



**IEA HIA Task 21 Semi-annual Report
Fall 2010
Bio-inspired Hydrogen and Biological Hydrogen**

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Task Description

Bio-inspired (*in vitro*, biomimetic, and artificial photosynthetic) Hydrogen and Biological Hydrogen (microbial) production processes have been active fields of basic and applied research for many years, with significant R&D programs currently carried out around the world.

IEA HIA Task 21 covers integrated areas of R&D, technological/economic evaluations, and societal acceptance issues in these areas, which are of mutual interest to the 13 countries currently constituting the Task. It also provides the basis for real collaborative research projects amongst the member countries and an overall coordinated program.

The Task was approved by the IEA HIA Executive Committee in May 2010 to operate for a three-year period, with an option for a 2-year extension, and it includes five major subtasks related to collaborative research activities on the production of H₂ using (a) bio-inspired systems; (b) dark biohydrogen fermentation systems; (c) basic studies of light-driven biological hydrogen production; (d) biological electrochemical systems (and integrated combinations of subtask a-e technologies); and (e) overall analysis. The primary objective is not only to sufficiently advance basic and applied science in these areas of research over the next five years but also to evaluate these technologies from the perspective of economics and social acceptance. A five-year period is considered to be sufficient time to initiate a significant directed research program, set metrics for evaluation of the developmental status and promise of this field of research and technology, and achieve some major advances.

Current Task 21 Membership

Current countries participating in Task 21 are Canada, Finland, France, Germany, Italy, Japan, Korea, The Netherlands, Norway, Sweden, Turkey, UK, and USA. A proposed Task 21 Expert in Denmark with the help of ExCo member, Jan K. Jansen, has received a formal invitation to join the task. Each country sends Experts to semi-annual Task 21 meetings.

Activities during the Last Half Year Period

Meetings

- An informal Task organizational meeting was held in Uppsala, Sweden, on June 30, 2010 (in conjunction with the 9th International Hydrogenase Conference). Minutes are available on request.
- The first formal task Meeting was in Famagusta, North Cyprus, on September 17-18, 2010 (in conjunction with the ICCE-2010 Conference). Minutes are available.
- The next Task 21 Meeting will probably be held in Singapore the end of February 2011 in conjunction with the Keystone Symposium on Biofuels (March 1-6, 2011).

Research Activities

- Canada reported activities in studies of (a) metabolism, genetic, and thermodynamics of H₂-producing bacteria; (b) genetic and physiological manipulation of fermentative bacteria; and (c) fermentative H₂ production from low cost biomass/organic substrates, including glycerol derived from biodiesel production.
- France reported continued research in six project areas: (a) selection and comparison of H₂-producing bacterial strains, (b) the role of hydrogenase enzymes in energy metabolism, (c) molecular studies and optimization of enzyme properties, (d) design of new H₂ catalysts, (e) biocaptors (biosensors or biotransducers) and biofuel cells, and (f) biological H₂ production and utilization.
- Italy has been examining H₂ photoproduction by both photosynthetic bacteria and algae (including the screening and characterization of D1 protein mutants) under outdoor conditions.
- Japan reported that the Ministry of Agriculture, Forestry and Fisheries supports biomass conversion to gas projects. Several larger test plants are under construction including biohydrogen plants.
- Korea started the 3rd stage of the National 21 Century Frontier H₂ Project (production, storage and utilization) on April 1 2010, which includes studies of biological H₂ from integrated dark- and photo-fermentation systems with bio-light catalysts. In addition the 2nd year of the H₂ production from hyper-thermophilic bacteria using off-gas project started on August 1, 2010.
- The Netherlands has been concentrating on dark H₂ production by *Caldicellulosiruptor saccharolyticus*, a thermophilic bacterium. Detailed insight into the H₂ metabolism of this bacterium was obtained using genome information and gene expression studies. In addition, research is being done on H₂ production by this bacterium with lignocelluloses-derived substrates in co-culture with other thermophiles, such as *Thermotoga neapolitana*. Other studies have emphasized microbial electrolysis cells using inexpensive electrode materials.
- Norway continued its study on how to combine H₂ production with the production of valuable metabolites. A theoretical study of metabolism in algae exposed to different forms of environmental stress, and the concurrent production of metabolites with pharmaceutical or industrial potential, has been performed. Species of algae with potential for both production of valuable metabolites and H₂ have been evaluated.
- Sweden has been examining bio-inspired H₂ catalysts, regulatory processes involved in cyanobacterial H₂ production, tools development for engineering cyanobacteria, and bioinformatics approaches for comparing the sequences of many different [NiFe]-hydrogenases.
- Turkey has confirmed that H₂ and valuable co-products can be produced from olive mill waste; produced H₂ from different types of integrated dark/photofermentation systems with wheat waste suspension, cheese whey wastewater, potato hydrolysate, molasses, and

thick juice; and engineered various photosynthetic bacterial strains for improved H₂ photoproduction.

- The USA maintains a comprehensive basic science program on fundamental systems biology and metabolic engineering research projects (focused on hydrogenase- and nitrogenase-related projects investigating algae, cyanobacteria, photosynthetic bacteria, archaea, co-cultures, non-photosynthetic bacteria, and cell-free systems); a growing program on bio-inspired H₂ production; and a small applied R&D program emphasizing H₂ production from algae, cyanobacteria, and dark fermentation.

Major Accomplishments

Subtask A (Bio-inspired Systems)

- Using an [FeFe]-hydrogenase (H₂ase) active-site model complex as the catalyst, 200 equivalents of H₂ per catalyst molecule at a maximum turnover rate of 3.7 H₂ per minute was recently demonstrated (see figure at the right) in a light-driven proton reduction process in near-neutral H₂O/DMF (pH 5.5) (Streich, Sweden).
- The covalent attachment of a nickel bisdiphosphine-based mimic of the active site of H₂ase enzymes onto multi-wall carbon nanotubes resulted in a high-surface area cathode material with high catalytic activity under the strongly acidic conditions. H₂ evolves from an aqueous sulfuric acid solution with very low over-voltages (20 millivolts), and the catalyst exhibits great stability (more than 100,000 turnovers). The catalyst is also very efficient for H₂ oxidation in this environment, exhibiting current densities similar to those observed for H₂ase-based materials (Fontecave, France).
- Efficient transfer of electrons from a photosensitizer to a catalyst was achieved by the use of a synthetic molecular wire, attached through Fe/S coordination bonds to both the F_B Fe/S cluster of isolated PSI complex and to the distal Fe/S cluster of an [FeFe]-H₂ase. The molecular wire tethers the two biological redox centers at a short distance, allowing electrons to tunnel from PSI to the [FeFe]-H₂ase at a rate faster than the inherent charge recombination between P700⁺ and F_B⁻ (Golbeck, USA). Furthermore, nc-CdTe nanoparticles and [FeFe]-H₂ase were found to spontaneously assemble into complexes that upon illumination transfer photogenerated electrons from core nc-CdTe states to the H₂ase, with low H₂ase coverage promoting optimal orientations for intramolecular electron transport and solar H₂ production (King, USA).

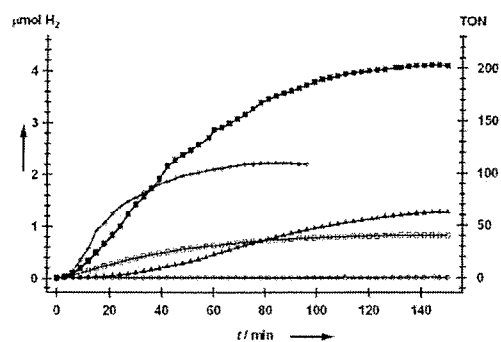


Figure 1. Light-driven hydrogen production by 1 (14 μM , 21 nmol) in the presence of $[\text{Ru}(\text{bpy})_3]^{2+}$ and ascorbic acid (100 mM) in deoxygenated 1:1 DMF/H₂O at 20°C. All samples were irradiated with light in the wavelength range 455–850 nm. H₂ was detected by in situ gas chromatography. ■ = 140 μM $[\text{Ru}(\text{bpy})_3]^{2+}$, pH 5.5; ● = 135 μM $[\text{Ru}(\text{bpy})_3]^{2+}$, pH 6.4; ▲ = 17 μM $[\text{Ru}(\text{bpy})_3]^{2+}$, pH 5.5; □ = 140 μM $[\text{Ru}(\text{bpy})_3]^{2+}$, pH 3.6; ○ = no catalyst 140 μM $[\text{Ru}(\text{bpy})_3]^{2+}$, pH 5.5.

Subtask B (Dark Biohydrogen Fermentation Systems)

- A novel, on-line, recycle fermentation system produced H₂ for over 70 days. This patented device is called a Biohydrogenator and has been connected directly to an anaerobic digester producing both H₂ and methane gas streams (Dr. Nakhla, Canada).
- Researchers detected ATP synthesis in the presence of formate as the sole energy source of an organism. Gene expression profiling and disruption identified the gene cluster

(*fdh2-mfh2-mnh2*) encoding formate hydrogen lyase, cation/proton antiporter and formate transporter, which were responsible for the growth of *Thermococcus onnurineus* NA1 on formate. This work presents evidence for the ability of a single microorganism to grow on formate along with H₂ evolution and ATP generation via a formate dehydrogenase and an energy-conserving hydrogenase (see the figure below). This represents one of the simplest anaerobic respirations described so far that produces H₂ (Korea).

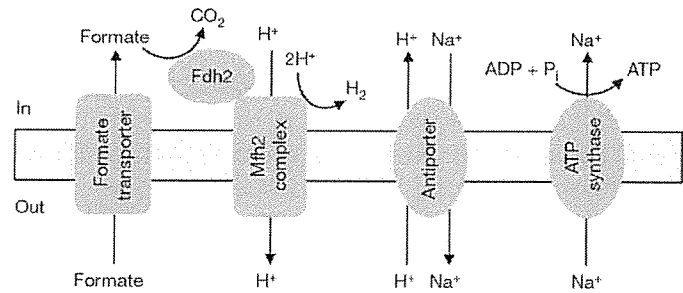
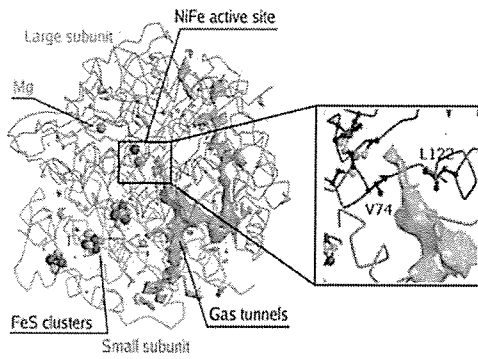


Figure 4 | Proposed mechanism. Diagram shows coupling of formate oxidation to CO₂ and H₂ with the synthesis of ATP in *T. onnurineus* NA1.

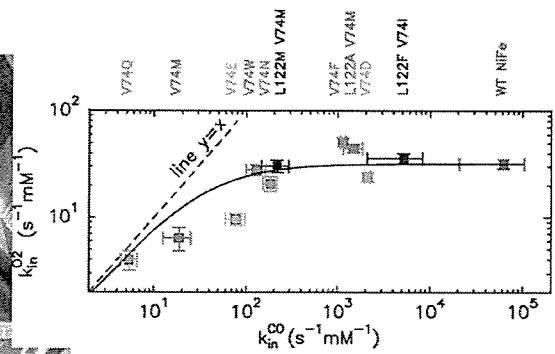
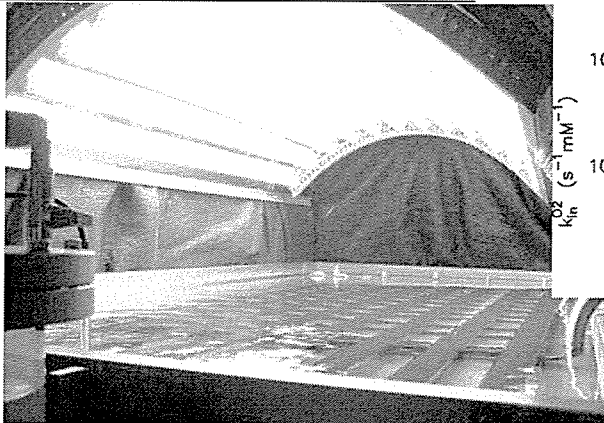
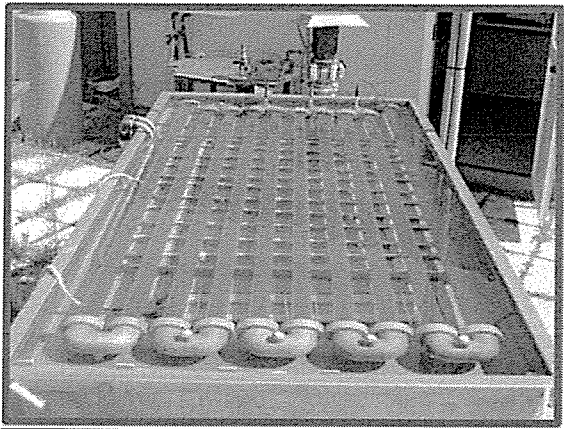
- *C. saccharolyticus* contains only two hydrogenases (a ferredoxin dependent and an NAD-dependent), which makes this bacterium an ideal model organism for study. Microarray approaches provided insight into metabolic bottle necks of biological H₂ production by *C. saccharolyticus* (The Netherlands).
- A heterologous expression system in *E. coli* has been constructed to express the NADP-dependent hydrogenase from the hyperthermophile, *Pyrococcus furiosus*, using 13 genes, including 4 structural genes and 9 maturation genes. Furthermore, functional hydrogenase can be produced in *E. coli* when the same four structural genes are expressed along with a single protease from *P. furiosus*. The methodology to generate a thermophilic NADP-linked hydrogenase in *E. coli* has significant application for use in H₂ production where an excess pool of NADPH is present in the host. Heterologous expression of [NiFe]-hydrogenase has been generally recognized as more challenging due to the heterogeneity of the enzymes and complexity of its maturation machinery (Adams, USA).

Subtask C (Basic Studies of Light-driven Biohydrogen Production)

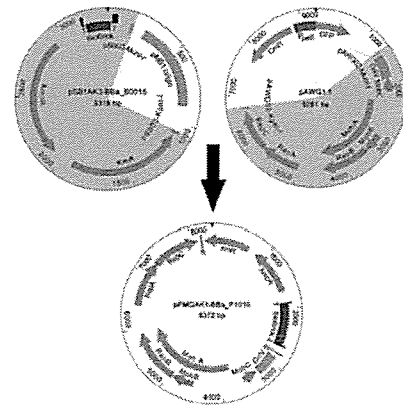
- Improvements in the O₂ tolerance of a [NiFe]-hydrogenase in *Desulfovibrio fructosovorans* has been demonstrated by substituting methionines for V74 and L122 (see figures below) located in the protein gas channel. The recombinant H₂ases exhibit decreases in aerobic inactivation rates and increases in reactivation rates compared to the WT (Rousset, France).



- The feasibility of outdoor H₂ photoproduction in 50L tubular photobioreactors (see figure below, left panel) at maximal rates (but not efficiencies) similar to those observed under laboratory conditions was demonstrated with *Rhodospseudomonas palustris* (De Philippis, Italy).

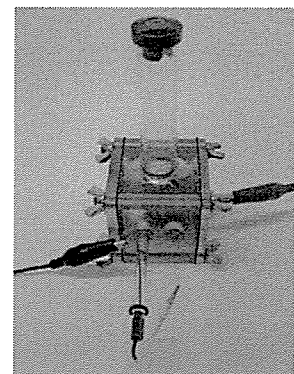


- Outdoor photoproduction of H₂ with sulfur-deprived, *Chlamydomonas reinhardtii* cc-124 cultures was accomplished in 50-110L tubular photobioreactors (see figure above, right panel) at output rates 20% of those found under laboratory conditions (Torzillo, Italy).
- The green alga, *Chlamydomonas noctigama*, was found to express three genes under anaerobic conditions, all of which have strong resemblance to hydrogenases (all other algae express only 2 hydrogenases). However, none of the 3 has been explored in terms of expression under different conditions. This discovery contributes to provide more knowledge about diversity of hydrogenases (Skjånes, Norway).
- A novel DNA-binding protein, CalA, was shown to interact with the regulatory region of *hycC* and acts as a repressor of its transcription in the cyanobacterium *Nostoc* PCC 7120. As a consequence it is possible to regulate H₂ production in this strain by directly modulating the level of CalA and thereby influence the maturation machinery needed to assemble an active hydrogenase (Lindblad, Sweden).
- Molecular tools have been developed (see the figure to the right) that make it possible to design and engineer cyanobacteria using a standardised Synthetic Biology approach. As a result, the first vectors with the capacity to function in many different microorganisms, inducible promoters, ribosomal binding sites, terminators and degradation tags are available to be used in cyanobacterial biotechnology (Huang, Sweden).
- Pilot scale tubular (65-100 L) and panel (4-40 L) photobioreactors have been developed for continuous H₂ production from purple non-sulfur photosynthetic (PNS) bacteria outdoors and contain an internal cooling system (Ieroglu and Yücel, Turkey).
- Continuous photofermentative H₂ production has been achieved on several real world dark fermentor effluents (DFE) in long term stable operations of up to 5 months. The maximum H₂ productivity and yield values obtained were 1.1 mmol/Lc.h and 91% on molasses DFT, and 1.5 mmol/Lc.h and 62% on thick juice DFT, respectively (Turkey).
- Improvements in photobioreactor systems and new mutants have addressed 3 challenges (O₂ sensitivity, an undissipated proton gradient, and inefficient light utilization) limiting algal H₂ photoproduction. Immobilized WT organisms currently exhibit laboratory-scale, light-to-H₂ conversion efficiencies of 1.4 to 2.4% under low levels of artificial light. These values should at least double when all mutations are recombinantly expressed in the same production strain (Seibert and Ghirardi, USA).



Subtask D (Biological Electrochemical Systems)

- High volumetric rates of H₂ production (4L H₂ L reactor⁻¹ day⁻¹) were achieved using a Ni-alloy cathode instead of the usual Pt-doped cathode in a microbial electrolysis cell (MEC) system (Guiot, Canada).
- In electricity-mediated biological H₂ production, acetate is oxidized at a biological anode. (A small amount of electricity input makes H₂ formation from acetate feasible.) The cathode where H₂ is produced can be an inorganic electrode with H₂-



producing capacity or a biological biocathode. The biocathode is composed of relatively cheap materials, at which H₂-producing bacteria adhere. This is important for further development of H₂ production from waste in a complete light-independent process (The Netherlands).

- Nickel powder can be used as a viable alternative to Pt in a MEC (see figure at the right), allowing for large scale production of cathodes with similar performance to systems that use precious metal catalysts (these results are similar to those reported by Canada above). Furthermore, additional studies showed that stainless steel mesh cathodes with performances similar to Pt have great promise for the development of low cost MEC systems for H₂ production (Logan, USA).

Subtask E (Overall Analysis)

- An analysis of primary energy use in Japan is underway, and a goal of 8% (non-hydro) renewable energy has been set for 2030. Energy itself is not seen as much of a problem as the ability to deliver energy (Japan).
- A major report entitled “Technoeconomic Boundary Analysis of Biological Pathways to H₂ Production (<http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/46674.pdf>) and sponsored by the DOE Fuel Cell Technologies Program is now freely available and presents cost projections for a number of potential biological H₂-production technologies (DTI, USA).

Status of Milestones (a list of Task 21 Milestones can be found at the end of this document)

Subtask A (Bio-inspired Systems)

- Sweden reports progress on Milestone 1 in that a relative stable and active H₂-evolving catalyst has been demonstrated.
- France reports progress on Milestone 2 with efficient electron transport and high turnover between a hydrogenase mimic and multi-walled carbon nanotubes under acidic conditions.
- The USA reports progress on Milestones 1 and 2 with efficient light-driven electron transfer established between either a biological or a synthetic primary charge transfer systems and a hydrogenase.

Subtask B (Dark Biohydrogen Fermentation Systems)

- Canada reported progress on Milestones 1, 2, 4, and 5 with various Clostridia and *E. coli* strains.
- Korea reported progress on Milestone 3 with the thermophile, *T. onnurineus*.
- The Netherlands has made progress on Milestones 1, 3, and 5 and reports under specific growth conditions that the H₂ production yield of *C. saccharolyticus* is close to the theoretical maximum of 4.
- Turkey reported substantial progress on Milestone 4 using integrated systems of dark and photofermentation processes with wheat waste solutions, cheese whey wastewater, potato hydrolysate, molasses and thick juice in indoor and outdoor systems.
- USA reported progress indirectly related to Milestone 2 with the demonstration of the heterologous expression of a [NiFe]-hydrogenase with the determination of the minimal number of maturation genes required.

Subtask C (Basic Studies of Light-driven Biohydrogen Production)

- France has made considerable progress on Milestone 3 with the successful engineering of a [NiFe]-hydrogenase with improved tolerance under aerobic conditions.
- Italy reported progress on Milestones 4 and 5 using both photosynthetic bacteria (photofermentation) and algae in outdoor systems.
- Norway reported progress on Milestone 1 by identifying and sequencing three distinct genes in the green alga, *Chlamydomonas noctigama*, that share strong similarities with hydrogenases.
- Sweden reported progress on Milestones 1 and 3 by identifying a novel green alga with high H₂-evolution capacity and Milestone 1 by examining similarities between 3 *Frankia* hydrogenases and 8 other H₂ases from 6 other organisms involve in H₂ evolution. Furthermore, Sweden has addressed Milestone 2 by investigating influences of external factors on H₂ production and H₂ase activities in the cyanobacterium *Synechocystis* and *Anabaena*.
- Turkey reported substantial progress on Milestones 3, 4, and 5 with several strains of PNS bacteria.
- The USA reported progress on Milestone 3 and 5 by improving efficiencies of algal H₂-photoproduction organisms.

Subtask D (Biological Electrochemical Systems)

- Canada reported progress on Milestone 2 with the observation that Ni cathodes can substitute for Pt in MECs.
- The Netherlands has made progress on Milestones 2 and 3 with a microbial electrolytic cell using waste acetate (this requires the input of a small amount of electricity). This demonstrated that integrating dark fermentation with MECs is feasible for maximizing dark, H₂ production.
- The USA reported progress on Milestone 2 with the observation that stainless steel cathodes can substitute for Pt in MECs.

Subtask E (Overall Analysis)

- Japan reported progress on Milestone 2 with an analysis of energy use in the country.
- The USA addressed Milestone 3 by releasing a cost analysis of several biological H₂-production systems.

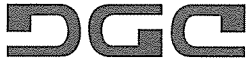
Information Plan—Information Dissemination and Outreach

- Canada is planning a pan-Canadian BioH₂ meeting in conjunction with the USA Fuel Cell Technology (H₂) Program Review in May 2011.
- France has published over 35 papers in the peer-review literature as of September, 2010.
- Italy reported their accomplishments at the 14th International Biotechnology Symposium on September 14-18, 2010, in Rimini, Italy.
- Japan is communicating regularly with other Asian countries including Taiwan, Korea, China, and Thailand to maintain and promote biohydrogen research in this region. Collaboration with the Netherlands on an integrated approach for treating wastewater from a potato chip factory is under way.

- Korea communicates through domestic conferences run by biochemical engineering and H₂ energy societies.
- Outreach in the Netherlands occurs through scientific meetings, Task 21 meetings, publications and the graduation of PhD. students.
- Norway's activities and major accomplishments have been communicated at 3 major international meetings in Europe over the last 7 months.
- Sweden has contributed a review (Dasgupta et al 2010) of recent trends on the development of photobiological processes for the improvement of H₂ production and has graduated several Ph.D. students.
- Turkey disseminated information in presentations at the WHEC2010 meeting in Essen and at both the September ICCE-2010 and the Task 21 meetings in Cyprus.
- The USA disseminates information at major Program reviews held by funding agencies (e.g., DOE Fuel Cell Technologies Program, DOE Office of Science BES and BER Program Reviews, AFOSR Program reviews), presentations at scientific meetings, peer-review and review chapter publications, presentations at Task 21 Meetings, and through international collaborations.

Work Plan and Milestones for the Next 6 Months:

- Canada reports that no major changes are anticipated in work plans over the next six months. The work currently underway is directly relevant to the proposed Milestones of Task 21.
- France will continue work on 5 projects ending in 2010, 5 projects ending in 2011, and 2 projects ending in 2012. Three new projects lasting until 2013-2014 were announced (Algo H₂, Hycofol-BV, and BIOPAC covering the areas of genetic and metabolic optimization of algal H₂ processes, coupled dark and light fermentation processes, and H₂ oxidation biocatalysts, respectively).
- Italy reports that in the next 6 months, it is planned an activity aimed at selecting the best H₂ producers among the purple photosynthetic bacteria belonging to the Culture Collection of the Department of Agricultural Biotechnology for testing outdoors. Italy also plans to continue our experiments with *Chlamydomonas reinhardtii* grown in a 110 litre tubular photobioreactor illuminated with artificial light or with solar light. Cultures will also be illuminated with solar light during day and artificial light at night.
- Japan will prepare a new plan for intensive research on the conversion of biomass to electricity (can be used to produce H₂ by the electrolysis of water) along with other countries, which have appropriate test facilities.
- Netherlands will continue current investigations, and expects to obtain detailed information about the general metabolism of *C. saccharolyticus*. Electricity-mediated H₂ formation will also be studied further, especially H₂ production using microorganisms with cheap carbon electrodes.
- Norway will continue work on exploring the expression of different hydrogenase genes in selected algal species under different environmental conditions and explore their diversity.



- Sweden will continue to explore Bioinspired and Biological systems as previously outlined.
- Turkey will continue investigations concerned with the immobilization of PNS bacteria, microarray and proteomic studies for understanding H₂ and acetate metabolism in PNS, and will complete research on its part of the European Hyvolution Program.
- The USA will continue to explore basic and applied research related to Task 21 Subtasks A, B, C, and D.

Effectiveness of Task Participation:

- Canada reported a number of informal (strain exchanges) and that more formal collaborations have been initiated with various BioH₂ researchers in Turkey as a result of the Task 21 meeting in Cyprus.
- Italy reported that participation in Task 21 facilitated joint outdoor research activities between the groups coordinated by Dr. Giuseppe Torzillo and Prof. Roberto De Philippis.
- Korea reports that Task 21 activities has brought together elements of the Korea Institute of Energy Research; Korea Ocean Research and Development Institute; Ensol Tech. Korea; Sogang University; Sungkyunkwan University; Seoul National University; the Korean Society for Hydrogen and New Energy; and the Ministry of Education, Science and Technology of Korea in various collaborations.
- The Netherlands reports that information obtained about different aspects of biological H₂ formation at Task 21 meetings helps in the design further of new experiments.
- Norway is partnering with Italy and Sweden on a proposal to the Research Council of Norway to collaborate on a project involving H₂ production with microalgae. All 3 partners are Task 21 members.
- Turkey acknowledged the contributions of other Task 21 members (Canada, Japan, Korea, and the USA) for valuable research suggestions to young Turkish researchers during the WHEC-2010 and ICCE-2010 Meetings as well as Dr. Patrick Hallenbeck for sharing strains of *Rb. capsulatus*. A number of Turkish students were able to attend the Task 21 Meeting in Cyprus and gained more global insight into the fields of bio-inspired hydrogen and biological hydrogen production.
- The USA reports international collaborations with other Task 21 countries including Canada, France, Germany, and Italy.

Matters Requiring ExCo Attention:

- Japan recommends that the ExCo encourages member nations to increase research activities in areas appropriate to Task 21.
- The Netherlands recommends that the ExCo be aware of technologies involving direct H₂ production from sunlight and water, indirect formation of H₂ via biomass and waste through dark fermentation, and electricity-mediated H₂ formation from organics produced as waste products of dark fermentations. A balanced research program encompassing all of these technologies is necessary.



- The USA basic research program encompassing Task 21 activities is well funded and robust. However, applied research has had reduced funding over the last 3 years and this has limited R&D progress.

Task 21 Milestones

Subtask A. Bio-inspired Systems.

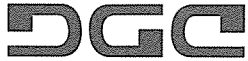
- 1) Select stable and efficient components (enzymes, photosynthetic proteins, etc).
- 2) Promote efficient electron transport between enzymes/photosynthetic proteins and artificial catalyst or chemicals.
- 3) Examine long term hydrogen production by the systems.

Subtask B. Dark BioHydrogen Systems.

- 1) Determine yields of anaerobic fermentations as a function of both genetic and environmental determinants with fermentative bacteria.
- 2) Metabolically engineer fermentative bacteria with improved H₂ production from model substrates and waste waters.
- 3) Examine thermophilic organisms for increased H₂ production.
- 4) Examine and optimize an integrated system incorporating a sequential dark anaerobic and photo-fermentation process to enhance H₂-production efficiency from biomass waste.
- 5) Report on fundamental studies for application to real-life waste treatment.

Subtask C. Basic Studies for Light-driven BioHydrogen Production.

- 1) Report on the diversity of H₂-production (hydrogenase) genes and their corresponding enzymes in microalgae, cyanobacteria, and other suitable organisms.
- 2) Determine the relationship(s) among electron transport pathways, carbohydrate catabolism and hydrogenase activities.
- 3) Improve hydrogen production by genetic engineering, identify salt-tolerant genes, and improve expression of critical genes.
- 4) Design and test innovative concepts for photobioreactor design and sustained exploitation of the metabolic potential of advanced strains for H₂ production. Demonstrate at the pilot scale (50-100 liters) H₂ photoproduction in an outdoor photobioreactor.
- 5) Improve the efficiency of light conversion to H₂ in cultures of photosynthetic microbes by optimizing the geometry of the photobioreactors.



Subtask D. Biological Electrochemical Systems.

- 1) Report on a technological survey of available methods.
- 2) Improve the growth conditions and power generation of current-generating organisms. Examine the durability and efficiency of operation under various environmental and operating conditions.
- 3) Determine the potential of and conditions for application to real-life wastewater treatment.

Subtask E. Overall Analysis.

- 1) Report on societal acceptance of renewable and recyclable energy systems like BioHydrogen.
- 2) Report on combining Task systems and other renewable and recyclable energy systems from an applications point of view, especially for developing countries.
- 3) Report on cost analyses of Bio-inspired Hydrogen and BioHydrogen production.

October 12, 2010