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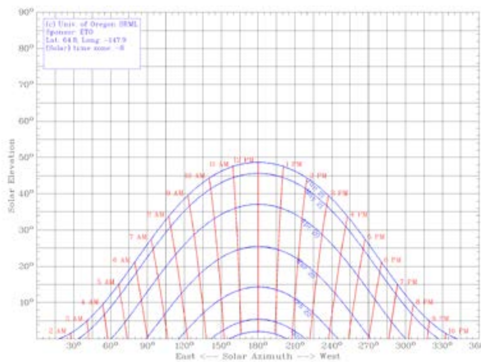

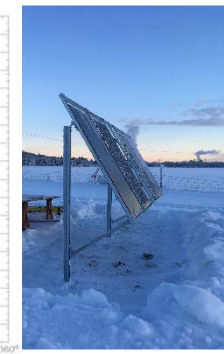

Solar PV Performance and New Technologies in Northern Latitude Regions

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Solar Resource in Alaska

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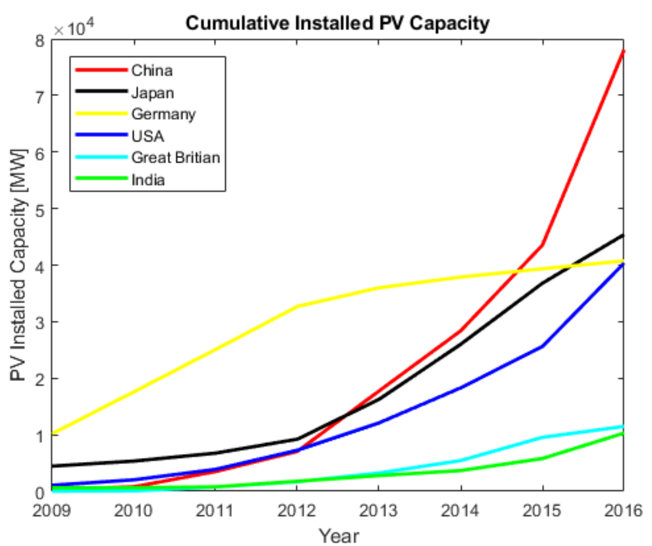
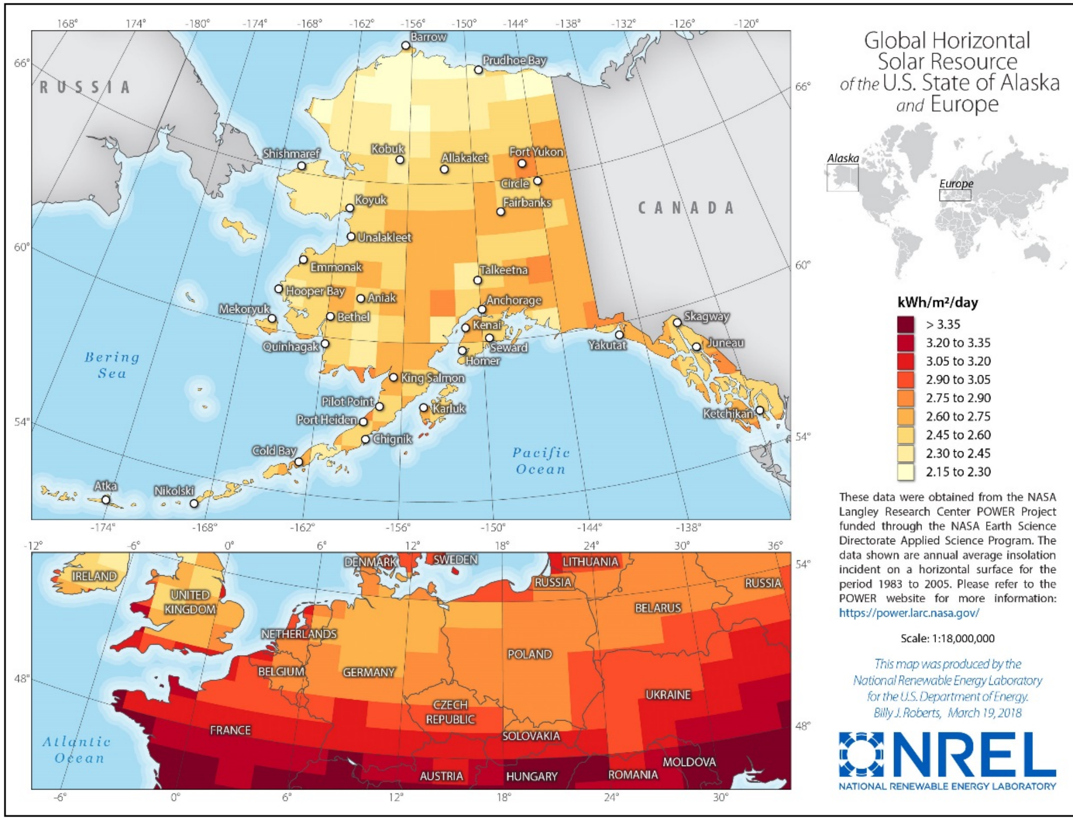
- Solar resource is ~30%-50% lower than much of the “lower 48”
- It is slightly less than Germany, a world leader in photovoltaic energy deployment.

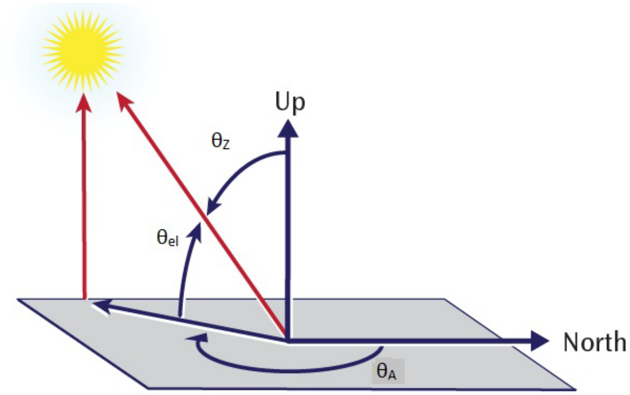


Data from EPIA, IEA, CPIA (Wang Sicheng, 2017)



Features of High Latitudes for PV

- Large range in length of day (short in Winter, but long in Summer)
- Large range in Solar Azimuth (Sun rises and sets in NNE and NNW in Summer)
- Smaller range in Solar Elevation
- Cold temperature (PV performs better at colder temperatures: 0.5%/deg-C)
- Snow (highly reflective and can cover PV modules and block light)

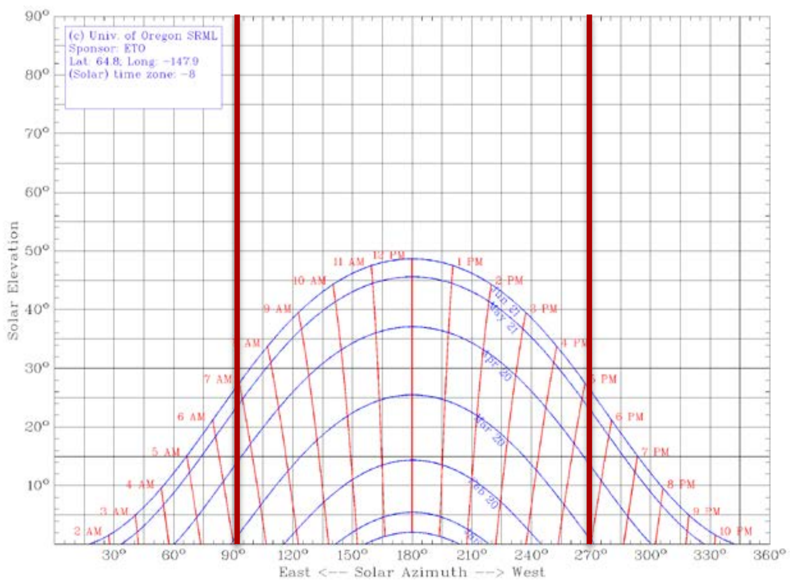


θ_{el} = elevation angle, measured up from horizon

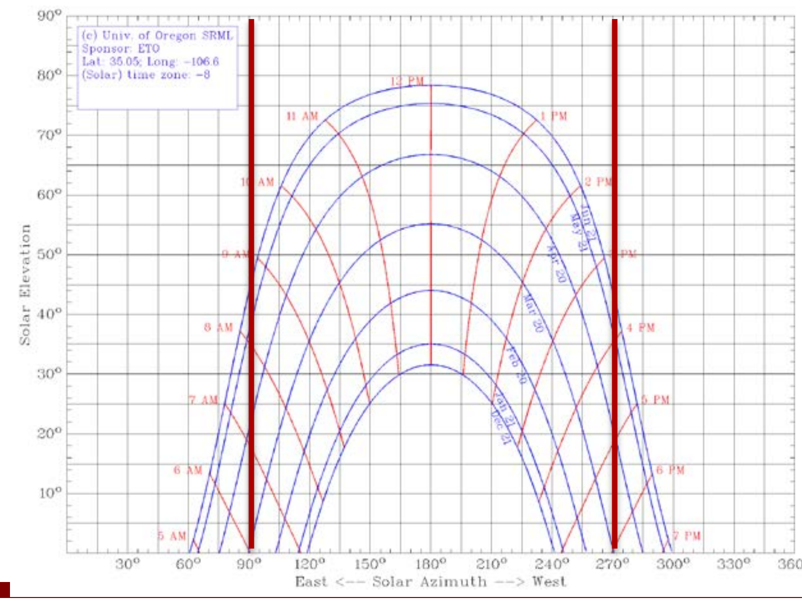
θ_Z = zenith angle, measured from vertical

θ_A = azimuth angle, measured from North

Fairbanks, AK (64° N)

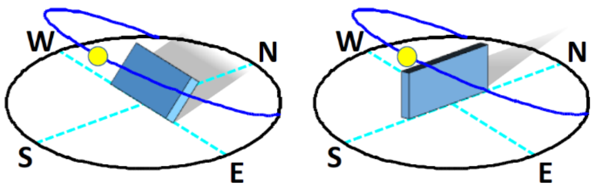


Albuquerque, NM (35° N)



Challenges in High latitudes

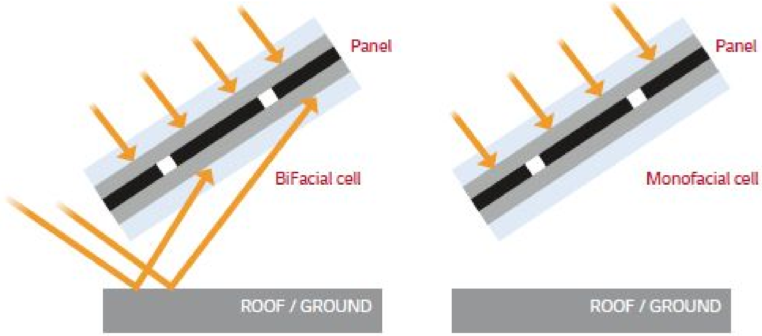
- Low Solar Elevation and large range in Solar Azimuth means the Sun spends a lot of time at high incidence angles to a fixed plane.



- Cold = higher PV efficiency
- Cold + Precip = Snow
- Snow has much higher reflectivity (albedo) which enhances ground-reflected irradiance.
  - Effect increases with tilt angle
- Snow can block light from reaching solar panels

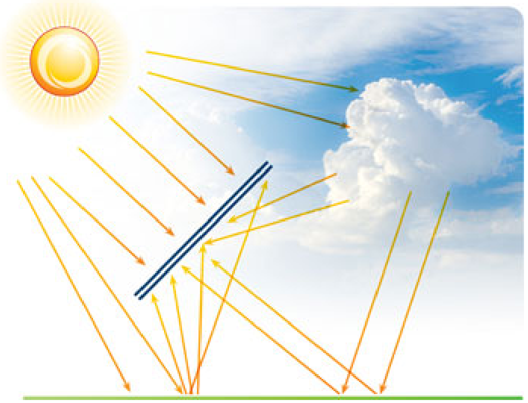
Bifacial PV Modules

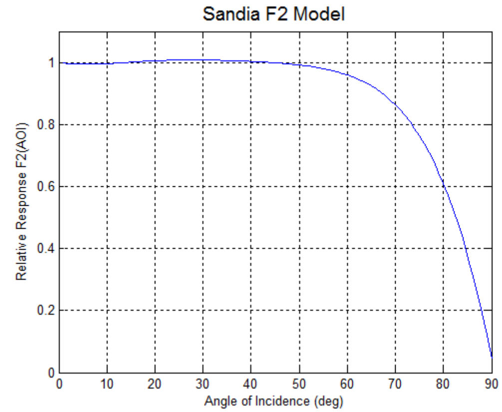
- New high-efficiency PV cell technologies are made bifacial (e.g., PERC, HIT)
- Power can be collected from the front and rear
- Rear efficiency is 60-95% of front (*bifaciality factor*).
- Produces more energy than monofacial modules: 5-20+%
- PV Magazine: “Overall, bifacial panels now add only about 3% to the total cost of a tracker system”



Very Simple Model of Bifacial PV Performance

- Model Assumptions
  - Weather from typical meteorological year (TMY) stations
    - GHI, DNI, DHI, Temperature, Wind Speed, Snow
  - Plane-of-array irradiance:
    - Beam + Sky Diffuse + Ground-reflected
      - Beam reduced at high angles of incidence due to reflection losses using Sandia's F2 Model
    - No snow periods: Albedo = 0.25
    - Snow on ground: Albedo = 0.7
    - Bifacial POA = front + back irradiance*bifaciality factor
      - Bifaciality factor = 90% for this simulation.
    - Albedo for bifacial reduced by 25% to account for shadow effects (based on empirical data).
  - Sky diffuse calculated with Perez transposition model
  - Module temperature: $T_m = T_a + E(e^{a+b*WS})$
  - Cell temperature: $T_c = T_m + E/E_0 * \Delta T$
  - Module power: $P_{mp} = P_{mp0} * E/E_0 * (1+\gamma[T_c - 25])$
  - Module parameters from spec sheet (Power rating, temp coefficient (γ))
- Model implemented in Matlab using PVLIB





GHI = Global Horizontal Irradiance
DNI = Direct Normal Irradiance
DHI = Diffuse Horizontal Irradiance

Model Validation

Validation was done by comparing model to measurements made at Sandia

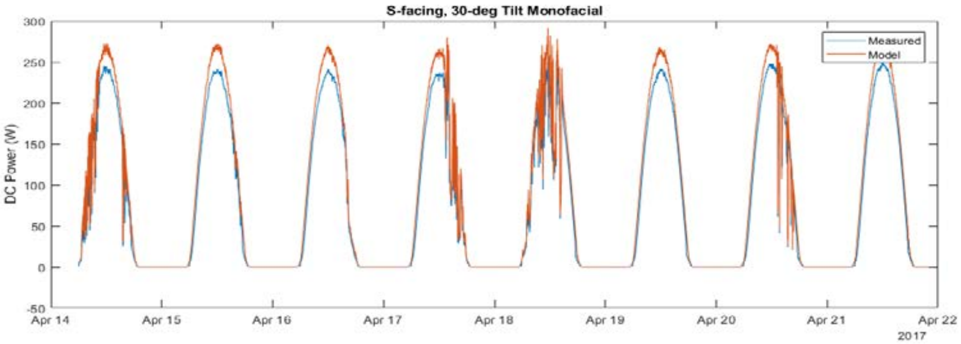
- Five orientations (each with monofacial and bifacial), Two albedos
- Module-level DC current and voltage measurements (module on microinverters).

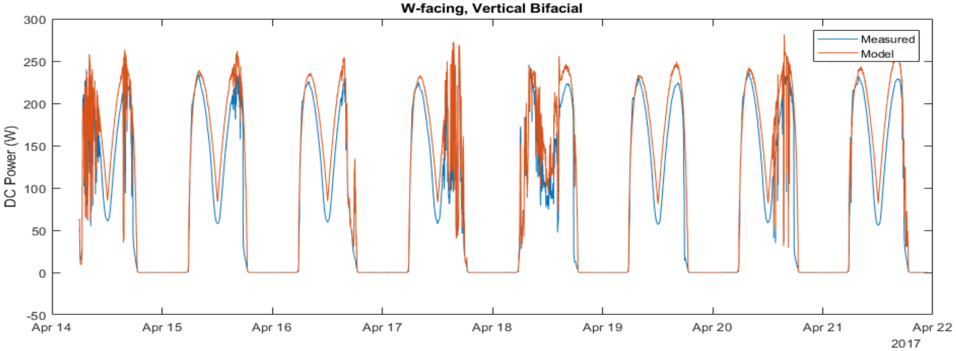
Inputs:

- Measured DNI, GHI, DHI, Air Temp, Wind speed, Albedo, Module spec sheet parameters (P_{mp0}, γ)

Results:

- Model slightly overestimates the measured system output.
  - Soiling is not included in model.

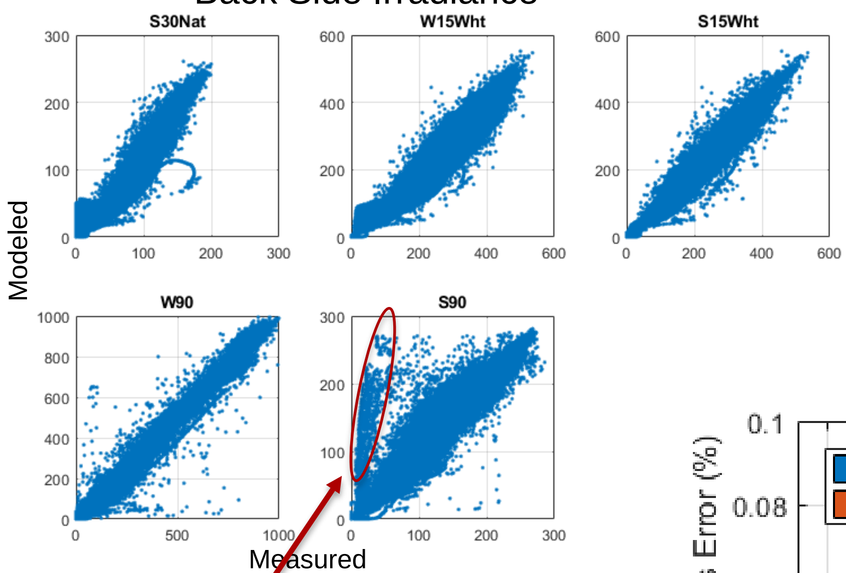




Model Validation Results

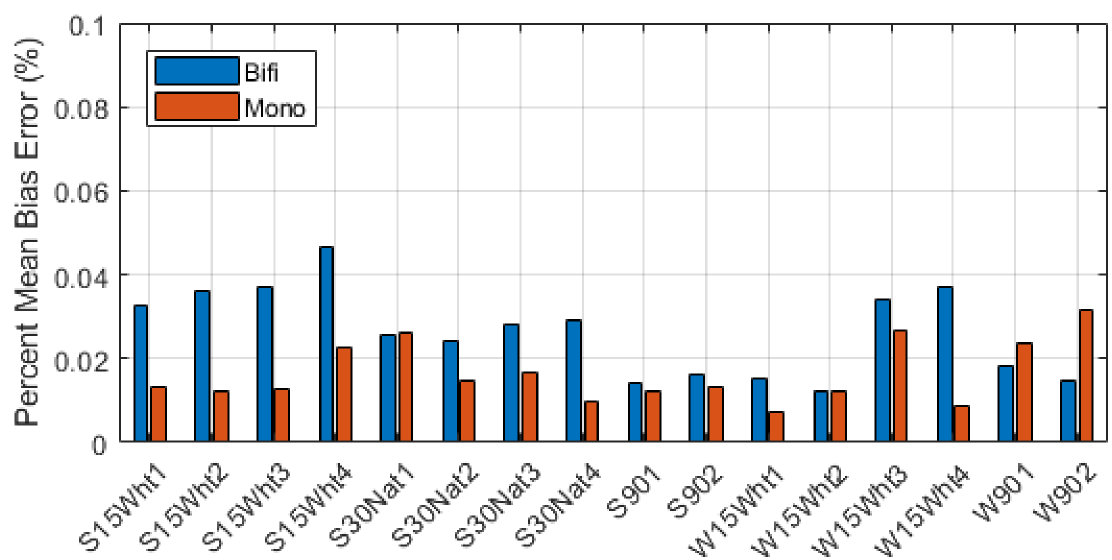
6 Month Comparison (Jan-June 2017)

Back Side Irradiance



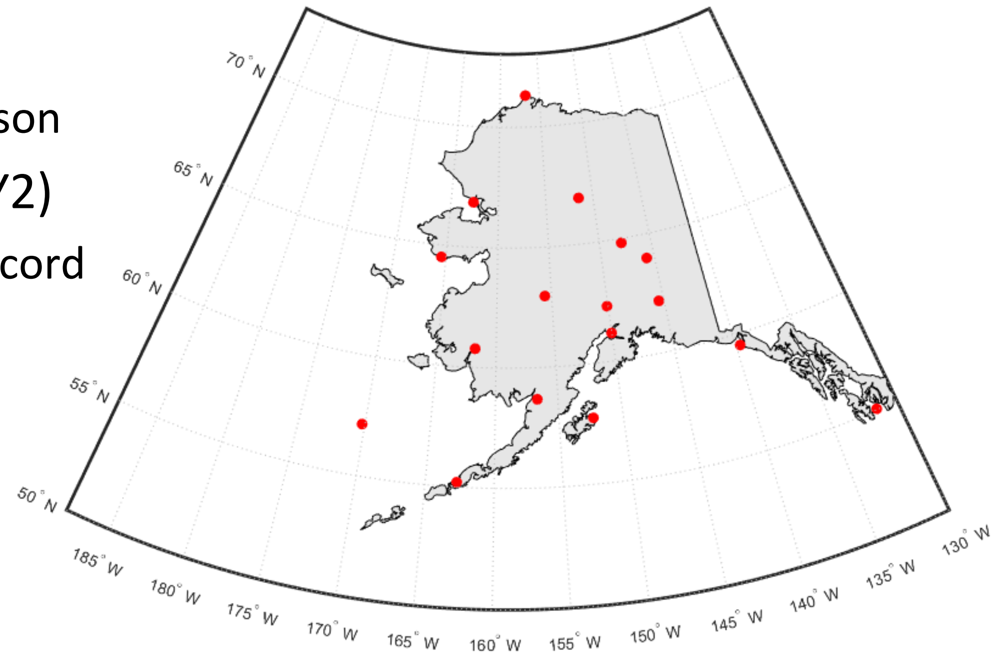
Shading from power pole

- Mean bias errors are all below 5%
- Back side irradiance model is very good for W90, W15, and S15.
- Minor systematic errors for S30, and S90
    - S90 has known shading

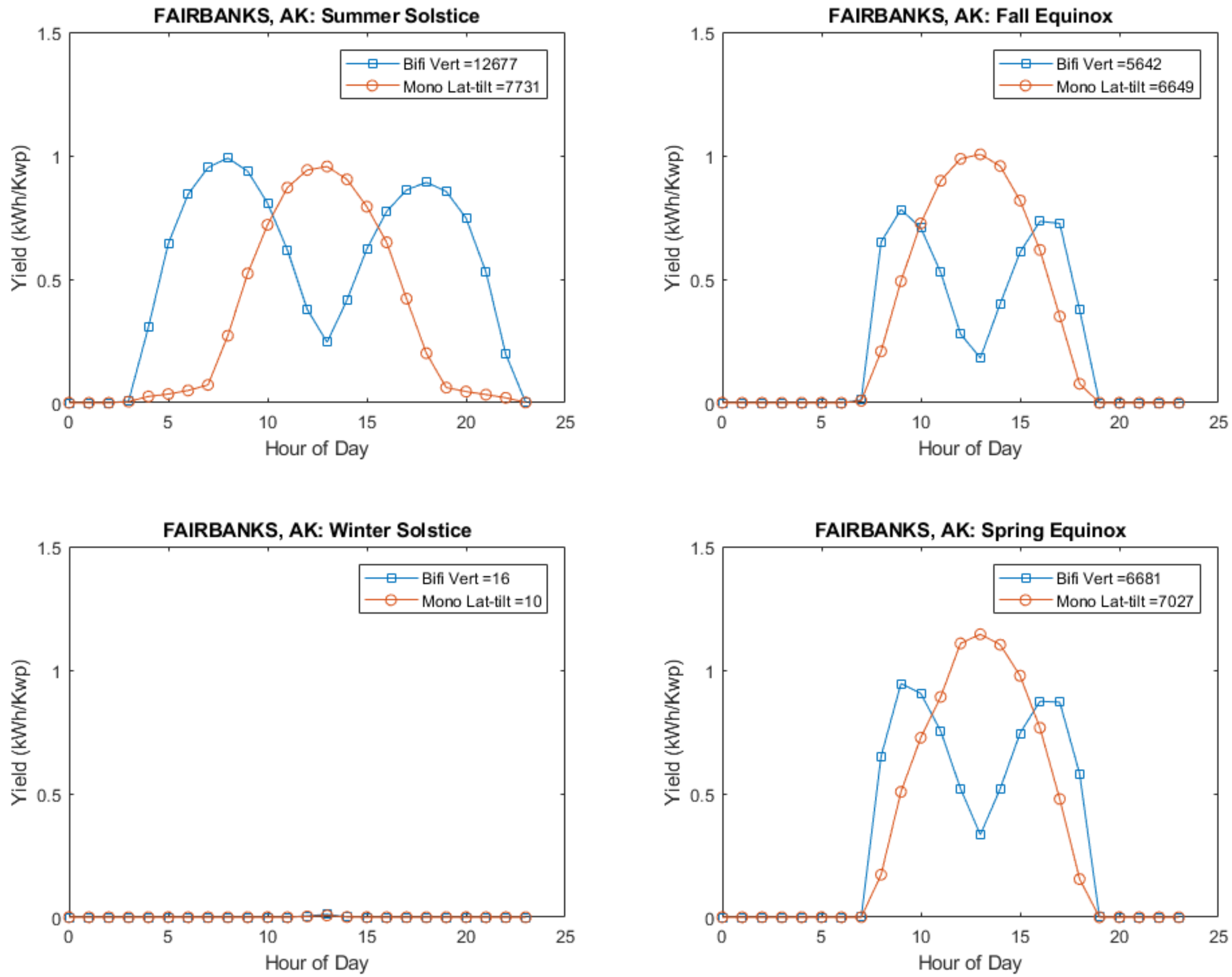


Predictive Alaska Model Scenarios

- Compare two design options:
  - South –Facing, Latitude-tilt standard monofacial PV (1 kW)
  - East-West-Facing, Vertical bifacial PV (1 kW)
- Weather Inputs
  - 17 weather stations in Alaska
    - Included Phoenix, AZ for comparison
  - Typical Meteorological Years (TMY2)
    - Months are selected from long record
    - Assembled into synthetic year
      - 8760 hours of data
    - Meant to be representative

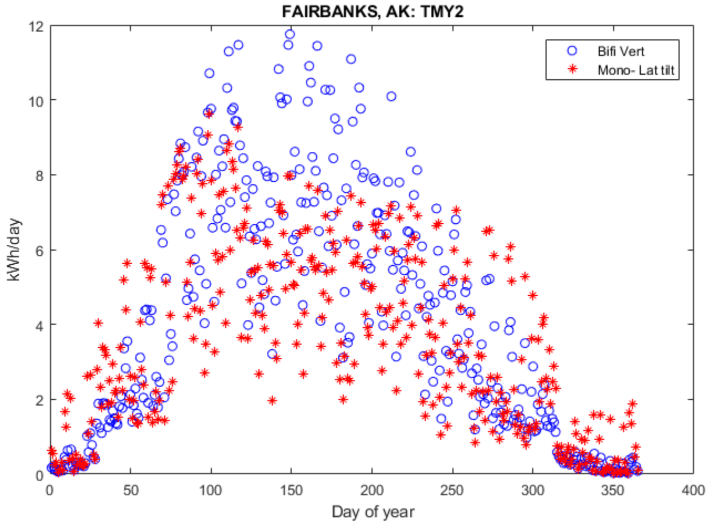


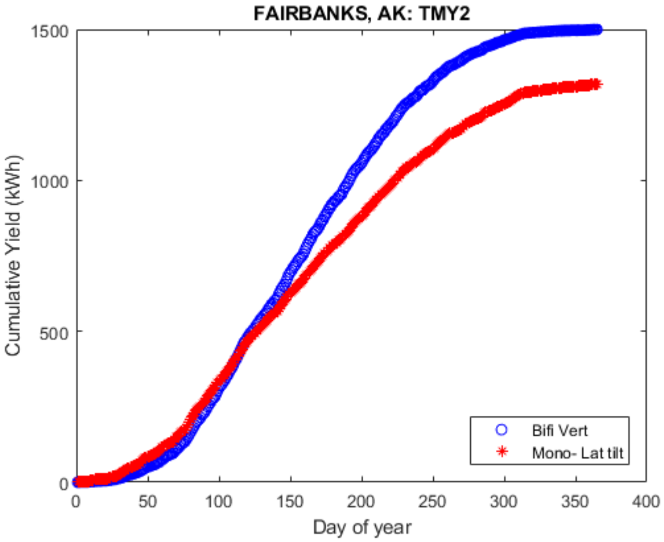
Model Examples: Fairbanks (Clear Sky)

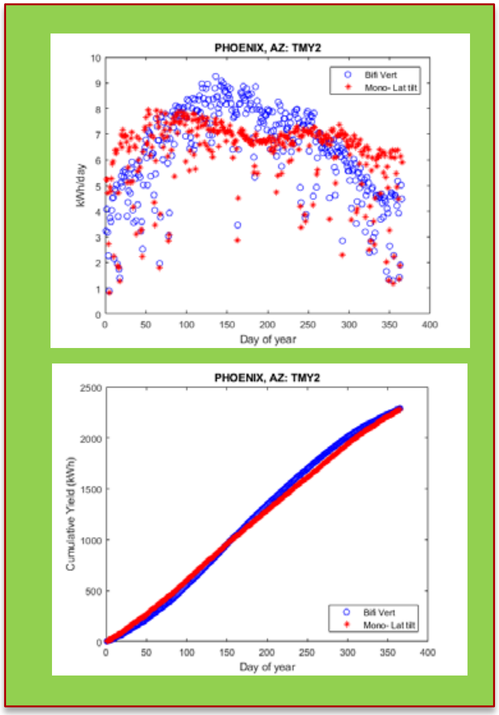


- E-W Vertical bifacial has potential to produce power earlier and later in day.
- Great for combining with latitude tilt PV systems

Model Examples: Fairbanks (TMY2)





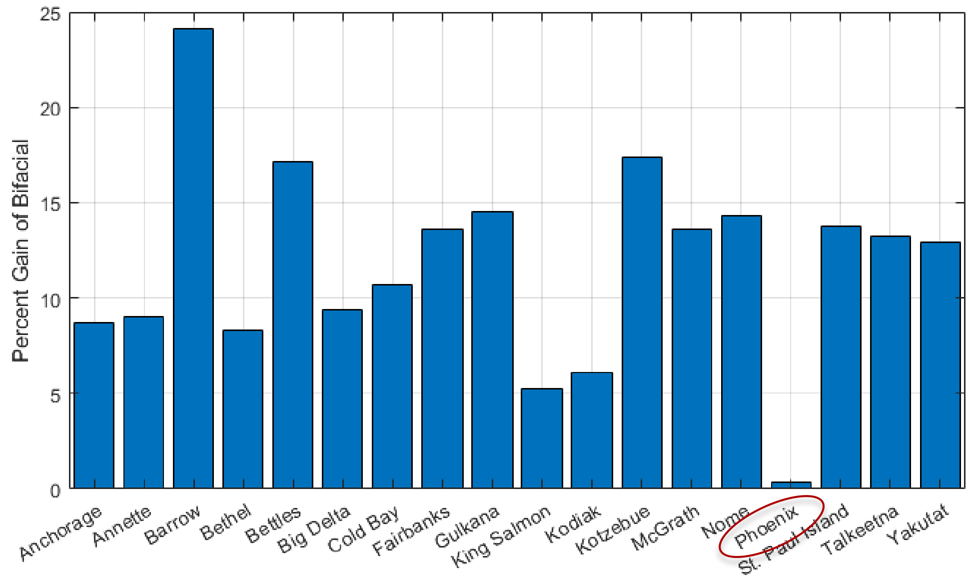


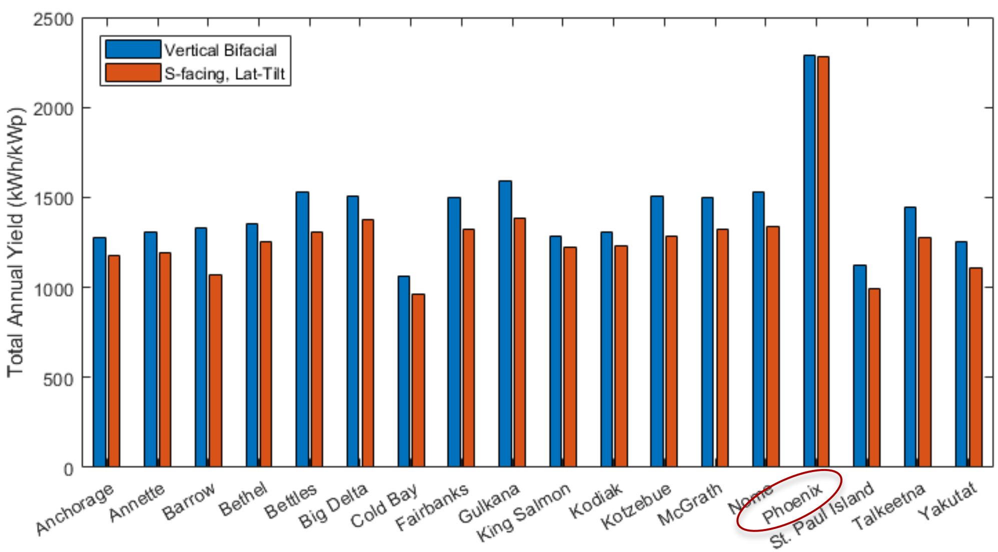
- This patterns repeats for most Alaska sites:
  - Early in year Lat-tilt system is better, but total energy is small
  - From Spring to early Autumn Vertical bifacial system significantly outperforms Lat-tilt monofacial.
- In Phoenix, vertical bifacial performs about the same as Lat-tilt monofacial.
  - We have confirmed this in Albuquerque, NM with measurements.

Results

- E-facing Vertical Bifacial outperforms S-facing Latitude-Tilt systems in Alaska.
  - Bifacial advantages increase with latitude and duration of snow on ground.
  - Power profile starts earlier and ends later, which may help with integration issues.

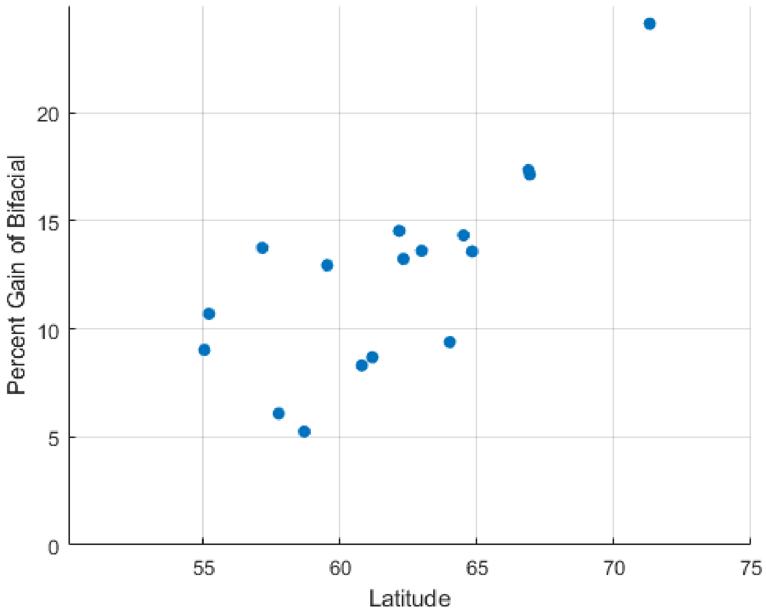
- Vertical bifacial takes advantage of large range in solar azimuths
- Vertical bifacial collects light from highly reflective snow covered ground.



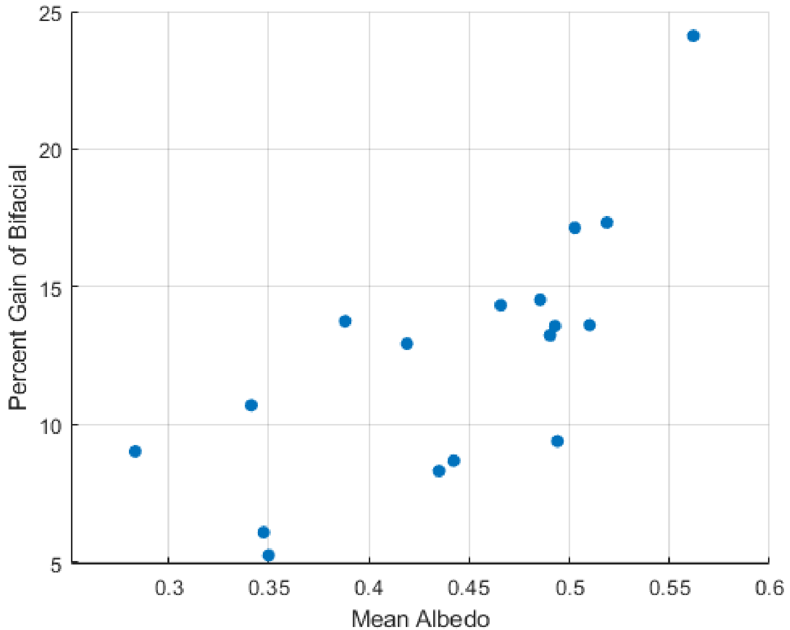


Results

Effect of Latitude



Effect of Albedo (Snow)



Annual mean albedo

Both Latitude and Snow duration are positively correlated and both are positively correlated with E-facing, vertical bifacial gains.

Case for Rethinking PV Design in the Far North?

- Bifacial PV modules are becoming available
  - Costs will come down as production increases.
- E-W Vertical bifacial may have advantages
  - Capable of 5-20% more energy than traditional designs.
  - Power profile is wider and may better match loads.
  - Vertical modules may shed snow better & collect less dirt.
- E-W Vertical bifacial challenges (opportunities?)
  - Commercial racking solutions for vertical bifacial is not developed.
  - Field layout to minimize shading needs to be designed.
  - Testing standards for bifacial modules is still under development.
- Sandia and UAF are collaborating on collecting needed field data in Fairbanks.

UAF – Sandia Bifacial PV Field Site