
H755	755	3090	1.0	0.589
Cu-0.30Si	803	7309	1.3	300[a]
Si-0.35Cu-0.28Mg	750-770	3402	1.75	200[a]
Mg - 0.38Si - 0.06Zn	800	4585	-	100[a]

- Over 30 PCM's considered in literature search
- Metallics heavily favored due to conductivity
- Thermophysical properties is limited for some materials
  - Conductivity
  - Melting point of eutectics
- Promising candidates identified

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

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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

Conclusions

- Dish storage can be economically feasible
  - Allowable cost of storage considerably higher than tower case
- Storage operational parameters must be optimized
  - Financial drivers
  - Operational requirements
- Metallic PCM's result in feasible embodiments
- Development must focus on materials issues
  - PCM
  - Compatibility
  - High performance heat pipe wick