

Report of the  
Alternative Sustainable Energy  
Research Initiative (AERI)

March 2013

Prof. David Cahen

Scientific Director



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## Executive summary

### **Prof. David Cahen, Scientific Director**

The Weizmann Institute has launched a major, three-year collaboration with the Technion—Israel Institute of Technology (IIT) funded by grant from the Helmsley Charitable Trust. The Helmsley grant expands the scope of renewable energy research conducted within the framework of the Alternative and Sustainable Energy Research Initiative (AERI), the Mary and Tom Beck-Canadian Center for Alternative Energy Research, the Brazil-Israel Alternative Energy Fund, and a number of other private philanthropic funds created by our worldwide supporters. Its timing is excellent as an earlier, more modest grant, from the Wolfson family trust, is now in its 3<sup>rd</sup> and last year.

The Weizmann and the Technion programs in solar energy conversion are strongly complementary. The Weizmann Institute's primary focus is on basic research with minor technological components; and the Technion emphasizes engineering technologies, using basic research-derived insights, with smaller basic research components. We are working together in three focus areas — photosynthesis for biofuels, photovoltaics for solar cells, and optics for solar energy collection — to develop viable, medium-term renewable energy options:

#### **PHOTOVOLTAICS (PV):**

- Weizmann teams work with IIT groups to synthesize organic semiconductors as building blocks for use in organic solar cells.
- Computer scientists, theoretical chemists, and physicists are working to develop computational ways to predict the electronic structure of PV materials.
- We work independently and with IIT teams to design and prepare hybrid and hybrid-inversion solar cells.

#### **BIOFUELS:**

- The Weizmann and IIT teams are setting up new strategies for designing and re-engineering metabolic pathways in plants, algae, and bacteria.
- We develop at the Weizmann an analytical (bio)chemistry facility for biofuel substances analysis (i.e., lipids and carbohydrates), derived from plants.
- Screening for biodiversity in wheat has led to discovery of wheat strains with low lignin content in the straw — a potential feedstock for biofuel.
- We have explored the effect of pretreatment on wheat straw degradation and evaluated biological and chemical pretreatments of this cellulosic substrate by native cellulosomes, designer cellulosomes, and free enzymes.



## OPTICS:

- We synthesize nanocrystals for up-conversion of far-red and infrared to green light via consecutive absorption processes in a double quantum dot.
- In collaboration with the Technion we optimize synthesis of doped heterostructure nanocrystals for use in a luminescent solar concentrator (LSC) and are developing a concentration scheme for diffused light.
- Time-resolved optical studies are carried out by the Weizmann group, on photovoltaic devices developed at IIT, to understand their mode of action and help design improved materials and structures.

These projects are 100% in line with the goals of AERI. As the director of both AERI and the Helmsley project, Prof. Cahen is working to make sure that these combined resources all contribute to a shared vision of clean, affordable, and sustainable energy. Therefore, all of the AERI projects underway in the 2011 – 2012 academic year are renewed for the current 2012 – 2013 year. Our biofuels efforts will benefit from the very significant funds that the Helmsley Trust grant provide for major equipment over the next two years, and those efforts, as well as our research in photovoltaics and optics will be strengthened by the increased cooperation with Technion scientists.

A number of commercial ventures launched in 2012 that were based on Weizmann Institute research in concentrated solar energy begun in the 1980s with the solar tower and laboratories of the Canadian Institute for the Energies and Applied Research (CIEAR). These include:

- A 100kW solar thermal plant built at Kibbutz Samar
- A 130kW solar thermal plant at the Rotem Industrial Park (Heliofocus)
- A 170 kW solar thermal energy plant in Almeira, Spain

And, a new venture has been launched in Israel by NewCO<sub>2</sub>Fuels Ltd., a subsidiary of the Australian company Greenerth Energy Ltd., to reduce carbon dioxide emissions from the burning of brown coal using solar technology developed at the Weizmann Institute. NewCO<sub>2</sub>Fuels acquired an exclusive worldwide license for the solar technology from Yeda, the Weizmann Institute's technology transfer arm.

Here are highlights in our AERI-sponsored research in the past year. Thank you again for your support of our efforts in clean and sustainable energy research.



## Enhancing biofuels production

Coordinated by Prof. Avraham Levy in the Department of Plant Sciences and guided further by four emeritus professors, 12 teams of scientists in three departments at the Weizmann Institute are conducting research in four major areas to increase biofuels production: 1) designing metabolic pathways, 2) developing plants optimized for biofuel and alcohol production, 3) advancing cell wall degradation and fermentation, and 4) developing microorganisms for biofuel production. In the past year, the biofuels groups have been able to:

- Test a large number of new, promising pathways for efficient carbon fixation
- Develop high-throughput methods for measurements of lignin, cellulose, and hemicellulose
- Make progress in the expression and purification of proteins *in vitro* for testing synthetic pathways predicted from computational design
- Discover low-lignin wheat lines, which constitutes a basis for studying the genetic control of this trait and its effect on yield
- Identify pretreatment conditions for the wheat straw substrate, which enable the native cellulosomes to completely convert the substrate into soluble saccharides



Wheat

Plants are expert at converting atmospheric carbon into high-energy sugars, using the abundant energy of the sun. The conversion of light energy and carbon dioxide into biofuel by plants and algae offers a desirable alternative to fossil fuel as it is renewable, more environmentally friendly, and free of geopolitical interests.

### Designing metabolic pathways

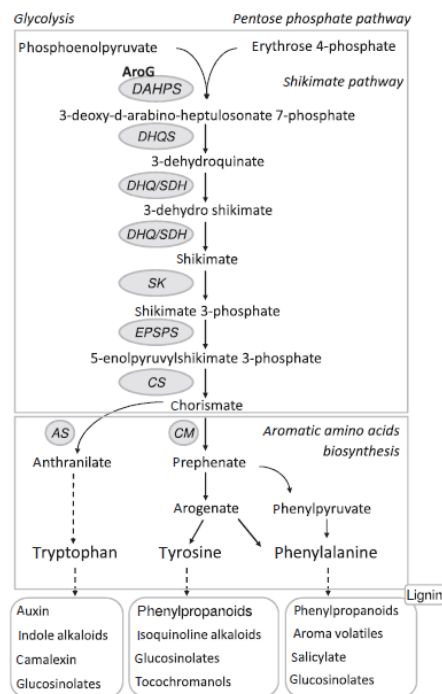
Plant scientists Profs. Asaph Aharoni and Gad Galili are working with computational biologist Dr. Ron Milo to look for ways to optimize several metabolic processes in plants,



including carbon (CO<sub>2</sub>) fixation, fatty acid metabolism, carbohydrate metabolism, and the production of secondary metabolites such as lipids and alcohols.

An estimated 20% of all carbon fixed in leaves passes through the Shikimate pathway and 30% of the plants dry weight comes from the products of this pathway, including the aromatic amino acids phenylalanine, tryptophan and tyrosine. These amino acids are the primary source of carbon for the formation of a myriad of secondary metabolites in both plants and microorganisms. Profs. Galili and Aharoni examined how plants tune the flow of carbon through the Shikimate pathway to the different branches of the downstream pathways during its development and under stress conditions.

They suspected that DAHPS (3-deoxy-D-arabino-heptulosonate 7-phosphate synthase) is a key enzyme regulating flux through the Shikimate pathway. To test their hypothesis, they created a mutant bacterial AroG gene that could modify DAHPS levels in transgenic Arabidopsis plants. This model helped them show that DAHPS is indeed a key regulatory enzyme of the Shikimate pathway. By tinkering with the expression of DAHPS they could increase the output of a number of primary and secondary metabolites by more than 4 times the normal levels. These results shed new light on other potential metabolic bottlenecks affecting plant primary and secondary metabolism.



*The Shikimate pathway produces aromatic amino acids such as phenylalanine, tryptophan and tyrosine. These amino acids are the primary source of carbon for the formation of a myriad of secondary metabolites in both plants and microorganisms.*

### Recent publications

Tzin V, Malitsky S, Ben Zvi MM, Bedair M, Sumner L, Aharoni A, Galili G, "Expression of a bacterial feedback-insensitive 3-deoxy-D-arabino-heptulosonate 7-phosphate synthase of the shikimate pathway in Arabidopsis elucidates potential metabolic bottlenecks between primary and secondary metabolism" NEW PHYTOLOGIST, Volume: 194, Page: 430-439, 2012

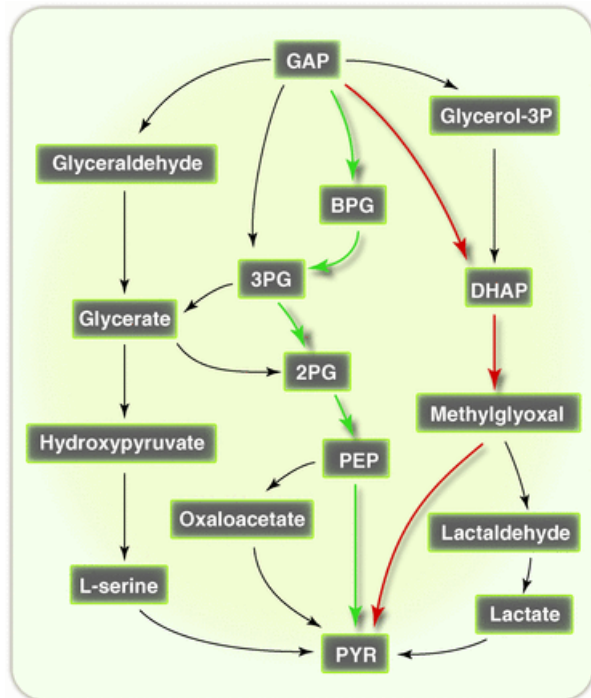


## Energy constraints guide plant metabolism

Although our understanding of plant metabolism increases at a rapid pace, relatively few plant metabolic engineering projects with commercial potential have emerged, in part because of a lack of understanding of the design principles and the dominant constraints on plant fitness; and the evolutionary innovations that have arisen in response to those constraints, giving rise to the enormous diversity of natural plant metabolic pathways.

Thermodynamics impose a major constraint on the structure of metabolic pathways: All reactions in a pathway must be thermodynamically favorable under normal conditions. In recent work, Dr. Milo focused on the effect of these energy constraints on the structure of natural carbon fixation pathways and on the cellular resources they consume, specifically adenosine triphosphate (ATP) the chemical power pack that runs many cellular functions. He created an energy profile of a number of typical reactions and showed that each reaction type displays a characteristic change in net energy. Although carbon fixation pathways display a considerable structural variability, he found that the major energy constraint is by two types of reactions: carboxylation and carboxyl reduction. These two reactions appear to be the thermodynamic bottlenecks of the carbon fixation pathways. In fact, all ATP molecules consumed by carbon fixation pathways – with a single exception – are used, directly or indirectly, to power one of these two energy-consuming reactions.

Carbon fixation is basically a reductive process, and the first challenge in the process is carboxyl reduction. His analysis revealed that several carbon fixation pathways require considerably more ATP molecules than required. This excess ATP investment suggests



*The large number of alternative possibilities for metabolic transformations. Results from an analysis of the possible pathways for transforming glyceraldehyde-3-phosphate (GAP) into pyruvate (PYR), using the set of characterized enzymes from all organism.*  
From: SCIENCE, Volume: 336, Page: 1663-1667, 2012

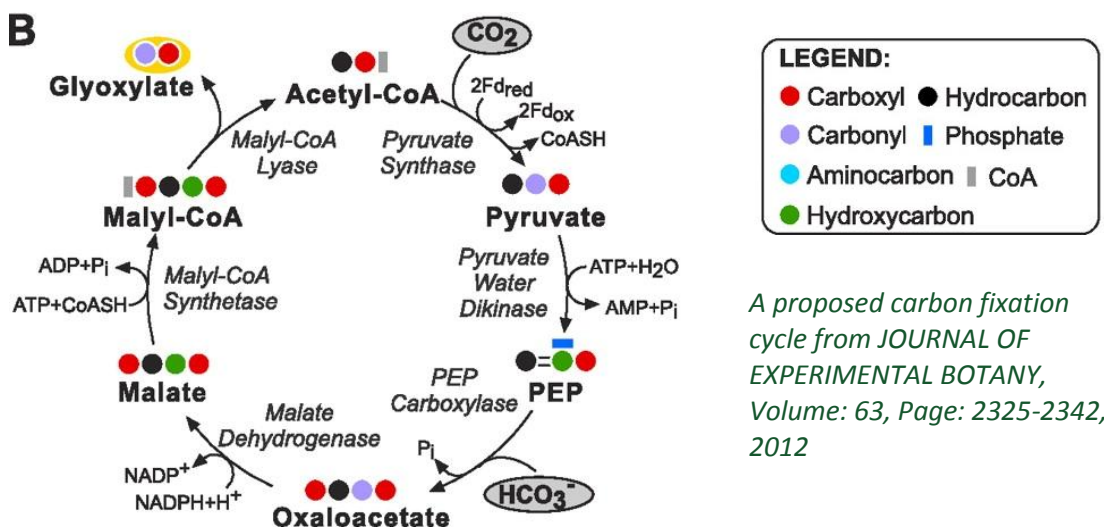


that there might be other “local” constraints that are overlooked in analyzing only the net reaction. On the other hand, other carbon fixation pathways use precisely the right number of ATP molecules required to achieve their overall reaction, suggesting that at least some pathways are able to bypass the local thermodynamic constraints without investing extra ATPs. His analysis uncovered mechanisms that several pathways employ to reduce their ATP requirement. For instance, the “C1” carbon fixation pathways use far less ATP by directly reducing CO<sub>2</sub> to formate (an ion derived from formic acid, HCO<sub>2</sub>H) bypassing the ATP-requiring carboxylation reaction.

In an article in *Science*, Dr. Milo proposed a framework for analyzing basic design principles to bioengineer more successful crops. He thought the process should start by identifying the major constraints on plant fitness, and then examine the evolutionary innovations in response to those constraints that gave rise to the enormous diversity of natural plant metabolic pathways.

Metabolic engineering promises opportunities to increase yield in agriculture and produce chemicals at lower economic and environmental cost. Despite progress, the rate of success in moving from concept to agricultural production or microbial fermentor has fallen short of expectations. For example, tens to hundreds of millions of dollars were spent in the public and private sector in efforts to increase RuBisCO carboxylase activity and thus improve photosynthetic productivity of C3 plants. These studies yielded information about the structure and function of the enzyme but did not achieve the desired improvement in its kinetic properties. It appears that RuBisCO’s kinetic properties seem already to be optimized by evolution. However, he argues that rational engineering of plant functions requires going beyond documenting the parts of the broad metabolic network; we need also to develop a deep understanding of the fundamental principles that govern metabolic regulation.





### Recent Publications

- Flamholz A, Noor E, Bar-Even A, Milo R, "eQuilibrator-the biochemical thermodynamics calculator" *NUCLEIC ACIDS RESEARCH*, Volume: 40, Page: D770-D775, 2012
- Bar-Even A, Noor E, Milo R, "A survey of carbon fixation pathways through a quantitative lens" *JOURNAL OF EXPERIMENTAL BOTANY*, Volume: 63, Page: 2325-2342, 2012
- Bar-Even A, Flamholz A, Noor E, Milo R, "Rethinking glycolysis: on the biochemical logic of metabolic pathways" *NATURE CHEMICAL BIOLOGY*, Volume: 8, Page: 509-517, 2012
- Noor E, Milo R, "Efficiency in Evolutionary Trade-Offs" *SCIENCE*, Volume: 336, Page: 1114-1115, 2012
- Milo R, Last RL, "Achieving Diversity in the Face of Constraints: Lessons from Metabolism" *SCIENCE*, Volume: 336, Page: 1663-1667, 2012
- Bar-Even A, Flamholz A, Noor E, Milo R, "Thermodynamic constraints shape the structure of carbon fixation pathways" *BIOCHIMICA ET BIOPHYSICA ACTA-BIOENERGETICS*, Volume: 1817, Page: 1646-1659, 2012
- Noor E, Bar-Even A, Flamholz A, Lubling Y, Davidi D, Milo R, "An integrated open framework for thermodynamics of reactions that combines accuracy and coverage" *BIOINFORMATICS*, Volume: 28, Page: 2037-2044, 2012
- Adadi R, Volkmer B, Milo R, Heinemann M, Shlomi T, "Prediction of Microbial Growth Rate versus Biomass Yield by a Metabolic Network with Kinetic Parameters" *PLOS COMPUTATIONAL BIOLOGY*, Volume: 8, 2012



## Developing plants optimized for biofuels and alcohol

Wheat straw is abundant and does not compete with growing food. World production is estimated at about 700 million tons, which could be sufficient for producing ~20% of the liquid fuel used annually in the U.S. Wheat straw is usually left behind in the fields as waste, plowed-under, or burned. It is also used as animal feed, but little is digested.

Plant cell walls, including wheat straw, have evolved to resist destruction by enzymes and microbes, making conversion of biomass such as straw into fermentable sugars costly and inefficient. Wheat straw is a potentially rich source of sugar with about 75% of the biomass consisting of polysaccharides such as cellulose (35%-40%) and hemicellulose (25%-35%). The breakdown of these polymers into simple sugars is however hindered by lignin which constitutes roughly 15% of the biomass.

Pretreatment disrupts the connection between the carbohydrates and the lignin as well as depolymerizes and begins to dissolve hemicellulose polymers, thus exposing the cellulose and the hemicellulose for enzymatic attack. In making biofuel, pretreatment is followed by using enzymes to turn cell-wall carbohydrates into sugars. Finally, microbial fermentation of the sugars produces ethanol. Pretreatment is expensive and partly responsible for the energy deficit in the biofuel process. Pretreatment costs can be dramatically reduced by improving digestibility, such as by reducing lignin content.

Prof. Avraham Levy and his team are working to identify genes that can be used to improve wheat straw as a feedstock for biofuel production by screening diverse strains of wheat and using genomics to compare wild and modern wheat. They hope to transfer useful genes to modern wheat.

They have screened a large collection of wheat lines, including wild, primitive, traditional, and modern wheat for cell wall composition (cellulose, hemicellulose and lignin) and for digestibility by enzymes.

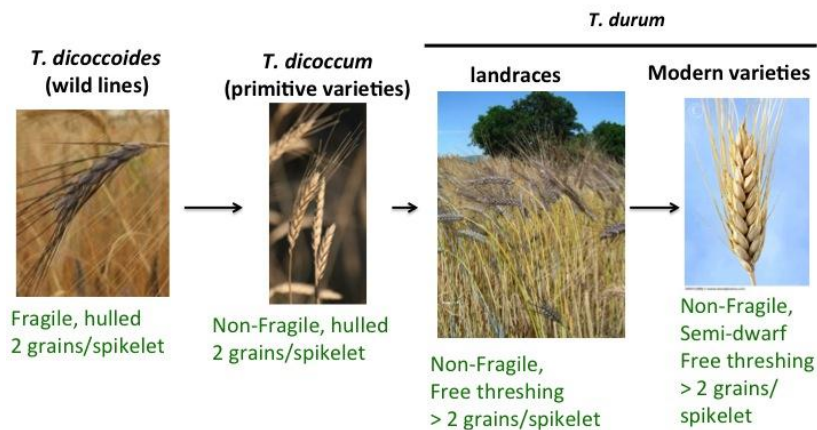
Preliminary results show that the lignin content (normalized to the cellulose content) is about five times lower in wild wheat than in modern wheat. This is a major finding that supports their expectations that combining traits from wild wheat could result in a lower lignin variety for modern agriculture.

In collaboration with Prof. Asaph Aharoni's lab, Prof. Levy's group is helping develop new methods to analyze lignin polymer content and composition by using gas chromatography-mass spectrometry (GC-MS). This part will be done next year when the equipment and protocols become available.



They are also using transcriptome and small RNA analysis to identify differentially expressed genes among wild, primitive, traditional and modern wheat, with particular emphasis on networks involved in cell wall functions (~ 2500 genes).

**Tetraploid (*Triticum turgidum*) wheat lines that were used as part of the screen for straw with low-lignin and high digestibility (a total of 48 lines were screened).**



So far, they have extracted RNA from the 48 genotypes and have given it to the genomic services at the Institute for expression profiling.

Based on preliminary data, they are focusing on the first developmental stage because it seems to be the period during development when most of the lignification occurs; and thus, when corresponding genes are the most active. They will use this data to identify genes involved in cell wall biosynthesis, and to identify candidate genes and metabolic networks affecting the low lignin trait found in a wild wheat.

In the long term, the scientists wish to transfer low-lignin traits to modern wheat through classical breeding or genetic engineering, and test performance in the field.

### Recent articles

Feldman M, Levy AA, Fahima T, Korol A. "Genomic asymmetry in allopolyploid plants: wheat as a model" *JOURNAL OF EXPERIMENTAL BOTANY*, Volume: 63, Page: 5045-5059, 2012

Feldman M, Levy AA, "Genome Evolution Due to Allopolyploidization in Wheat" *GENETICS*, Volume: 192, Page: 763-774, 2012

Melamed-Bessudo C, Levy AA, "Deficiency in DNA methylation increases meiotic crossover rates in euchromatic but not in heterochromatic regions in *Arabidopsis*" *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA*, Volume: 109, Page: E981-E988, 2012



## Advancing cell wall degradation and fermentation

Biochemist Prof. Ed Bayer concentrates on two strategies to break down the abundant cellulose and associated polysaccharides that comprise the main byproducts of agriculture and plant wastes: (i) genetic approaches to enhance the natural organisms that digest cellulose, and (ii) bio-engineering approaches to combine these natural elements in new ways, such as creating artificial cellulosomes.

The heat-loving bacterium *Clostridium thermocellum*, often found in nature in hot springs or degrading manure, is the one of the best known cellulose digesting enzymes. This anaerobic, thermophilic, cellulolytic bacterium is capable of directly converting cellulosic substrates into ethanol, an ability that is of serious interest for turning plant wastes into fuels. Prof. Bayer led a team of US and Israeli scientists that sequenced and published the genome of *C. thermocellum*.

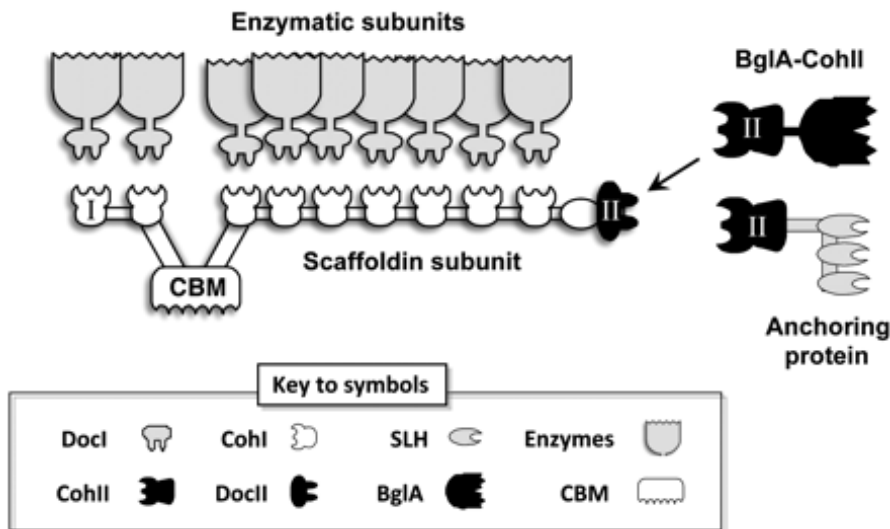
In previous work, Prof. Bayer and colleagues engineered an enhanced cellulosomal endoglucanase enzyme from *C. thermocellum* that was stable over a wide range of temperatures. Exploring the genetics of this bacterium and its active enzymes further, his team found that one of their mutants (G283P) displayed a higher thermal stability than the wild-type enzyme. Introducing this mutation into the previously engineered Cel8A triple mutant resulted in an optimized enzyme, increasing the half-life of activity by 14-fold at 85°C, and maintaining activity well below the average thermal range of the native bacterium.

He also explored  $\beta$ -xylosidases from the aerobic cellulolytic bacterium *Thermobifida fusca*.  $\beta$ -Xylosidases are hemicellulases that hydrolyze short xylo-oligosaccharides into xylose units, thus complementing endoxylanase degradation of the hemicellulose component of lignocellulosic substrates.



## Redesigning the cellulosome

To speed up and streamline the cellulose-digesting powers of bacteria, Prof. Bayer and colleagues have been re-engineering the cellulosome, the specialized, multienzyme complex that they produce that breaks down lignocellulose into more digestible byproducts. They have noticed that one of the “speed limits” found in natural cellulosomes is that they are strongly inhibited by the major end product, cellobiose. To try to avoid this roadblock, Prof. Bayer and his team designed a  $\beta$ -glucosidase (BglA-CohII) enzyme fused to a cohesin module that binds directly to the cellulosome at the immediate site of cellobiose production by the cellulosomal enzymes. They found that their re-engineered BglA-CohII retained cellobiase activity and was readily incorporated into the native cellulosome complex. The resultant fortified cellulosome showed higher overall degradation of microcrystalline cellulose and pretreated switchgrass compared to the native cellulosome alone.



*Schematic view of the *C. thermocellum* cellulosome and the proposed attachment of the chimeric  $\beta$ -glucosidase-fused type-II cohesin (BglA-CohII). From: PNAS Volume: 109, Page: 10298-10303, 2012*

### Some recent articles

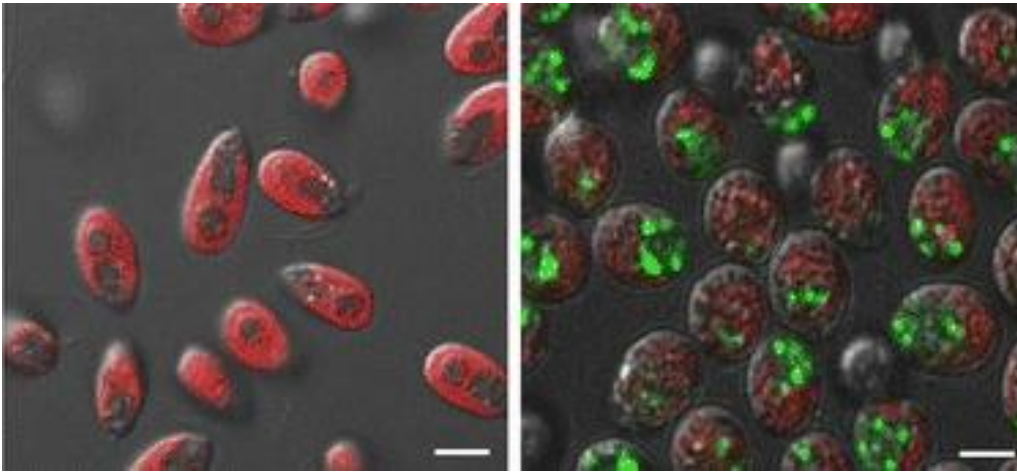
Anbar M, Gul O, Lamed R, Sezerman UO, Bayer EA, “ Improved Thermostability of Clostridium thermocellum Endoglucanase Cel8A by Using Consensus-Guided Mutagenesis” *APPLIED AND ENVIRONMENTAL MICROBIOLOGY*, Volume: 78, Page: 3458-3464, 2012

Gefen G, Anbar M, Morag E, Lamed R, Bayer EA “ Enhanced cellulose degradation by targeted integration of a cohesin-fused beta-glucosidase into the Clostridium thermocellum cellulosome” *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA*, Volume: 109, Page: 10298-10303, 2012



## Developing microorganisms for biofuel production

Many green algal species can accumulate large amounts of triacylglycerides when deprived of nutrients, making them a potential source for production of biodiesel. The algae *Dunaliella salina* has an advantage as a potential source for biodiesel production because of its ability to grow in high salt concentrations. The algae store these oily triacylglycerides in lipid bodies found in the cytoplasm, and which contain a major lipid droplet protein termed MLDP. Prof. Uri Pick and his colleagues isolated MLDP from three species of the extremely salt-tolerant (halotolerant) green algae *Dunaliella*. Their work strengthened scientific knowledge about the relation between oil accumulation and MLDP expression and identified MLDP as a potential marker for identification of oil production.



*To visualize TAG accumulation in D. salina, cells were deprived of nitrogen (right), stained with the lipid-sensitive fluorescent dye Nile red, and viewed by confocal microscopy in comparison to N-sufficient control (left) cells. Whereas N-sufficient cells reveal a well-defined cup-shaped chloroplast and no lipid droplets, N-deficient cells were characterized by a fragmented low-fluorescence chloroplast, and by multiple cytoplasmic lipid droplets (tagged with green fluorescent dye)*

*From: PLANTA, Volume: 236, 2012*

### Recent Articles

Davidi L, Katz A, Pick U. "Characterization of major lipid droplet proteins from Dunaliella"

Source: *PLANTA*, Volume: 236, Page: 19-33, 2012

Peled E, Pick U, Zarka A, Shimoni E, Leu S, Boussiba S, "Light-induced oil globule migration in Haematococcus pluvialis (Chlorophyceae)" *JOURNAL OF PHYCOLOGY*, Volume: 48, Page: 1209-1219, 2012

Pick U., Rachutin-Zalugin T. "Kinetic Anomalies in the Interactions of Nile Red with Microalgae." *JOURNAL OF MICROBIOLOGICAL METHODS* 88 (2) :189-96. 2012

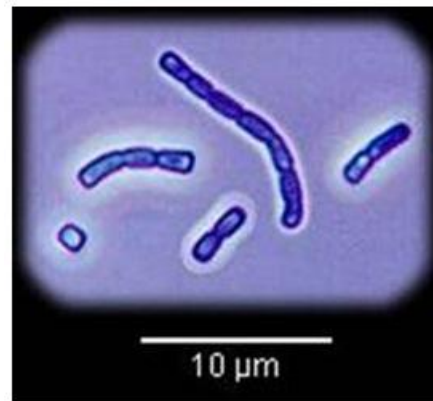


## Developing salt and heat tolerant biofuel stocks

Prof. Avigdor Scherz and his group are focusing on new photosynthetic strains to provide biomass generating platforms under global warming and increased concentrations of carbon dioxides. As the first model system, they selected cyanobacteria, and current studies aim to implement their finding into algae farms and higher plants productivity. Photosynthetic cyanobacteria are among the oldest photosynthetic organisms in nature, responsible for generating a large percentage of atmospheric oxygen. They are relatively simple to cultivate, requiring only sunlight, water, CO<sub>2</sub> and a few nutrients. Thus, they do not require arable land at the expense of food production, and are tolerant of a wide range of salinities and pH conditions. Cyanobacteria can achieve a high biomass yield and can be also used for hydrogen production. In addition to biofuels, which are extracted from fat-containing lipids in the cyanobacteria, the organisms can also produce different metabolites useful for industrial applications. The ease of genetic manipulations in some cyanobacteria make them also a good prototype for screening modifications that can be beneficial for growth and acclimation of higher organisms that are used for biofuel production and possibly hydrogen generation.



*Synechocystis b*



*Thermosynechococcus elongates*

Following extensive screening, computational and biophysical studies (*Nature*, 2006) Prof. Scherz and his team have succeeded in creating thermotolerant strains of the cyanobacteria *Synechocystis* by adding traits from the heat-tolerant *Thermosynechococcus elongates*. Their new variation shows good growth and extensive biomass production at both mild and elevated temperatures. It also grew well at elevated temperatures with higher (up to about 1%) CO<sub>2</sub> concentrations.

In the past year, they have also focused on the effect of differing periods of light and dark (photoperiodism) on the expression the mRNAs of the different photosystem II (PSII) genes and their influence on the growth at elevated temperature. This knowledge is being used to engineer a new strain that can grow under differing amounts of light,



from normal field conditions to continuous illumination. The new findings suggest that by mutating two of the three gene copies that encodes the D1 protein subunit of photosystem II, the biomass productivity under elevated temperature can be tripled.

Currently, biomass production is being up-scaled to allow field translation.

They hope to combine their findings to engineer and cultivate a thermotolerant cyanobacterium that can be grown continuously and at low cost under realistic conditions, such as open pools or sea water, medium levels of carbon dioxide, and differing day/night photoperiods.

In parallel and in collaboration with Prof. Avihai Danon from the Department of Plant Sciences, the Scherz lab is implementing similar mutations in algae aiming at expanding these findings into higher plants as well.

### Recent Articles

Shlyk-Kerner, O., Samish, I., Kaftan, D., Holland, N., Sai, P. S. M., Kless, H. and Scherz, A., (2006), "Protein flexibility acclimatizes photosynthetic energy conversion to the ambient temperature", *NATURE*, 442(7104): 827-830.

Dinamarca J , Shlyk-Kerner O , Kaftan D , Goldberg E , Dulebo A et al. 2011 Double Mutation in Photosystem II Reaction Centers and Elevated CO<sub>2</sub> Grant Thermotolerance to Mesophilic Cyanobacterium. *PLOS ONE* 6(12): e28389. doi:10.137129.

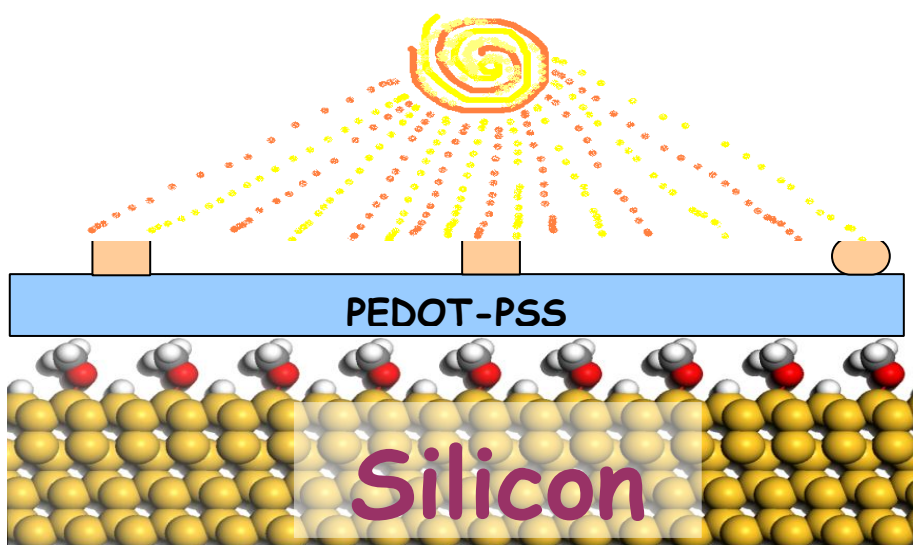


## Converting light more efficiently

### Inversion solar cells

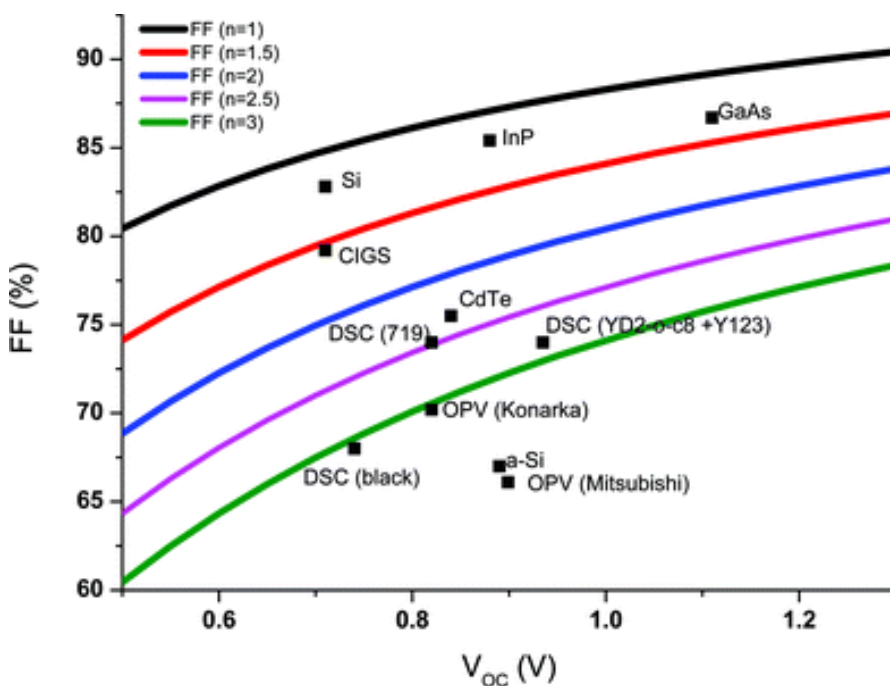
The standard process for producing commercial silicon solar cells is highly energy intensive. Prof. David Cahen has been actively searching for new ways to make solar cells more affordable and easier to build. He and his group recently showed a possible way to avoid these high production costs by demonstrating a new way to create inversion layer solar cells by using an organic top contact layer. His new method uses the organic conductor poly(ethylenedioxy thiophene):poly(styrenesulfonate) (PEDOT:PSS see illustration below) as the top contact, using a soft-deposition method at room temperature. Their experiments showed substantial energy savings and material costs while showing a reasonable potential output as a solar cell.

Building on his extensive work to be able to compare the efficiency of a wide range of available solar cell types, Prof. Cahen and colleagues from the U.S. and Spain recently published an analysis that looks at one of the basic limitations of solar cells. They noted that after decades of research and development, solar cells that are based on “disordered” materials lag behind those made with ordered “crystalline” materials in efficiency as well as in commercialization. They examined the reasons for this fundamental difference, noting the inherent physico-chemical limitations and showed how disorder affects the electronic energies available in these materials. However, solar cells based on disordered materials, such as organic semiconductors, can be substantially cheaper to make in terms of materials and production energy costs.



*(credit: Dr. Rotem Har-Lavan, Weizmann Inst.)*





Fill Factors (FF) of best laboratory cells (as of Dec. 2011) of different categories. The solid lines represent the expected FF value for a given value of  $n$ , the dark diode ideality factor. Disorder impacts the FF value of the cell due to increased probability of recombination. CIGS stands for Cu (In,Ga)Se<sub>2</sub>; OPV stands for Organic PhotoVoltaic cell, with the laboratory that made the cell in parentheses as, unfortunately, the actual material compositions are not always released; DSC indicates Dye sensitized solar cell with the dye used in parentheses.

From: *ENERGY & ENVIRONMENTAL SCIENCE*, Volume: 5, Page: 6022-6039, 2012

### Recent publications

Erickson AS, Kedem NK, Haj-Yahia AE, Cahen D, "Aluminum oxide-n-Si field effect inversion layer solar cells with organic top contact" *APPLIED PHYSICS LETTERS*, Volume: 101, 2012

Yaffe O, Qi YB, Scheres L, Puniredd SR, Segev L, Ely T, Haick H, Zuilhof H, Vilan A, Kronik L, Kahn A, Cahen D, "Charge transport across metal/molecular (alkyl) monolayer-Si junctions is dominated by the LUMO level" *PHYSICAL REVIEW B*, Volume: 85, 2012

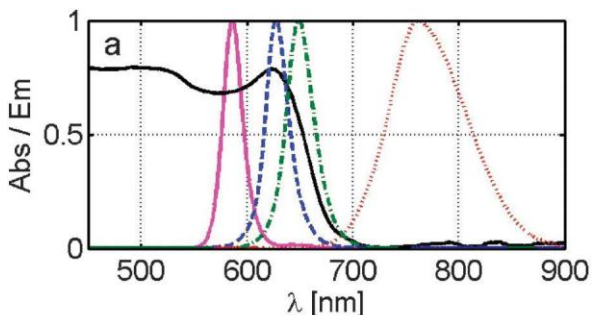
Shpaisman H, Cohen H, Har-Lavan R, Azulai D, Stein N, Cahen D, "A novel method for investigating electrical breakdown enhancement by nm-sized features" *NANOSCALE*, Volume: 4, Page: 3128-3134, 2012

Nayak PK, Garcia-Belmonte G, Kahn A, Bisquert J, Cahen D, "Photovoltaic efficiency limits and material disorder" *ENERGY & ENVIRONMENTAL SCIENCE*, Volume: 5, Page: 6022-6039, 2012

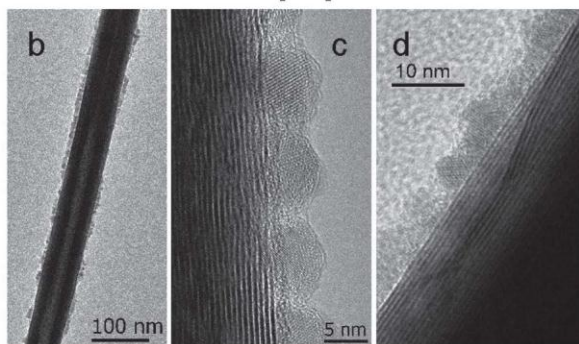


## Quantum dot solar cells

Working with nano-materials pioneer, Prof. Reshef Tenne and others, Dr. Dan Oron developed tungsten sulfide ( $WS_2$ ) inorganic nanotube (INT)–colloidal semiconductor quantum dot (QD) hybrid structures. This new system, analogous to carbon nanotube–QD hybrids, holds potential for a variety of applications, including photovoltaics, luminescence tagging and optoelectronics.



(a) Emission spectra of QDs used in this study and ensemble absorption of the bare INTs (black line). The three emission peaks denoted by solid, dashed and dashdotted lines are for the 586 nm, 627 nm and 649 nm emitting CdSe/CdS/ZnS QDs, respectively. The dotted emission curve is for the CdTe/CdSe QDs. (b) TEM and (c) HRTEM micrographs of an INT- $WS_2$  decorated with 627 nm emitting CdSe/CdS/ZnS QDs. (d) HRTEM image of INT- $WS_2$  decorated with 760 nm emitting CdTe/CdSe QDs.



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## CO<sub>2</sub> to energy conversion

Prof. Igor Lubomirsky and his team improved the performance of their molten lithium carbonate ( $\text{Li}_2\text{CO}_3 + \text{Li}_2\text{O}$ ) and CO<sub>2</sub> system that captures carbon dioxide from the atmosphere and reduces it to carbon monoxide (CO)—a non-corrosive gas that can be burned directly in turbines and generators, or converted on-site into liquid fuel. By changing one of their electrodes from graphite to titanium, and coating it with titanium carbide (TiC), they made the process even more efficient. The improved electrode makes their method even more attractive for CO<sub>2</sub> to CO conversion for energy storage at fossil fuel power plants and other major sources of carbon dioxide production. It has higher conductivity than the graphite electrode used previously and can be prepared *in situ*.



*Prof. Lubomirsky and his team designed an industrial scale prototype containing about 150-200 kg of  $\text{Li}_2\text{CO}_3$ , which was built by a private company (see part of the apparatus at left)*

### Recent publications

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