### Our Team:

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**National Renewable Energy Laboratory**
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**Research Thrust Leadership**
- Indian Institute of Technology Bombay
- Sandia National Laboratories
- Center for the Study of Science, Technology and Policy
- RAND Corporation

### Consortium Leads

<table>
<thead>
<tr>
<th>India</th>
<th>United States</th>
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### Consortium Partners

#### Institutes and National Laboratories
- Lawrence Berkeley National Laboratory
- International Advanced Research Centre for Powder Metallurgy and New Materials
- Solar Energy Center

#### University Partners
- Arizona State University
- Carnegie Mellon University
- Colorado School of Mines
- Massachusetts Institute of Technology
- Purdue University
- Stanford University
- University of Central Florida
- University of South Florida
- Washington University in St. Louis

#### Industry Partners
- Corning Incorporated
- General Electric Company
- Cookson Electronics
- MEMC Corporation
- Solarmer Energy, Inc.
- THERMAX
- Moser Baer India Ltd.
- Thermax Ltd.
- TurboTech Precision Engineering Ltd.
- Wipro Ltd.

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DE-FOA-0000506: U.S.-India Joint Clean Energy Research and Development

Our Objectives:
- High-impact, Disruptive-Technology R&D (PV, CSP)
- Collaborative Project Structure, Joint Management at Every Level, & Joint IP Management (TEAMING)
- Effective Bi-National Collaboration
- Workforce Development
- Fellowships (MAGEEP and Indian Organizations)
Collaborative Research Thrusts, Activities, and Projects

Research Design
- Analysis- and assessment-driven
- Multidisciplinary, bi-national teams
- Industry integration into multi-institutional projects
- “Use-inspired” R&D

Research Thrusts
- Sustainable Photovoltaics (PV)
- Multiscale Concentrated Solar Power (CSP)
- Solar Energy Integration (SEI)

Activities
- Earth Abundant PV
- Novel Process Technology
- Multiscale Modeling and Reliability
- High-T, Closed-Cycle, Bravton Cycle
- Low-T Organic Rankine Cycle
- Thermal Storage & Hybridization
- Roadmapping, Analysis and Assessment
- Grid Integration and Energy Storage

Projects
- Consortium Projects
- Core Projects
- Consortium Projects
- Consortium Projects
- Core Projects

Two-tier Project Structure

- **CONSORTIUM PROJECTS**: disruptive, transformative R&D
- **CORE PROJECTS**: core industry partner-led and focused
## Collaborative Research Thrusts, Activities, and Projects

**Research Thrusts**

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<th>Thrusts</th>
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<th>Projects</th>
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<td>Thermal Storage &amp; Hybridization, Roadmapping, Analysis and Assessment, Grid Integration and Energy Storage</td>
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<td>Solar Energy Integration (SEI)</td>
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<td>Core Projects</td>
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### IMPACT:
- Significantly accelerate disruptive PV technologies
- Provide foundation on which future Indian PV industry can build

### IMPACT:
Significantly reduce levelized cost of electricity:
- increasing the power block efficiency
- decreasing the solar collector cost with innovative designs & optical materials.

**CONSORTIUM PROJECTS:** disruptive, transformative R&D  
**CORE PROJECTS:** core industry partner-led and focused
Collaborative Research Thrusts, Activities, and Projects

IMPACT:
Provide critical technical, economic, environmental, and policy guidance:
- For SERIUS research-planning and review to ensure relevance/priorities in meeting objectives
- For stakeholders-critical information with roadmapping and analysis.

- **CONSORTIUM PROJECTS**: disruptive, transformative R&D
- **CORE PROJECTS**: core industry partner-led and focused
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Implementing Advanced Concepts:
- PV: Roll-to-roll/solution processing; compliant substrates
- CSP: Low-cost optical & collector materials; storage, hybridization
- Crosscutting: Nanotechnology, reliability/durability, field testing, soiling
- Core Industry Projects (accelerating current technologies)
- Implementing Advanced Concepts: Assessment and Guidance
  - Solar Energy Integration
    - Performance Limits
    - Grid Integration, Dispatchability
    - Roadmapping and Bankability
    - Links to Nehru Solar Mission and SunShot Initiative (reality)

Consortium Project Focus:
- PV: Thin-film PV (CIGS, CZTS, OPV)
- CSP: Multiscale concepts
  - Closed-Cycle CO$_2$ Brayton
  - Organic Rankine-Cycle

Deployment in Terawatts (Log Scale)
The Science of Sustainable Photovoltaics . . .

Materials: CIGS, CZTS, and OPV

Inks and synthesis
- Understanding metal-organic decomposition
- Molecular precursor design
- Synthesis to desired materials
- Inks:
  - Absorbers
  - Transparent Conductors
  - Contacts/Packaging

Deposition
- Desired precursor with no residual organics
- Designed to densify and allow grain growth
- Compatible with other layers

Processing
Device quality:
- Rapid thermal processing
- Optical processing

Integration
- Materials/devices integrated onto flexible substrates

The Technology of Developing Low-Cost Atmospheric Processes . . .
Concentrating solar power (CSP) cost arithmetic

Solar field cost: ~60%

5 MW Parabolic Trough
Cost Breakdown (CSTEP Analysis)

<table>
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<tr>
<th>Cost Category</th>
<th>Percentage</th>
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<tr>
<td>Other Costs</td>
<td>9%</td>
</tr>
<tr>
<td>Mirror</td>
<td>16%</td>
</tr>
<tr>
<td>Steam cycle</td>
<td>27%</td>
</tr>
<tr>
<td>Structure</td>
<td>23%</td>
</tr>
<tr>
<td>Absorber tube</td>
<td>17%</td>
</tr>
<tr>
<td>Tracking</td>
<td>6%</td>
</tr>
<tr>
<td>Thermal Fluid</td>
<td>2%</td>
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</table>

Aim:
- **Solar field**
  - _decrease_ cost
  - _increase_ durability

- **Power Plant**
  - _increase_ cycle efficiency

Low-cost structures, tracking; _new optics & coating materials_

Develop _new cycles, new engines_
The Science of Multiscale Concentrating Solar Power...

Scientific Challenges/Technology Innovations

High-temperature, closed-cycle CO₂-Brayton (100kW-1MW)
– High-temperature receivers, expanders, low-cost heliostats and Brayton power cycles to increase the gross cycle efficiency to >50% to meet SunShot goals.

Low-temperature organic Rankine cycle (25kW-1MW)
– Low-cost, parabolic trough collectors that have optical efficiencies of >70%, operate up to 230°C, and have <2% thermal loss (overcome scale-down penalty).
– Develop small (25 kWe) turbo-expanders that have greater than 80% isentropic efficiency.

Thermal storage and hybridization
– Advanced, low-cost thermal storage for integration into high temperature Brayton CO₂ cycles and low temperature organic Rankine Cycles

Key Focus: Water Independent, Hybridization
The Science Solar at the Nanoscale . . .

Nanostructured Materials for PV

Coupling novel nanostructures to new dyes for enhanced performance in dye-sensitized solar cells (DSSC)

- Science Challenges:
  - To develop & integrate dye/nanostructure
  - To enhance performance and stability of DSSC

- Shared US-India knowledge:
  - nanostructured materials from US
  - novel BODIPY dyes from India

Novel Nanostructured Coatings for CSP and PV Dust Mitigation

New generation dust resistant coatings

- Science Challenge: To develop & validate novel nanotechnology-based, durable superhydrophobic (and superhydrophilic) plasmonic metamaterials
- Low-surface energy metal nitrides (CrN, MoN, TIN, ZrN) as protective films for CSP reflectors (and PV modules)

Image of superhydrophobic structure (left) that forms a surface with virtually no contact area with water (right).
The Science and Technology of Solar Energy Integration (SEI)

Roadmapping
- Barriers to deployment (India vs. US)
- Bankability
- Technology/policy assessments
  - grid-connected and off-grid
  - storage requirements
  - hybridization
- Identification of R&D needs

Grid Integration and Dispatchability
- Grid analysis in India
- Rural/off-grid power
- Storage, hybridization
Major Milestones and Deliverables by Research Thrust

**Sustainable Photovoltaics**
- **Year 5:** Develop >15% thin-film PV technology from Earth-abundant materials on a flexible substrate, roll-to-roll processing using ink technology (industry-ready).
- **Year 2:** Develop and validate (field testing in India) a nanotechnology-based coating for PV module dust mitigation with >1 year durability.
- **Year 1:** Establish field-testing with U.S. PV manufacturers (modules and coatings).

**Multiscale Concentrating Solar Power**
- **Year 3:** Develop low-cost, parabolic trough collectors that have optical efficiencies of >70%, operate up to 230°C, and have <2% thermal loss.
- **Year 4:** Develop 25-kWe turbo-expanders with >80% isentropic efficiency.
- **Year 5:** Develop high-temperature supercritical CO₂ receivers, low-cost heliostats, and Brayton power cycles to increase the gross cycle efficiency to >50% to meet SunShot Initiative goals.

**Solar Energy Integration**
- **Year 2** (and updated annually thereafter): Technology roadmap for PV and CSP in India (Barriers, Technology Needs and Requirements, Policy).
US-India Joint Clean Energy Research and Development Consortium
Solar Energy Research Institute for India and the United States (SERIIUS)
Organization Structure

US-India JCERDC

Executive Oversight

India-US Leadership and Coordination
Co-Directors
L.L. Kazmerski, NREL-US
K. Chattopadhyay, IISc Bangalore-India

Deputy Managing Directors
W. Tumas, NREL-US
P. Dutta, IISc Bangalore-India

SERIIUS Council

Industry Board

Research Thrusts

Competency Gateway

Technical Advisory Board

SERIIUS Council: Internal Governing Board for Consortium
(Core Industry, University, SERIIUS Leadership)
Industry Board: SERIIUS Core Industry Partners
SERIIUS Web Gateway (www.SERIIUS.org)
REAL-TIME INTERNATIONAL RESEARCH PARTNERING

Web Gateway
www.SERIIUS.org
- Public Information Access
- Research Partner Secure Access

Modeling & Simulation Hub
- Solar (PV, CSP modeling)
- Simulation routines ADEPT toolbox
- Materials and device design
- Computational science portal

Remote Access Hub
- Remote learning and training
- On-line equipment, data acquisition
- Secure research information access
Thank you • शुक्रिया