# Measured Versus Predicted Photovoltaic Performance

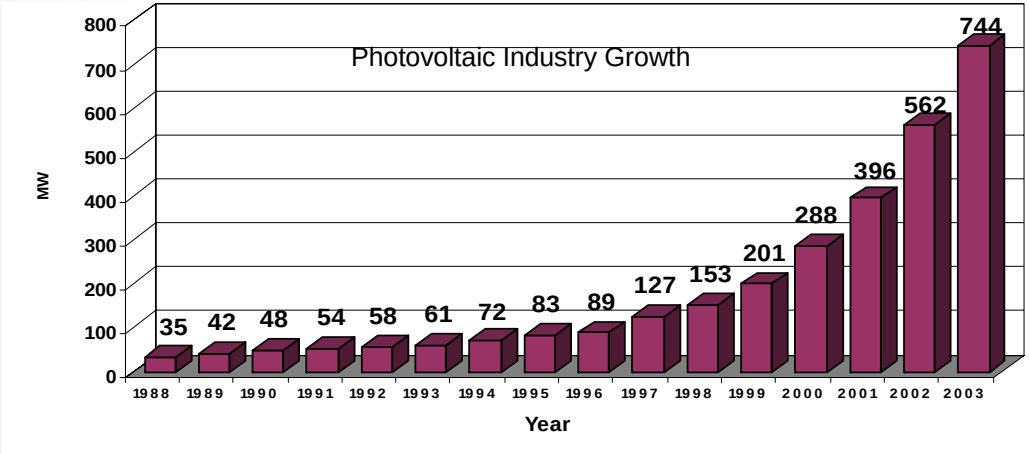
National Institute of Standards and Technology
Gaithersburg, Maryland 20899

# 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

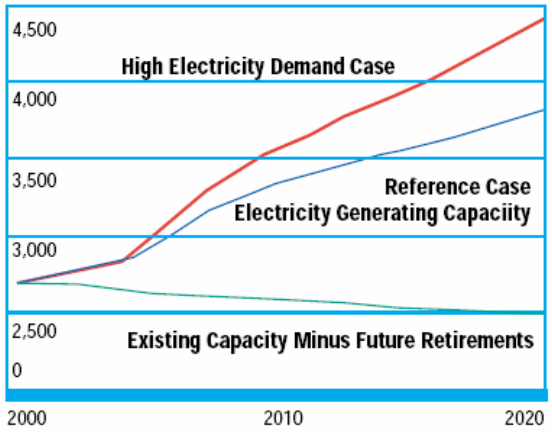
# Motivating Dynamics

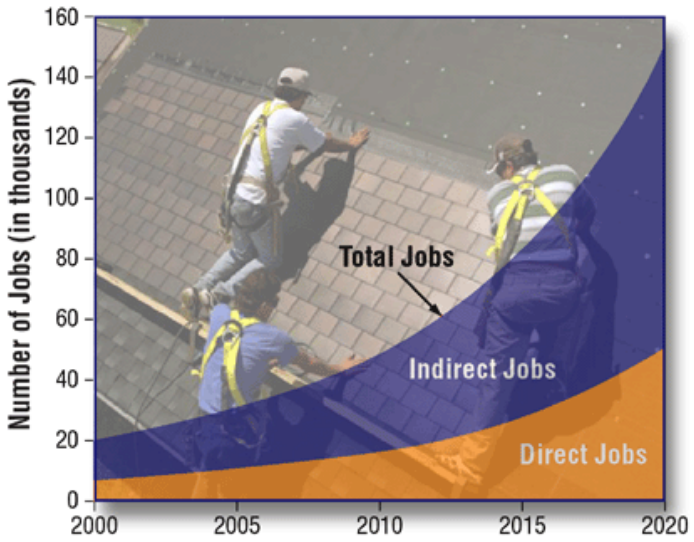
- World Energy Consumption is Projected to Increase by 54% by 2025 (*Energy Information Administration)*
- U.S. Will Need The Equivalent of 60 to 90 New Power Plants Per Year for the Next 20 Years
- Photovoltaic Systems
  - Reduce Need for Additional Power Plants
  - Provide Energy During Disasters/Terrorism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

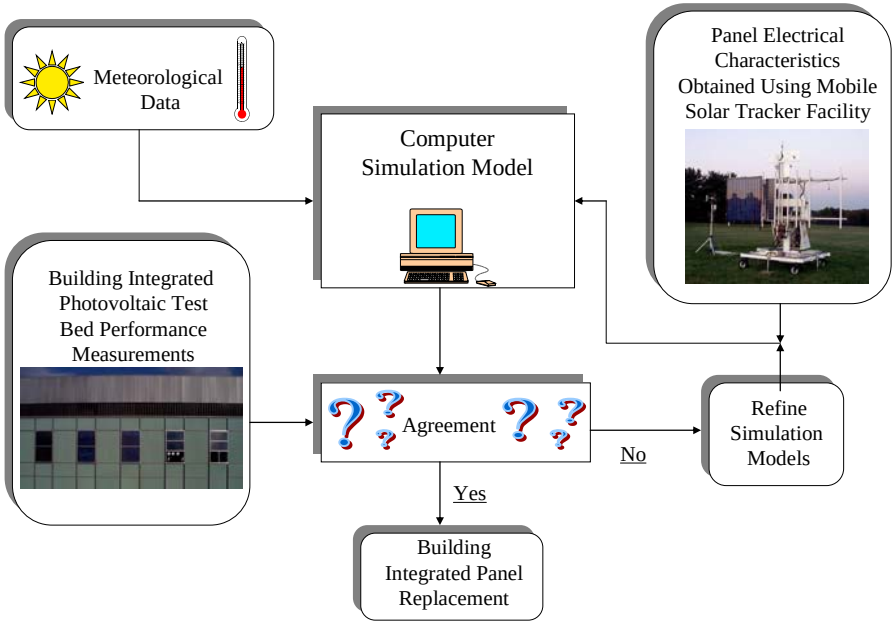
- Photovoltaic Modules Only
- Vertical South-Facing Façade BIPV Installation
  - Gaithersburg, MD (Latitude 39.1, Longitude 77.2)
- 12 Month Comparison
  - January 1 - December 31, 2004
  - 5 Minute  Data Collection Interval

- 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

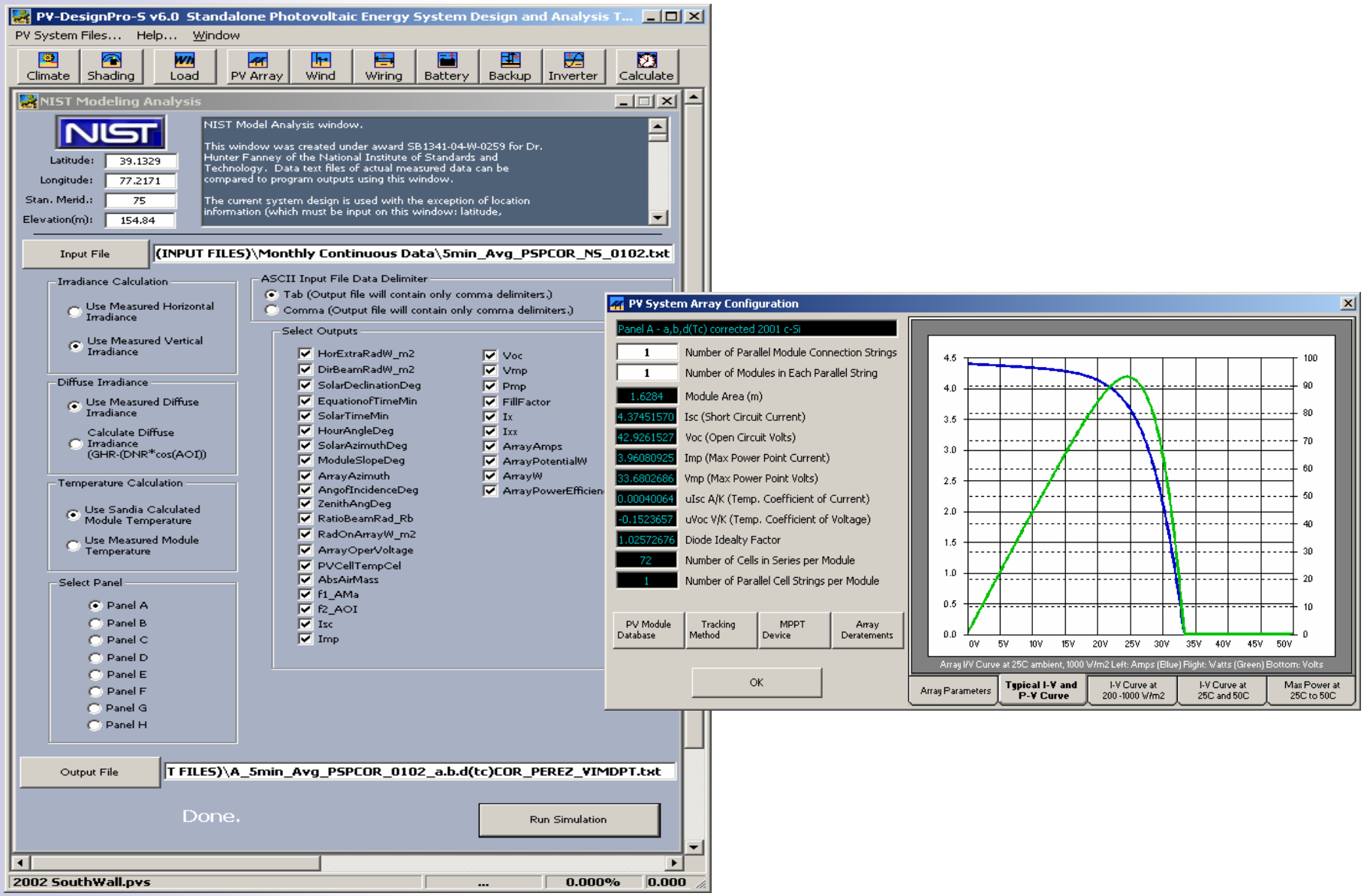
**NIST's Building Integrated Photovoltaic Program**



# 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

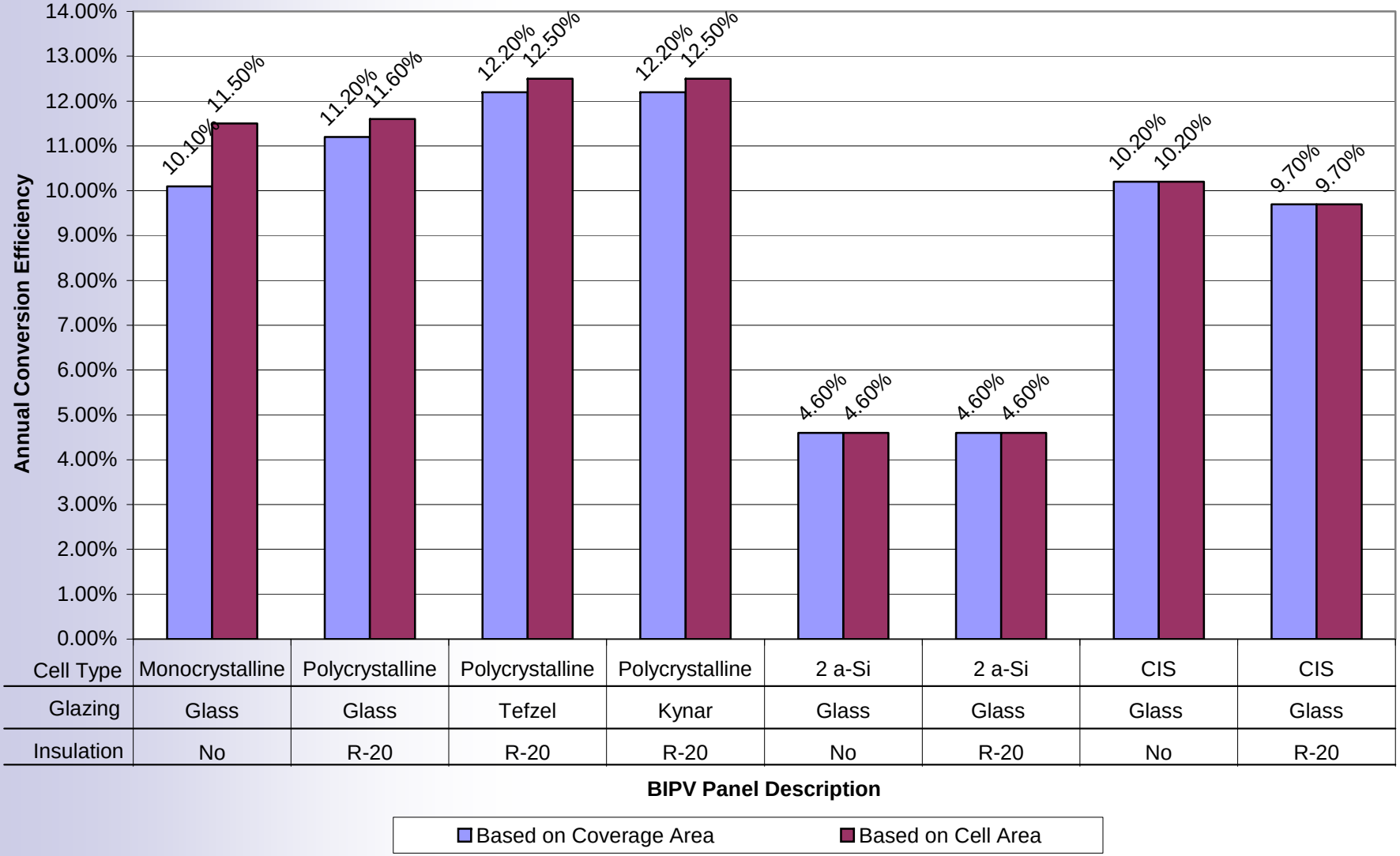
# PV Design Pro Input Screens



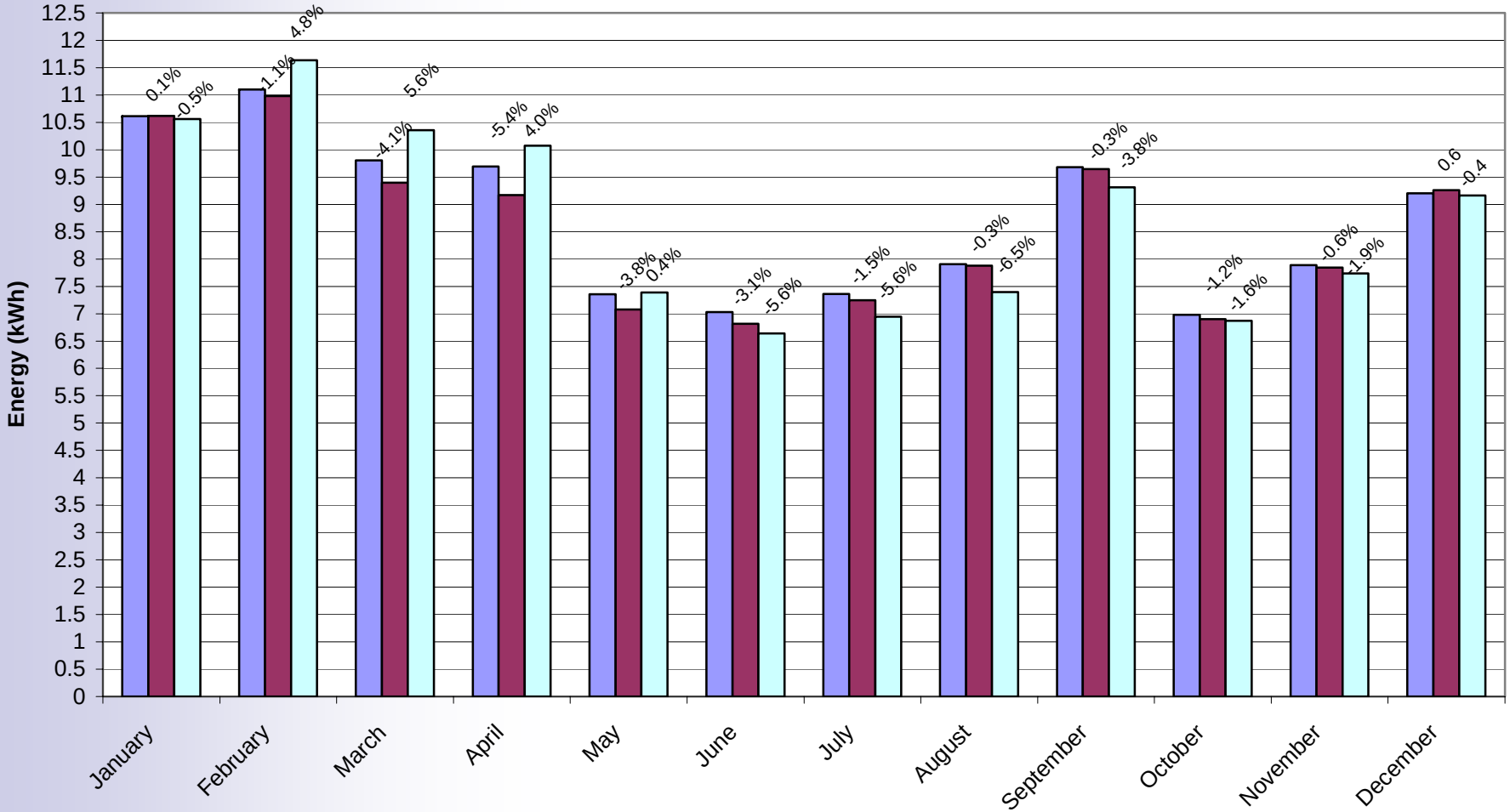
# Comparison Results

- 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



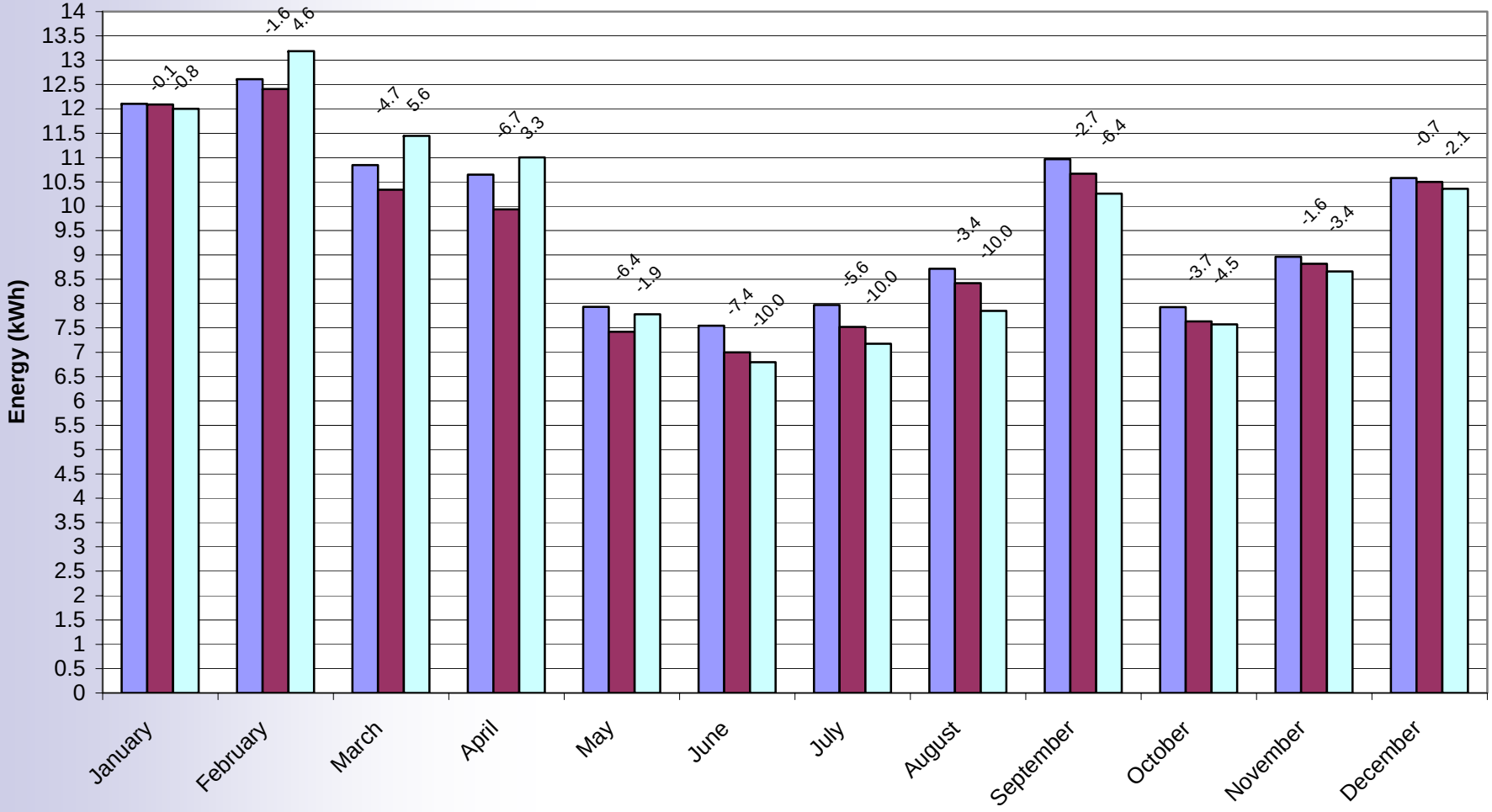
## Measured vs. Predicted Energy Comparisons
## Monocrystalline Custom BIPV Module with Glass Glazing




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

Annual Difference using Vertical Irradiance = -1.7%
Annual Difference Using Horizontal Irradiance & Perez Model = -0.5%

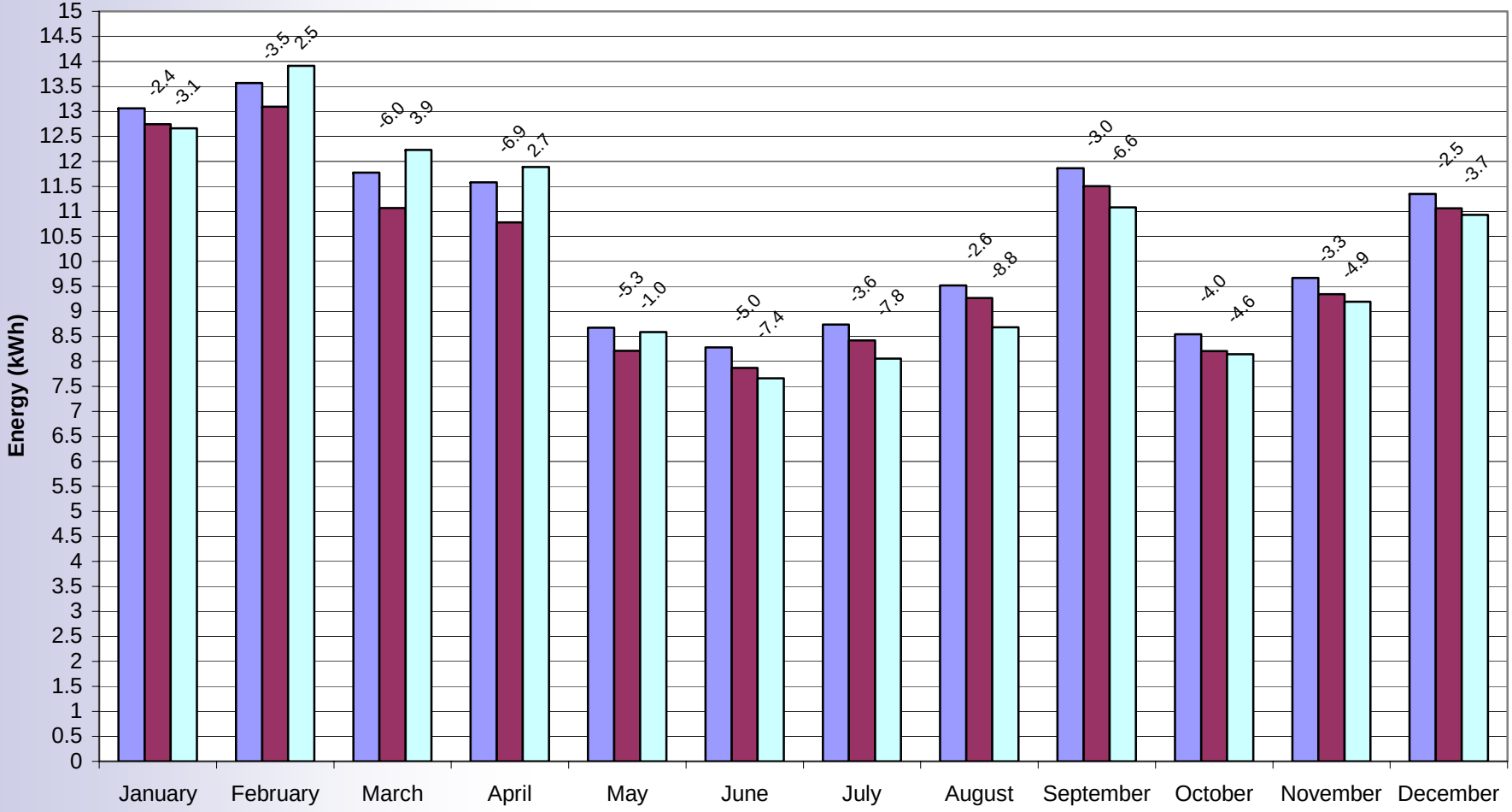
## Measured vs. Predicted Energy Comparisons
## Polycrystalline Custom BIPV Module with Glass Glazing




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

Annual Difference using Vertical Irradiance = -3.5%
Annual Difference Using Horizontal Irradiance & Perez Model = -2.3%

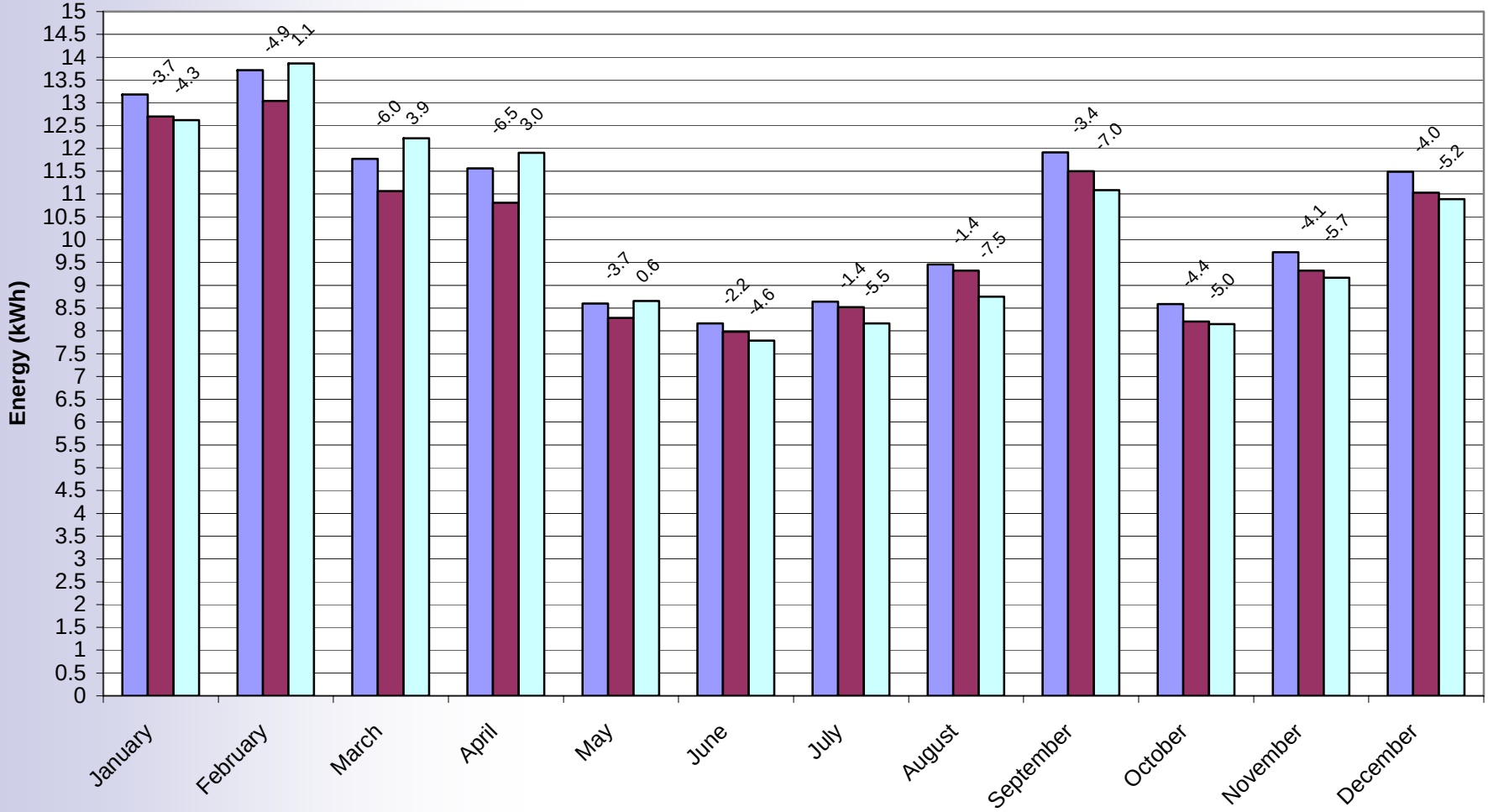
## Measured vs. Predicted Energy Comparisons
## Polycrystalline Custom BIPV Module with Tefzel Glazing




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%

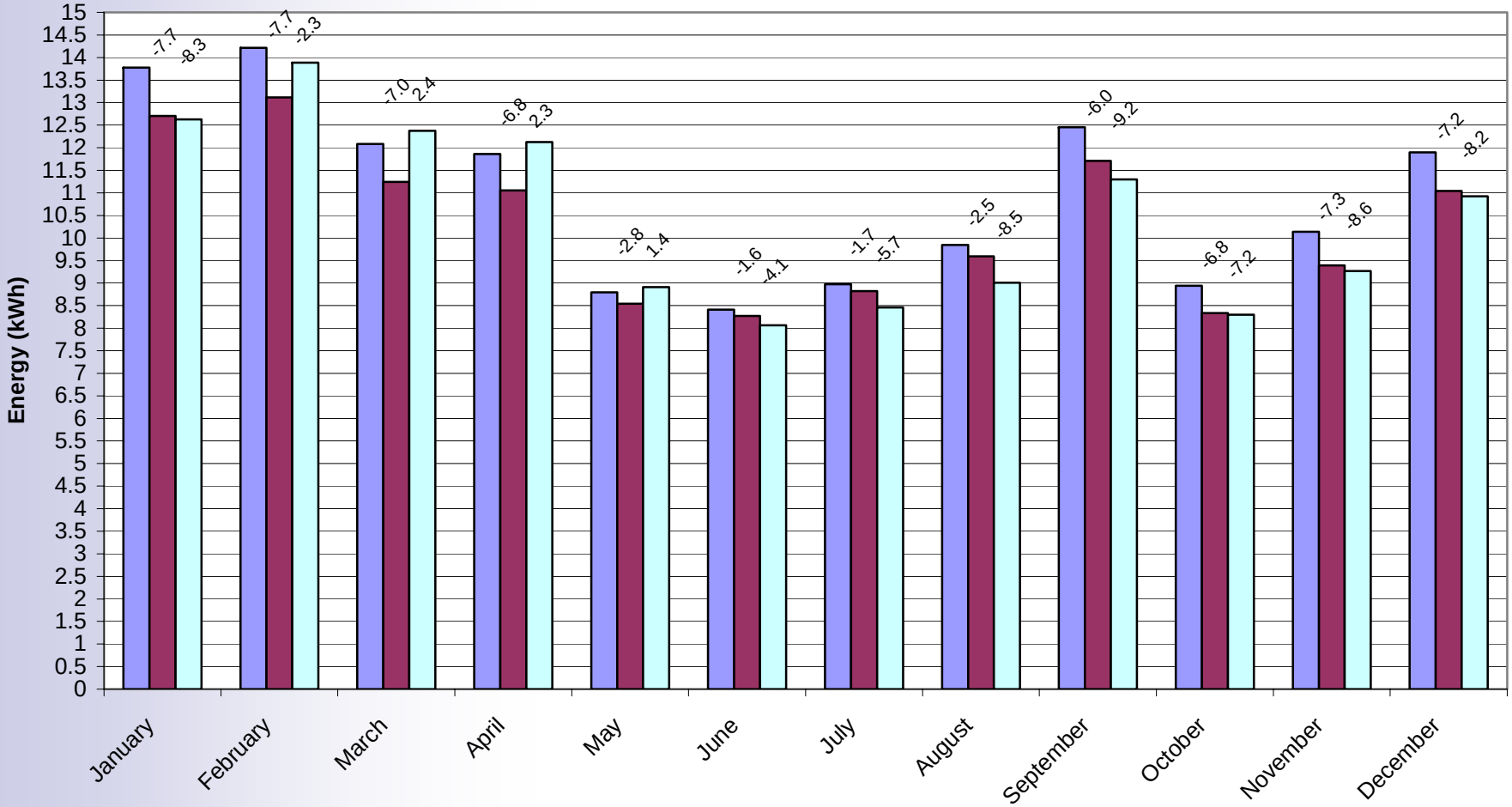
## Measured vs. Predicted Energy Comparisons
## Polycrystalline Custom BIPV Module with Kynar Glazing




Measured
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%

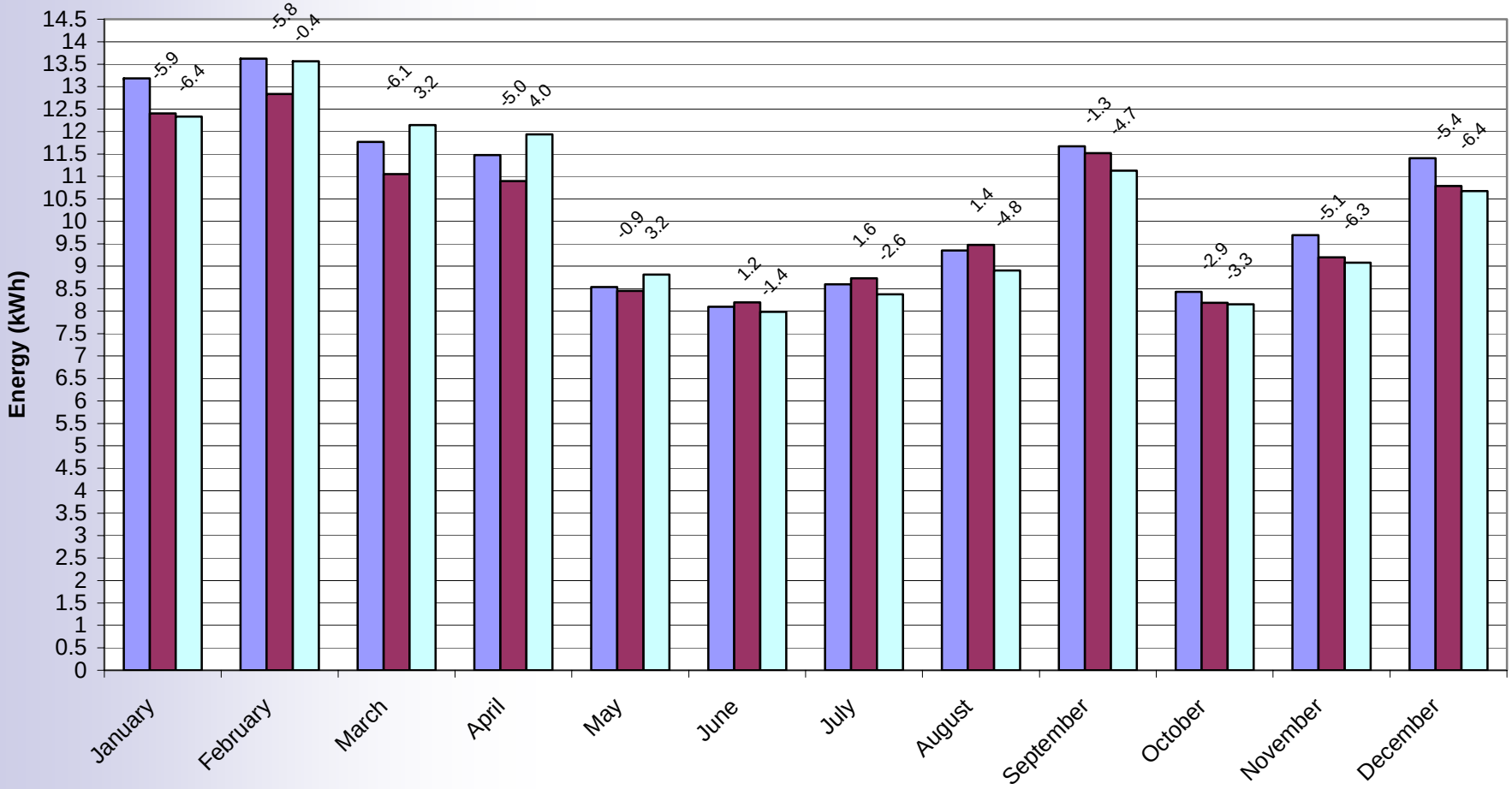
## Measured vs. Predicted Energy Comparisons
## CIS Module with Glass Glazing




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%

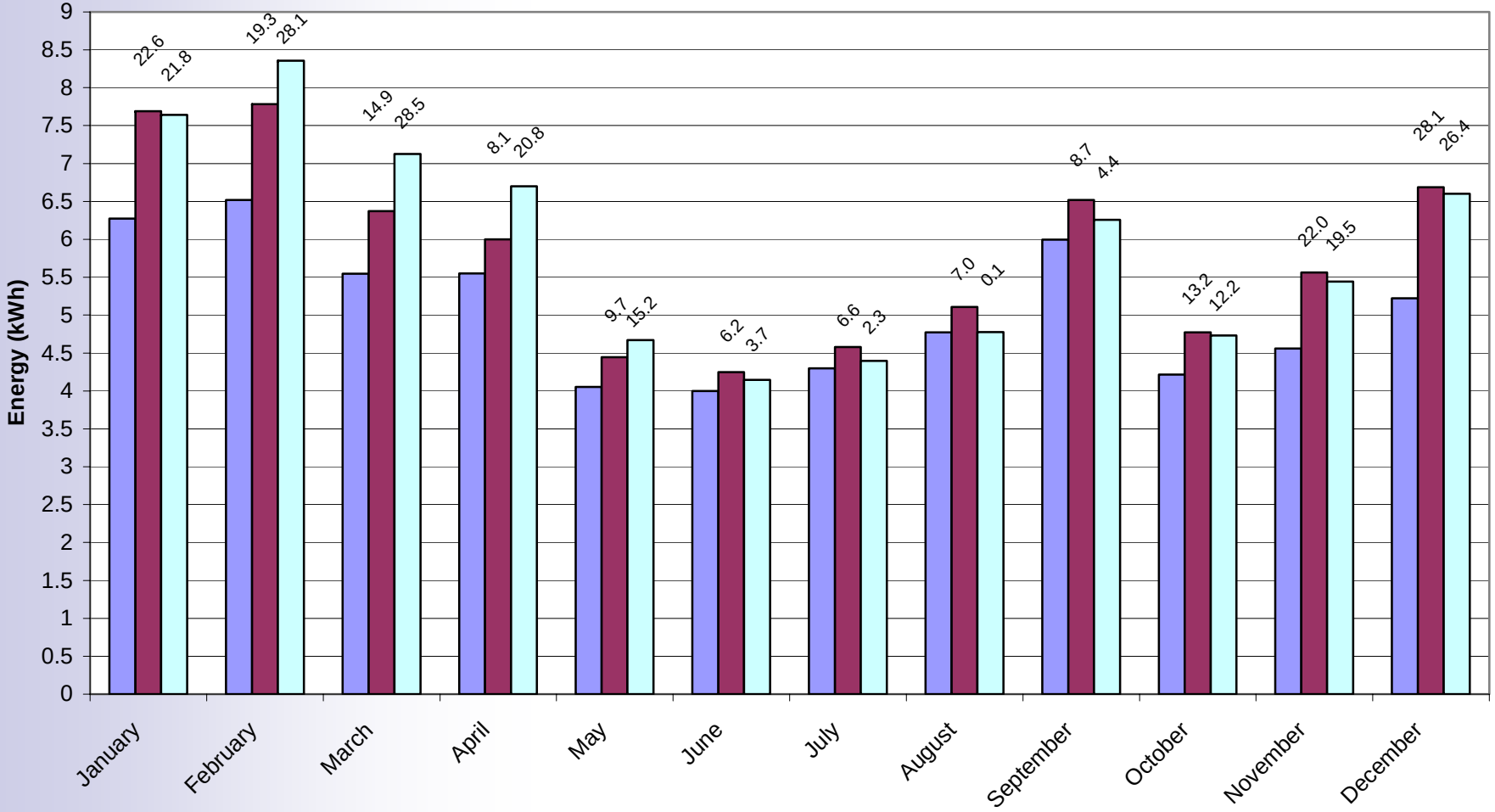
## Measured vs. Predicted Energy Comparisons
## CIS Module with Glass Glazing
## Thermal Insulation




Measured
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%

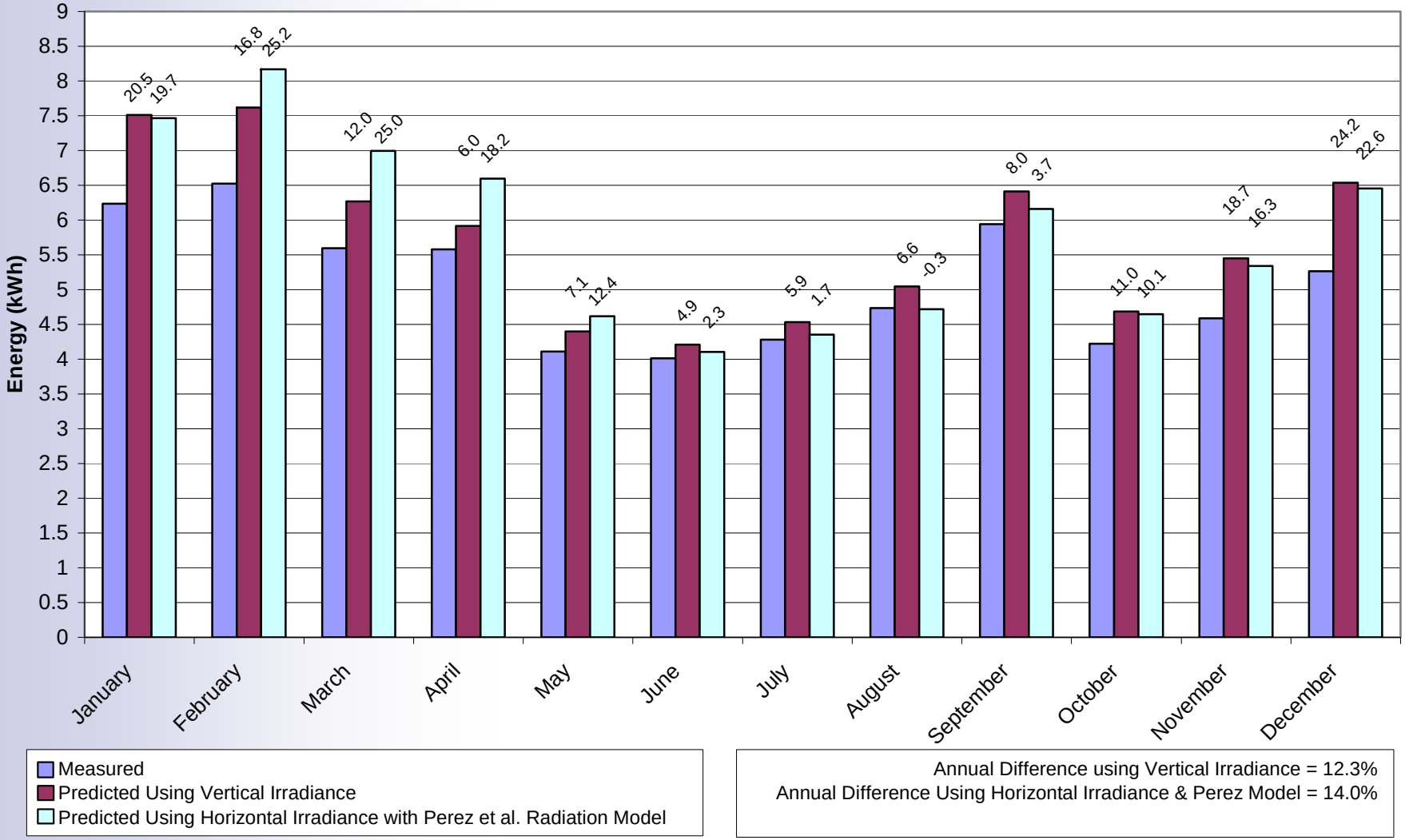
## Measured vs. Predicted Energy Comparisons
## Tandem Junction Module Original Characterization with Glass Glazing




Measured
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%

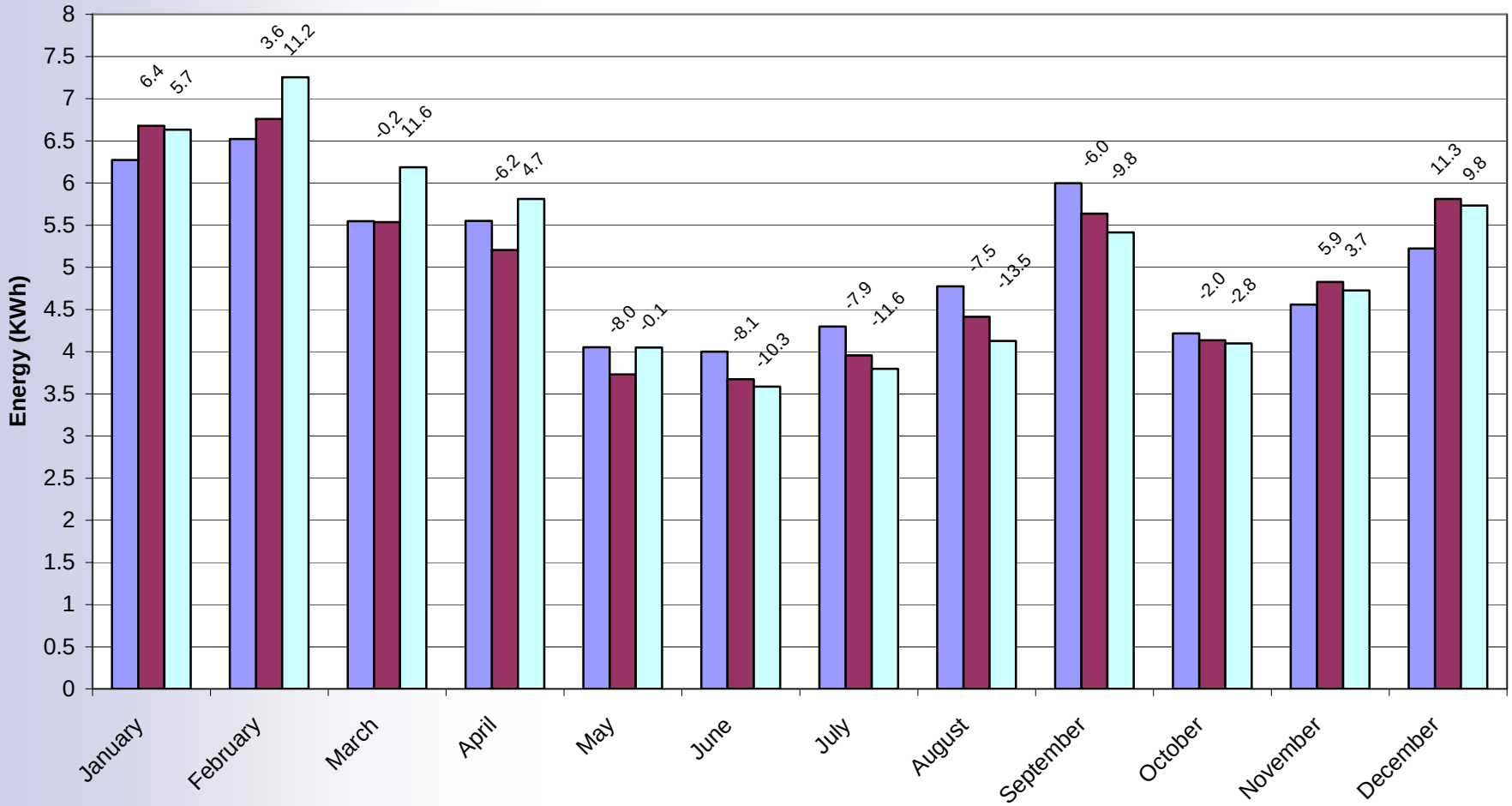
## Measured vs. Predicted Energy Comparisons
## Tandem Junction Module Original Characterization with Glass Glazing
## Thermal Insulation



# Tandem-Junction Amorphous Performance vs Exposure Time

| Panel | Characterization/Tracker | | BIPV-Insulated | BIPV-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 |

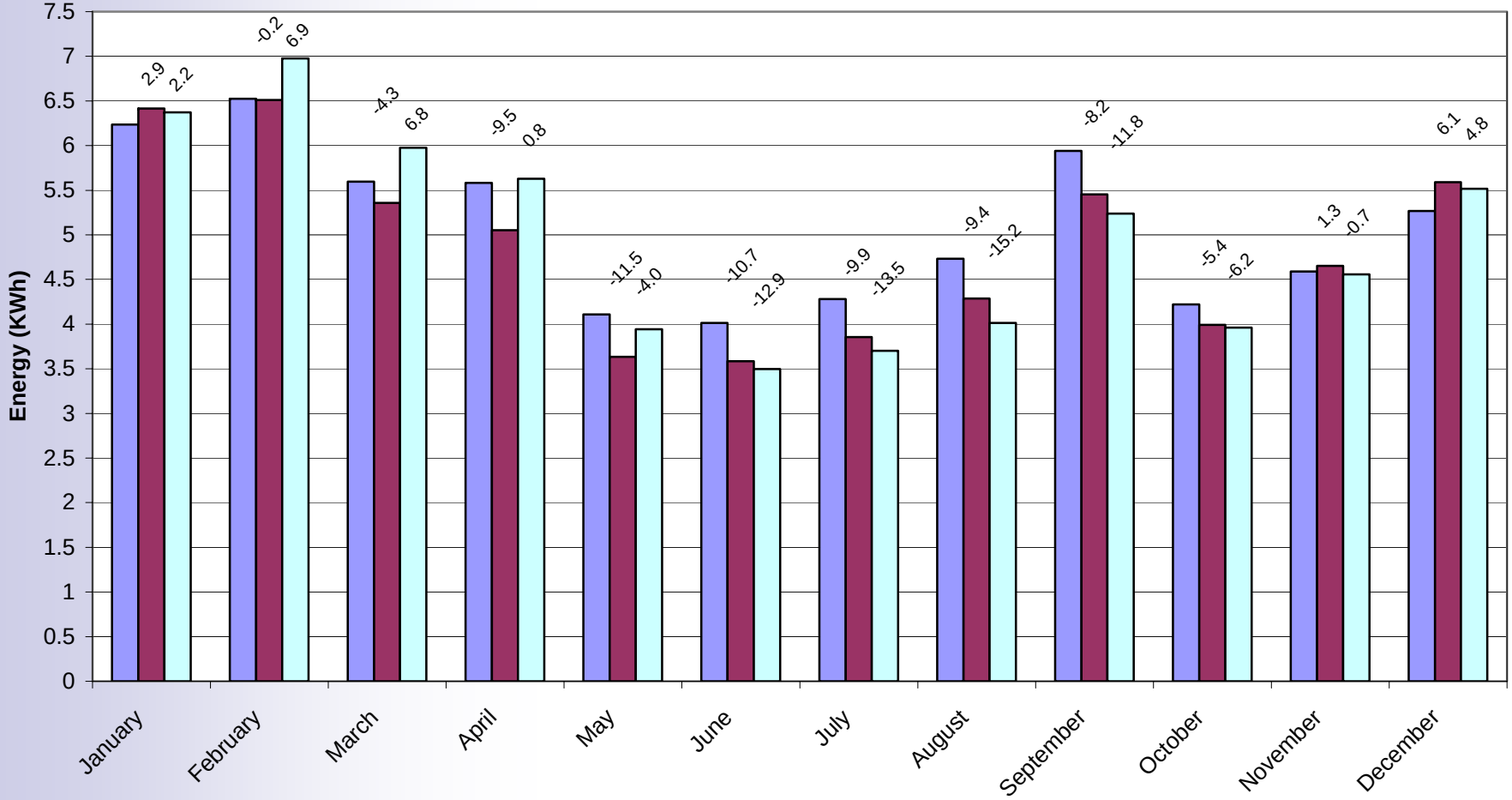
## Measured vs. Predicted Energy Comparisons
## Tandem Junction Module 2nd Characterization with Glass Glazing




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%

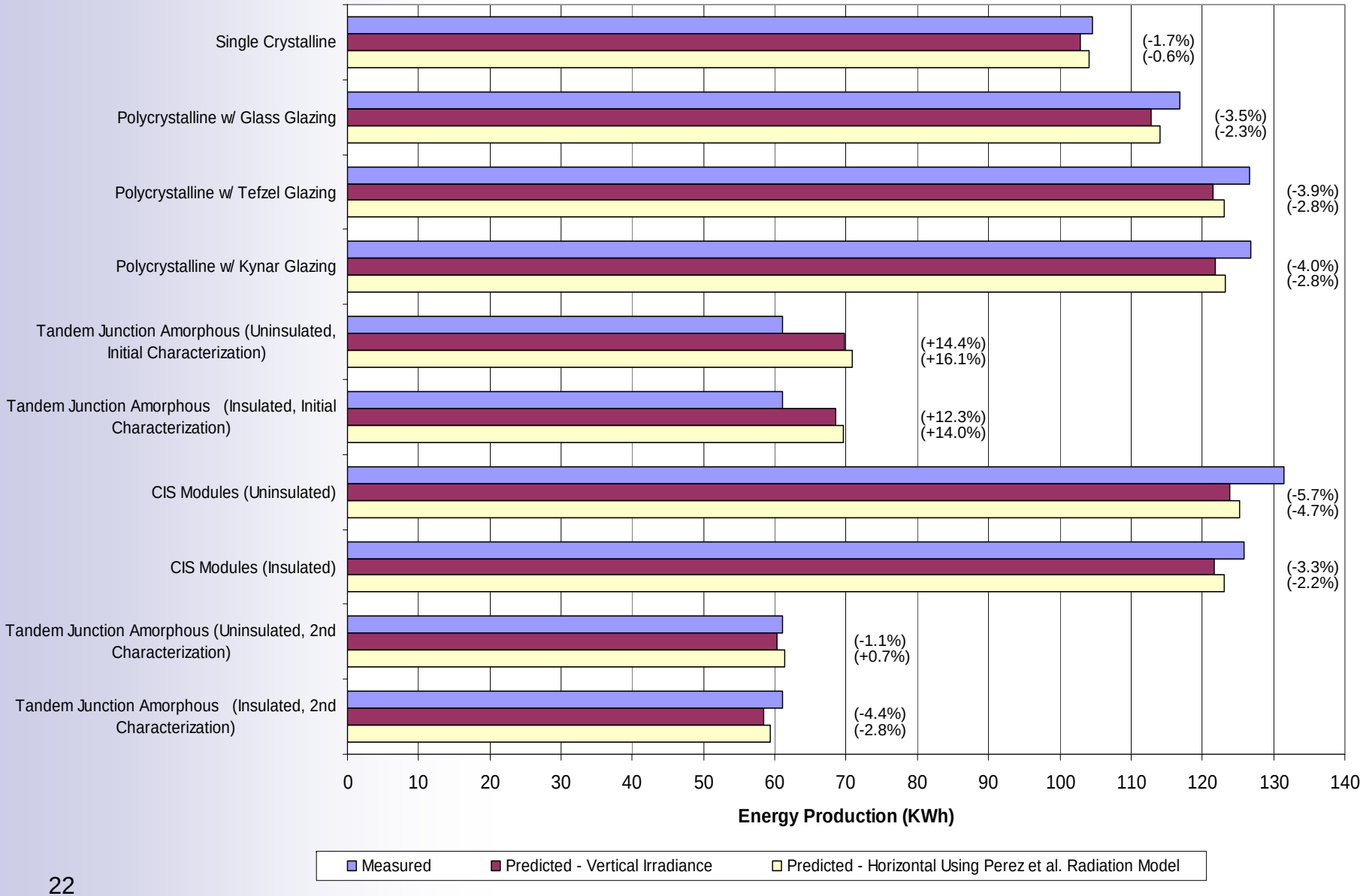
## Measured vs. Predicted Energy Comparisons
## Tandem Junction Module 2nd Characterization with Glass Glazing Thermal Insulation




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



# 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