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Robert Schlögl:

The Role of Chemistry in the Global Energy Challenge



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Chapter 30 The Role of Chemistry in the Global Energy Challenge Robert Schlögl

30.1 Introduction

The fifth oil price shock (Doroodian and Boyd 2003; Kilian 2008; Herrera and Pesavento 2009) started from anticipated shortages in the availability and supply of the most visible energy carrier, and created intensive responses throughout society that have now prevailed for several years. Besides coping with the eco-political issues, for the first time we all feel that the present energy supply system needs some fundamental changes. Both the finite supply of liquid fossil fuels and the high awareness of climate change¹ resulting from our fossil fuel consumption have sensitized society and hence the scientific community as well. Chemistry is reacting more sensitively than in earlier oil crises as it promises critical contributions, in the form of catalysis and material science, to the development of all non-nuclear alternative energy conversion processes on the grid-level scale. This time, however, many other sciences are also reacting to the challenge² thus creating a wave of interdisciplinary activity in energy research.

This chapter intends to introduce the reader to a framework of challenges faced by science in approaching energy research. Chemistry is at the forefront of traditional disciplines responding to the challenge of supplying non-fossil regenerative energy. For this reason, the chemical sciences are used to illustrate the underlying challenges posed by the operation of science in a global context. The text exemplifies the technical issues that need to be addressed in some depth. This provides a firm basis for the second part, which presents an essay on the disciplinary strengths and shortcomings of chemistry in the context of energy research (Velden and Lagoze 2009). A personal account of the global aspects is presented rather than a detailed disciplinary critique of the emerging energy-for-chemistry community. It is stressed that energy science is intimately connected with nonscientific issues that exert strong influence on the science and demand a critical reflection by individual scientists on the global and local factors affecting their practical work.

 $^{^1({\}rm Morison}$ and Lawlor 1999; Zachos et al. 2001; Parmesan 2006; Archer and Brovkin 2008; Egan 2009).

 $^{^{2}}$ (Arico et al. 2005; Balaya 2008; Manthiram et al. 2008; Hu et al. 2009).

Energy research is a broad interdisciplinary topic. A large variety of fundamental approaches are proposed and actively pursued in order to address the different issues of sustainable and safe energy supply strategies. Several reviews³ deal with the overall strategy for creating an energy mix that introduces many completely novel approaches to energy conversion. As it is clear that energy cannot be created, all approaches amount to a kind of conversion process. Since many of them involve molecular or solid energy carriers, it is evident that chemistry is at the core of the energy challenge. Chemistry provides the processes and materials for energy conversion reactions. Chemical science can control the energetic "cost" of both energy conversion and its utilization. After all, our current fossil energy carriers were created by biochemical processes in photosynthesis and later converted to their present high-density forms by geochemical processes.

This chapter attempts to elucidate the pivotal role of chemistry in actively pursuing the transition from fossil energy scenarios to more sustainable energy supply systems. The equally relevant issues of primary electricity generation, electricity distribution (Beccali et al. 2004; Charles 2009) and strategies for saving energy in our current scenario are not covered here to maintain some clarity in the approach. The role of nuclear fission and fusion technologies is not considered here (see chapter 27). The following text intends to clarify some underlying lines of thought and thus refrains from discussing individual examples for its theses. Examples can be found in the cited literature to illustrate points made in the text, which does not claim to cover the issue in any exhaustive way.

30.2 Energy and Climate

It is now universally recognized that global warming is a large-scale experiment (Parmesan 2006) that mankind started without knowing the boundary conditions and the complexity (Mitchell 1989; Egan 2009) of the interactions in the climate system (see chapter 31). The cause of climate change is the chemical conversion of carbonaceous materials into thermal and derived forms of energy. Not only direct combustion, but also excessive and inadequate land use practices (Paustian et al. 2000; Lal 2004; Cheng et al. 2006) contribute substantially to greenhouse gas emissions. The most important lesson to learn from the evolving situation is not to create alternative or "renewable" energy systems (Smeets et al. 2007) without understanding exactly how they are involved in the complex regulatory systems of our planet. This means that all concepts of future energy conversion must be designed and verified in light of their impact on the various biological and physico-chemical regulatory systems on Earth. The often used word "sustain-ability" contains not only a term describing the balance between input of energy

 $^{^3({\}rm Islam}$ et al. 2004; Ghanadan and Koomey 2005; da Silva et al. 2005; Nath and Das 2007; Cosmi et al. 2009; Shaahid and El-Amin 2009).

carriers and output of waste, but also a kinetic term⁴ describing the time constant of equilibration between input and output. Neglecting this kinetic term caused the climate change problem to arise. Great care is needed when energy scenarios are classified as "renewable" or "regenerable," as much less obvious (Berntsen et al. 2006; Montenegro et al. 2007) unwanted consequences than the emission of carbon dioxide can arise from large-scale chemical conversions of energy carriers. Typical examples are the consequences of energy farming for biodiversity, the residence time of emitted carbon dioxide in the atmosphere over various ecosystems,⁵ or the consequences of large-scale deposition of carbon dioxide in deep seawater or in aquifers underground (Ketzer et al. 2009; de Best-Waldhober et al. 2009).

In the essay part of the chapter, the term sustainability will also be used to describe a quality of research conduct. Energy science is sustainable for science only if validated understanding or reliable basic knowledge for technologies can be extracted from it. This hypothesis generates multiple consequences for individuals and the scientific community as a whole.

It is most relevant to consider energy conversion scenarios as hierarchical systems of process chains encompassing the generation of energy carriers, the conversion of energy carriers, the management of the waste products and effects of using of the energy liberated. A typical example of the complexity of interactions was the recent price explosion for foodstuffs caused by the still small-scale sector of energy farming (Muller 2009). This example highlights that not only scientific factors, but also socio-political ones (Voorspools 2004) are of decisive influence on the evolution of the energy challenge. These implications are not discussed in the present work, although some basic assumptions influence the construction of plausible energy scenarios described below.

Even for purely chemical considerations, the systemic approach demands not only considerations about the efficiency, security and sustainability of the processes, but also about the availability of critical materials for the intended scale of use. In this respect, the application of noble metals or their compounds is a critical issue, exemplified by the use of Pt and Ru. For all grid-scale sustainable applications, chemistry has to provide solutions that circumvent the use of such elements or minimize their application to an absolutely essential minimum. The extent to which this is possible is not yet clear, as only limited systematic approaches have been applied (Greeley et al. 2006; Greeley and Norskov 2007), despite phenomenological approaches like high-throughput screening (Woodhouse and Parkinson 2009). A promising development (Kanan and Nocera 2008; Kanan et al. 2009) is the simple creation of a complex molecular electrocatalyst based on Co-phosphate species. The highly dynamic character of this system capable of oxygen evolution is reminiscent of the dynamics of the phosphate catalysts (Havecker et al. 2003; Conte et al. 2006) used for the inverse process of catalytic selective ox-

 $^{^4({\}rm Berntsen}$ et al. 2006; Montenegro et al. 2007; Archer and Brovkin 2008; Van Hise 2008; Hofmann et al. 2009).

 $^{^5}$ (Montenegro et al. 2007; Archer and Brovkin 2008; Van Hise 2008; Hofmann et al. 2009).

idation. The deliberate exploitation of structural dynamics for a catalytic system is considered to be a guiding principle for finding novel material solutions that can be used under the constraints of sustainable energy conversion.

The already significant modification of the climate through CO_2 emission calls for a most rapid reduction of further emissions. Chemistry can contribute to this task in multiple ways as discussed below, but few of these contributions will be significant on the scale of present emissions within short timescales of below one decade. The fastest method would be to reduce emissions by saving energy through existing technologies and behavioral adaptations. Large emission savings also can be realized by immediately using the already existing solutions to improve the efficiency of thermal energy conversion, even if this requires the rapid replacement of fossil power stations. This measure must be supported by intelligent management of distribution grids (Charles 2009; Shaahid and El-Amin 2009), allowing the initial production of primary electricity to be utilized. These measures can buy time to allow chemistry to develop and implement the measures described below. It is unrealistic to promise that rapid and large-scale novel solutions from chemistry will solve the energy challenge in the immediate future.

30.3 The Scale of the Energy Challenge

Global consumption of primary energy is about 5×10^{14} MJ/a. This very large number contains the net energy used plus an estimated 30% contribution for losses during energy conversion. In Germany in 2007, the losses amounted to 4307×10^{12} kW (url BMwi energy), against a total crude oil consumption of 4678×10^{12} kW. These numbers indicate that any effort to reduce losses from converting energy carriers is of great relevance for energy scenarios today and in the future. Chemistry can play a limited but relevant role in this endeavor by maximizing the selectivity of molecular transformations and by helping to minimize physical losses through the development of appropriate materials (high-temperature materials, solid-state lighting).

To get a feeling for the dimension of energy requirements, the following "Gedankenexperiment" is suggested. The energy content of hydrogen gas at 200 bar pressure in a process that burns it with pure oxygen to gaseous water is 530 kWh/m³ gas. This is equivalent to roughly $2x10^3$ MJ. To satisfy the global energy demand, we would need $2.5x10^{11}$ m³ hydrogen gas. This is roughly equivalent to the capacity of all storage caverns for natural gas on the planet. More tangible is the equivalence of this amount of hydrogen to the number of $5x10^{12}$ laboratory gas cylinders of hydrogen that we consume per year. Knowing that about $1.5x10^9$ people consume 75% of this energy, we learn that, statistically, in the first world about six hydrogen gas cylinders are consumed each day. The socio-political dimension of this consideration becomes apparent when we conclude that the majority of the global population is left with a consumption rate of about 0.9 cylinders per day.

The purpose of this example, which does not include any growth in energy demand, is to illustrate the enormous challenge for any new energy supply technology. It shows that we cannot afford to develop just one technology, but that we must use every approach that fulfills the criteria of sustainability described above. The dimension of energy demand further illustrates the enormous sizes of the technological installations required as well as the capital needed to construct them. Both factors further imply that the timescale for such a replacement of fossil energy to sustainable scenarios must be on the order of decades. This implies that we will need a phased approach in which several scenarios provide for a gradual transformation, and that in any phase there must be enough room to adjust for technological improvements based on future scientific breakthroughs without endangering the efforts and funds already invested.

The scale of chemical conversions for energy is roughly twenty times larger than the scale of the global chemical industry. When we create new processes, it is thus important not only to be as effective as possible, but also to consider the scalability of a process both in terms of its material requirements and its unit operations. The design strategy of chemical plants has provided an excellent toolbox (Van den Heever and Grossmann 1999) for estimating such aspects of any new processes already in early stages of development. This practice should also be implemented in the search for energy solutions.

This paper does not aspire to describe all of the many approaches towards energy conversion⁶ that chemists have described over the years, and especially recently in response to the general awareness of the energy challenge. Instead, it focuses on the contributions expected from chemistry to initiate technologically the restructuring of our present energy scenario. Many of the novel approaches, such as those intending to design the "artificial leaf" (Lubitz et al. 2008), are still far from becoming relevant to grid-scale technologies, and many of these approaches will face problems with fulfilling the criteria for sustainability (Voorspools 2004; Alanne and Saari 2006) when considered as technological systems. Some of them will overcome all of these obstacles to become advanced generations of energy conversion technologies and contribute to future energy scenarios. It is thus detrimental to the total effort to preselect the topics on which energy research should concentrate. Chemical energy research should enable the identification and verification of ingenious concepts of chemical conversion and of materials that create new technologies.

On the other hand, it is necessary to focus to a certain extent on those issues⁷ that are critical for the near or foreseeable future. Many of them concern the conversion of solar energy into a storable energy carrier.⁸ Storing primary energy in energy carrier chemicals and/or battery electrodes (Tarascon and Armand 2001;

⁶(Voorspools 2004; Ni et al. 2007; Deshmukh and Deshmukh 2008; Khan et al. 2008).

⁷(Herbert et al. 2007; Deshmukh and Deshmukh 2008; Khan et al. 2008; Ramachandra 2009).

 $^{^{8}({\}rm Hall}$ 1978; Bolton and Hall 1979; Bak et al. 2002; Kodama 2003; Aroutiounian et al. 2005; Umeyama and Imahori 2008).

Wakihara 2001) has the advantage of providing for simple recovery of electrical energy. What appears to be most critical is to enable the transition from purely fossil energy systems to a mixed constellation with an increasing contribution by renewable energy to allow fossil fuel technologies to be phased out (such as saving on building or rebuilding thermal power stations). It is the purpose of this paper to propose a rational approach of selecting some of these focal challenges for chemistry. This approach consists in assuming generalized energy supply scenarios and analyzing the resulting systems network in terms of bottlenecks. Fundamental research challenges result from this analysis of how to circumvent such bottlenecks on a large scale while observing the boundary conditions of sustainability and climate compatibility outlined above.

30.4 Energy and Chemistry: EnerChem

Chemistry is the strategic core discipline for all future energy conversion processes based upon primary solar energy. In addition, chemistry is indispensable to all efforts to save energy by performing our technical production processes with optimized utilization of resources. Not only energy conversion from fossil sources, but also many material production processes, benefit from improved chemical reactions and from optimized processes, frequently achieved through optimized catalysts. Material science contributes to energy savings in many additional ways, enabling more energy-efficient processes such as home air conditioning, high-temperature combustion, solid-state lighting and more efficient transportation. Electrical energy storage in Li-ion or redox flow batteries requires redoubled efforts from chemistry to design functional electrodes and storage materials.

A rough outline of the multiple role of chemistry is given in Figure 30.1. Material developments fall within all synthetic disciplines of chemistry, ranging from supramolecular and organic chemistry (lighting, molecular electronics, organic solar cells) over metal-organic chemistry (selective chemo catalysis of complex molecules, MOCVD processes for solar cells) to inorganic metals and ceramic chemistry. Catalysis plays the pivotal role among the process development efforts. This science deals with the control of energy barriers and thus allows the design of reactions with high selectivity and rapid performance. Heterogeneous and electro-catalysis will be the workhorses of the initial generations of energy conversion systems. Molecular catalysis in artificial or biological systems may, however, increasingly contribute not only to effective transformations of energy storage systems, but in later generations of energy systems perhaps even to direct solar light conversion through photocatalytic systems.⁹ Bio-catalytic processes will be relevant to the safe sequestration of CO_2 , as they use direct solar energy to convert gaseous diluted CO_2 into carbon-dense precursor materials for safe and useful deposition.

 $^{^9(\}mbox{Gratzel}$ 1981; Meyer 1989; Milliron et al. 2004; Alstrum-Acevedo et al. 2005; Kanan and Nocera 2008; Barber 2009; Yagi et al. 2009).



Figure 30.1: EnerChem designates the multiple contributions of chemistry to the energy challenge. The shading indicates the main contribution from material (dark grey) and process (light grey) developments.

Delivering the results required to address the energy challenge requires close collaboration among all conventional disciplines of the synthetic, physical and engineering branches of chemical sciences. The energy challenge is a strong motivation to further overcome traditional disciplinary boundaries and to consider chemistry not as a science auxiliary to applications, but as a broad-based discipline that creates materials and processes within its own paradigm based upon the molecular understanding of transformation processes of matter. This perception is expressed in the term "EnerChem," which designates the interdisciplinary contribution to the energy challenge by chemistry, working together with the biological sciences to develop biomass-based energy conversion approaches, and with the physical/ engineering sciences on electrical and mechanical energy conversion systems.¹⁰

The following text concentrates on the contributions of EnerChem to the challenge of integrating regenerative energy into supply chains of energy. Within this segment, the contributions of chemistry to the development of solar cells and to materials for windmills producing primary electricity are not considered. Neither are the multiple applications of improved materials and processes to saving energy by reduced consumption and through better utilization of fossil fuels considered here, despite their enormous importance. The applied solution strategies are firmly embedded in existing process chains and technologies. The reader is reminded that non-chemical issues of energy savings remain beyond the scope of this chapter.

30.5 Energy Scenarios

In the literature, several applications of energy scenarios are discussed¹¹ that describe economic or climatic consequences of regional developments. These scenarios assume different types of pressure from markets and politics and predict the consequences in macroscopic variables. The approaches document the necessity of discussing energy chemistry in systemic contexts. Non-technical factors are emphasized, with a strong emphasis on controlling the implementation and use of energy technologies. The technologies themselves appear as mere parameters in these scenarios.

In the present work, a different type of scenario is used. It is based on networks of technologies required to convert and store energy. Disregarding economic or political pressure, it describes the interaction of critical unit operations for providing energy to various non-related and non-coordinated applications (transportation, communication, production, domestic, retailing). The networks omit all physics-based components and are reduced to chemical processes. They assume the existence of grid systems for the exchange of electrical energy, for information exchange and for bulk material transport.

It is proposed to use the instrument of energy scenarios to identify research efforts leading—through the elimination of bottlenecks in the network—to a rapid impact of sustainable energy generation on the present fossil energy mix. An essential ingredient of future energy scenarios, besides sustainability (Asif and Muneer 2007), is continuity in the utilization of existing technologies wherever

¹⁰See http://www.enerchem.de.

¹¹(Islam et al. 2004; Ghanadan and Koomey 2005; da Silva et al. 2005; Solomon et al. 2007; Cosmi et al. 2009; Shaahid and El-Amin 2009).

possible. Further, the scenarios rely on primary solar energy and minimize the usage of fossil energy carriers. The contribution of biomass is indispensable, as long as carbon-based energy storage systems and structural materials like polymers are used to close the carbon cycle. In these scenarios, the use of biomass is restricted to a minimum due to potential interference with food production (Mader et al. 2002; Muller 2009) and the unknown risks for biodiversity and ecology presented by an excessive shift to energy farming.

It is imperative to minimize greenhouse gas emissions as fast as possible in order to keep to a minimum the already unavoidable consequences of climate change (Parmesan and Yohe 2003; Parmesan 2006; Archer and Brovkin 2008). For the scientific justification of this postulate, see the reports of the Intergovernmental Panel on Climate Change (IPCC).¹² This has motivated the consideration of utilizing the "raw material" of CO_2 (Aresta and Dibenedetto 2007) as an integral part of the solar energy storage portfolio. The use of this energetically unfavorable raw material would create an additional sink for the most relevant greenhouse gas.

Realistic energy scenarios take into account that, because the ownership of fossil and non-fossil energy carriers is not identical, competition will emerge with a strong pressure retarding the phasing out of fossil energy carriers. The timescales and intensity of this competitive situation will be determined largely by sociopolitical factors and by the awareness of the general public. The complex aggregation of non-scientific factors cannot be discussed in this work.

30.6 One Possible Target Scenario

Figure 30.2 presents a target scenario for an energy supply system based on regenerative primary energy coming from physical solar energy harvesting systems such as photovoltaic power (PV), solar thermal power sources and wind power. In any case, the raw energy is primary electricity.

The general structure of the scenario represented in Figure 30.2 concerns the flow of primary electricity from physical solar energy conversion. Although some will be used directly, or stored in stationary and mobile batteries, the bulk of primary electricity needs to be stored by chemical conversion. This is due to the fact that bulk amounts of primary electricity cannot be matched in their temporal availability to the temporal evolution of demand, not even with the most advanced regulatory tools of the smart grid (Beccali et al. 2004; Charles 2009). With the long-term reduction of base-load fossil power stations, it will become impossible to supply electricity upon request and the grid system will become unreliable. Thus every energy scenario based on primary electricity will need a chemical bulk storage solution to become operable as a replacement or complement to fossil power. The difficulty of achieving effective chemical energy storage with present technologies is the largest single bottleneck to the widespread application of solar energy. This

 $^{^{12}}$ See (Solomon et al. 2007); see also chapter 31.



Figure 30.2: A network of energy conversion processes requiring a minimal participation of carbon-based fuels that could be operative before fossil fuels are phased out. The shaded boxes designate families of chemical processes, whereas the unshaded boxes denote processes of physical origin. The boxes marked 'syn fuels,' 'H carrier' and 'H converter' indicate primarily catalytic reactions, whereas the other boxes designate other chemical processes in which catalysis may play a role. 'Future technologies' stands for all direct photochemical processes.

justifies placing the energy storage issue at the top of the priority list for future energy scenarios.

Without effective and fast storage plus recovery systems there is no control over the temporal distribution of energy. Even with intelligent management strategies, the capacity of the electrical energy grid to regulate temporal differences between supply and demand is limited to about 15–20% of the load. With respect to the sustainability criteria, hydrogen is the suitable carrier, although other chemicals could become relevant in grid dimensions from solar-thermal processing (Fletcher 1999; Lechon et al. 2008), which is not considered here.

A great number of future energy consumers has no access to an electricity grid infrastructure. It may be debated whether the construction of grid infrastructures will be the most suitable solution (Kaundinya et al. 2009); if not, then decentralized chemical energy storage of primary electricity will be required. Suitable technologies may be not the most effective storage systems, but they must operate in rough environments without much supervision and without being able to rely on economy-of-scale advantages. This may require completely different solutions than scaled-down strategies of the systems indicated in the present scenarios. Developing such strategies must have a very high priority, so that alternatives will be available in time to compete with the tendency to build a grid in all of these locations. It is remarkable that in this debate (Kaundinya et al. 2009) it is not the technological possibilities, but mostly socio-economic arguments that play the decisive role.

The chemical utilization of solar energy (Milliron et al. 2004; Alstrum-Acevedo et al. 2005; Barber 2009), leading directly to energy storage molecules (the photosplitting of water or other photochemistry) which represents a huge challenge for the chemist (Archer and Bolton 1990; Osterloh 2008), is not expected to contribute to energy conversion on the grid scale within the next decades, but is considered as potential later-generation technology. This assumption is based upon the notion that it is very hard to optimize a network of photon-driven charge separation systems while simultaneously developing devices to allow the immediate use of the energy from the charge separation (as hydrogen, for instance) to be converted into chemical energy.¹³ Due to conflicting property demands, this task is all the more difficult when charge-separation and energy conversion are coupled in a single device (such as a chemical water splitter or an "artificial leaf"). The fascination of the idea to combine solar energy conversion with chemical energy storage in a single-step process should not be disregarded (Barber 2009; Yagi et al. 2009), but from the present status there is still a long way to go before a sustainable and scalable process is achieved.

30.6.1 Batteries

Only a small fraction of the primary electricity from solar sources (Figure 30.2) can be used directly; a larger portion may be stored in batteries (Tarascon and Armand 2001; Wakihara 2001; Shaahid and El-Amin 2009), some of them operating in mobile applications such as cars. A substantial amount will have to be stored chemically: the day-night cycle and seasonal fluctuations require buffering on the medium and large scales, and a strategic buffer is required for large-scale and infrequent energy conversion. An intermediate form of energy storage systems is the redox-flow battery (de Leon et al. 2006), in which energy is stored in electrolyte

¹³(Bak et al. 2002; Aroutiounian et al. 2005; Ni et al. 2007; Yagi et al. 2009).

fluids; such systems are fast and can store large amounts of energy, but are of low energy density and thus suitable only for stationary applications.

Current research on batteries is largely phenomenological.¹⁴ resulting in a multiplicity of apparently competing "design" philosophies and still incremental improvements in performance. The necessary breakthrough to increase specific storage capacities will have to rely on an in-depth understanding of the complex interface processes of the charge-carrying chemical species (Li) during discharge and charge of the battery (Breger et al. 2007; Wontcheu et al. 2008). Only few studies discuss the battery as a system of electrodes, electrolyte and membrane. As a result, the most studied process of Li metal storage is much better developed than the other equally necessary component operations of the battery. Furthermore, besides research on electrolytes, more study of the cathode is required: the need to store Li-ions and electrical charge carriers simultaneously has proved to be a bottleneck in the advancement of batteries. Many aspects of material transport through membranes, adsorption or intercalation into electrode solids and chargeexchange processes, are not vet understood on the necessary atomic level. In particular, the solid-solid reaction processes occurring during the charging and discharging of batteries (Padhi et al. 1997; Tarascon and Armand 2001; Pasero et al. 2008) constitute an area of theoretical research¹⁵ concentrating on issues of defect dynamics, grain boundary chemistry and the reversibility of internal nanostructuring.

The design and control of these properties in functional storage materials require robust synthetic concepts and in-situ analytical tools rarely used so far (Breger et al. 2007; Agrawal et al. 2008; McBreen 2009). The augmented use of solid-state NMR has given clear insight into the complexity (Breger et al. 2007; Wontcheu et al. 2008) of the Li-ion battery system under operation. New in-situ tools are needed to provide experimental access to solid-fluid interfaces at ambient conditions. Synchrotron-based electron spectroscopy at tunable high energy and high resolution (Salmeron and Schlögl 2008) can offer such information.¹⁶ Scalable synthetic concepts based upon composite materials such as nanostructured carbon systems (Zhang et al. 2008; Hu et al. 2008, 2009) will be carried further and extended to other functions, as chemists aspire to replace electrode materials such as Ru oxide, which are expensive or unavailable in bulk (Armand et al. 1985; Music et al. 2002). Progress in this area depends on the capacity to handle the complexity of solid-liquid and solid-solid interfaces without present-day oversimplifications that prevent the simple translation of existing fundamental knowledge into functional systems.

Combining solid-state chemistry with electrochemistry (Jamnik and Maier 2003) is critical for the entire energy issue and has far-reaching implications for

 $^{^{14}({\}rm Gao}\ {\rm and}\ {\rm Dahn}\ 1996;$ Padhi et al. 1997; Croce et al. 1998; Tarascon and Armand 2001; Wakihara 2001; Shaahid and El-Amin 2009).

 $^{^{15}(\}mbox{Arico et al. 2005}; \mbox{Balaya 2008}; \mbox{Manthiram et al. 2008}; \mbox{Hu et al. 2009}).$

¹⁶(Chan et al. 2006; Knop-Gericke et al. 2009; McBreen 2009; Mori et al. 2009).

many aspects of the energy challenge such as fuel cells and water electrolysis. The operation of all solid-state storage systems for thermal energy (Kalogirou 2004; Steinfeld 2005) or hydrogen (Schlapbach and Zuttel 2001; Nath and Das 2007; Wang and Yang 2008) depends crucially on defect engineering and on nanostructuring in order to allow reversible diffusion processes to occur with constant kinetics. Electrochemistry would serve as diagnostic tool in these systems. The interdisciplinary nature of such research is realized (Gooch 2000) but rarely approached,¹⁷ as substantial disciplinary boundaries between experimentalists and theorists in both fields hamper rapid progress.

30.6.2 Hydrogen

An intermediate chemical energy carrier is hydrogen,¹⁸ which may be used in energy conversion plants either as a direct buffer molecule or as a precursor to other chemical systems intended for longer-term storage or bulk transportation. In the scenario of Figure 30.2, hydrogen is the central storage form. In contrast to the common perception of a "hydrogen economy" (Barreto et al. 2003; Muradov and Veziroglu 2008; Woodhouse and Parkinson 2009), here it is assumed that hydrogen will not become an energy carrier for the end user but rather be applied in processes concerning energy storage in the background of the electricity grid. This use of hydrogen has no adverse effects on the climate and avoids the downsides of insufficient energy density, and of potential dangers in handling and storage under mobile applications. Mobile energy applications may be operated through batteries, as indicated in Figure 30.2, or, if necessary, using synthetic fuels (see below).

Hydrogen generation from water electrolysis¹⁹ is a fundamental challenge to electrochemistry and material science. Neither the present efficiency nor the applied electrode materials render present technologies scalable to grid dimensions. As this challenge has been addressed for quite some time, it is expected that massive progress in understanding the underlying interfacial processes (Bockris and Potter 1952; Conway and Bockris 1957) and the tailoring of surface electronic structures (Heller 1981) of non-noble metals used in electrodes (Martin et al. 1996; Jaramillo et al. 2007) will be necessary for any scenario utilizing primary solar energy. Substantial help for designing and understanding the relevant experiments (Rossmeisl et al. 2007; Salem 2008) comes from theory. Reaction mechanisms and derived descriptors for the prediction of the most relevant surface properties of electrode materials are being developed, allowing the conclusion that new compositions besides the conventional noble metals focusing on Ru and Pt can be found for applications to split water (Rossmeisl et al. 2007). The discovery of

¹⁷(Arico et al. 2005; Balaya 2008; Manthiram et al. 2008; Hu et al. 2009).

 $^{^{18}({\}rm Fischer}$ 1986; Bak et al. 2002; Nath and Das 2007; Muradov and Veziroglu 2008; Tributsch 2008; Barber 2009).

¹⁹(Kanan and Nocera 2008; Tributsch 2008; Clarke et al. 2009; Kanan et al. 2009).

the Co-phosphate system (Kanan and Nocera 2008) is a promising step in this direction.

The combination of water electrolysis and primary electricity generation from PV (Clarke et al. 2009) or from wind has been studied quantitatively and reveals clearly that a combination of electrolysis with hydrogen storage is a technologically and scalable option far superior to other forms of electricity storage in terms of efficiency and storage capacity. The study using a PV array (Clarke et al. 2009) further demonstrated that such technologies can operate well in a stand-alone mode and would not require a grid system to back them up.

Hydrogen is not a perfect energy carrier when it comes to mobile applications, which may be better served with a combination of mobile batteries and stationary electricity storage. Hydrogen is particularly unsafe for energy transfer over long distances. The transformation of hydrogen into a safe transport form is thus desirable for bulk energy transport. Ammonia is a transport form of hydrogen²⁰ that does not contribute to the carbon footprint of energy supply (Klerke et al. 2008; Kothari et al. 2008). It can be manufactured with practically no energy loss, and a transport infrastructure for grid-relevant dimensions of ammonia already exists to meet the world's demand for fertilizer. The ammonia-splitting reaction is less-well developed and requires a fundamentally different catalyst (Hellman et al. 2006) than the one used for the forward synthesis (Ertl and Freund 1999) reaction. Multiple efforts in this direction show promising results, suggesting that an ammonia-exchange energy chain (Lovegrove 1996; Schlögl 2003; Klerke et al. 2008) is quite feasible. The frequent concerns expressed about the possible use of ammonia as an energy storage system address its toxicity and smell as well as its potent greenhouse effect, which entail severe constraints on leakage. Most of these concerns arise from a biased comparison of energy carrier systems: were the existing petrochemical energy carrier systems to be evaluated on the basis of the same criteria of handling safety, odor and toxicity, and were the decades of development towards optimized handling systems considered, then little difference in risk potentials would remain. The concerns are all valid to a certain extent, but many measures can be taken to minimize the risks. This is evident in the existing global system of trading ammonia, which operates on a large scale without any major accident. The scant attention that ammonia is receiving as a potent energy storage system (not for end-use applications, but as a medium to long-term trading and storage form) is caused by a strong influx of non-scientific arguments, resulting in the premature exclusion of a potential solution with low barriers to large-scale application.

 $^{^{20}(\}mbox{Lovegrove 1996};$ Schlögl 2003; Christensen et al. 2005; Sorensen et al. 2005; Christensen et al. 2006).

30.6.3 Carbon Dioxide

Alternative forms for hydrogen transport are methane or methanol (Olah 2005; Olah et al. 2009), which could be generated in dry sunny areas from CO_2 and solar hydrogen in a bi-directional gas transport operation yielding the valuable by-product water. Here, substantial efforts in catalyst development and process design are still necessary (Xu and Moulijn 1996; Aresta and Dibenedetto 2007) to reach grid-scale molecular conversions with acceptable energy losses (compared to those we face in the present energy supply system). CO_2 may be considered as the raw material for a variety of uses, as shown in Figure 30.3.

There are multiple uses of the greenhouse gas wherever abundant solar hydrogen allows the chemical transformation of CO_2 , or biological processes can harvest CO_2 and the resulting biomass can be fermented or chemically refined. However, all of these uses are energetically unfavorable and require excessive solar energy to compensate for this inefficiency. Figure 30.4 presents some thermodynamic data. It is clear that CO_2 is a stable molecule, such that its activation through reductive transformations requires substantial energy, generated mainly by the formation of water or of a larger oxidized hydrocarbon. It is interesting to see that the coordination of water or of an additional oxygen atom significantly lowers the energy needed, disproving the argument that CO_2 is the "most stable molecule" and should not be used for further chemistry. These data also constitute the basis for understanding that aqueous solutions of CO_2 are still reactive with respect to corrosion or mineralization, a fact that is most relevant for the underground dumping in CCS technology. CO_2 is a useful raw material on a large scale, especially when the inevitable high-energy byproduct water is of additional value. It should be added that the collection and purification of CO_2 presents a significant and energy-consuming "detail" often ignored in the energy discussion. Otherwise, the sequestration of CO_2 alone may be achieved more effectively by biological collection and chemical transformation into solid carbon, as described in Figure 30.3 and below.

The key purpose of CO_2 chemistry is to remove large quantities of the greenhouse gas. This must be done without creating immediate or long-term dangers from the high-density storage of this gas, which is toxic in concentrated form. In Figures 30.2 and 30.3, its use is indicated in a cycle of converting solar hydrogen to synthetic fuel. This cycle may be seen as a chemical alternative to photosynthesis, yielding hydrocarbons instead of the oxygenated molecules like carbohydrates resulting from the biological process. The energy density of the resulting products from such a chemical process chain is high. The efficiency per photon of solar energy may be low, but could be substantially higher if existing biological systems were used to generate synthetic fuel (e.g., by growing corn and fermentation to alcohol, followed by acid-base chemistry to yield hydrocarbons). If solar hydrogen is combined with solar thermal process energy (Steinfeld 2005), quite substantial efficiencies can be expected.



Figure 30.3: Uses of CO_2 as a raw material. Solar hydrogen is required in all conversion processes, including biological fixation. The boxes marked 'electro reduction,' 'chemo reduction,' 'dry reforming,' 'syn gas' and 'reductive dehydration' denote catalytic processes, the boxes 'fermentation' and 'biological fixation' stand for biological transformations. Methane is an intermediate product and energy carrier; the boxes 'hydrocarbons' and 'methanol' denote products for the chemical industry.

The catalytic technologies necessary to reduce CO_2^{21} are not ready for application in large-scale processes. There is a good understanding of the basic chemistry of the molecule and its activation by coordination to active metal sites (Leitner 1996). The creation of either homogeneous or heterogeneous catalytic processes with acceptable energy parameters has yet to be achieved. A benefi-

 $^{^{21}({\}rm Nakamura \ et \ al. \ 2003;\ Sloczynski \ et \ al. \ 2004;\ Yang \ et \ al. \ 2006;\ Liu \ et \ al. \ 2007;\ Raudaskoski \ et \ al. \ 2009;\ Tang \ et \ al. \ 2009).$



Figure 30.4: Heat of formation data for some species related to CO_2 . The data was taken from (Aresta and Dibenedetto 2007).

cial boundary condition of such a process should be its stand-alone technology, i.e., its operation without having to link the process to other chemical syntheses. This design is a pre-requisite for scalability in decentralized units attached to the points of CO_2 creation, avoiding further losses by transportation of this already energetically unfavorable process.

The reverse conversion process of hydrogen generation is the oxidation of hydrogen to water leading to electrical energy. This can be done rather conventionally by combustion in motors or turbines, or by fuel cell technologies.²² The resulting clean water is an additional valuable product in areas of the world where energy is used to generate drinking or irrigation water. The underlying chemical issues of the catalytic oxidation of hydrogen have been studied for a long time (Conway and Bockris 1957; Fisher et al. 1982; Volkening et al. 1999) and have yielded many technologically viable solutions. One of the greatest problems is the need to use noble metals, presenting the same problem as water electrolysis. It can be expected that the material issues will be solved for both processes in combination. There are additional challenges associated with high-temperature combustion, requiring catalysts to avoid nitrogen oxidation and special materials for the mobile parts of turbines in high-temperature zones. The general advancement of combustion science (Law and Kwon 2004) suggests that these issues do not

²²(Minh 1993; Singhal 2000; Steele and Heinzel 2001; Haile 2003).

represent as critical a bottleneck as the storage of primary electricity in chemical bonds.

A certain fraction of applications that require high energy density, such as planes, trucks and ships, will need synthetic fuels based on hydrocarbons. Using solar hydrogen and biological carbon sources, several process chains involving catalytic conversions that provide high quality synthetic fuels are feasible. The inclusion of biomass collection (McKendry 2002a,b; Islam et al. 2004) balances the carbon dioxide emissions: alternatively, carbon dioxide, if collected at the source, can be hydrogenated with solar hydrogen (Damen et al. 2006) as a sequestration measure. In such a way, a sink for already emitted carbon can be constructed, and a bypass provided for the continuous emission of man-made CO_2 to the natural deposition of carbon dioxide. All steps of the chemical transformations and the plant biology for the harvesting organisms need to be optimized substantially over existing technologies. Besides the challenging problem of CO_2 hydrogenation on the global scale (Xu and Moulijn 1996; Aresta and Dibenedetto 2007), the coupling of efficient plant biology to an effective chemical work-up of the biomass and the chemo-catalytic transformations require combined and concerted development.

This process chain is probably not suitable²³ to generate the bulk of transportation energy as biofuel. Neither should it be pursued as such a large-scale option, since the CO₂ involved has such a long atmospheric lifetime that a sustainable reduction of the atmospheric CO₂ level (Montenegro et al. 2007; Archer and Brovkin 2008) to early industrial times would hardly be possible. A combination of physical solar energy conversion and chemical energy storage systems involving no carbon emission will be required for the largest single energy utilization in transportation. Solar electricity (wind, PV) with hydrogen bulk storage (or redox flow batteries) coupled with battery-powered vehicles (hybrids for heavy load) may satisfy the needs of many transportation applications.

30.6.4 Synthetic Fuels

Synthetic transportation fuels for applications that require high energy density can be generated chemically by a variety of methods, all of which are known in principle and are or have been operated on industrial scales. Figure 30.5 summarizes some options. Synthetic fuels are storage forms of solar hydrogen. The carbon part can come from fossil sources, from biomass or from CO_2 as indicated in Figures 30.2 and 30.3. This part of the energy scenario is to a large extent proven chemical technology and a large body of knowledge exists on these transformations. All steps can still do with improvements in catalysts and processes, but none of them will represent a bottleneck in the energy supply system. An interesting area of research deals with the direct valorization of methane to olefins or synthetic fuels. Despite a concerted scientific effort (Fierro 1993), the results are still unsatisfactory: the energetic difference of methane from all its possible

 $^{^{\}overline{23}}$ (Cheng et al. 2006; Nath and Das 2007; Smeets et al. 2007; Muller 2009).

desired products requires the difficult combination of a tailored catalyst for activation and a dedicated reactor/process to preserve the desired products from post-synthetic combustion.



Figure 30.5: Synthetic fuels can be generated by a wide variety of processes. Solar hydrogen is required and synthetic fuels are thus a storage form of hydrogen. The carbon part can be taken from fossil sources or from CO₂ as shown in Figure 30.2.

Biological fixation of CO_2 offers the attractive option of depositing carbon dioxide as inorganic carbon after harvesting through biomass. In this way, a sink for CO_2 emissions is created, which can be operated such that no extra energy besides that stored in the biomass is utilized to generate "synC." This product is a largely aliphatic carbon polymer with a substantial oxygen content (Titirici et al. 2007, 2008; Paraknowitsch et al. 2009). Its structure is fundamentally different from that of $coal^{24}$ The material is thus not suitable as a novel fossil energy carrier

²⁴(Marsh et al. 1986; Haenel 1992; Gorbaty 1994; Van Heek 2000).

substitute (Longwell et al. 1995; Van Heek 2000), termed "artificial coal" or "accelerated coal." It may be used to regenerate the soil losses from carbon (Mader et al. 2002; Lal 2004) and thus help enhance agricultural productivity. Additional non-energy uses of this carbon feedstock are conceivable (Haenel 1992; Song and Schobert 1996; Schobert and Song 2002), but much additional work will be required to tailor the structure according to potential uses. A novel field for carbon chemistry may emerge, following in the long tradition of coal chemistry (Marsh et al. 1986; Haenel 1992; Gorbaty 1994), and exploiting the tremendous progress in our analytical and mechanistic understanding of carbon-based polymeric structures. In any case, large quantities of carbon can be stored safely as a solid (Lal 2004; Li and Tang 2006), avoiding the multiple unknown risks of direct CO_2 underground sequestration (Damen et al. 2006; Ketzer et al. 2009; de Best-Waldhober et al. 2009). In addition, the biological fixation of CO_2 uses solar energy directly to solve the separation and purification issues without requiring engineering solutions and their energy costs. However, the process is sustainable only if the inner energy content of the biomass is sufficient for the structural transformation, and if all non-carbon components (fertilizers, minerals) are isolated and redistributed into the biological cycle.

30.7 Technical Summary

The transition from fossil to solar energy is impossible without the ability to store primary energy in chemical carriers. Only then can the erratic, seasonal and geographic disparities be matched with the demand structure for energy. This requirement is independent from the existence of an energy distribution grid, but may require different solutions for grid-based and stand-alone energy supply structures.

Chemistry is a strategic science for solving the energy challenge. By way of process design, it provides central elements of sustainable energy supply chains (Asif and Muneer 2007; Deshmukh and Deshmukh 2008) based on the physical separation of charge carriers driven by solar radiation. In all of these processes, as well as in the necessary intensification of fossil energy utilization, which was not discussed here, chemistry will have to provide tailored structural and functional materials. The controlled synthesis of materials (with controlled and reproducible property profiles) rather than "samples" is another central task for chemistry in the energy challenge. EnerChem is chemistry's contribution to energy science and designates a multidisciplinary, long-term approach that integrates synthetic, analytical and engineering capabilities throughout the entire field, ranging from theoretical and physical chemistry over inorganic and organometallic to organic and biological disciplines. The provision of sustainable energy on the global scale is a major, long-term and international challenge. It cannot be solved in the foreseeable future by, for example, a single funding program. An educational effort to train chemists in this interdisciplinary sense will be essential to enable the engineering disciplines creating the system networks to develop creative and scalable solutions. Among scholars, an awareness of the diverse research needs within the energy challenge is also essential; the penetration of energy aspects into personal research agendas can be substantially improved.

The effective conversion of the simplest molecules like methane, water and carbon dioxide presents an enormous challenge to chemistry. Mastering these reactions will be the pre-requisite for all renewable and sustainable energy supply strategies. Nature was also confronted with this difficulty, and soon resorted to the photosynthesis (Barber 2009) of more complex molecules that can be more easily stored and handled. The benefit of this was the enormous complexity in functional materials and processes, with the overall result of low energy densities. Fossil fuels are so attractive largely due to their complexity, resulting from denaturation processes that take place during their geochemical transformation, and beneficially providing for simple energy transformations at high-energy densities.

The three disciplinary sub-forms of heterogeneous, homogeneous and biological catalysis bear a pivotal responsibility in solving the challenge of converting small molecules. Clearly, the present efforts in "energy catalysis" are still insufficient. The frequent discussion of potential energy conversion processes in terms of the technological hurdles of "inefficiency" should not be conducted in the conventional phenomenological manner, by recurring to qualitative concepts. A fundamental approach is needed, respecting the unity of catalysts and reactant as a system with multiple feedback relations in between (Norskov et al. 2002), which could be derived using the examples of converting energy storage molecules. From there, breakthroughs in improving the present technology levels can be expected.

Chemical energy research must expand as broadly as possible in order to capture many possible solutions. The research strategy may be structured in the long-term "discovery searches" discussed elsewhere,²⁵ and in activities driven by the shorter-term intention to facilitate the transition from pure fossil into a fossil-plus-renewable energy process chain. In order to identify the most pressing research needs, it is proposed to use the tool of energy scenarios as networks of energy conversion processes and to analyze these networks with respect to critical bottlenecks in knowledge and technology, as elaborated in the text. The scenario discussed highlights the necessity to think of energy supply systems in terms of systems rather than as isolated challenges. The processes discussed in the text are likely to be important, but clearly serve as examples rather than solid predictions of the future of the energy system. The science-based approach contrasts with the suggestion to structure energy research according to economic and societal needs (Voorspools 2004).

Converting primary electricity into chemical energy and storing renewable energy in chemical bonds (Lewis 2006) is the most effective storage strategy. This approach includes energy storage in molecules and in batteries. The present

 $^{^{25}(\}mbox{Claassen et al. 1999};$ Lewis 2006; Ni et al. 2007; Muradov and Veziroglu 2008; Turner et al. 2008).

work suggests adding to the ingenuity of the chemist two sets of boundary conditions: First, existing infrastructure and technologies, as well as existing knowledge, should be used as much as possible. This requires networks of processes with a maximum number of known elements and a small number of critical bottlenecks. Major technological implementations may then be possible within relatively short timescales of decades. The second boundary condition is to absolutely minimize the utilization of rare compounds like noble metals in global applications. This requires substantial theoretical and experimental material science efforts in addition to the demanding process design.

The immediacy and urgency for finding a large-scale solution makes it tempting to prioritize the various concepts. However, it seems inappropriate to favor or disfavor any of these strategies at present, while we have still insufficient insight into the structure of future energy supply networks. The scientific exploration of all of the concepts must have priority before decisions can be taken outside the scientific community in favor of or against any of these concepts.

As there will always be the need for non-electrical energy, it is further useful to study direct chemical solar energy harvesting through high-temperature processes and solar-thermochemistry (Fletcher 1999; Kalogirou 2004). These processes and their chemical implications are not covered here. Solar-thermal power generation requires energy absorbers with unprecedented functional properties. Solarchemical processes present major challenges to solid-state chemistry, as ways must be found to control the kinetic issues of solid-gas transformations.

The present approach stands in some contrast to the more radical suggestion of using chemistry to build an artificial photosynthesis device²⁶ as a single-step (Lewis 2006) process. This most challenging approach may be an element in later-generation energy supply networks (Grubler et al. 1999). The enormous hurdles to developing, optimizing and implementing such a device into a worldscale technology may take more time than we have at our disposal to begin with the transition to stable, renewable energy scenarios characterized by a controlled availability of energy. To this end, the storage of solar energy in chemical bonds is the common strategy, but a modular rather than an integrated approach is suggested here. The integrated generation of chemical storage molecules can be accommodated without difficulty into the scenario presented in Figure 30.2. Their development is not a rival but a valuable addition to the process portfolio. It should further be recognized that economical factors may not support a rapid, disruptive technology change based on an entirely new process.

The use of hydrogen has been the subject of multiple and controversial discussions in the past (Barreto et al. 2003; Muradov and Veziroglu 2008). Acknowledging the arguments and taking into account the critical need to reduce our carbon footprint, we suggest using hydrogen as a universal energy storage molecule as soon as possible. This does not imply using small mobile hydrogen storage devices

 $^{^{26}}$ (Gratzel 1981; Meyer 1989; Milliron et al. 2004; Alstrum-Acevedo et al. 2005; Kanan and Nocera 2008; Barber 2009; Yagi et al. 2009).

(Schlapbach and Zuttel 2001), but rather buffering the grid against fluctuations using stationary installations (Christie et al. 2000). Transportation energy, a key target of the concept of a "hydrogen economy" (Barreto et al. 2003), can be supplied to a large extent from electric traction, with batteries being charged partly from primary electricity and partly from the stored energy. With respect to reducing carbon emissions, it is essential to minimize the use of carbon-based chemical storage systems to buffer short-term fluctuations in solar energy supply systems. Frequent use of the stored energy would mean a further large contribution to greenhouse gas emissions. Solar hydrogen is further needed in large quantities to provide chemical alternatives to geological CO_2 storage. Such alternatives also provide clean water and synthetic fuels.

It may be concluded that the task of transforming primary electrical energy into hydrogen is the single most pressing bottleneck faced by the sustainable use of regenerative energy. The fundamental scientific challenge is to control the kinetics of oxygen redox chemistry. Oxygen evolution and oxygen reduction are critical steps in all energy harvesting and transformation systems. This results from the fact that 4 redox equivalents are needed to reduce or oxidize one di-oxygen molecule. A whole sequence of elementary steps dealing with highly energetic and reactive intermediates of oxygen (peroxides, radicals) needs to be managed, such that only minimal damage of the reaction center takes place during the complete turnover. Besides reactions to split water, fuel cell reactions and even transformations of biomass into less-oxygenated hydrocarbons are additional examples that call for the improved control of oxygen reactivity.

Largely carbon-free energy storage is a medium-to-long-term target; intermediate scenarios using methane, methanol or ammonia or any combination of these carriers as storage forms may be implemented as a transitional solution. Carbon dioxide sequestration measures taken to compensate for emissions, even when they are energetically unfavorable, must be introduced in parallel to such large-scale storage. It is strongly suggested that sustainable and safe chemical transformation strategies be designed and implemented, and that underground storage be used minimally. This should serve only as a temporary measure, with the clear goal of recovering CO_2 later for safe disposal. The enthusiasm about geological sequestration as a permanent measure²⁷ is not shared by this author, as no evidence for the permanent safety of such a large-scale experiment can be given if the CO_2 is deposited underground in a non-recoverable, and non-mineralized form.

Biomass-based technologies have potential for the sequestration process. In addition to carbon mineralization, a possible auxiliary role for biomass through synthetic fuels is seen for transportation energy, along with the atomic-efficient use of biomass as a feedstock for the chemical industry, which requires about 3% of all primary energy supply. Transformation of biomass into the required olefins is thus an important step toward decoupling the continuing needs of the chemical industry for hydrocarbon feedstock from the present fossil sources.

²⁷(Zwart and Boerrigter 2005; Li and Tang 2006; Friedmann 2007; LeNeveu 2008).

30.8 Global Aspects of Chemistry for Energy

The discussion so far has clearly shown that there is an option to meet the energy challenge with regenerative energy harvesting techniques, coupled with as yet nonexistent storage technologies and using the existing infrastructure for electricity. There is no fundamental need to invoke novel, non-existent technologies like nuclear fusion with magnetic or fast reaction concepts. We can and must effectively utilize highly concentrated electrical and process energy if these nuclear technologies are to succeed. In view of the potential of regenerative energy, and considering the socio-political consequences of the emergence of vet another oligopoly of nations controlling such high-end technologies, it is assumed that regenerative energy supply will always play an important role in long-term scenarios. It has also been discussed that the timescale for the transition from fossil-based to fossil-supported and then fossil-free energy scenarios is decades rather than years. With these prospects, it is appropriate to discuss the status of chemistry as the science discipline enabling this transformation. Both processes and materials will be critically needed for the generation, storage and distribution of regenerative energy. We note that the structures of physical sciences and of life science are substantially different from that of chemistry. It is thus difficult to investigate the state of an "energy science" which does not yet exist as discipline in science with respect to its structure and dependence on external factors in a global context. Neither is it necessary to discuss the general global character of the sciences as forerunners of economic globalization, as discussed in this volume.

The technical summary presented above serves as a basis for identifying the needs and challenges of regenerative energy research to the extent that chemistry is involved. In more general discourses on the subject, it is clearly accepted that the necessary knowledge forming the basis of technologies either already exists or can be generated without much effort and many resources. It must be emphasized that this is not correct. The preceding text shows clearly that the most fundamental and basic questions of chemistry are at center stage of the energy challenge. More than a century of fundamental and applied chemical science have not been sufficient to solve these issues, to an extent that the existing answers are anything more than a basis for designing research strategies as illustrated above.

This surprising knowledge gap is due in part to lacking technology demands, and in part to the present socio-economic system's inertia in responding to the challenge. The global nature of this system, outlined in several contributions to this volume, creates the global dimension of the energy challenge. It is stated here that the availability of sufficient energy in suitable forms is the foundation for all of man's sociocultural activities and thus a strategic enabling condition of human existence, requiring the utmost attention of those responsible for the progressing development of mankind.

The following section will elaborate on some factors affecting the necessary rapid adaptation and change in our energy supply scenario. These factors are illustrated from the point of view of a scientist. We identify factors inherent in science and other factors from outside the field that represent boundary conditions of energy research. The term "science" is understood here as describing a global scientific community of researchers active in energy research and more closely in EnerChem. It is no limiting factor that these scientists are distributed over many countries, as chemical science is fully globalized in the sense that no cultural barriers to cooperation among scientists exist. Many institutional barriers do exist, however, some of which will be discussed below.

The origin of the internationalism of chemistry goes back to the symbiotic relation between chemical science and the chemical industry. This unique relation between theory and practice, which does not exist, for example, between physics and industry, was and still is a key driver in the evolution of the chemical industry as a strategic but rarely seen enabler of all technologies; the chemical industry provides the material solutions to most modern industries. The global character of the chemical industry in turn created a global network of academic relations, forming the basis of a global science. The excellent scholarly organization of chemistry, and today's successful collaboration among many learned societies creating international networks of dissemination of chemical knowledge, have built a strong foundation for global scientific activities. This network has responded sensitively to the challenge of energy science in a plethora of conferences and new publication channels such as books and journals. It began to incorporate energy issues in teaching and international student exchange programs. It initiated the creation of many national programs for funding research. The intensive evaluation process controlling every activity of a chemist is a further strong impetus toward internationalism, as international review is a common practice for projects, research programs and even individual research papers.

30.9 Limiting Factors Within the Science

Under these excellent internationalist conditions, the energy challenge should be in good hands, with chemistry expected to provide strategic contributions. A non-exhaustive description of these solutions was given in the technical section of this chapter. Even for this set of answers, it becomes apparent that substantial interdisciplinarity (between inorganic, physical and organic chemistry, biology, physics and engineering sciences) and strong collaboration will be essential. Most researchers share this view, but there is a set of serious shortcomings preventing the desired rapid and deep impact of chemical science on technology needs. Many of them are of global character in the sense that they are present in many national communities. The close cooperation of individuals leads to de-facto standards of practice. This causes strong trends toward mainstreaming paradigms, and fails to support local attempts to overcome deficiencies. In this way, the normative power of global cooperation is auto-inhibiting adaptive trends toward optimizing internal and external scientific practices.

30.9.1 Lack of Awareness

Chemistry traditionally has been directed towards the synthesis of novel compounds and materials. That the functional analysis of chemical processes is being equally important for the directed synthesis of material solutions in energy science is less well accepted as an area of chemical research. The response of chemistry to energy is thus to a large extent a synthetic approach of providing new molecules and solids to be used in energy applications. This is misunderstood, but unfortunately sometimes practiced as the "repackaging" of familiar research activities. The notion that the energy challenge requires a functional understanding of basic chemical reactions not yet under the control of chemistry as exemplified in the technical section (e.g., splitting water or activating CO_2) is not well communicated. This is particularly true for an understanding of these processes beyond deciphering the biological mode of operation. A popular view that copying biological processes would automatically lead to effective and structurally simplified processes has proved to be incorrect. The history of the ammonia synthesis process (Schlögl 2003) delivers an excellent example for this conceptual fallacy.

Another aspect of lacking awareness is the sheer dimension of the energy challenge, also outlined in the technical section of this chapter. Intelligent and elegant synthetic pathways to energy chemicals such as hydrogen are of little use if they cannot be executed in global dimensions. A typical example of this dilemma is the splitting of water directly into the elements performed in nature by photosynthesis (Gratzel 1981; Barber 2009). A tremendous effort is undertaken to copy or mimic this reaction that is not particularly effective in nature. Given that we have many more degrees of freedom for choosing reaction conditions than nature did, we may consider other solution strategies. Despite the well-known fact that the extremely complex biochemical process of photosynthesis has an overall efficiency of about 0.5%, synthetic chemists have gone to great lengths to copy it. From a theoretical point of view, understanding the details of biological water splitting holds important answers for the design of artificial systems as well, but it should be made more clear that re-engineering biological processes is a very demanding objective which chemistry has not often succeeded in achieving.

Many energy conversion reactions use noble metals (Pt, Ru) or other rare components such as nanoparticles with organic modifiers. As outlined above, sustainability clearly precludes building an energy solution upon a resource that is insufficiently abundant. On the scale of energy applications, many material resources are rare, limiting the choices of chemistry. This holds not only for absolute abundance, but also for the life cycle of these materials: if nanoparticles degrade rapidly under operating conditions, it makes no sense to suggest their use under considerations of energy efficiency and waste minimization. This aspect of global chemistry, dealing with mineral resources and their mining or recycling, is not a popular research topic. It must be noted, however, that industrial chemists are well aware of such issues and are trained to look for resource diversity and feedstock changes. An interesting gap between the perceptions of academic and industrial chemistry can be noted here, having to do with the dislike of many academics for "applied" aspects of their work.

30.9.2 Lack of Sustainability

In energy research, sustainability has to address both the solutions and the research effort. All chemical energy conversion processes are complex sequences of individual reactions, which must be carried out at separate spaces and times to qualify as an energy storage solution. The creation and optimization of chemical process flows is a long-term challenge that will require multiple design iterations. Many projects in energy chemistry ignore this critical need and try to solve an isolated problem without considering the systemic effects.

Energy research is not sustainable unless it follows an initial idea, via laboratory feasibility studies, to a level of execution at which life-cycle considerations can assess the idea's usefulness on a larger scale. What is at stake here is the complex issue of the interface between science and technology as a strong barrier to diffusing scientific solutions into technological realizations. One consequence of globalization is that many theoretical scientists become aware of this barrier and, in some communities, actively surmount it by supporting small companies.

The evolution of new dimensions of synthetic chemistry, to allow the modification of supra-molecular properties of materials in a much better way than is presently possible (Schreiner 2003), is another aspect of sustainability. Within the synthetic ingenuity of chemistry, we still are confined to synthesizing objects of low hierarchy, as it is difficult to control the aggregation of molecular objects to the complex, non-translational packing so frequent in natural systems (enzymes), and so desirable for energy conversion. Chemistry must refocus more broadly on its own methodical evolution (Grimsdale and Mullen 2005) than on its enabling function for many other sciences (life science, material science). The short-lived character of many funded project initiatives precludes the necessary long-term efforts. In this respect, the globalization of science, with its strong trend towards harmonizing procedures and conditions of funding, is not beneficial.

A critical scientist's estimation of the extent to which a hypothetical solution to an energy problem may be sustainable is often considered "non-scientific" or "applied" and hence not highly valued. This prejudice may be of some value with respect to predictions concerning the possibilities of industry and engineering to improve the quality and efficiency of complex processes. The semiconductor or photovoltaic industries are lucid examples for the beneficial effects of global markets and global competition in driving technological evolution. However, there are multiple aspects of an energy-related reaction that can be interrogated for sustainability beyond sensible estimates of economy of scale. Many research projects might not be necessary if this argument were applied, although it is important not to discourage revolutionary novel solutions. The simplest way to safeguard against such streamlining is to perform a life-cycle analysis at a stage of maturity defined by the reproducible repetition of the intended function in a research project. The tremendous demand for speed in science, partly inflicted by global competition for rewards, is contra-productive for such measures that could help to self-protect against research efforts that must be deemed superfluous in terms of achieving an energy research objective.

30.9.3 The Role of Theoretical Science

The arguments made in the preceding section open the discourse about the role of theoretical science in the energy arena. From the view of augmenting our fundamental understanding, no project can be rejected, provided that it is conducted with the scientific rigor necessary to allow insights to be derived from it. Many involved in the energy challenge believe, however, that solutions must be imminent given the enormous amount of funding and the pressing need for solutions. This creates a strong preference all over the world for two science trends, both of which are adverse for sustainable solutions.

One trend is the belief in a phenomenological search for solutions. Besides many dead-ends, several creative and new concepts may arise from this approach. However, they do require serious and rigorous investigation after their identification. Yet the global practice is to initiate the founding of start-up companies and attempt to commercialize solutions without having the necessary scientific understanding. The other trend is that nothing follows upon an initial report of a new discovery and the science "caravan" moves on.

This practice wastes many resources in academia and in the economy. Moreover, it has the strong negative effect of discouraging whole lines of solution strategies once the first element fails to be realized commercially, or to set a research trend thanks to rapid and simple reproduction. The approach further creates a spirit of exaggerated expectations by societal forces, which is anything but justified in view of the magnitude of the energy challenge. This difficulty is an import to Europe from Anglo-American science culture. Its adverse effects will be felt only in longer-term perspectives. It should be said, however, that this culture of attempting a rapid transition from science to technology also has the positive aspect of stimulating more risk-averse communities.

It is extremely important, however, to recognize from the technical part of this chapter that the energy challenge cannot be solved by a phenomenologicalengineering type of approach. What it requires is a deep fundamental research effort that revisits the basic research issues of several disciplines. The technical summary lists several examples and highlights the strategic relevance of solving these issues for the energy challenge.

The fundamental aspects of energy science and the long timescale of its operation also entail the need to develop suitable curricula to educate energy science specialists in several research fields inside and outside of chemistry.²⁸ This has

²⁸See also chapter 25.

been realized in some engineering disciplines, but is not so common in traditional basic sciences.

30.9.4 Interdisciplinarity

The technical part of this chapter has clearly shown that a key characteristic of energy science is its interdisciplinary nature. Although generally agreed and strongly advocated by funding agencies, there are serious hurdles to practicing this interdisciplinary research. Many energy research projects consider only intradisciplinary solution strategies. Systemic considerations or even systemic research strategies are rare. This allows faster action in the initial phases of a project, but creates serious problems in later stages of integrating knowledge to the extent that new solution strategies need to be applied. A useful example is the conversion of biomass to biofuels (Ragauskas et al. 2006), where after initial hype, the complexity of selecting useful pathways is only now becoming apparent (Kunkes et al. 2008; Clark et al. 2009). Reasons for the preferred intra-disciplinary research strategies are:

- 1. The lack of a suitable technical language shared by neighboring disciplines. This deficit inhibits the first contacts between scientists, creates prejudices and builds hurdles to communication.
- 2. The lack of basic knowledge about best practices between disciplines and the limitations to facilitating interdisciplinary discourse through the transfer of knowledge. A typical example is a lack of mathematical training hampering the concise exchange and evaluation of data.
- 3. The disharmony of practices by graduate and undergraduate students between disciplines as well as between countries in frequently needed international interdisciplinary collaborations. This encompasses aspects of education and training, and aspects of executing research. The much-lauded global character of science is not reflected when it comes to executing practical collaboration on a level of training below the Ph.D. Yet, at this academic level disciplinary socialization is already strong, and academics' openness for truly interdisciplinary work is decreasing. The strong push by industry to hire students at the earliest possible point in time is another obstacle to investing the extra time required to learn interdisciplinary research.
- 4. The dominant role of the pressure to seek immediate rewards for scientific efforts. This greatest of all obstacles prevents collaborators from finding the time to overcome the above-mentioned hurdles. Many researchers simply consider it too time-consuming to engage in serious interdisciplinary research requiring them to understand new techniques and procedures.

This incomplete list looks quite negative in light of the clear trend of global science to foster and encourage interdisciplinary research. Against this stands merely the time horizon to bring researchers of different national and disciplinary backgrounds together and let them develop the necessary common working ground beyond superficial demonstrations. Such forced interdisciplinary activity is not suitable to bring about truly new science and, due to its bureaucratic overhead, can prevent even effective disciplinary research. It should be emphasized that many positive counter examples of fruitful interdisciplinary collaborations do exist. They result from the long-term efforts of individual researchers who feel that the advantages of collaboration do surpass the adverse barriers indicated above. In Berlin, an example exists of an interdisciplinary collaboration in the field with strong multilateral global nodes in the network. It was created through the national Excellence Initiative (*Exzellenzinitiative*) as a "Cluster of Excellence" (UNI-CAT).

30.9.5 Scholarly Coordination

Some areas of science are traditionally well coordinated on a global basis. Highenergy physics, genetics, astronomy and earth system science may serve as examples.²⁹ These sciences developed many of the practices enabling globalization in the economic sector long before the wider society recognized the strategic character of developments like the Internet or digital data sharing and archiving.

Science thus has the ability to globally self-organize its activities. In the energy challenge, this coordination has yet to take place. This would be most desirable in view of the great pressure put on decision makers in economy and society. The pivotal discipline of chemistry is not used to major collaborative activities and follows internal reward systems that support the individual achievements over collaborative activities. This is deeply rooted in the character of chemical science, with its concentration on synthetic efforts that today can be handled by small teams or even individuals with perfected descriptive rigor (synthesis protocols and structural analysis of the products). Chemistry that does not follow this paradigm was outsourced from the core discipline into neighboring disciplines such as physical chemistry, chemical physics, material science or chemical biology.

It is thus not expected that traditional chemistry will take the lead to better organize the research efforts in energy sciences from within the community of practitioners. It is more likely that a new community of "energy chemistry" may form from the boundary regions of disciplinary chemistry. This new community may then practice self-organization in a way that includes coordinated efforts directed toward internal projects as well as toward interaction with the external parts of the scientific community.

It is not advocated that external bodies such as funding agencies or science planners occupy this niche of organization of scientific activity. Neither is the sometimes inadequate presentation of normal scholarly discourse to the general public (as recently with the IPCC) helpful in a situation where society expects from its many scientists a constructive and serious attempt to solve this major

²⁹See, for example, chapter 28.

challenge. Any moves presenting individual views or even profiling measures to the public are fatal to the aspired-to and essential self-organization of energy science.

30.10 Global External Interfaces

We assume that the ability of chemistry to deliver its critical contributions is also limited by factors outside the scientific community. These factors are not independent from the community, as there are multiple transactions across the boundary. But because decisions to moderate the adverse influences cannot come from within the community these factors are classified as external.

30.10.1 Lack of Independence

Energy science is an expensive operation requiring billions of dollars for its effective operation. There is great public support for energy science, at least within the usual five-year life cycle of standard funding. Indeed, the fact that many energy science centers have been created worldwide documents that the long-term character of the challenge has been recognized. This should give science the necessary independence to develop its strategic views and to bring about reliable solutions based upon rigorous understanding.

This ideal view is distorted by the strong influence of economic factors. Both individual researchers and funding bodies readily follow the argument that a given research idea has to be evaluated on the grounds of real or hypothetical economic feasibility against the backdrop of the present energy market. This is a dangerous evaluation criterion that blocks many useful concepts, as they appear either uneconomical or even "disruptive" in the way that they would not fit into today's economic paradigm.

It is argued that new energy scenarios must find a connection to the present situation due to the mere magnitude of remodeling the global energy infrastructure. At least for technologies bridging to existing energy supply chains (such as solar fuels or batteries for transportation), this requires the potential to break even with current technologies. The following important points should be considered when new technologies are evaluated.

The energy economy is not a free market, but highly regulated by local and international political settings. Global enterprises, cartels of production, subsidies on energy use and the fact that no price has to be paid for producing CO_2 are strong factors that make energy prices dependent on politics rather than on non-speculative market forces. The accuracy to which an economic break-even of a technology can be judged is thus limited and may be obsolete when political boundary conditions change. The debate about the value of photovoltaic devices in Europe is a timely example for such a critical influence of "economic" considerations.

Economic factors directly influence decisions to fund energy projects. The debate about electro-mobility and required advanced battery technology strongly affects funding opportunities in inorganic chemistry and electrochemistry. The quest for biofuel from agricultural products is a massive impetus for science projects in biology and chemical engineering aspiring to "biorefineries." There is little longterm analysis behind such decisions, as useful as they may turn out to be. Science investigating the adverse effects of monocultures of energy crops on biodiversity and the stability of ecosystems finds little support, as does climate science looking into experimental verification of "CO₂ neutrality." Energy storage by chemical conversion is less popular for funding than research into smart grids and components of solar thermal power and windmills, as these are established technologies. The trend emerges that research supporting existing infrastructure and technology is much more readily funded than disruptive concepts. This represents an autoinhibiting effect for conceptually different approaches to an energy scenario not based on traditional fossil fuels. It is advocated here that more diverse funding for science would be strongly needed to complement the large-scale programs planned for energy science approaching technological application. The bottom-up creative power needed for truly innovative concepts is strongly suppressed in science close to the product development phase. Both aspects are needed, but there should be a sensible balance between research and development.

Economic factors also affect the development of regionally adapted solutions. Global trade and the massive trend to outsource production from high-level societies into emerging economies exports not only labor but also energy supply pressures. This massive but rarely discussed consequence of globalization means that emerging countries not only have to provide for their own energy needs, but also for our energy in the form of imported products, with the effect of minimizing the latitude for seeking local, non-Western answers to the energy challenge. Decentralized distribution, unusual feedstock or unconventional transportation solutions are hardly possible with a global technology-exporting industry selling power stations, grid solutions and transportation systems based on identical concepts to all places in the world. A science-driven debate about alternatives to the first-world's energy supply and models of consumption for areas still without such infrastructure has found insufficient support.

Economic factors stabilize the existing infrastructure and thus tend to delay the market penetration of novel technologies. This argument is not inherently connected to market economics, as a far-sighted economic development would welcome the diversification of its technologies and resource streams. In many cases, we observe globally a defensive attitude of the economy against such diversifications. This may be rooted in the regional view that there is no need for diversification that causes additional costs. This is amplified by the deep global interdependence of financial institutions. This mechanism narrows the view of global players that their regional diversity may require different answers in different markets at different stages of maturity and local development. Failure to follow such a diverse trend reduces the options for science to turn results into technology and thus to prove the validity of novel concepts and materials. The global economy should exert massive pressure on science to come up with diverse solutions.

30.10.2 Dissemination and Open Access

A substantial portion of all shortcomings discussed so far can be related to communication problems. Without analyzing this important point any more deeply, it is easy to see that hurdles in dissemination of scholarly information have a fundamental effect. The many researchers in institutions and regions who are not privileged by wide access to scholarly dissemination results are simply not aware of the knowledge and communities dealing with issues critical to their work. The fact that most scholarly information is still enshrined behind the walls of commercial publishers (Velterop 2003; Antelman 2004; Armbruster 2007).³⁰ constitutes a high hurdle to global cooperation and exchange. This is also true, to a lesser extent, for the flow of information between academia and industry. The fact that the explosion of academic productivity makes it even more difficult to follow the important developments from outside the community creates a growing barrier to the equal dissemination of knowledge and understanding among all stakeholders of the global energy issue.

If open access cannot be realized for the global scientific community,³¹ then it would be a critical enabling project to collect and sort the energy-relevant information and make this consolidated body of information available to the global community. Such an action could copy the activities of the IPCC to perform a similar, yet critical analysis for the earth system sciences.

30.10.3 Relation to Politics

The uneven distribution of information within the science community is one factor affecting the communication between science and politics. Politics has almost no independent access to scholarly information and relies on aggregation through experts and their dialogue with political actors. Politics has to decide on science sponsorship and on measures to implement the results from science. Comprehensive information for both politicians (access to primary science results at least for selected uses) and experts is key to the best possible consultation. The transformation process required to render scientific primary information useful in the political discourse is a critical yet neglected action in global energy science. The normal dispute within the science community needs to be consolidated and transmitted in the form of trend statements to the outside world. The failure to do so creates information gaps filled by non-experts spreading opinions that are dangerous and hard to refute with arguments based upon validated facts.

The history of chemical accidents in production is a vivid example of how inadequate communication can ruin the efforts of a whole science. Today, chem-

 $^{^{30}\}mathrm{See}$ also chapters 28 and 32.

³¹(Velterop 2003; Antelman 2004; Poschl 2004; Schlögl and Velden 2005; Armbruster 2007).

istry has a bad reputation in society and politics stemming from the false image that it has denied risks and scrimped on safety measures. This reputation represents another hurdle for dialogue between science and politics. The chemical science community is not as attractive as other branches of science and thus not so present in the small budget of attention that politics tends to share with all sciences.

The complex relation of chemical sciences with politics in general has an adverse effect on the flow of information, with the consequence that incorrect views spread easily within the political debate. This does not enhance the influence of science versus economic interests when it comes to strategic decisions or the design of funding programs. These deficits are less a challenge for Anglo-Americans, with their different approach to discourse and lobbying than in Europe. In Asia, politics pays a great deal of attention to the energy challenge, and despite the strong influence of economy, science organizations also enjoy substantial influence in the debate. It can be stated that inadequate self-organization, paired with the issue of chemistry's reputation, results in a deficit in the dialogue with politics. This is less a problem for issues affecting the traditional chemical industry, where the longstanding industry-academia relations are helpful. In the more interdisciplinary part of chemical energy science, this is a more serious problem, as can be judged from the quality of many political statements on energy issues. The consequences can be critical if incorrect decisions on energy policy are taken on the basis of substantially incomplete scientific information. An example in Europe was the biofuel program, which caused multiple image disasters for the future of helpful biomass conversion concepts within and outside of the energy science community. Another example of such a process is the ongoing debate about carbon capture and storage as a measure that would make it possible to continue using fossil carbon without damaging the climate. The technical part contains a number of facts known in chemistry but not clearly understood in other sciences, yet politics has stepped forward with firm conclusions about the usefulness of this method. The observation that much is unclear and that other alternatives for carbon sequestration (albeit less commercially attractive under today's conditions) may be investigated should cause politicians to be more open to the evolution of knowledge and to strongly boost the speed at which critical knowledge gaps are closed.

30.10.4 Chemistry and Society

The demand for energy is a global issue. However, its origin and the societal context in which it is projected are local and quite diverse. Energy science will thus have to develop diverse solutions against the unifying trend exerted by the global operations of the energy industry. A global challenge requires a set of local answers.³²

 $^{^{32}}$ See also the discussion in the survey chapters 16 and 24.

Chemistry may have to learn that these diverse needs do exist in addition to local perceptions. The local view of an individual scientist in a local society finds its reflection in controversial views on approaches and solutions within the global community. Much of this discussion is not fruitful and hinders the evolution of our understanding. It further spills out to society, where it is often abused for political debates not intended by the scientific discourse. It would be a great achievement if energy researchers would become open enough to improve contact with their local society and then reflect their experiences upon the global view of consolidated international results. These contacts should be bi-directional in the sense that both parties exchange information. Societal concerns are serious boundary conditions to science and technology as illustrated by the example of nuclear energy. Early awareness and serious analysis of such concerns, but also effective dissemination of the results of such studies through independent bodies, are obligations that science and scientists owe to their societies. This aspect also has a global dimension, as the immediacy of information dissemination may create rapid worldwide concerns over local issues that are difficult to comprehend elsewhere. An example is the speculation about the possible reduction in the area of the rain forest area for sugar cane production. In reality the two areas are thousands of miles apart from each other and would not compete. Unfortunately, in other respects of bio-renewable feedstock this competition does or did exist, calling for a differentiated view rather than for a general statement.

The energy issue demands from its researchers a substantial dose of societal reflection that goes far beyond the requirement of purely academic research. It is not only the possible consequences of individual findings that need such consideration, but research practice as a whole that requires critical reflection. The international composition of this newly emerging scientific community facilitates such reflection, as it reduces the sharp boundaries for paradigmatic modification inflicted by the traditional disciplines.

The societal context of energy science demands critical competence by the researcher to perform a rudimentary assessment of a product life cycle and of process sustainability. Both criteria are better indications for priorization of resources than the expected distance to market. The central responsibility of the energy researcher is, however, to remain driven by curiosity and rigor in practical actions. Missed opportunities are the greatest loss that society can suffer from the work of science. This is true globally, calling for moderation in the speed of the race toward academic rewards and demanding that room remains for critical consideration and interdisciplinary systemic discourse over the results.

It is superficial to analyze the behavior of science and society within a single point of view. Many activities support energy science both within the community and within society as a whole. The global operation of science greatly accelerates these activities, leading to similar thoughts and concepts. It remains the responsibility of individuals to use the positive momentum of global science and combine it with the local character of challenges and required solutions.

30.11 Conclusions

The quest for a sufficient and sustainable energy supply is a global issue of strategic relevance. This has been recognized widely in the many incidents of technical and economic dysfunctionalities of the globalized fossil-based energy industry. It is also emerging that energy supply and climate protection are two aspects of the same challenge.

Most efforts to cope with the challenge are directed towards enabling strategies put forward by the international industry, dovetailed with national short-term interests of various political kinds. Climate protection targets, protectionism to industry sectors and regional interests are among the causes retarding a sciencebased rational treatment of the situation acceptable for the global community.

Science would have to play a pivotal role in this situation. It is the only institution that can provide a basis of facts free of political or economic interests. It would have to deliver reliable information for decision makers in industry and politics. Moreover, it would have to construct a sustainable basis for creating the technology options required to make responsible strategic decisions. Such decisions are frequently demanded within short timescales. The need to sustain the value of capital investments and the target of minimizing the consequences of climate change are helping to drive this trend. For the most part, science is still not prepared to meet this challenge and does not see that its efficiency needs to be optimized between creativity and responsible priorization.

The analyzing and modeling part of climate science has made an impressive effort to coordinate its actions under the umbrella of the IPCC, which may still need improvement.³³ This truly global science organization may serve as a prototype for other energy sciences that have to provide the solution strategies and serve those who bear the responsibility for implementation. In these areas of science, encompassing both natural and social disciplines, globally responsible and sustainable operation is still lacking, resulting in disorientation, duplication of activities and overall inefficiency. The present chapter does not advocate a gigantic coordinating structure. Instead, it calls for a global network to provide a blueprint for a hierarchical structure of energy science. This hierarchy would be multi-dimensional in traditional disciplines and in the distribution between theoretical and applied research. In such a strategy the hurdles of lacking communication, dissemination and archiving the research efforts should be solved, as all the technology required is at our disposal.

The role of chemistry in its cross-disciplinary role of EnerChem could be pivotal as its globalized culture and proven performance constitute critical factors for success. Moreover, the multiple contributions chemistry can deliver to energy science qualifies this discipline as a key player among the classical disciplines in the areas of energy conservation as well as regenerative energy storage and use. Its output is knowledge critical to the engineering sciences. They will have to

³³See chapter 31.

provide multiple regionalized solution strategies that fit within the global boundary conditions of sustainability and scalability. Such a functional distribution of tasks cannot be created by fiat, but requires self-organization motivated by mutual exchange and understanding. This casts global dissemination and discourse in a critical role. The development of infrastructure and funding are needed to optimize existing efforts and structures that are based largely on individual and temporary activities. Funding agencies must orchestrate this in a globalized manner without killing the creativity of emerging solutions.

Energy is an area where science, society and economy meet in a critical discourse. The fact that the present energy supply is fully globalized through economic players and international political bodies (IEA, OPEC) requires an equally globalized response from the sciences. This is a dimension of scientific activity comparable to the nuclear challenge, to high-energy physics, astronomy or the exploration of space, all of which serve as positive examples for science operating responsibly in the global dimension. Any truly stable solution to the energy issue can be achieved at a reasonable price and with a minimum of socio-political tensions only if global science lives up to this expectation. The present dominance of the economic factors is a result of the lack of organization of the bodies of knowledge providing sufficient deep and wide insight to those who determine the societal boundary conditions. In this way energy science is a test example of our ability to organize local needs within a set of global boundary conditions.

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