

Global Centers for Solar Fuels & Artificial Photosynthesis

Siddharth Dasgupta

NSF Center for Chemical Innovation: Solar Fuels
Caltech

The New York Times

Business Day

WORLD U.S. N.Y. / REGION BUSINESS TECHNOLOGY SCIENCE HEALTH SPORTS OPINION

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NOVELTIES

The Answer Is (Artificially) Blowing in the Wind



5/24/2011

NSF CENTRE

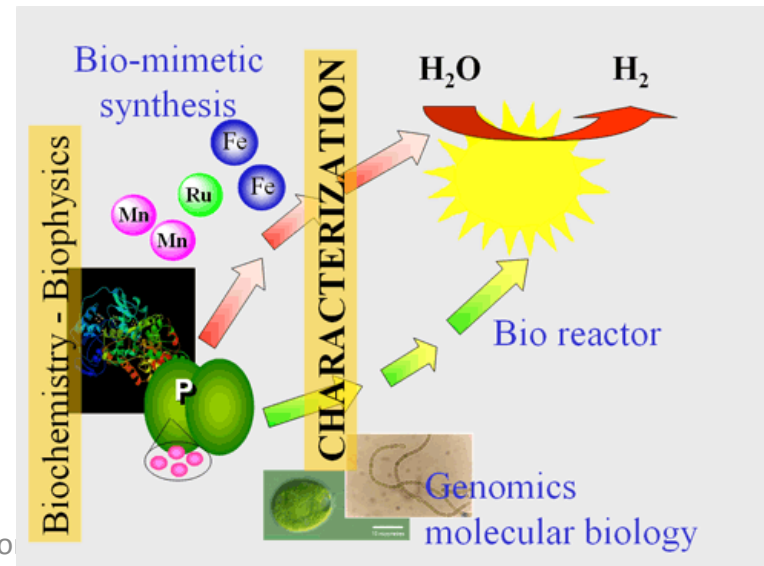


Swedish Consortium for Artificial Photosynthesis

Uppsala, Lund, Stockholm

<http://www.fotomol.uu.se/Forskning/Biomimetics/consortium/index.shtm>

- 1994-2005
- integrated, basic research on
 - Artificial photosynthesis (Mn, Ru, Fe catalysts)
 - photobiological H₂ production in living organisms (*Nostoc punctiforme* via nitrogenase)
- molecular biology, biophysics, biochemistry, organometallic, and physical chemistry
- ~250 published papers 1997-2009
- 31 thesis submissions



EU Commission SOLAR-H

Uppsala



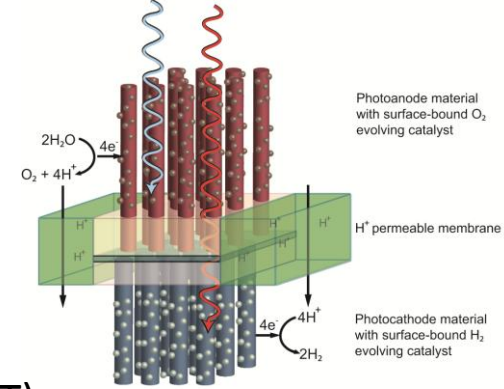
<http://www.fotomol.uu.se/Forskning/Biomimetics/solarh/overview.shtm>

- Funded by FP-6: 1.8M€ - total cost 2.3M€
- 6 partner institutions, 17 Investigators
 - Uppsala, CEA, Orsay, Max Planck, Ruhr, Szeged, Wageningen, Geneva
- Two Thrusts
 - Photo-biological H₂ production from green algae and cyanobacteria
 - Artificial photosynthesis
- 13 publications
 - Top 2 most cited publications
 - Principles, Efficiency, and Blueprint Character of Solar-Energy Conversion in Photosynthetic Water Oxidation – *Accounts of Chem Res* 2009 (13)
 - The Mechanism of Water Oxidation: From Electrolysis via Homogeneous to Biological Catalysis - *CHEMCATCHEM* 2010 (9)
 - h-index: 5
 - Avg. citations: 5.1

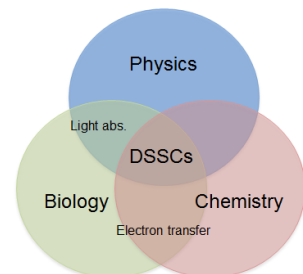


NSF Center for Chemical Innovation: Solar Fuels Caltech

<http://www.ccisolar.caltech.edu/>



- Phase I – 2005-2008
 - 5 PI – Gray, Lewis, Peters, (Caltech) + Nocera, Cummins (MIT)
 - \$500K/year
- Phase II – 2008-2013 (with renewal for another 5 years in 2012)
 - 19 PI, 13 Universities – UC Davis, Stanford, CSU-LA, Wyoming, Purdue, Wisconsin, Penn State, Texas A&M, Southern, Oshkosh, EPFL
 - \$4M/year
- Three thrusts
 - Membranes and light capture
 - Oxygen evolving reactions
 - Hydrogen evolving reactions
- Major emphasis on outreach
 - Solar Hydrogen Activity Research Kit
 - Juice from Juice



NSF Center for Chemical Innovation: Solar Fuels

Caltech

- 56 publications

- 9 in Phase I

- Top 2 most cited publications

- Cobalt-phosphate oxygen-evolving compound – *Chem Soc Rev* 2009 (49)

- Electrolyte-Dependent Electrosynthesis and Activity of Cobalt-Based Water Oxidation Catalysts – *JACS* 2009 (37)

- h-index: 5

- Avg. citations: 15.8

- 57 in Phase II

- Top 3 most cited publications

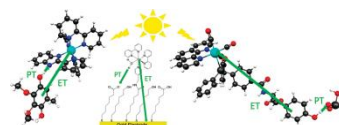
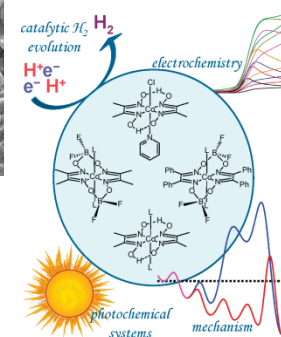
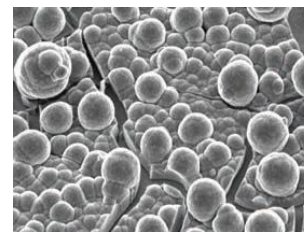
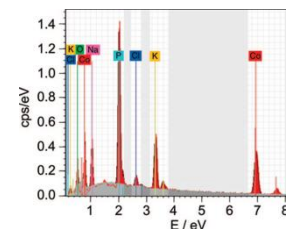
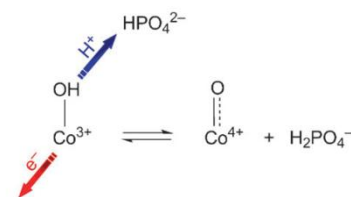
- In situ formation of an oxygen-evolving catalyst in neutral water containing phosphate and Co^{2+} - *Science* 2008 (197)

- Hydrogen Evolution Catalyzed by Cobaloximes – *Acc Chem Res* 2009 (37)

- Theory of Proton-Coupled Electron Transfer in Energy Conversion Processes - *Acc Chem Res* 2009 (29)

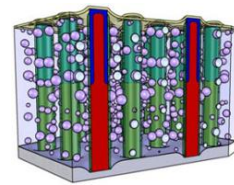
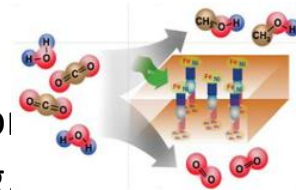
- h-index: 11

- Avg. citations: 10.5





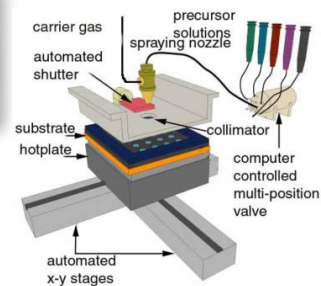
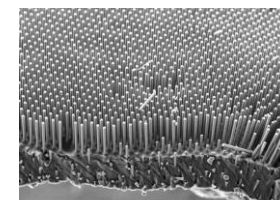
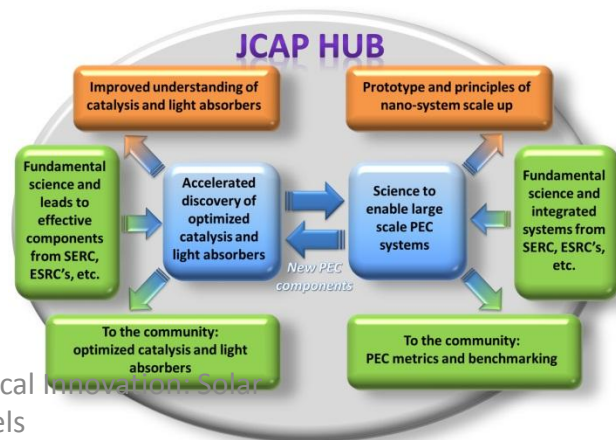
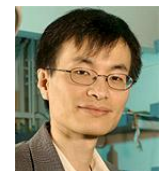
- Mission
 - develop and demonstrate a manufacturable solar-fuels generator
- \$122 M for 5 years
- 2 locations
 - Caltech
 - Lawrence Berkeley National Lab
- 3 thrusts
 - Accelerated discovery: light absorbers, catalysts, membranes, and system components
 - Science-based scale up: assemble components on increasingly larger length scales
 - Develop enabling technologies: high-throughput systems for evaluation, benchmark performance, theoretical tools for discovery and modeling, advanced synchrotron-based techniques, and public database mining



DoE Joint Center for Artificial Photosynthesis



- 41 Investigators – participating in single or multiple projects
- 2 Departments, 7 Projects
 - Science of Large Scale Systems – Peidong Yang
 - Molecular Nanoscale Interface
 - Membrane and Mesoscale Assembly
 - Scaleup and Prototyping
 - Accelerated Discovery – Harry Atwater (acting)
 - Light Capture and Conversion
 - Heterogenous Catalysts
 - Molecular Catalysts
 - Catalysis and Photoelectrochemical Benchmarking
 - Cross Cutting Support Group
 - Theory
 - Instrumentation
 - High Throughput Experiments
 - Scalability & Sustainability



Helios Solar Energy Research Center (SERC)

Lawrence Berkeley National Lab

<http://www.lbl.gov/LBL-Programs/helios-serc/index.html>

- 5 Thrust Areas, 33 Investigators
 - NanoPVs
 - Catalysts
 - Light Protection
 - Electrochemistry
 - Integration
- 31 publications



Korea Center for Artificial Photosynthesis

Sogang University, Korea



<http://www.k-cap.or.kr/eng/info/index.html?sidx=1>

- Funding through National Research Foundation of Ministry of Education, Science & Technology
- 75,000+ sq. feet space being developed by POSCO (Korean steel giant) – completion July 2012
- POSCO will commercialize products
- Stages & goals:
 - I: 2009-2012 – Laying foundation
 - II: 2012-2016 – Science & technology for >1% efficiency
 - III: 2016-2019 – Efficiency >3%
- 5 thrusts – not clear what they are
 - Director K B Yoon – zeolites, ET, charge transfer



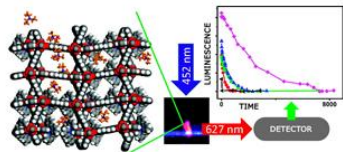
Energy Frontiers Research Centers EFRC

US Department of Energy

<http://science.energy.gov/bes/efrc/centers/>

- Solar Fuels and Next Generation Photovoltaics – Thomas Meyer, University of North Carolina, Chapel Hill - \$3.5M/yr
- Argonne-Northwestern Solar Energy Research Center – Michael Wasielewski, Northwestern University - \$3.8M/yr
- Energy Materials Center at Cornell – Hector Abruna, Cornell University - \$3.5M/yr
- Center for Bio-Inspired Solar Fuel Production – Devens Gust, Arizona State - \$2.8M/yr
- Light-Material Interactions in Energy Conversion – Harry Atwater, Caltech - \$3M/yr

Solar Fuels & Next Generation Photovoltaics



U. North Carolina

<http://www.efrc.unc.edu/>

- 4 Thrust Areas, 25 Faculty Investigators
 - Solar Fuel Catalysis – Tom Meyer
 - Solar Fuel Materials – Wenbin Lin
 - Photovoltaics & Devices – Kirk Schanze
 - Advanced Spectroscopy & Theory – John Papanikolas
- 42 publications
 - Top 2 most cited publications
 - Porous Phosphorescent Coordination Polymers for Oxygen Sensing - *JACS* 2010 (34)
 - Mechanism of Water Oxidation by Single-Site Ruthenium Complex Catalysts - *JACS* 2010 (25)
 - h-index: 7
 - Avg. citations: 3.6

SOLAR
FUELS
& NEXT GENERATION PHOTOVOLTAICS

ENERGY FRONTIER
RESEARCH CENTER

The University of North Carolina at Chapel Hill



Argonne-Northwestern Solar Energy Research Center

<http://www.ansercenter.org/>



- 3 Thrust Areas, 26 Faculty Investigators
 - Bio-inspired molecular materials for solar fuels
 - Interface science of organic photovoltaics
 - Nanostructured architectures for photovoltaics & photochemical energy conversion
- 32 publications
 - Top 2 most cited publications
 - Ni(III)/(IV) Bis(dicarbollide) as a Fast, Noncorrosive Redox Shuttle for Dye-Sensitized Solar Cells - *JACS* 2010 (15)
 - Solution-Processable Low-Molecular Weight Extended Arylacetylenes: Versatile p-Type Semiconductors for Field-Effect Transistors and Bulk Heterojunction Solar Cells - *JACS* 2010 (6)
 - h-index: 4
 - Avg. citations: 1.7

- 3 Thrust Areas, 18 Faculty Investigators
 - Batteries & Fuel Cells
 - Complex Oxides
 - Theory & Computation
- 18 publications
 - Top 2 most cited publications
 - Tunable High Performance Cross-Linked Alkaline Anion Exchange Membranes for Fuel Cell Applications - *JACS 2010 (10)*
 - Solvent Processable Tetraalkylammonium-Functionalized Polyethylene for Use as an Alkaline Anion Exchange Membrane – *Macromolecules 2010 (2)*
 - h-index: 2
 - Avg. citations: 1

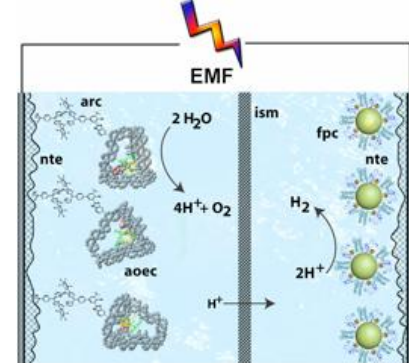


Center for Bio-Inspired Solar Fuel Production

Arizona State University

<http://solarfuel.clas.asu.edu/>

- 5 Thrust Areas, 17 Faculty Investigators
 - Artificial Oxygen Evolving Complex for Water Oxidation
 - Fuel Production Complex
 - Artificial Photosynthetic Reaction Center – Antenna Complex
 - Nanostructured Transparent Electrodes
 - Total Systems Analysis, Assembly and Testing
- 21 Publications
 - Top 2 most cited publications
 - Gold Nanoparticle Self-Similar Chain Structure Organized by DNA Origami – *JACS* 2010 (22)
 - DNA-Origami-Directed Self-Assembly of Discrete Silver-Nanoparticle Architectures – *Ange Chem Int Ed* 2010 (14)
 - h-index: 5
 - Avg. citations: 3.5



Light Matter Interaction

Caltech

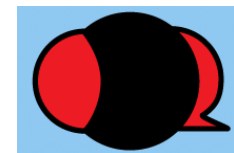
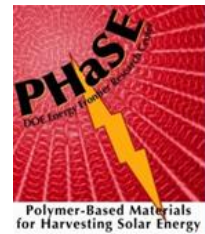
<http://lmi.caltech.edu/>

- 4 Thrust areas, 10 Faculty Investigators
 - Visible and Ultraviolet Generation by Cooperative Upconversion
 - Metal Optics for Spontaneous Emission and Absorption Enhancement
 - Transformation Optics for Photovoltaics
 - Self-Architected and Complex Architecture Absorbers
- 13 Publications
 - Top 2 most cited publications
 - Enhanced absorption and carrier collection in Si wire arrays for photovoltaic applications – *Nature Materials* 2010 (90)
 - A single-layer wide-angle negative-index metamaterial at visible frequencies - *Nature Materials* 2010 (13)
 - H-index: 5
 - Avg. citations: 9.6



Other relevant university based EFRCs

- **Polymer Based Materials for Harvesting Solar Energy, U Mass, Amherst;** 18 investigators, 3 thrusts - polymer based architecture, controlled assemblies and morphologies, characterization, device design, and integration
- **Center on Nanostructuring for Efficient Energy Conversion, Stanford;** 11 investigators, 3 thrusts – thermodynamic potentials, control of photons and electrons, control of catalysis
- **Center for Gas Separations Relevant to Clean Energy Technologies, UC Berkeley;** 16 investigators, 4 thrusts – characterization, computational, inorganic materials, polymer membranes
- **Center for Atomic Level Catalyst Design, LSU;** 22 investigators, 7 thrusts – developing tools, CO₂ to CH₃OH, metal oxide surfaces, metal oxide nanoclusters, rare earth oxides, CO hydrogenation, size-defined metal clusters
- **Center for Interface Science: Solar Electric Materials, U. Arizona;** 17 investigators, 3 thrusts – theories for CT; interface characterization, nanostructured hybrids,



Dutch Institute for Fundamental Energy Research Eindhoven

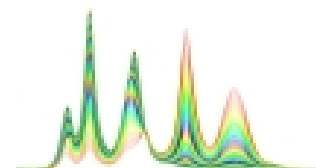


- Similar in spirit to the DoE HUB program
 - National coordinating role for basic energy research
 - Contact point for industry
 - In principle will be ongoing
 - Mixture of top-down (specific area announced) and bottom-up (individual proposers allowed broad freedom) approach
- Start 2012 – fully functional by 2016
- Three thrusts – use inspired basic research
 - Solar fuels (non-biological)
 - PV
 - Nuclear Fusion
- 15-20M €/year (dependent on earned income)
- 20-25 Investigators

Energy Materials Lab - SolarCAP

East Anglia, Nottingham, Manchester, York, UK

<http://www.solarcap.org.uk/default.asp>



- Funded in 2009 by EPSRC through SolarCAP – US \$1M (ending in 2012)
 - Associated funding through EPSRC/BBSRC/Royal Society research grants and UEA capital grants of US \$5M
- 5 Thrust Areas, 7 Academic Staff
- 27 publications
 - Top 2 most cited publications
 - Structural and Functional Analogues of the Active Sites of the [Fe]-, [NiFe]-, and [FeFe]-Hydrogenases – *Chem Reviews*, 2009 (113)
 - The Use of Calixarenes in Metal-Based Catalysis – *Chem Reviews*, 2008 (64)
 - h-index: 7
 - Avg. citations: 10.6

Solar Energy Conversion Cluster

U College Dublin, Dublin City U, U Limerick

www.seccluster.ie



ADVANCED BIOMIMETIC MATERIALS FOR
SOLAR ENERGY CONVERSION
SFI STRATEGIC RESEARCH CLUSTER



Prof Don MacElroy
Head of School

- Funded by Science Foundation Ireland
 - 2007-2013
 - 4.7M€
 - 6 industrial partners providing matching funds of 340K€
 - Associate funding of 5.5M€ (primarily from Irish Research Council for Science Engineering and Technology)
- 4 Thrust Areas, 18 Funded Researchers
- 14(*50) publications
 - Top 2 most cited publications
 - Deposition and characterization of NiO(x) coatings by magnetron sputtering for application in dye-sensitized solar cells – *SURFACE & COATINGS TECHNOLOGY*, 2010 (4)
 - A multi-rate kinetic model for spontaneous oriented attachment of CdS nanorods – *PHYSICAL CHEMISTRY CHEMICAL PHYSICS*, 2010 (2)
 - h-index: 2
 - Avg. citations: 1

SolarChem

Bologna, Ferrara, Messina



- Funded by Public and Private Sources
 - 6 yr lifetime
- 6 Thrust Areas, 14+2 Investigators
- 17 publications



NSF Center for Chemical Innovation: Solar
Fuels



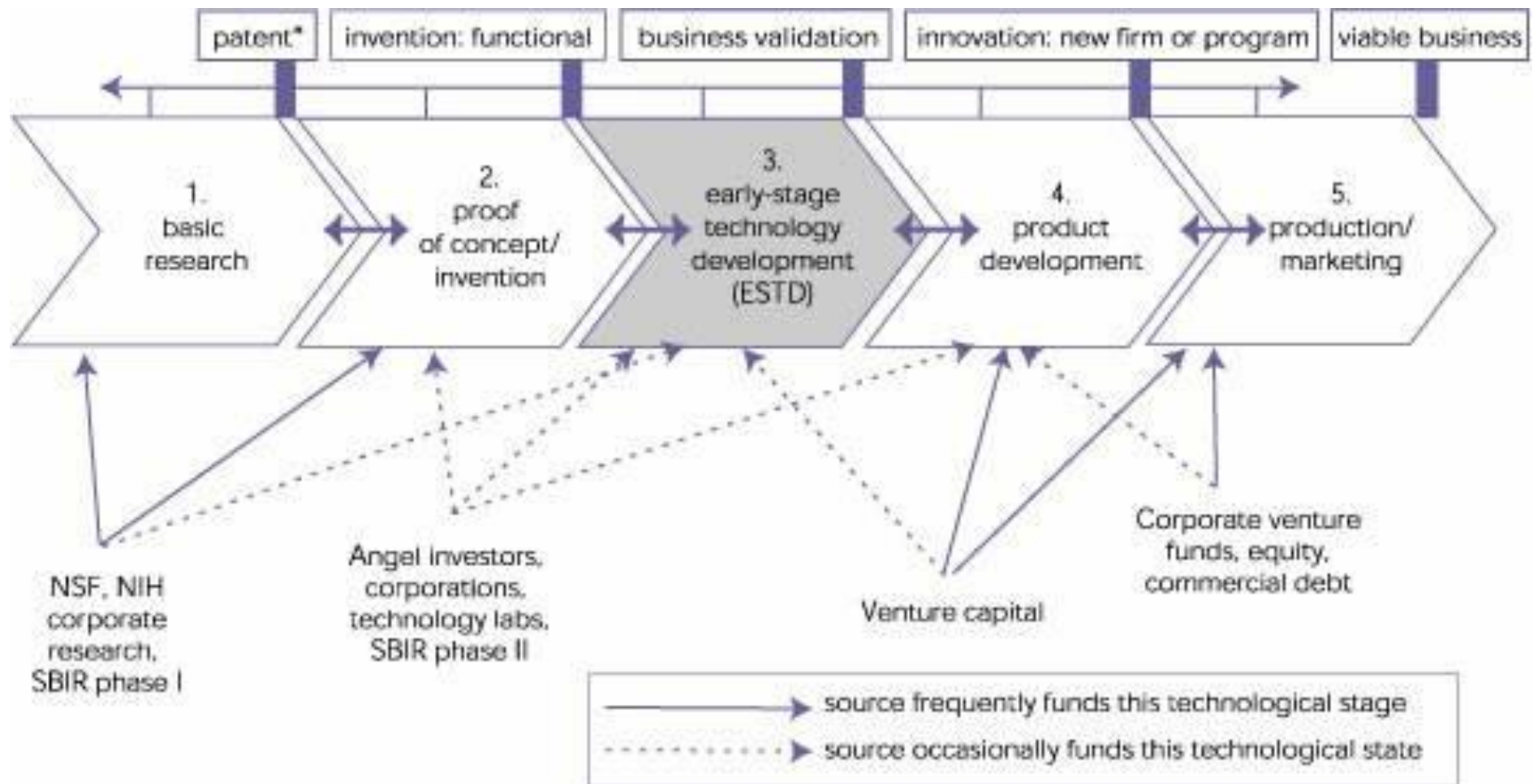
Additional Programs

- BIOSOLENUTI – Heraklion, Crete
 - 1M €
 - 8 investigators
- Brazilian Center for Artificial Photosynthesis – no information available
- Japanese effort
 - Nobel Laureate Negishi lead
 - funding from MEST
 - Hokkaido (Catalysis Research Center), Tokyo U. Tokyo Inst. Tech., Tsukuba U., Kyoto U., Kyushu U.
- Effort in China

NSF Programs Supporting University-Industry Research Collaboration

NSF Program	Number of Centers	Number of Industry Members/Partners	Total Annual Budget, All Centers
Industry/University Cooperative Research Centers	55	700	\$75 million
Engineering Research Centers	22	600	\$200 million
Science and Technology Centers	11	N/A	\$60-80 million
Materials Research Science and Engineering Centers	28	400+ industry partners	\$100 million
Nanoscale Science and Engineering Centers	14	143 industry partners	\$32 million

Technology Lifecycle – NIST ATP Model



World Centers positioned on NIST Model

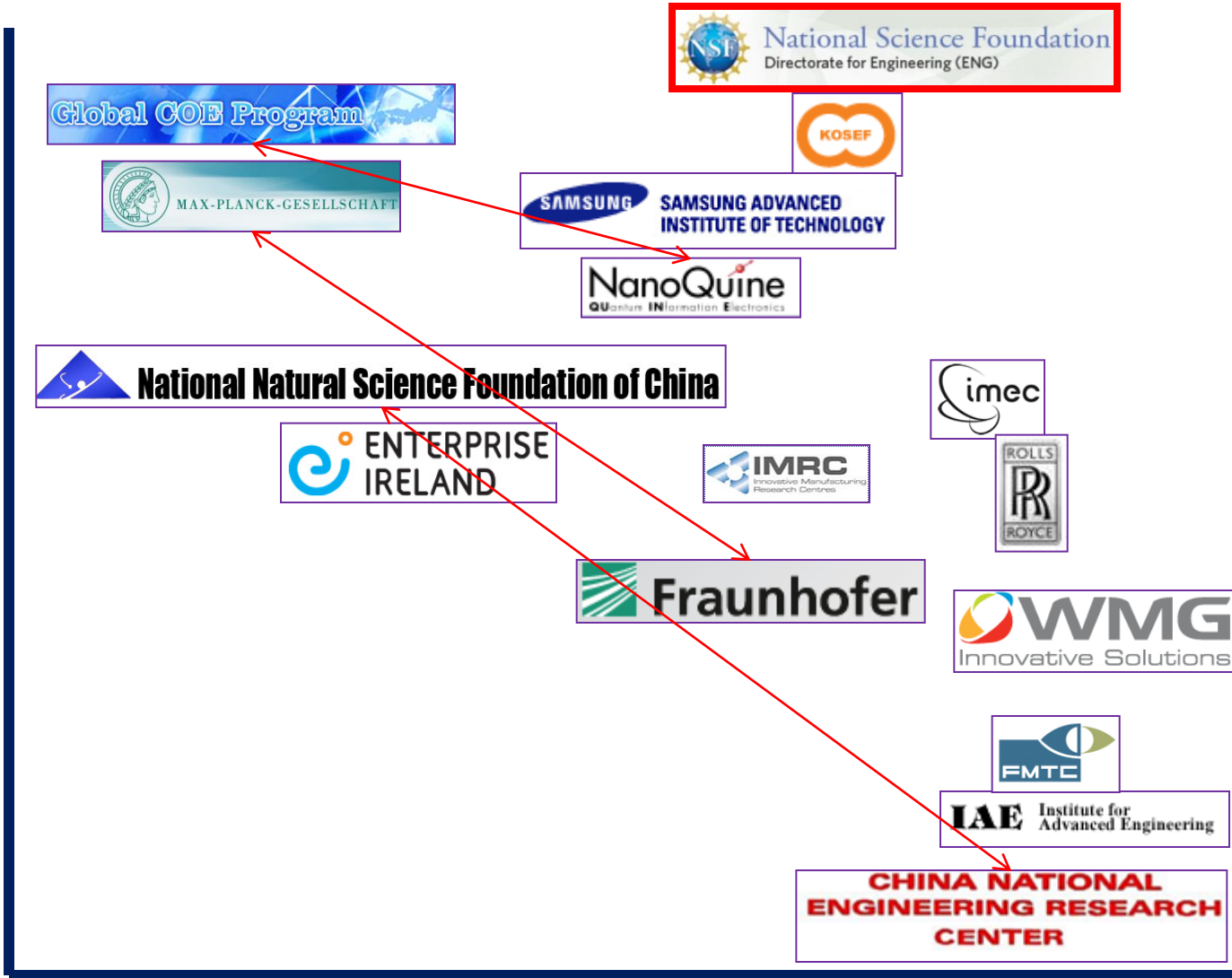
Name	Basic Research	Proof of concept	Early Stage Tech. Dev.	Product Dev.	Production & Marketing
Japan: Earthquake Research Institute	█				
Japan: Disaster Prevention Research Institute	█				
Japan: MEXT Centers of Excellence (COE) Program	█				
Japan: MEXT Global COE program	█				
Japan: MEXT World Top-Level Research Centers	█				
Germany: Max Planck Institutes	█				
China: Key Laboratories	█				
UK: Tissue Engineering Initiative		█			
Japan: Advanced Industrial Science and Technology (AIST)	█	█			
Korea: Centers within Korea Institute for Science and Technology (KIST)	█	█			
Korea: Korea Advanced Institute of Science and Technology (KAIST)	█	█			
Korea: ERC Program, National Core Research Centers (NCRC) Program	█	█	█		
U.S.: Engineering Research Center Program	█	█	█		
Belgium: International Microelectronics Center (IMEC)	█	█	█	█	
Japan: Institute for Nano Quantum Information Electronics (CINQIE)	█	█	█	█	
Korea: Samsung Institute for Advanced Technology (SAIT)		█	█		
UK: Energy Futures Lab		█	█		
UK: Leeds Particle Science Institute		█	█	█	
Ireland: Centers for Science, Engineering, and Technology (CSET)		█	█	█	
UK: Innovative Manufacturing Research Centers (IMCRC) Program		█	█	█	
UK: Warwick Manufacturing Group		█	█	█	
UK: Rolls Royce Vibration Technology Center		█	█	█	
Germany: Fraunhofer Institutes			█	█	█
Belgium: Flanders' Mechatronics Technology Centre			█	█	█
China: National Engineering Research Center (NERC) Program			█	█	█
Korea: Institute for Advanced Engineering				█	█



Global Centers

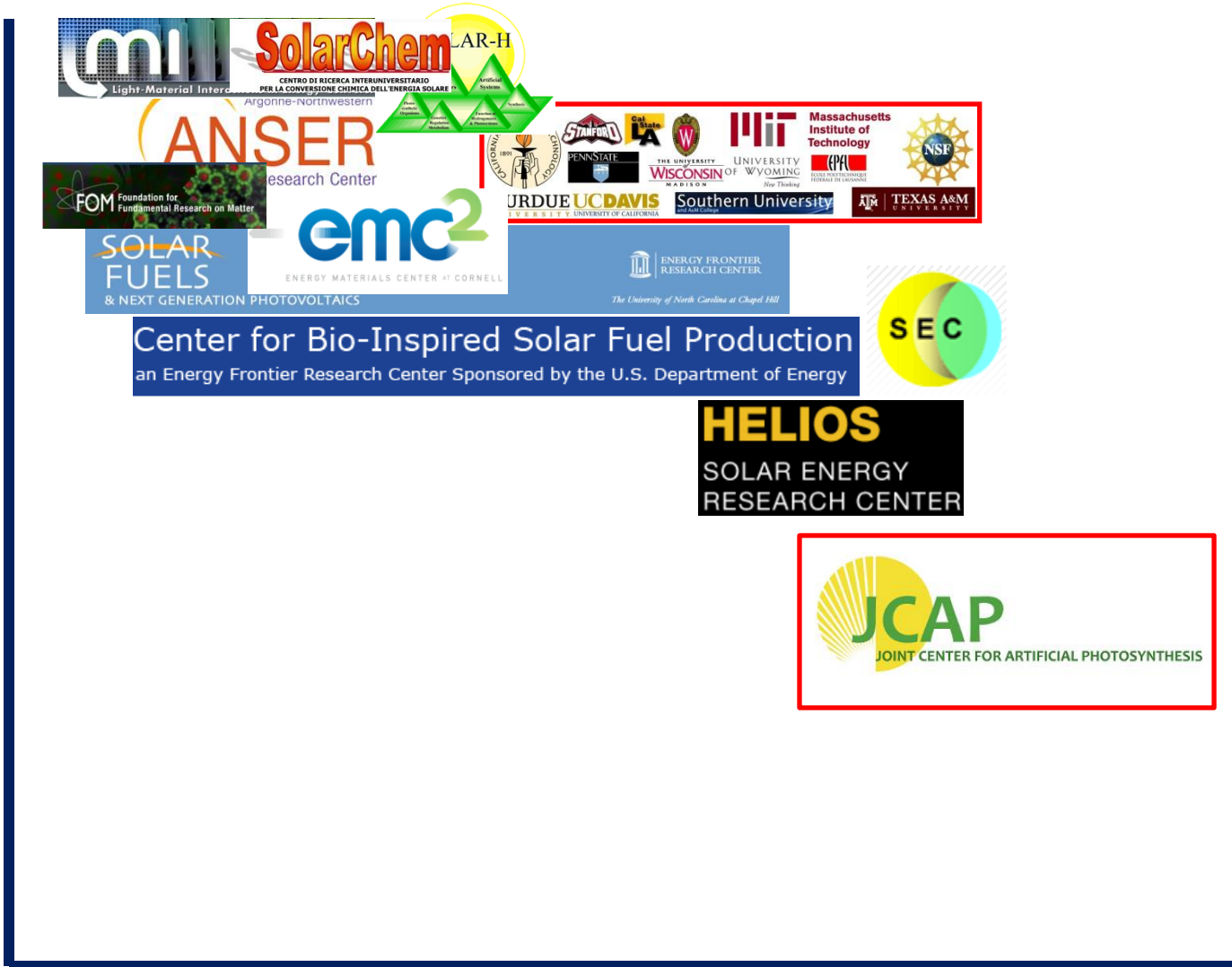
Focus on Basic/Curiosity Driven Research

Focus on Technology Transfer and Industry Needs



Solar Fuels Centers

Focus on Basic/Curiosity Driven Research



Focus on Technology Development

