Bifacial PV System Performance: Investigation of Shading Conditions

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May 2, 2018

Team Acknowledgements

This work is a collaborative project among three institutions funded by the US DOE SuNLaMP funding

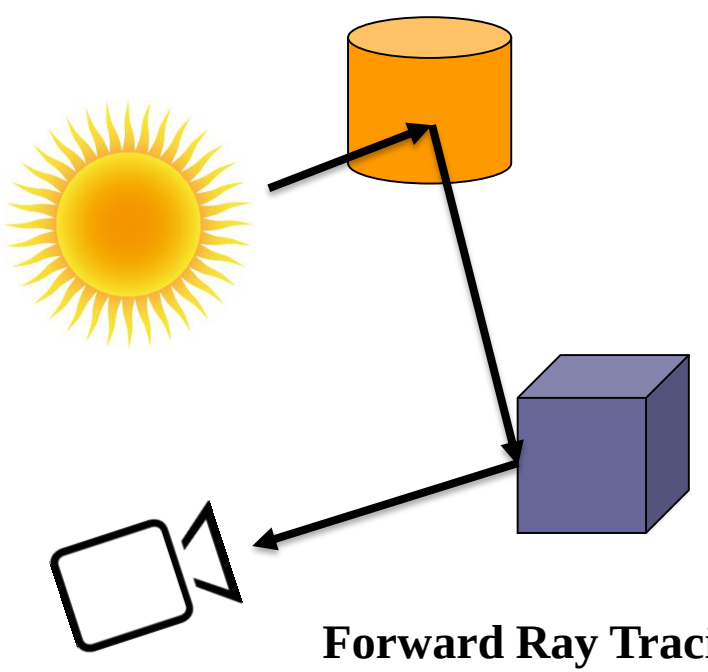
- Sandia National Laboratories
  - Joshua Stein - PI
  - Cliff Hansen
  - Dan Riley
  - Matthew Lave
- National Renewable Energy Laboratory
  - Chris Deline – Co-PI
  - Bill Marion
- University of Iowa
  - Prof. Fatima Toor
  - Amir Asgharzadeh (graduate student)

Agenda

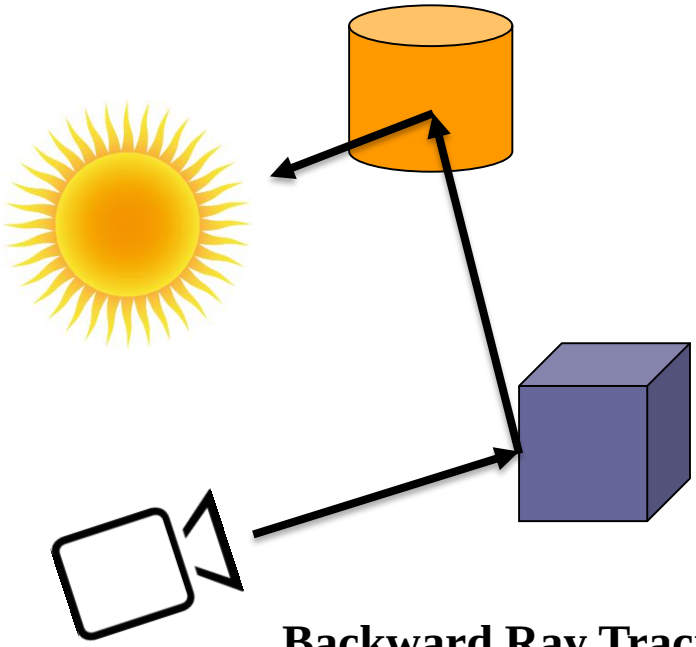
- Photovoltaic (PV) Performance Modeling
  - RADIANCE Modeling
  - Cumulative Sky Approach
- Performance Comparison of Bifacial PV Systems with Different Orientations
  - Optimally tilted Facing South/North vs Vertically Installed Facing East/West
  - No Shading
  - Under Shading Conditions
- Conclusions and next steps

RADIANCE Modeling

- RADIANCE, a simulation software that utilizes the backward ray-tracing method



Forward Ray Tracing



Backward Ray Tracing

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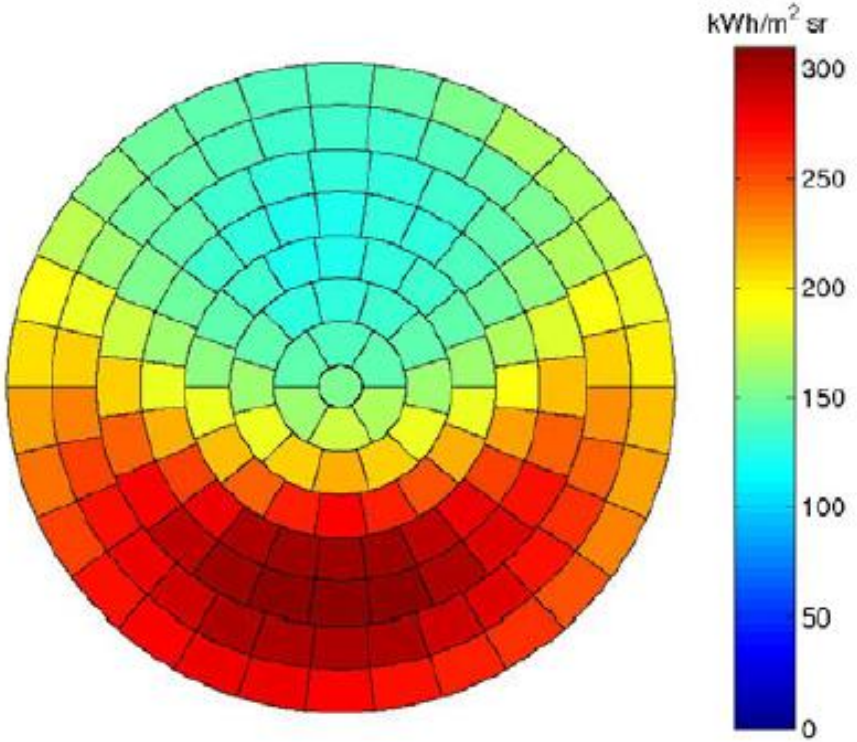
Cumulative Sky Approach

- Producing annual results by running hourly simulations is computationally expensive
- To perform annual simulations, we use Cumulative Sky Approach



Cumulative diffuse sky radiance distribution for Oslo (based on 10 yr mean solar data)

[1] D. Robinson and A. Stone, "Irradiation modelling made simple: The cumulative sky approach and its applications," in *Proc. 21st Conf. Passive Low Energy Architecture*, Eindhoven, The Netherlands, 2004, pp. 1255–1259.

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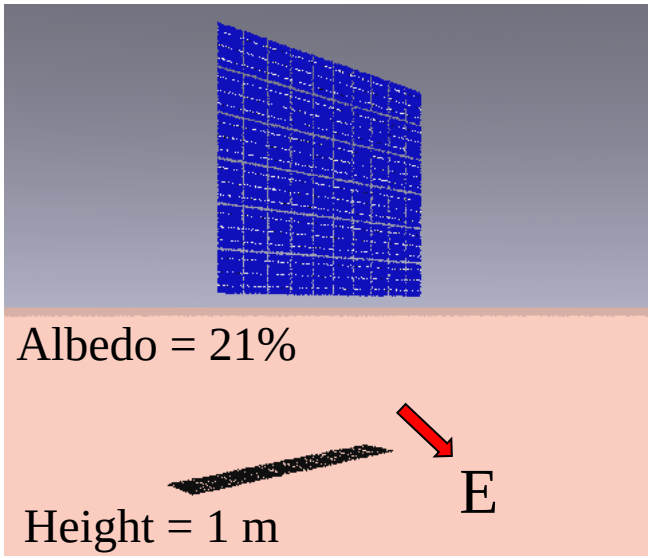
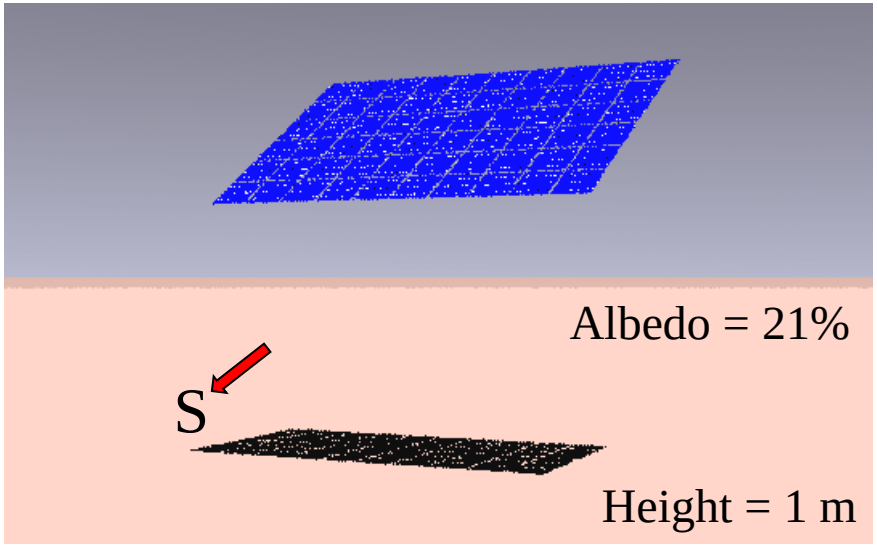
Optimally tilted Facing South/North vs Vertically Installed Facing East/West

- Among different possible orientations for bifacial modules, the two most popular options are:
  - Optimally tilted south/north-facing module ($Bi_{S/N}$)
  - Vertical east/west-facing module ($Bi_{E/W}$)

Optimum tilt angle for south-facing bifacial module is latitude of the location [1]

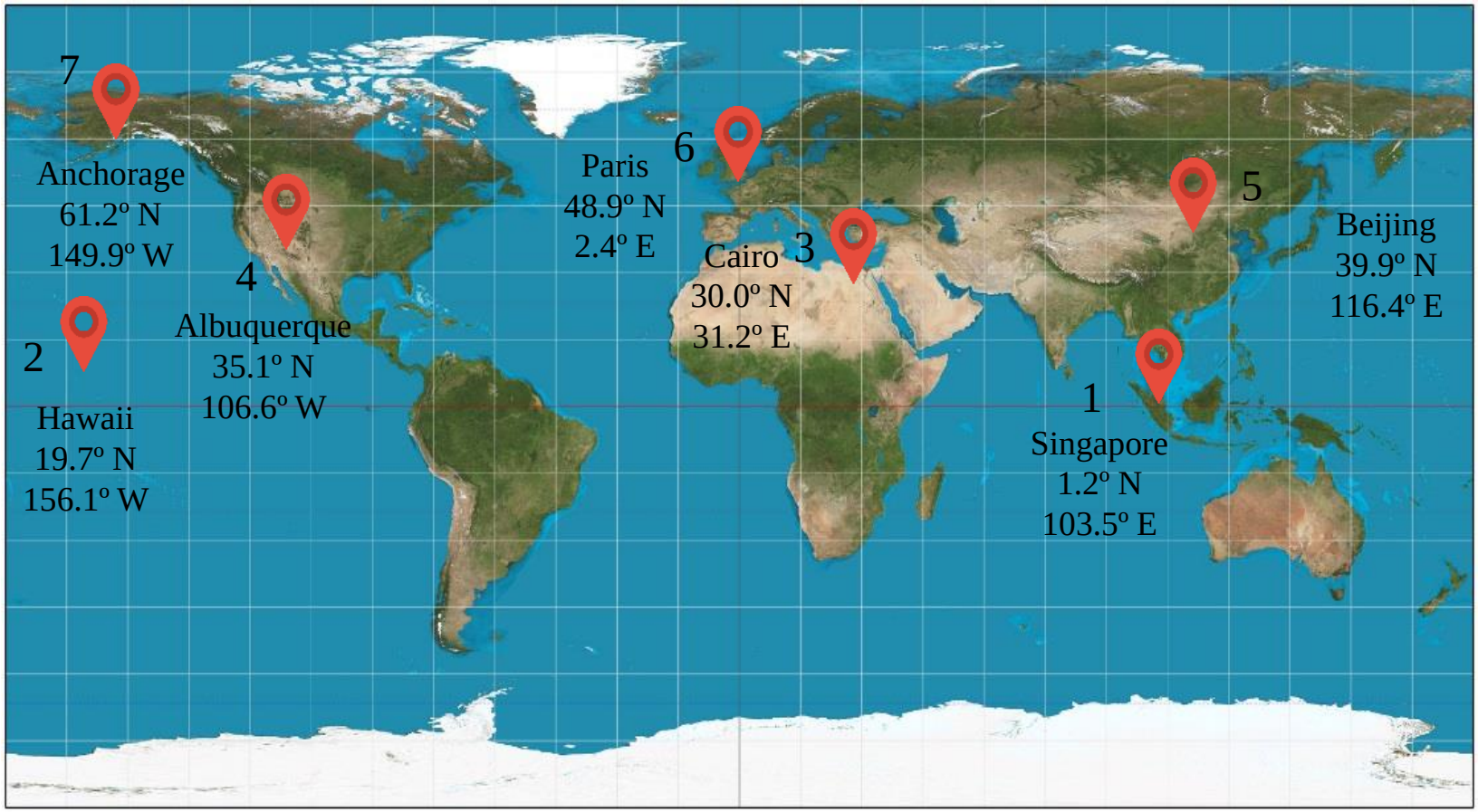




[1] A. Asgharzadeh, B. Marion, C. Deline, C. Hansen, J. S. Stein and F. Toor, "A Sensitivity Study of the Impact of Installation Parameters and System Configuration on the Performance of Bifacial PV Arrays," in *IEEE Journal of Photovoltaics*, vol. 8, no. 3, pp. 798-805, May 2018. doi: 10.1109/JPHOTOV.2018.2819676

Simulation Setup

- Multiple locations were chosen for the simulation purpose



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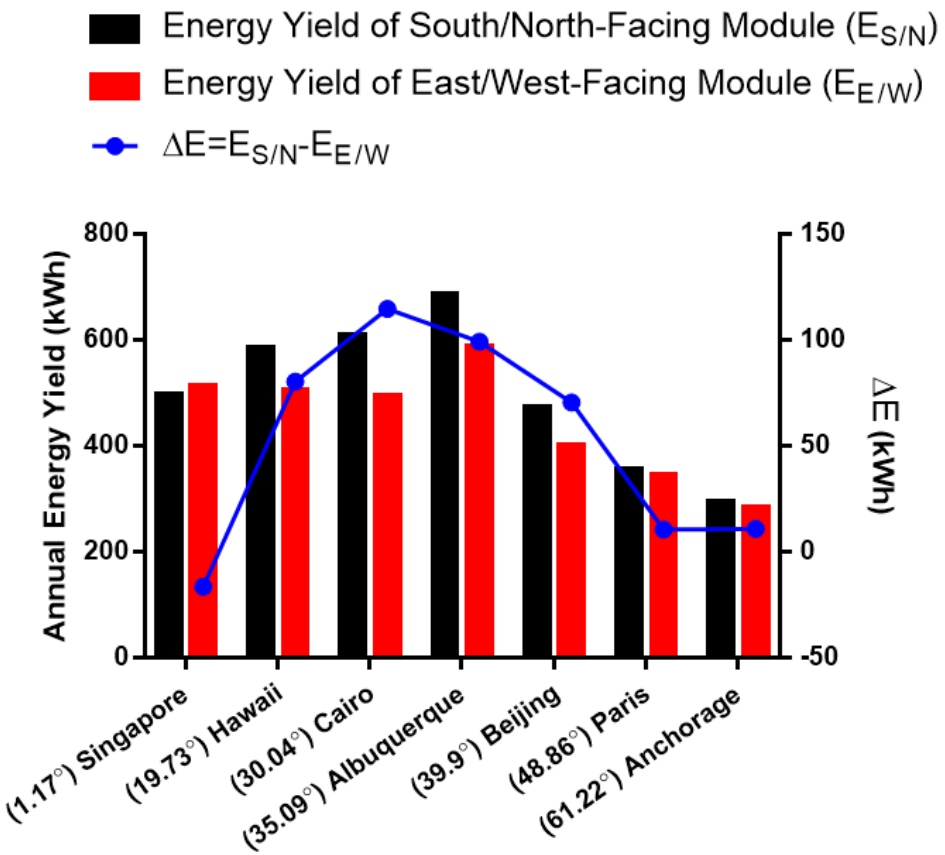
No Shading



- Observed that for all locations, except Singapore, the $Bi_{S/N}$ has more annual energy yield than $Bi_{E/W}$ (up to 120 kWh/year)
- Performance of the PV system installed in Singapore, installed at low tilt, is affected adversely by self-shading and therefore the yield of $Bi_{S/N}$ is slightly lower than $Bi_{E/W}$

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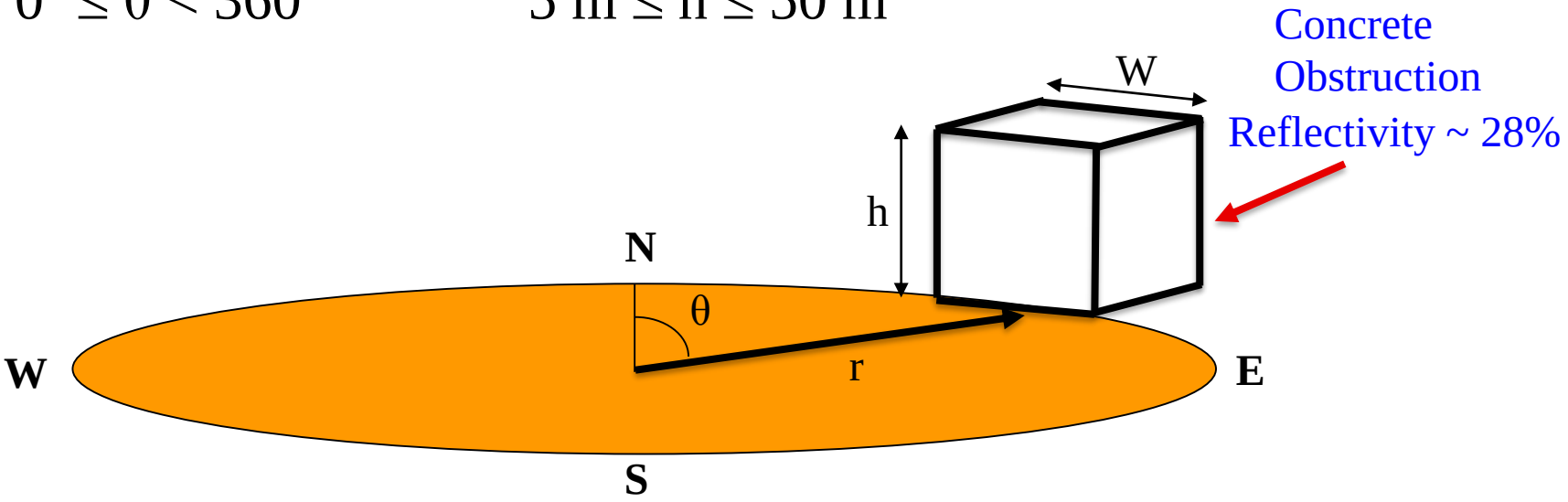
Under Shading Conditions

- Horizon obstructions can decrease the diffuse and direct light received by photovoltaic (PV) modules
- We ran simulations sweeping parameters shown below for both $Bi_{S/N}$ and $Bi_{E/W}$

$5\ m \leq r < 100\ m$ $\quad\quad$ $5\ m \leq W \leq 50\ m$

$0^o \leq \theta < 360^o$ $\quad\quad$ $5\ m \leq h \leq 50\ m$

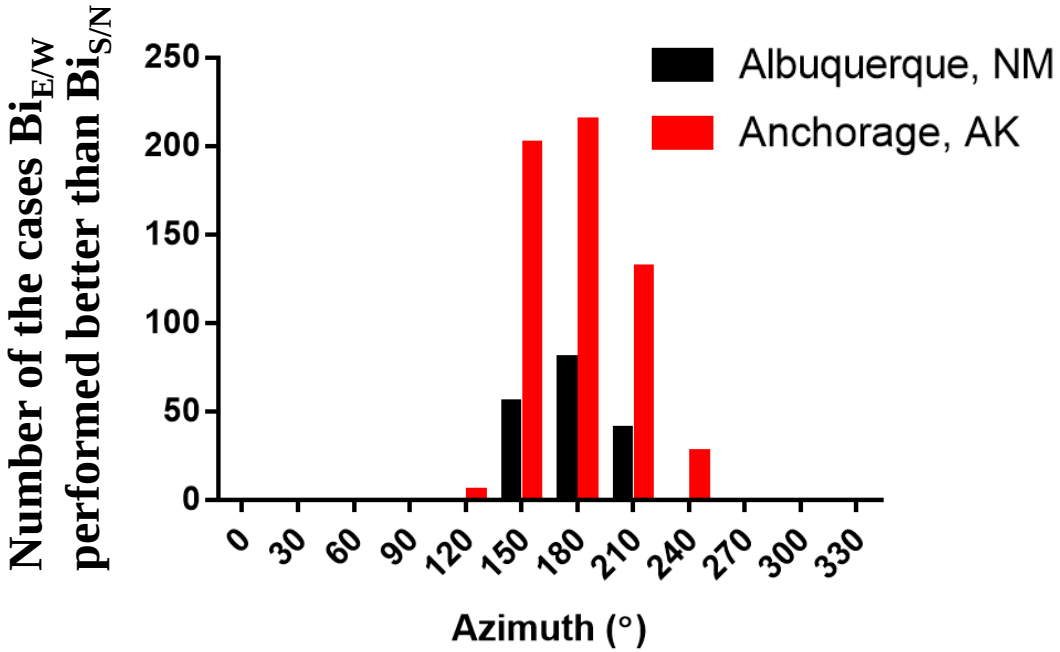


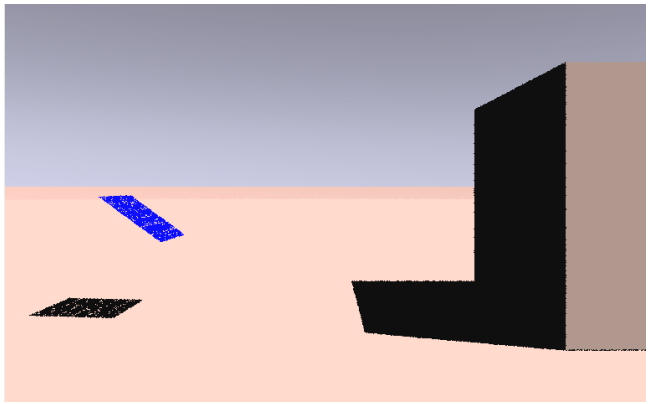
Study of System Performance for $Bi_{S/N}$ vs $Bi_{E/W}$

- The goal is to determine under which shading conditions $Bi_{E/W}$ system performs better than $Bi_{S/N}$
- We analyzed two locations: (i) Albuquerque, NM and (ii) Anchorage, AK
- Of the 6000 simulations for each of the two locations and for each of $Bi_{S/N}$ and $Bi_{E/W}$ systems, the cases where the performance of $Bi_{E/W}$ was higher than $Bi_{S/N}$ were identified

Effect of Obstruction's Orientation

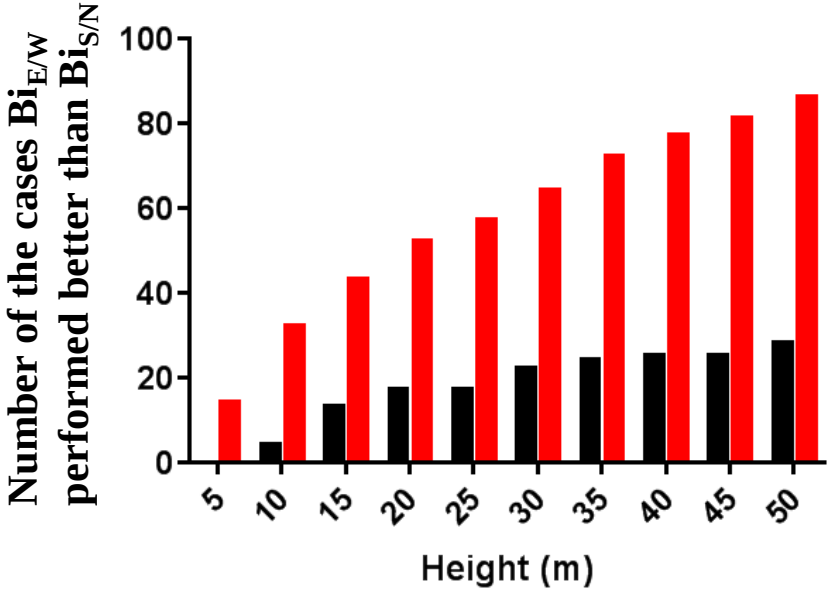
- Obstructions around south (azimuth angle of 180º) can cause $Bi_{E/W}$ perform better than $Bi_{S/N}$
  - Closer shadow to the module and therefore decrease in the diffuse ground reflected irradiance
  - Occasional direct shading
  - No reflection from the obstruction due to its shaded surface

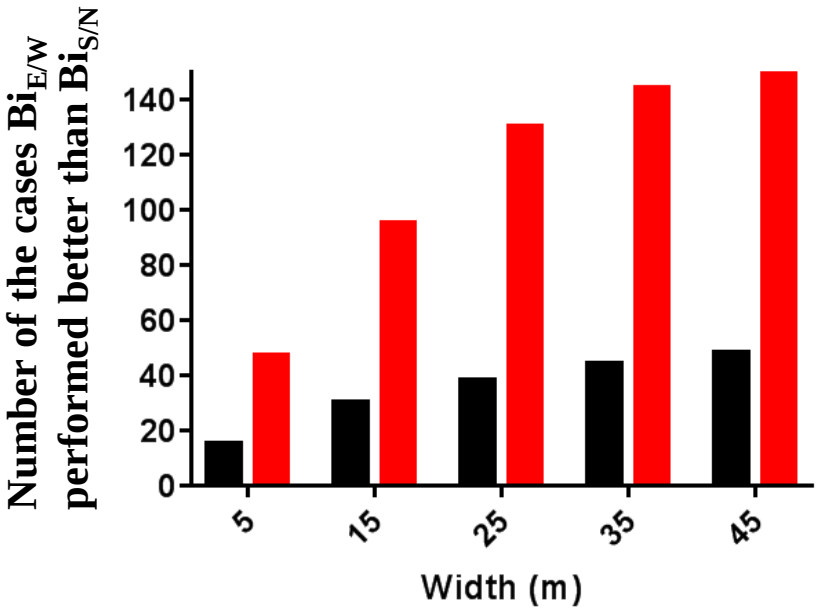




Effects of Obstruction's Height and Width

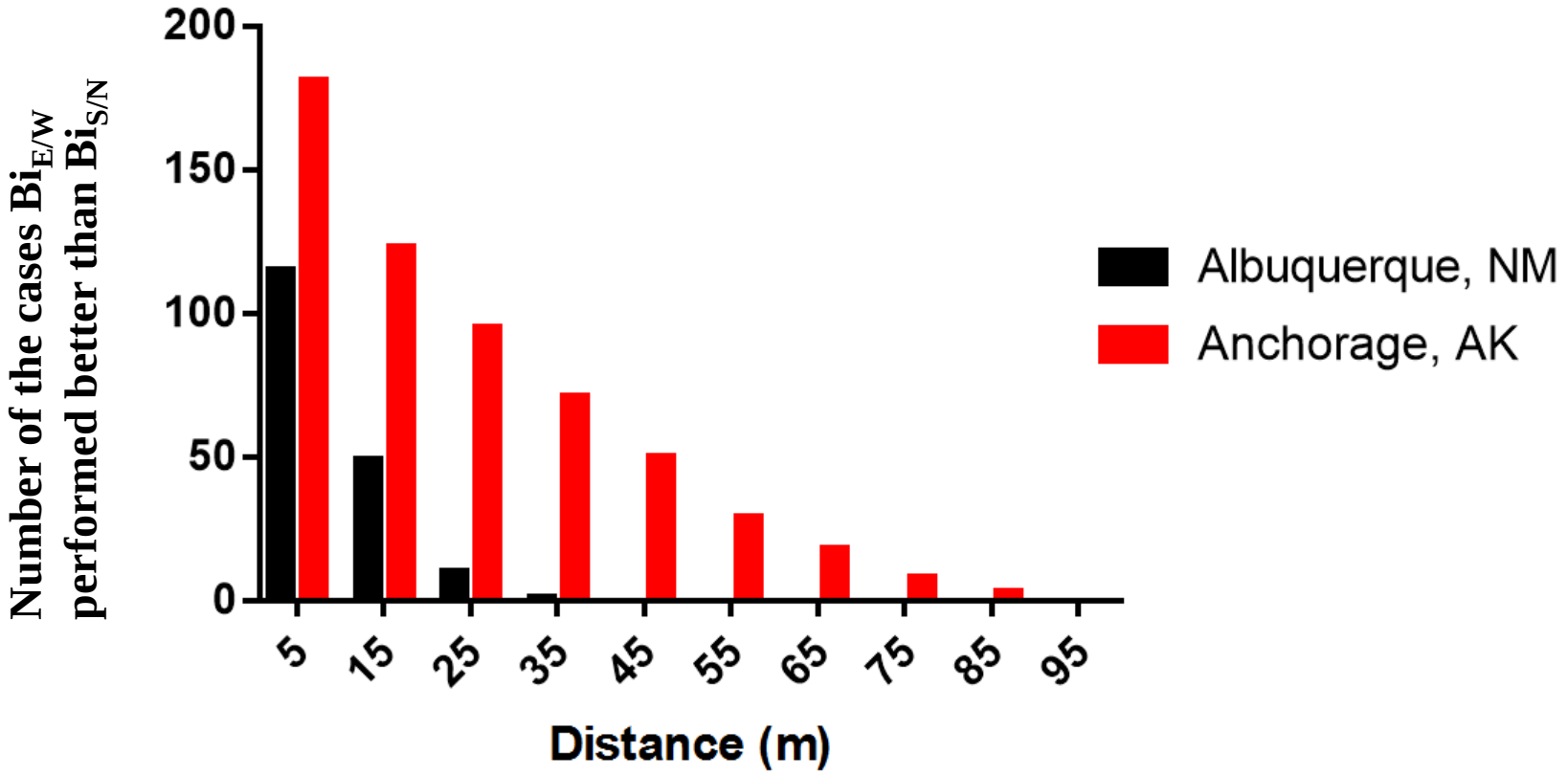
- Larger obstructions results in greater diffuse and direct irradiance loss on modules





Effect of Obstruction's Distance to the Module

- From the view of the module, closer obstructions seem larger

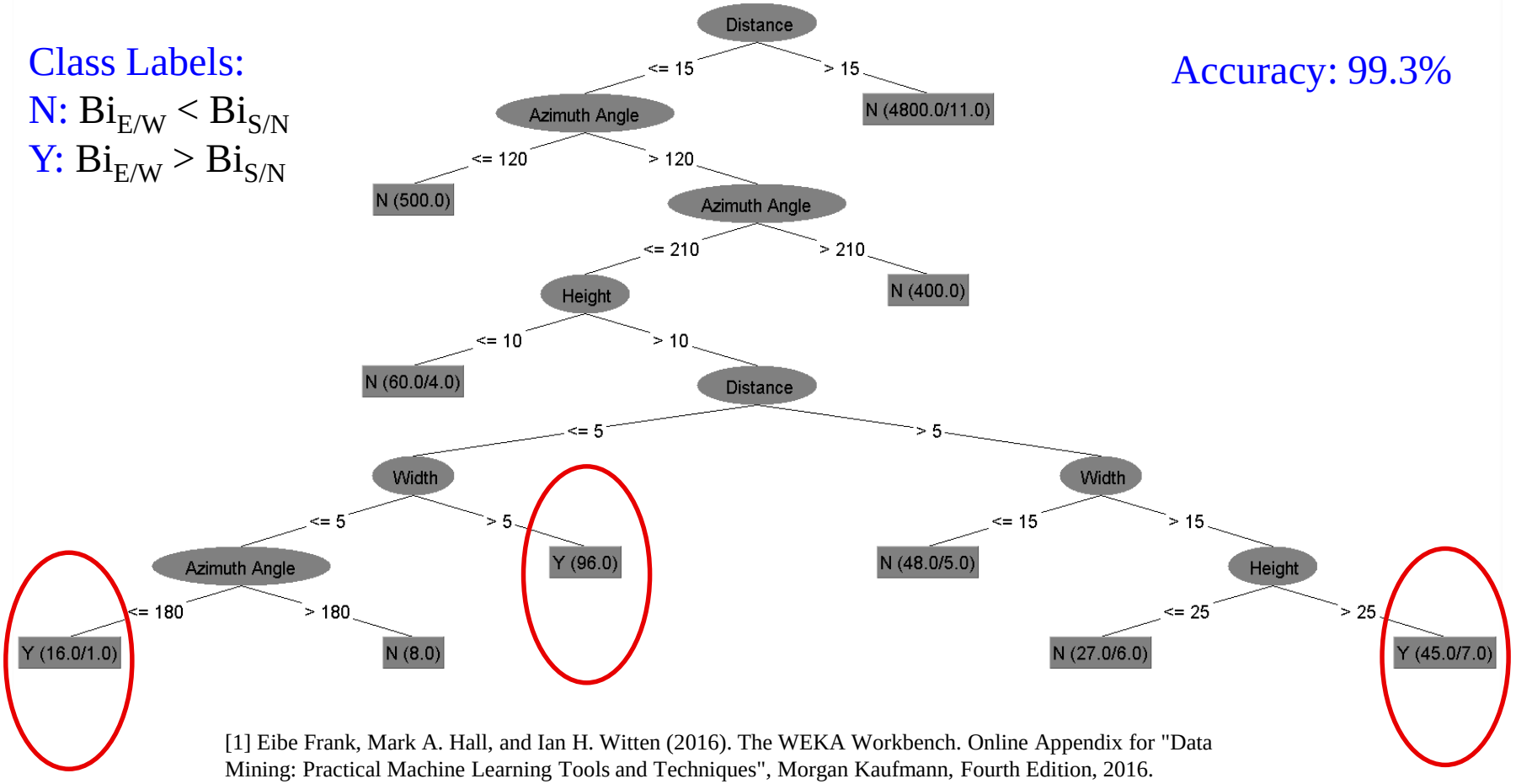


Decision Tree: Albuquerque, NM

- In order to identify the obstruction which resulted in better performance for $Bi_{E/W}$ than $Bi_{S/N}$, J48 decision trees were developed for both locations using Weka [1]

Class Labels:
N: $Bi_{E/W} < Bi_{S/N}$
Y: $Bi_{E/W} > Bi_{S/N}$

Accuracy: 99.3%



[1] Eibe Frank, Mark A. Hall, and Ian H. Witten (2016). The WEKA Workbench. Online Appendix for "Data Mining: Practical Machine Learning Tools and Techniques", Morgan Kaufmann, Fourth Edition, 2016.

Cont. Decision Tree: Albuquerque, NM

- Characteristics of obstruction which resulted in having better performance for $Bi_{E/W}$ than $Bi_{S/N}$ in Albuquerque, NM:

$r \leq 5$ m $120^o < \theta < 180^o$ $W = 5$ m 10 m $\leq h$	$r \leq 5$ m $120^o < \theta < 210^o$ 5 m $< W$ 10 m $\leq h$	5 m $\leq r \leq$ 15 m $120^o < \theta < 210^o$ 15 m $\leq W$ 25 m $\leq h$

These conditions are basically the large obstructions in south which are also very close to the module resulting in heavy direct shading

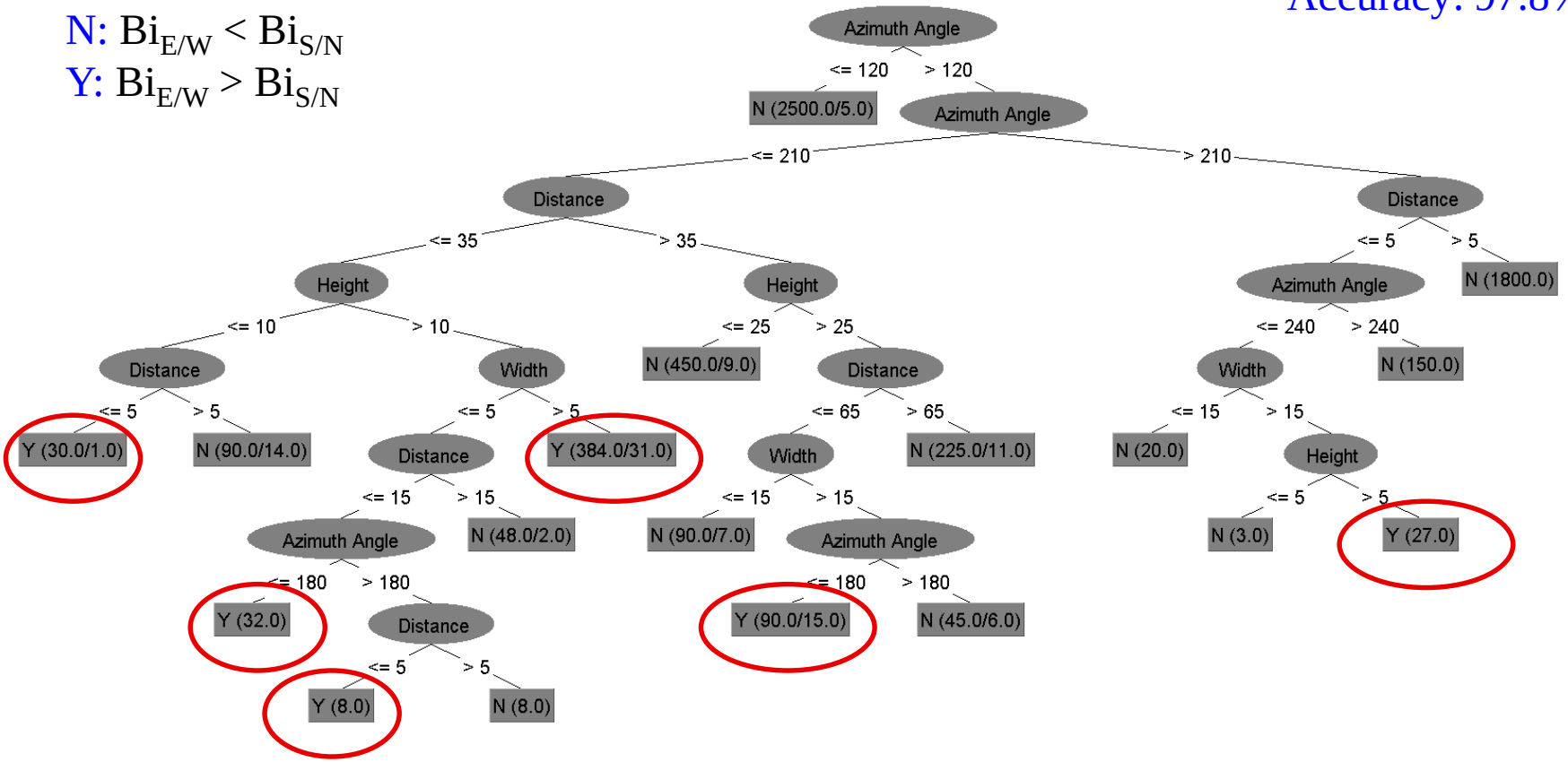
Decision Tree: Anchorage, AK

Class Labels:

N: $Bi_{E/W} < Bi_{S/N}$

Y: $Bi_{E/W} > Bi_{S/N}$

Accuracy: 97.8%



Cont. Decision Tree: Anchorage, AK

- Characteristics of obstruction which resulted in having better performance for $Bi_{E/W}$ than $Bi_{S/N}$ in Anchorage, AK

$r \leq 5$ m $210^o < \theta \leq 240^o$ 15 m < W 5 m ≤ h	$r \leq 5$ m $180^o < \theta \leq 210^o$ W = 5 m 10 m < h	$r \leq 5$ m $120^o < \theta \leq 210^o$ 15 m ≤ W 5 m ≤ h ≤ 10 m	$r \leq 15$ m $120^o < \theta \leq 180^o$ W = 5 m 10 m < h

large obstructions which are also very close to the module

$r \leq 35$ m $120^o < \theta \leq 210^o$ 5 m < W 10 m < h	35 m < r ≤ 65 m $120^o < \theta \leq 180^o$ 15 m ≤ W 25 m < h

Can result in having up to 75 kwh/year more energy yield for $Bi_{E/W}$ than $Bi_{S/N}$

Conclusions and Next Steps

- RADIANCE utilized to model a bifacial PV module with two orientations: optimally tilted facing south/north ($Bi_{S/N}$) and vertically installed facing east/west ($Bi_{E/W}$)

- Compared annual energy yield of the two systems for different locations and observed that $Bi_{S/N}$ module had higher energy yield than $Bi_{E/W}$ for all locations except for Singapore (latitude of 1.2º) for which $Bi_{E/W}$ outperformed $Bi_{S/N}$

- Investigated performance of two PV systems installed at two locations under shading conditions caused by horizon obstructions
  - For a high latitude location such as Anchorage (~61º), the presence of certain obstructions can result in having up to 75 kwh/year more energy yield for $Bi_{E/W}$ than $Bi_{S/N}$

- Next steps include (i) studying the impact of other parameters such as reflectivity of the obstruction and (ii) studying the performance of PV systems installed in practical scenarios by integrating building data into our bifacial model

Thanks for your attention

Any Questions?