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The Revolution Continues: Energiewende 2.0

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The energy regimes of the world are subject to constant change. This is a consequence of developments in available raw materials, technological advancement in the transformation, distribution, and usage of energy, and changing societal as well as economic expectations. It has seldom been attempted to strategically influence these developments and the German "Energiewende" (energy revolution) has taken on precisely this challenge in a one-country effort. Although the reactor catastrophe of 2011 in Japan gave the movement renewed impetus, it is not the reason for striving toward the "Energiewende" nor has it had any real influence upon it.

The "Energiewende 1.0," in addition to eliminating nuclear power, strategized a two-part approach consisting of renewable energy (RE) as well as regulatory measures in consumer and mobility sectors in order to make a meaningful contribution to environmental protection. This was to be realized through accessibility to CO_2-neutral electrical energy and a lowering of the primary energy consumption across the entire electrical grid. The approach makes sense with respect to the main goal of environmental protection, and if possible, will help initiate similar measures within the European Union. Also beneficial would be the export of these ideas in the political arena as technology and policy recommendations. The subsequent, very general discussion which has been initiated has questioned these assumptions and, together with a very narrow public understanding of the "costs of regenerative energy", has lead to a rather skeptical public opinion on the subject. Now a "master plan" is needed.

The dynamic character[1] of the energy sector and the influence of many factors that cannot be controlled by a national master plan make this kind of conception illusory. Instead, an ordered and continuous public discourse is needed on the development of the energy regime through which political decisions can be made concerning a calculable and functioning framework. Due to their relatively constricted reach, national and regional attempts at environmental protection may be detrimental for Europe-wide solutions without which actual qualitative improvements in environmental protection are not possible. This would render well-intentioned and often influential economic efforts completely ineffective.

Constant control and continuity in steering the long-term transformation of the energy regime are prerequisites not only for the necessary economic engagement but also for the continuous involvement of the public, who must be considered the target group of the energy revolution. At this time, the reactions of industrial partners range from observant to rejecting; they complain of the heavy burden although none are making a discernible effort to constructively shape the change. The transformation process will bear enormous benefit if realizable goals are set and are not influenced by ideology. Currently selective, technology-based rules are in place which can lead to undesirable consequences such as increased CO_2 emissions even though RE has improved access to electricity. What should be a general discussion is bogged down in details such as questions of cost and the market situation concerning the supply of electricity.

Figure 1 gives information to help frame this debate. The energy market for private customers (Figure 1 A) is appreciably larger than that for industrial customers. The Renewable Energy Law (German: *Erneuerbare-Energien-Gesetz* or "EEG") surcharge has had a significant impact on both markets. However, the electric bill for industrial customers exceeds 3 % of the production costs in only a limited number of cases, for example in the chemical industry, and this has been heavily discussed in connection with the exemption from the EEG surcharge. On the other hand, for private customers the costs of electricity and its distribution are approximately the same as the corresponding taxes and fees (Figure 1 B,C). It can be seen that electricity costs are a significant but minor factor in the energy regime and that the general discussion must again revolve around the major aspects of the energy revolution. The term "Energiewende 2.0" is meant to encompass both such an expansion of the discussion as well as activity on a systematic level. The international community which is closely watching the energy revolution in Germany would be disappointed if we were unable to progress beyond the present impasse. Also, this failure would surely be a detriment to climate protection.

A motivation for the discussion could be the analysis of the consequences of the fact that Germany not only has very ambitious goals for the reduction of greenhouse gases but is at the same time discontinuing the use of nuclear energy as a low-CO_2 source of power. The result is a considerably

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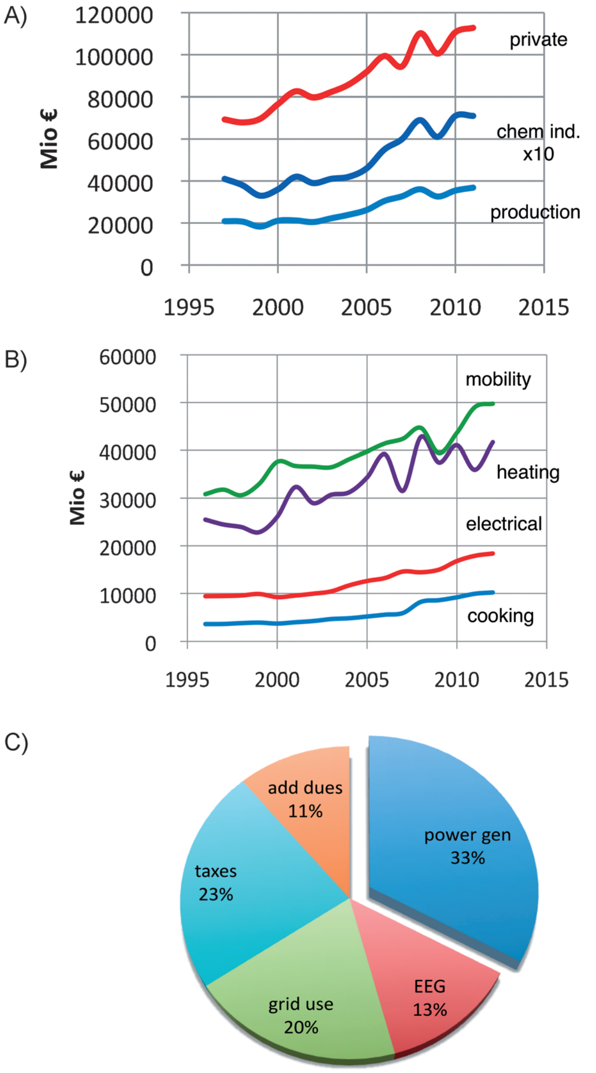

Figure 1. Key data for the development of the German electricity market over time since 1990 (source: BMWI Databank http://www.bmwi.de/DE/Themen/Energie/energiedaten.html). A) Expenditures for energy in Euros per year for the production industry, the chemical industry (×10), and private households. B) Distribution of energy costs for private consumers according to usage. C) Cost components for private electricity customers in Berlin (source: Vattenfall).

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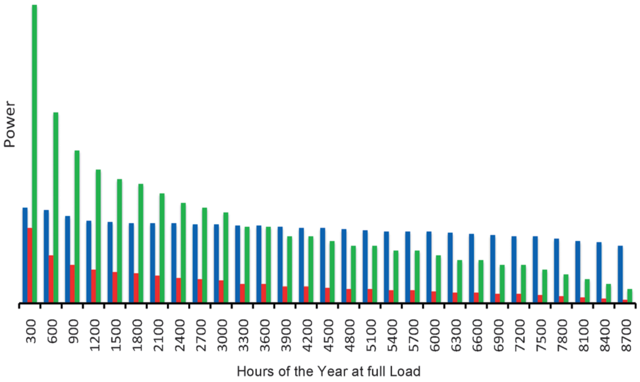

Figure 2. Schematic load profile in Germany (maximum load approximately 80 GW). Blue: necessary load, red: RE power input today, green: RE power input in approximately 2035. Abscissa: hours at full load per year. The profile of the RE results from the assumed stable mix of water, wind, PV, and bioenergy.

stronger push toward integration of RE energy regimes in order to each potential CO_2 reduction as soon as possible.

Figure 2 shows the impact of power input from regenerative energy sources on an electricity regime which is not continuous due to dependence on weather conditions.[2] It is evident that the contributions from RE today are already substantial but in no way follow the trends of the consumer market. Consequently, the operation of current fossil fuel power plants must be increasingly flexible. However, with the planned substantial increase in RE found in the "Energiewende 1.0" the discrepancy between supply and demand will be made worse. Also, the tremendous excess in generated energy within a narrow time window is exacerbated by a simultaneous lack of demand. This means that conventional power plants are still needed and leads to a long-term coexistence of the two systems of power production to support constant (or, as is planned, decreasing) energy needs. The consequences of the current conflict between power plants is reflected in a rise in CO_2 emissions in Germany.

This duplicate structure and further strain owing to the required improvements to the electrical grid will lead not to a solution consisting of energy storage and individual regenerative power input, but rather to a scenario in which fossil fuels[3] will continue to be an energy source in the long term, even with moderate costs for CO_2 emission from the EU emissions trading system. This may be a good general solution in the sense of an optimized development of the energy regime if the excess electricity from renewable sources can be used elsewhere effectively and economically to reduce CO_2 emission. One way this could be realized will be discussed further below and should offer a contribution to the required discussion on the systematic development of the energy revolution. This discussion must also be steered away from the often overemphasized issue of electricity.

For excess electricity available for only a short time, economical thermal applications are reasonable, for example central heating systems, because a direct CO_2 reduction in the heating sector can be achieved with a rather small investment. However, most of the available energy product "electricity" should find use in high-quality products through chemical energy conversion. Primary electricity stored in chemical bonds can be used, for example, in the transportation sector, although we are still quite far from the solutions required by the chemical industry. The use of RE will indeed play a role in electromobility but will likely remain quantitatively limited. Also the chemical industry itself still must still make significant progress toward manufacturing efficient and inexpensive batteries.

A possible scheme for such an overall system is shown in Figure 3. This should not be seen as the only possible solution or as the much-desired master plan. In this scheme it is assumed that the future fossil and bio-based energy carriers will be either gasified or burned in a combination unit in order to, together with RE, produce synthesis gas or electricity according to the current need. Subsequently, in a "solar refinery,"[4] platform molecules like methanol or methane will be produced either from synthesis gas or from stored solar hydrogen and CO_2. Also, synthesis gas may be directly converted into liquid fuel. A future relevant target range of solar refineries is the generation of feedstock for the chemical industry. This is currently far too uneconomical. The use of methanol produced from fossil fuels as a universal platform for supplying energy has been highly developed over the last 40 years and a useful summary can be found in a book by F. Asinger.[5] A later concept from G. Olah[6] was also propagated to close the CO_2 cycle. Combinations of the synthesis reaction for methanol, the Sabatier reaction, and the Fisher–Tropsch reaction, each with individually optimized catalysts, would also be conceivable to obtain nearly full conversion of hydrogen under constantly changing load requirements. Methane can either be used as fuel, stored through the "power-to-gas" scheme, or fed back into the system. Thus, there are several ways in which renewable primary electricity can be used to solidify the entire energy regime. This leads to many flexible options which, depending on the load situation and financial requirements, can ensure that maximal CO_2 reduction is possible together with positive economic conditions.

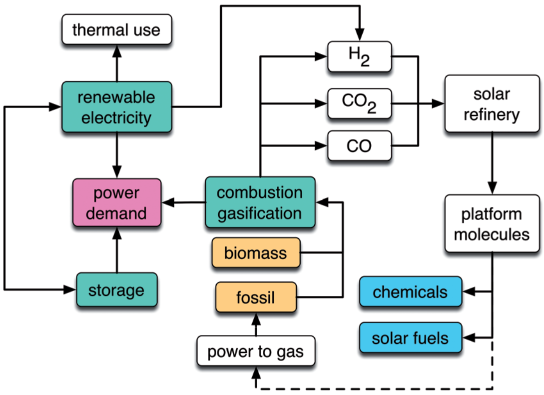

Figure 3. A scheme coupling regenerative, volatile electricity to the rest of the energy regime. The power supply is assumed to be a mix of renewable and fossil primary sources, like that given in Figure 2 (green bars). Also assumed is the accessibility to a large excess of primary electricity. The system would be regulated according to the current demand for electricity. Conventional thermal power plants would be replaced by a gasifier which provides heat or synthesis gas and may be adjusted flexibly according to load requirements.

A few general estimates can help illustrate how this cooperation might work. The world's largest production plant for the synthesis of fuel from synthesis gas (PEARL in Qatar) produces about 5000 tons per day, or about 5% of the German daily fuel consumption. If synthetic fuel were produced in Germany on this scale from CO_2 and renewable excess electricity and if, instead of diesel, an oligoether (a mixture of oximethylene ethers 3 and 4[7]) were chosen as a simply produced alternative additive with half the energy density of diesel, two synthesis gas production plants would be needed, each with daily capacities of 5000 tons. Such plants would consume approximately 16000 tons of CO_2 and 85 GWh of electricity for the production of the necessary renewable hydrogen each day. These estimates contain no values for the energy consumption of the plants and peripheral operations. Still, according to this model an economically viable product can be produced which can be easily introduced into existing markets. In addition, emissions will be reduced by burning less fossil fuels. A secondary advantage of these "designer fuels" that feature a homogenous chemical structure is their particle-free combustion; however, significantly larger quantities of these fuels are needed to have a noticeable effect in automobiles. In this way the production of RE would be pushed by the need for chemical energy storage and no longer by electricity.

The numbers indicate the dimensions of the hurdles to be overcome in the energy revolution. Seen from the perspective of basic research, in catalysis the relevant processes for change in the energy regime, with current known losses of about 50% of the available energy, still present significant challenges for the development of a comprehensive, rational design rooted causally in know-how and not phenomenologically through correlation of material and function. Only this kind of knowledge, at least in the long term, can ensure the optimal efficiency in these very large technical-chemical processes.

For implementation of the suggested process chain found in Figure 3, extensive systematic, scientific, and technical research is required before a concrete plan may be conceived. In addition to the chain of efficiency paralleling these processes from RE production to fuel allocation, the critical points are mainly questions of stability and investment costs for limited operation times which make any implementation currently somewhat risky. The reaction of CO_2 with hydrogen[8] and the subsequent processing include well-understood steps. But this does not mean that each step can be scaled up without problems especially when one considers the repercussions of the economic conditions on the technology in question. Several steps of each of the discussed conversions of CO_2 are complex sequences of chemical conversions and separation. They could be made easier if we had processes at our disposal which led directly to the final product through complete conversion of the reactants (an example for this is methanation and the Fischer–Tropsch synthesis of liquid fuels). An economical electrolysis method serving as an intermittent load would also offer significant challenges[9] for research and technical development. The development of stable electrodes and the use of non-precious metals, suitable membranes, and efficient reactor designs are relevant topics for basic research. The results of verified test installations can be built upon for the development of large-scale facilities. If we were also able to conduct the subsequent catalytic steps intermittently at the pace set by volatile primary electricity, which is not possible at this point, the necessary facilities would become simplified because temporary energy storage would no longer be necessary. The scheme in Figure 3 could be realized as demonstrator by 2035 with the necessary concentration of resources.

The example illustrates how chemistry, process engineering, and systems research can work together with the chemical industry, the energy providers, and the electrotechnical and automobile industries to find systematically advantageous solutions. Especially the chemical industry together with plant construction could take on a leading role through interdisciplinary efforts based on relevant individual experience. It seems to be important in chemical research, partly due to the scale of the project, to not be limited to biomimetics[10] and structures stabilized by self-assembly under mild conditions, but also to put improved emphasis on the solution of the older challenges[11] of hydrogen production and usage. Also, since nature does not require precious metals,[12] it can serve as an important role model for us when deciding which materials to choose.

Naturally the question should be asked whether the complexity of the developments discussed here is necessary or whether there are simpler solutions to build a sustainable energy regime. For this we define "sustainability" in a specific way to mean the closing of all material cycles which markedly affect our living environment. In that case we must eliminate fossil fuel sources and the use of carbon as energy carriers beyond simply implementing renewable raw materials if we wish to significantly improve the process shown in Figure 3. A hydrogen economy in which the only catalytic processes are water splitting and the catalytic conversion of biomass could be a possibility. In contrast, the combination of regenerative primary electricity with batteries and thermomechanical storage would not be feasible: we will always need chemical energy storage in part due to material energy supplies for high-energy applications as well as for an economical compensation of discrepancies between supply and demand stemming from the volatile nature of primary regenerative energy. The main message of this contribution remains that an energy revolution cannot succeed without chemistry and catalysis,[13] even if one chooses not to adhere to all of the ideas discussed in this paper.

The concepts used until now of selective efforts based on single fixed parameters are not suitable for achieving the energy revolution in a cost-efficient way in the next 30 years—especially if climate protection should also result from a modern energy regime. In order to reaching these goals, much research is still needed. Here there must be a balance between basic research and finding novel solutions and methods, on the one hand, and the cooperation of science and industry for transferring concepts into usable technology, on the other. This latter process will be accomplished after we have gained industrial experience from test runs on the relevant dimensions. The public can then decide on ways of implementation after assessing critical technical and economic realities as well as the nontechnical consequences of their decisions. A cost appraisal also belongs to this process which, in contrast to the current practice of comparing estimated costs to the cost of the production of electricity from fossil fuels, must describe extensively the difference in costs between new and conventional technologies.

The involvement of the public in the transformation of the energy regime should be eased through communication and transparency even during the research phase. However, without support from politics, which would inform the public, organize international application, and devise suitable regulations, these extensive research efforts would all be for naught.

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