



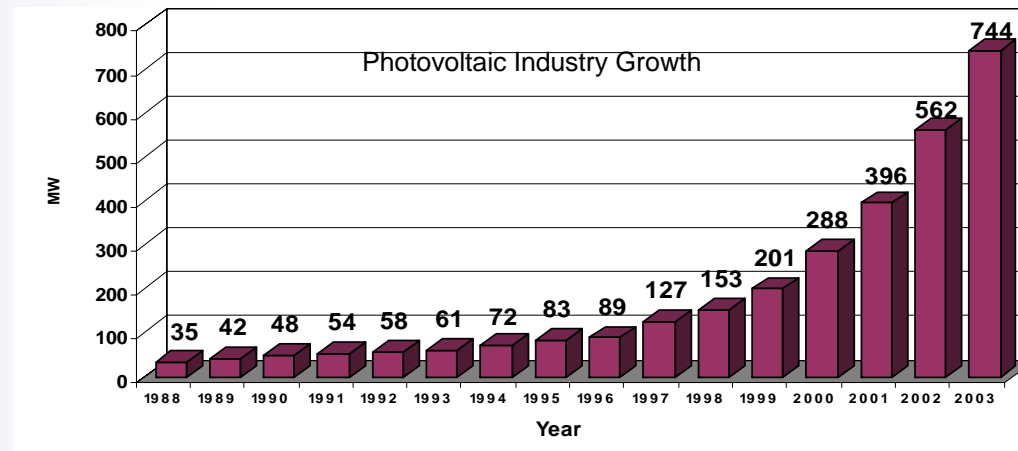
Measured Versus Predicted Photovoltaic Performance

National Institute of Standards and Technology
Gaithersburg, Maryland 20899

Background

- NIST Team:
 - Staff – A. Hunter Fannery, 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



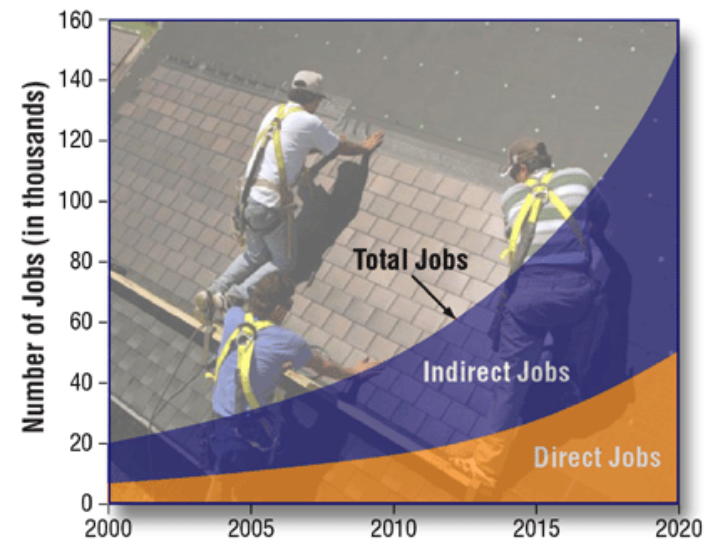
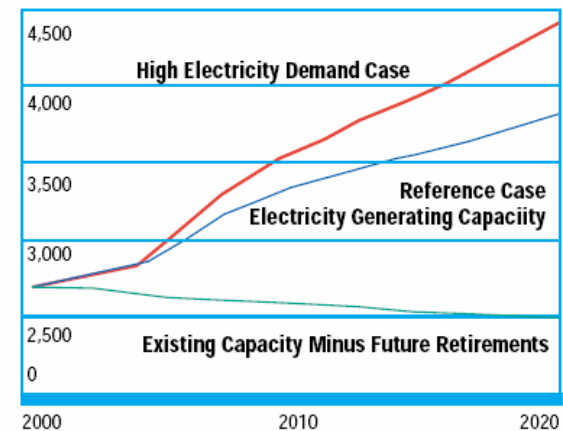
Motivating Dynamics

- 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



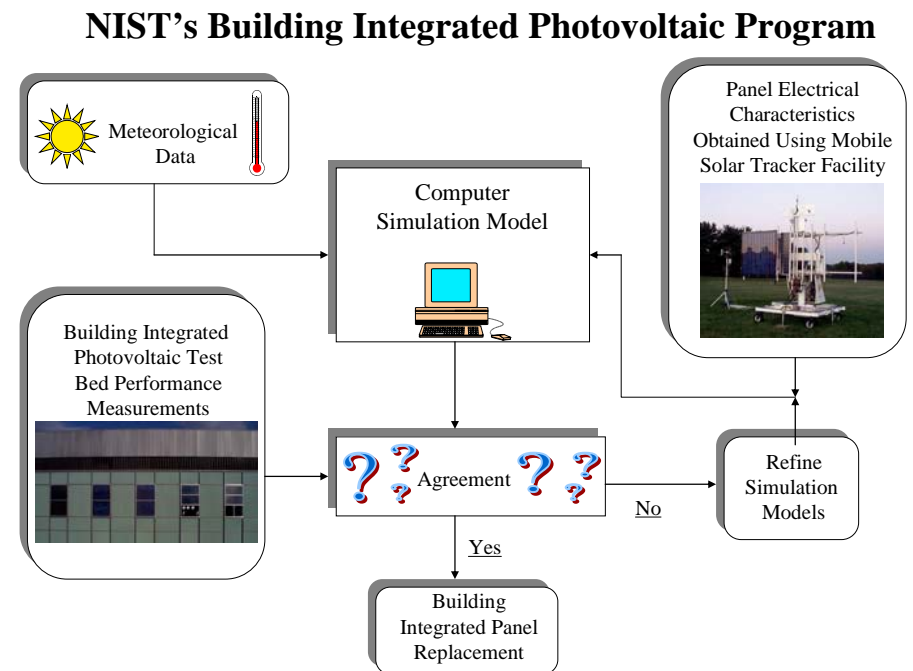
Scope

- 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 ($3.5 \text{ m}^2 \cdot \text{K/W}$)
 - Without Insulation
 - Copper Indium Diselenide
 - With Extruded Polystyrene Rear Insulation ($3.5 \text{ m}^2 \cdot \text{K/W}$)
 - 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 Interval
- Measure Meteorological Conditions
 - Vertical Irradiance
 - Horizontal Irradiance
- Run Simulation Model
- Compare Predicted to Measured Results



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
 - I_{sc} , I_{mp}
 - V_{oc} , V_{mp}

PV Design Pro Input Screens

PV-DesignPro-S v6.0 Standalone Photovoltaic Energy System Design and Analysis T...

PV System Files... Help... Window

Climate Shading Load PV Array Wind Wiring Battery Backup Inverter Calculate

NIST Modeling Analysis

NIST
 NIST Model Analysis window.
 This window was created under award SB1341-04-W-0259 for Dr. Hunter Faney of the National Institute of Standards and Technology. Data text files of actual measured data can be compared to program outputs using this window.
 The current system design is used with the exception of location information (which must be input on this window: latitude,

Latitude: 39.1329
 Longitude: 77.2171
 Stan. Merid.: 75
 Elevation(m): 154.84

Input File: (INPUT FILES)\Monthly Continuous Data\5min_Avg_PSPCOR_NS_0102.txt

Irradiance Calculation
 Use Measured Horizontal Irradiance
 Use Measured Vertical Irradiance

Diffuse Irradiance
 Use Measured Diffuse Irradiance
 Calculate Diffuse Irradiance (GHR-(DNR*cos(AOI))

Temperature Calculation
 Use Sandia Calculated Module Temperature
 Use Measured Module Temperature

Select Panel
 Panel A
 Panel B
 Panel C
 Panel D
 Panel E
 Panel F
 Panel G
 Panel H

ASCII Input File Data Delimiter
 Tab (Output file will contain only comma delimiters.)
 Comma (Output file will contain only comma delimiters.)

Select Outputs

<input checked="" type="checkbox"/> HorExtraRadW_m2	<input checked="" type="checkbox"/> Voc
<input checked="" type="checkbox"/> DirBeamRadW_m2	<input checked="" type="checkbox"/> Vmp
<input checked="" type="checkbox"/> SolarDeclinationDeg	<input checked="" type="checkbox"/> Pmp
<input checked="" type="checkbox"/> EquationofTimeMin	<input checked="" type="checkbox"/> FillFactor
<input checked="" type="checkbox"/> SolarTimeMin	<input checked="" type="checkbox"/> Ix
<input checked="" type="checkbox"/> HourAngleDeg	<input checked="" type="checkbox"/> Ixx
<input checked="" type="checkbox"/> SolarAzimuthDeg	<input checked="" type="checkbox"/> ArrayAmps
<input checked="" type="checkbox"/> ModuleSlopeDeg	<input checked="" type="checkbox"/> ArrayPotentialW
<input checked="" type="checkbox"/> ArrayAzimuth	<input checked="" type="checkbox"/> ArrayW
<input checked="" type="checkbox"/> AngofIncidenceDeg	<input checked="" type="checkbox"/> ArrayPowerEfficien
<input checked="" type="checkbox"/> ZenithAngDeg	
<input checked="" type="checkbox"/> RatioBeamRad_Rb	
<input checked="" type="checkbox"/> RadOnArrayW_m2	
<input checked="" type="checkbox"/> ArrayOperVoltage	
<input checked="" type="checkbox"/> PVCellTempCel	
<input checked="" type="checkbox"/> AbsAirMass	
<input checked="" type="checkbox"/> f1_AMa	
<input checked="" type="checkbox"/> f2_AOI	
<input checked="" type="checkbox"/> Isc	
<input checked="" type="checkbox"/> Imp	

Output File: T FILES\A_5min_Avg_PSPCOR_0102_a.b.d(tc)COR_PEREZ_VIMDPT.txt

Done. Run Simulation

2002 SouthWall.pvs ... 0.000% 0.000

PV System Array Configuration

Panel A - a,b,d(Tc) corrected 2001 c-Si

1	Number of Parallel Module Connection Strings
1	Number of Modules in Each Parallel String
1.6284	Module Area (m)
4.37451570	Isc (Short Circuit Current)
42.9261527	Voc (Open Circuit Volts)
3.96080925	Imp (Max Power Point Current)
33.6802686	Vmp (Max Power Point Volts)
0.00040064	uIsc A/K (Temp. Coefficient of Current)
-0.1523657	uVoc V/K (Temp. Coefficient of Voltage)
1.02572676	Diode Idealty Factor
72	Number of Cells in Series per Module
1	Number of Parallel Cell Strings per Module

PV Module Database Tracking Method MPPT Device Array Deratements

OK

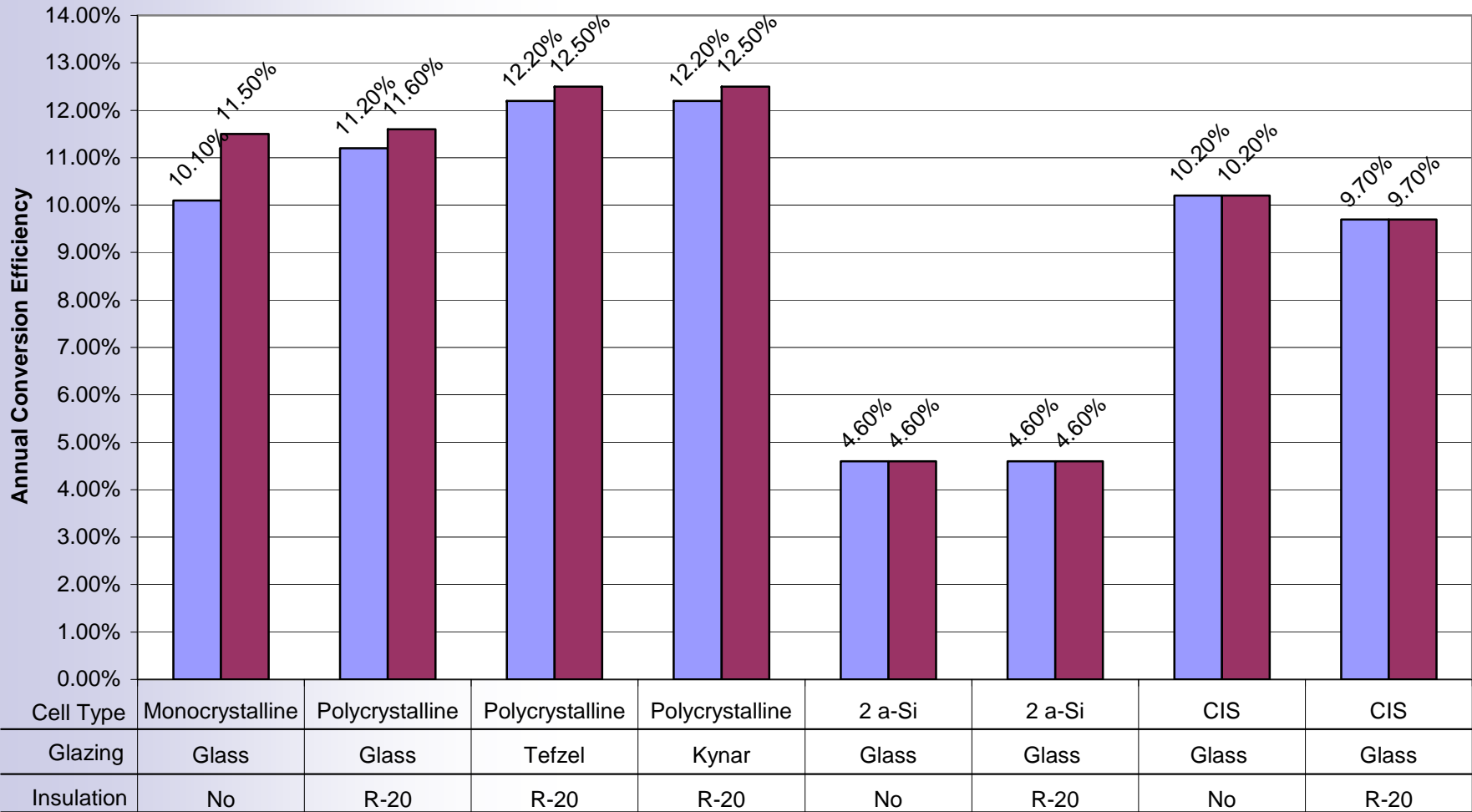
Array I-V Curve at 25C ambient, 1000 W/m2 Left: Amps (Blue) Right: Watts (Green) Bottom: Volts

Array Parameters **Typical I-V and P-V Curve** I-V Curve at 200-1000 W/m2 I-V Curve at 25C and 50C Max Power at 25C to 50C

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%

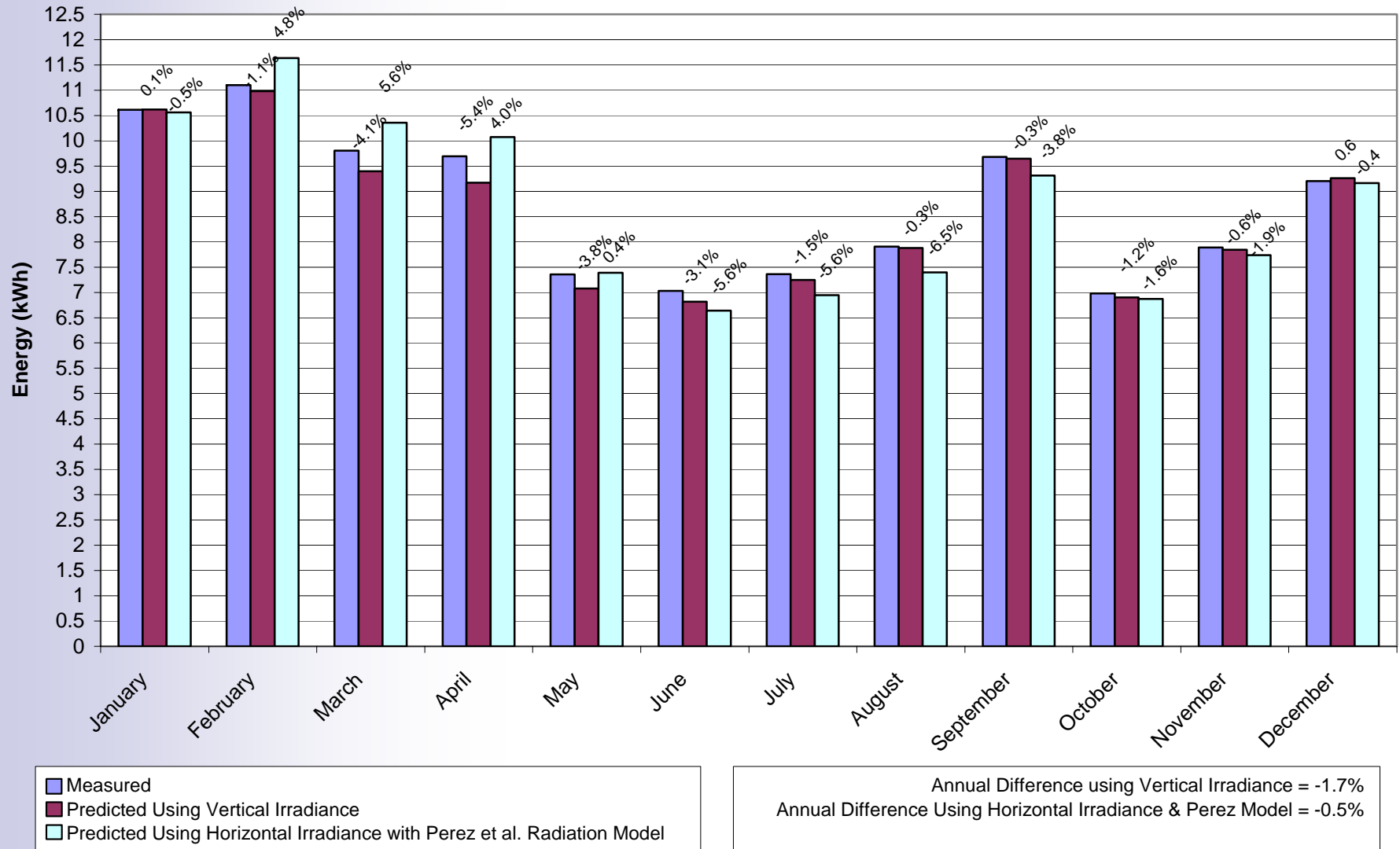
NIST's Building Integrated Photovoltaic Test Facility



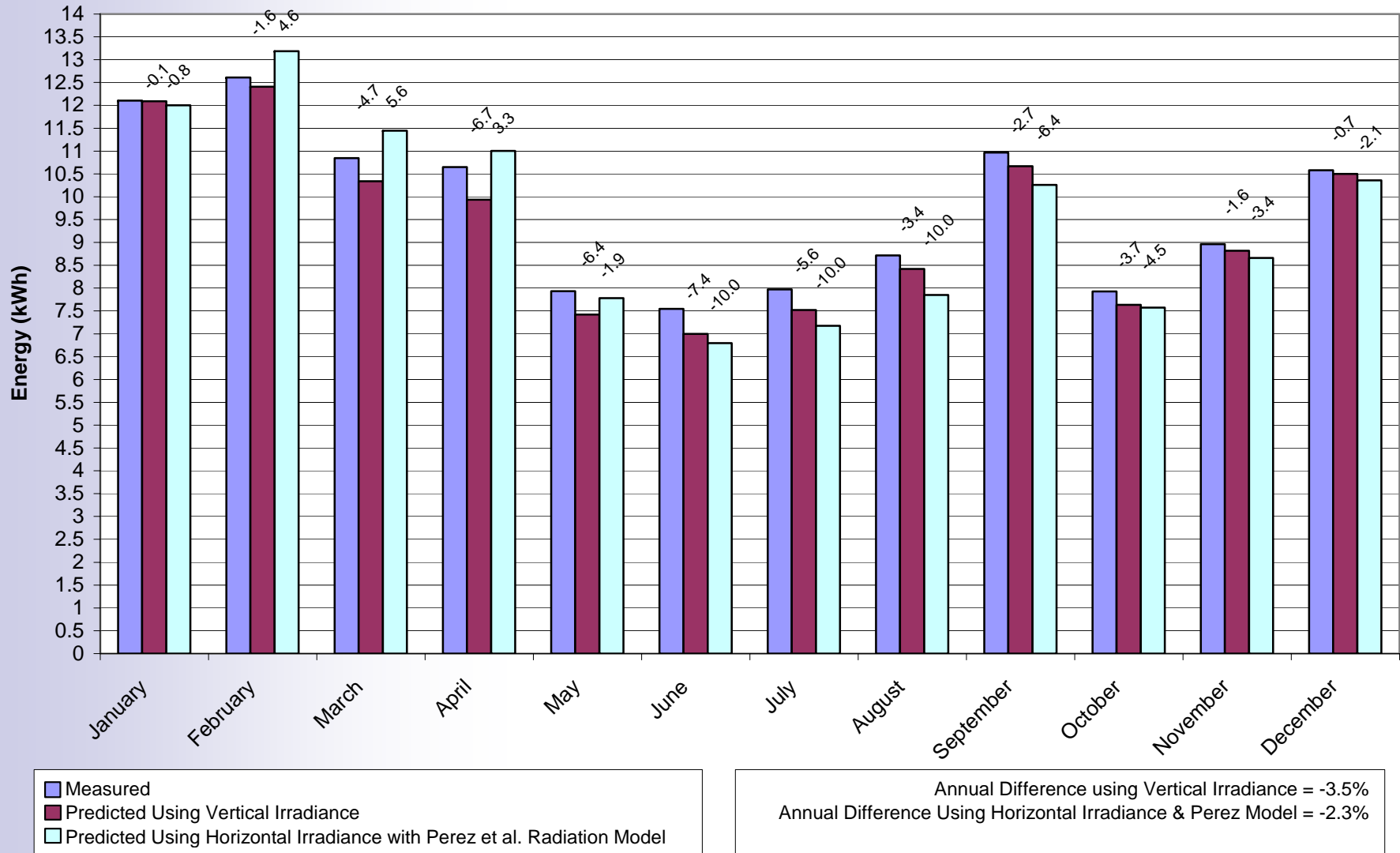
BIPV Panel Description

Based on Coverage Area
 Based on Cell Area

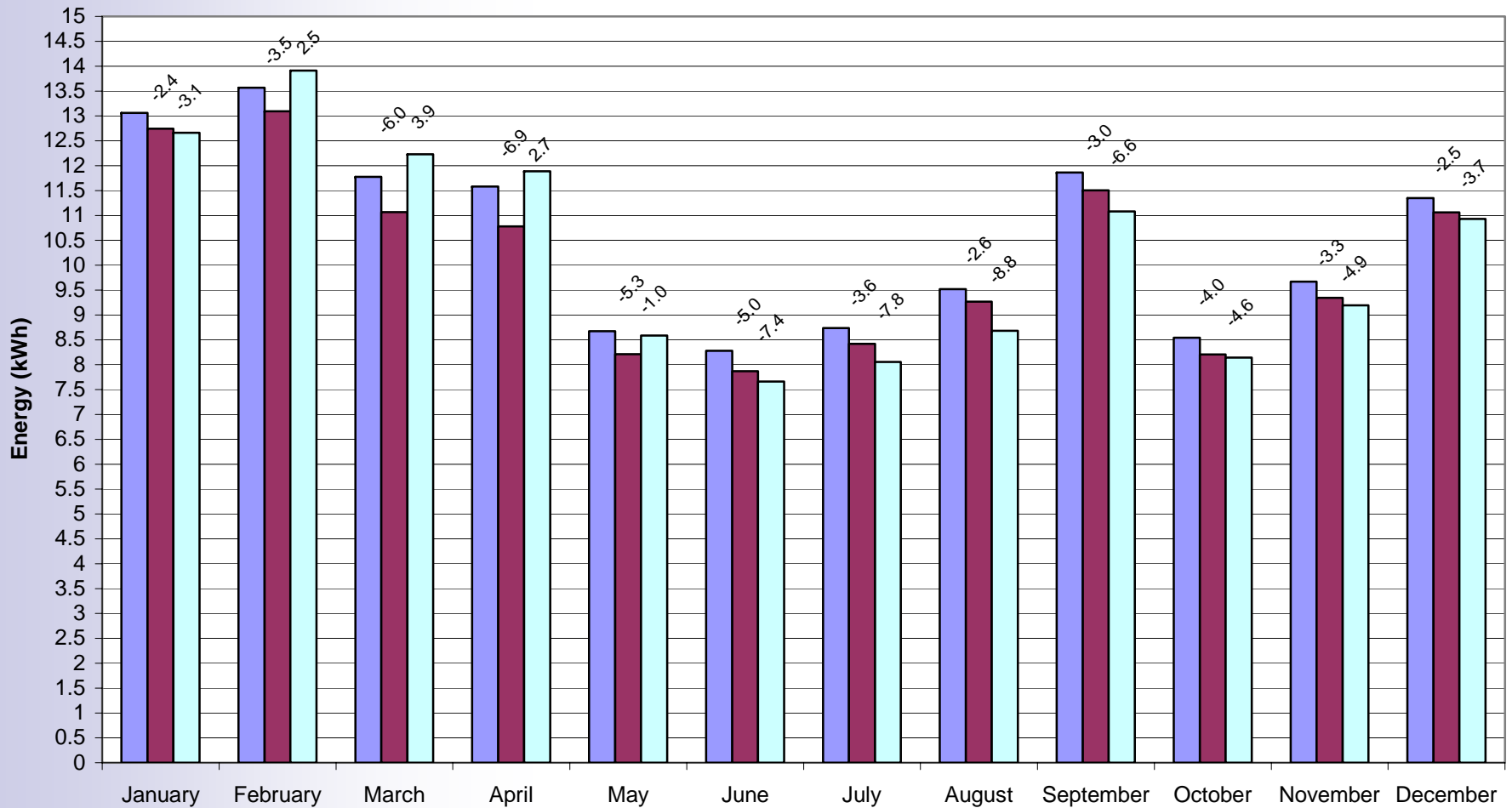
Measured vs. Predicted Energy Comparisons Monocrystalline Custom BIPV Module with Glass Glazing



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



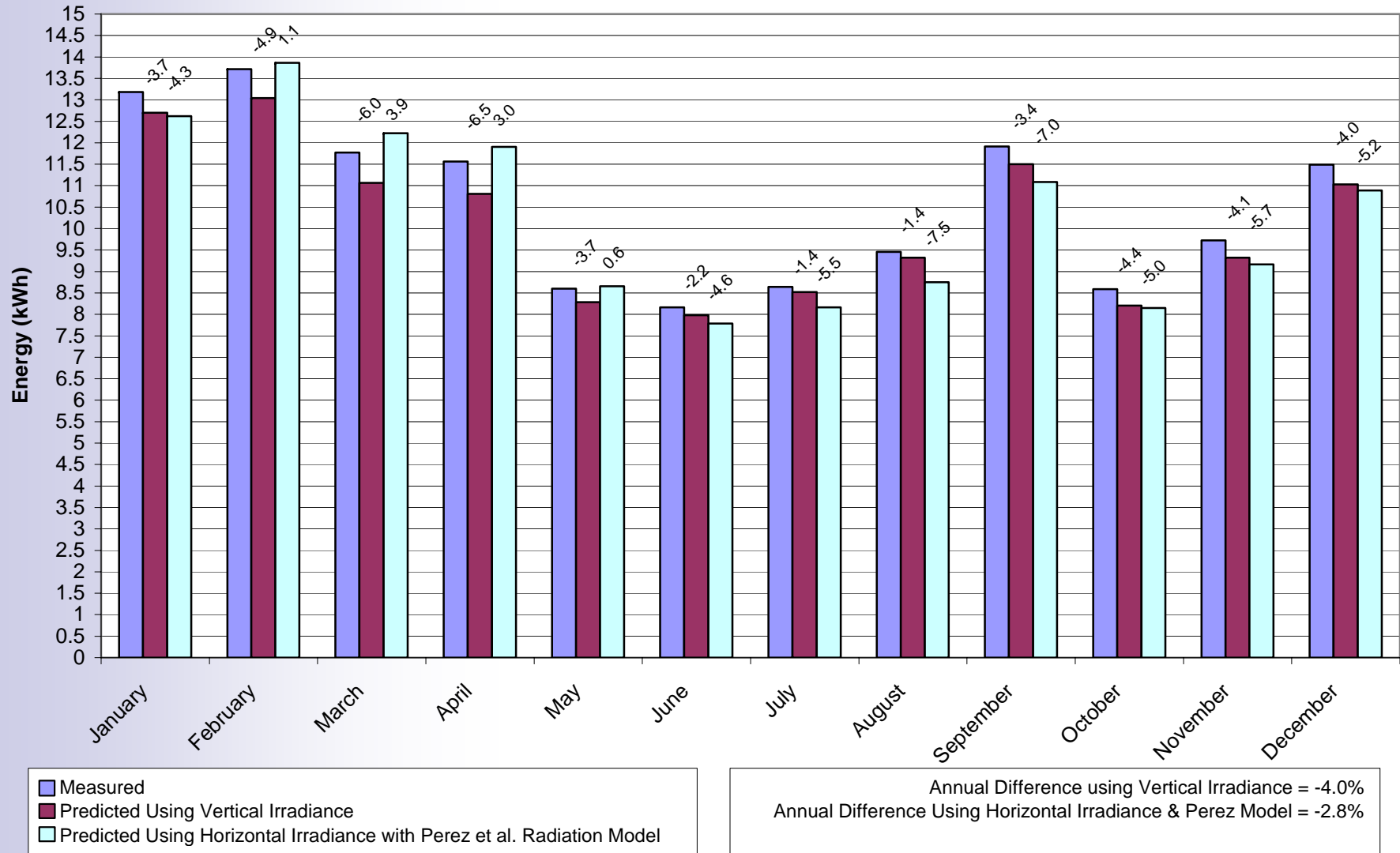
Measured vs. Predicted Energy Comparisons Polycrystalline Custom BIPV Module with Tefzel Glazing



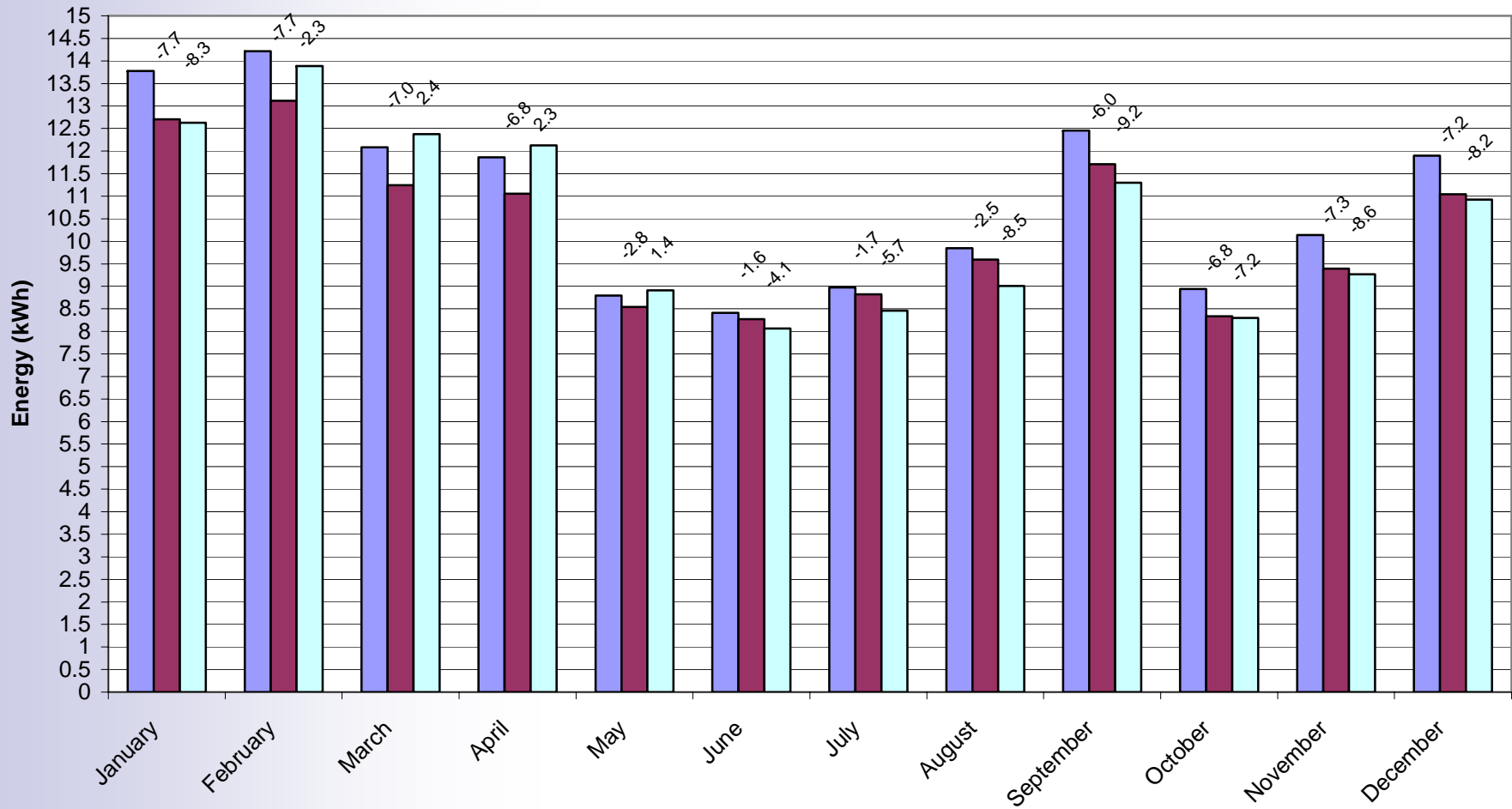
■ Measured
■ Predicted Using Vertical Irradiance
■ Predicted Using Horizontal Irradiance with Perez et al. Radiation Model

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



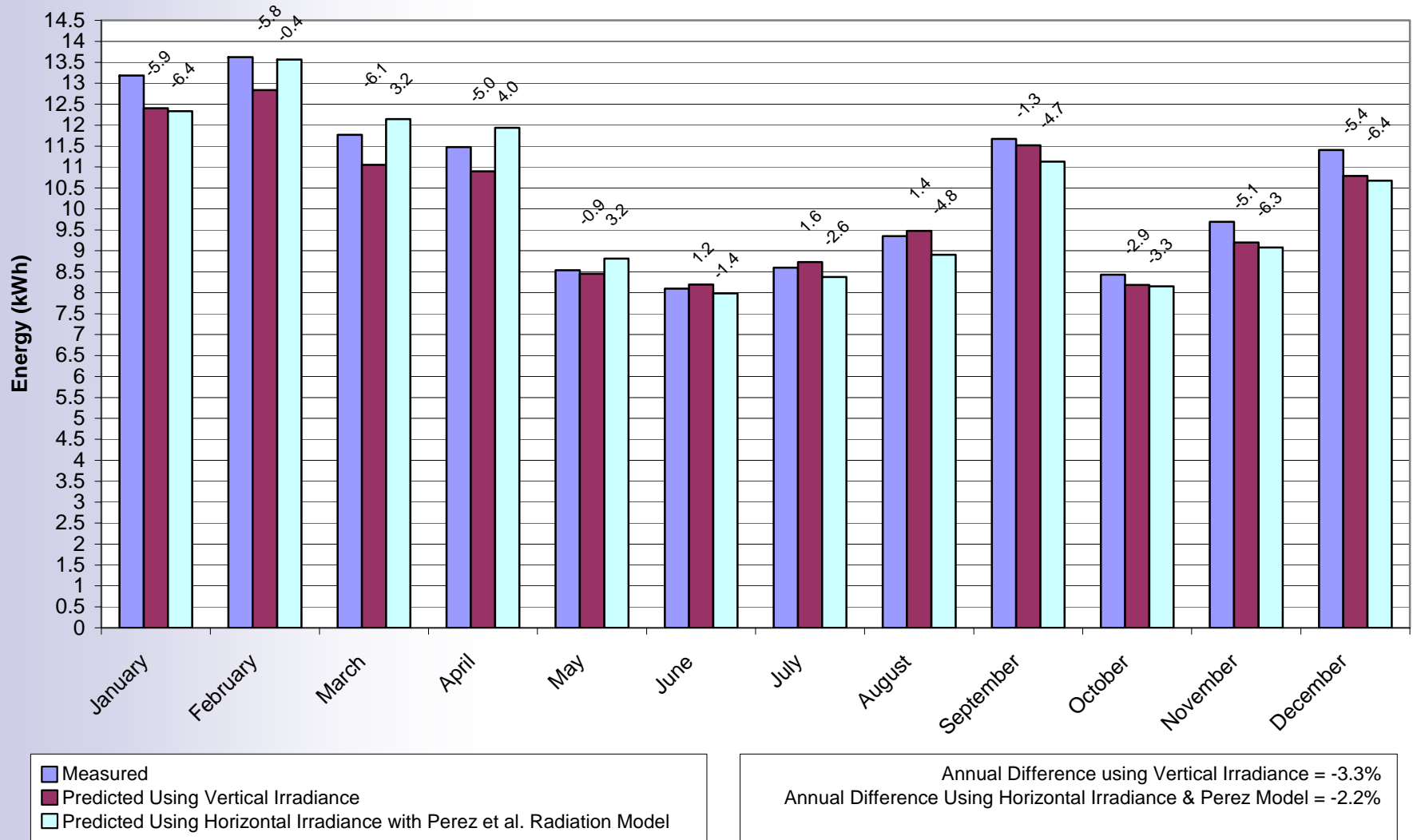
Measured vs. Predicted Energy Comparisons CIS Module with Glass Glazing



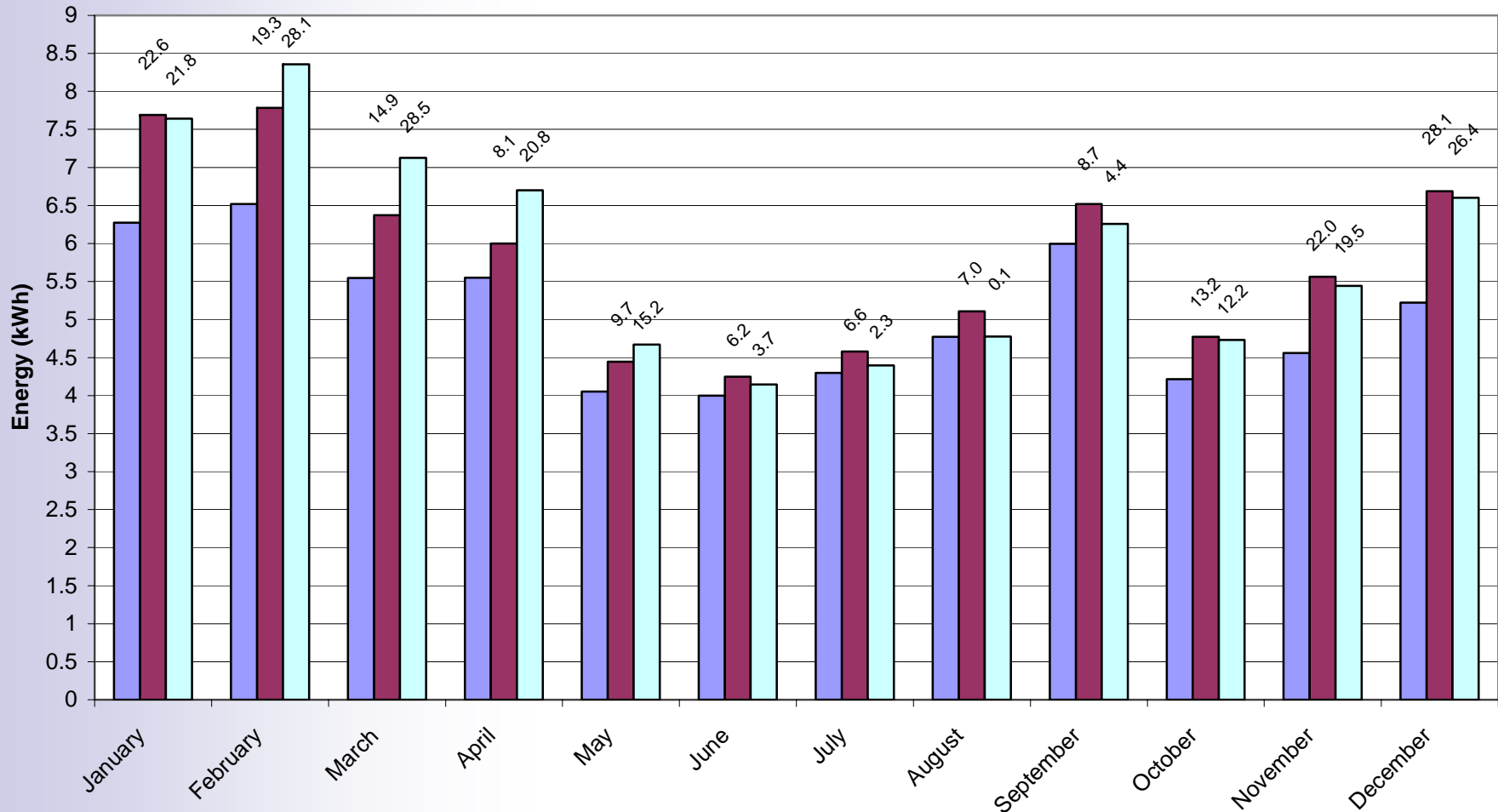
■ Measured
■ Predicted Using Vertical Irradiance
■ Predicted Using Horizontal Irradiance with Perez et al. Radiation Model

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



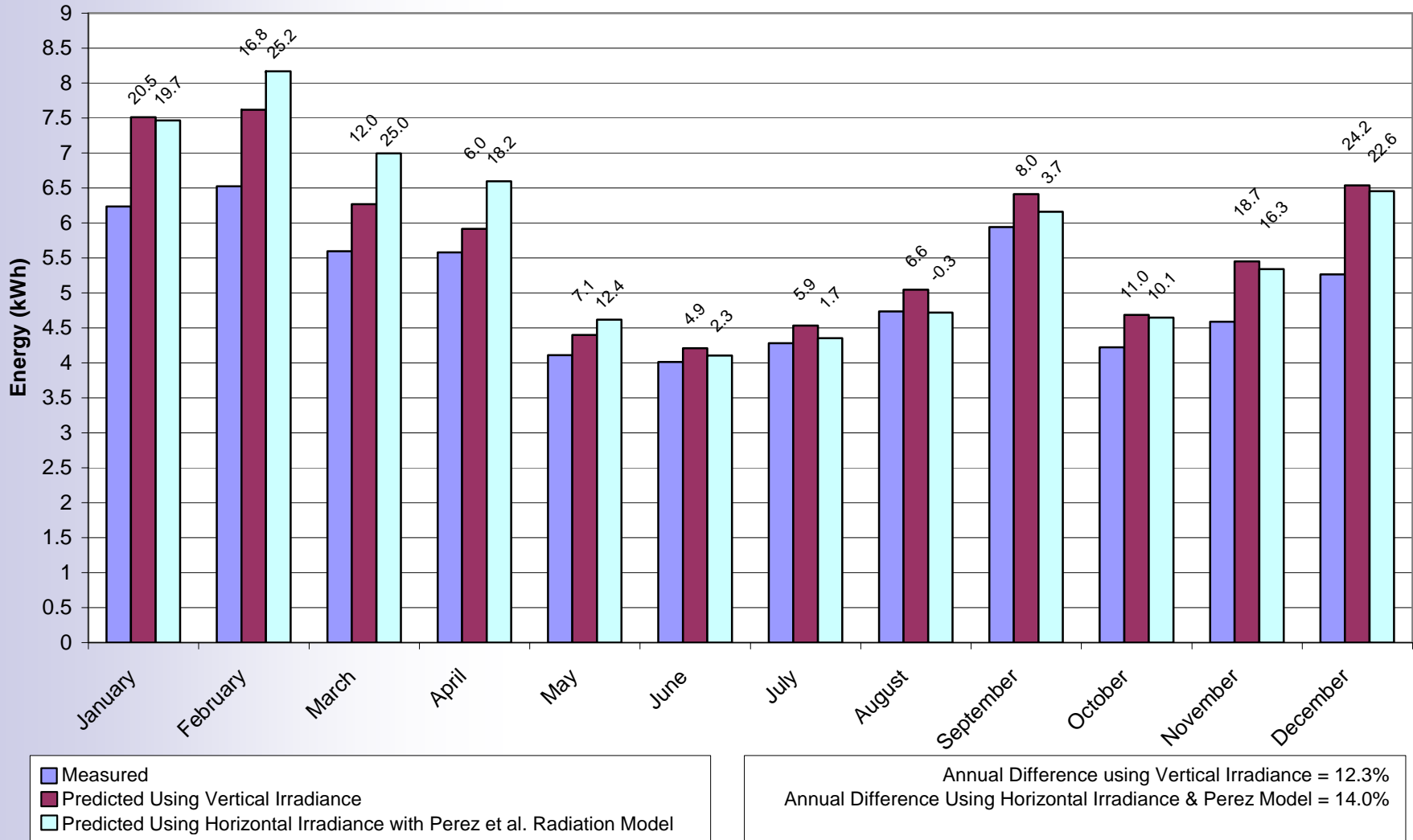
Measured vs. Predicted Energy Comparisons Tandem Junction Module Original Characterization with Glass Glazing



■ Measured
■ Predicted Using Vertical Irradiance
■ Predicted Using Horizontal Irradiance with Perez et al. Radiation Model

Annual Difference using Vertical Irradiance = 14.4%
 Annual Difference Using Horizontal Irradiance & Perez Model = 16.1%

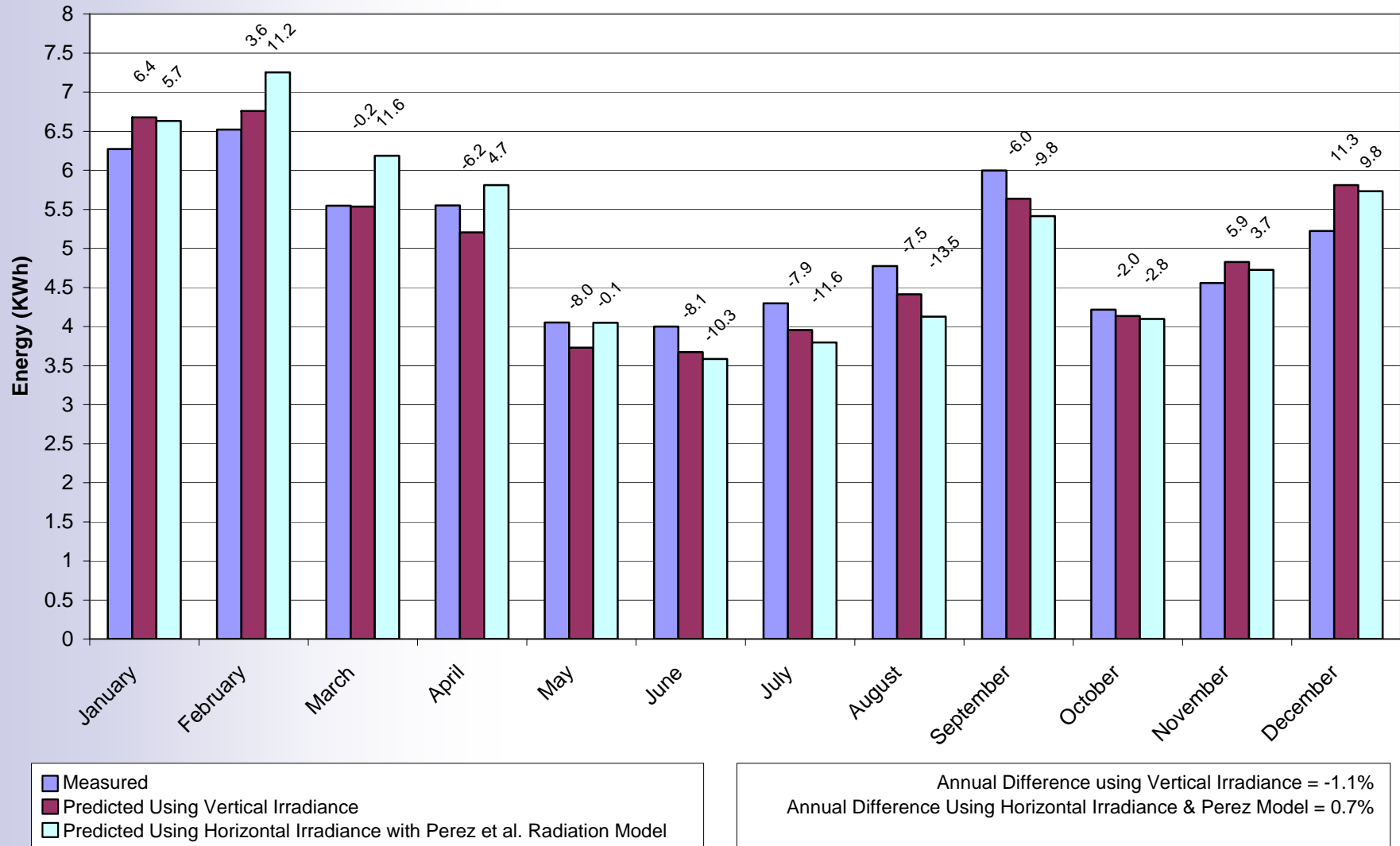
Measured vs. Predicted Energy Comparisons Tandem Junction Module Original Characterization with Glass Glazing Thermal Insulation



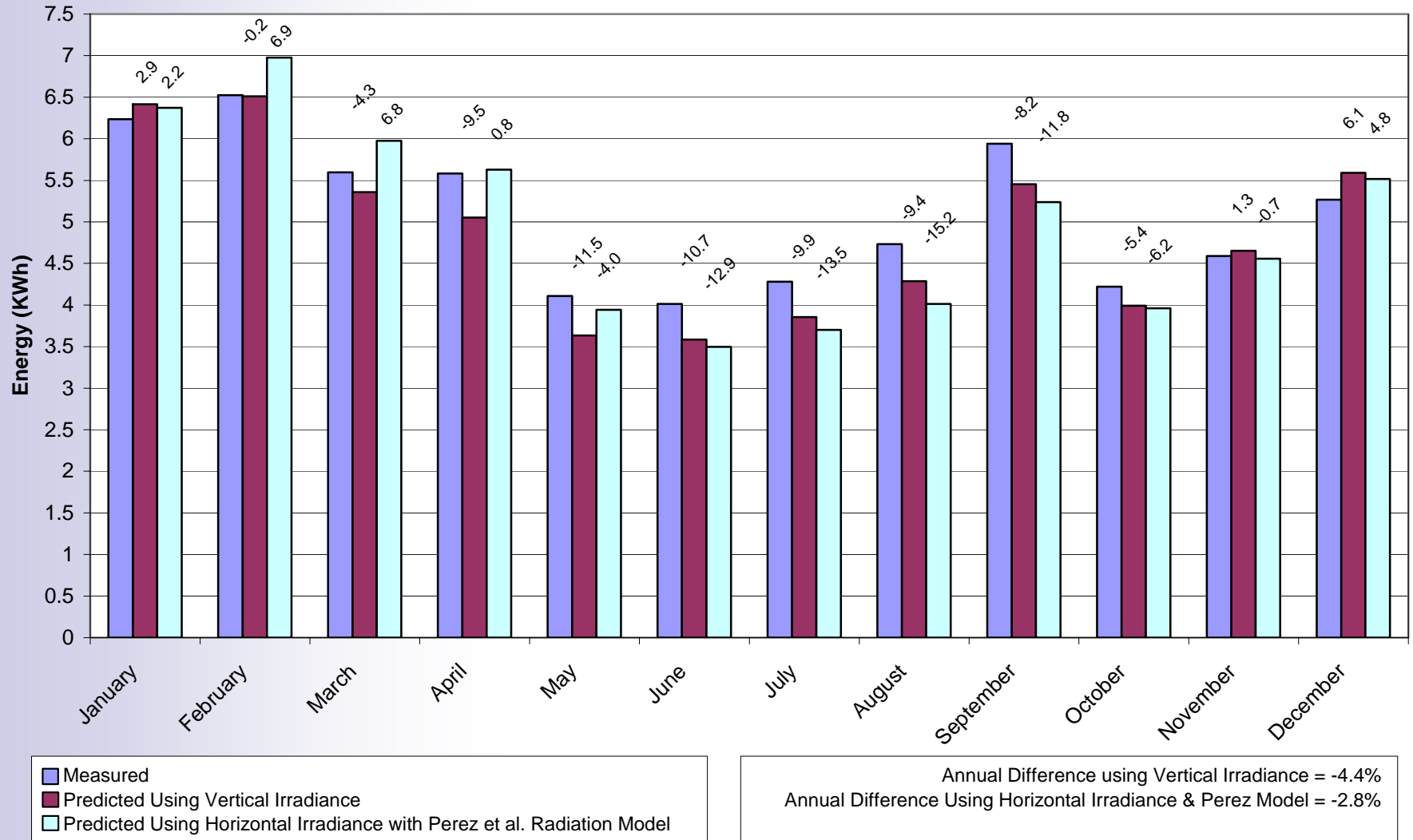
Tandem-Junction Amorphous Performance vs Exposure Time

Panel	Characterization/Tracker		BIPV-Insulated	BIPV-Noninsulated
	124h	344h	>14 months	>14 months
I_{sc}	0.73	0.71	0.69	0.68
I_{mp}	0.61	0.59	0.56	0.55
V_{oc}	99.6	97.7	95.6	96.5
V_{mp}	76.5	74.2	73.0	73.5
P_{mp}	46.8	43.8	40.9	40.4

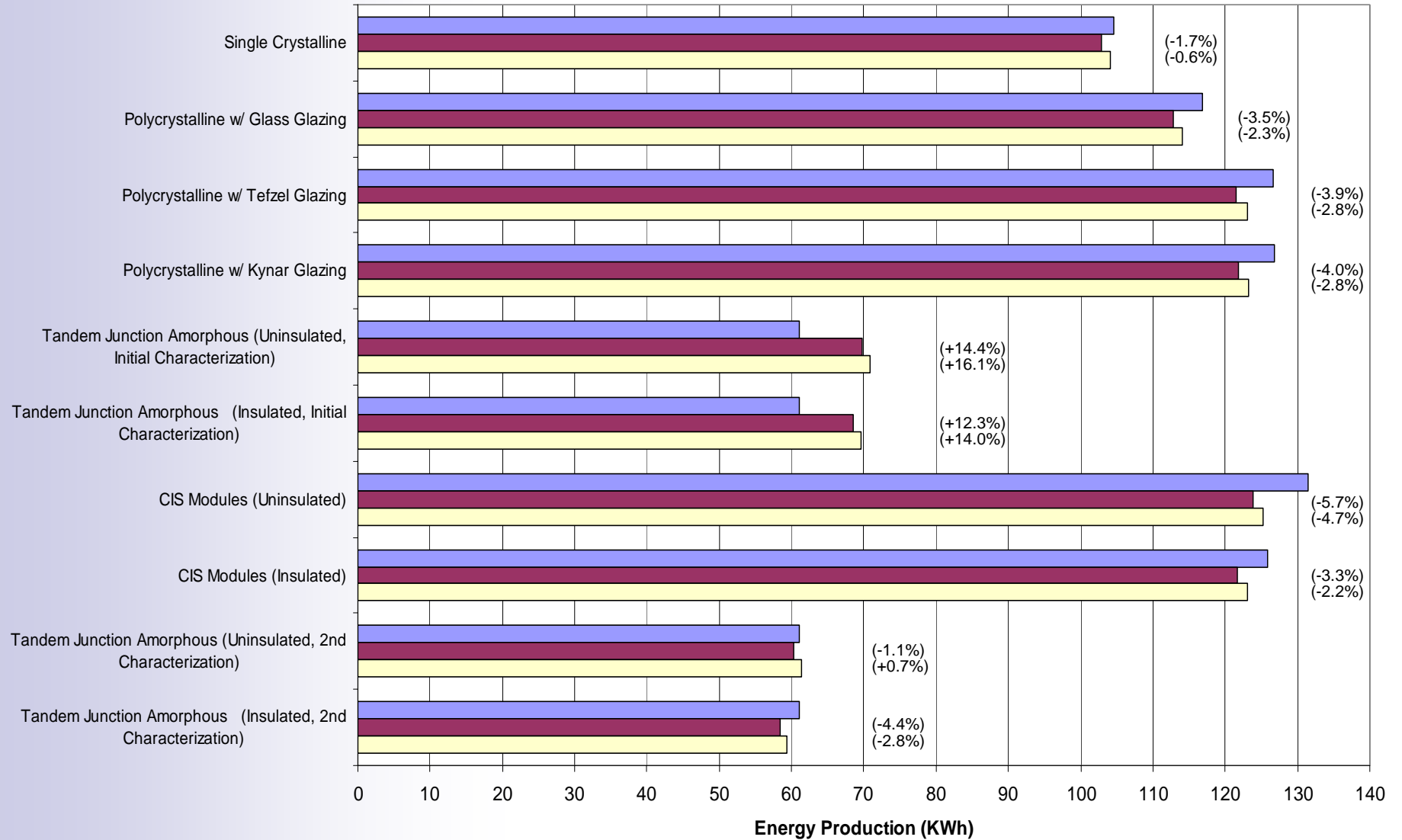
Measured vs. Predicted Energy Comparisons Tandem Junction Module 2nd Characterization with Glass Glazing



Measured vs. Predicted Energy Comparisons Tandem Junction Module 2nd Characterization with Glass Glazing Thermal Insulation



Measured vs. Predicted Annual Results



■ 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 Tandem-Junction Amorphous Panels
 - 4.4% Using Vertical Irradiance
 - 2.8% Using Horizontal Irradiance/Perez Model