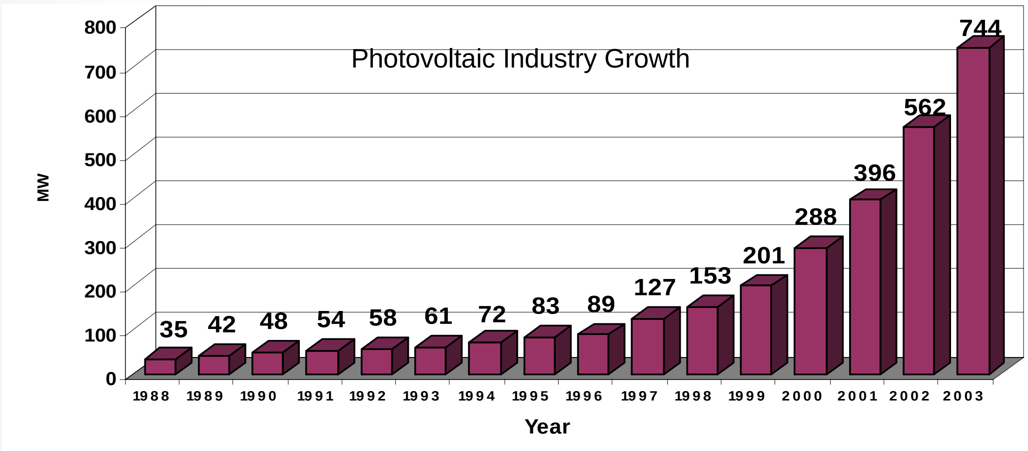
Measured Versus Predicted Photovoltaic Performance

National Institute of Standards and Technology
Gaithersburg, Maryland 20899

Background

- NIST Team:
  - Staff – A. Hunter Fanney, Brian Dougherty, Mark W.Davis
  - Students – Steven Bushey, Paul Shinneman
- Supporting Characters
  - David L. King – Sandia National Laboratories (SNL)
  - Mike Pelosi – Maui Solar Energy Software Corporation
- Project Responds to Barriers Facing PV Industry
  - Lack of Validated Performance Prediction Models
  - Unbiased In-Situ Performance Data

PV Cell Manufacturers	
Sharp	General Electric
Kyocera	Sanyo
RWE Schott	Uni-Solar
BP Solar	First Solar
Shell Solar	Global Solar



Source -Photovoltaic News, April 2004

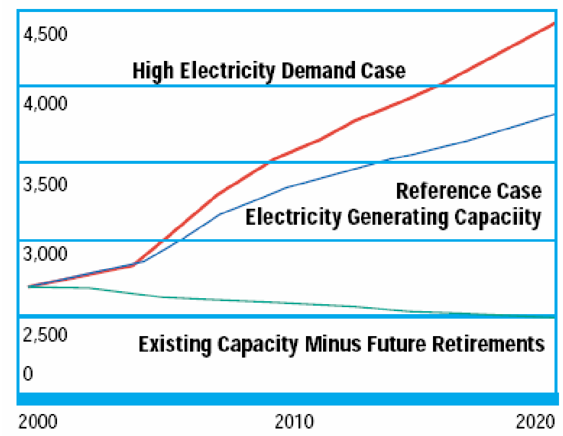
Motivating Dynamics

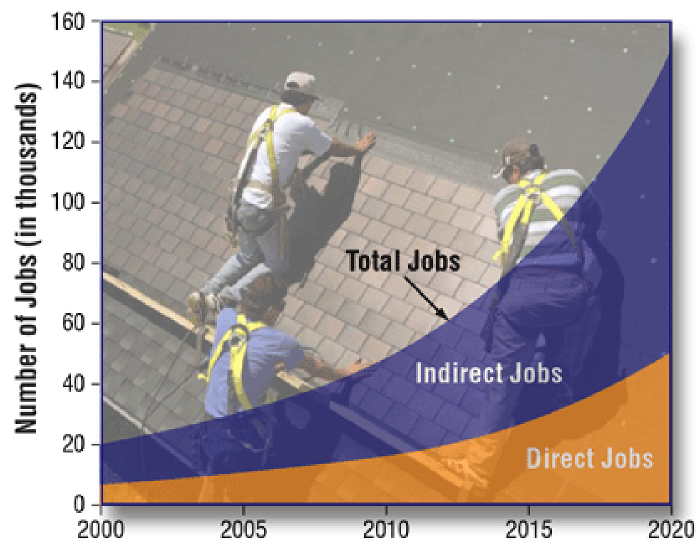
- World Energy Consumption is Projected to Increase by 54% by 2025 (*Energy Information Administration)*
- U.S. Will Need The Equivalent of 60 to 90 New Power Plants Per Year for the Next 20 Years
- Photovoltaic Systems
  - Reduce Need for Additional Power Plants
  - Provide Energy During Disasters/Terrorism
  - Provide Job Growth
  - Reduce Emissions
  - Eliminate Electrical Transmission Losses (5 -15%)

Power Outages Cost the U.S. Economy
$119 Billion/Year
Brokerage Operations - $6,480,000/hour
Credit Card Operations - $2,580,000/hour

Source – Teleconnect Magazine, June 2004

The U.S. Needs More Power Plants





Project Objective

- Quantify SNL's Performance Model's Ability to Predict Photovoltaic Module Performance
  - Using Vertical Irradiance
  - Using Horizontal Irradiance
    - Perez Radiation Model
- Provide Experimental Data for
  - PV Technology Comparisons
  - Other Model Validation Efforts

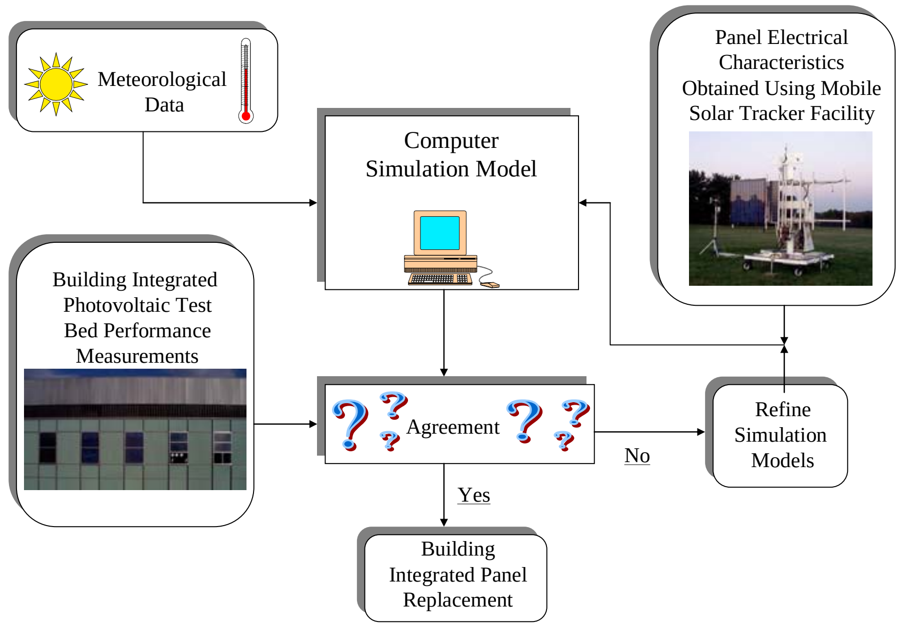
Scope

- Photovoltaic Modules Only
- Vertical South-Facing Façade BIPV Installation
  - Gaithersburg, MD (Latitude 39.1, Longitude 77.2)
- 12 Month Comparison
  - January 1 - December 31, 2004
  - 5 Minute Data Collection Interval
- Various Cell Technologies and Glazings
  - Monocrystalline with Glass
  - Polycrystalline with
    - Glass
    - Tefzel
    - Kynar
  - Tandem Junction with Glass
    - With Extruded Polystyrene Rear Insulation (3.5 $m^2 \cdot K/W$)
    - Without Insulation
  - Copper Indium Diselenide
    - With Extruded Polystyrene Rear Insulation (3.5 $m^2 \cdot K/W$)
    - Without Insulation

Methodology

- Characterize Photovoltaic Panels
  - Temperature Coefficients
  - Incident Angle Response
  - Air Mass (Solar Spectrum) Response
  - Performance at Standard Rating Conditions
- Measure Photovoltaic Panel Performance
  - Vertical Façade
  - 5 Minute Data Collection Internal
- Measure Meteorological Conditions
  - Vertical Irradiance
  - Horizontal Irradiance
- Run Simulation Model
- Compare Predicted to Measured Results

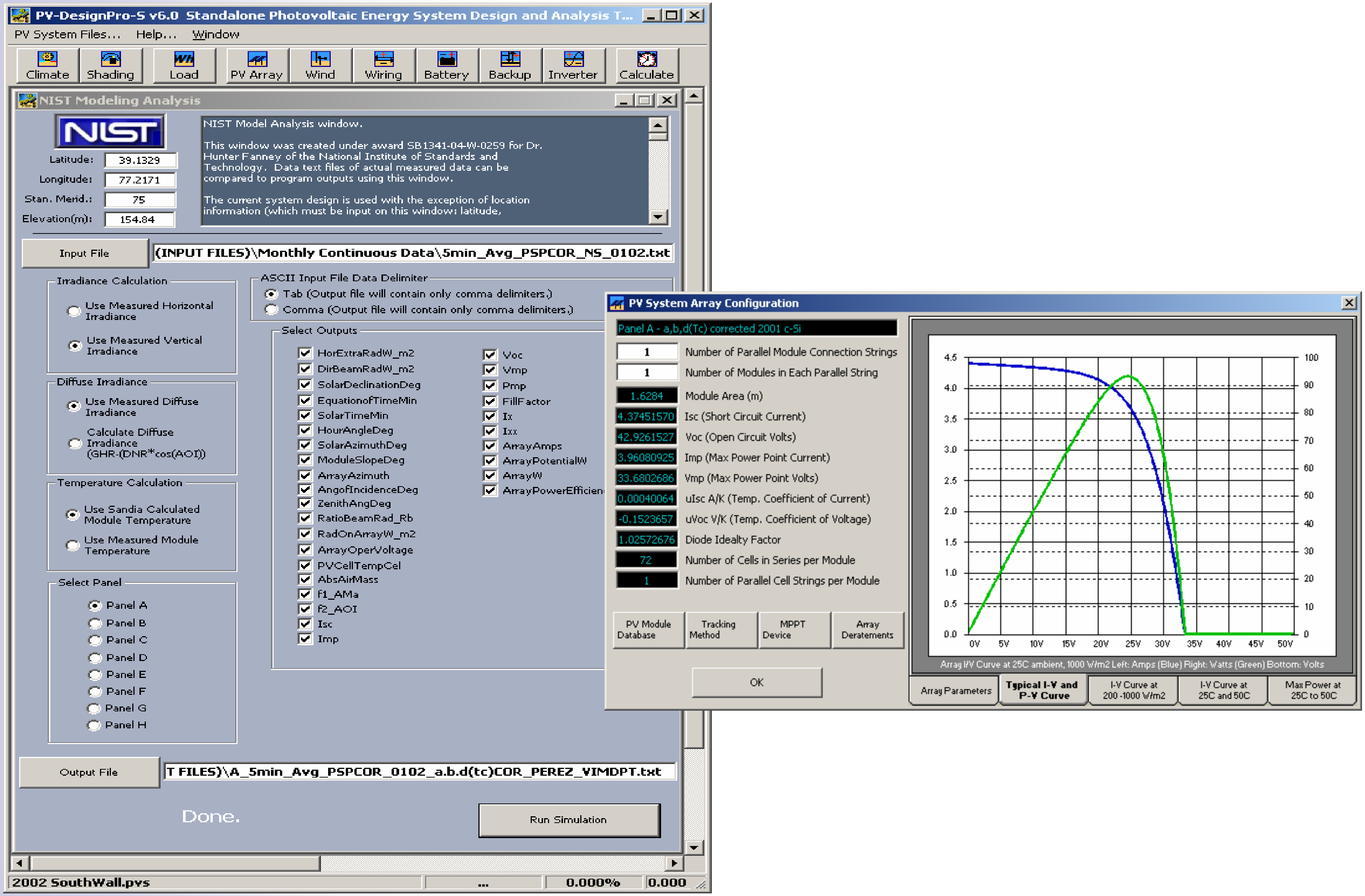
NIST's Building Integrated Photovoltaic Program



Simulation Model

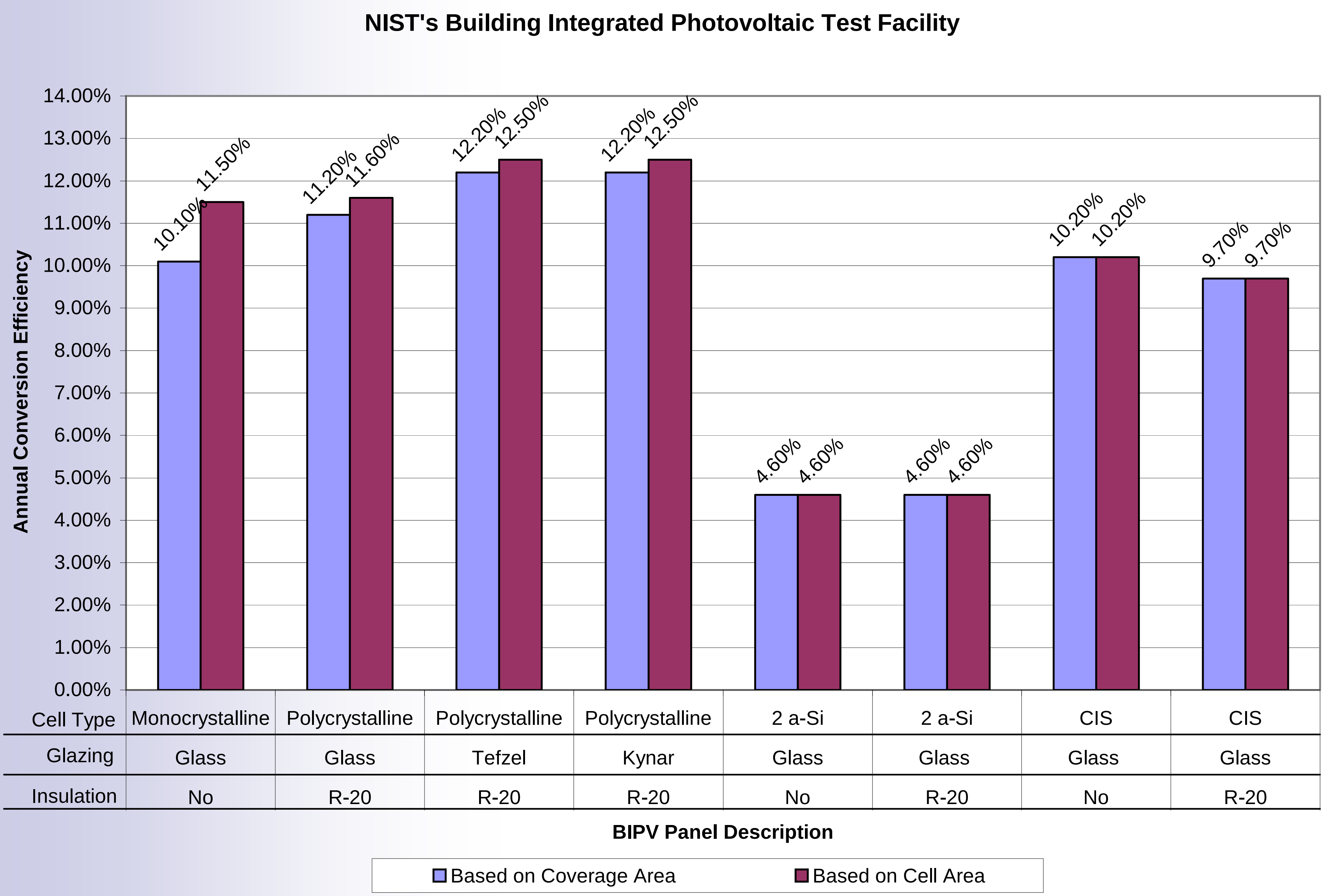
- PV Design Pro
  - Algorithms Based on SNL's Photovoltaic Model (King et al.)
    - PVFORM (1986) -> PVMOD (1998) -> PV-DesignPro (1999-Present)
  - User Selected
    - Modules (SNL's Database > 200 Modules)
    - Inverters, Wiring, Battery Storage, etc.
- NIST's Custom PV Design Pro
  - Focused on PV Modules Only
  - Modules Assumed to be Operated at Max Power Point
  - Input Data Includes
    - NIST Measured Performance
    - Vertical Irradiance Measurements
    - Horizontal Irradiance Measurements
  - Incorporates Graphical Tools That Facilitate
  - Measured Versus Predicted Comparisons
    - Power
    - Isc, Imp
    - Voc, Vmp

PV Design Pro Input Screens



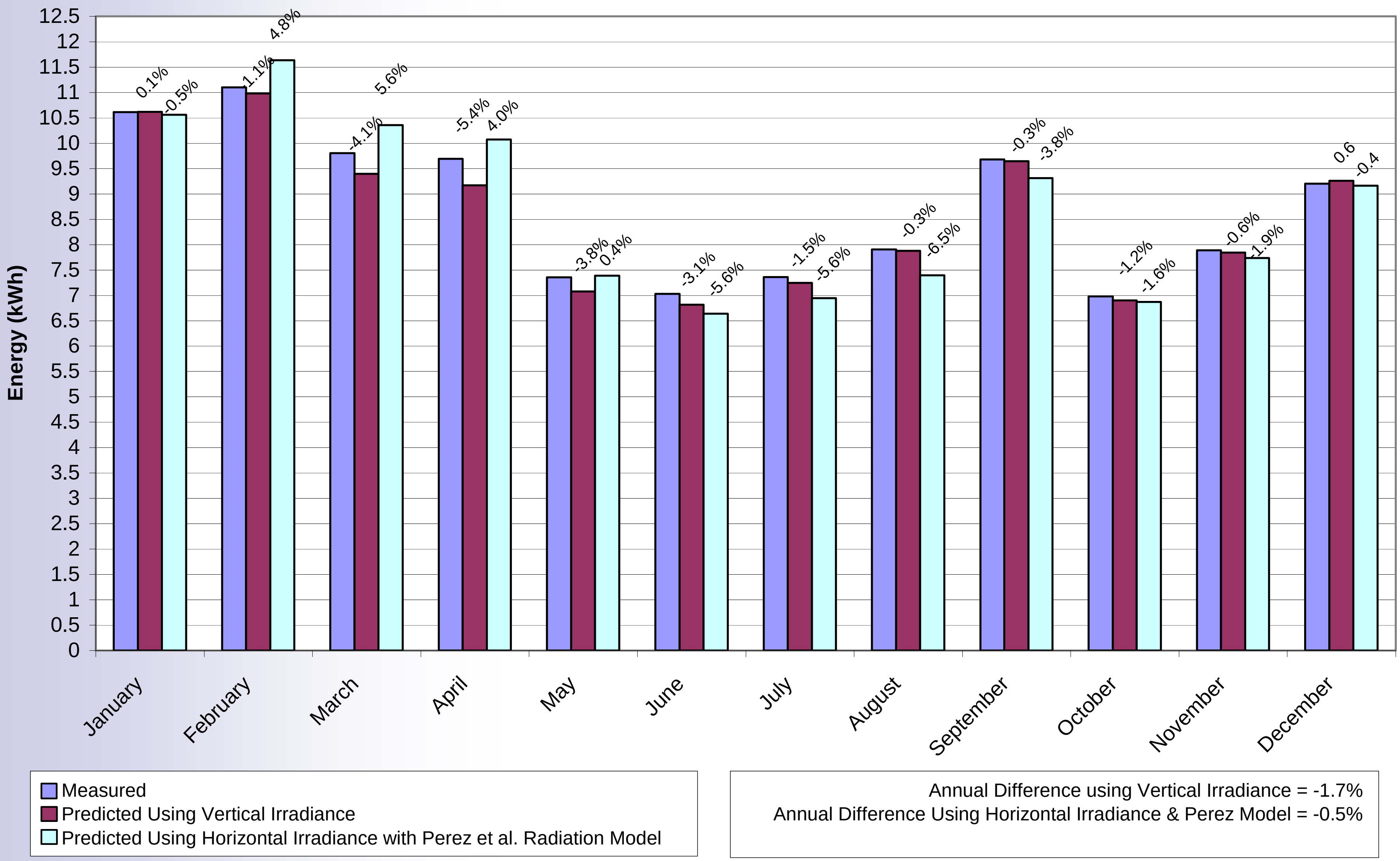
Comparison Results

- Installation
  - Vertical Façade
  - South Facing
  - Modules Only
- Photovoltaic Modules
  - Four Different Cell Technologies
  - Three Different Glazing Materials
  - Insulated and Non-Insulated
- Measurement Uncertainties (k=2)
  - Energy 1.0%
  - Solar Irradiance 2.3%
  - Module Efficiencies 2.5%

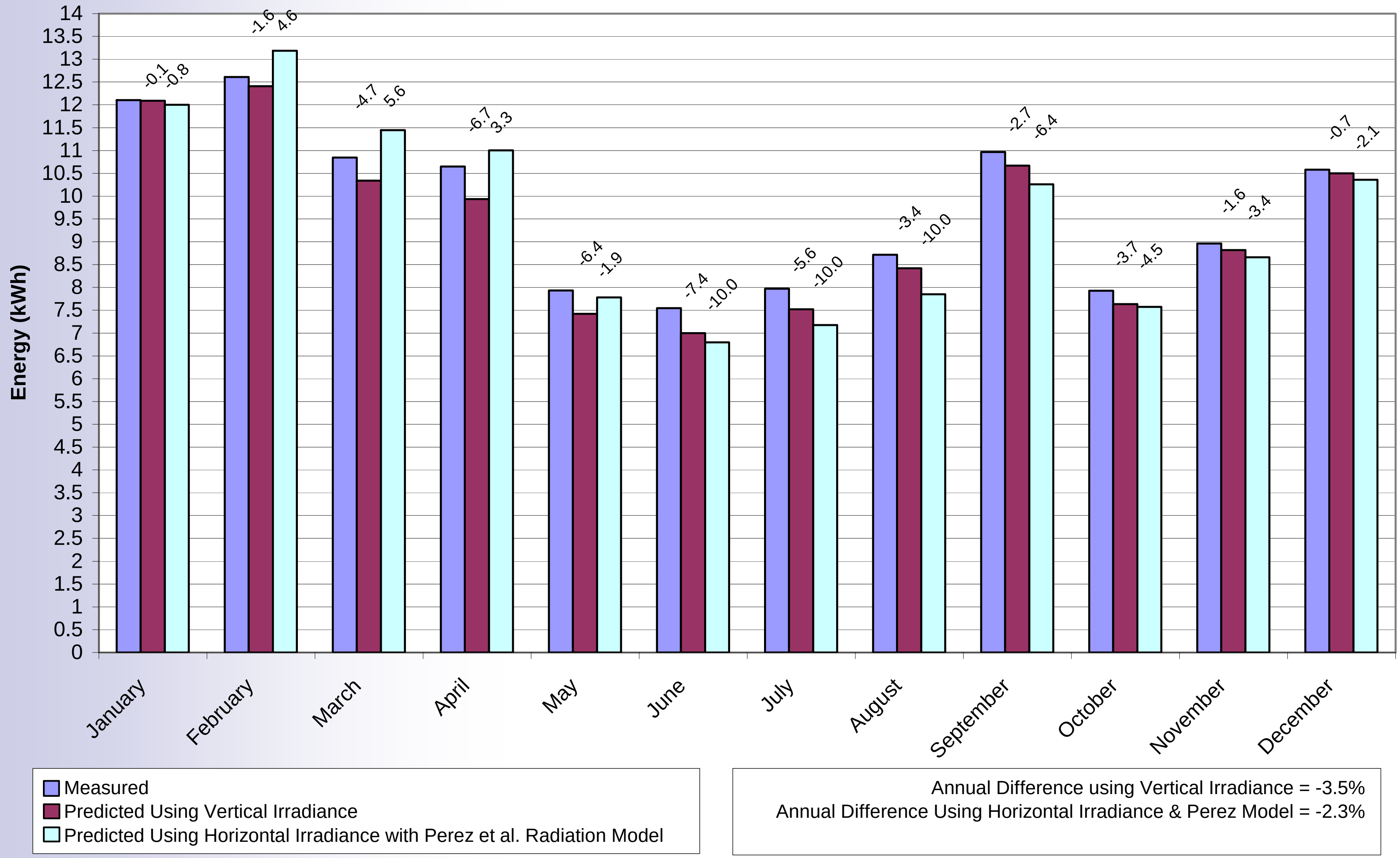


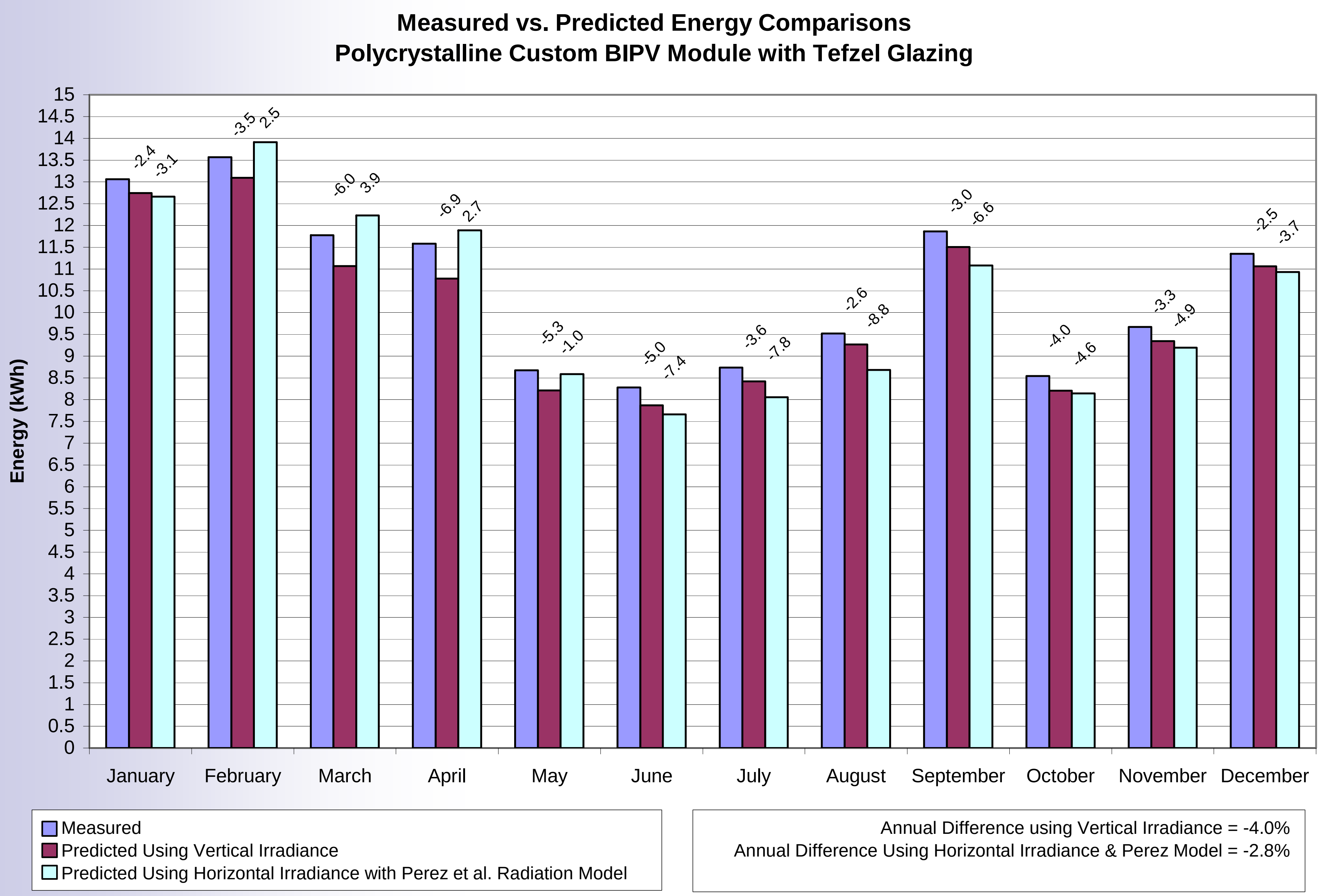
NIST's Building Integrated Photovoltaic Test Facility
Annual Conversion Efficiency
14.00%
13.00%
12.00%
11.00%
10.00%
9.00%
8.00%
7.00%
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
10.10%
11.50%
11.20%
11.60%
12.20%
12.50%
12.20%
12.50%
4.60%
4.60%
4.60%
4.60%
10.20%
10.20%
9.70%
9.70%
Cell Type
Monocrystalline
Polycrystalline
Polycrystalline
Polycrystalline
2 a-Si
2 a-Si
CIS
CIS
Glazing
Glass
Glass
Tefzel
Kynar
Glass
Glass
Glass
Glass
Insulation
No
R-20
R-20
R-20
No
R-20
No
R-20
BIPV Panel Description
Based on Coverage Area
Based on Cell Area

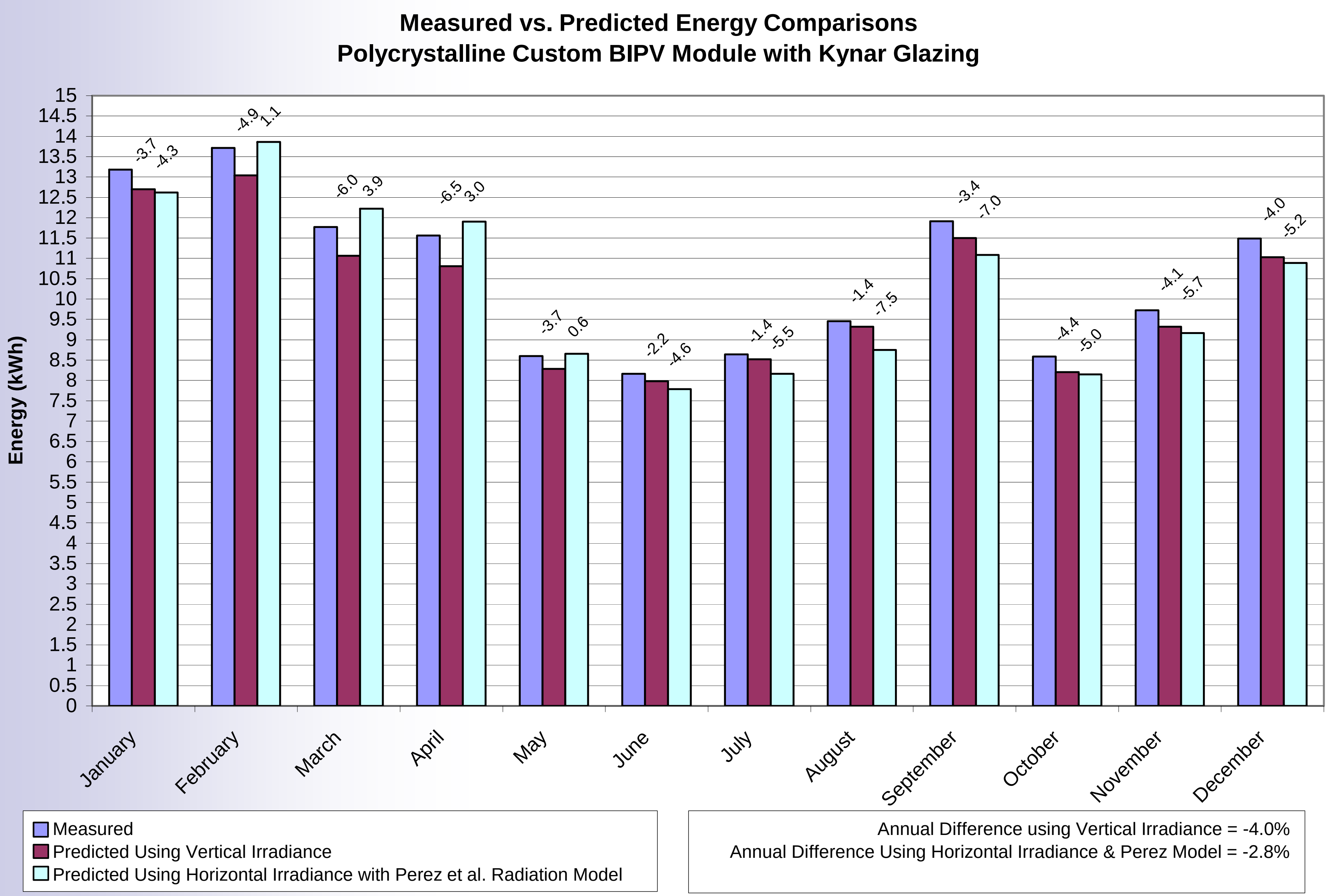
Measured vs. Predicted Energy Comparisons
Monocrystalline Custom BIPV Module with Glass Glazing



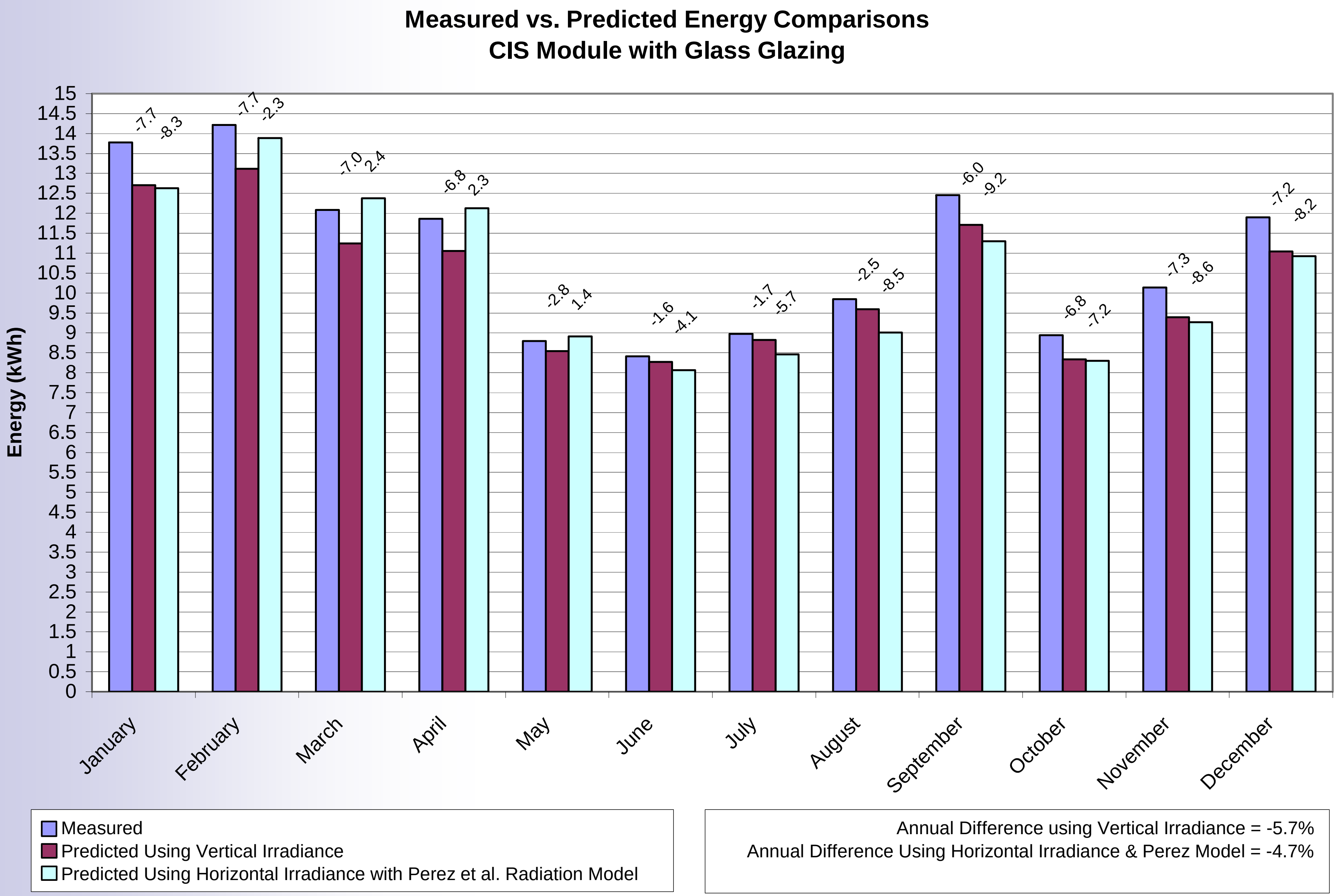
Measured vs. Predicted Energy Comparisons
Polycrystalline Custom BIPV Module with Glass Glazing



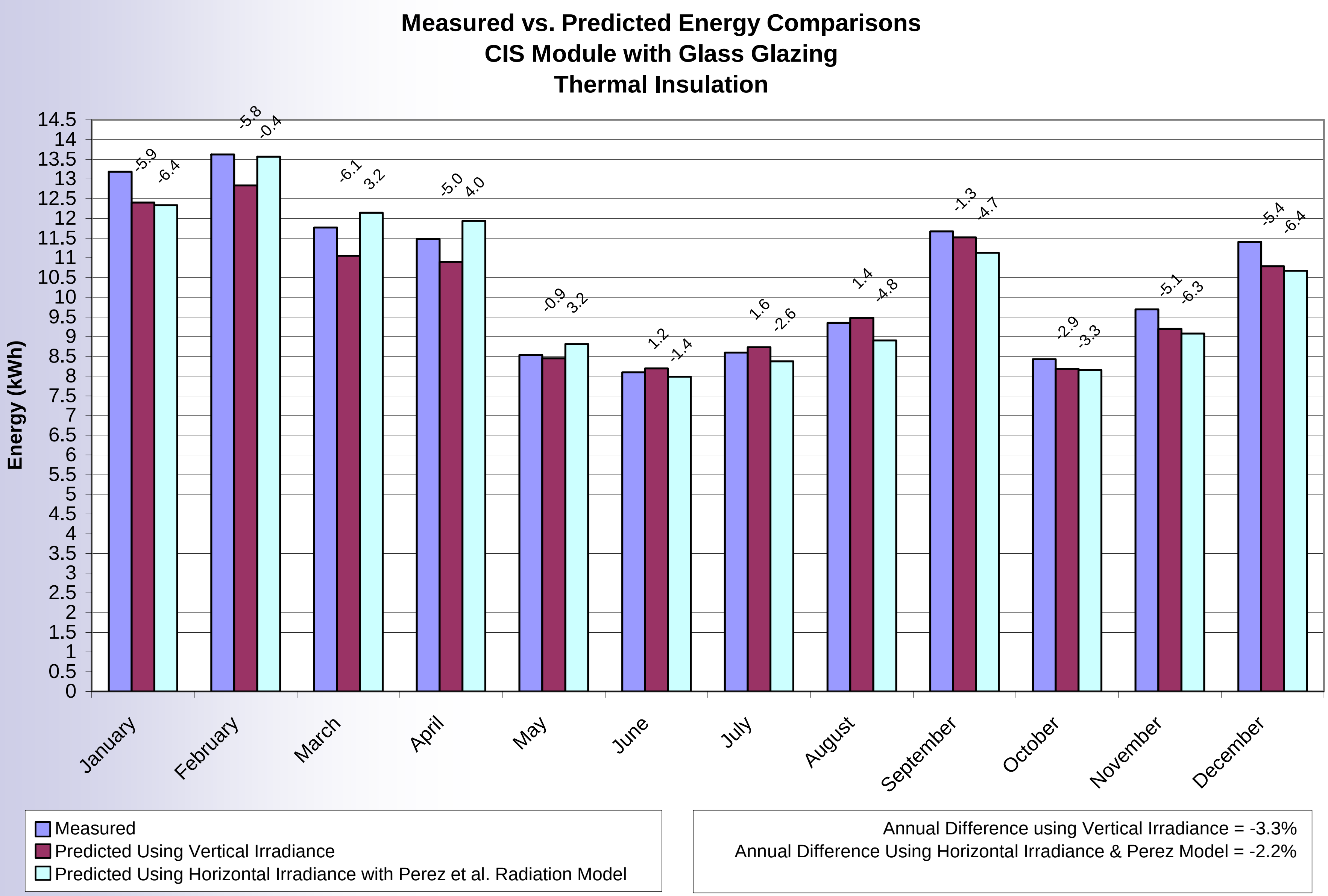

Measured vs. Predicted Energy Comparisons
Polycrystalline Custom BIPV Module with Tefzel Glazing
Energy (kWh)
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-2.4
-3.1
-3.5
2.5
-6.0
3.9
-6.9
2.7
-5.3
-1.0
-5.0
-7.4
-3.6
-7.8
-2.6
-8.8
-3.0
-6.6
-4.0
-4.6
-3.3
-4.9
-2.5
-3.7
January
February
March
April
May
June
July
August
September
October
November
December
Measured
Predicted Using Vertical Irradiance
Predicted Using Horizontal Irradiance with Perez et al. Radiation Model
Annual Difference using Vertical Irradiance = -4.0%
Annual Difference Using Horizontal Irradiance & Perez Model = -2.8%



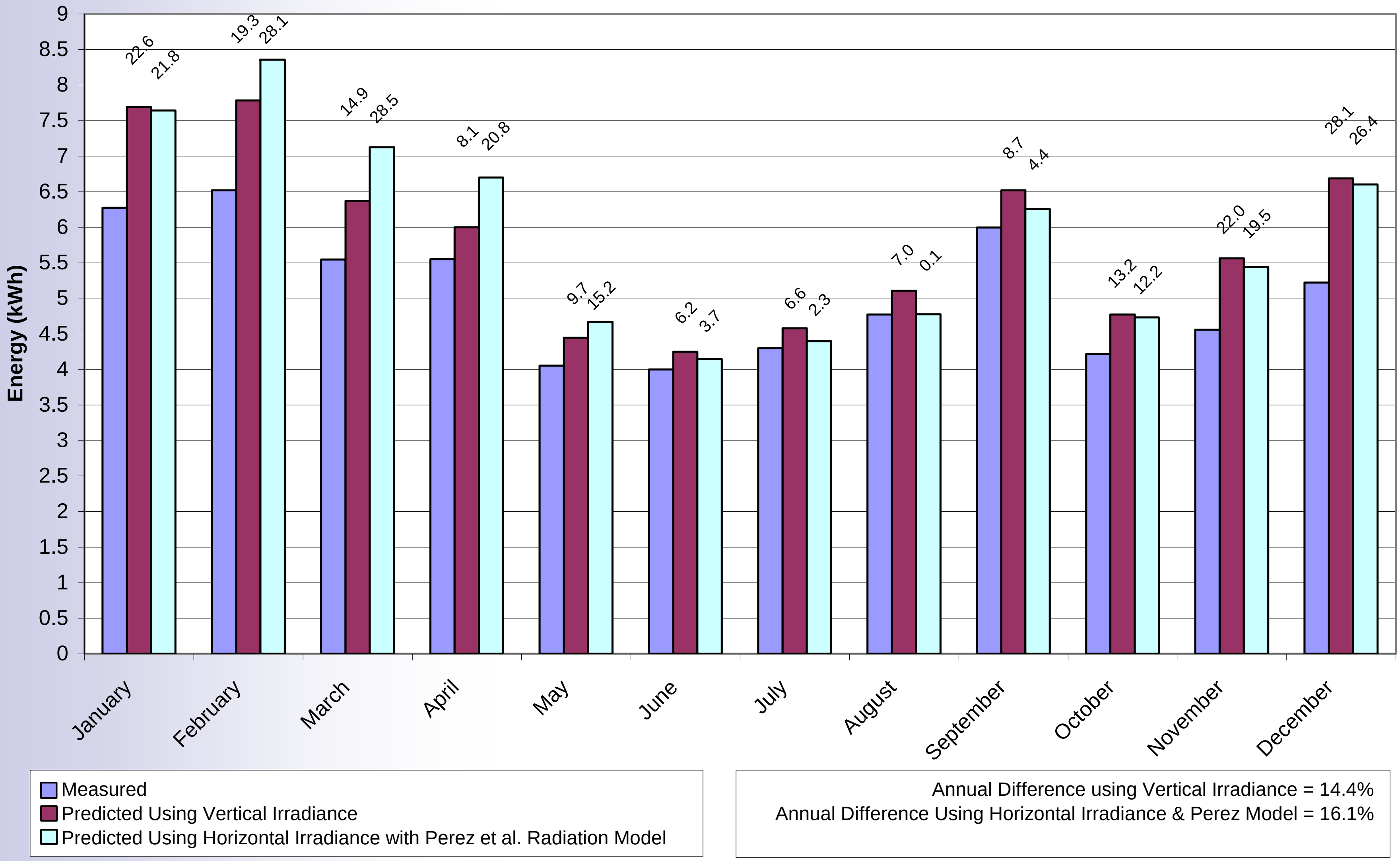
Measured vs. Predicted Energy Comparisons
Polycrystalline Custom BIPV Module with Kynar Glazing
Energy (kWh)
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-3.7 -4.3
-4.9 1.1
-6.0 3.9
-6.5 3.0
-3.7 0.6
-2.2 -4.6
-1.4 -5.5
-1.4 -7.5
-3.4 -7.0
-4.4 -5.0
-4.1 -5.7
-4.0 -5.2
January
February
March
April
May
June
July
August
September
October
November
December
Measured
Predicted Using Vertical Irradiance
Predicted Using Horizontal Irradiance with Perez et al. Radiation Model
Annual Difference using Vertical Irradiance = -4.0%
Annual Difference Using Horizontal Irradiance & Perez Model = -2.8%



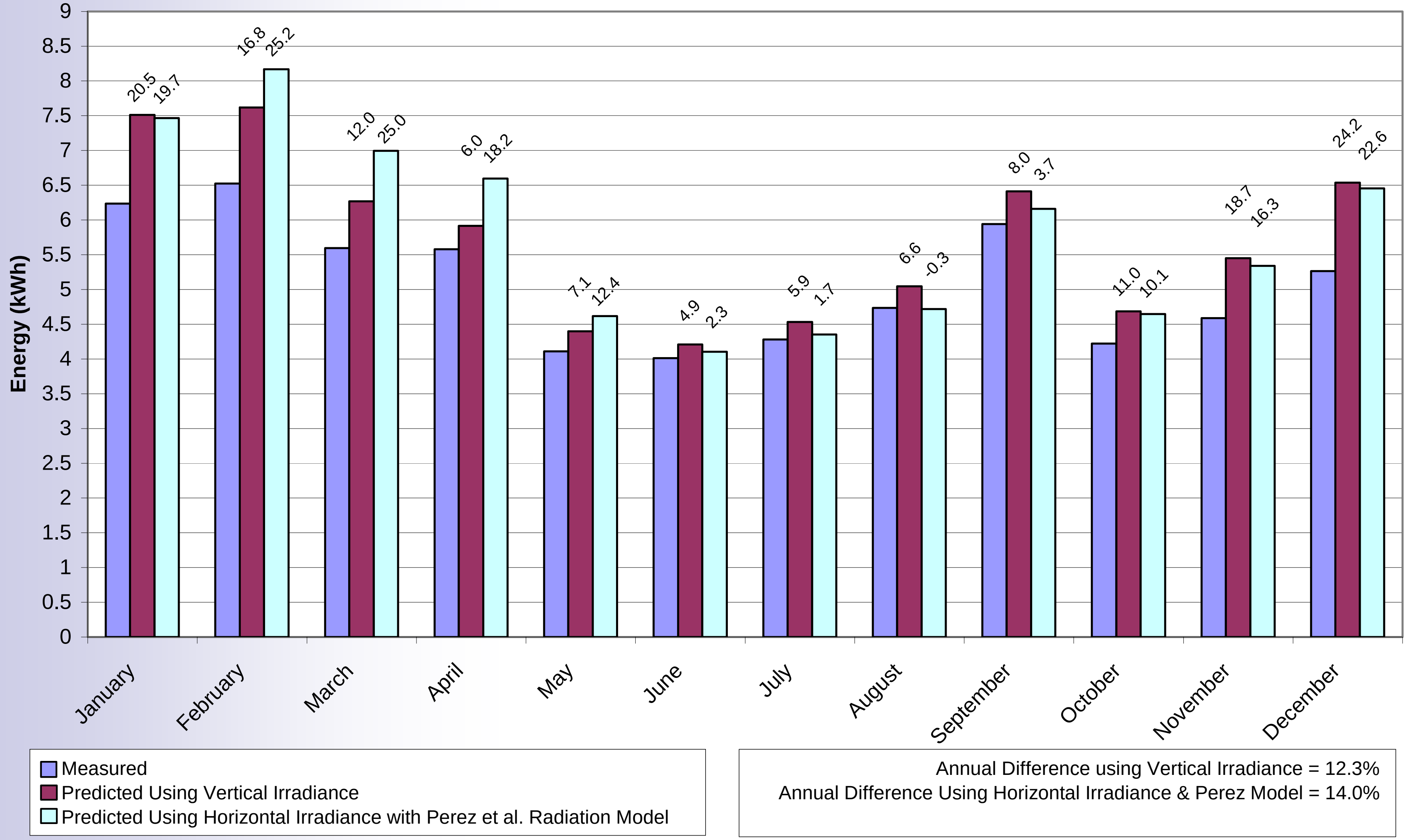
Measured vs. Predicted Energy Comparisons
CIS Module with Glass Glazing
Energy (kWh)
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-7.7
-8.3
-7.7
-2.3
-7.0
2.4
-6.8
2.3
-2.8
1.4
-1.6
-4.1
-1.7
-5.7
-2.5
-8.5
-6.0
-9.2
-6.8
-7.2
-7.3
-8.6
-7.2
-8.2
January
February
March
April
May
June
July
August
September
October
November
December
Measured
Predicted Using Vertical Irradiance
Predicted Using Horizontal Irradiance with Perez et al. Radiation Model
Annual Difference using Vertical Irradiance = -5.7%
Annual Difference Using Horizontal Irradiance & Perez Model = -4.7%


Measured vs. Predicted Energy Comparisons
CIS Module with Glass Glazing
Thermal Insulation
Energy (kWh)
January -5.9 -6.4
February -5.8 -0.4
March -6.1 3.2
April -5.0 4.0
May -0.9 3.2
June 1.2 -1.4
July 1.6 -2.6
August 1.4 -4.8
September -1.3 -4.7
October -2.9 -3.3
November -5.1 -6.3
December -5.4 -6.4
Measured
Predicted Using Vertical Irradiance
Predicted Using Horizontal Irradiance with Perez et al. Radiation Model
Annual Difference using Vertical Irradiance = -3.3%
Annual Difference Using Horizontal Irradiance & Perez Model = -2.2%

Measured vs. Predicted Energy Comparisons
Tandem Junction Module Original Characterization with Glass Glazing

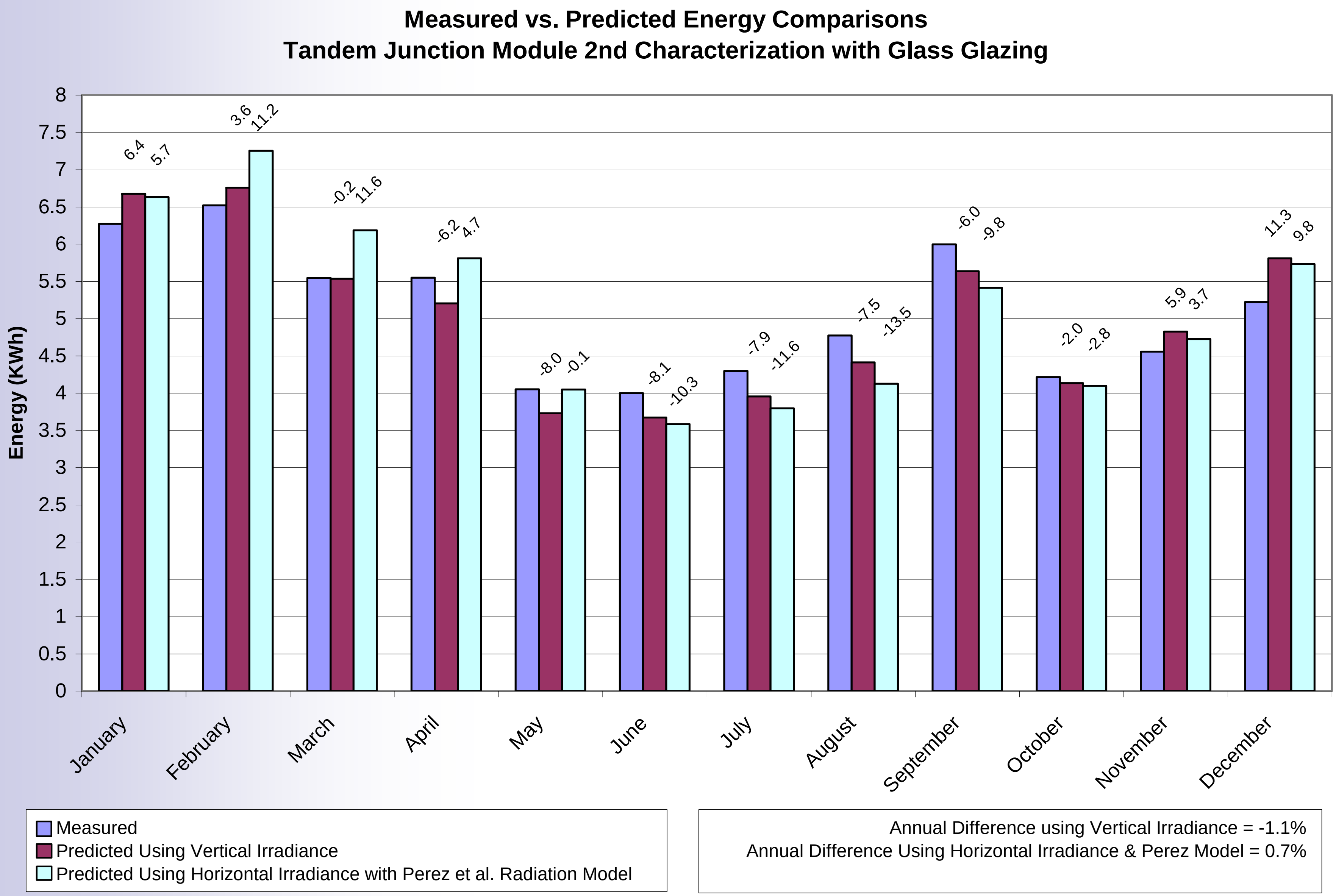


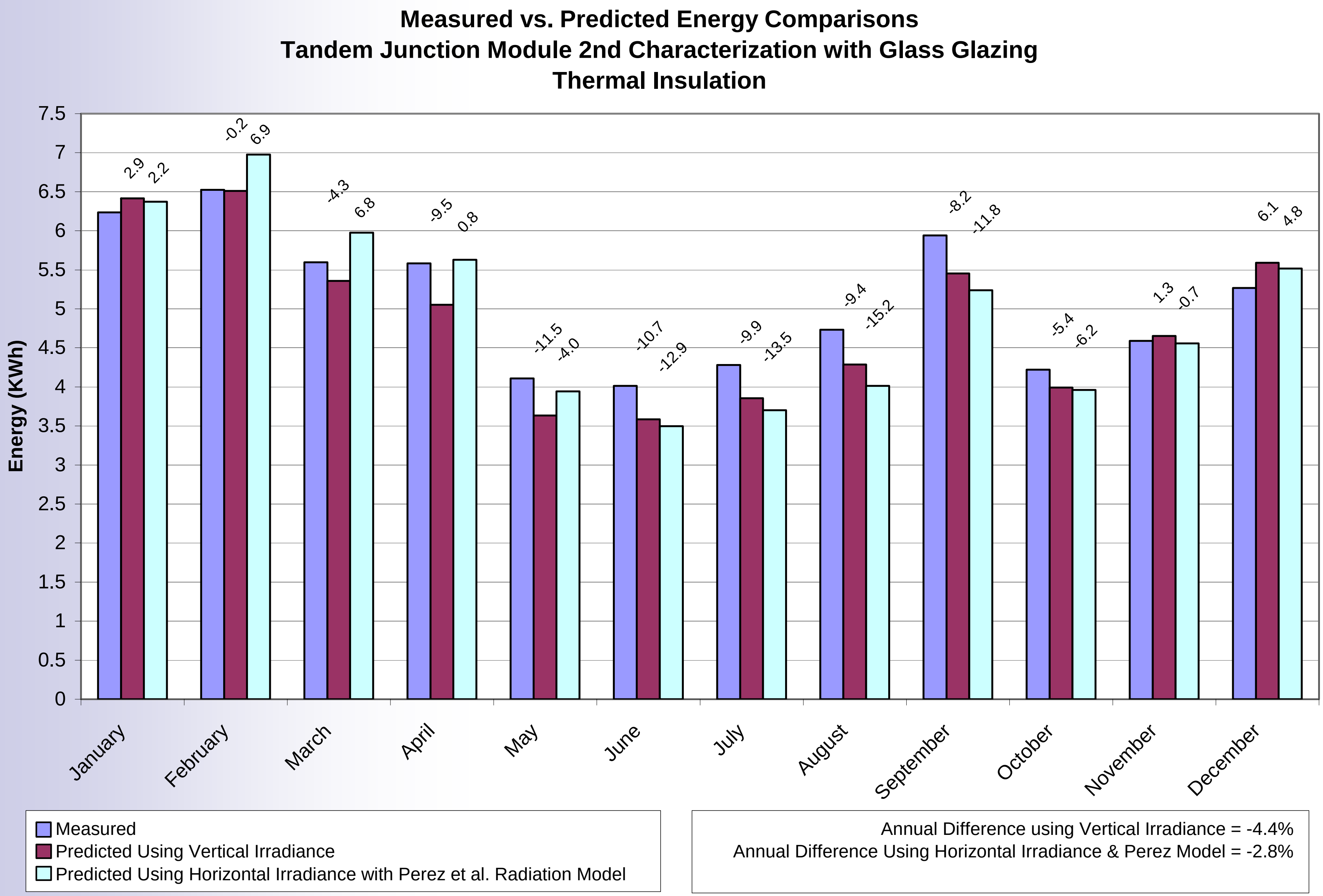
Measured vs. Predicted Energy Comparisons
Tandem Junction Module Original Characterization with Glass Glazing
Thermal Insulation



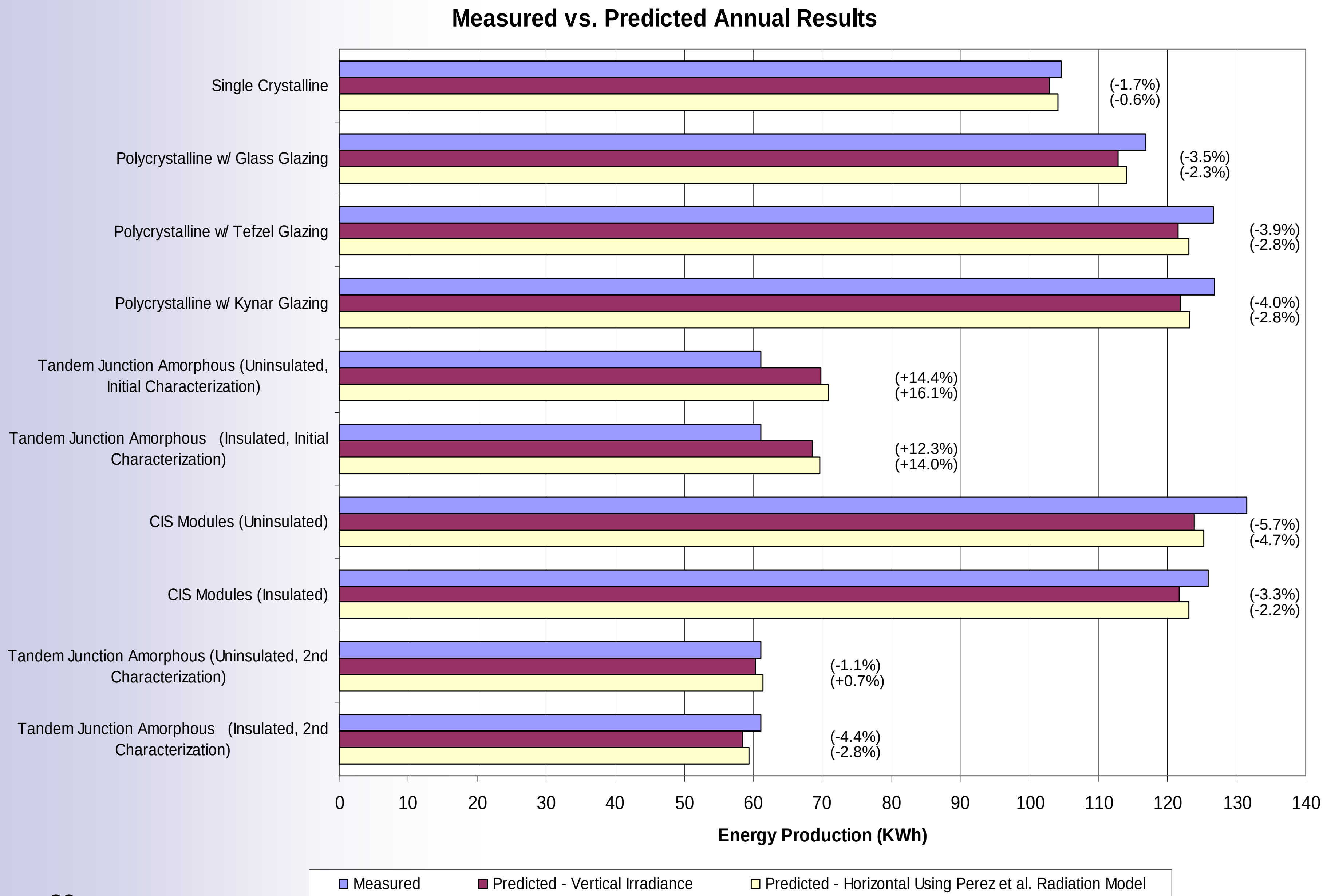
Tandem-Junction Amorphous Performance vs Exposure Time

Panel	Characterization/Tracker		BIPV-Insulated	BIPV-Noninuslated
Exposure Time	124h	344h	>14 months	>14 months
I_{sco}	0.73	0.71	0.69	0.68
I_{mpo}	0.61	0.59	0.56	0.55
V_{oco}	99.6	97.7	95.6	96.5
V_{mpo}	76.5	74.2	73.0	73.5
P_{mpo}	46.8	43.8	40.9	40.4


Measured vs. Predicted Energy Comparisons
Tandem Junction Module 2nd Characterization with Glass Glazing
Energy (KWh)
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
6.4
5.7
3.6
11.2
-0.2
11.6
-6.2
4.7
-8.0
-0.1
-8.1
-10.3
-7.9
-11.6
-7.5
-13.5
-6.0
-9.8
-2.0
-2.8
5.9
3.7
11.3
9.8
January
February
March
April
May
June
July
August
September
October
November
December
Measured
Predicted Using Vertical Irradiance
Predicted Using Horizontal Irradiance with Perez et al. Radiation Model
Annual Difference using Vertical Irradiance = -1.1%
Annual Difference Using Horizontal Irradiance & Perez Model = 0.7%



Measured vs. Predicted Energy Comparisons
Tandem Junction Module 2nd Characterization with Glass Glazing
Thermal Insulation
Energy (KWh)
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2.9
2.2
-0.2
6.9
-4.3
6.8
-9.5
0.8
-11.5
-4.0
-10.7
-12.9
-9.9
-13.5
-9.4
-15.2
-8.2
-11.8
-5.4
-6.2
1.3
-0.7
6.1
4.8
January
February
March
April
May
June
July
August
September
October
November
December
Measured
Predicted Using Vertical Irradiance
Predicted Using Horizontal Irradiance with Perez et al. Radiation Model
Annual Difference using Vertical Irradiance = -4.4%
Annual Difference Using Horizontal Irradiance & Perez Model = -2.8%


Measured vs. Predicted Annual Results
Single Crystalline
Polycrystalline w/ Glass Glazing
Polycrystalline w/ Tefzel Glazing
Polycrystalline w/ Kynar Glazing
Tandem Junction Amorphous (Uninsulated, Initial Characterization)
Tandem Junction Amorphous (Insulated, Initial Characterization)
CIS Modules (Uninsulated)
CIS Modules (Insulated)
Tandem Junction Amorphous (Uninsulated, 2nd Characterization)
Tandem Junction Amorphous (Insulated, 2nd Characterization)
(-1.7%)
(-0.6%)
(-3.5%)
(-2.3%)
(-3.9%)
(-2.8%)
(-4.0%)
(-2.8%)
(+14.4%)
(+16.1%)
(+12.3%)
(+14.0%)
(-5.7%)
(-4.7%)
(-3.3%)
(-2.2%)
(-1.1%)
(+0.7%)
(-4.4%)
(-2.8%)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Energy Production (KWh)
Measured
Predicted - Vertical Irradiance
Predicted - Horizontal Using Perez et al. Radiation Model

Conclusions

- Annual Conversion Efficiencies
  - Lowest - 4.6% 2 a-Si
  - Highest – 12.5% Polycrystalline
- Glazing Material Can Have Significant Impact
  - Glass Glazing – 11.6%
  - Tefzel Glazing – 12.5%
  - Kynar Glazing – 12.5%
- Excluding Tandem Junction Amorphous Panels, SNL Model Predicted Annual Energy Production Within
  - 5.7% Using Vertical Irradiance
  - 4.7% Using Horizontal Irradiance/Perez Model
  - Typically Under-predicts
- Initial Comparisons to Tandem Junction Amorphous Panels Poor
  - 14.4% Using Vertical Irradiance
  - 16.1% Using Horizontal Irradiance/Perez Model
- After Recharacterizing Tadem-Junction Amorphous Panels
  - 4.4% Using Vertical Irradiance
  - 2.8% Using Horizontal Irradiance/Perez Model