Materials by Design and Advances in Photovoltaic R&D

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Photovoltaics Summary

Rapid progress has been made in PV but we aren’t done yet

Solar energy can deliver low-carbon energy to mitigate Climate Change BUT further advances are needed for TWs

• Grid parity ≤ 2020
• Systems approach (module, BOS/soft costs, reliability, grid integration)
• Policy/markets; Utility models, Financing

Beyond Grid Parity with significant further cost reductions (2-3¢/kW-hr)

• Next-Gen technologies: new materials, concepts and processes for high efficiency, low cost, AND manufacturability
• Novel processing technologies (low CAP-EX mfg)
• Mitigate devaluation of solar at high penetration
• Grid flexibility, energy mix, and low cost energy storage

Solar energy can also provide power to the underserved

• Multi-scale approaches to energy systems
• Distributed and dispatchable energy, microgrids, storage
• Since 2011, costs down 65% and 70% towards grid parity goals
• 8 reports DOE and 4 National Labs (NREL, Berkeley, Argonne, Sandia)
  • Lessons Learned; Challenges/Opportunities

PHOTOVOLTAIC EFFICIENCY, RELIABILITY, AND COSTS
ADVANCING CONCENTRATING SOLAR POWER TECHNOLOGY

U.S. SOLAR MANUFACTURING

INTEGRATING HIGH LEVELS OF SOLAR INTO TRANSMISSION
INTEGRATING HIGH LEVELS OF SOLAR INTO THE DISTRIBUTION SYSTEM
FINANCING SOLAR
UTILITY REGULATION AND BUSINESS MODEL FOR FINANCIAL IMPACTS
ENVIRONMENTAL AND PUBLIC HEALTH BENEFITS

http://energy.gov/eere/sunshot/path-sunshot
• Continued innovation in system-level S&T critical for grid parity and beyond

• Need to pursue multiple strategies to maintain the value (costs + benefits) of solar

• Increasing grid flexibility, next-gen power electronics and other strategies could enable 25% solar

• Monetizing environmental benefits could add ~3.5¢/kWh to the value of solar energy
NREL Solar R&D: Materials, Cells, Modules, Systems

- Cost, Performance
- Manufacturability
- PV and System Reliability
- Analysis
- Balance of System & Soft Costs
- Grid Integration
- Energy Storage
NREL Solar R&D: Materials, Cells, Modules, Systems

Understand limitations and enhance performance in current systems

Accelerate emerging concepts

Develop next generation concepts and materials

PV R&D

Systems Integration

Analysis
Hydride Vapor Phase Epitaxy for GaAs

Now >23% GaAs homojunction cell (no cladding layers):

• Dual chamber HVPE reactor for Ga, In, As, P alloys
  • full 3D computational fluid dynamics (CFD) modeling
• Produced epitaxial GaAs materials at growth rates exceeding 1.8 μm/min
• Can produce flat, parallel, low-defect homo- and hetero-interfaces
• Demonstrated very high metal utilization (~70% for Ga)

A. Ptak, J. Simon, NREL
Development of World Record GaInP/Si Dual-Junction, One-Sun Solar Cell

- A two-junction structure with a silicon bottom junction
- New device structure combining a III-V GaInP top junction and a silicon bottom junction,
- Demonstrated a world record 29.8% efficiency – significantly exceeding the best conventional silicon efficiency of 25.6%.
- Four-terminal structure allows ease of construction, and optimal energy production under real-world operating conditions.
- Developing an improved, manufacturable bonding

1.8-eV GaInP top junction with a silicon bottom junction, with a four-terminal interconnection

CdTe Technology
Cataloging the role of GBs, surfaces and bulk defects

Overcoming 20-year $V_{oc}$ barriers

- Worked w/o universal CdCl$_2$ treatment
- Switched to anion Group V doping
- Shifted to Cd-rich stoichiometry to improve lifetime by removing Te$_{Cd}$ antisites, and hole density by placing P on Te sites.

Histogram of $V_{oc}$ values for about 2200 polycrystalline CdTe devices

T. Barnes, W. Metzger et al.
Solar Devaluation with Increasing Deployment

Mills, Wiser, LBNL, 2012

Denholm, NREL, 2012
Grid Modernization Lab Consortium

• Grid Modernization Laboratory Consortium involves 14 DOE national laboratories and industry, academia, and state and local government partner
• Energy Systems Integration Facility
  - Multiple parallel AC and DC experimental busses (MW power level) with grid simulation
  - “Hardware-in-the-loop” simulation capability to test grid scenarios with high penetration of renewables
  - Peta-scale high-performance computing and data management system
  - Virtual utility operations center and visualization rooms
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  - Frequency regulation – load shifting
  - Backup energy generation – Power, response time, energy stored
  - Integration vs. storage

- Flexible Grid
- Vehicles to Grid, Buildings
- Water purification/desalination
- Fuels, Chemicals
  - CO₂ reduction; N₂ → NH₃; C

- Solar (light)
- Thermal (heat)
- Electrical Storage
- Fuels (chemical)
Conceptual H₂@Scale Energy System

*Illustrative example, not comprehensive

Solar Hydrogen Generation for Energy Storage

**PV-Electrolysis**

- Renewable Wind
- Utility Grid
- Fuel Cell
- Electrolyzer
- Hydrogen Storage

**Photoelectrochemical Water Splitting**

- Novel cell uses light to produce H₂ at 12.4% efficiency

K. Harrison *et al.*

J. Turner *et al.*

*Note: n and p refer to n- and p-type semiconductors*

*Credit: Adapted with permission from Science, copyright 1996 AAAS*
World Record: Photoelectrochemical (PEC): $\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2$

**Technology**

- Inverted metamorphic multijunction (IMM) PEC device enables more ideal bandgaps
- Grown by *organometallic vapor phase epitaxy*
- Incorporates *buried p/n GaInP$_2$ junction* and *AlInP passivation layer*

**Solar-to-hydrogen Efficiency**

16.4%

Benchmarked under outdoor sunlight at NREL

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**IMM device cross sections**

- Top surface
- III-V tandem
- Au contact/reflectector
- Epoxy
- Si wafer handle
- 10 μm, 1 μm

**Current density vs. bias graph**

- Upright GaInP$_2$/GaAs
- Inverted GaInP$_2$/GaAs
- IMM (GaInP$_2$/InGaAs)
- p-n IMM
- p-n IMM w/ passivation

Credit: NREL
New ultrafast laser spectroscopy technique uncovers how photoelectrodes produce solar hydrogen from water

Semiconductor photoelectrodes convert solar energy directly into chemical fuels.

NREL’s new probe measures transient electrical fields and shows how semiconductor junctions convert sunlight to fuels.

The field formed by the TiO$_2$ layer drives electrons to the surface where they reduce water to form hydrogen.

The oxide prevents photocorrosion by keeping holes away from the surface.

This new understanding will lead to more stable and efficient solar fuel generators.

Perovskites

- Minority carrier diffusion lengths > 1μm in thin films, 175μm in single xtal cells
- Monomolecular recombination lifetimes of 280 ns
- Minority carrier mobilities ~ 10 cm^2/V/s are reasonable
- High $\varepsilon_r = 60-70$; Low $m^* = 0.1, 0.16$

Molecular approaches to solution-processable, defect-tolerant GaAs
Potential Costs

16% Perovskite compared to other PV

Stable perovskite PV meets 2020 targets (Woodhouse/NREL)
NREL R&D Themes

‣ Basic understanding of photophysics & transport
‣ Theory and modeling
‣ Discovery
‣ Device fabrication and characterization
‣ Synthesis & processing
‣ Interfaces
‣ Device operation & physics
‣ Stability and degradation mechanisms

![Graph showing device efficiency progress from 2013 to 2016.](image-url)
Fundamental Perovskite work at NREL

- **Hot carrier dynamics**
  - Phonon bottle neck carrier cooling rate (~3x more efficient than GaAs) - *Nature Photonics* (2015)

- **Role of excitons**

- **Surface recombination**
  - Intrinsic surface recombination velocity is very low *Nature Comm*, 2015, 6, 7961
  - Difference in single crystal and thin film surface recombination velocities
  - Grain boundaries impact on recombination

- **Interface charge transport**
  - Substrate controlled electronics (Kahn/Princeton)
  - SAM layer for enhanced charge separation (Snaith/Oxford, Ginger & Jen/UW, Friend/Cambridge)
Some Perovskite Advances

• Band bending at model SWCNT:perovskite interface using PES. Ultrafast spectroscopy shows efficient photoexcited hole extraction
  

• Developed new tools and techniques to evaluate absorber structure as function of processing. Using quantitative x-ray diffraction at SLAC showed that high efficiency device structures have a large amount of material in amorphous phase.
Square-Centimeter Solution-Processed Planar MAPbI$_3$ PSC with PCE >15%

Novel solution chemistry for uniform, high-crystallinity, planar perovskite films with high-aspect-ratio grains over a square-inch area; and >15% efficiency PSC with 1.2 cm$^2$ active area

New Device Level Stability Capabilities

Functional device studies using combinatorial device testing rig
New stability parameter analysis systems

- Flow cell geometry, controlled temperature, humidity and atmosphere
Clean Energy Materials Challenges

Structural Materials
- lightweight alloys & composites
  - cars, buses, wind turbines, fuel tanks...
- high temp materials
  - CSP, combustion, geothermal...

Optical Materials
- advanced optical absorbers
  - PV, solar fuels, solar purifiers...
- efficient solid-state converters
  - thermoelectrics, LED lighting...
- WBG semiconductors
  - power electronics, grid integration...

Thermal Materials
- energy storage materials
  - thermal, thermochemical...
- electrode materials
  - batteries, fuel cells, electrolyzers...
- alternative fuels
  - advanced combustion, bio/synthetic fuels...

Chemical Materials
- non precious catalysts
  - fuel cells, electrolyzers, reformers...

Numerous materials classes are vital to “Clean Energy Technologies”
Address four Critical Gaps limiting Materials by Design

1. Multiple-Property Design
2. Accuracy and Relevance
3. Metastability
4. Synthesizability

1. Design and discover new energy-relevant materials with targeted functionalities.
2. Develop foundational theoretical, synthesis, characterization tools.
3. Incorporate functional metastable materials into MbD.
4. Develop a systematic theory-driven approach to guide synthesis.

www.cngmd-efrc.org
CNGMD Team Integrates Theory, Experiment, Data

LBL-Berkeley – Gerd Ceder (Chief Theorist)  
   Kristin Persson  
NREL – Stephan Lany  
CSM – Vladan Stevanovic  
MIT – Alexie Kolpak

NREL – David Ginley (Chief Experimentalist)  
   Andriy Zakutayev  
CSM – Brian Gorman  
MIT – Tonio Buonassisi  
Harvard – Dan Nocera  
   Roy Gordon  
OSU – Janet Tate  
SLAC – Mike Toney

NREL – Bill Tumas (Director), John Perkins (Program Integrator)
Theory Tools Development: DFT Improvements

**GW Corrections for bandgaps**
- One empirical parameter per TM atom, good transferability, e.g., to ternaries
  

**Fitted Elemental Reference Energies (FERE)** for heats of formation
- $\mu^0\,\text{(FERE)} = \mu^0\,\text{(GGA+U)} + \delta\mu^0\,\text{(FERE)}$
- FERE reduces the mean average error (MAE) to $0.054$ eV/atom $\approx 1$ kcal/mol
  

**SCAN functional to reproduce basic MnO$_2$ properties**
- First functional to simultaneously reproduce strong covalent-like bonds and weaker long-range interactions
- J. Perdew (Temple), CCDM EFRC
  

**Neural Networks for large-scale Defects**
A. Kolpak et al., in progress
High-throughput calculations

**DFT level (atomic structure and total energy)**
- ca. 20,000 crystalline ordered materials
  - Repository of atomic structures
  - Thermochemistry and stability

**GW level (electronic structure)**
- ca. 250 semiconducting and insulating materials
  - So far: Mostly oxides, chalcogenides, nitrides
  - Direct and indirect band gaps
  - Band-edge shifts wrt DFT (defects, IP/EA, band offsets)
  - Effective masses, density of states
  - Optical properties, dielectric function, absorption spectra
NREL High-Throughput Experimental Tools

Thin Film Deposition

- 4 Dedicated PVD System
- 3 RF sputtering
- 1 PLD
- Composition Gradients
- Thickness Gradients
- Temperature Gradients
- Ar, N, O, Ar/H₂S gases
- Atomic S & N sources

Property Mapping

- 15 Mapping Tools
  - Composition (XRF, RBS)
  - Structure (XRD, Raman)
  - Transport (4pp, Seebeck)
  - Optical (UV-Vis, IR, PL)
  - Surface (KP, XPS/UPS)
  - Microscopy (SEM, AFM)

Analysis & Visualization

- Advanced Data Tools
  - NREL Data Network
  - Igor PRO framework
  - Extensible
  - User-assisted analysis
  - Data mining/analysis
In-Situ Tools at SLAC: In-situ crystallization of amorphous films

Deposition → Amorphous films

△ Crystallization

X-rays
In-Situ Tools at SLAC: In-situ crystallization of amorphous films

Deposition → Amorphous films → X-rays

Some of the CNGMD team with various SLAC tools
Two Main Approaches to Materials by Design

Design by Design Principles
- Many material systems with known structure and composition (e.g. ICSD)
- Functionality unknown
- Search via design principles for targeted functionalities

Missing Materials
- Many material systems, but structure unknown
- Many (~ 50–100) possible configurations, requiring energy minimization and stability analysis
- Target properties: first existence, then other properties

G. Ceder, and K.A. Persson
Two Main Approaches to Materials by Design

Desig
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define search goals and search space

High-throughput materials search

Focused studies, theory and experiment

Implementing Inverse Design

Designing p-Type Ternary Oxides

**DEVELOP** p-type TCO design principles

**SEARCH** $\text{A}_2\text{BO}_4$ w.r.t. design principles

**IMPROVE** $\text{Co}_2\text{ZnO}_4$ based on design principles

Novel inorganic materials with tailored properties
Optical and Electrical: Region of Interest

Optical and Electrical properties optimized in composition region.
Zn-Co-O as a hole transport layer (HTL) for OPV

- Performance comparable to PEDOT:PSS on the first try

"Zn-Ni-Co-O wide-bandgap p-type conductive oxides with high work functions"
High-throughput Discovery of New $A_2BX_4$ Compounds

Rules:
1. Only one transition metal at a time
2. Respect possible oxidation states

Total 656 possible combinations
250 are reported
406 are not reported ("missing compounds")
Predicted New $A_2BO_4$

Out of 63 missing oxides
46 not stable
17 stable

Newly predicted:
- $Hg_2SiO_4$
- $In_2HgO_4$
- $Ti_2BeO_4$
- $Ti_2SrO_4$
- $Ti_2BaO_4$
- $Ti_2ZnO_4$
- $V_2BeO_4$
- $V_2SiO_4$

$A_2BX_4$ search:
- ~80,000 individual total-energy calculations
  (incl. structures and magnetic configurations)

7 already predicted by Hautier et al., Chem. Mater., 2010
**CID Predicted Ternary Materials**

**$A_2BX_4$ materials main group and 3d elements:**

Out of 684 variations, 429 are unreported

**100 predicted stable, 11 undetermined, and 318 predicted not stable**


**ABX materials with 8 electrons:**

Out of 714 variations, 488 are unreported

**235 predicted stable, 18 undetermined, and 235 predicted not stable**

Identification of ABX ternary materials

HfIrSb, ZrRhBi, ScRhTe, TaCoSn, TaIrGe, VIrSi, VRhSi and HfRhP have been shown to crystallize in their predicted crystal structure.

**Example:**

HfIrSb $F\text{-}43m$

Predicted crystal structure

The symmetry of a predicted stable compound makes possible:

1) Simulation of diffraction pattern
2) Fast identification in the experimental pattern

**Fast identification in multiphasic sample**

With Confirmation By Electron diffraction

$F\text{-}43m$

Single crystallite

Experiment

Simulation

(110) zone

X. Zhang et al. Nature Materials
Missing TaCoSn Compound

Not known in ICSD or ICDD

Large stability range

Predicted to have semi-conducting gap ~ 1.3 eV (GGA + U)

Competing phases:
Ta, Co, Sn
Ta₃Sn, TaSn₂
CoSn, CoSn₂, CoSn₃, Co₃Sn
Validation: growth of new TaCoSn

Perovskite Search: Proxy for Transport/Defect Tolerance

- Minority carrier lifetimes challenging for both computation and experiment
- The concept of defect tolerance can used as a proxy (qualitative)
- Defect tolerance is a consequence of the electronic structure

Classic III-Vs and II-Vis are defect intolerant: GaAs, InP, GaN, ZnO,…

Electronic structure of a defect tolerant material

Brandt et al. MRS Communications 5, 265–275 (2015)
Electronic structure of MAPbI$_3$

In MAPbI$_3$:

• Pb 6s orbitals provide antibonding character to the VBM (s-p repulsion)
• With spin-orbit coupling, conduction band is more disperse

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R.E. Brandt, V. Stevanović, D.S. Ginley, T. Buonassisi,

Search 27,000 Inorganic Materials for s-VBM

R.E. Brandt, V. Stevanović, D.S. Ginley, T. Buonassisi, MRS Comm. 5, 265 (2015)
www.materialsproject.org
Multiple Material Classes Identified

- Compounds with “lone-pair” cations: In\(^+\), Sn\(^{2+}\), Sb\(^{3+}\), Tl\(^+\), Pb\(^{2+}\), Bi\(^{3+}\)
- Building libraries of hybrid materials through inorganic analogues
Bismuth Triiodide (BiI$_3$)

- First films synthesized exhibited room-temperature photoluminescence

• Informed new design criterion – purity of materials and growth environments

Incorporating Metastability

Thermochemically metastable

Polymorphs

Semiconductor alloys

Defects

x in A_{1-x} X_x
Search for New Nitrides

Data-Mined Ionic Substitution


Known Compounds

OsN
ICSD #167514

Cross-validated by “predicting” known nitrides. \( \sim 80\% \) chance of recovery

Suggested Compounds

492 suggested binary nitrides (Alkali, Transition, Main Group)

Train data-mining algorithm on known Oxides+Pnictides

Candidate Stable Phases

\[
\begin{align*}
\text{Co}_2\text{N}, & \quad \text{CoN}, \quad \text{Cr}_3\text{N}_2, \quad \text{Cr}_3\text{N}_4, \quad \text{CrN}, \quad \text{Hf}_3\text{N}_4, \quad \text{Nb}_2\text{N}, \\
\text{SbN}, & \quad \text{Sr}_2\text{N}, \quad \text{Ta}_2\text{N}, \quad \text{TeN}_2, \quad \text{V}_2\text{N}, \quad \text{V}_3\text{N}_2, \quad \text{VN}, \quad \text{Zn}_3\text{N}_2
\end{align*}
\]
Optoelectronic properties *(Work in progress)*

Pathway to new nitrides – from search to application

**From design & discovery to properties search**
- We calculate *optoelectronic properties* of newly predicted nitrides.
- Promising semiconductor nitrides *accessible via sputtering* will be further screened using higher levels of theory \((G_0W_0)\)
- **Down-selection** for experimental synthesis and characterization
**In progress:** Ternary Nitride Search

Ternary Convex Hull

4000 potential ternary nitrides

**Ternary Nitride Phases**

- ABN$_2$

**Alloyed Binary Nitrides**

- A$_x$B$_{1-x}$N

**Metal Oxynitrides**

- Me-O-N

*Enormous* exploration and design space for new nitrides!
Sn Nitride Thin Films

Entry point material: metastable Sn$_3$N$_4$

Improved material: metastable Sn$_{3-x}$Ti$_x$N$_4$

- **Sn$_3$N$_4$ is a potential PEC material:**
  - good optical absorption ($E_g$ = 1.6 eV)
  - suitable VB position for H$_2$O oxidation
  - n-type conductivity (light electrons)
- **However:** large hole effective masses


- **Sn$_{3-x}$Ti$_x$N$_4$ has better properties than Sn$_3$N$_4$**
  - Theory: lighter $m_h$, same $m_e$, and lower $E_g$
  - Experiment: strong optical absorption
  - Also: SnTi$_2$N$_4$ is a new spinel nitride!!!
  - Structure: pure by XRD, spinodal by TEM
Realization of tetrahedral MnO by alloying with ZnO

ZnO has tetrahedral wurtzite structure similar to zinc-blende

Mixing enthalpy

\[ \Delta H_{\text{mix}}(x) = (1 - x) \cdot H_{\text{MnO}} + x \cdot H_{\text{ZnO}} + \beta \cdot x(1 - x) \]

- \( \beta = 46 \) meV (RS), \( \beta = 94 \) meV (WZ)

T-x phase diagram

- Common tangent construction
- Ideal solution model for entropy

Theory

Phase transition predicted at \( x = 0.38 \)
However, desired alloy composition is deep inside miscibility gap

Experiment

Realization of single-phase WZ MnZnO by non-equilibrium PLD growth
Predicted phase transition confirmed
Optical absorption: Theory vs experiment

Metastable transition metal oxide alloy with unique semiconducting properties

- Band gap control through alloying
- Non-equilibrium growth via PLD
- PEC measurements
  - Band alignment, carrier transport

Measured absorption coefficient $\alpha$ (contour plot) and calculated band gaps (dashed line)
MOx Polymorphs

Manganese Oxides
• Over 30 known polymorphs
• Energy storage, catalysis, pigments

Vanadium Oxides
• Highly complex phase diagram
• Batteries, reagents, coatings

Titanium Oxides
• Poorly understood nanoscale transformations, polymorphs
• Widely studied photocatalyst
Challenging Energetics for MnO$_2$

- All known DFT methods fail to reproduce basic MnO$_2$ properties
- First functional to simultaneously reproduce strong covalent-like bonds and weaker long-range interactions
- Formation energies of MnO$_2$ polymorphs are reproduced in SCAN

\[ \Delta H_f \text{ (meV/MnO}_2\text{) relative to } \beta\text{-MnO}_2 \]

- PBE+U
- PBE
- PBEsol+U
- PBEsol
- HSE
- SCAN
- Exp.

Understanding of synthesis paths is required to rationally and effectively design metastable compounds.

Controlled synthesis

Nucleation

Surface Energy

Bulk Energy

Defect Energy

Atomic Nanoscale Bulk

In-situ experiments

Apply the same fundamental science used to understand properties to understand synthesis.
Polymorph selection

Need to understand thermodynamics in all relevant environments

1. Bulk energy of polymorphs
2. Intercalation of ions from solution
3. Surface energies in solution
   Predicting nucleation behavior
4. Electrochemical transformations
5. Modeling solid-solid transformations
   Kinetics of polymorph conversion
6. Substrate-controlled depositions
Polymorph Sampler

- Volume of configuration space ("width") of local minima shown to correlate with realization of different polymorphs
- Random structure sampling followed by local DFT relaxations used to estimate the "width"
- All experimentally realized polymorphs appear as high frequency structures in random sampling
- Translates into a simple and elegant approach for predicting polymorphism - Polymorph sampler
- Easy to apply in a high-throughput fashion

Realizability from the “width” of local minima

- For majority of systems, even well studied, only a relatively small number of polymorphs is known (experimentally realized)
- Theoretical predictions usually suggest a large number of low energy structures
- Our approach: “Width” of local minima matters, i.e. it is more probable to create exp. conditions that will prepare the system nearby larger (“wider”) minima
Random sampling to measure the “width”

- Random structure sampling followed by DFT relaxations can be used to measure/estimate the “width” of local minima
- Frequencies of occurrence in random sampling to assess the “width” of individual basins
Validation of the hypothesis - MgO and ZnO

- 2,000 random structures per system
- All experimentally realized polymorphs appear as high freq. structures in random sampling
- RS MgO about 25 times more frequent than any other structure, indicates why is RS the only exp. realized MgO structure
- Experimentally realized ZnO structures are three top occurring in random sampling
CNGMD - Poly sampler applied in nitrides search

SnN

Sb(III)'Nitride'(SbN)'structures'

SbN poly sampler
N=1-20 f.u.

Pmmn (SG59)

Paper submitted
(NREL/CSM/SLAC/LBNL/MIT)

Nitride search
Brief Summary: Materials by Design

Materials by Design has advanced considerably
- Increasing number of active centers
- Structural and functional materials
- Tools being developed, databases being developed

Integration (and iteration) of theory and experiment is critical
- Tool development
- Validation, accuracy

Materials Properties for have been predicted and confirmed

New materials have been predicted and synthesized
  oxides, charge transport layers, absorbers, perovskite-analogs

Computational databases are becoming readily available, applied research can be built on top of these more basic science efforts

Theory and experiment can provide information on metastable systems, e.g. new nitrides, alloys, polymorphs

Predicting synthesis constitutes a grand challenge for materials science
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  Paul Denholm, Kristen Ardani, Jim Cale, Sarah Truitt

Terawatt PV Challenge (Fraunhofer-ISE, AIST, NREL, …)
  Eicke Weber F-ISE, Martin Green (UNSW)
  TW Challenge Workshop (Freiburg, March 2016)

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Others: Mike McGehee, Tonio Buonassisi, David Cahen
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www.centerforinversedesign.org
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