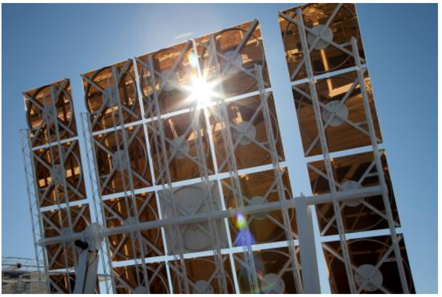

Evaluation of Avian Solar-Flux Hazards and Mitigation Measures at the Ivanpah Concentrating Solar Power Plant

Clifford K. Ho,[1] Timothy Wendelin,[2] Luke Horstman[1], and Cianan Sims[3]

[1]Sandia National Laboratories
[2]National Renewable Energy Laboratory
[3]Sims Industries

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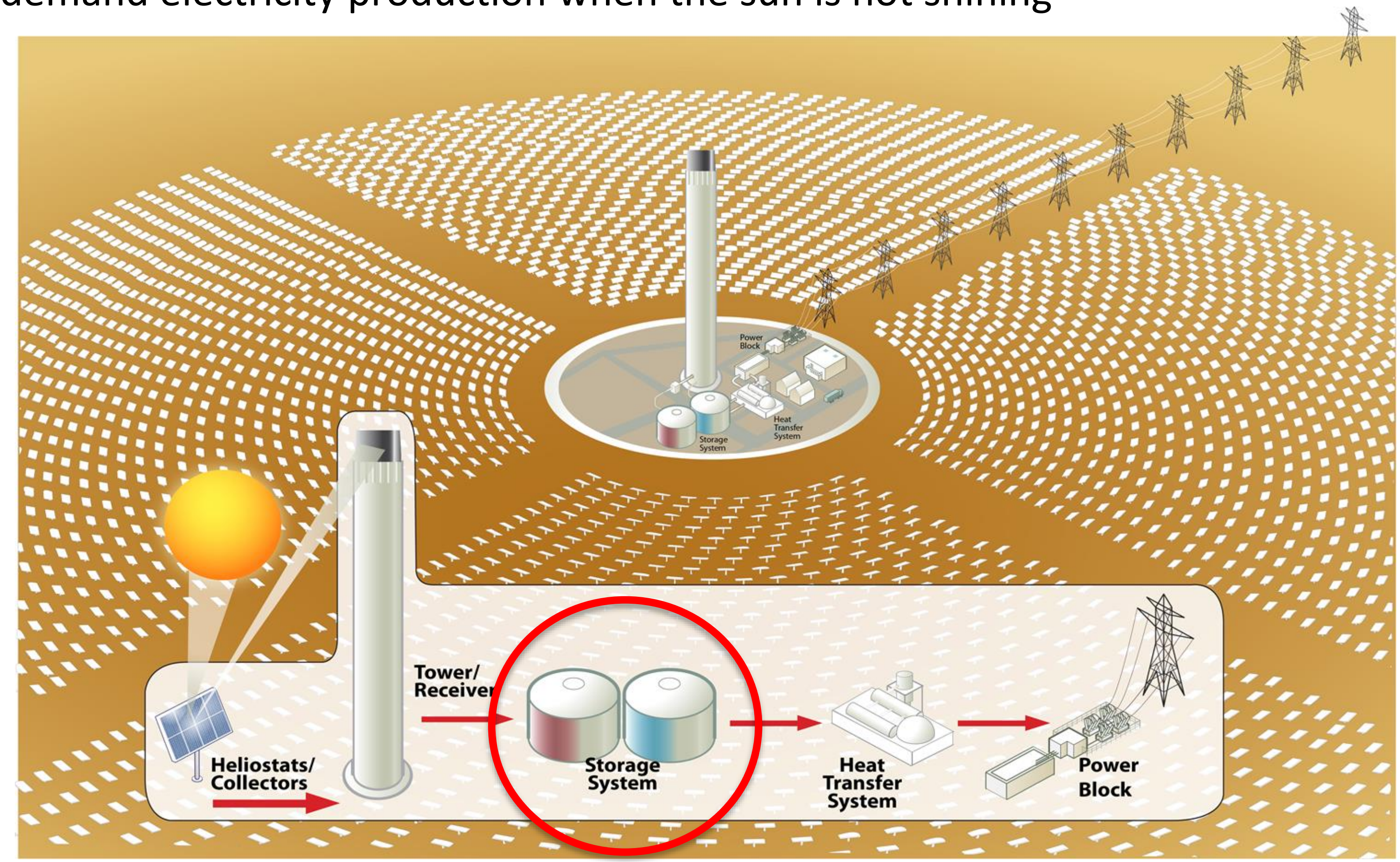
Overview

- Background and Objectives
- Avian Hazard Metrics and Models
- Results
- Conclusions

Concentrating Solar Power

- Concentrating solar power uses mirrors to concentrate the sun's energy onto a receiver to provide heat to spin a turbine/generator to produce electricity
- Hot fluid can be stored as thermal energy efficiently and inexpensively for on-demand electricity production when the sun is not shining



Problem Statement

- Reports of birds being singed and killed by concentrated solar flux at CSP plants
  - Kagan et al. (2014)
  - Kraemer (2015)
  - Clarke (2015)
- Flux hazards attributed to heliostat standby aiming strategies
  - McCrary et al. 1984, 1986 (Solar One)

MacGillivray Warbler with "Grade 3" solar flux injury found at Ivanpah CSP Plant (Kagan et al., 2014)

Bird Deterrents

- Acoustic
  - Painful or predatory sounds
- Visual
  - Intense lights and decoys
- Tactile
  - Bird spikes, anti-perching devices
- Chemosensory
  - Grape-flavored powder drinks (methyl anthranilate)

- Ivanpah has implemented deterrents, but impact is uncertain

Objectives

- Develop metrics and models to assess avian solar-flux hazards
  - Identify important model parameters
- Evaluate alternative heliostat standby aiming strategies
- Identify aiming strategies that reduce hazardous avian exposures and minimize impact to operational performance

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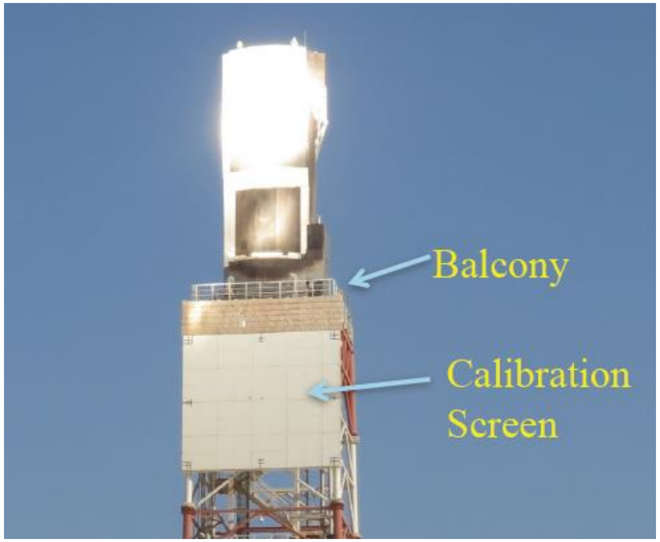
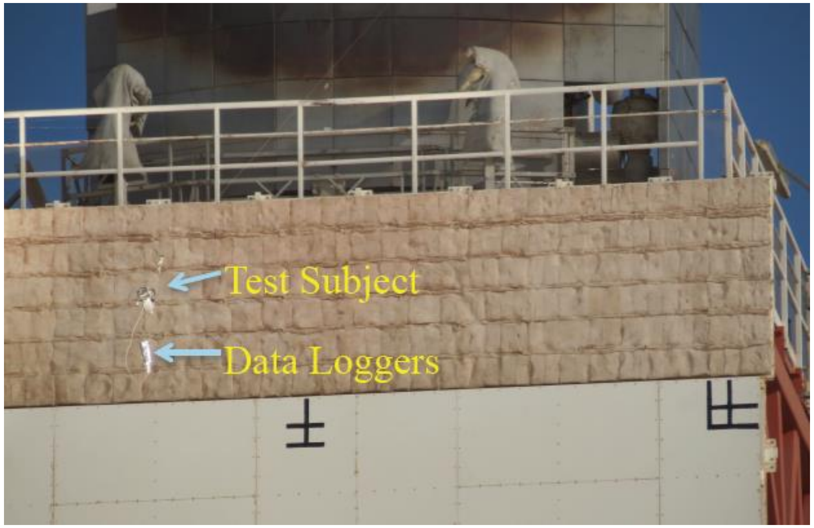
Avian Hazard Metrics – Solar Flux

- Tests conducted with bird carcasses exposed to different flux levels (Santolo, 2012)
  - "no observable effects on feathers or tissue were found in test birds where solar flux was below 50 kW/m^2 with exposure times of up to 30 seconds."
  - California Energy Commission analytical study found that "a threshold of safe exposure does not exist above a solar flux density of 4 kW/m^2 for a one-minute exposure"

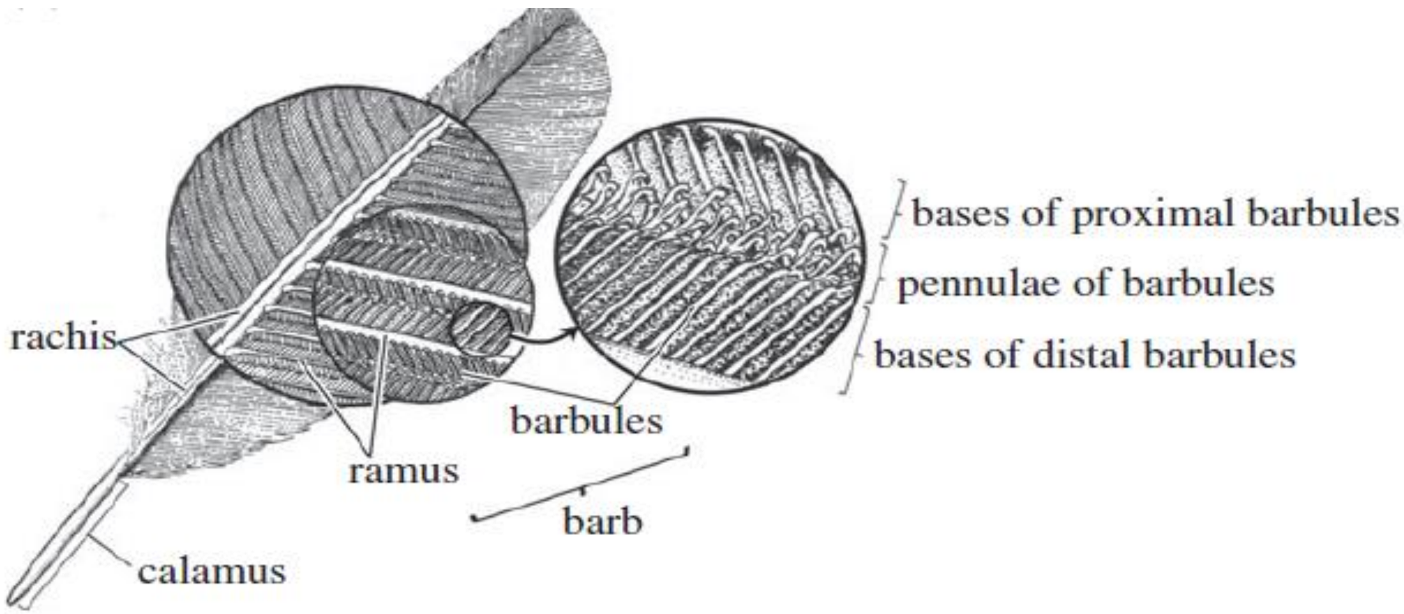




Avian Hazard Metrics -

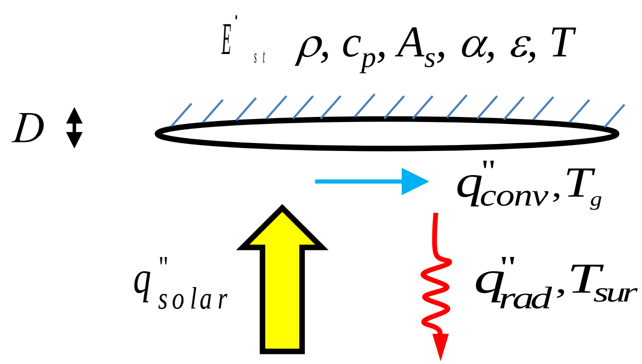
Bird Feather Temperature

- Feather structure can be permanently weakened at~160 ˚C
  - Bonds in the keratin structure are broken (Senoz et al., 2012; CEC Tyler et al., 2012)



Modeling Approach

1. Develop heat transfer model of bird feather temperature as a function of irradiance and convective heat loss
2. Develop models of irradiance in airspace above heliostat field for alternative aiming strategies
3. Determine bird feather temperature along flight paths above CSP plant
4. Record total time that bird feather exceeds safe threshold for each aiming strategy



$$T_{i+1} = T_i + \frac{1}{\rho D c_p}\left(\alpha q''_{solar} - h\left(T_i - T_g\right) - \varepsilon\sigma\left(T_i^4 - T_{sur}^4\right)\right)\Delta t$$

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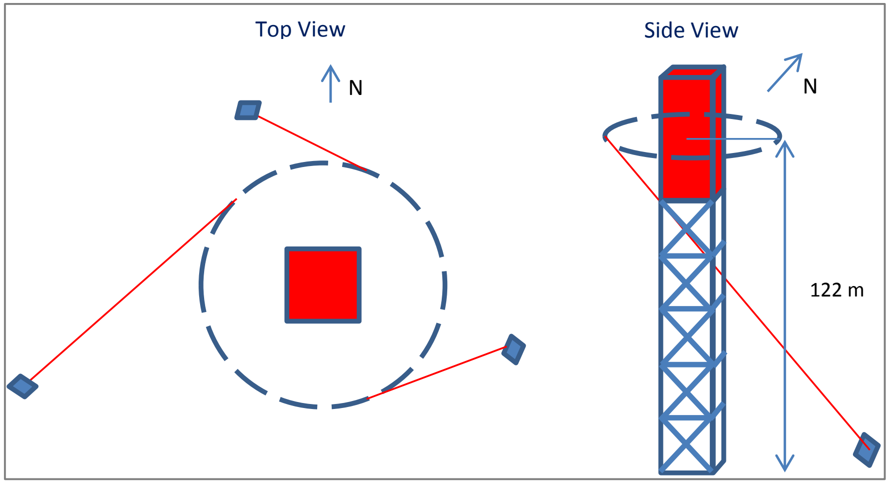

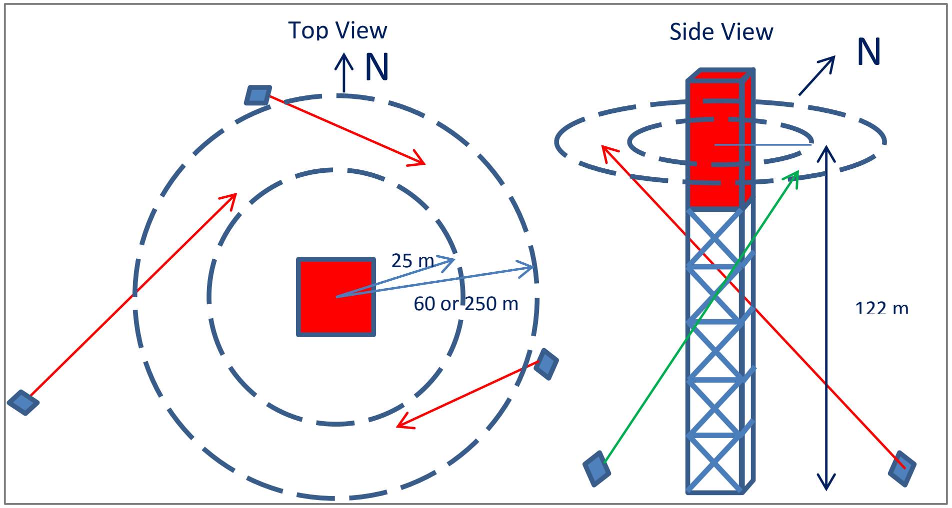

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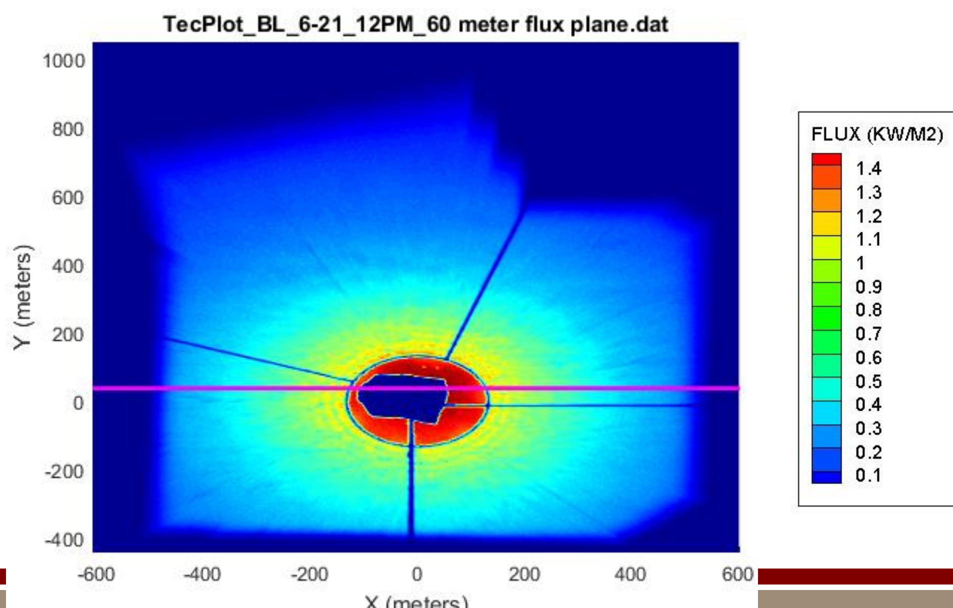

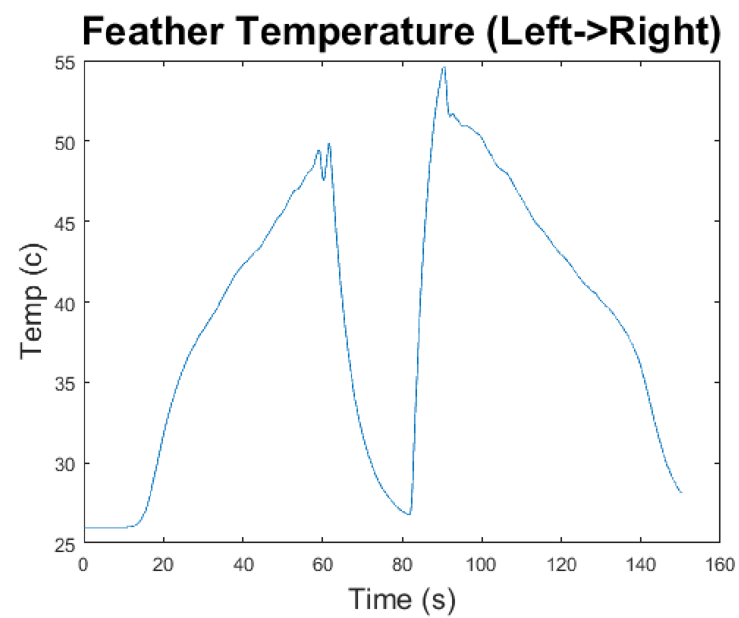

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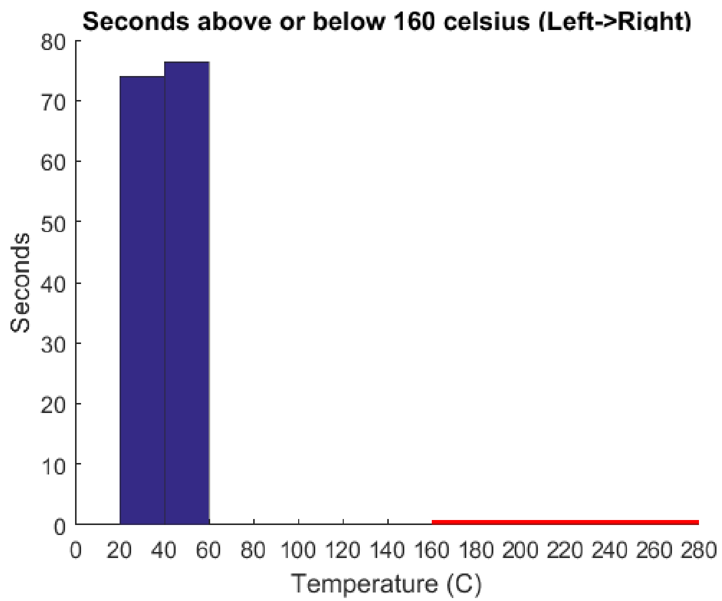

Modeling Approach

- Identify aiming strategies that minimize hazardous exposure time and impact on operational performance
  - Identify heliostat travel (slew) time for each aiming strategy
  - Correlate slew time to energy production using SAM
    - Greater slew times → reduced energy production

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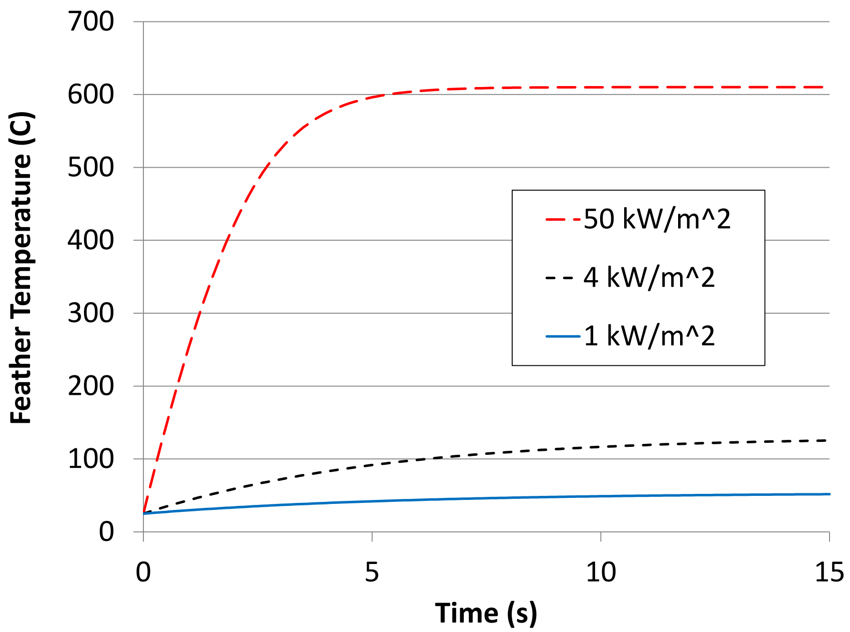
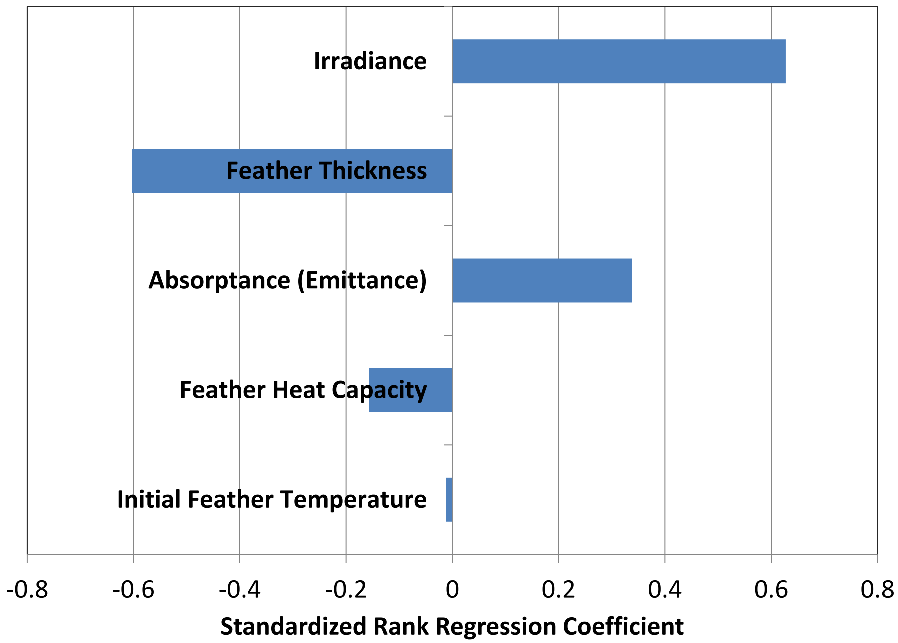
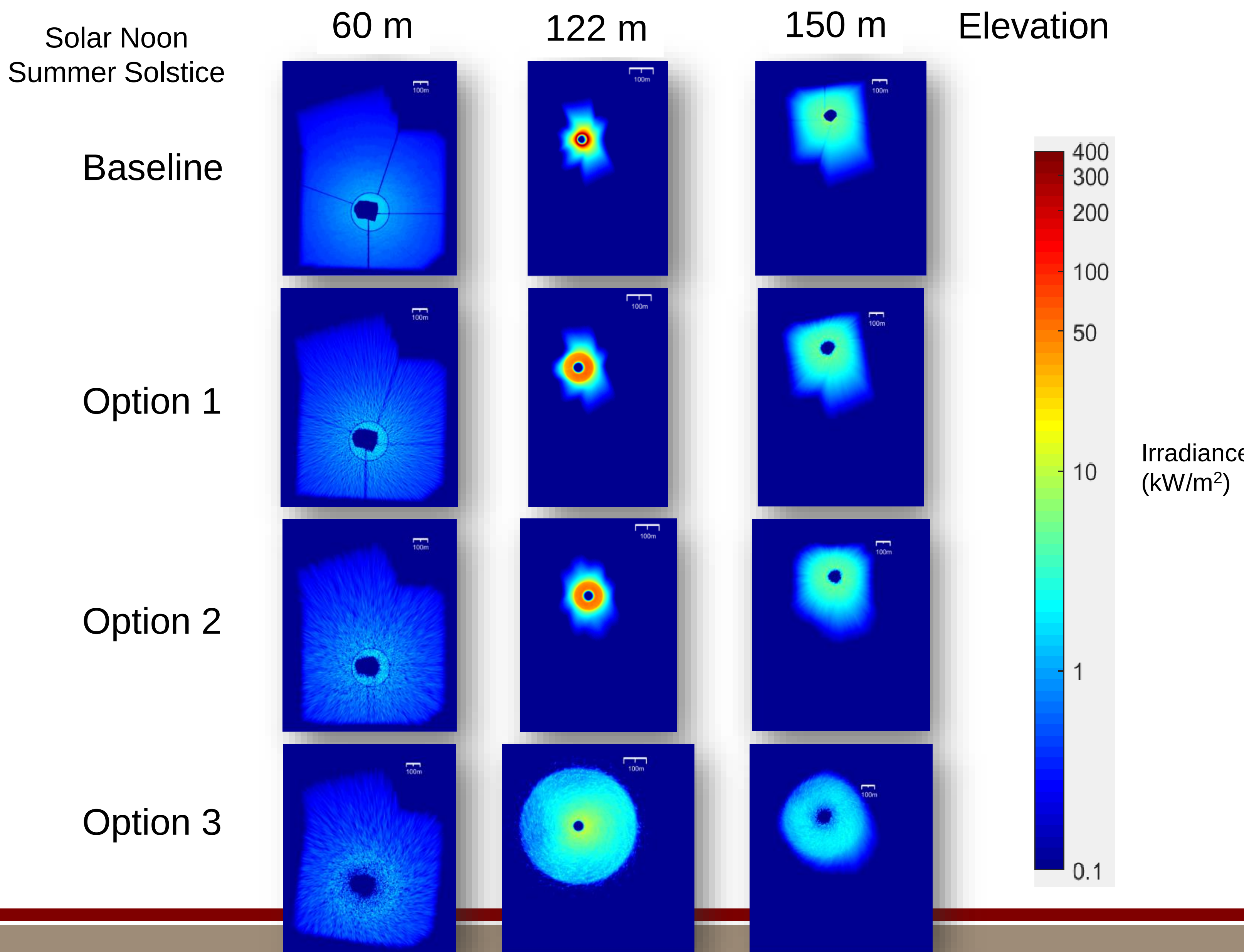
Bird Feather Temperature





Bird feather temperature strongly dependent on irradiance, which varies in the airspace depending on heliostat aiming strategy

Sample Flux Maps (Ivanpah Unit 2)

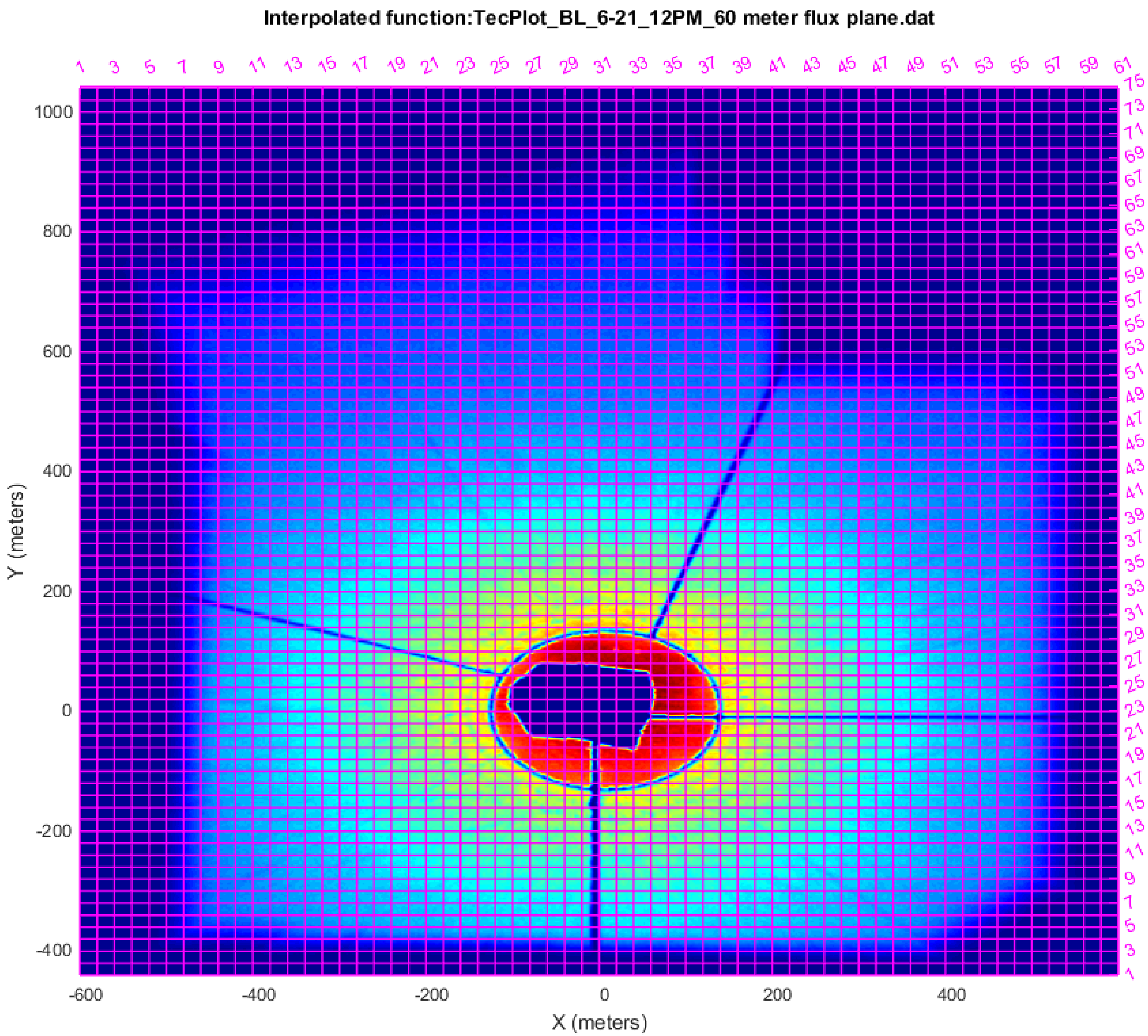


Simulated Bird Flight Paths

Sandia National Laboratories

- Equally spaced grid of flight paths every 20 m
- 12 elevations
  - 80 – 300 m at ~20 m intervals
- 3 dates
  - Winter solstice
  - Summer solstice
  - Equinox
- 2 Times
  - Solar noon
  - 3 hours before solar noon

➢ Analyzed thousands of flight paths for each aiming strategy

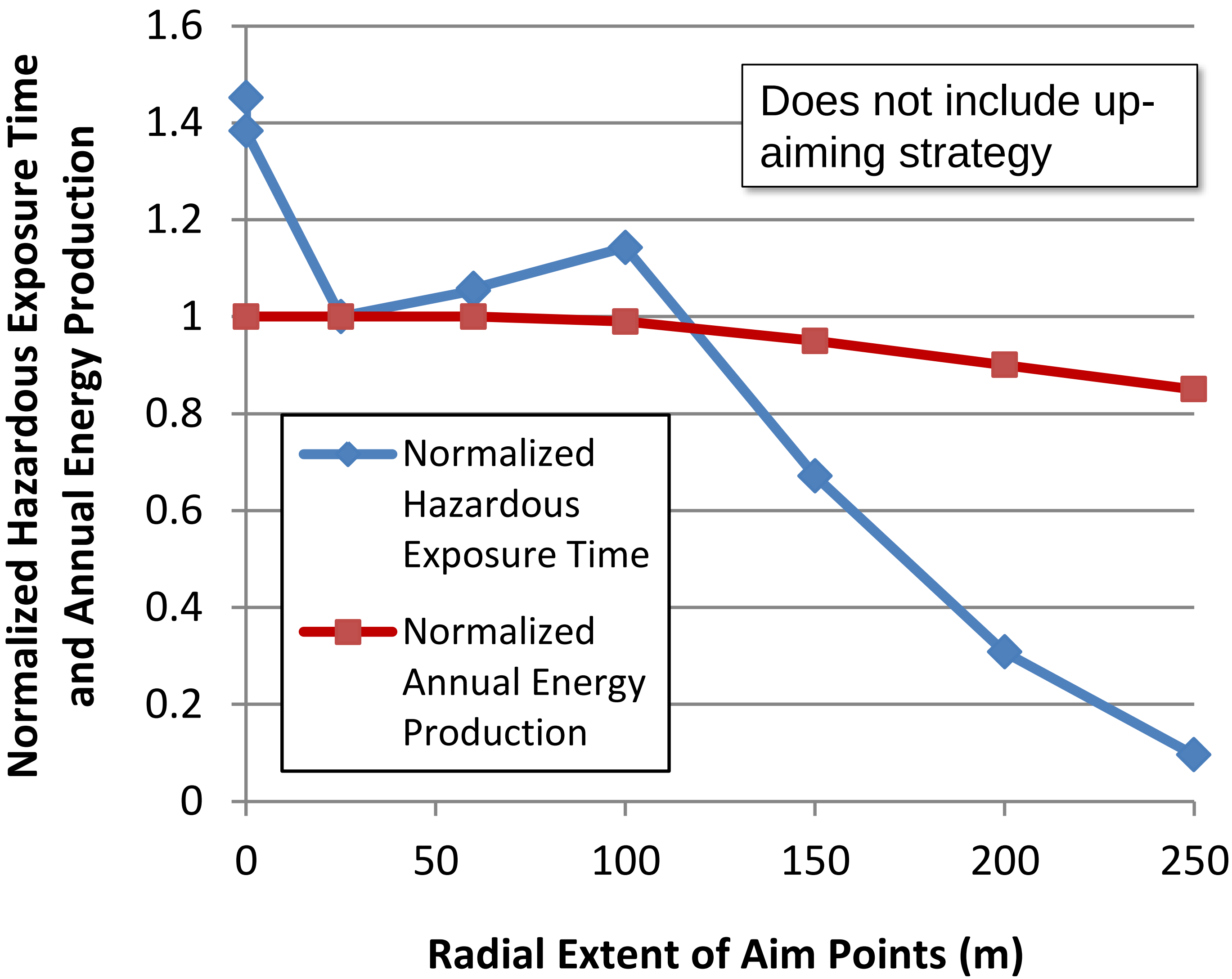


Results

Heliostat Aiming Strategy	Exceedance Time (s) >160 ˚C	Exceedance Time Normalized to Baseline	Annual Energy Normalized to Baseline
Baseline (25 m radius CW)	5689	1	1
Option 1 (25-60 m CW)	5993	1.05	0.98
Option 2* (25-60 m)	6021	1.06	0.98
Option 3* (25-100 m)	6501	1.1	0.95
Option 4* (25-150 m)	3820	0.77	0.90
Option 5* (25-200 m)	1751	0.32	0.85
Option 6* (25-250 m)	543	0.12	0.81
Point Focus (160 m)	8258	1.39	1
Up-Aiming	0	0	0.002

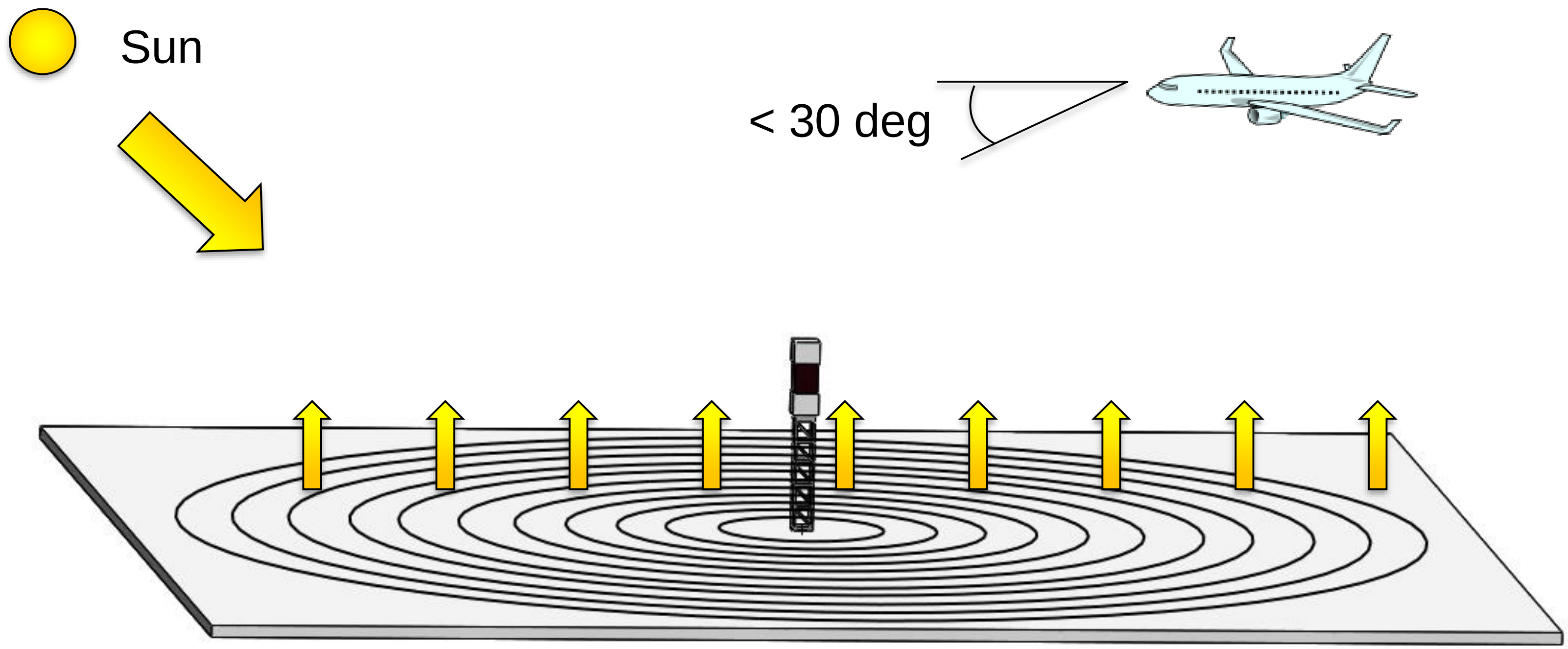
*Standby heliostats aimed in both directions around receiver; CW = clockwise aiming direction around receiver

Results


Normalized Hazardous Exposure Time and Annual Energy Production
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
Radial Extent of Aim Points (m)
Does not include up-aiming strategy
Normalized Hazardous Exposure Time
Normalized Annual Energy Production

Up-Aiming Strategy

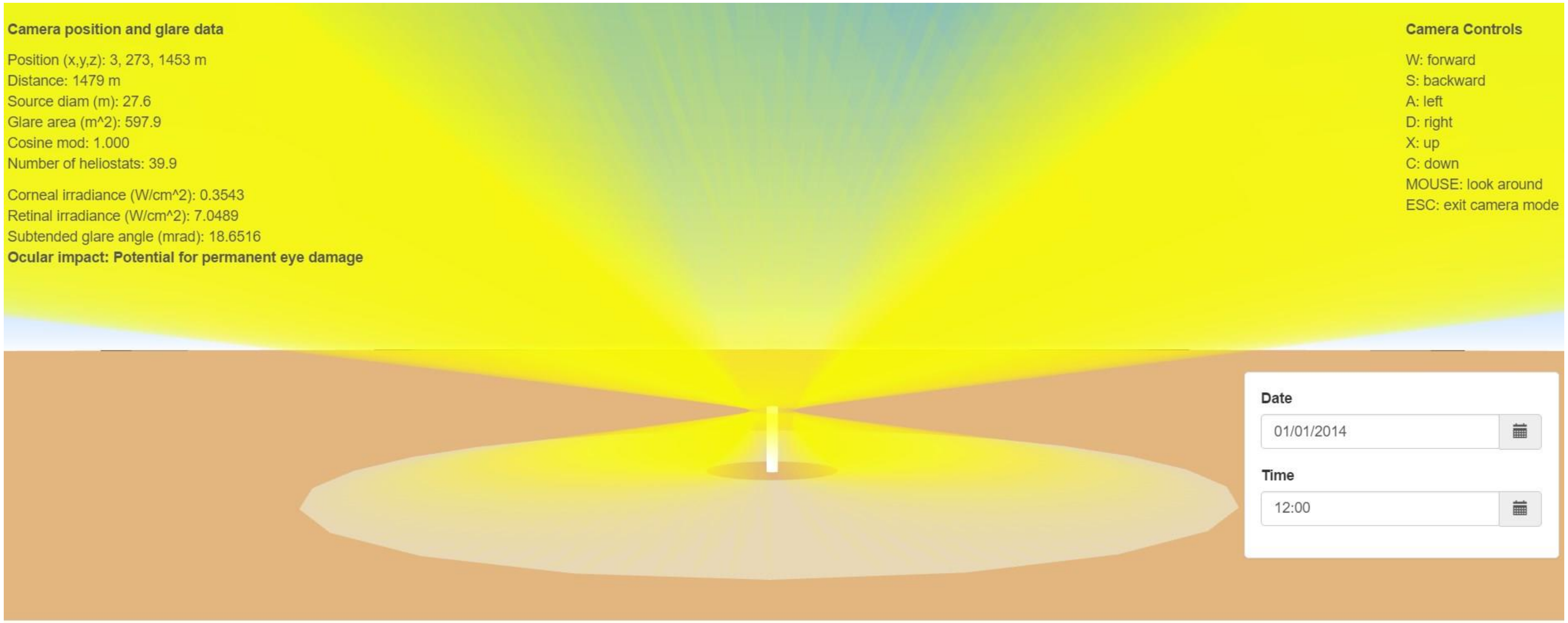
- Up-Aiming can eliminate glare and avian flux hazards, but it increases heliostat travel time to receiver



Tower Illuminance Model (TIM)

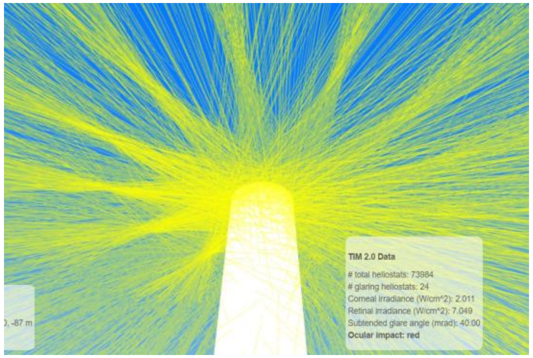
Web-based tool evaluates glare and avian hazards for CSP power tower plants

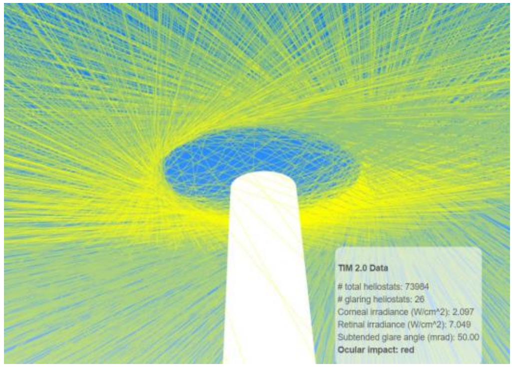
- Considers heliostat aiming strategies; flyover controls
- Location-dependent irradiance with visualization

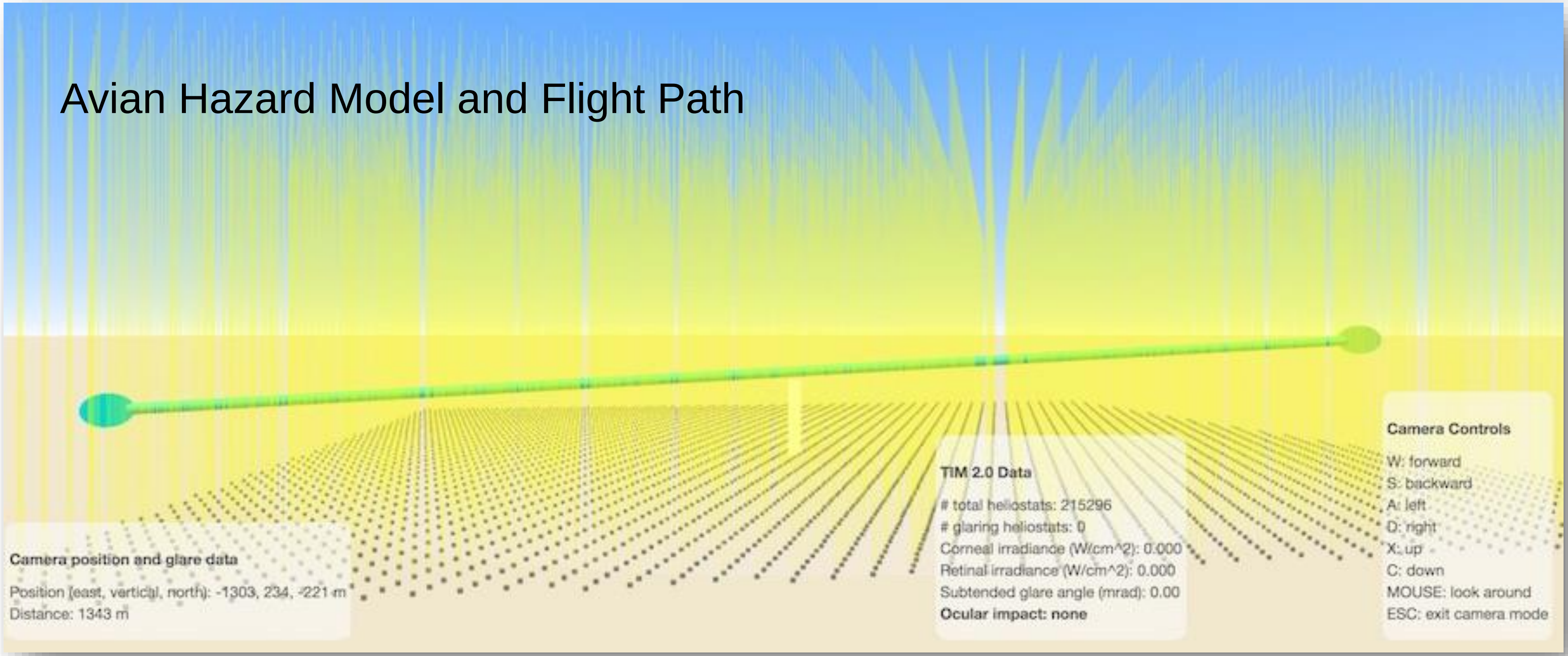


Screen Shots of “TIM”

Alternative heliostat aiming strategies







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Conclusions

- Models and methods developed to evaluate avian flux hazards from heliostat standby aiming strategies
  - Bird feather temperature used as metric
    - Cumulative exceedance time > 160 ˚C
  - Energy balance model of feather to determine temperature as a function of irradiance, wind, and other parameters
  - Irradiance determined by ray-tracing models of alternative heliostat aiming strategies
- Results show spreading aiming points may increase hazardous exposure times (time exceeding 160 ˚C)
  - Also reduces performance
- Need to implement aiming strategy that reduces hazardous exposure time, slew times to target, and glare

Meetings with Industry and Stakeholders

- Introduced our work and objectives at Stakeholder meeting on March 10, 2016
  - CEC, USF&W, DOE, NRG, WEST, SolarReserve, Abengoa, SENER, NREL, SNL
- Presented work to US Fish & Wildlife in Sacramento on Feb. 1, 2017 (part of CSP Gen 3 trip)
- Held meeting with NRG, Brightsource, NREL, and Sandia on May 24, 2017, at Ivanpah
  - Presented summary of glare and avian-flux modeling and impact of alternative aiming strategies
  - Discussed implementation at Ivanpah

Team / Collaborators

- **Sandia**
  - Cliff Ho (PI), Luke Horstman (avian hazard modeling), Julius Yellowhair (optical modeling)
- **NREL**
  - Tim Wendelin (flux modeling, avian hazards)
- **Sims Industries**
  - Cianan Sims (TIM)
- **CSP Industry**
  - NRG/Ivanpah
    - Doug Davis, George Piantka, Tim Sisk, William Dusenbury

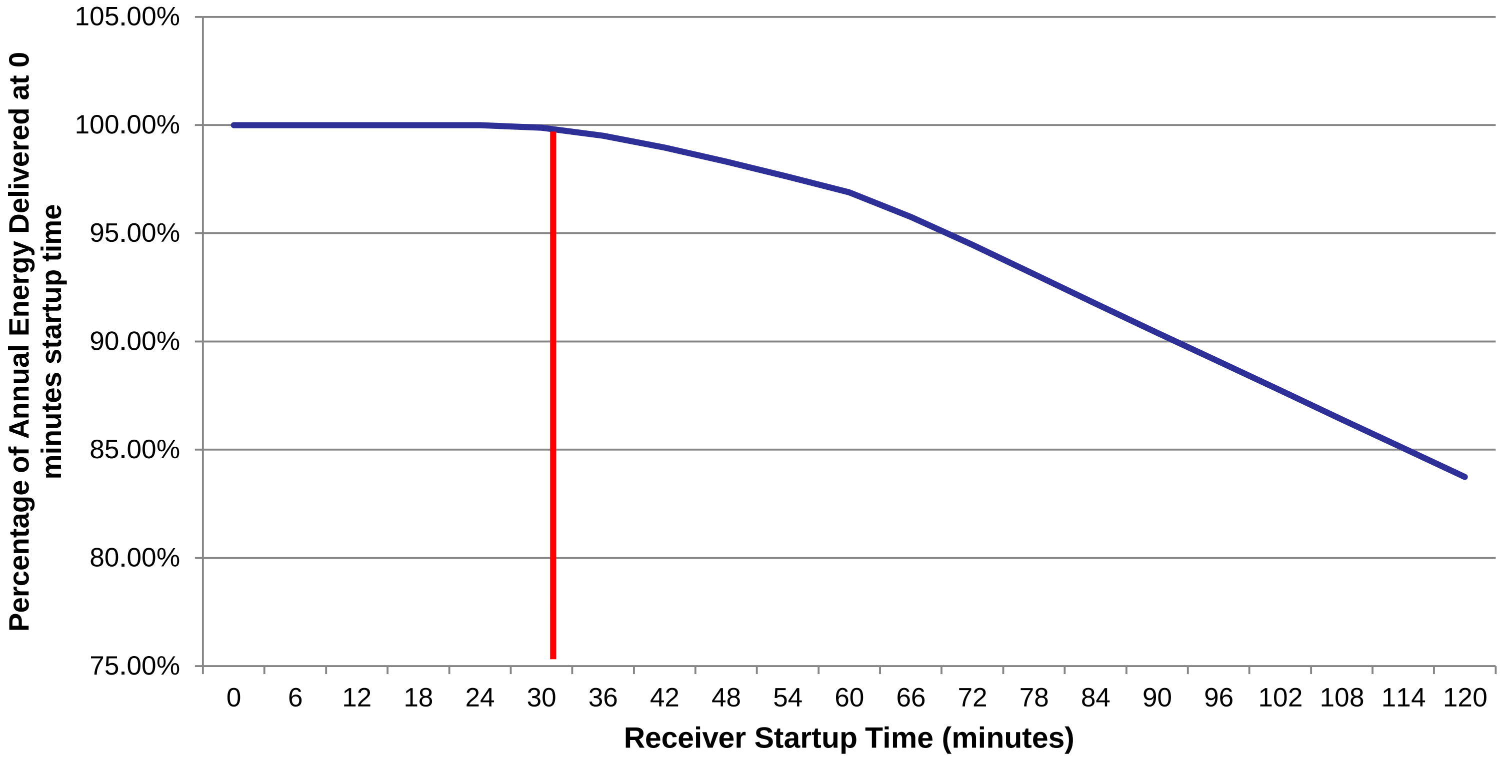
SunShot
U.S. Department of Energy

Clifford K. Ho

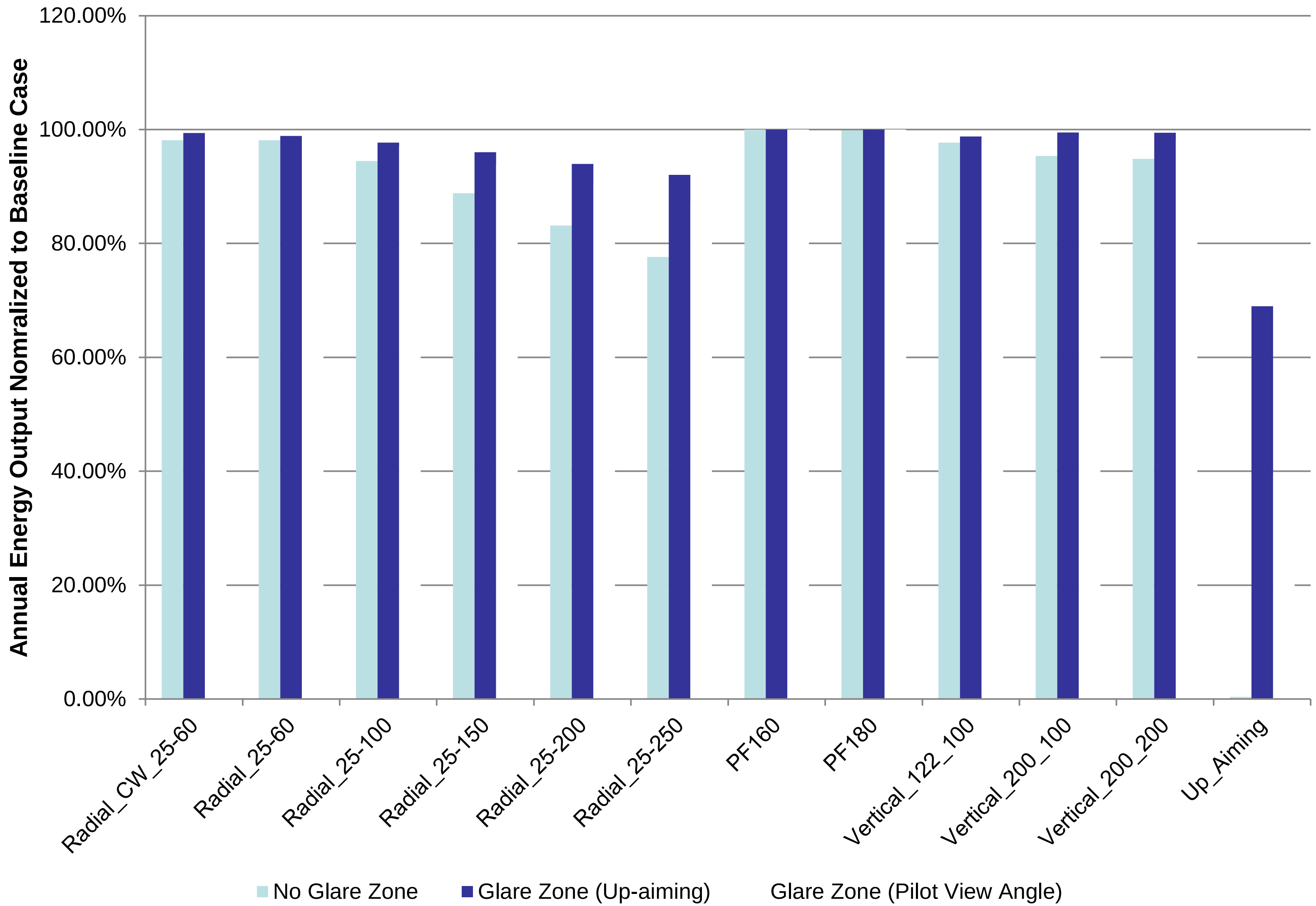
Sandia National Laboratories

ckho@sandia.gov

SAM Parametric Analysis of Receiver Startup Time



Annual Performance Impact Relative to Baseline



Some Conclusions

- Up-aiming yields best avian health result – zero time @ > 160^{O} C
- Relative to baseline case, up-aiming has largest impact on annual performance.
- Baseline case is most affected by addition of directional glare zone due to its relatively tight focusing initially.
- For all cases, maximum heliostat slew time on the order of ~15 minutes.
- Distribution of heliostat slew times varies as a function of aiming strategy.

Solar One (Daggett, California)

- 10 MW_e direct-steam pilot demonstration project
- 40 weeks of study from 1982 to 1983 (McCrary et al. 1984, 1986)
  - 70 documented bird deaths
    - 81% from collisions (mainly heliostats)
    - 19% from burns
  - Impact on local bird population was considered minimal
  - Nearly all observed incinerations ("small flashes of light within the standby points, accompanied by a brief trail of white vapor") involved aerial insects rather than birds

Barn Swallow

White-Throated Swift

Ivanpah Solar Electric Generating System

(Ivanpah, California)

- 390 MW_e direct steam power-tower plant (3 towers)
- Kagan et al. (2014) found 141 bird fatalities Oct 21 – 24, 2013
  - 33% caused by solar flux
  - 67% caused by collisions or predation
- H.T. Harvey and Associates found 703 bird fatalities in first year at ISEGS
  - Study estimated 3500 bird fatalities accounting for search efficiency and scavengers removing carcasses
- ISEGS has since implemented new heliostat aiming strategies and bird deterrents

Cause	Number of Detections				
	Winter	Spring	Summer	Fall	Total
Singed	27	100	42	147	316
Collision	14	15	10	45	84
Other*	5	5	2	3	15
Unknown	51	82	61	94	288
Total	**97**	**202**	**115**	**289**	**703**

* Includes detections in ACC buildings without evidence of singeing or collision effects.

H.T. Harvey and Associates, 2013 - 2014

Crescent Dunes

(Tonopah, Nevada)

- 110 MW_e molten-salt power tower
- In January 2015, 3,000 heliostats were aimed at standby points above receiver
  - 115 bird deaths in 4 hours (Stantec compliance report)
  - SolarReserve spread the aim points to reduce peak flux to < 4 kW/m^2
    - Reported zero bird fatalities in months following change*

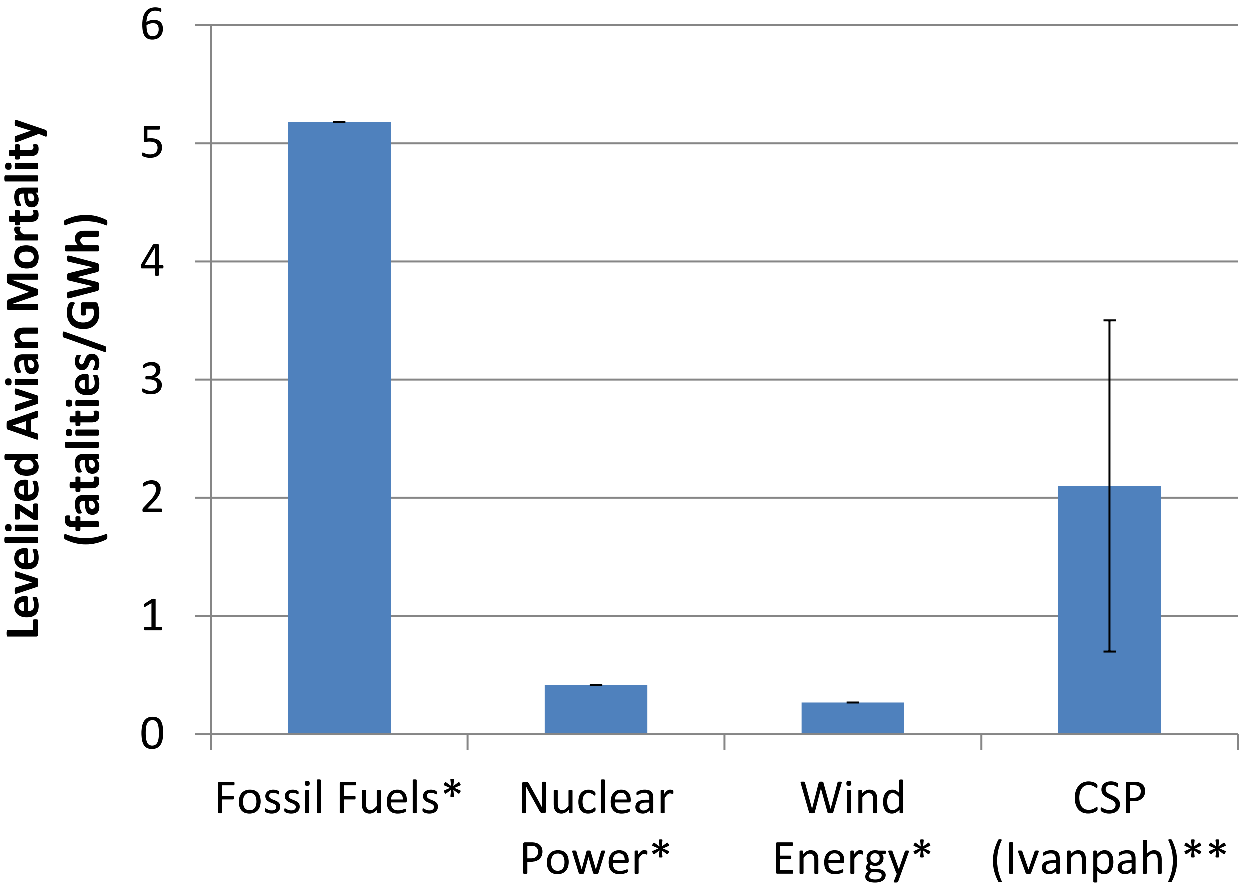
Figure 1 – The halo created by the reflected light of 3,000 heliostats which caused the bird mortalities.

* https://cleantechnica.com/2015/04/16/one-weird-trick-prevents-bird-deaths-solar-towers/

Images from http://cleantechnica.com

Levelized Avian Mortality for Energy

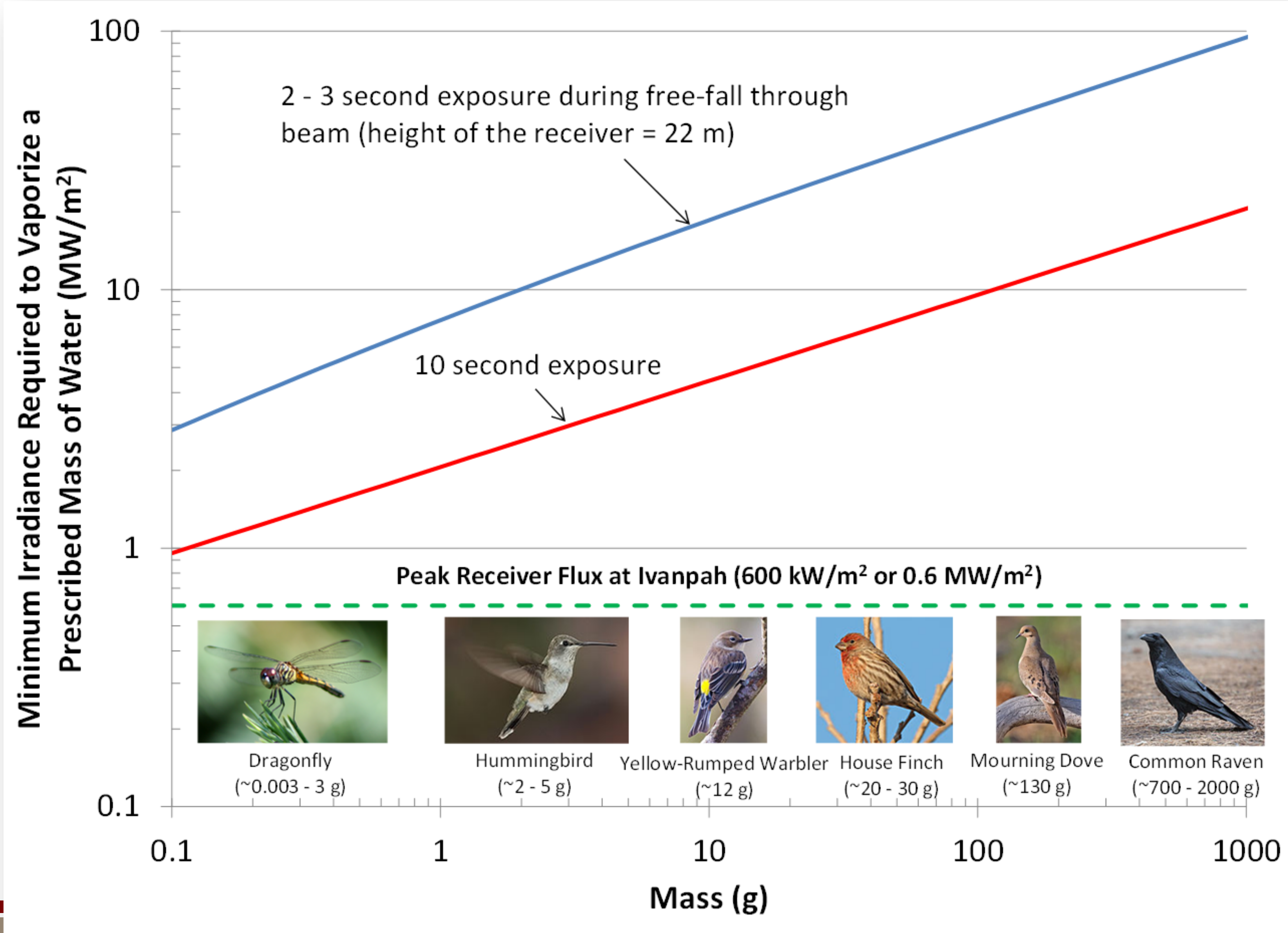
(Ho, 2015)



*Sovacool (2009)

**During first year of operation at Ivanpah (2013 – 2014) before mitigation measures and deterrents were implemented

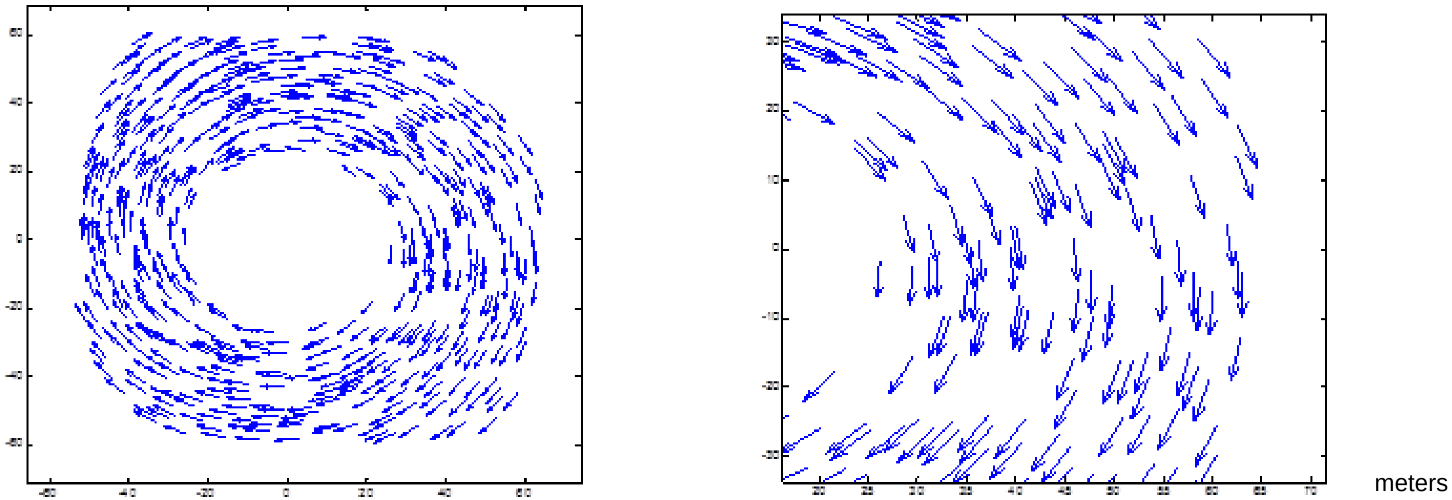
Feasibility of Bird Vaporization



Heliostat Standby Aiming Strategies

(Personal communication – Nitzan Goldberg, Brightsource Energy, 7/22/14)

- Option 1 (original)
  - Standby points are as close to the receiver as possible
  - Each heliostat as its own aim point depending on azimuth and distance
  - Each heliostat aims to the left side of the receiver

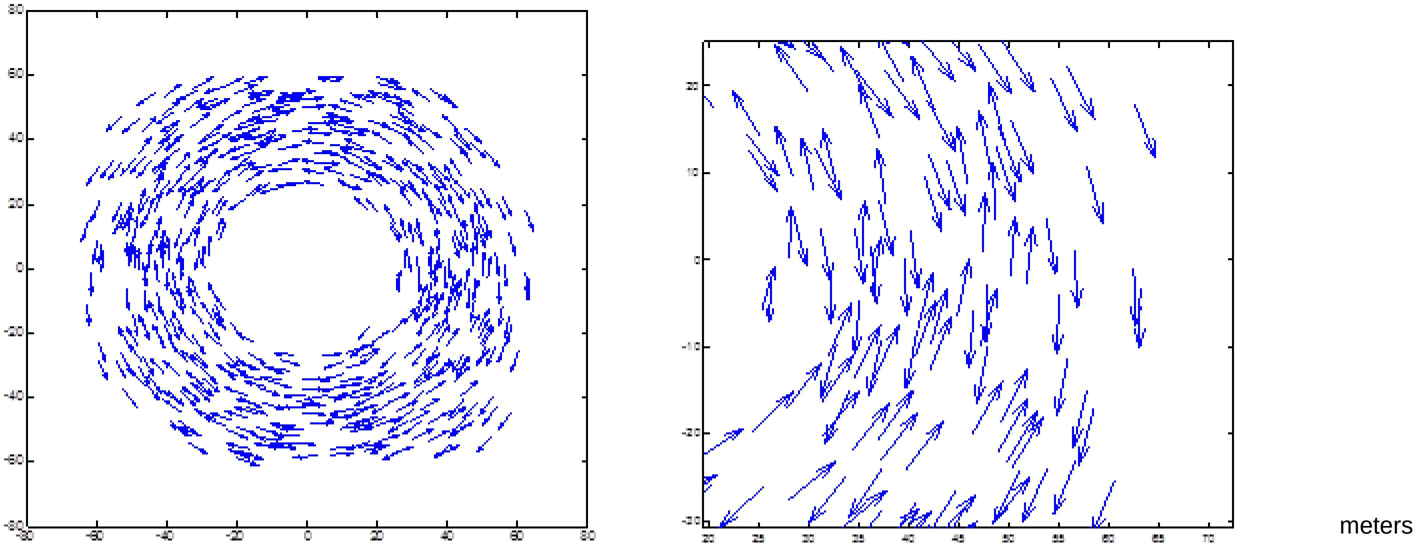


Quiver plots showing flux vectors near the receiver from a sample of heliostats for Option 1

Heliostat Standby Aiming Strategies

(Personal communication – Nitzan Goldberg, Brightsource Energy, 7/22/14)

- Option 2 (Unit 1 during April 24 flyover?)
  - Standby points are as close to the receiver as possible
  - Each heliostat as its own aim point depending on azimuth and distance
  - Aiming is to both sides of the receiver

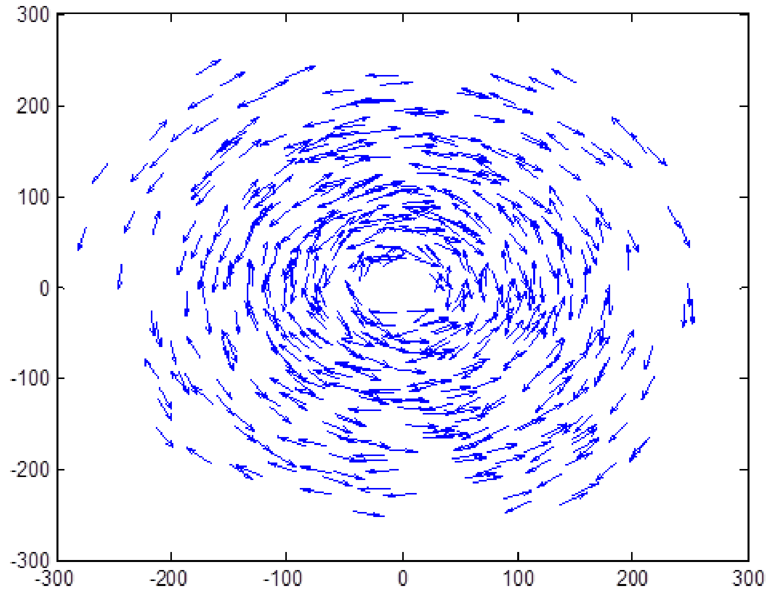


Quiver plots showing flux vectors near the receiver from a sample of heliostats for Option 2

Heliostat Standby Aiming Strategies

(Personal communication – Nitzan Goldberg, Brightsource Energy, 7/22/14)

- Option 3 (Units 1 and 2 during July 22 flyover)
  - Spread standby points to reduce flux density in air around receiver and to disperse the observable glare
  - Aiming is to both sides of the receiver



Quiver plots showing flux vectors near the receiver from a sample of heliostats for Option 3