Introduction to Solar Energy Conversion

Solar energy represents the largest energy input into the terrestrial system. Despite its relatively low power density, this resource could potentially satisfy the global energy demand on its own. The challenges that need to be addressed to make solar energy viable and competitive on a large scale include: enhancing the performance of solar energy conversion systems through increased efficiency and use of durable materials; reducing the material, fabrication, and installation costs so that these systems can be deployed at a large scale; and overcoming the intermittent nature of the resource to allow supply to meet demand at all times.

Photovoltaic energy conversion efficiency has increased steadily in the past decade through enhanced photon absorption and charge transport. Moreover, continuous development of novel device concepts, materials, and fabrication processes has contributed to lowering the cost of solar power. Thin-film solar cells are regarded as a promising route for low-cost energy conversion. Inorganic thin films are relatively mature technologies with record efficiencies around 20%. Organic solar cells are at an earlier stage of development with efficiencies reaching around 11% for polymeric heterojunctions and dye-sensitized cells. Further research in thin-film technologies is required to increase their efficiency up to the thermodynamic limits, to enhance their stability, and to further reduce their fabrication cost.

Solar thermal technologies are appropriate for large-scale energy production and can be combined with thermal energy storage systems to offer a practical solution to smooth supply intermittency over time periods of several hours.

Photo electrochemical systems are another option under investigation to circumvent the intermittency issue of solar power. They hold the promise to efficiently harvest solar energy and convert it into chemical fuels with a single, potentially low-cost device. This conversion strategy allows for the carbon-free – or even carbon-negative when CO_2 is used as a feedstock – synthesis of fuels for electricity and/or transportation, and provides a solution to the intermittency problems without requiring the use of ancillary energy storage systems to match supply and demand.

Currently, GCEP has three ongoing projects in the solar area that fall across the areas of (photo-assisted) thermionic systems, nanoscale light-management and photo electrochemical production of hydrogen.

Professors Brongersma at Stanford University, Polman at AMOLF, and Atwater at CalTech, have a project that began in 2012 on “Dielectric Metasurfaces for Light Trapping in High-efficiency Low-cost Silicon Solar Cells”. In this project, the Brongersma group has demonstrated that flat optical elements can be realized that redirect and trap light as well as concentrate light for concentrated solar photovoltaics. They optimized the size, shape and arrangement of the dielectric scatterers. The aim is to apply these metasurfaces to thin (5-50 μm) single-crystalline silicon solar cells that are made using commercially available lift-off and layer transfer techniques. Numerical simulations show that it is feasible to realize a dielectric-metasurface-enhanced single-crystalline Si solar cell thinner than 20 μm with an AM1.5 conversion efficiency over 20%. If successful, this will demonstrate a highly efficient silicon solar cell that can be made at low silicon materials cost. As the cost of silicon is a major cost factor in conventional wafer scale Si solar cells (c. 0.25 $/Wp) this project would present a major step forward in Si solar cell technology. The team has recently demonstrated the ability to spectrally split and concentrate light with a single optical component. This is of great value in solar systems that rely on semiconductor cells with different bandgaps to enhance power conversion efficiency. In the next phase of the project they will integrate these elements with high efficiency thin Si solar cells. At Caltech such cells have already been created using metallic finger electrodes. The Si structures will be used to further enhance efficiency by light concentration and spectral splitting. By studying different light trapping designs, the researchers hope to further elucidate the potential and limitations of dielectric metasurfaces for use in high performance light trapping layers. The work led by AMOLF demonstrated that optical and electrical management within high performance cells leads to further efficiency gains. They are working on demonstrating a Si cell with both nanophotonic antireflection and conduction, which would then be fully compatible with ultrathin crystalline cells. They have also started working on metasurfaces embedded within ultrathin cells to further reduce interfacial recombination losses, and couple directly into wave-guided and local modes. The Retro-reflection work is currently being extended from a one-dimensional system to multiple polarizations and orientations. So far this project has led to: one patent, "Solar Cells and Methods of Manufacturing Solar Cells Incorporating Effectively Transparent 3D Contacts," US 20160322514 A1, H. A. Atwater, R. Saive, A. M. Borsuk, H. Emmer, C. Bukowsky, and S. Yalamanchili; one provisional patent application on "Dielectric metasurface optical elements," by Mark L Brongersma, Dianmin Lin, Pengyu Fan, Erez Hasman; 13 peer-reviewed publications including one in *Science*; and 4 additional research papers submitted or under review.

Professors William Chueh and Nick Melosh are working on "Maximizing Solar-to-Fuel Conversion Efficiency in Oxide Photo-electrochemical Cells Using Heat and Concentrated Sunlight". The goal is to substantially increase the solar-to-fuel conversion efficiency in photoelectrochemical cells (PECs) by using heat and intense light from concentrated solar radiation. The team will address these shortcomings by designing earth-abundant, oxide-based heterojunction photoanodes that can operate at temperatures significantly above ambient. These oxide-based PECs aim to capture excess thermal energy resulting from the absorption of intense concentrated sunlight, which is normally discarded. In the first one and half years of this work, substantial progress has been made in demonstrating the strong performance enhancement with temperature and optical concentration in iron oxide and bismuth vanadate photoelectrode in liquid electrolytes. A solid-state electrolysis cell operating between 300 and 600 °C has been developed. This result lays the foundation towards high efficiency solid-state PECs operating beyond room temperature. The recent solid-state results indicate that high-current performance can be achieved at elevated temperature by utilizing a micro-YSZ membrane architecture, and that a heterostructure can be used to enhance charge separation. The thermal enhancement under optical concentration of the photocurrent is consistent with previous results at lower temperatures using a liquid photoelectrochemical cell, further confirming that this is a promising method for solar water splitting. Future work will build upon the initial proof of concept device by: extending the OER results to include full solar water splitting by sealing the solid-state device and quantifying the solar to hydrogen efficiency and the amount of hydrogen and oxygen produced; exploring alternate material systems (light absorber, ionic conductor) that yield higher photovoltages under illumination; and systematically understanding the mechanistic limitations for photovoltage and photocurrent.

Professors Shanhui Fan, Mark Brongersma, and James Harris began a project in 2015 entitled "Solar Thermophotovoltaics: Improving the Efficiencies of Emitters and Narrow Band Gap Photovoltaic Cells". Solar thermophotovoltaics have the potential to overcome the Shockley-Queisser limit with a single junction cell by utilizing nearly the entire solar spectrum. In an STPV system, sunlight is converted into heat through a broadband absorber. The heat is then used to generate narrow-band thermal radiation from an emitter. High theoretical efficiency can be achieved if the emitter generates narrow-band radiation that is well matched in wavelength to the band gap of a single-junction solar cell. The researchers propose to significantly advance the fundamental science in solar TPV, by significantly improving the performance of both thermal emitters and narrow band gap solar cells. They will develop novel high-temperature refractive materials, such as TiN, that exhibit strong plasmonic responses (Brongersma), and combine this with a nanophotonic approach for emission control (Fan). For the development of low band gap semiconductor solar cells, they will build upon previous experience in demonstrating world record multi-junction cells (Harris). So far they have conducted research in optimizing the emitter design for the high efficiency solar thermophotovoltaic device. This design is very important towards implementation and demonstration of the emitter efficiency, and is also crucial for the final integrated solar thermophotovoltaic system. This team has successfully optimized a cell with a 0.75ev bandgap. This cell, under the right conditions can reach an efficiency of 49.3% at a temperature of 300K.