National Renewable Energy Laboratory
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Spectral Effects in CPV Performance

NREL
Test & Evaluation

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Reliability Workshop
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Outline

- Overview of NREL CPV testbed
- Overview of Spectral Variation as it relates to triple junction PV cells
- AirMass based Spectral corrections for 3 distinct modules on-sun @ NREL
- Baseline PV USA ratings for the same modules
- Predicted energy performance comparison for 2009 in Golden CO, based on the AM corrections specific to 2009 Golden, CO data
- Conclusions and continuing work

NREL CPV Testbed

- 2-axis tracker (+/-0.15 degree sun pointing error)
- Data acquisition provides module peak power tracking
- IV sweeps, 5 minute intervals
- DNI, GNI, wind speed, Tambient, Tmodule, and tracking error are measured and recorded with module electrical measurements
- Spectral data is available from SRRL (Mesa top adjacent tracker location)
- First CPV modules mounted in February, 2009
- All modules under measurement to this point contain III-V triple junction cells
- All modules are high concentration ~500 suns or greater

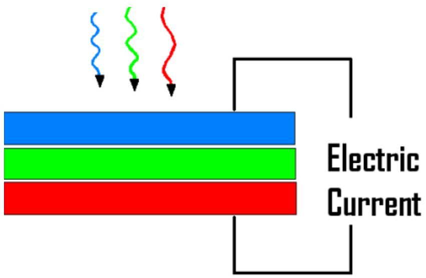
Triple Junction Cells and G173/AM1.5 spectrum

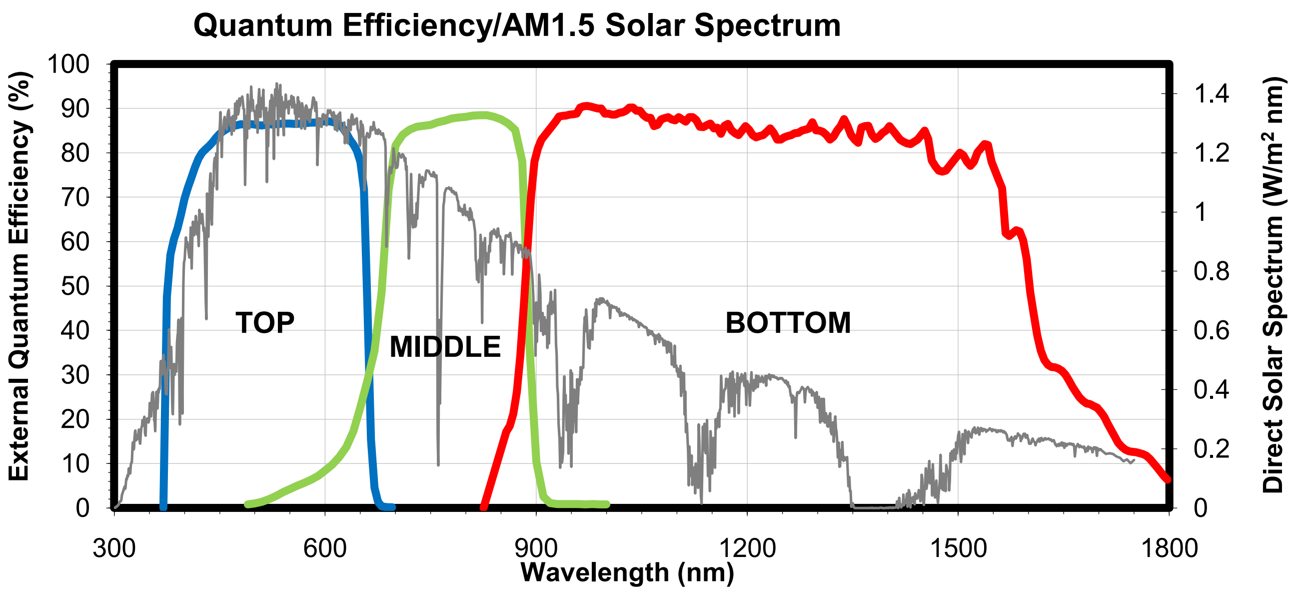
- Junctions are in series and therefore the cell must operate according to the junction with the lowest current

- Bottom junction produces excess current and typically will not be the limiting junction

- For G173-03/AM1.5 Top/Middle junctions are current matched for peak performance

- In a red rich spectrum the top junction limits while in blue rich the middle junction limits



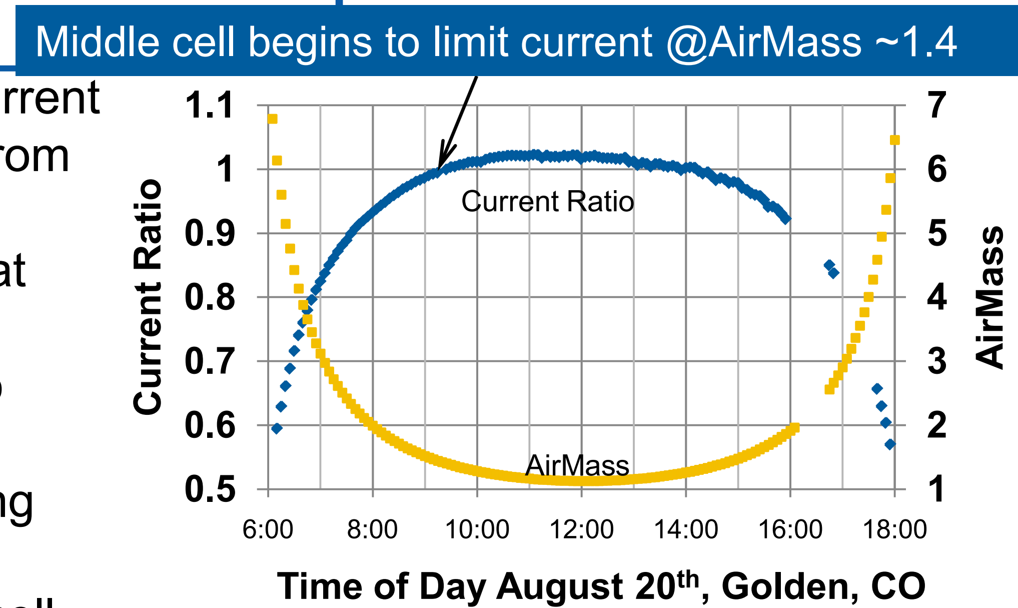


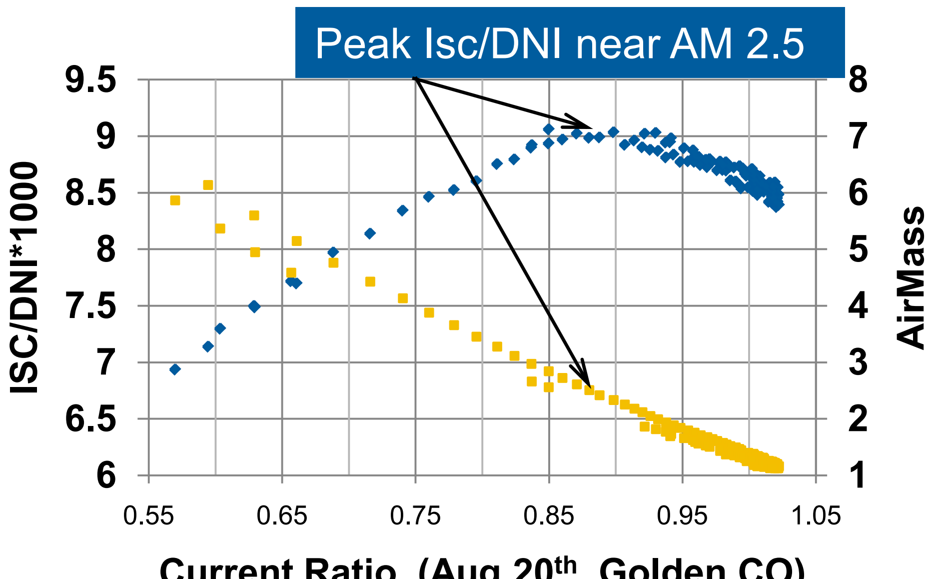
Factors Causing Deviations from G173 Spectrum

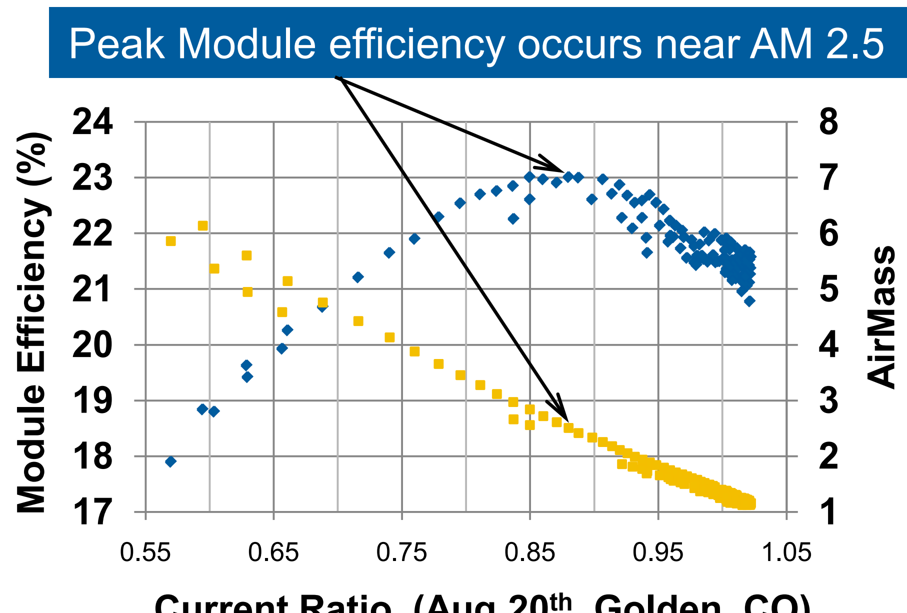
- **AirMass** (path length through atmosphere which is a function of the zenith angle) greater path length results in increased Rayleigh scattering of blue light.
  - Ranges from 1-5 when CPV produces significant power
  - AM1 blue rich spectrum (middle junction limits current)
  - AM5 red rich spectrum (top junction limits current)
- **Aerosols or Turbidity**, particles in the air that result in radiation attenuation in the range of 400 to 2000 nm. The rate of attenuation decreases with wavelength but is dependent on the quantity and size of particles.
  - G173 specifies a Turbidity of 0.084 @ 500 nm
  - 0.05 to .3 common range in U.S.
  - Boulder,CO ~0.05 winter months, ~0.09 summer months
- **Precipitable Water Vapor, PWV,** (cm of condensed water vapor in the vertical direction) Water vapor absorption bands (720, 820,940,1100, 1380, 1870, 2700, and 3200nm).
  - Absorption in the wavelengths corresponding with the bottom junction are the strongest. The bottom junction does not limit current and therefore PWV impacts performance primarily through efficiency measurements. (Efficiency = Pmax/DNI) As PWV increases DNI will decrease more than Pmax resulting in an increase in efficiency.
  - G173 specifies a PWV of 1.42 cm.
  - 0-4 cm is a common range of PWV
  - Boulder,CO ~0.6 cm winter, 1.7 cm summer
  - An increase from 0 to 0.4cm PWV decreases radiation by 10% while an increase from 0.4 to 4cm only decreases radiation an additional 10%.

Performance of cell /module under measured spectral conditions

•Upper right graph, ratio of top junction current to the middle junction current calculated from Q.E. data and measured spectra
•Lower left graph, module Isc/DNI peaks at AM2.5
•Lower right graph, module efficiency also peaks near AM2.5
• Generally, plots are repeatable for varying spectrum, temperatures, and time of year
•Consider optics, multiple cells in series, cell QE deviation from manufacture specs



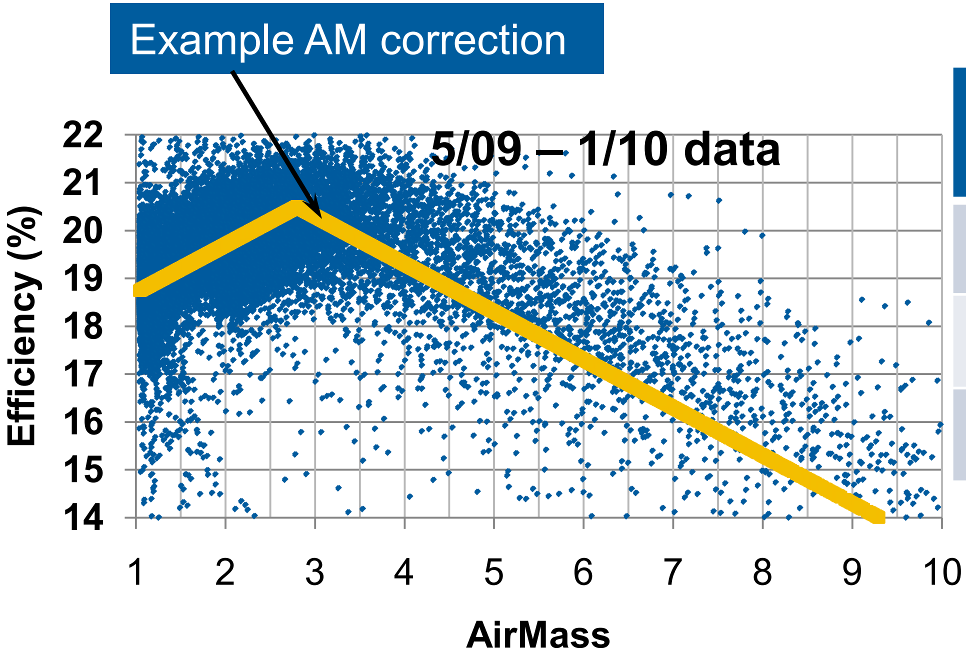




Multi-Month Data Analyzed to Predict Module Performance

- Performance variation was examined in terms of temperature and spectral effects
  - Ultimately AirMass was the only factor used in predicting performance variation
  - Issues such as heat sink variation make it difficult to accurately predict cell temperature
  - Uncertainty in turbidity measurement was often greater than day to day variation
  - PWV measurement device is in need of calibration that occurs in mid-2010
  - Spectroradiometer measurements are not available for the entire data set and the instrument is currently under repair
- AirMass Correction applied: $Rated\ Efficiency - a|AM - b|$

$a = rate\ efficiency\ changes\ with\ AM,\ \ b = AM\ at\ which\ the\ efficiency\ peaks$



Module	PVUSA Efficiency	AM Peak	Rate of Change
1	25.5	1.7	1.6
2	20	2.8	1
3	22.4	2.5	0.95

PVUSA Ratings for 3 Modules

PV USA Ratings (850 W/m2, 20C Ambient, 4m/s wind)													
Module #		March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	AVG
1	Power (W)	69.5	68.2	69.5	71.3	72	72.5	72	69.9	68.7	70.9	67.9	70.2
	%S.E. *	1.90%	3.50%	2.10%	2.40%	2%	1.00%	1.70%	2.80%	4.20%	3.70%	2.20%	
	# of data	111	339	227	734	466	499	176	932	1156	172	88	
2	Power (W)			77.2	78.4	78.9	79.3	82.1	79.1	78.1	81.1	75.9	78.9
	%S.E. *			2.50%	2.90%	1.70%	1.70%	1.50%	2.90%	2.50%	2.00%	2.20%	
	# of data			228	741	464	497	166	930	1157	172	87	
3	Power (W)			111	110	110	107	107	105	104	106	99.5	106.6
	%S.E. *			1%	2.60%	1%	0.80%	1.10%	1.9%	2.7%	1.9%	1%	
	# of data			112	702	465	502	179	939	1155	172	85	

*% standard error

Predicted Energy Comparison 2009 @ NREL

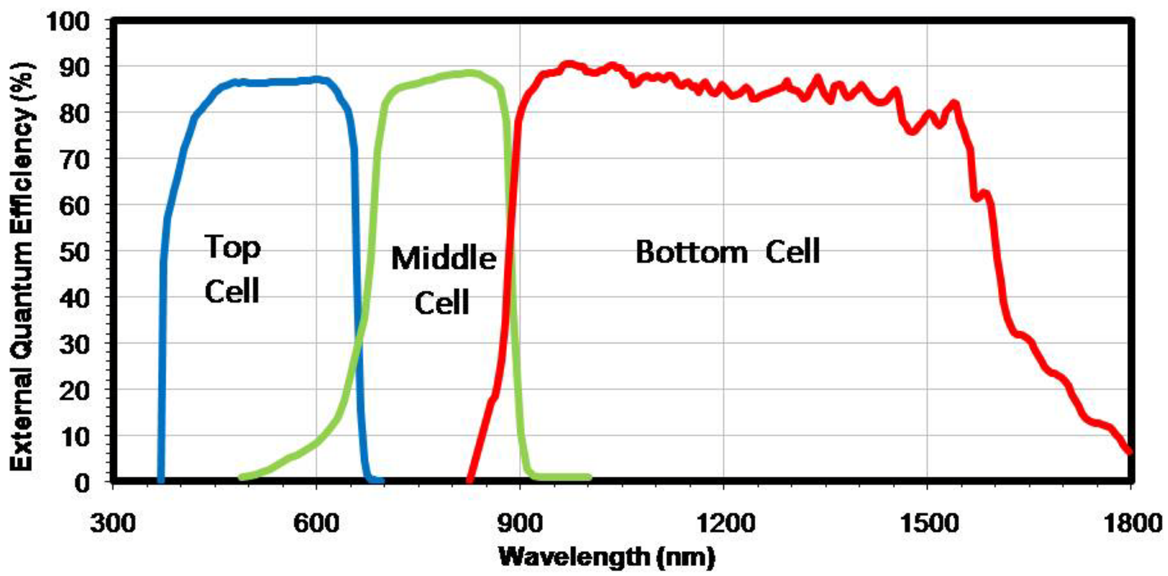
- AM corrections are used to gauge the impact of spectral variations
- To Normalize the comparison a 25% efficiency is applied to all AM corrections
- SRRL 1 minute average DNI data is used for the energy availability

2009, NREL	Module 1 25%-1.6|AM-1.7|	Module 2 25%-1|AM-2.8|	Module3 25%-0.95|AM-2.5|
Jan-March KWH	118.07	120.74	121.69
April-June KWH	113.70	113.22	114.52
July-Sept KWH	130.44	130.04	131.50
Oct-Dec KWH	97.84	101.96	102.55
2009 total KWH	460.05	465.95	470.27

A fixed efficiency of 25% results in 493.5 KWH for 2009
~ 7% difference in energy produced between fixed efficiency and Module1
~2.2% difference in energy produced between Module 1 and Module3

Summary

- CPV module performance data clearly shows spectral sensitivity
  - Clearly defined AM response peak
  - Relative sensitivity to changing AM can be determined
- PVUSA ratings taken on a monthly basis vary from 5-10%, most likely a result of spectral sensitivity
- Spectral sensitivity, as measured through an AM correction factor for 2009 data, results in significant deviations in energy production.
  - 2.2% deviation between modules
  - 7% deviation between spectrally sensitive module and a module with a fixed efficiency
- Future work will examine specific impact of AM, PWV, and Turbidity on Normalized Isc



100
90
80
70
60
50
40
30
20
10
0
External Quantum Efficiency (%)
300
600
900
1200
1500
1800
Wavelength (nm)
Top
Cell
Middle
Cell
Bottom Cell