# Business plan
# Center of Competence / Centre of Excellence:

# Technologies for Sustainable Energy

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# Contents

# Summary



Shifting towards sustainable energy sources is of utmost importance to fulfill the needs of generations to come. This trajectory represents a great societal and technological challenge. The Centre of Competence (CoCo) focuses both on the transition phase of the coming decades and on the elements of a completely sustainable future energy supply system and covers a broad range of technologies in different stages of scientific and technological development. Using sunlight as the ultimately sustainable source of energy, directly by converting it to electricity and/or hydrogen, and indirectly in the form of biomass, is the core theme of the Centre of Excellence (CoE). Sub-themes within the CoE were selected to strengthen fundamental research, but also to enhance knowledge exchange between fundamental and application oriented areas within and over the borders of the 3TU community.

New energy supply systems based on sunlight conversion, are of key interest to support major driving forces of the Dutch economy. Our natural gas resources will desiccate in the next decennia, which will have major implications for our gross national product. The Swedish government has recently announced that it strives to completely eliminate Swedish dependence on fossil fuels. In order to eliminate or reduce this dependence, fundamental research is of paramount importance as today simply no technology exists that supports a sustainable and reliable energy supply. Hence, fundamental breakthroughs are required, both to allow for a sustained economic development by reducing the dependence on energy supply from abroad and to reduce greenhouse gas emission effects. For the near future both issues are particularly relevant to the Netherlands. Each of the three Technical Universities has an internationally recognised position in selected topics in fundamentally oriented energy research. With a fast integration of these research efforts a strong third pillar is created next to public organisations (e.g. ECN) and industry (e.g. Shell, Gasunie) that are responsible for application oriented research and product development in the Netherlands. Top level academic research will enable the Dutch industry to maintain and expand the leading role it has taken in the transition towards a sustainable energy supply. The need for scientific research on technologies for sustainable energy is underlined by a recent report of the KNAW[1].

Major topics for research described in this proposal are materials and methods for efficient utilization of solar energy conversion to electrons and hydrogen, for storage of these energy carriers in lightweight materials, batteries and supercapacitors, for fundamental improvements of fuels cells, and for using these in integrated, efficient devices. For the medium and long term we foresee a prominent role for energy derived from biomass as well. Here the concept of biorefinery for the production of gaseous and liquid energy carriers as well as the efficient utilization of these biofuels in clean combustion technology are important factors in the suppression of $CO_2$ emissions and in security of fuel supply.

The total package of research proposed here is aimed to stimulate further developments in industry, both in large companies such as Shell and Philips, as well as in Small and Medium Sized Enterprises and start-up companies, fostered by the incubator programs at the three technical universities.

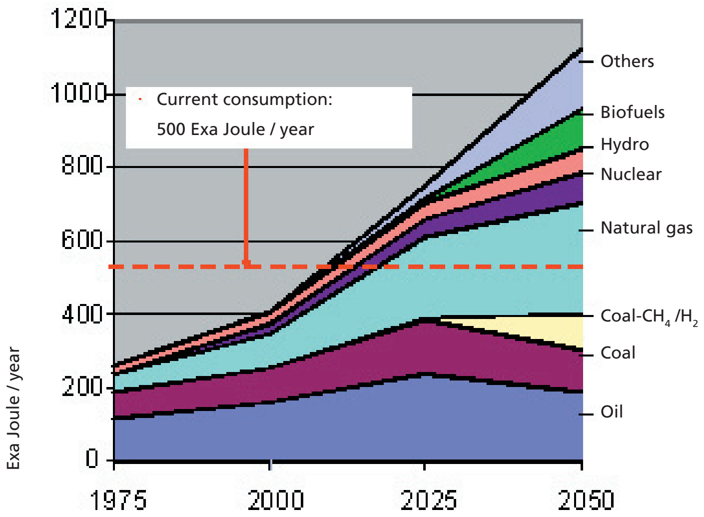
[1] Voorstudie Wetenschapsverkenning Duurzame Energieconversie; Werkgroep onderzoek duurzame energieconversie, Koninklijke Nederlandse Akademie van Wetenschappen, October 2005.

# Introduction



Energy scenarios (e.g. provided by Shell, IEA, EU) project that the world's annual energy consumption will increase enormously in the time span from now to 2050 (from 500 to 1000 - 1500 Exa Joule, see Figure below). These scenario studies also forecast that the increase in the energy consumption can only be dealt with by diversification of the production system, thus by including energy from sustainable sources. By the year 2050, ca. 500 Exa Joule of energy per annum (the total current consumption) has to be produced from sustainable sources in order to fulfill the needs of that generation.

Typical example of an energy scenario (Primary energy demand in Exa Joule per annum, Shell's "Spirit of the coming age" scenario)




Shifting from fossil to sustainable sources not only secures the world's energy supply, but will also result in a much lower load on the environment (e.g. $CO_2$). The progress towards a sustainable energy supply is without doubt one of the biggest challenges that mankind ever faced. Consequently, the subject should be placed with top priority on the agenda of national and international governments.

This Centre of Competence (CoCo) covers the transition phase of the coming decades and the elements of a completely sustainable future energy supply system, with a broad range of technologies in different stages of scientific and technological development.

The Centre of Excellence focuses on sunlight as ultimate sustainable energy source, both directly by converting it to electricity and hydrogen, and indirectly via the growth of biomass. Capturing only a very small percentage of the sunlight radiated to the earth (< 0.1%) will be sufficient to generate enough energy for generations to come. The theoretical limits of sunlight utilization are currently far from being met. Important scientific breakthroughs are therefore required to use sunlight to its full potential and to transport, store and utilize the derived products (electrons/power, fuels, chemicals) as efficiently as possible.

Two central themes have been selected:
1. Sunlight conversion to electrons and $H_2$, including storage and utilization of the products.
2. Biomass conversion to transportation fuels with heat and power as by-products.

# Part A
# Centre of Competence

# 1 Contact



| | |
|---|---|
| Name | University Research Group on Sustainable Energy Technologies |
| Acronym | URGENT |
| Contact person | prof. dr. ir. T.H.J.J. van der Hagen |
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# 2 Chairs and research areas



In the selection of research areas for the Centre of Competence, the boundary was drawn around the exploitation and use of sustainable energy sources, storage of energy carriers, and energy conversion and distribution technology (new technology and efficiency improvement of existing technology). The focus has been directed towards energy supply and not to end-use in order to maintain coherence. Therefore, areas such as chemical process optimization and energy savings (in the built environment) have been left out.

The Centre of Competence focuses both on the transition phase of the coming decades and on the elements of an ultimately sustainable energy supply system in the more distant future. This implies a broad coverage of technologies in different stages of scientific and technological development. In addition to the availability of new technology, public perception and acceptation, international politics and market developments play an important role in the implementation of new opportunities. As a consequence, research towards socio-economic effects of the energy transition is included in the centre's activities.

This centre will be established with the ambition to become the leading university centre on sustainable energy technology development and education in Europe. Especially the almost complete coverage of all major technologies, for many of them with leading scientific positions, makes the centre unique. External communication is therefore an important issue. Currently the research areas are quite dispersed, and rather hidden to society. With a professional communication strategy, including a web-site, brochures and events, more transparency is pursued for knowledge transfer. Within the 11 research themes (appendix 1), scientific collaboration between the universities will be further strengthened. At present, it is clear that a mix of energy conversion options will be needed to guarantee sustainable energy supply. Which options will be part of the ultimate mix is not clear, yet. Development of alternatives until some major options prevail requires a broad research domain and thus a large centre of competence. In some areas scientific cooperations between groups can and will be pursued. More generally, interaction between prominent specialists in the various domains is believed to be essential to evaluate emerging opportunities for the energy transition. In doing so, extra dynamics is introduced to set the priorities for future research in the centre. Also, the centre has the potential to become an important partner for policy development with respect to sustainable energy, in- and outside the Netherlands.

Appendix 1 lists the chairs that participate in the Centre of Competence along with the corresponding 11 research areas.

# 3 Contributing (>50%) research institutes and research schools



| | |
|---|---|
| DISE | - Delft Institute for Sustainable Energy |
| DUWIND | - Delft University Wind Energy Research Institute |
| IMPACT | - Institute of Mechanics, Processes and Control-Twente |
| SKI | - Schuit Institute of Catalysis |
| CPS | - Centrum voor Plasmatechnologie en Straling |

# Part B
# Centre of Excellence

# 4 Contact



| | |
|---|---|
| Name | SUNlight utilization for Novel Energy Technologies |
| Acronym | SUNNET |
| Contact person | prof. dr. J.W. Niemantsverdriet |
| Address | TU-Eindhoven |

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# 5 Participating chairs



**University of Twente**

| **Professor** | **Chair** | **Visitation scores** |
|---|---|---|
| prof.dr.ir. W.P.M. van Swaaij | Thermochemical conversion of biomass | 5; 4; 5; 4; 1998 |
| prof.dr.ir. L. Petrus | Chemical conversion of Biomass | Leading scientist Shell |
| prof.dr.ir. Th.H. van der Meer | Thermal engineering | 4; 3; 5; 4; 2000 |
| prof.dr. H. Rogalla | Low temperature physics | 4.5; 4; 5; 4.5; 2004 |

**Eindhoven University of Technology**

| **Professor** | **Chair** | **Visitation scores** |
|---|---|---|
| prof.dr.ir. R.A.J. Janssen | Molecular materials and nanosystems/ organic solar cells | 4; 4; 4; 5; 2002 |
| prof.dr.ir. M.C.M. van der Sanden / prof.dr.ir. R.J.C. van Zolingen | Plasma technology and solar cells | 4; 4; 4; 4; 1996 (prof.dr. D.C. Schram) |
| prof.dr. R.A. van Santen / prof.dr. G.J. Kramer / prof.dr.ir. P.H.L. Notten | Molecular heterogeneous catalysis; Electro catalysis, Electro chemistry | 5; 5; 5; 4; 2002 |
| prof.dr. L.P.H. de Goeij / prof.dr.ir. R.S.G. Baert / prof. dr. L.E.M. Alden | Combustion technology; Automotive technology | 4; 4; 4; 4; 2000 |

**Delft University of Technology**

| **Professor** | **Chair** | **Visitation scores** |
|---|---|---|
| prof.dr. L.D.A. Siebbeles / prof.dr.ir. S.J. Picken | Opto-electronic materials; Nanostructured materials | 4; 3.5; 4.5; 5; 2003; 4; 4; 4; 4; 2002 |
| prof.dr. G.J. Kearley | Neutron physics | 3.5; 4.5; 4; 4; 2003; |
| prof.dr. J. Schoonman | Inorganic chemistry | 4; 4; 4; 4; 2002; |
| prof.dr. J.A. Moulijn | Catalysis engineering | 4; 4; 4; 4; 2002; |
| prof.dr.ir. P.J. Jansens | Separation technology | 4; 4; 5; 5; 2000; |
| prof.dr.ir. L.A.M. van der Wielen/ prof.dr.ir. M.C.M. van Loosdrecht/ prof.dr.ir. J. Pronk | Bio-separation technology; Biological recycle and environmental biotechnology; Microbiology | 5; 5; 5; 4; 2002; 5; 5; 5; 5; 2002; 5; 4; 5; 5; 2002; |

# 6 Sub-themes of the CoE



Whereas the Center of Competence covers technologies and social studies for transition to sustainable energy supply on the long and medium term, the Centre of Excellence focuses on one of the most promising areas for our ultimate sustainable energy supply system: the utilization of sunlight at its full potential. Today, our energy economy is based on fossil fuels: the 'Carbon Valley'. In a future 'Sun Valley', the rising energy demand of mankind (500 Exa Joule per annum now, 1000-1050 Exa Joule per annum in the near future) is met by 'tapping' solar energy (influx is ca. 60000 Exa Joule per annum), which is ultimately sustainable. Here, major scientific breakthroughs need to pave the way to cost effective applications. Two central themes were distinguished having a strong common research agenda and that can well be covered with combined effort of the three Technical Universities. Moreover, these themes are highly relevant within the framework of Dutch knowledge and industrial infrastructure.

1. Sunlight conversion to electrons and $H_2$, including storage and utilization of the products, with the research topics:
- Solar cells
- Photocatalyis
- Energy storage
- Hydrogen fuel cells

2. Biomass conversion to transportation fuels with heat and power as by-products, with the research topics:
- Biorefinery
- Utilization of biofuels

# 7 Sub-themes of EU FP-7 covered by the CoE



| Theme | Activities |
|---|---|
| Energy | - Hydrogen and fuel cells<br>- Renewable electricity generation<br>- Renewable fuel production |
| Transport | - The greening of surface transport |
| Food, Agriculture and Biotechnology | - Life sciences and biotechnology for sustainable non-food products and processes |
| Nanosciences, Nanotechnologies, Materials and New Product Technologies | - Materials<br>- Integration of technologies for Industrial applications |

# 8 Top EU research groups for the CoE themes



| Sub-Theme | Top EU-research groups |
|---|---|
| Solar cells | - prof. dr. James Durrant, Imperial College , London, UK<br>- prof. Serdar Sariciftci, Linz University, Austria<br>- prof. dr. W. Sinke, ECN, Petten |
| Photocatalyis<br>Energy storage<br>Hydrogen fuel cells | - prof. Dr. R. Bormann, Dept. Materials Science and Technology Hamburg University of Technology<br>- prof. Dr. L. Schlapbach, CEO of EMPA (Swiss Federal Lab for Materials Science and Technology) and Full Professor of Physics at the Ecole Polytechnique Fédérale de Lausanne.<br>- prof. Dr. M. Grätzel, Ecole polytechnique fédérale de Lausanne Institut des sciences et ingénierie chimiques EPFL, Lausanne (also solar cells)<br>- prof. Dr. M. Ch.Lux-Steiner, Hahn-Meitner Institut Berlin |
| Biorefinery | - prof.dr. J. Nielsen, Center for Process Biotechnology, Technical University of Denmark, Lyngby, DK<br>- prof.dr. A.V. Bridgwater, Aston University, Bio-Energy Research Group, Birmingham, UK<br>- prof.dr. H. Hofbauer, Vienna University of Technology, Institute of Chemical Engineering, Vienna, Austria |
| Utilization of biofuels | - FEV Motorentechnik GmbH, Neuenhofstraße 181, 52078 Aachen, Germany, www.fev.com<br>- Iskender Gökalp, Directeur Laboratoire de Combustion et Systemes Réactifs-LCSR, CNRS, France |

# 9 Chairs to be acquired from CE-budget



| location | chair area |
|---|---|
| TU/e | Inorganic materials chemistry, aimed at photovoltaic conversion, hydrogen storage, batteries and fuel cells |
| TUD | Integrated sustainable energy systems for mobile applications |
| | Solar cells based on novel materials and new fundamental concepts |
| | Photocatalysis for chemical synthesis, photocorrosion, electrochemical cells and photocatalysis reactors |
| UT | Materials for efficient energy transport and storage |
| | Thermal and chemical conversion of biomass |

Section 17 gives a detailed overview of the requested funding, including positions for assistant professors and major equipment, while further motivation for the funding is included in Section 11.

# 10 Societal relevance translated in 'technical dreams'



The central mission of SUNNET is to provide fundamental breakthroughs for the exploitation of solar energy and thus liberate our society from its vulnerable fossil fuel chains. As a handle to the corresponding research agenda, more specifically, the following goals are leading in this Centre of Excellence. Here the technical dreams are presented in summarized form; in appendix II more details are given.

**Cheap, highly efficient solar cells**
The current generation of solar cells is far too expensive to provide a large scale contribution to our energy needs. Moreover, their production yields greenhouse gas emissions, that are only balanced after 4-7 years of electricity production, and the efficiency is low(15-20%). One of the most challenging R&D areas of our time is to develop a new generation solar cells with cheap materials, a minimum environmental load during production, and a much higher efficiency. The resulting kWh-price must be competitive with alternative electricity generation to facilitate market conform introduction.

**Solar reactors for cheap energy carrier production from water and carbon dioxide (photocatalysis)**
Hydrogen production from sunlight and water with solar panels and electrolysers is expensive. Instead, highly efficient, light sensitive catalysts will be developed in transparent reactors to produce hydrogen and methanol much more cost effectively.

**Solar energy available at any time, any place**
Electricity and hydrogen storage and transport provides the link between solar energy generation and energy use in static and mobile applications, anywhere. The tandem of fundamental research towards (sub-)molecular interactions and technology development can deliver the breakthroughs for new, high capacity batteries, cheap, light weight hydrogen storage devices, and lossless electricity transport via superconductivity.

**Solar energy for emission-free transportation**
Transportation is one of the foremost energy consuming sectors. Solar energy stored in hydrogen, is the ultimate sustainable source for zero-emission vehicles. New (intermediate temperature) fuel cells, integrated with small, high capacity hydrogen and electricity storage systems is a most promising power source, requiring still a major R&D effort.

**Biorefinery for the production of transportation fuels**
There are already some biomass based processes operational. However, generally these processes cannot compete economically with their fossil counterparts, because yields of target products are not maximized and by-products have often a very low or even a negative value. A bio-refinery is an integrated concept aiming at full utilization of biomass, in which different fractions of biomass are converted in large-scale plants (economy of scale) or in standardized small-scale units (economy of numbers) in an economically optimal product slate around transportation fuels by a variety of chemical, biological and thermal processes However, the conversion processes necessary and their integration to realise the biorefinery are in an early stage of development or have not been invented yet.

**Utilization of Biofuels**
Within the biorefinery concept new bio-based fuels will be developed. On the other hand, current research activities for the next generation of new engines and gas turbines for the coming 30 years are directed towards new ultra-clean and ultra-efficient engines. These two developments have to be tuned in order to achieve a seamless acceptation of biofuels in next generation prime movers.

# 11 Corresponding R&D agenda & new CoE chairs



## 11.1 Solar cells

The theoretical energy conversion efficiency of a standard silicon based solar cell is limited to approximately 40 %, with the major loss of energy being due to conversion of the incident photon energy into heat. The limited efficiency and high production costs make the development of improved solar cell concepts essential. The 3-TU research program will focus on the development of the next generation solar cells, as well as on integrated devices to achieve higher efficiencies in the shorter term. For the next generation solar cells, a combination is required of fundamental research towards energy transfer from photons to electrons in relation to material structure, and technological solar cell development. The co-operation between Eindhoven and Delft will be strengthened by intensifying fundamental research (Delft – optoelectronic properties, structure and dynamics) on novel materials developed in Eindhoven. Key research items are:

**Next generation solar cells**
- Improved utilization of the solar spectrum in layered multi-component PV systems, including organic and inorganic materials
- Enhanced conversion efficiency of silicon based solar cells by developing new silicon based materials and solar cell structures
- Enhanced conversion of photon energy into electrical energy (rather than heat) by generating multiple charges per photon or extraction of hot carriers
- Improved charge transport efficiencies in nanostructured solar cells
- Hot carrier solar cells to prevent conversion of solar light into heat

**Development of integrated devices**
- Solar spectrum conversion for that part of the solar spectrum that is difficult to use directly via photo-luminescent layers
- Direct conversion of the infrared part of the solar spectrum for heating

| **Existing chairs** | |
|---|---|
| Siebbeles, Picken, Kearley (TUD) | dynamics of photo-excited states and charge carriers in relation to material structure (fundamentals); |
| Van der Sanden, Van Zolingen, Janssen (TU/e) | novel materials and layered structures for photovoltaic applications;<br>novel devices based on such materials;<br>cheap production of thin layers for solar cell applications; |

| **New CE-chair** | |
|---|---|
| Full-time chair (TUD) | prototyping of new solar cells based on new materials and fundamental concepts; |

## 11.2 Photocatalysis (sustainable hydrogen production)

In terms of (hydrogen) production, direct photo-electrolysis, with nano-structured photocatalysts splitting water under illumination with sunlight is the Holy Grail of electrochemistry. The development of highly efficient photocatalysts is required, as well as reactors with optimal light absorption. The design rules for conventional chemical processes have to be adapted to photocatalytic processes. Stability against unwanted side reactions (photocorrosion) is also of great importance.

For the development of efficient, low cost processes, key issues in photocatalysis are: the transport of photo-excited carriers, their recombination, relaxation through electron-phonon coupling, and localization on photo-catalytic centers. In addition knowledge and control over photocorrosion and the separation of hydrogen and oxygen is required. In general we will use preparative techniques, first-principles design and experimental validation for most aspects of this work. Nano≠structured materials have unique characteristics to cope with these challenges.
Additionally, fundamental insight in the processes occurring physically inside the materials as well as the chemical interactions of reactants and products with the catalytic surfaces, preferably supported by mathematical modelling, is essential to rationally design novel nano-structured materials and reactors.

| | |
|---|---|
| **Existing chair** | |
| Moulijn, Schoonman, Picken (TUD) | photoelectrolysis, photocatalysis, reactor design;<br>Synthesis, reactor construction and validation |
| **New CE-chair** | |
| Full-time chair (TUD) | Mechanisms of photocatalysis, photocorrosion, electrochemical cells.<br>Fundamental studies and modelling |

## 11.3 Energy storage

The ideal hydrogen-storage material is a cheap, lightweight host that is optimized for its hydrogen interaction and – capacity, such that it can be used for rapid and reversible storage and recovery under the wider range of conditions that are made possible by integration with an intermediate-temperature fuel-cell.

For electron storage lithium-ion batteries and supercapacitors (e.g. for transport applications) require a breakthrough in the power they can deliver. For batteries this can be obtained by nanostructuring, and then investigating the materials characteristics, partial supercapacitor behaviour, and electrolyte stability. A better understanding of the interactions and dynamics of hydrogen molecules, protons, and lithium ions in energy storage and conversion materials is vital to achieve breakthroughs. To arrive at technically feasible systems, as required for transport applications, new device management systems (DMS) must be developed to control energy flows. Also, the control of energy flows to more integrated level (including e.g. fuel cells) requires new modeling and simulation tools.

Electrical energy can be stored by the use of superconductors nearly lossless in e.g. underground toroidal magnets as magnetic energy over a long amount of time, and it can be released very quickly. Such storage could be located inside a liquid hydrogen storage vessel. It would combine hydrogen as excellent cooling liquid with high chemical energy density, with the high electromagnetic energy density of superconducting magnets. Whereas magnetic storage could be used for the quick-response energy demand, the liquid hydrogen storage would be available for small fluctuations in the basic energy demand. Recent developments (e.g. superconducting cables and storage in strong magnetic fields) point towards an enormous potential for applications 20-50 years from now. In the field of materials and systems a lot has still to be done, but demonstrators already show the feasibility.

| | |
|---|---|
| **Existing chairs** | |
| Schoonman, Kearley, Picken (TUD) | Gas phase storage in catalyzed light metal hydrides and large surface area materials like MOFs and clathrates; Synthesis design and validation. Lithium-ion electrodes and electrolytes, nanopowder synthesis and processing |
| Kramer, Notten, van Santen (TU/e) | Electrochemical storage in light metal hydrides; computational modeling; H-storage |
| Rogalla (UT) | Low temperature physics |
| **New CE-chairs** | |
| Full-time chair (UT) | Materials for efficient energy transport and storage. |
| Full-time chair (TU/e) | See under 11.5 |

## 11.4 Hydrogen fuels cells

For decentralized electricity generation based on hydrogen as for mobile applications, a major research effort is still required to develop robust, low cost fuel cells with a considerable lifetime. To achieve high overall energy efficiencies, the integration of system functions ($H_2$ storage and use) is an important issue.

At fuel cell level, the general challenge is to develop new electrolyte membranes (intrinsic proton conduction, high temperature resistance) and reduction of costs by using less noble metals. Stable electrodes that are less sensitive to poisoning must be developed.
An important focus is on new intermediate-temperature fuel-cells (150 – 250°C), having a number of potential advantages. Not only do they reduce catalyst poisoning, but also they are much easier to cool than low-temperature fuel cells due to the greater temperature gradient. Further, their excess heat can be used to facilitate the liberation of hydrogen from its storage material. However, they require a breakthrough in ionic conductivity, which has been recently shown to be feasible with nanostructured superprotonic conductors.

**Existing chairs**

| | |
|---|---|
| Kearley, Picken, Schoonman (TUD) | Design, synthesis and validation of nanostructured proton electrolytes |
| van Santen / De Bruijn (TU/e) | Fuel cell catalysts |

## 11.5 Integration of the above areas

The items in the above chapters have a strong common research agenda, especially at the fundamental level for understanding interactions and dynamics at the (sub-)molecular level (hydrogen molecules, protons, lithium ions, etc.) Expertise, preparation and characterisation of materials, etc., needed to address the challenges and breakthroughs is present, but dispersed across the 3 TUs. In order to establish a true Centre of Excellence, there need to be binding elements that link not only the pure research aspects, but also link these to the technological challenges and opportunities as each of these develop. This is important for the core activity, as well as for identifying spin-offs and niche applications that may be worthy in their own right, and may also guide the way to large-scale applications. Two chairs are applied for that especially address the strengthening of an integrated approach at a fundamental and applied level.

| new CE-chairs | | remarks |
|---|---|---|
| Full-time chair(TU/e) | Inorganic materials chemistry | 1 |
| Full- time chair (TUD) | Integrated sustainable energy systems for mobile applications | 2 |

**Remarks**

1. TU-Eindhoven intends to establish a strong disciplinary oriented chair in inorganic materials chemistry, which aims at novel materials for solar conversion, photocatalysts, hydrogen storage, batteries, supercapacitors and fuel cell systems. Such a chair would provide an excellent centre of mass for a coherent multidisciplinary approach to solar conversion and storage of hydrogen and electricity (i.e. materials for electrochemistry, fuel cells and photocatalysis) and connects activities that are going on in this area, both in Eindhoven and Delft, such as material synthesis, electrochemistry, spectroscopic and structural characterisation and computational methods.

2. Zero-emission transport has been identified as a strong issue to integrate the areas of energy storage and hydrogen conversion with the need for compact, efficient on-board hydrogen storage, economic fuel cells and high power batteries. Moreover, a clear link is provided with economic interests and corresponding parties at a national level. This chair is a binding element for fundamental and applied research areas in Delft and Eindhoven, and will play an important role in long-term valorisation.

The two chairs complement each other in a chain-of-knowledge approach where Eindhoven strengthens the fundamental development of new materials and Delft the application of such materials.

## 11.6 Bio-refinery

**Yield improvement in fermentative ethanol production from lignocellulosic biomass**
Full utilization of lignocellulosic biomass towards biofuels and biochemicals is the Holy Grail in the biomass-to-energy theme. The various (enzymatic, thermochemical) hydrolysis processes yield feedstocks containing hexoses (which can be readily fermented towards ethanol and other biochemicals) but also substantial amounts of 5-carbon sugars (the pentoses xylose and arabinose), sugar acids, fatty acids, furfural etc. Some (xylose) can recently, but most others cannot yet be fermented by, or are toxic for the industrial "workhorse" S. cerevisiae. Novel, integrated concepts in the CoE-based work for fast and high yielding fermentation concepts will be developed on the basis of challenging, more oxidized feedstock compounds such as uronic acids. A typical target product is ethanol, but also the direct production other bulk biochemicals (monomers, solvents) and potentially also diesel range derivatives are important goals.

**Utilization of wet and diluted biomass streams**
While dry biomass can be utilized in existing entrained flow gasifiers, wet and diluted biomass streams need intense and complex processing. Nevertheless, they are considered as very interesting feedstocks because of their low cost. By utilizing these streams, cheap sustainable end-products (hydrogen, synthesis gas, SNG, biocrude) and reactants for other conversion units in the bio-refinery ($H_2$ for deoxygenation of bio-liquids) can be produced. The development of technology for these conversions is a challenge, because the processes run at extreme conditions (400 – 600 $^{o}$C, 300 bar) and should be able to cope with catalysis under fouling conditions.

**Advanced liquefaction methods**
Due to logistic reasons and difficulties, resulting in high costs, associated with the processing of solid feedstock, many current biomass-based technologies are not compatible with their fossil counterparts. Liquefaction of solid biomass makes biomass transport, storage and processing cheaper and easier. To this end, two processes will be studied:

- Pyrolysis, in particular the optimization towards energy densification of the product and the downstream upgrading processes of pyrolysis oil (deoxygenation), and closing the mineral balance at the oil production location.
- Development of organosolv: solving biomass in biomass-based solvents. Both fermentative and thermochemical routes will be studied for the production of such solvents. In addition, the potential of ionic liquids for processes based on extraction of biomass will be considered.

**Co-processing of biomass in mineral oil refineries**
The possibility of co-processing biomass in a mineral oil refinery would significantly lower capital investments for biomass utilization and offers guaranteed markets for the products. For biomass as such this is however currently not possible. To enable this route, liquefaction (see above) and deoxygenation of biomass is required. For the development of cheap deoxygenation technology for bio liquids, integrated front-end research on catalysis and process technology is necessary.

**$CO_2$ sequestration**
If combined with $CO_2$ separation and storage (sequestration), biomass based production processes will actually lower the $CO_2$ content in the atmosphere. Optimal separation technologies have to be selected and looking for new ways to store $CO_2$ efficiently and long-lasting opens a completely new research line.

**Integrated bio-refinery concepts**
In this research line the knowledge concerning individual conversion processes (see list above) will be merged to establish cost effective bio-refinery concepts for selected feedstocks. These bio-refinery concepts, consisting of both biochemical (for fuels and chemicals) and thermochemical (for fuels and power) conversion units, will be analysed with system studies and will be validated experimentally at the smallest representative scale.

| | |
|---|---|
| **Existing chairs** | |
| Van Swaaij (UT) | Thermochemical conversion of biomass |
| Petrus (UT) | Chemical conversion of biomass |
| Van der Wielen (TUD) | Bio-separation technology |
| Van Loosdrecht (TUD) | Biological recycle and environmental biotechnology |
| Pronk (TUD) | Microbiology |
| Jansens (TUD) | Separation Technology |
| **New CE-chairs** | |
| Full-time chair (UT) | Thermal and chemical conversion of biomass |
| Full-time chair (TU/e) | Feedstock Innovation Technology |

For the new generation of thermal and chemical conversion processes within the biorefinery concept a full professor is required. Process development, chemical reaction engineering, and chemistry will be focussed in this chair on thermochemical conversion routes from the present embryonic state to integral process steps. The new full professor will ultimately take over from the present part-time professor and expand the present activities, creating a new chair that covers the whole area of thermal and chemical biomass conversion processes. In the added value section more details are given on the corporation of the 3TU's in this field.

## 11.7 Utilization of biofuels

**Biofuels utilization in combustion engines**
Promising conversion techniques based on homogeneous combustion instead of flaming combustion, (like homogeneously charged compression ignition), will be studied. It is interesting to note that this development currently drives research institutes and industry (SWRI in the USA and Volkswagen, DaimlerChrysler and Shell in Europe) towards a redefinition of the fuel-formulation to optimize this concept in the new generation of engines. The characterization of the combustion of these new fuels in special combustion equipment (burners, engines and combustion vessels) will become essential and will be studied in cooperation with TNO Automotive and the automotive industry.

**Biofuels utilization in gas turbines**
Utilization of gaseous or liquid biofuels in gas turbines opens a number of unresolved items on flame stability, combustion efficiency, thermo-acoustic stability and emission reduction.
Parting from liquid biofuels a totally new concept is the integration of gasification, pre-mixing and gas turbine firing. It is interesting to note that Siemens is highly interested in this new development. Like in biomass based production processes $CO_2$ sequestration is an interesting topic leading to a positive $CO_2$ balance. Here the research agendas of biorefinery and utilization of biofuels meet. The concept of flameless oxidation for gas turbine combustion with biofuels is certainly worthwhile to follow, because of its high potential in both thermo-acoustic stability and in the expected further reduction of $NO_x$-emission.

| **Existing chairs** | |
|---|---|
| van der Meer (UT) | Thermal Engineering |
| de Goeij (TUe) | Combustion Technoloy |
| **New CE-chair** | |
| Assistant professor (UT) | Biofuels utilization in gas turbines |

# 12 Master education



The 3-TU graduate school Sustainable Energy Technology (SET) is in the phase of accreditation by NVAO as a national MSc program[2]. Currently, slightly different courses are provided at the 3 locations, which will be integrated in the near future. In total, 78 professors and staff members contribute to the courses. All areas from the Centre of Competence are covered (appendix 1), with the exceptions of nuclear energy (fission) and clean and efficient fossil. (More explicit) inclusion of these themes (relevant as transition technologies) is under consideration. In addition, nuclear fusion – to be covered by FOM-Rijnhuizen – may be an interesting addition.

In order to encourage knowledge transfer and learning, Ph.D. students active in biofuels (utilization) meet each other at an annual national conference, which was held at Shell Amsterdam (2001), Twente (2002), Eindhoven (2003), Delft (2004) and Wageningen (2005). It is proposed to organize such an event also for Ph.D. students active in the theme solar energy – photocatalysis – energy storage – fuel cells. The two events can be combined in the form of a Summer School into a top-quality knowledge exchange platform. Visiting professors will be invited to teach in specific SET subjects, so that M.Sc. students also benefit. To enhance cooperation between the 3 TU's, it is proposed that in every promotion committee, an external member from the other 2 technical universities must be present.

As a spin-off of the current centre-formation, a new initiative has been started for knowledge transfer on sustainable energy to secondary schools. In the framework of the current revision of the science curricula at the secondary schools (to be completed in 2010), a sustainable co-operation with the SLO (Stichting Leerplan Ontwikkeling, national curriculum centre) organization is pursued, with input from the 3 TUs. SLO coordinates this innovation on behalf of the ministry of education, culture and science. Sustainable energy is an ideal carrier for integrating education on mathematics, physics, biology and chemistry and will promote enthusiasm for technical studies.

[2] TU/e received NVAO accreditation for the MSC SET programme in June 2005. For more information, see "Master Sustainable Energy Technology; Information in support of the application for accreditation by NVAO", October 25, 2005.

# 13 List of existing facilities



| Research | TUD | TU/e | UT |
|---|---|---|---|
| **Solar cells photovoltaics** | - Pulsed electron accelerators and lasers to generate charge carriers and excited states; detection by time resolved conductivity and optical techniques. | - Transmission Electron Microcospy Standard and CryoTEM)<br>- X-ray Diffraction<br>- Solid State NMR<br>- Clean Room and Thin Film Deposition Fac. | |
| **Photocatalysis** | - Infrastructure for the production of nano powders (e.g. laser assisted chemical vapor pyrolysis).<br>- Magnetic pulse compaction machine for the compaction of nano structured materials. | - Plasma Deposition Technology + Diagnostics<br>- Cluster Tool CASCADE for thin film solar cell deposition<br>- UHV system for dedicated beam studies<br>- Plasma enhanced atomic layer deposition | |
| **Energy storage (hydrogen, electrons)** | - X-ray diffractometers (XRD).<br>- Infrastructure for periodic and aperiodic electrochemical impedance measurements.<br>- High-resolution transmission electron microscopy (TEM). Scanning Electron Microscopy (SEM). Computational facilities and software.<br>- Research reactor with state of the art neutron scattering and positron annihilation instruments at the Reactor Institute Delft.<br>- Remote Real-time In-situ Electron Microsc.;<br>- State of the art Raman and Infrared vibrational spectroscopy instruments<br>- State of the art analytical instruments for product detection and photocatalytic reactor performance (including GCs, Mass Specs, and Microreactor Technology tools)<br>- Mössbauer Spectroscopy<br>- Access to: ISIS at Rutherford Appleton Laboratories; collaborations with Institut Laue-Langevin (ILL).<br>- Access to the European Synchrotron Radiation Facility (ESRF)<br>- Access to NoE ALISTORE platforms; Daresbury Synchrotron Radiation Facility via University of Kent at Canterbury; Nuclear Magnetic | - Laser Optical Spectroscopy<br>- Surface Science Lab. XPS, SIMS, LEED, AFM<br>- Vibrational and Electronic Spectroscopy, Raman spectroscopy and microscopy<br>- Electrochemical laboratory<br>- Access to Low and High Energy Ion Scattering (RBS, LEIS)<br>- Access to Preparational facilities at Holst Centre, TNO and Philips<br>- Access to dedicated equipment for battery testing at Philips<br>- Access to Fuel Cell Testing at ECN Computational facilities | - State of the art laboratory for large scale applications of superconductivity including wire and cable test facilities for transport currents up to 100kA in magnetic fields up to 16T and under mechanical stress. Either in-house or access to micro-/nano-analysis facilities for studying local materials properties.<br>- Cooperation with the most important groups and industries in the field worldwide and access to their infra-structure such as 'high magnetic field' centers, wire and cable fabricating facilities and microanalysis laboratories via European networks and mutual cooperation agreements<br>- A cryogenic system development group with design and verification infrastructure and very good links to related Dutch and European Industry.<br>- Infrastructure for the fabrication and handling of cryogenic fluids.<br>- Experience in handling liquid hydrogen.<br>- In-house theoretical support and a wide variety of measurement systems for all sorts of characterizations of electromagnetic transport with superconductors. |
| **Hydrogen fuel cells** | Resonance Facility at ICMCB-CNRS, Bordeaux and University of Kent at Canterbury; Battery benchmarking at University of Picardie and Uppsala University; | | |
| **Biomass conversion in biorefinery** | - Biotechnological; Advanced fermentation facilities, including DNA microarray equipment, genomics database.<br>- Chemical; Equipment for advanced fluid separations using dense gases (supercritical CO2, etc.). | | - High-pressure lab with instr. and technical support (perm. experiments up to 500 bar).<br>- Pilot plant (30 kg/hr) for the processing of bioliquids at elevated pressure (300 bar).<br>- Advanced thermochemical biomass lab for experiments at micro and bench scale. |
| **Biofuel utilization (engines, turbines)** | - Combustion systems (atmospheric (50 kWth) and pressurized (300 kWth) - flameless oxid.).<br>- Shock tube (FAST) – gas dynamic behaviour.<br>- 100 kWth atmospheric CFB gasifier/ceramic ßfilter gas cleaning unit. | - Biomass Combustion Laboratory<br>- Computational Fluid Dynamics<br>- Laser diagnostics for flame studies<br>- Automotive engine testing | - A combustion laboratory for combustion - experiments at 1 till 5 bar, 25 till 400 kW, using a large variety of combustion gases.<br>- Laser diagnostics consisting of high speed (400 Hz) laser induced fluorescence and Ramn/Rayleigh spectroscopy for the in flame measurements of species concentrations and temperature |

# 14 Added value from 3-TU cooperation



In a timeframe where the Dutch knowledge based society tends to lag behind the group of European leaders, as was noted by the AWT in a recent advice to the Dutch government[3], it is important to strengthen the coherence of the research towards sustainable energy supply at the 3 Technical Universities, thus forming a strong pillar for research and education. In combination with ECN and large Dutch energy companies such as Shell and the Gasunie, a strong chain is created from fundamental innovations to market introduction. The 3 TUs cover a vast area of the major options for energy transition towards sustainability, but research is still rather dispersed across the 3 TUs. The need for scientific research on technologies for sustainable energy is underlined by a recent report of the KNAW[4]. The Centre of Competence will enhance interfacing within and across the borders of the Technical Universities.. The 3 partners have decided to start up a platform on sustainable energy supply, that will prepare the formation of the Centre of Competence, develop a communication strategy and position the expertise at the 3-TU's coherently in the Dutch and European context.

The Centre of Excellence is the concrete kernel to enhance this process and consists of leading scientists at selected areas, relevant for long term development, to introduce additional dynamics for initiating or revitalizing research agendas. For the Centre of Excellence, themes covered by the universities were selected that 1) require still major scientific breakthroughs for long term sustainable energy supply, and 2) protects Dutch interests in fuel production, processing and trading in which environmental issues dictate clean, efficient and sustainable solutions. With this, a clear focus has been achieved to enhance technology development in key areas.

The development of truly innovative energy supply systems requires a strong interaction between fundamental research towards material properties and technology for designing highly efficient and robust devices. New chairs to be financed from the CE-budget were especially selected to enhance this interaction at 3-TU level as is explained below.

**Sunlight conversion to electrons and H2, including storage and utilization of the products.**
Both Eindhoven and Delft have a leading position in solar cell development. In Delft, emphasis is put on designing new cells from first principles, for which an infrastructure on fundamental materials science is available. Eindhoven focuses on fundamental materials development. The new chair in Delft "Solar cells based on novel materials and new fundamental concepts" especially aims at valorizing results from fundamental research in close interaction with the groups of Van der Sanden, Janssen and Van Zolingen in Eindhoven. In Eindhoven, fundamental research towards solid state, inorganic materials of use in solar conversion, H-storage, batteries, and fuel cells will be strengthened with a new chair, enabling a more efficient knowledge transfer at the fundamental level between the universities and giving extra impetus to the materials development for solar cells, energy storage and hydrogen conversion. This chair is complementary to existing activities in Delft, where inorganic chemistry more explicitly focuses on nano-materials.

For hydrogen, the complete chain from sustainable production with sunlight (photocatalysis) to electricity generation in hydrogen fuels cells is covered. Photocatalysis is primarily elaborated in Delft with contributions from several chairs. A new Delft chair on photocatalysis will integrate these efforts, add focus to this area and establish new research lines on subjects not covered yet (such as photocorrosion, and fundamental aspects of photocatalytic reactions, including modeling).

[3] Time for a KIQ start! More investment in education and research; AWT (Adviesraad voor het Wetenschaps- en Technologiebeleid); October 2005.
[4] Voorstudie Wetenschapsverkenning Duurzame Energieconversie; Werkgroep onderzoek duurzame energieconversie, Koninklijke Nederlandse Akademie van Wetenschappen, October 2005.

# 14 Added value from 3-TU cooperation



The new chair will cooperate closely with Eindhoven (van Santen, Niemantsverdriet) and Twente (Lefferts), especially in the area of electrocatalysis. Experiments in electrocatalysis provide a first indication what is possible on photocatalytic materials, if electrons are the primary reactive species.

Hydrogen conversion and energy storage have a strong common long-term fundamental and application oriented research agenda. The above mentioned new chair in inorganic materials at TU/e will play an important role in research on novel materials for storage. By selecting the central theme “Integrated sustainable energy systems for mobile applications”, with a new chair in Delft, a framework will be established to perform fundamental research on integrated systems, and use results from fundamental research in applications with high feasibility in the Dutch context, i.e. create spin-off. Selection of this theme also aims on integration of storage and conversion devices to bring forward overall energy efficient solutions, and to relax the current constraints on hydrogen storage materials.
Complementary research on system integration, energy storage and fuel cells is available, especially in Eindhoven and Delft.

**Biomass conversion to transportation fuels and chemicals with heat and power as by-products.**
This Centre of Excellence focuses primarily on conversions of biomass to biofuels within the biorefinery. Thermal and chemical conversions are studied in Twente (Van Swaaij, Petrus), biological conversions in Delft (Van der Wielen, Van Loosdrecht, Pronk). The cooperation between the thermochemical and biotechnological groups of this CoE will result in technology combinations that enable optimal and economical feasible utilization of biomass. To achieve this main goal of biorefining and to create integration of thermochemical and biological conversion steps, as well as new processes on their interface: i) an associate professor (TUD) in the field of industrial biotechnology on the basis of components arising from thermochemical processes (pyrolysis, organosolv) will be appointed and ii) the new requested chair on thermal and chemical conversion of biomass (UT) will start, amongst others, research lines on the conversion of by-products for biotechnological conversions (e.g. lignin derivates, diluted streams). Equipment and knowledge of these groups with respect to the scale of the processes are complementary, which enables facility sharing and knowledge transfer. The two research groups involved in the topic on “Utilization of biofuels” (UT and TUe) have a long period of cooperation within the research school for fluid mechanics the J.M. Burgers Centre. Their research with respect to biofuels utilization and experimental laser diagnostic equipments are complementary. The UT focuses on gaseous fuels, Eindhoven on liquid fuels. Also in the theoretical/numerical research the groups are complementary. It is foreseen that the groups will exchange the numerical codes.

# 15 Valorisation



Energy is the most important sector in the world economy. To protect the Dutch interests in this area, with one of the largest energy companies worldwide and desiccating natural gas resources, new energy supply systems based on sunlight conversion are of key interest.

For valorisation as an active strategy to exploit the knowledge and expertise of SUNNET , the collaborating groups have many existing contacts and collaborations with publicly and privately funded partners, including multinationals such as Shell and Philips, research institutes such as ECN, Holst Centre, companies active in gas and electricity generation, solar cell and fuel cell manufacturers, etc. In addition the three universities have their incubator programs as well as a joint strategy on valorisation, with the opportunity for new spin-off companies to be established. A good example is EcoSun Systems in Eindhoven (winners of the European Innovact Award for Innovation 2005 and the Dutch Kickstart Student-Business Plan competition) which, funded by STW, is commercializing technology to make solar panels 4-5 times cheaper. BTG, a spin-off company from the University of Twente has successfully commercialized the pyrolysis technology that was developed within the group of professor van Swaaij and is now one of the biggest pyrolysis technology providers with customers worldwide.

One of the great advantages of joined efforts in the Centre of Excellence and in the Centre of Competence is the opportunity to create a better interface to society as the knowledge domains have become less dispersed. A web-site is already under construction (CoCo-level) where the expertise at the joint universities is presented by theme. Clear mission statements, introductions to research areas and links to specialists will provide a better portal, especially for smaller Dutch companies without already established relations. This is particularly the domain for spin-offs such as integrated solar devices, initially suited for niche markets. To more actively enhance knowledge transfer, the partners intend to organize an attractive program of meetings, with an annual national energy conference, and several topical symposia and workshops, such to facilitate and strengthen interactions with existing and new external parties.

Long term developments need strategic alliances between SUNNET and major public and private energy organisations, both at Dutch and European level. Especially in the area of biomass conversion, important progress has been made in the past years for extending collaborations[5]. Via the Centre of Excellence a link is provided between the various coalitions, enhancing a better adjustment of research agendas towards the needs of industry and society. As a result of such collaborations, the Dutch industry can maintain and expand the leading role it has taken in the transition towards sustainable energy production. The zero-emission car has been selected as a case for new hydrogen and electricity technology especially to link fundamental research agendas to applications of high practical significance. Regular workshops will be organized around this theme to communicate new developments with interested (commercial) parties.

[5] The involved research groups in industrial biotechnology (Delft) have strong commitments in the public-private Netherlands Institute for Industrial Biotechnology (NIIB, supported by DSM, AKZO Nobel and Shell) and its founding programs (B-basic, Kluyver Center for Genomics). Thermochemical biomass conversion routes are jointly being studied by the 3 technical universities within a program called BIOCON (supported by NWO, Shell, BTG, BioFuels and the Japanese NEDO). Recently, a large integrated EU-FP6 project on biorefinery is started with Dutch participation from the University of Twente, RUG, BTG and Shell. The research groups studying the utilization of biofuels (Eindhoven, Twente) to ensure seamless acceptation of new biofuels in next generation prime movers work closely together with TNO-Automotive, Volkswagen and DaimlerChrysler, united in CCAR.

# 16 Required from CoE budget [amounts in k euro]



| Research | TUD | TU/e | UT |
|---|---|---|---|
| **Solar cells photovoltaics** | **New chair: Photovoltaic devices**<br>Hgl: 4,5 x 200 | **New chair: Inorganic Materials Chemistry**<br>Hgl: 4,5 x 200<br>Visting professor in computational materials science: 1 x 200<br>UD fuel cell catalysts: 2,5 x 156<br>Technician: 2 x 130<br><br>Equipment<br>Environmental Scanning Electron Microscopy + EDX: 485 k euro<br>X-ray Photoelectron Spectroscopy facility with automated sample stage: 500 k euro | |
| **Photocatalysis** | **New chair: Photocatalysis**<br>Hgl: 4,5 x 200 | | |
| **Energy storage (hydrogen, electrons)** | **New chair: Integrated energy systems for mobile applications**<br>Hgl: 4,5 x 200 | | **New chair: Materials for efficient energy transport and storage**<br>Hgl: 5 x 200 |
| **Hydrogen fuel cells** | | | |
| **Biomass conversion in biorefinery** | **Chair: Bio-separation Technology**<br>UD Feedstock Innovation Technology: 4,5 x 156<br><br>**Chair: Separation technology**<br>Particle image velocimetry (PIV): 350 | | **New Chair: Thermal & Chemical Conversion of Biomass**<br>Hgl: 5 x 200<br>UD: 2 x 156<br><br>Equipment: High throughput micro fluid bed test facility,<br>Steady state transient isotopic kinetic analysis: 100<br>(contribution to the total costs) |
| **Biofuel utilization (engines, turbines)** | | **Chair: Combustion Technology**<br>Technician (Application testing of biofuels in internal combustion engines): 3 x 130 | **Chair: Thermal Engineering**<br>UD: 4 x 156<br><br>Equipment<br>PIV for velocity measurements in combustion chambers and turbines: 90 (contribution to the total costs) |
| **Total** | **3750 k euro** | **3125 k euro** | **3125 k euro** |

# 17 Suggestions for external consultation



- SHELL
- Gasunie
- ECN
- NUON
- Essent
- EON-Benelux
- Ecofys
- Transition platforms Groene Grondstoffen, Nieuw Gas en Duurzame Mobiliteit
- FOM
- DSM- NedStack
- TNO-Separation technology
- AKZO
- Stork (-Thermeq)
- TNO-Automotive
- DAF Nederland
- NedCar
- Philips
- CCAR
- Nedalco
- Avebe
- Urenco

# Appendix

# Centre of Competence, contributing chairs



| Name | Chair | Location | Faculty | Fte | **Solar Cells** | **Photocatalysis** | **Energy storage (incl. Hydrogen storage)** | **Hydrogen fuel cells** | **Biomass conversion** | **Biofuel utilization (engines, turbines)** | Wind energy | Nuclear energy | Clean fossil energy | Electricity distribution | Environmental and transition studies |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| prof.dr. C.I.M. Beenakker | Electronic Components, Technology and Mat. | TUD | EWI | 1 | ● | | | | | | | | | | |
| prof.dr.ir. R.A.J. Janssen | Molecular Materials and Nanosystems | TU/e | ST/N | 1 | ● | | | | | | | | | | |
| prof.dr. G.J. Kearley | Neutron Physics | TUD | TNW | 1 | ● | | ● | ● | | | | | | | |
| prof.dr. W.J. Ockels | Aerospace for Sust. Eng. and Technology | TUD | L&R | 1 | ● | | | | | | ● | | | | |
| prof.dr.ir. M.C.M. v.d. Sanden | Equilibrium and Transport in Plasmas | TU/e | N | 1 | ● | | | | | | | | | | |
| prof.dr. L.D.A. Siebbeles | Opto-electronic materials | TUD | TNW | 1 | ● | | | | | | | | | | |
| prof.dr.ir. R.J.C. van Zolingen | Solar cells in photovoltaic systems | TU/e | W | 0.2 | ● | | | | | | | | | | |
| prof.dr. P.W. Appel | Chemical Product Design | TUD | TNW | 0.8 | | ● | | | | | | | | | |
| prof.dr. J.A. Moulijn | Catalysis Engineering | TUD | TNW | 1 | | ● | ● | | ● | | | | | | |
| prof.dr. J. Schoonman | Inorganic Chemistry | TUD | TNW | 1 | | ● | ● | | | | | | ● | | |
| prof.dr.ir. M.O. Coppens | Physical Chemistry and Mol. Thermodynamics | TUD | TNW | 1 | | | ● | | | | | | | | |
| prof.dr. W.R. Hagen | Enzymology | TUD | TNW | 1 | | | ● | | | | | | | | |
| prof.dr.ir. G.J. Kramer | Fundamental Heterogeneous Catalysis | TU/e | ST | 0.2 | | | ● | | | | | | | | |
| prof.dr.ir. P.H.L. Notten | Electrochemical Energy Storage | TU/e | ST | 0.2 | | | ● | | | | | | | | |
| prof.dr.ir. S.J. Picken | Polymer Materials | TUD | TNW | 1 | | | ● | | | | | | | | |
| prof.dr.ir. I.M. de Schepper | Neutronenverstr. en Mössbauerspectroscopie | TUD | TNW | 1 | | | ● | | | | | | | | |
| prof.dr.ing. A. Schmidt-Ott | Particle Technology | TUD | TNW | 1 | | | ● | | | | | | | | |
| prof.dr. R.A. van Santen | Molecular Heterogeneous Catalysis | TU/e | ST | 1 | | | | ● | | | | | ● | | |
| prof.dr.ing. M. Wessling | Membrane Technology | UT | TNW | 1 | | | | ● | | | | | ● | | |
| prof.dr.ir. J.H. Blom | Electrical Power Systems | TU/e | E | 1 | | | | | ● | | | | | | |
| prof.dr.ir. G. Brem | Thermal Process Technology | UT | CTW | 0.2 | | | | | ● | | | | | | |
| prof.dr.ir. J.J.H. Brouwers | Process Technology | TU/e | W | 1 | | | | | ● | | | | | | |
| prof.dr. L.P.H. de Goey | Combustion Technology | TU/e | W | 1 | | | | | ● | ● | | | ● | | |
| prof.dr.ir. A.B. de Haan | Separation Technology | UT | TNW | 1 | | | | | ● | | | | | | |
| prof.dr.ir. J.J. Heijnen | Biokinetics | TUD | TNW | 1 | | | | | ● | | | | | | |
| prof.dr.ir. P.J. Jansens | Separation Technology | TUD | 3mE | 1 | | | | | ● | | | | ● | | |
| prof.dr.ir. F.J.J.G. Janssen | Environmental Technology | TU/e | ST | 0.2 | | | | | ● | | | | | | |
| prof.dr. F. Kapteijn | Reactor and Catalysis Engineering | TUD | TNW | 1 | | | | | ● | | | | | | |
| prof.dr.ir. J.A.M. Kuipers | Fundamentals of Chemical Reaction Eng. | UT | TNW | 1 | | | | | ● | | | | ● | | |
| prof.dr.ir. L. Lefferts | Catalytic Processes and Materials | UT | TNW | 1 | | | | | ● | | | | ● | | |
| prof.dr.ir. M. van Loosdrecht | Biological Recycle and Environmental Techn. | TUD | TNW | 1 | | | | | ● | | | | | | ● |
| prof.dr.ir. I. Obernberger | Thermal biomass utilization | TU/e | W | 0.2 | | | | | ● | | | | | | |
| prof.dr.ir. L. Petrus | Chemical Conversion of Biomass | UT | TNW | 0.2 | | | | | ● | | | | | | |
| prof.dr.ir. J. Pronk | Microbiology | TUD | TNW | 1 | | | | | ● | | | | | | |
| prof.dr.ir. A. van Steenhoven | Energy Technology | TU/e | W | 1 | | | | | ● | | | | | | |
| prof.dr.ir. W.P.M. van Swaaij | Thermo Chemical Conversion of Biomass | UT | TNW | 1 | | | | | ● | | | | ● | | |
| prof.dr. H.J. Veringa | Thermo Chemical Conversion of Biomass | UT | TNW | 0.2 | | | | | ● | | | | | | |
| prof.dr.ir. L. van der Wielen | Bio-separation Technology | TUD | TNW | 1 | | | | | ● | | | | | | |
| prof.dr. M. Aldén | Laser Diagnostics in Combustion | TU/e | W | 0.2 | | | | | | ● | | | ● | | |
| Prof.dr.ir. R.S.G. Baert | Internal combustion engines | TU/e | W | 0.4 | | | | | | ● | | | ● | | |

## Centre of Competence, contributing chairs



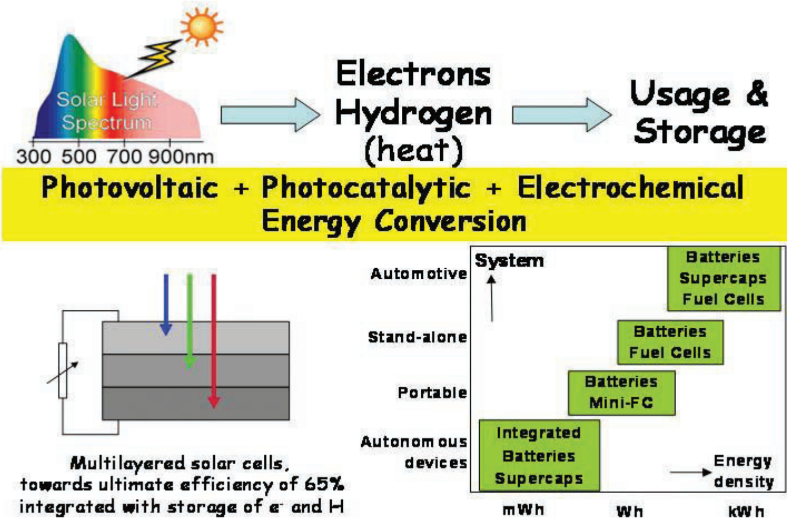
| Name | Chair | Location | Faculty | Fte | Solar Cells | Photocatalysis | Energy storage (incl. Hydrogen storage) | Hydrogen fuel cells | Biomass conversion | Biofuel utilization (engines, turbines) | Wind energy | Nuclear energy | Clean fossil energy | Electricity distribution | Environmental and transition studies |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| prof.dr.ir. T.H. van der Meer | Thermal Engineering | UT | CTW | 1 | | | | | | ● | | | | | |
| prof.dr.ir. P. G. Bakker | Aerodynamics | TUD | L&R | 1 | | | | | | | ● | | | | |
| prof.ir. A. Beukers | Composite Structures | TUD | L&R | 1 | | | | | | | ● | | | | |
| prof.dr.ir. H.W.M. Hoeijmakers | Engineering Fluid Dynamics | UT | CTW | 1 | | | | | | | ● | | | | |
| prof.dr.ir. Th. Van Holten | System design and performance | TUD | L&R | 1 | | | | | | | ● | | | | |
| prof.dr.ir. G.A.M. van Kuik | Wind Energy | TUD | L&R | 1 | | | | | | | ● | | | | |
| prof.ir. J. Meek | Offshore technology | TUD | CiTG | 0.3 | | | | | | | ● | | | | |
| prof.dr.ir. T. Tomiyama | Reliability Based Design | TUD | 3mE | 1 | | | | | | | ● | | | | |
| prof.dr.ir. M. J. L. van Tooren | System design and performance | TUD | L&R | 1 | | | | | | | ● | | | | |
| prof.dr.ir. M. Verhaegen | Control Engineering | TUD | 3mE / DCSC | 1 | | | | | | | ● | | | | |
| prof.dr.ir. T. van der Hagen | Reactor Physics | TUD | TNW | 1 | | | | | | | | ● | | | |
| prof.dr.ir. A.H.M. Verkooijen | Large Scale Energy Prod. and Nuclear Energy | TUD | 3mE | 1 | | | ● | ● | | | | ● | ● | | |
| prof.dr.ir. A.P.C.M. Backx | Control Systems | TU/e | E | 0.2 | | | | | | | | | ● | | |
| prof.ir. J.P. van Buijtenen | Energy Supply with emphasis on Gas Turbines | TUD | 3mE | 0.3 | | | | | | | | | ● | | |
| prof.dr. J.W. Niemantsverdriet | Physical Chemistry of Surfaces | TU/e | ST | 1 | | | | | | | | | ● | | |
| prof.dr. D.J.E.M. Roekaerts | Heat and flow | TUD | TNW | 1 | | | | | | | | | ● | | |
| prof.dr.ir. J.C. Schouten | Chemical Reaction Engineering | TU/e | ST | 1 | | | | | | | | | ● | | |
| prof.dr.ir. G.F. Versteeg | Development and Design of Industrial Proc. | UT | TNW | 1 | | | | | | | | | ● | | |
| prof.dr. eng. J.A. Ferreira | Electric Power Processing | TUD | EWI | 1 | | | | | | | | | | ● | |
| prof.ir. W.L. Kling | Electric Power Processing | TUD TU/e | EWI | 0.2 | | | | | | | | | | ● | |
| prof.dr. H. Rogalla | Low Temperature Division | UT | TNW | 1 | | | | | | | | | | ● | |
| prof.ir. L. van der Sluis | Electricity Supply | TUD | EWI | 1 | | | | | | | | | | ● | |
| prof.dr.ir. A.J.A. Vandenput | Electromechanics and power electronics | TU/e | E | 1 | | | | | | | | | | ● | |
| prof.dr. J.Th.A. Bressers | Policy Studies and Environmental Policy | UT | CSTM | 1 | | | | | | | | | | | ● |
| prof.dr.ir. J.C. Fransoo | Operations Planning & Supply Chain Manag. | TU/e | TM | 1 | | | | | | | | | | | ● |
| prof.dr. S.J.M.H. Hulscher | Water Engineering and Management | UT | CTW | 1 | | | | | | | | | | | ● |
| prof.dr.ir. P.A. Kroes | Philosophy | TUD | TBM | 1 | | | | | | | | | | | ● |
| prof.dr. C.J.H. Midden | Human Technology Interaction | TU/e | TM | 1 | | | | | | | | | | | ● |
| prof.dr.ir. W.A.H. Thissen | Policy Analysis/ | TUD | TBM | 1 | | | | | | | | | | | ● |
| prof.dr.ir. M.P.C. Weijnen | Process and Energy Systems Engineering | TUD | TBM | 1 | | | | | | | | | | | ● |

# Societal relevance translated in 'technical dreams' Detailed version



## Solar Cells

Ultimate sustainability implies that the energy of sunlight be used at its full potential, i.e. with maximum efficiency (at the thermodynamic limit).
The R&D challenge for solar cells is therefore to capture the full spectrum of sunlight (from infrared to UV- e.g. in multilayered devices). Furthermore, solar cells need to become cheaper, in combination with high efficiency. Integration of solar conversion devices with energy storage functions is highly promising.




Conversion of the full energy spectrum in sunlight into electrons and hydrogen as energy carriers along with typical storage systems and their application areas

## Photocatalysis

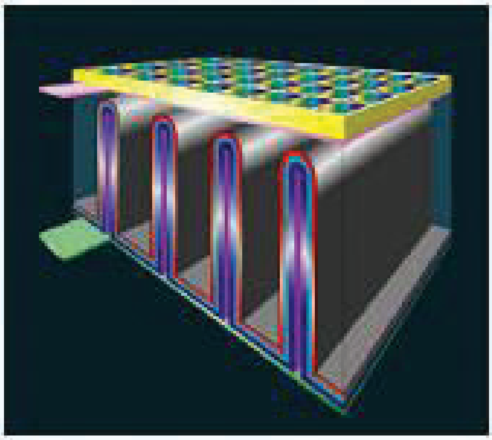
Efficient conversion of solar energy into hydrogen by splitting water is a major enabling milestone for a viable Hydrogen Economy because it represents a clean and abundant source of hydrogen. The grand challenge for solar hydrogen is to become economically competitive with energy from fossil fuel sources, requiring devices that reside on a 0.15/peak-Watt line. While indirect photo-electrolysis (solar cell + electrolyser) can be carried out quite efficiently, the high costs prohibit large scale application. In contrast, direct photo-electrolysis in which a photo-catalyst directly splits water under illumination is a much cheaper solution, and is often referred to as the Holy Grail of electrochemistry. For this, cheap and highly efficient visible-light sensitive photocatalysts need to be developed.
Methanol may also be produced by photocatalysis from $CO_2$ and $H_2O$. This principle has been shown to work. Methanol produced in this way does not depend on the availability of fossil fuels, is easy to handle, represents a $CO_2$-neutral solution, and may be an alternative fuel for hydrogen in PEM-fuel cells.

## Energy storage

Efficient storage of energy represents another formidable R&D challenge, particularly in connection with the exploitation of solar radiation. Peaks in solar intensity do not match with demand for electricity. Furthermore, several attractive locations exist where the solar radiation is high (e.g. the Sahara), but where the local demand for electricity is low. Therefore, energy has to be transported, e.g. using superconductivity, and/or stored in batteries or in the form of hydrogen. An exciting possibility is to combine the production and storage of hydrogen in a single device.

In the future of energy handling, superconductivity can play an important role in the transformation of energy (e.g. electrical generators and motors of very high efficiency and small volume). It enables nearly lossless transport of electrical energy over long distances (superconducting cables) and storage in the form of strong magnetic fields in toroidal superconductive magnets (SMES = Superconductive Magnetic Energy Storage). A very efficient way for combining the cooling of superconductors with electrical energy transport would be the transport of liquid hydrogen in cryogenic pipelines with center conductors of the low-cost superconductor $MgB_2$. The same configuration could also be used for SMES.

Idea for integration of solar cells and a battery (courtesy Peter Notten TU/e & Philips)



## Hydrogen fuel cells

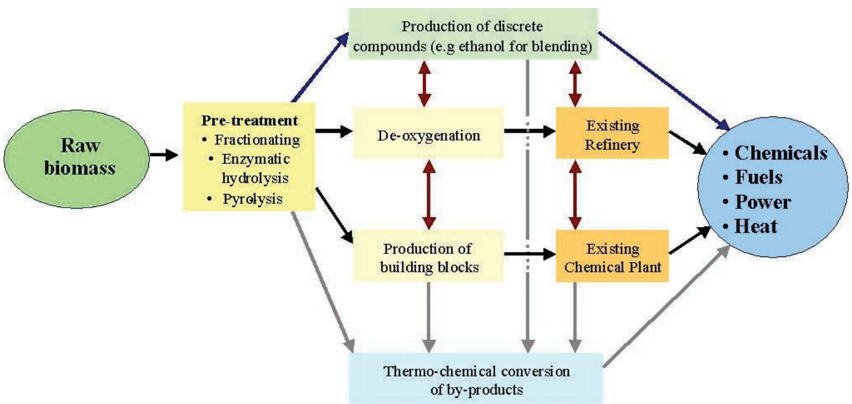
Finally, solar hydrogen as well as hydrogen from more conventional sources can be used as a sustainable energy carrier in fuel cells. Transportation vehicles powered by fuel cells are emission-free, noise-free and highly fuel efficient, solving many problems associated with today's road transport. Due to electrochemical oxidation of fuels in a fuel cell, the process can take place at maximum thermodynamic efficiency (avoiding the Carnot limitation of internal combustion engines). Although the principle of fuel cells has been known for over 150 years, only recent advances in catalysis and materials research have enabled the first prototypes, such as the Ballard fuel cells that are used in the Amsterdam fuel cell buses. Still, more R&D challenges are ahead, such as the development of an 'intermediate temperature' fuel cell (150-200C vs. ca. 80°C in PEM fuel cells and 650-800°C in SOFC's). Such a cell would be able to use relatively impure, cheap hydrogen, in combination with high power density and long lifetime. By integrating a hydrogen storage unit with an intermediate-temperature fuel cell, the heat produced by the latter can be efficiently used to liberate the hydrogen from its storage medium. This heat would otherwise be lost. Peaks in power demand can be met by rechargeable lithium batteries and/or supercapacitors. An integrated approach to energy storage and conversion is the optimal solution for the road-transport sector, and solutions that work here will be readily adaptable to less demanding applications.

## Biorefinery for the production of transportation fuels

Biomass is an especially interesting renewable and sustainable feedstock and source of energy, because it is available abundantly and it can be stored. Biomass can be used to generate heat and power and can be converted to a wide range of products, including (liquid) transportation fuels with a high energy density and chemicals. Within the CoE we focus on biofuels. There are already some biomass-based processes operational. However, generally these processes cannot compete economically with their fossil counterparts, because yields of target products are not maximized and by-products have often a very low or even a negative value. A bio-refinery is an integrated concept aiming at full utilization of biomass, in which different fractions of biomass are converted in large-scale plants (economy of scale) or in standardized small-scale units (economy of numbers) in an economically optimal product slate. To start-up the bio-refinery concept it is essential to integrate and to partner-up with existing industries and markets. This lowers the required capital investments and offers guaranteed markets for the products. Partnering can be at the level of the products only, e.g. by producing biomass based blending compounds for transport fuels, or by co-processing biomass in existing refineries and chemical plants. In a later stage, 100% biomass based products can gradually replace the functionality of existing fossil-fuel-derived products or can be linked with new applications.

It is expected that a multitude of conversion steps will be used (like in a mineral oil-refinery). A bio-refinery may include thermal, chemical and biological conversion processes and its development requires input from a variety of disciplines, viz. process technology, chemistry, biotechnology, catalysis, (micro) biology and separations. However, the conversion processes necessary to realise the bio-refinery are in an early stage of development or have not been invented yet.

Biorefinery concept based on thermochemical and biotechnological conversion processes



## Utilization of biofuels

Biomass based fuel technology for transport purposes and for power generation opens opportunities to develop a range of new fuels (100% bio-based or blends). On the other hand, current research activities for the next generation of new engines and gas turbines for the coming 30 years are directed towards new ultra-clean and ultra-efficient engines. These two developments have to be tuned in order to achieve a seamless acceptation of biofuels in next generation prime movers. Research will be conducted in the areas of homogeneous combustion engines and utilization of gaseous or liquid biofuels in gas turbines.