ENERGY COMMITTEE
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Abstracts

Renewables — systems and storage

Thursday 19 September (09.30–18.00) and Friday 20 September (09.00 –15.15) 2013
The Royal Swedish Academy of Sciences, Lilla Frescativägen 4A, Stockholm

Photo: Yanan Li/mediabank.visitstockholm.com.

This is an event organized through the European Academies Science Advisory Council (http://easac.eu), which gives scientific advice and input to policy makers in the European Union. The Royal Swedish Academy of Sciences (RSAS) has taken the lead in organizing hearings on the topic of sustainable energy systems towards the year 2050. The topic of sustainable energy systems has been divided into topics related to nuclear technology (fission and fusion) and renewable energy technologies and systems.

This workshop is supported by the Royal Swedish Academy of Sciences Nobel committees in physics and chemistry, Swedish Natural Science Research Council (VR), The Energy Agency (Energimyndigheten) and the Joint Research Centre (JRC).

Nanoscience and the Future of the Global Carbon Cycle

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Anthropogenic gas emissions and land use changes are increasingly perturbing the global carbon cycle. A major focus of energy research is to seek ways to establish a future balanced carbon cycle while providing energy to the world's population, including those in developing economies. The advent of nanoscience has created a new foundation for the design and manufacture of energy conversion systems, and nanoscience will be a key component in the effort to establish a balanced carbon cycle. This talk will describe how nanoscience can enable combinations of carbon capture and management, improved utilization of solar energy, and access to energy storage on a large scale. In this way, nanoscience will enable critical elements of a future balanced global carbon cycle.

Recent progress in organic solar cells:
From a lab curiosity to a serious photovoltaic technology

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Carbon-based organic semiconductors have many potential advantages like easy large-area preparation on flexible substrates, large variety of materials, and low cost. Although known for a century, organics have achieved little impact until OLED displays entered the market about a decade ago, demonstrating that organic semiconductors are ready for significant commercial markets.

In contrast to light-emitting devices, organic solar cells have so far achieved little commercial impact due to low efficiency and lifetime. However, organic solar cells have recently achieved significant progress and have crossed the 10% efficiency mark. For a broad application, further significant improvements are needed.

In this talk, I will present an overview over the key features of solid-state organic solar cells and recent developments in the field. One central research area is the design of the bulk heterojunction active layer, requiring a nanoscale phase separation and optimized morphology to achieve efficient operation. A key challenge of the field is to find design rules which relate the molecular structure of absorber materials to layer morphology and cell properties. The difficulty is that small changes of the molecular structure, leaving the electronic properties of the individual molecule nearly unchanged, can lead to large changes in the crystal packing and molecular orientation, causing significant differences in the electronic properties in the active layer. Furthermore, I will discuss highly efficient tandem structures with optimized electrical and optical properties. Very efficient recombination contacts can be realized by n- and p-type doped transport layers. Structures based on these approaches have reached efficiencies of 12% and have the potential to reach approximately 20%. Furthermore, these high-efficiency cells also show encouraging lifetimes.

Lactid Acid, Ionic Liquids and Energy Storage Materials: Perspectives of Hydrothermal Biomass Upgrade

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Hydrothermal reforming (HTR) and hydrothermal carbonization (HTC) are chemical processes to turn carbohydrates (such as forestry side products, but waste biomass in general) into products which –depending on reaction conditions- can result in value chemicals but also artificial peat (for soil improvement) and industrial high value carbons. All these processes occur naturally, but are highly accelerated under hydrothermal conditions. Lactid acid "fermentation" for instance can be ran from glucose with 80% yield in only 3 minutes, of course without biocatalysts. Even coalification as the final product is highly accelerated to about 1 – 24 h reaction time by employing elevated temperatures between 180 – 230 °C and appropriate catalytic schemes. The processes not only work with a broad variety of "waste biomasses", they are also exothermic and therefore potentially independent of outer energy sources. In addition, it is "chemistry", that is for molecules the composition, for carbon solids the nanostructure, the surface functionalities, and properties as biodegradability can be varied in a systematic fashion.

In this talk, I will present the processes and a variety of the potential products generated, such as lactid acid, bio(ionic liquids), but also soil conditioner, battery electrode materials und supercapacitors. I will also try to evaluate the potential and scale of such type of technology. If time allows, I will also discuss about first fully orthogonal biorefinery schemes and first simple path explorations to illustrate how carbohydrates can potentially replace crude oil in the near future.

EASAC Solar Study
Stockholm Sweden
Sept. 19-20, 2013

Title:
Photovoltaics, High Efficiency Together with Low Cost

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Abstract:

Solar cell science and technology is changing. New efficiency records are being set. Alta Devices has reached 28.8% efficiency in a thin film single-junction cell at 1-sun, and 30.8% efficiency in a thin-film dual junction cell at 1-sun.

Counter-intuitively, efficient external fluorescence is a necessity for approaching the ultimate limits. A great Solar Cell also needs to be a great Light Emitting Diode. Why would a solar cell, intended to absorb light, benefit from emitting light? Although it is tempting to equate light emission with loss, paradoxically, light emission actually improves the open-circuit voltage, and the efficiency.

The single-crystal thin film technology that achieved these high efficiencies, is created by epitaxial liftoff, and can be produced at cost <$0.50/Watt, well below the other less efficient thin film solar technologies. The path is now open to a 30% efficient photovoltaic technology at low cost.

Suggested Reading: "Intense Internal and External Fluorescence as Solar Cells Approach the Shockley-Queisser Efficiency Limit", O. D. Miller, Eli Yablonovitch, and S. R. Kurtz, IEEE J. Photovoltaics, vol. 2, pp. 303-311 (2012).

"The Opto-Electronics of Solar Cells", E. Yablonovitch and O. D. Miller, IEEE Photonics Society Newsletter, vol. 27, No. 1, p. 4, (February 2013).

Efficient polymer solar cells and first steps beyond that

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The recent significant increase in power conversion efficiency (PCE) of polymer-fullerene solar cells largely originates from the successful development of new electron donor polymers. The donor-acceptor (D-A) or push-pull design, where electron rich and electron deficient units alternate along the copolymer chain is commonly used to tune the HOMO and LUMO energy levels and the optical band gap of these polymers. While structure-property relations for energy levels are well established, these are less clear for the actual photovoltaic performance. Creating morphologies in which nanometer-sized, interconnected, semi-crystalline domains of both polymer and fullerene exist seems crucial for high photovoltaic performance. These semi-crystalline domains optimize the conjugation along the polymer backbone and allow delocalizing the carrier wave functions to assist efficient charge separation. High molecular weight and a tendency to crystallize are important in achieving such morphologies.

For a range of diketopyrrolopyrrole-based small band gap polymers it will shown how the molecular weight of semiconducting polymers and the nanomorphology are crucial parameters in obtaining high power conversion efficiencies in the range of 6-8% for single junctions, with optical band gaps down to 1.3 eV. When the new semiconductor materials are combined with a wide band gap material it is possible to make create tandem and multi-junction devices in tandem or triple layer configurations with efficiencies close to 9%. The favorable efficiency of the tandem cell is achieved by an almost perfect complementarity of the absorption spectra of the different absorber layers that reduce thermalization losses.

Because of their high voltages, triple junction solar cells can be used for photo-electrochemical water splitting and we have performed the first experiments to explore how we can use multi-junction polymer solar cells to split water to create hydrogen. Because of overpotentials, water electrolysis only occurs at potentials larger than then 1.23 V. The required potential of ~1.7 V is exceeds the open-circuit voltage of common single and tandem junction organic solar cells. The voltage deficiency however, can be solved using a triple junction cell. Recent experiments demonstrate the viability of this approach and allow efficient artificial water splitting, driven by photoinduced electron transfer between organic compounds.

Photovoltaic research for the support of European energy transition

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Abstract

Photovoltaics is the direct conversion of sunlight into electricity. Semiconductor materials are used to absorb incoming light, separate carriers by an internal pn-junction and collect the carriers in an external circuit. Silicon as one of the most abundant elements on earth has proven to be an excellent semiconductor for this purpose and nearly 90 % of todays PV modules are based on this material. The cost of PV solar cells and modules has been dramatically reduced over the last decades allowing electricity generation at approximately 10-15 cent/kWh in Germany today based on a module lifetime of 20 years. This is at a low solar irradiance of 900-1200 kWh/m2/year which can be two times higher in the South of Europe. If frameworks are set correctly and PV systems are integrated into the electricity grid without bureaucratic barriers, then the generation cost of PV electricity can drop well below 10 cent/kWh. PV system costs have been falling continuously over the last decades. This is mainly due to the larger scale of production, but certainly also thanks to research and development which has led to substantial improvements in efficiency and material use.

A photovoltaic system requires a large investment in the beginning but afterwards runs continuously over 20-30 years without fuel costs. The lifetime of the photovoltaic system and its degradation in performance is essential when calculating the levelized cost of electricity (LCOE). Today, feed-in tariffs provide a fixed sales price for the PV electricity over 20 years which is the basis for calculating the economics of a photovoltaic investment. But, it is also well understood that PV systems can run for 30 years or longer which may increase the profit for the investor. Reliability of the PV modules is therefore an important subject which requires further R&D, industry standards and adequate testing procedures.

Conversion efficiency of PV modules has always been an important focus of R&D as it leverages the cost of all system components. Higher efficiencies reduce the required land area, support structures, cables, glass for the modules, and so on. Silicon single-junction PV devices are theoretically limited to below 30 % in their efficiency and record performance has not increased over the last decade. Tandem solar cells on the other hand have proven to reach efficiencies up to 38 % and 44 % if the sunlight is concentrated by a factor of 300-500. Material science will allow to combine high efficiency tandem solar cells with silicon in the future and provide new opportunities for cost reduction. At the same time other approaches will reduce material use of silicon PV. This will lead to technological advances which will ultimately bring PV electricity generation cost down to below the cost of conventional energy sources. The presentation will highlight some of the latest achievements in this field and try to give an outlook to what may come next.

Photovoltaic energy conversion has come down in cost to a level where large scale deployment has started and where it can make a major contribution to the European Energy transition. Europe has to make sure that value creation is maximized locally. For this we have to create innovation in Europe, produce PV modules, manufacturing equipment and materials with superior quality and performance. For this R&D will play a major role to keep European industry competitive and reduce the cost of future PV products and power plants.

Nanowires with promise for high efficiency photovoltaics

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Semiconducting nanowires have been recognized as promising materials for high-performance electronics and optics where optical and electrical properties can be tuned individually. The feasibility of III-V nanowire integration with existing silicon processing technology due to the small footprint between the silicon substrate and the nanowire material has further sparked that interest. Especially, InP NW PV has been grown epitaxially on Si substrates [1]. For NWs to provide the new architecture for next generation photovoltaics there is a strong need to take complete control over synthesis. By optimizing growth conditions with respect to tapering we created nanowire-InP nanowire based solar cells using Au seed particles for growth.

We will report on the growth, processing and characterization of nanowire array-based solar cells with 13.8 % efficiency [2]. First, gold particles were patterned on InP substrates with a 500 nm pitch, using nanoimprint lithography. Then, about 1.5 µm long InP nanowires were grown using DEZn and TESn as doping precursors, to create an axially defined *p-i-n* junction. HCl was used to prevent radial overgrowth. The nanowires were processed as-grown with a transparent conductive oxide as top contact to create 1x1 mm^2 solar cells, with 4 million nanowires per cell.

The solar cells were investigated using a sun simulator at Fraunhofer ISE CalLab reference setup. Although the 180 nm-diameter NWs only covered 12 % of the surface, the photocurrents were 71 % of the theoretical maximum for an InP solar cell. This is six times the limit in a simple ray optics description, and comparable to the record planar InP cell. To understand the absorption, we used three-dimensional electromagnetic optical modeling [3, 4]. We find excellent agreement between the spectra of modeled absorption and the experimentally measured external quantum efficiency.

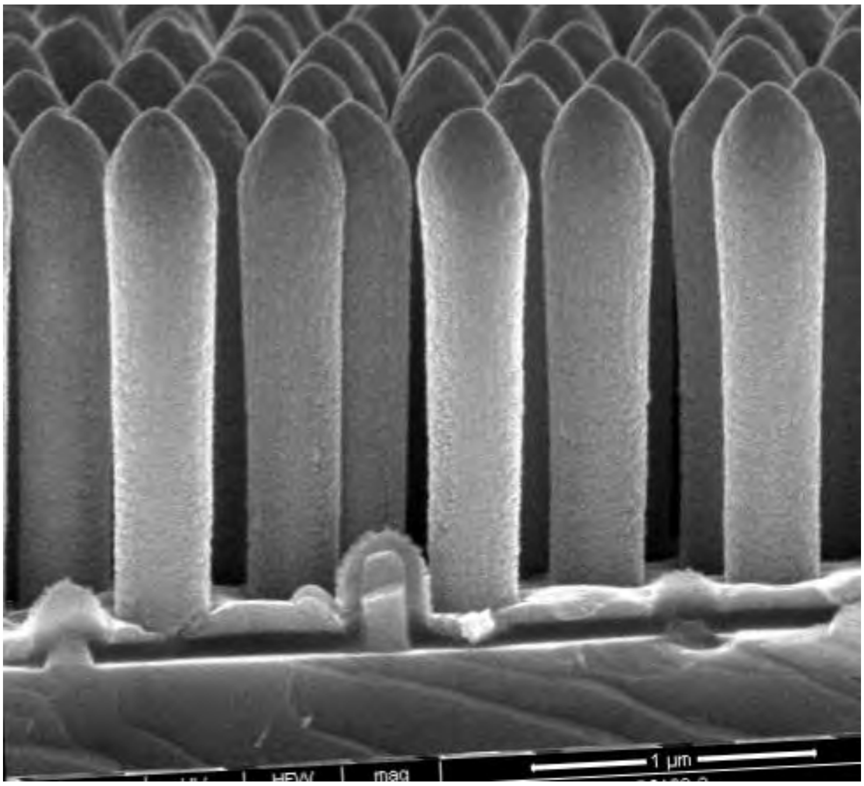

FIG. 1: Legend: Cross-sectional SEM image nanowire based solar cell. The InP nanowire pn junctions have been imbedded in insulating silicon oxide which was opened up at the tip of the nanowires to enable contacting by use of a transparent conducting oxide.

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Hybrid inorganic-organic photovoltaics — HI-OPV

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Cyanobacteria as the ultimate photo-catalysts of the conversion of CO_2 into chemical commodities and liquid fuel, driven by either sunlight or electricity

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Introduction: A sustainable society must harvest solar energy in the most efficient way possible for most of its energy- and materials needs. In such a society photovoltaics presumably will be the prime route for energy harvesting. This already is an established technique which shows great promise, so much so that in due time (~ 15 years) electricity may be a commodity that is in excess during certain periods of circadian time.

Regarding future materials needs, be it in the form of a liquid energy carrier or of chemical commodities for materials synthesis, priority has to be given – in addition to sunlight as the source of energy - to the use of CO_2 as the source of carbon. Hence, natural oxygenic photosynthesis is the obvious candidate process to provide these materials. It is therefore of immediate and utmost importance to enhance the efficiency of product formation in oxygenic photosynthesis. The organisms of choice to use for this are the cyanobacteria and microalgae, because they photosynthesize more efficiently than plants. In addition, they can be straightforwardly engineered to bypass biomass formation via cloning of a heterologous product-formation pathway. In such engineered organisms activity of the Calvin-Benson cycle then leads to a 'photofermentative' type of metabolism in which product formation takes place according to the equation:

$$CO_2 + H_2O \rightarrow C_xH_yO_z + O_2$$

at the expense of photon energy. When applied at large scale, this approach, next to allowing high efficiencies of the exploitation of solar energy, also solves problems regarding minerals management, which is a burden on first- and second generation biofuel production processes.

Recent literature testifies that indeed a large range of products can be made this way. Examples range from ethanol to fatty acids and isoprene. For some products, like ethanol and butyraldehyde, productivities have been achieved that warrant introduction of the term 'photosynthetic cell factory'. This is because the cyanobacteria that are the catalysts in this processes channel the majority of the carbon of the incoming CO_2 into the selected product. However, for this approach to be economically competitive with fossil-based production processes it is important that yield and efficiency in this approach are further optimized. Nevertheless, the developments in this field have raised the expectation that engineered cyanobacteria will be the future "plu*Gb*ugs for CO_2". A range of research specializations, all focused on cyanobacteria and microalgae will have to be exploited and integrated to achieve this. These are briefly outlined below.

Recent developments in society have brought a downward pressure on energy prices through *e.g.* shale gas exploration. Furthermore, increased dependence on photovoltaic energy will necessitate circadian 'peak-shaving', not only for electricity from the grid, but also for CO_2 from distribution systems of this greenhouse gas. This may generate a new opportunity for the application of cyanobacteria as catalysts of an economically viable, sustainable, CO_2- and light-driven production process. In large volumetric reactors light may be generated through LEDs inside the reactor, which allows one to optimize the conditions to which the photosynthetic cell factories are exposed and increase their efficiency. This contrasts the large two-dimensional reactors in which, due to the distributed nature of sunlight, cells are exposed to large fluctuations in light intensity, due to the turbulence of the liquid medium inside the reactor, on top of the ambient fluctuations in sunlight intensity due to clouds and the circadian cycle. Depending on further increases in the efficiency of solar panels and light-emitting diodes, photosynthesis in such volumetric reactors may even become competitive with traditional crops.

For further development of the successful application of biosolar cell factories, research in several directions will have to be extended. The fields are briefly indicated below:

Systems and synthetic microbiology: Sustainability applications of cyanobacteria and microalgae will have to make use of the most recent developments in systems- and synthetic biology available. For this, the systems-biology cycle of: modeling, experiment and computational analysis, will have to be interlaced with a similar cycle in the area of synthetic biology, to arrive at an integrated synthetic systems biology approach. Inclusion of synthetic biology is essential because phototrophic metabolism needs to be expanded with a product-forming metabolic pathway, optimally coupled to cyanobacterial intermediary metabolism.

Strain selection: Ecophysiology and evolution of oxyphototrophic microorganisms: Sustainability applications with oxyphototrophic microorganisms have so far have focused on *Synechocystis*, to a lesser extent on *Synechococcus*, and on a limited range of green algae, like *Chlamydomonas, Nanochloropsis* and *Bottryococcus*. These are all model organisms for which genome sequence information is available, and that are genetically well-accessible. However, for development of large-scale, highly efficient processes, it may be an advantage to involve more robust strains. Features for which such further optimization may be beneficial are *e.g.* growth rate, thermal resistance, optimal pH range, etc. Strains possessing such characteristics can be isolated from selected ecosystems. After physiological characterization and genome sequencing, the first priority here will be to make a few selected organisms genetically accessible.

Genome reduction and –design: The ultimate 'cyanobacterial cell factories' will not only possess a product-forming metabolic pathway, that re-directs carbon from new cells to the selected product, but these cells will also have a streamlined endogenous metabolism. Two parallel approaches are available for this: genome reduction, in which successively (large parts) of the resident genome are deleted, and bottom-up genome design, which starts with an assertion of the minimum set of genes for a specific designer organism and then has this genome synthesized and expressed.

Computational analyses: For the synthetic systems biology analysis of oxygenic photosynthesis at the cellular level detailed computational studies will be necessary. Examples are the rate of light-induced exciton- and electron flow (e.g. with dissipation analysis), intermediary metabolism (e.g. with kinetic flux balance analysis), analysis of the regulation of expression- and of signal transduction networks (via network reconstruction).

Towards the '*at-omics*' of sustainable production: So far most studies in synthetic systems biology take the physiological parameters of biomolecules (e.g. the K_M and V_{max} of enzymes, ligand affinities, super-complex formation, etc.) as the starting point of experimental design and computational analysis. The time has come [1] to integrate the next level of understanding of biomolecules in this approach, i.e. their atomic structure. This is particularly important for optimization of the 'highway of metabolism' in a photofermentative cell factory. Enzymes in this pathway will have to be engineered in such a way that they can provide the high-capacity conversions required for efficient metabolism without becoming a protein burden to the cell, *i.e.* they all have to have a relatively small size and a high k_{cat}. Integrating **at**omic structural information into multi-**omics** analyses will make this possible.

Reference:

1] Chang RL, Andrews K, Kim D, Li Z, Godzik A, Palsson BO (2013) Structural systems biology evaluation of metabolic thermotolerance in *Escherichia coli*. Science **340**: 1220-1223.

Suggested further reading:

a) Angermayr et al. (2009) Energy biotechnology with cyanobacteria. Curr Opin Biotechnol. 20: 257-63.
b) Lan EI, Liao JC (2012) ATP drives direct photosynthetic production of 1-butanol in cyanobacteria. Proc Natl Acad Sci USA 109: 6018-23.
c) Angermayr SA, Hellingwerf KJ (2013) On the Use of Metabolic Control Analysis in the Optimization of Cyanobacterial Biosolar Cell Factories. J Phys Chem B., in press

Integration of renewable energies: competition between storage, the power grid and flexible demand

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Rational design of cyanobacteria for hydrogen production

Dr. Sascha Rexroth
EASAC-Workshop: Renewables – systems and storage
19-20 September 2013

Abstract

The solar-driven hydrogen production has tremendous potential as renewable and carbon-neutral energy source, since the substrate, water, and the energy source, sunlight, are virtually unlimited. Cyanobacteria, which perform oxygenic photosynthesis, can under certain conditions produce hydrogen using electrons extracted from water. Our goal is to improve the efficiency of hydrogen generation at the expense of biomass production.

An important part is the efficient coupling of the linear photosynthetic electron transport from water to an imported, engineered hydrogenase. For this coupling the photosynthetic electron metabolism has to be engineered in many individual steps towards this goal. The result of each single engineering step (such as antenna size reduction, partial uncoupling of the thylakoid membrane, re-routing of electrons at the photosystem 1 acceptor site) has to be monitored by both functional as well as metabolic characterization on the whole cell level (for instance by an in depth quantitative proteome, lipidome- and metabolome analysis). Engineering of ferredoxin-dependent pathways – especially FNR-dependent steps – is a decisive step for re-routing electrons from water for hydrogen production instead of CO_2-fixation. Studies of protein-protein-interactions in isolated model systems, as the affinity of ferredoxin for FNR and hydrogenase, are an important guide for the rational design of these regulatory elements.

Optimization of photobioreactor systems and improved fermentation conditions are integral parts of the process design. Optimal culture conditions can be found and kept constant for several months by using continuous cultivation techniques which allow the systematic optimization of each individual parameter. Provided such systems are optimized both on the individual cell level and on the systems level, a more than 100-fold increase of hydrogen production in comparison with the most productive natural systems existing to date can be estimated, which would be a promising basis for an economically competitive H_2 production.

Molecular science for artificial photosynthesis: from bio-inspired catalysts to nanomaterials.

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Among the biological processes, few of them have attracted the interest from bio-inorganic chemists as photosynthesis.[1] Photosynthesis allows bacteria, algae and plants to use solar energy in order to sustain their growth, through the production of biomass. Actually, the amount of solar energy reaching the Earth is several orders of magnitude greater than that required for human development so that even low conversion efficiency would be sufficient to solve the upcoming energetic crisis.[2] The issue here is to find a way to store this energy since worldwide energy demand does not correlate with the availability of sunlight. Hydrogen production, through the reduction of water in electrolyzers is currently one of the most convenient ways to durably store energy, if the electric energy is initially obtained from renewable resources. While electrolysis is a mature and robust technology, the most promising devices, based on proton exchange membranes, rely on the use of platinum as electrocatalysts to accelerate both hydrogen evolution (eq.1) and water oxidation (eq.2). However, this rare and expensive metal is not itself a renewable resource so that the viability of a hydrogen economy depends on the finding of new efficient and robust electrocatalytic materials based on earth-abundant elements.

$$2\ H^+ + 2\ e^- \rightarrow H_2 \qquad \text{(eq 1)}$$

$$H_2O \rightarrow \tfrac{1}{2}\ O_2 + 2\ H^+ + 2\ e^- \qquad \text{(eq 2)}$$

Another issue resides in using sunlight directly as the energy source for water splitting, without the intermediate production of electricity, thereby reproducing the direct light-to-chemical energetic transduction achieved by photosynthetic organisms. Interestingly, cyanobacteria or micro-algae are even able to photosynthesize hydrogen, in a fully sustainable way, called "light-driven water splitting" and shown in Eq. 3.

$$H_2O \rightarrow\ H_2 + \tfrac{1}{2}\ O_2 \qquad \text{(eq 3)}$$

In natural systems, eq. 1 and 2 are efficiently catalyzed by enzymatic sites such as the dinuclear NiFe[3] and FeFe[3b, 4] clusters in hydrogenases or the oxygen–evolving center (OEC) of photosystem II. Significant achievements have been made in the recent years

regarding the design of molecular catalysts, taking inspiration from these two enzymatic systems. These comprise biomimetic FeFe or NiFe models of the active sites of hydrogenases or polynuclear manganese or ruthenium catalysts for water oxidation though cobalt[5] also emerged as a versatile non-noble metal for the design of efficient and robust electrocatalysts. It has also been demonstrated that such catalysts could be coupled with molecular light-harvesting systems (photosensitizers) so as to produce photocatalytic systems for hydrogen or oxygen evolution.[6] The introduction of electron reservoirs between the light-harvesting and the catalytic moieties also hold promises for the development of such systems with improved efficiency.[7]
Practical applications of such catalytic systems require that they can be grafted onto conducting material so as to form electrode[8] or photoelectrode[9] materials that can be implemented into technological devices such as electrolysers or photoelectrochemical (PEC) cells for water splitting.

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"Solar energy conversion inspired by Nature: Renewable 21st century fuels from water, carbon dioxide and sunlight"

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Artificial photosynthesis is a chemical process that captures and stores the energy from sunlight in a chemical fuel (a so called solar fuel). This renewable process requires the finely tuned combination of light absorption and chemical catalysis, which is superbly coupled in natural photosynthesis but much less so by artificial systems. Many efforts around the globe therefore centre on adopting natural principles in a bio-inspired approach to construct artificial, synthetic systems that generate sustainable fuels. A major focus by the research community is the efficient light-driven conversion of abundant raw materials such as water and carbon dioxide into the renewable energy carriers hydrogen and carbon-feedstocks. My research group recently inaugurated the Christian Doppler Laboratory for Sustainable SynGas Chemistry, which addresses application-oriented basic research questions for a sustainable carbon-based economy. Specifically, the Doppler laboratory aims to develop the basic principles for a purely synthetic photochemical device that allows for the light-driven conversion of the greenhouse gas carbon dioxide and water to carbon monoxide and hydrogen, a mixture known as syngas. Syngas is an invaluable chemical feedstock for the petrochemical industry and an attractive precursor to produce hydrocarbons, liquid fuel. Syngas is currently produced from fossil fuels and is therefore neither clean nor renewable; our approach offers a solution to both of these drawbacks by using a sunlight-driven process. The Doppler laboratory receives substantial funding from the European oil- and gas-industry (OMV Group), demonstrating the attractiveness of this emerging approach to the industrial sector.

The artificial leaf

Daniel G. Nocera

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The artificial leaf is a buried junction device that can achieve solar-to-fuels efficiencies in excess of 10%. The device is constructed simply with coatings (no wiring). And operates under simple conditions (from a glass of water) New science is being developed that will allow such architectures to be produced under high throughput manufacturing conditions.

An artificial leaf can perform direct solar-to-fuels conversion via water splitting. The artificial leaf is a buried junction, in which the rectifying junctions are protected from solution or "buried". Whereas water splitting catalysis is combined with charge separation, current rectification, and photovoltage generation in a solution junction PEC device, in a buried junction device, catalysis is separated from the current rectification, charge separation, and photovoltage generation, which occur at the internal junction. The buried junction photoelectrochemical (BJ–PEC) cell is free from many of the design limitations of a traditional solution junction photoelectrochemical (SJ–PEC) cell. First and foremost, in a SJ–PEC, water splitting catalysis is combined with charge separation, current rectification, and photovoltage generation. Accordingly, most candidate materials are based on metal–oxides. Decades of research have shown that it is extremely difficult to produce a competent photovoltaic (PV) material that at the same time is capable of facilitating the demanding four–electron, four–proton chemistry of water splitting. Second, in a SJ–PEC, the band edges of the flatband potentials of the semiconductor must straddle the thermodynamic potentials of OER and HER under the conditions of operation. These foregoing limitations are circumvented in a buried junction device. In a BJ–PEC, water–splitting catalysis is separated from the internal junction where current rectification, charge separation, and photovoltage generation occur. Accordingly, the OER and HER catalysts may be optimized independently from the PV device such that the maximum power characteristics of the PV and catalyst may be matched independently. Of equal significance, in a BJ–PEC, the potential drop across the outer Helmholtz layer will adjust automatically to move the Fermi levels to energetic positions that allow the water splitting reaction to proceed. For this reason, the photovoltages produced at buried junctions need not be fixed relative to a specific material flatband potential and consequently there is no requirement for the flatband potentials of the semiconductors to straddle the thermodynamic potentials of the OER and HER. There simply has to be sufficient potential generated by the PV device to enable water splitting. This talk will focus on the three topics: (1) Analysis of Tafel and photovoltaic power curves to achieve the most efficient solar-to-fuels efficiencies (SFEs). (2) New architectures will be presented that allow the overall SFE to be in excess of 10%. And (3), new science will be presented to enable the artificial leaf to be constructed from techniques that will allow it to be fabricated on rigid (flat glass) and flexible (flexible glass) substrates at production line speeds of 1000 m/h.

Electrochemical energy storage, activity on all fronts

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The National Center for Scientific Research
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Integration of renewable energies: competition between storage, the power grid and flexible demand

Prof. Thomas Hamacher
Technical University Munich
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EASAC-WORKSHOP
Royal Swedish Academy of Science
Stockholm, September 19-20th, 2013

Wind Energy Systems – Present Status and Ecobalances

by Hermann-Josef Wagner, Ruhr-Universitaet Bochum, Germany[1]

1. Status of Wind Energy Today

In terms of installed capacity, Germany had the leadership until 2007. Then USA has taken over the leadership. Recently, China has become world leader. Table 1 shows the detailed figures at the end of the year 2012.

Table 1: Use of wind energy worldwide.

	Rated Capacity 31.12.2012 [GW]	Share worldwide [%]
China	76	27
USA	60	21
Germany	31	11
Spain	23	8
India	18	6
Italy	8	3
UK	8	3
France	7	3
Remaining countries	51	18
Total	282	100

2. Technical design of wind turbines

2.1 The design with gearbox

The main aspect of the classic design is the split shaft system, where the main shaft turns slowly with the rotor blades and the torque is transmitted through a gearbox to the high-speed secondary shaft that drives the few-pole pair generator.

The transmission of torque to the generator is shut off by means of a large disk brake on the main shaft. A mechanical system controls the pitch of the blades, so pitch control can also be used to stop the operation of the turbine in e.g. storm conditions. The pitch mechanism is driven by a hydraulic system, with oil as the popular medium. This system needs almost yearly maintenance and constant pressure monitoring, along with the

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gear box which is lubricated with oil. For constructions without a main brake, each blade has its pitch angle controlled by a small electric motor.

To reduce weight generators with permanent magnets was developed. Some producers are equipping their converters with it last years.

Wind speed and direction measuring apparatus are located at the back of the hub head. A rack- and- pinion mechanism at the join of the hub and the tower, allows the hub to be rotated in to the wind direction, and out of it in storm conditions.

2.2 The design without gearbox

Some companies e.g. the German company Enercon, design another turbine type, without gearbox.

This design has just one stationary shaft. The rotor blades and the generator are both mounted on this shaft. The generator is in the form of a large spoked wheel with e.g. forty-two pole pairs, around the outer circumference and stators mounted on a stationary arm around the wheel. The wheel is fixed to the blade apparatus, so it rotates slowly with the blades. Therefore, there is no need for a gearbox, rotating shafts or a disk brake. This minimising of mechanical parts simplifies the maintenance and production of the turbine.

The whole system is automated; pitch control and hub direction are controlled by a central computer, which operates the small directional motors.

2.3 Technical systems

More details and information about the technical design and systems are descripted in [1].

3. Life Cycle Assessment

3.1. Basic Targets and Approach

Life Cycle Assessments (LCA) is an important tool for industry and policy makers, used to determine the actual emissions of a product or technology throughout its whole life cycle. In case of energy production systems or power plants, analysis of energy required to produce the materials and processes; emissions resulting from various processes for materials production and processes resulting into their Cumulated Energy Demand (CED) and Global Warming Potential (GWP) become important parameters when making decisions on further research, development and deployment of any technology. The method of carrying out such analysis is explained through a case study.

The four different steps of a life cycle assessment are defined in the international standards DIN EN ISO 14040 [2] and DIN EN ISO 14044 [3]:

The **Goal and Scope Definition** includes the description of the balance object, the system boundaries and the assumptions made.

During the **Inventory Analysis** all material, energy and emission flows (input and outputs) are investigated and lead to the life cycle inventory analysis result.

Within the **Impact Assessment**, the impact categories as well as their indicators are defined. The inputs and outputs are classified by these impact categories. Using characterization factors, the impact category indicators are calculated.

Finally, in the **Interpretation** step, the results of the life cycle assessment are evaluated to reach conclusions. Additionally, an optional sensitivity analysis can investigate responsive parameters and their influence on the results.

3.2. Case Study of alpha ventus

Results and characteristics of wind energy LCA can be best described using an example. Therefore in the following chapters the carried out LCA of the offshore wind farm alpha ventus will show the different steps and important conclusions of results of LCA of a wind energy system. In conjunction with the operating company, the maintenance and maintenance assignments for the use phase of each wind energy converter was assembled (table 2).

Table 2: Overview of system boundaries

Description	Technical Lifetime	Full Load Hours [a]	Maintenance Assignment [b]	Number of WEC
alpha ventus	Foundation and Submarine Cable 20 years	3,900 h/a	10 Helicopter and 15 Shipping Services per year and WEC	12

a) Including down time and losses during transmission to on-shore transformer station

b) Maintenance for each wind energy converter (WEC) over the technical lifetime: replacement of 0.5 gearboxes and 1.25 rotor blades

3.3. Results

For the wind farm, fig. 1 displays the total material balance itemizing different substances. All together about 29,000 tons of material is installed. Of major significance is the proportion of the ferrous metal (>73 %)..

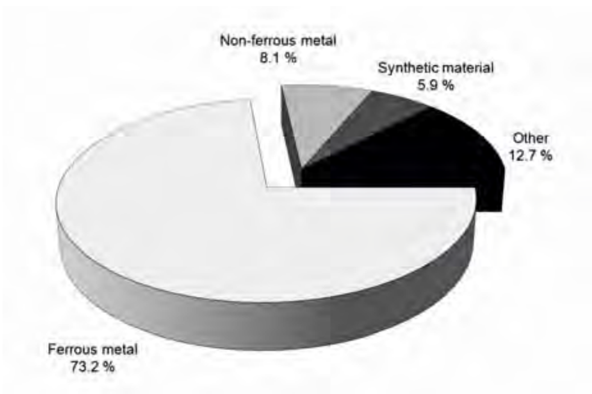

Fig. 1: Material balance of the wind farm alpha ventus (including the grid connection)

In total, about 2,300 TJ Cumulated Primary-Energy Demand (CED)-Equivalent have to be expended for the entire life cycle of alpha ventus (fig. 2). Concerning the Global Warming Potential (GWP), about 149,000 t CO_2-Equivalent are expended. The proportions of the different life cycle phases nearly equal the respective one of the CED.

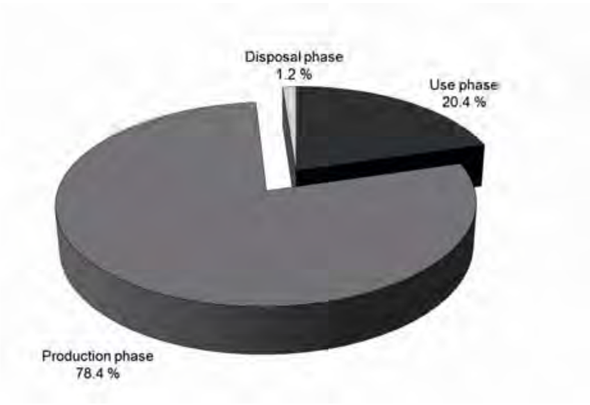

Fig. 2: CED of the wind farm alpha ventus itemized respecting life cycle phases

The energetic payback time is an important key figure to determine the sustainability of power plants using renewable energies. It describes the time frame to compensate the energetic expenses, valued as primary energy, for the entire life cycle of the power plant. In this case, the offshore wind farm generates electricity without any additional energetic input to compensate the energetic expenses for production, use and disposal. To value the generated electricity as primary energy, Germany's electricity mix was chosen as the comparing system. The calculations are based on the computational method of VDI 4661 [4].

To investigate the influence on the climate change, the greenhouse gas payback period was calculated, too. This key figure describes the time for the compensation of the carbon dioxide equivalent emissions during the entire life cycle. Again, as the comparing system, the German electricity mix was chosen.

Table 3: Energetic and greenhouse gas payback period

Description	Generated Electricity [a] over 20 years	Energetic Payback Period [b]	Greenhouse Gas Payback Period
alpha ventus (60 MW)	4,680 GWh	8.8 Month	9.1 Month

a) Unwaighted = secondary energy

b) Energetic supply factor for the German electricity mix at the high-voltage grid:
3.007 kWh PE-Eq./kWhel

c) Greenhouse gas supply factor for the German electricity mix at the high-voltage grid:
0.665 kg CO_2 Eq./kWhel

The results show that the energetic input for the wind farm is amortized after less than 10 months (table 3). The greenhouse gas payback period is about a half month longer than the energetic payback period. The results show a strong correlation between each other.

Therefore, within less than one year the energetic expenditure as well as the greenhouse gas emission of the entire life cycle of alpha ventus is amortized.

In LCAs further indicators, such as the eutrophication potential (EP), the human toxicity potential (HTP), the photochemical ozone creation potential (POCP) and the acidification potential (AP), can be investigated. Depending on the Scope Definition of the LCA, these categories can deliver important results. Fig.3 shows the results in comparison to the German electricity mix at the high voltage grid.

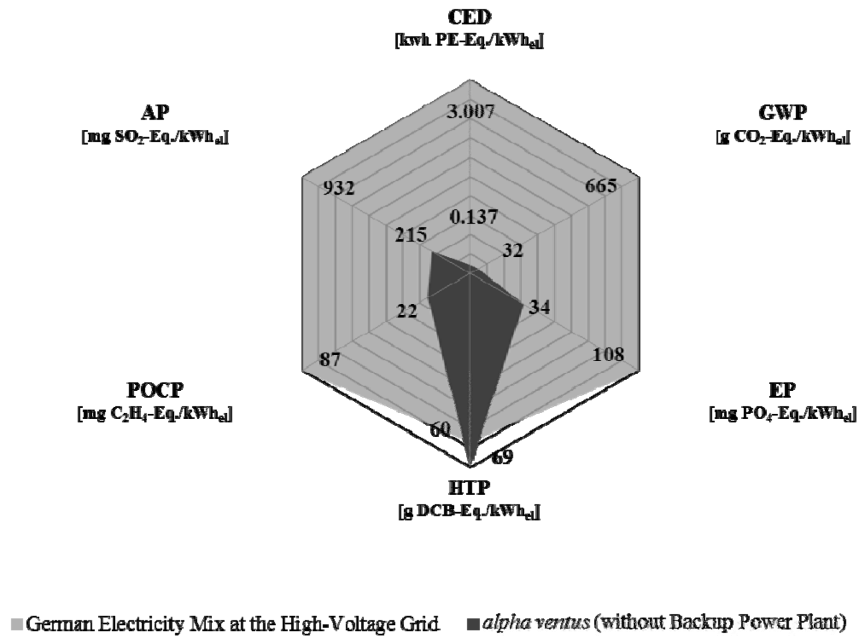

Fig. 3: Indicators of alpha ventus in comparsion of German electricity mix

More results of further sensitivity calculations are published in [5].

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Paper for Swedish Academy of Sciences Conference,
Stockholm, September 19-20, 2013

"Renewables-intensive Energy Scenarios for the UK"

Godfrey Boyle* 23 July 2013

Abstract

The paper begins by describing a number of 'conventional' energy scenarios for the UK's energy future, published by the UK Department of Energy and Climate Change (DECC) and other semi-official sources, with horizon dates between 2030 and 2050.

It then describes some more ambitious scenarios produced by respected consultants, in some of which the contribution of renewables to *electricity* supply rises to levels approaching 100%.

It then looks at scenarios for *all* energy in the UK, produced using the DECC 'Pathways Calculator' software. These include a very high renewables scenario which illustrates the feasibility of deriving some 80% of the UK's energy supply by 2050 from renewables. It also includes proposals to utilize high capacity interconnectors linking the UK to the continent of Europe, which would be used to help smooth surpluses and deficits of electricity supply from variable renewables.

The paper then goes on to discusses the recent scenario *Zero Carbon Britain: Rethinking the Future*, published by researchers at the Centre for Alternative Technology (CAT) in July 2013, which explores the feasibility of deriving 100% of the UK's energy from renewables by 2030. The scenario includes a very large contribution from variable wind power, mainly located off-shore. The underlying calculations include a detailed, ten-year hourly model of UK energy supply and demand, showing that there are some periods of large electricity supply surpluses, and other periods of large deficits. The solution proposed is to combine hydrogen, produced by electrolysis from surplus wind electricity, with carbon from biomass, using the Sabatier process. This produces synthetic methane which, like conventional 'natural gas", can be stored and burned in gas fired power plants to provide backup on occasions of high demand and low wind.

The paper then compares and contrasts the various scenarios, highlighting the strengths and weaknesses of each. It also discusses their technological, economic and political feasibility, including a comparison of the rates of deployment that would be required to achieve very high renewables contributions.

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From Prognostication to Prudence: The Importance of Failure in Renewable Energy Planning

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When it comes to new technologies and future planning, predicting winners and losers is difficult—many say impossible. This problem is not unique to renewable energy or sustainability, but it certainly applies. Policy decision-making in these areas is particularly difficult for two reasons. The planning process is often immune from scrutiny for political or ideological reasons and the chasm between proof-of-concept technology and full commercialization is generally ignored or solved by magical thinking.

Policymakers must differentiate between prognostication (predicting the future without employing skepticism) and prudence (managing uncertainty while embracing skepticism). Prognostication ignores or rationalizes failures to service validation biases while prudence actively learns from failures to better comport policy decisions to policy outcomes.

This session will address four standard problems in technology prognostication that are especially apt for the renewable energy context: technology embedment and path-dependence, the difficulty of achieving commercial viability in rapidly developing technology markets, lack of "mortality and morbidity" analysis for failed technology solutions, and the over-politicization of technological options. The session will close by discussing an iterative process that gives equal status to analyzing renewable energy and sustainability policy failures as a first step in creating a more coherent and prudent path for renewable energy success.

Requirements for system adaptions to intermittent energies

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