Impact & dessimination SOLAR-H2 final report

EU project number: **212508**

Project acronym: **SOLAR-H2**

Website: http://www.fotomol.uu.se/Forskning/Biomimetics/solarh2/Solarh2.shtm

Project title: **European Solar-Fuel Initiative – Renewable Hydrogen from Sun and Water. Science Linking Molecular Biomimetics and Genetics**

1. Potential impact

Our research will have impact on several levels of importance for social goals, for science and for the European dimension of our research.

Overall impact. Our research has been dominated by basic research bringing in-depth fundamental knowledge (WPs 1-3). This is critical at this stage in the development of these visionary routes for our future fuel production from the renewable resources solar energy and water. A large emphasis on fundamental research was also one expected impact factor in the original call text.

In the bioreactor branch of our project (WP 4) we have also accomplished technical developments concerning photo-bioreactors. These have provided opportunities to validate, albeit at small scale, the concept of photo-biological hydrogen production using genetically designed photosynthetic microorganisms in photo-bioreactors. This has brought our research on photo-biological H_2 production closer to larger demonstration projects, which might be possible in a future research program.

In the biomimetic branches of our program (Artificial photosynthesis, WP 1) the demands for breakthroughs in the basic science are large. The research here has therefore had a very large visionary component being world-leading, at the brink of what at all can be accomplished, at the present stage of this science. Again this visionary concept was mentioned in the original call text where the funding scheme was defined.

Addressing social goals.

Europe depends heavily on outside energy resources – and these are dwindling and their supply can easily be endangered. In addition, many of the present dominating energy systems (energy sources and energy carriers) are connected to environmental and social problems that clearly affect the quality of life in many European areas. In particular this concerns the heavy use of fossil fuels that lead to large pollution problems in many areas, to climate change and fast growing CO_2 emissions. The recent disaster with nuclear power in Japan has increased the worries for large nuclear power programs.

January 25, 2006 the members of the Energy council of the Royal Swedish Academy of Science (13 eminent scientists and industrial leaders) published a full page debate article in a series of main Swedish newspapers. The article was about the energy supply and the huge use of fossil fuels. They wrote (our translation) ….” The question is not *if* we must decrease our demand on oil but *when*. In our opinion it has to happen now! The faster we take action to change to a sustainable system the better for society, the environment and the fight against

poverty on a global scale"…..they continue …" Here we are, researchers, politicians, industrialists and the general public facing an enormous challenge [.....]. There is demand for action based on long term and responsible thinking. We must move forward the frontiers of knowledge and build up capacity in the worlds developed countries and also in the less developed countries."

For each day these lines become increasingly valid and similar texts are now written almost every day in all countries in Europe. We share the fundamental ideas of the authors and the research carried out in SOLAR-H2 shall be seen on this back ground. The dire need to develop new concepts for a sustainable energy supply has during the project period become top-priority on the agenda. In addition, the development of new, non-polluting energy carriers now is a vital interest in most countries. In part the work carried out in SOLAR-H2 and by scientists in SOLAR-H2 has been important for this development in several countries involved. The SOLAR-H (first) and the present SOLAR-H2 networks were early in Europe and in the world and there are now attempts to follow these research paths in several countries.

The intention in SOLAR-H2 was to take on our responsibility and carry our burden in this work. We did this by organizing and carrying out the European research aiming for the production of a Solar-fuel (H_2) from solar energy and water.

These issues were reinforced in the work program for ENERGY.2007.3.5.1: **Fuel production using solar radiation**. Here, the perspective of introducing **hydrogen as an important future energy carrier is one central objective**. There were several important social reasons for this trust in H_2 to become an important energy carrier. These included the worries for the global heating induced by the huge CO_2 formation and release into the atmosphere from the heavy use of fossil fuels. This could be avoided if H_2 came into common use. A second important reason was that combustion of H_2 is likely to lead to lower atmosphere pollution as compared to most options to burn fossil fuels. This would be a major benefit in most cities where heave traffic lead to severe pollution and the development of H_2 driven vehicles is high on the agenda.

The work program identified **photo-biological or biomimetic conversion concepts as a future production mechanism for fuel** as one strategically important area for both medium and long-term research. The goals of SOLAR-H2 were to be found here. In the near foreseeable future, H_2 production will mainly involve production from natural gas. However, even if the available resources are still huge, this is an exhaustible energy source that will not last forever. Production of H_2 from natural gas is also connected to problems with CO_2 release even if these might become possible to control in the future. Therefore, for H_2 to become a dominating energy carrier, production techniques must be developed using renewable sources. This is recognized both world wide and was recognized in the work program.

The strategic objective of SOLAR-H2 was to meet these demands – by production of renewable H_2 from the infinite resources, solar energy and water. This research is complex and consequently long-term. SOLAR-H2 concentrated its resources during the proposed 4 years project period on exploring **two novel ideas.** One of them was developed towards a functional bio-reactor able to demonstrate the concept of H_2 production from solar energy and water.

The impact of our research results in SOLAR-H2 can be divided at two levels. It was foreseen that neither artificial (biomimetic) photosynthesis nor photobiological H_2 production would become important techniques during the project period. Thus, we did not aim for large technical devices that could be tested for delivery of solar derived H_2 to cars and buses. Instead our work was mainly focused on the **necessary** basic research that must be carried out now, for these methods to have any chance to become important in the future. However, this basic research was of a novel kind. SOLAR-H2 did not only seek new results and knowledge because a process is interesting per se. Instead our research had a clear, coordinated target – to create the knowledge basis and real opportunities for our much more far distant goal, the production of a Solar-fuel. It is quickly said but much more difficult to do to synthesize biomimetic complexes that can make H_2 from solar energy and water or to design and improve photosynthetic organisms for the same purpose.

Thus SOLAR-H2 was built with very strong Partners that all were driven by the spirit from basic research but at the same time took on the responsibility to carry out this research with a long-time goal. This is an unusual combination and not always easy to justify within the scientific community. In this respect it was rewarding and helpful that the call text so clearly indicated the demand and expectation for "in depth fundamental knowledge of importance for future development" throughout the text. The researchers in SOLAR-H2 have a proven, outstanding publication record at all levels in research. This continued to be true during the work in SOLAR-H2 and nearly 400 scientific papers were published in mainly high profile research journals. This is an outstanding number and has clearly resulted in a broad and strong international impact from SOLAR-H2 research at all levels in research. The many international lectures on conferences, workshops, invited seminars etc given by the researchers in SOLAR-H2 proves this again and again. During its scientific "life" SOLAR-H2 was simply the best known network in the world in the fields of SOLAR-H2. In the last years a couple of US initiatives have reached the same level of attraction but this rather reflects the fast response to the scientific challenges in the US than a lowered speed or decreased impact of SOLAR-H2 research which still (several months after the formal end of the network) is often acknowledged and cited in talks at leading conferences in the field.

The research in SOLAR-H2 also had a component of technology in WP 4. Here the design of new photo-bioreactors was one of the core agendas. The other key elements in this WP were modeling of photobioreactor performance and organism function and to test novel, improved organisms provided by the molecular biology groups in WP 3. The vision was to demonstrate, on small scale, H_2 production from solar energy directly with a photosynthetic organism. In WP 4 we offered new design principles for the photo-bioreactors. We also aimed to test the first genetically improved microorganisms. Both these ambitions were met achieved during the project period and thereby, this part of the science in SOLAR-H2 could be brought closer to (we cite the call text) "technological knowledge of importance for future development".

Creation of a European research team and a forum for future interactions and concerted efforts. Overcoming European fragmentation.

The concept in SOLAR-H2 was to explore and develop both natural and artificial (biomimetic) photosynthesis. The combination of these two research fields on a European scale was novel and has so far only been attempted (even world wide) in SOLAR-H2.

The task is complex and cannot be achieved by a one European nation alone (there is probably not enough competence in any single nation). At the onset of SOLAR-H2 there were

world leading European laboratories in every sub-field, but the lack of European-scale, concerted research efforts separated the existing expertise. Combination of the abilities in these laboratories, assembled on a continental scale in SOLAR-H2, clearly changed this. A main effect of SOLAR-H2 was the creation of a large, tightly integrated European collaboration that, given it could continue in new generations of networking collaborations, would be most effective to reach our common goal – surely the sum of our collaborative efforts was much greater than the sum of our individual attempts. The competition is presently (spring 2012) extremely strong mainly from the US, and Europe must continue to support and assemble its forces now to remain competitive scientifically and to benefit in the future.

A couple of years before the start of SOLAR-H2 a *young investigator stated "The US were first to the moon, but why should Europe be second to produce an environmentally friendly fuel from sun and water?"* Thus the bearing idea behind SOLAR-H2 was to collect and integrate the best European laboratories in a joint research and development effort with one focus – to make Europe the international leader and patents holder for efficient production of H_2 from renewable resources. SOLAR-H2 assembled the leading groups in Europe, some undisputed world-leaders, in their particular field. In fact, all groups in the world that study the both water splitting photosynthesis and the active site of hydrogenases seemed to be part of SOLAR-H2. Almost all groups in Europe that attempt H_2 production from green algae and/or cyanobacteria were part of SOLAR-H2. In the synthetic field, world leading groups attempting photochemical water splitting and metal-organic hydrogenase mimics were part of SOLAR-H2 that also engaged the leading group in the world studying the genetics of photosynthesis in green algae and cutting edge knowledge in bio-reactor design. During the "life" of SOLAR-H2 several new groups/laboratories started in the field in Europe. In some cases these were started by former SOLAR-H2 collaborators (for example post doctors) and in a couple of cases these have remained attached to SOLAR-H2. They have not had any funding but they have become part of the SOLAR-H2 team and work intimately with groups in SOLAR-H2. This is a very positive outcome from SOLAR-H2 and the spreading of our science to younger generations of researchers is vital.

The multidisciplinary SOLAR-H2 has provided rich options for new interactions, rich training and multi-facet intellectual challenges of our future scientific leaders. Our three research schools (2 summer and 1 winter school) have been very appreciated by the young researchers.

SOLAR-H2 spanned a wide range of fields that had not been integrated before. This concerted, focused and integrated effort has been unique for SOLAR-H2. It succeeded because SOLAR-H2 had assembled the best European expertise, with outstanding reputation in their respective field. The scientific ground has been built, if we succeed, it is highly likely that we can produce H_2 more efficiently than any other foreseeable renewable system. The potential is enormous, the stakes are large and the way may be winding and long. **The formation of SOLAR-H2 was therefore an effort intended to last longer than the actual project period and this is also why SOLAR-H2 involved as many as 12 Partners**.

This contributed directly to the strengthening of the European Research Area. When the science in SOLAR-H2 now can be read off after the project period, the formation of the network itself and the creation of all the new interactions proves to be a second major impact of the program together with the scientific achievements.

European added value - increasing the competitiveness of European research

The primary selection criteria of the partners were (i) the scientific leadership in their research field and (ii) to achieve full coverage of necessary competencies. Some partner groups were extremely large, while others were small. However, they were carefully selected to complement each other: The SOLAR-H2 research teams possessed a very large combined expertise and competence. Our workshops gathered nearly 70-90 participants each time. Many of the partners were driven by the same social empathy: to use their science and give their best to the creation of renewable fuels from solar energy and water.

In addition, we emphasize that already existing collaborations constituted the shoulders we started from. Thus, close connections to groups outside the network itself in almost every European country (and many overseas) provided direct, early and easy access to expertise and techniques we were not directly involved in SOLAR-H2. However, earlier existing collaborations and projects carried out in single laboratories could never have been enough to accomplish the ambitious tasks set out by SOLAR-H. These tasks were too large to be handled by a single laboratory or even in a single nation (all off Sweden, Germany and France have fair-sized national initiatives in this field, explaining the dominant presence from these countries in SOLAR-H2). Therefore SOLAR-H2 was created to assemble Europe´s forces to stay competitive in this area.

The importance of resource and competence concentration of this research has been increased during the project period. In particular from the US where several very big initiatives in our and related fields have been started during the project period. Many large centers, where the Joint Center for Artificial Photosynthesis (JCAP) in California is the largest have completely changed the speed in the research and the complexity in the competitive research schemes. Thus, the added value for Europe from the work in SOLAR-H2 seems clear. It was vital that the proposed assembly of European top laboratories in a collaborative effort like the one proposed in SOLAR-H2 could happen at an early stage - the research envisaged is of long-term character, and had SOLAR-H2 not been started Europe would clearly have lost its edge in this field that rapidly emerges to become a major renewable energy field. The research in SOLAR-H2 was clearly original and world-leading.

After SOLAR-H2, Europe is thus in a good position to hold the lead in this innovative field, if resources are made available again and collaborative efforts can be continued. The potential of our proposed technologies for H_2 production is to explore, but stakes are large and the potential social and economic benefits are enormous. The entire science for solar fuels has moved to higher level thanks to the work in SOLAR-H2. Some tracks will be left behind, others have emerged as good ideas during the project and yet others are now being planned for future networks and research agendas.

2. Dissemination and exploitation of project results; management of intellectual property

Contacts with society – dissemination to the public.

The conversion of solar energy and the availability of renewable energy is a concern of almost all European societies and concerns very many citizens in our countries. This puts a special type of social demand and responsibility on research of the type carried out in SOLAR-H2. Since there are so many interested, the knowledge level is high and the curiosity large also outside the immediate academic and research institutions. In SOLAR-H2 we have met this

interest with a very open and positive attitude to meet and access media and other channels to the general public.

In SOLAR-H2, several of the Partners have used the press and media channels provided by the universities to reach and invite expert and general journalists to interviews and to write articles. The strongest media are radio and television. Accompanying our workshops in Spain and Sweden we have reached these media. In Spain the coordinator and the PI of the Spanish partner participated in a panel interview TV program directly committed to our workshop. During the final workshop in Sweden we brought in a journalist from the Swedish science radio program. The results was a 20 minutes long radio program, broadcast in the Swedish main radio channel P(rogram)1 at peak hours. The content was on solar fuels with interviews of the coordinator, a couple of Swedish scientists and also Partners leaders from several partner laboratories. Doubtless, knowing the popularity of Swedish science radio, there were probably 100 000 listeners or more.

SOLAR-H2 has also created quite large attention from International media and the coordinator has given interviews via Skype and telephone for many journals. Clear high lights are the interviews in Nature (vol 452, 2008) and Scientific American (October issue, 2010), in both the science in SOLAR-H2 was discussed. In the Nature article the coordinator was presented with a photography and SOLAR-H was even mentioned with name while the name was not mentioned in Scientific American unfortunately.

Contacts with research society – dissemination of scientific results. Workpackage 6.

Scientific publications and congresses*.** The publication of our scientific results has followed normal procedures for basic research. We continuously published our results in the best possible ***peer-reviewed journals and at all ***conferences and meetings*** we attended. In total the science in SOLAR-H2 resulted in ca 383 papers; 92 in work package 1, 157 in work package 2, 115 in work package 3 and 19 in work package 4.

Work shops. The work shops in SOLAR-H2 also became extremely useful. The science presented was fantastic and the workshops were visited by 70-90 scientists from the notwork partners each time. This has resulted in an embryo of a conference line in Europe for this type of science. This would be much needed.

***Acknowledgements*.** When the published work was presented the EU contribution to our research was of course properly acknowledged. However, the team leaders and senior staff in SOLAR-H2 have also be pro-active and presented posters and flyers about the science in SOLAR-H2 at many scientific and more “political” meetings (for example conferences about energy supply and similar). In particular this occurred during the first 3 years of the program and the result was that we attracted both media interest but in particular interest from young scientists wishing to enter on or other of the Partner laboratories as student or post doctor. Many times the coordinator has received e-mail asking which group a young scientist should preferentially contact to enter SOLAR-H2. The answer has been to direct the candidate to the best Partners considering the candidates own expertise.

Home page. The home page was important and many students, generally interested and journalists obtained their first contact with our science through the home page.

Details of the dissemination:

The Management Board had the overall responsibility for the SOLAR-H2 dissemination strategy and used use energy and the allotted resources to:

- publication of articles in high level peer reviewed journals such as Proc. Natl. Acad. of Science, USA; Nature; Science; J. Amer. Chem. Soc; Plant Physiology; Biochemistry, etc. *This was essentially achieved even if we did not publish our results in Science there are articles in Nature (Nature, 2011, vol 479, ps 249-252) and all the other Journals where SOLAR-H2 is acknowledged. This includes also Plos1.*
- presentations at European conferences such as the EUROBIC and many other meetings. *This was achieved to an unexpected high extent and the periodic reports contain long lists of meeting where the work in SOLAR-H2 has been presented in lectures and on posters.*
- invite a few, mainly young researchers from outside the consortium to attend SOLAR-H2 workshops. The workshops have also been used to spread our science to for example developing projects in the Netherlands.
- write articles for scientific magazines aimed at the public in several of the partners countries. - articles in magazines aimed for politicians and decision makers in particular at the international level. In particular we aimed for presentation in EU related political magazines like the Parliament Magazine and similar. *This was found to be too costly and the coordinator has turned down most of the offers to buy advertisements in these magazines. Perhaps a budget should be set aside for this in forthcoming networks.*
- articles for the press and other media
- A SOLAR-H2 website was created rapidly and was much used.
- to produce press releases of our main achievements to build up interest. This was accomplished in Spain and Sweden.
- An idea was to present press releases of "better" PhD theses. This has not been found useful and most Partners have not used this format.
- to promote directly or via the coordinator excellent research by junior scientists for national prizes and rewards. This proved useful and Maria Pandelia from Partner 3 won a distinguished price for her Ph D work that was to a large extent part of the SOLAR-H2 work. Dr Pandeli was also a presenter at several of the work shops in SOLAR-H2.

Creating competence for the future. Young investigators.

Most of the young investigators hired by SOLAR-H2 have been Ph D students or post doctors. It has been a core agenda to bring those in contact with the large network in SOLAR-H2 to benefit from the wide range of expertise available. The two SOLAR-H2 summer schools and the SOLAR-H2 winter school were very popular and proved to be a critical asset to expose the young scientists to science, techniques and expertise they normally not meet (in their normal training programs). Our vision has been to educate and motivate, over a period of several years, a new generation of researchers that are aware of social demands, able to communicate to the public and students ideas and research from more than their own specialized field, and interested and welcoming to new ideas from scientists outside their own expertise. We feel that this is one of the main results of SOLAR-H2. The many post doctors and students that have already left our laboratories or will relatively soon leave now when the network has ended will for a long time bring the results and the need for this science toward a large public in many European and other countries. This will be like a prairie fire, once it has now started this will not end soon, instead these young scientists will long after the end of the network spread its ideas and talk about the very collaborative working style and habits in SOLAr-H2.

3.2.6. Exploitation, intellectual property.

Our research was dominated by basic science. Therefore hardly any results have been possible to even try to patent or develop into products over the short 4 year program period.