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Systemic aspects of the transition to sustainable energy

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Summary. — The supply of free energy to our societies is today an intricate system comprising the regimes of technologies, regulatory frameworks, socio-economic impacts and techno-ecological interactions. As a consequence it is challenging to define clear directions or even device a master plan for the transformation of a single national energy system into a sustainable future. Even the term "sustainable" needs extensive discussion in this context that should not be defined solely in technological or ecological senses. The contribution illustrates some of the elements of the energy system and their interdependencies. It will become clear that multiple reasons exist to change the traditional generation and use of energy even when climate protection is not a sufficiently strong argument for a change.

The desire to transform national energy systems into more sustainable forms is a growing global trend. The motivations behind this are, however, quite different. In Germany the dominant official driving force is the desire to contribute to climate protection. As the greenhouse gas emission (GHG) of Germany is limited (about 3%), the direct effect of national measures remains small. The German GHG emissions are of the same order of magnitude as the GHG emissions of single large industrial processes in the world

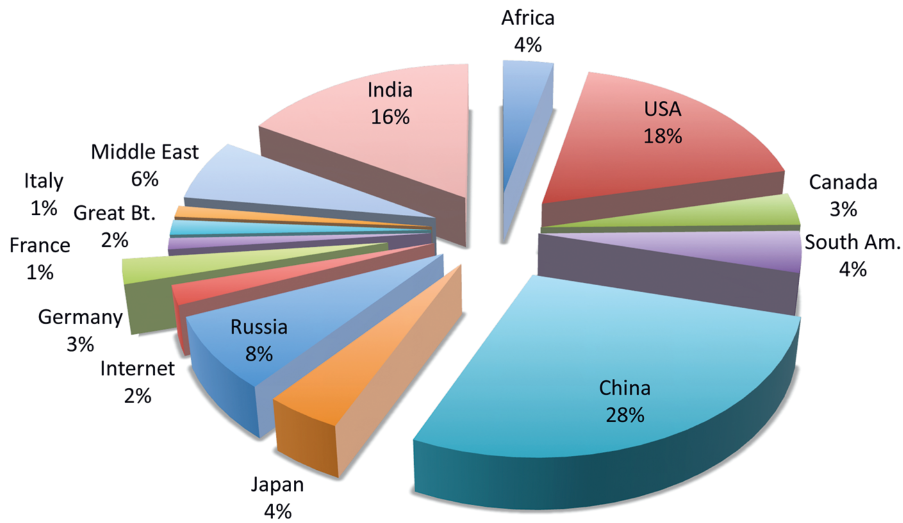

Fig. 1. – GHG emissions in the world. Selected emittents are shown. The whole emission in the world accumulated in 2013 to 35000 million tons CO_2 equivalents. (Source BMWI, 2014.)

(ammonia synthesis, steel making) offering possibilities to their reduction in a much simpler setting than the GHG reduction of a whole complex society. On the other hand, if we cannot demonstrate that a sustainable energy system is compatible with societal goals then we will not be able to make any impact on the energy issue on a global scale (fig. 1).

In China air quality issues force a reduction of emissions of dust and of fossil combustion products. In Japan energy supply issues force the use of natural gas and of criticised nuclear power. In Russia, India and Canada expansive fossil combustion is justified with economic growth requests.

A critical motivation for cutting back on fossil fuels for energy conversion is the unclear future of the supply for gas and oil. The extreme changes of the oil price in the last 30 years precludes the notion that supply and demand dictate the price that may thus be used as indicator for the availability. The debate about "peak oil" and its quite political interpretation as indicated in fig. 2 exemplifies that economic parameters are not suitable as indicators for the systemic development of an energy system. The same can be deduced in the gas market with the observed volatility of the price with the advent of shale gas and expected uncertainty with the future of this heavily debated technology.

In summary, the energy supply of societies and countries is a hot political target with multiple consequences for the evolution of our societies. Among the many scenarios for its evolution the motivation to minimize the GHG emission is often advocated but much less often put into the centre of practical measures. Many reasons ranging from "climate change disbelief" (can an observation be "believed"?) to the uncontrolled maximization of economic success impede practical measures. The long time scales involved and the

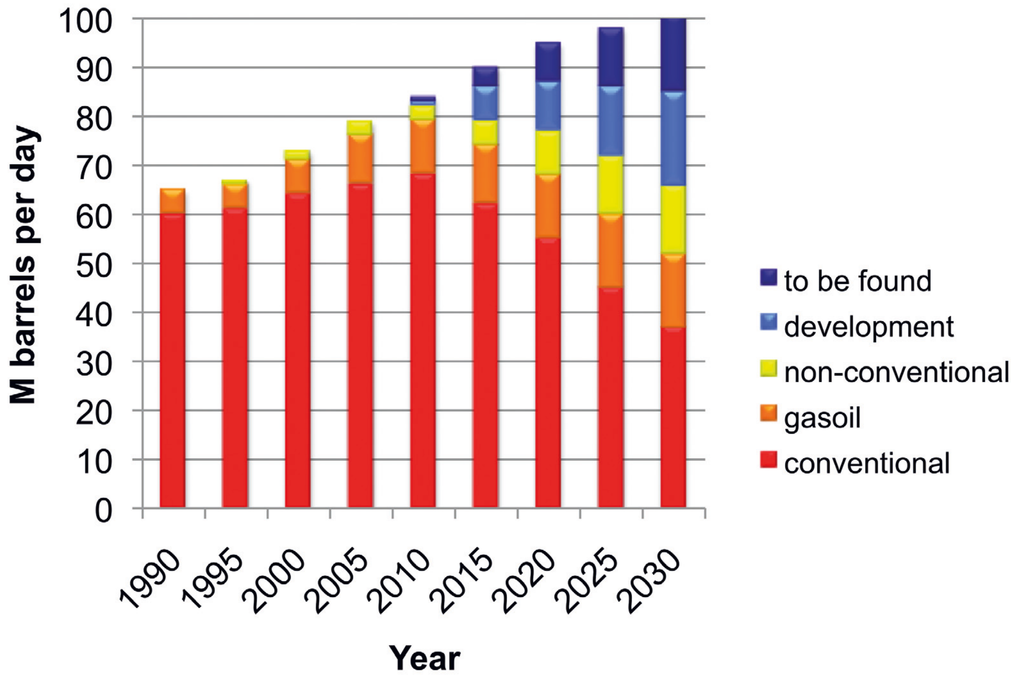

Fig. 2. – Peak oil. Temporal evolution of the oil production in million barrels per day. Depending on the way how known and unknown reserves are brought into the picture, we can see the signature of a peak in conventional oil production that is, according to the projection of the IEA (source, 2012) compensated by several measures.

absence of short-time return on investments are limiting factors as well the lack of general orientation as to what are targets and what are measures. A minority of citizens strongly demand the transformation of the energy system into a sustainable future by radical measures and without a full view on all implications of their demands. Industry tried to fight any changes until recently and now a concept that could serve as reliable "compass" into the future is missing.

The term "sustainable" by itself is not well defined and contains many more elements than "CO_2 reduction" for which it is often used synonymously. In addition there are complex technical issues that prevent the drop-in solution of replacing fossil by renewable energy (REN). Although this is often demanded and supported with numerical arguments based upon integrated data of production and consumption, it is a fundamental challenge to replace a controllable form of free energy (fossil) by a non-controllable form (REN) in the absence of powerful energy storage technologies and with inadequate grid and demand side control.

In fig. 3 it is indicated without much discussion in the present context that the reduction of the energy transformation issue into a technical systemic problem is inadequate.

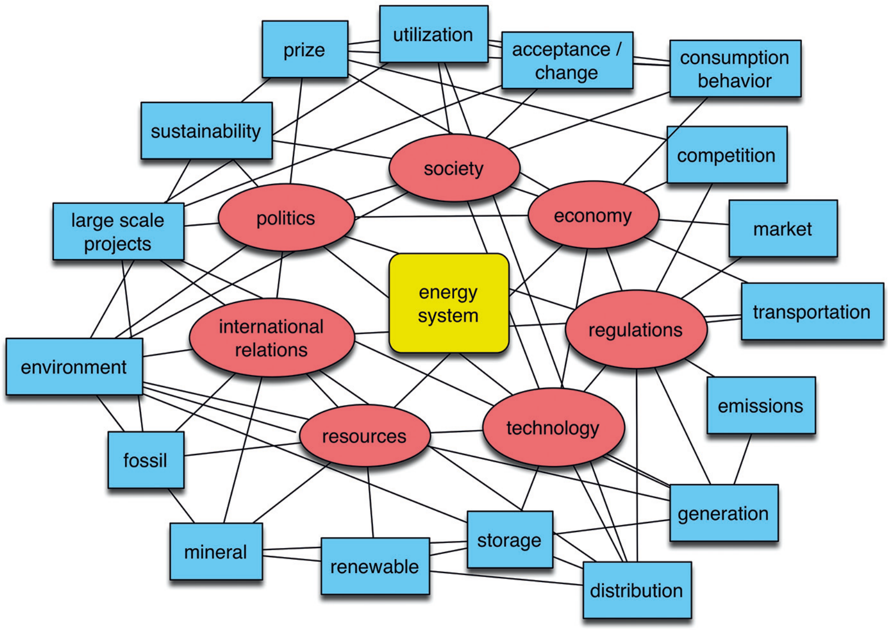

Fig. 3. – The energy system as network representation. In the inner hierarchy some critical components are shown. These consist of multiple sub-components from which some selected items are shown in the outer hierarchy. The lines indicate important relations. It is obvious that the technological aspects, although critically enabling the function of the energy systems are by no means sufficient to define the energy system and its transformation.

Energy systems are made for human desires and needs and are controlled by human activities. These control parameters are hierarchically nested in space and time and are outside of any rational or political control.

We may thus infer that the mode of operation of the energy system at any dimension of space and time cannot be described in a causal way and cannot be correctly modelled in its responses. Nevertheless, multiple stakeholders make continuous modifications to the system in uncoordinated manners creating a constant need for "quick fixes". A consistent energy policy or systemic development does not yet exist. Its formulation would require using the network indicated in a quite primitive form in fig. 3. Alone describing the function of this network is a formidable scientific challenge for which only limited efforts are currently undertaken.

Taking this as *caveat* it is still useful to discuss the nature of the transformation of a hypothetical energy system from a technically non-sustainable form into a sustainable form. We define technical sustainability as the property of the system to close all its material streams except those of oxygen and water, which we define as so abundant on our planet that they cannot be changed by human activities. Our present system is then represented by the scheme of fig. 4.

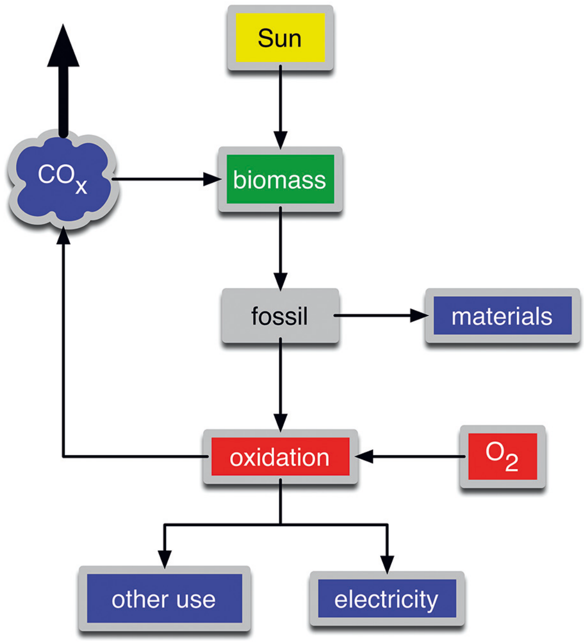

Fig. 4. – A minimal representation of a typical present energy system. It is not sustainable in the definition of this work, as the CO_2 stream is not closed (arrow). Nuclear energy sources are omitted for simplicity.

We see that almost all present free energy comes through chemical energy conversion and storage from the Sun. In ancient times biomass was converted to fossil resources that we oxidize to CO_2 and water (not shown) to generate thermo-mechanical energy that we convert in all useable forms of free energy. We further take most of our carbon-containing materials from fossil sources and generate transportation fuels and fertilizers from them. The CO_2 emission shown in fig. 1 is the consequence of these activities. About 50% of the emissions are retained in the global carbon cycle, the rest increases the CO_2 content of the atmosphere by about 2 ppm per year. Besides CO_2, also other GHG contribute to these processes whereby we note that some of these gasses are orders of magnitudes more effective as climate changers [1] than CO_2 itself.

If we want to avoid conducting an experiment with the global energy system with unknown consequences, then we should stop the emission of CO_2 and close its cycle by using the natural and some synthetic components of the global carbon cycle. Technologies like CCS are unacceptable [2] in this context, as they also do not close the cycle in a controlled manner and give rise to possible modification of global material streams that we cannot foresee. The effects of CCS do not disappear even in geological time scales, as CO_2 is a stable molecule and is not subject to a decay. It may be bound in the underground but for chemical reasons only at the expense of liberation of other anionic species (metathesis of carbonate against oxo-anions) with unforeseeable results.

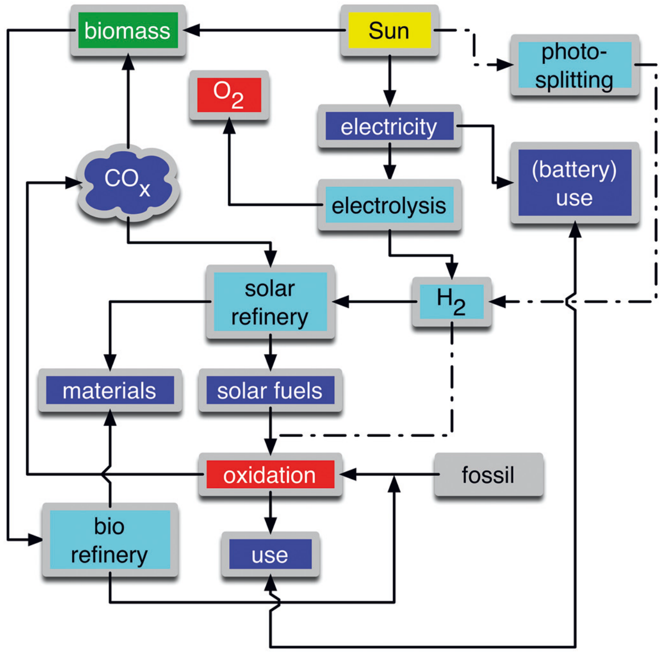

Fig. 5. – A sustainable energy system in the definition of this work. The CO_2 cycle is closed through reducing much of its volume by direct electricity generation and by chemical energy conversion (CEC) using solar hydrogen. A parallel process leading to solar fuels may be the direct photo-conversion of water and CO_2 that should, however, always be secondary to direct electricity generation due to the much higher efficiency of light-to-electricity conversion than light-to-chemical conversion followed by combustion.

In fig. 5 we illustrate as an example how we avoid much CO_2 formation by using sunlight to generate electricity. The temporal excess is used to split water and to transform hydrogen with excess CO_2 in a solar refinery into solar fuels and carbon materials. Emission of CO_2 from distributed sources can be collected by biomass. This non-food biomass can be processed in a bio-refinery with solar hydrogen to give residues for combustion and a valuable feedstock for chemical industry to generate materials. Such a system is sustainable as no open material streams are left.

Fossil fuels are used as long as possible to back up the volatility of the electricity generation. This is by far the most cost-effective way to help migrating the energy system from a state shown in fig. 4 to the state described in fig. 5. On a very long time scale this contribution will need to be replaced by storage and back-conversion, being then technically possible but always more expensive due to the intrinsic losses and the complexity increase of the system. This does not preclude small and decentralized systems of electricity supply to operate independent of fossil backup already now using batteries or CEC with solar hydrogen.

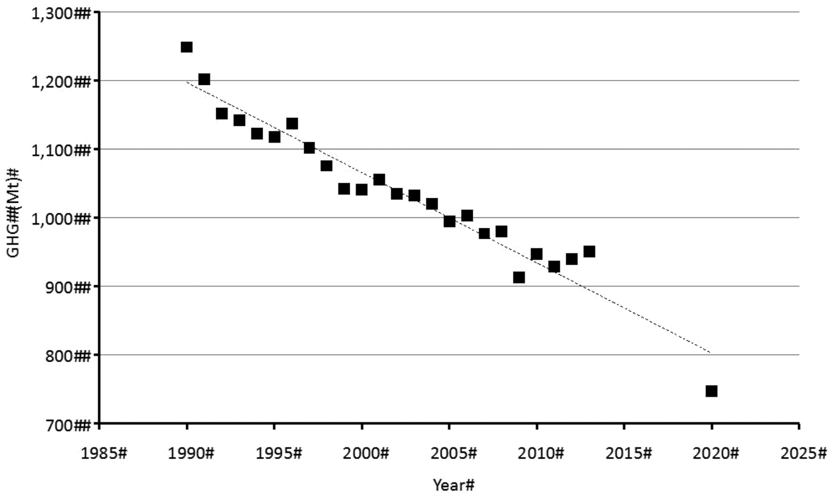

Fig. 6. – Temporal evolution of GHG emission in Germany in CO_2 equivalents. The data point for 2020 is the set political target, the dashed line is a linear extrapolation of the trend. It is likely that the target will not be met despite the massive use of renewable energy for power generation. (Source: BMWI, 2014.)

The light blue boxes in fig. 5 comprise critical contributions from chemistry. The system cannot operate without these elements being effective and scalable to worldwide application. Here we see a strategic contribution of chemistry to the energy issue. The other likewise important contribution is supporting energy efficiency through dedicated materials and through improved production processes. This field is so wide that it cannot be discussed here. Its short mentioning is no sign, however, for secondary relevance. It is stressed that according to fig. 3, energy-saving strategies will depend in their effectiveness much more on non-scientific factors than only on technologically viable options.

The enabling character of chemistry for the energy transformation process remains and represents a key challenge for those involved in the respective disciplines of fundamental and applied chemistry. The main and foremost obligation of chemistry is seen in getting the blue boxes to work. This requires a massive, global and interdisciplinary research effort bridging science and industrial application. Although many, who are responsible for organizing the necessary efforts, see this need, we still lose resources, time and good ideas by multiple adverse phenomena within science and its organisations. The author postulates that efforts are needed to straighten these activities as failure to deliver scalable solutions in time can hamper the whole transformation process of energy systems and thus discredit science in the broader society

In Germany a substantial reduction of GHG emission was observed with respect to the base year of 1990. From fig. 6 we see that after the rapid de-industrialization of the former East Germany, a steady decline of GHG emission occurred with a recent

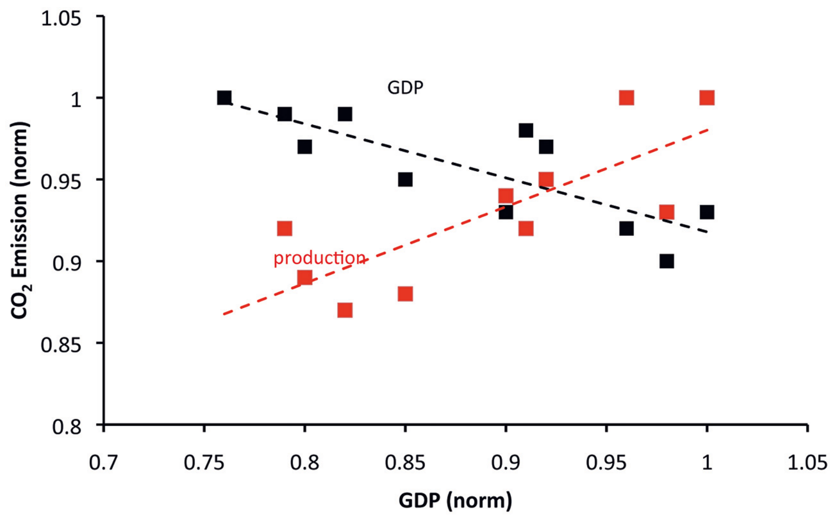

Fig. 7. – Relations between CO_2 emission (normalized to the value of 1990) and the German GDP (normalized to 1990) (black) and the contribution of the production sector to the GDP (red).

possible inversion of the trend. This trend was extrapolated (dashed line) by politics in formulating GHG saving a target for 2020. It is most likely that the target will not be met despite of the "German Energiewende". An analysis of the origin of the trend and its sustainability is complicated, as multiple aspects of economic development are interwoven with underlying technical improvements, changes in agriculture and land use and a modulation by annual weather changes.

The trend in fig. 6 that would save us from many challenges if it were a reliable property of our economic and societal system (fig. 3) is difficult to assess for its stability. The uncertainty associated with relevant arguments shall be illustrated with fig. 7. One frequent argument is that the trend shall arise as the consequence of a market economy to be energy-efficient with the cost of energy being the driving force in the wanted direction.

If one plots the relation between the change in German GDP and CO_2 emission one indeed finds such an underlying trend. Seeing, however, the reality of modern production, we recognize an ever increasing replacement of human labour by electrically actuated instrumentation and control systems. So it is no surprise that the specific energy intensity of the production sector of our national economy becomes more energy intensive and thus emits more CO_2. That this trend is not more pronounced may well be the consequence of the energy-saving efforts in industry that is a clear trend. In most industries the cost of energy is, however, a minor factor in comparison to other influences. This reduces the steering function of the price of energy in most but the energy-intensive industries. What we see as trend to apparent energy-efficiency on the national scale is mainly caused by the ongoing transformation of our economy away from production (only less than 15% total

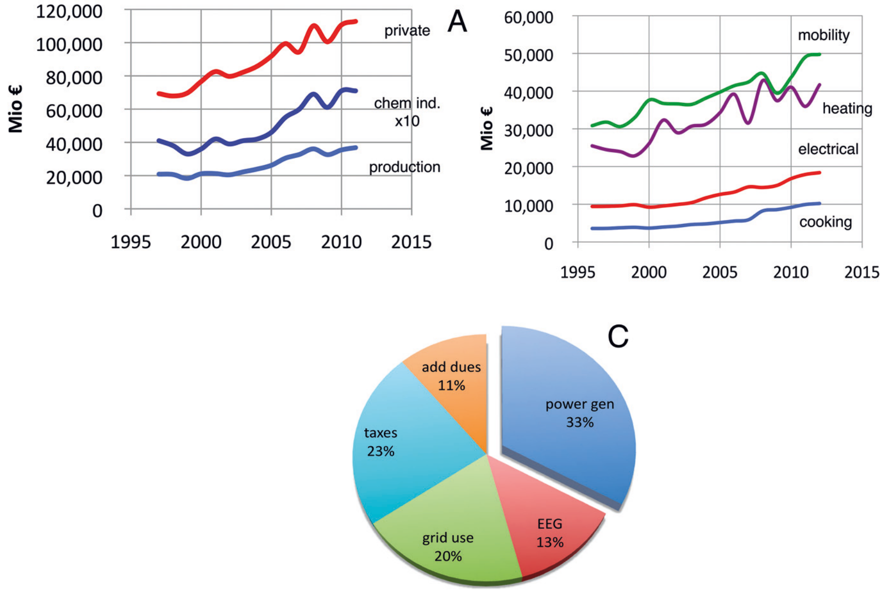

Fig. 8. – Some economic data in the German energy system. (A) Expenditure for energy for the whole production industry, for the energy-intensive chemical industry (multiplied by10) and for the private households. (B) Breakdown of energy expenditure for key applications. (C) Share of cost factors for one kWh of electricity in Berlin in 2014. Source for (A,B): ref. [4], for (C): VATTENFALL.

value) to services and financial activities that generate contributions to GDP without requiring much energy. We can formulate that the positive trend of fig. 6 in Germany is to a substantial degree the effect of transferring energy-intensive activities to other countries where the CO_2 emission is growing. We are thus winners of globalization in our positive regional CO_2 emission balance and contribute limited own efforts to the climate protection issue. This is clearly not sustainable and requires additional dedicated contributions.

The debate about the energy transformation into a sustainable future in Germany has turned away from climate change and reached a stage of particular emphasis on cost and price of electrical energy. This hinders the view on the fact that energy supply of a society is a system comprising societal, economic technical and resource subsystems [3]. It seems evident that such a system should not be described and optimized by a sole economic target function. Recent geopolitical events illustrate clearly that supply security and economical-political dependencies are additional strong factors in controlling the energy system. To rationalize the arguments in the present discussion we recall in fig. 8 some economic data of the German energy system.

We see that the private households spend much more on energy than the producing industry with the ratio being roughly inverse of expenditures to the volume of end energies consumed. The chemical industry is a heavy user of energy and hence is strongly affected by the evolution of energy prices. This industry together with few others is a user of stoichiometric amounts of energy meaning that free energy is a constituent in every molecule of their products. This is truly energy-intensive. We also can see that the electricity bill is minor for private households in comparison to their expenditures for heating and mobility. This sheds light on the systemic nature of the energy system: as much as the generation of electricity is a main area of activity for the energy transformation, as much the other sectors should obtain equal attention.

Figure 8(C) illustrates that the cost of electricity generation is only a minor factor in the electricity bill of a private household. The cost of distribution is also substantial. The implementation of the smart grid [5] designating a coupled power-data solution exhibiting bidirectional distribution, metering and controlling functions will have still unknown implications on amount and organization of private electricity consumption and generation. Its existence is a pre-requisite for a structured use of renewable power. We see further the dominant role of taxes and dues in determining the end user price of electricity. This represents a critical intersection of the technical, economic and societal subsystems of the national energy system explaining the intense public debate about "the price".

The energy system [6] may be described by a target function comprising three sets of variables standing for availability, affordability and sustainability. The nature of a target function requires that the sum of the three variables add up to unity with the consequence that there is no possibility to optimize any of three variables independently of the other two. This means in plain words that if we opt on high values for availability and affordability then we have to compromise with sustainability. Conversely if we wish to develop the system into high values of sustainability and keep our expectations on availability, then affordability will become a challenge. The simplicity of this statement vanishes quickly if we look into details of the definition of variables where we find multiple interdependencies. It is in the end a societal decision as indicated in fig. 3 how to define the target function.

Moreover, there is little agreement as to what values of the contributions to the target function are desirable in different societies. The German quest for high sustainability is not shared with many societies (not even in the European Union) struggling with availability and others with affordability. Some nations have secured access to fossil or nuclear energy resources whereas others have not and also the existing infrastructures are grossly divergent. Without any intention to resolve these complex matters the following discussion rests upon the German example. It is believed that many conclusions to be reached are qualitatively generic for other energy systems and thus of general interest.

The energy transformation focuses on the electricity generation (see the last part of ref. [3] and ref. [7]). This can be justified by the significant role [6] it plays in the greenhouse gas emission. The overall limited conversion efficiency of about 40% represents a lever in controlling CO_2 emission. It is noted that radical modernization [8] of coal-fired power stations with coupling to uses of low-temperature heat could half this lever. Even more desirable would be flameless oxidation [9] with direct conversion into electricity.

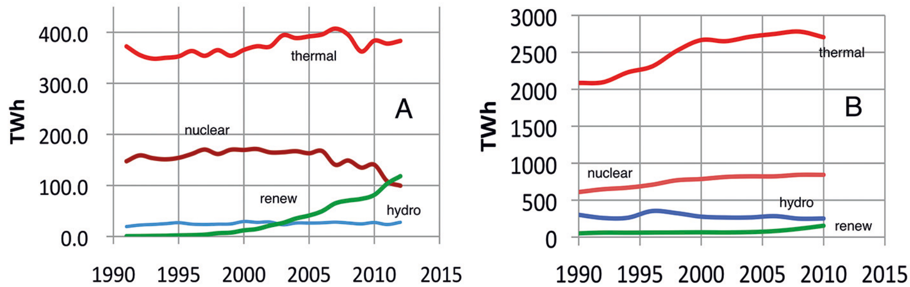

Fig. 9. – Temporal evolution of electricity generation and CO_2 emission. (A) Sources of electricity and consumption of electricity in Germany. Note that the contribution from renewables has crossed the contribution from nuclear power. (B) Sources of electricity in the U.S. Note the different ordinates. Source for (A): ref. [4], for (B): ref. [10].

In fig. 9 we see the temporal evolution of the contribution of primary energy sources to electricity generation in Germany and for comparison in the U.S. The differing trends in figs. 9(A) and (B) underline the above statement about differing concepts of energy system target functions. The differences in production volume contribute extensively to the values in fig. 1.

The growth of the infrastructure for renewable energy generation in Germany (fig. 9(A)) has left the energy system with two independent and parallel infrastructures for electricity generation. These systems are also regulated under different concepts. The renewable system carries no responsibility for the stability and continuity of the electricity system (frequency and power), as it delivers with priority electricity independent of local and temporal needs. The fossil system alone has to guarantee availability and stability. A consequence of the non-synchronized operation of the two electricity generation systems can be the formation of feedback loops that counteract the intentional reduction of greenhouse gas emission from electricity generation as illustrated in fig. 10.

We consider the power demand as given. Then more renewable power means less conventional power and hence less CO_2 emission as the intended effect. This is regulated by the German EEG and we all pay a price (see fig. 8(C)) for this contribution to climate protection. Simultaneously a chain of unintended effects indicated in fig. 10 is put into operation. They act both on the technological level (efficiency of power stations at variable load) and on the economic level (runtime effects and specific fuel consumption) of the energy system and lead to emission of more CO_2. In Germany the effects led to a substantial increase in the use of lignite coal in old power stations instead to the intended use of dynamical and modern gas-fired power stations. The balance between the factors decreasing total CO_2 emission and increasing it depends on many factors such as the relative proportion of the renewable *vs.* conventional power with respect to the base load of the grid. As we see from fig. 10 this balance is presently negative and so we pay more for "green" electricity and simultaneously emit more CO_2. This is strong evidence for the neglect of the systemic nature of an energy system also in its non-sustainable form

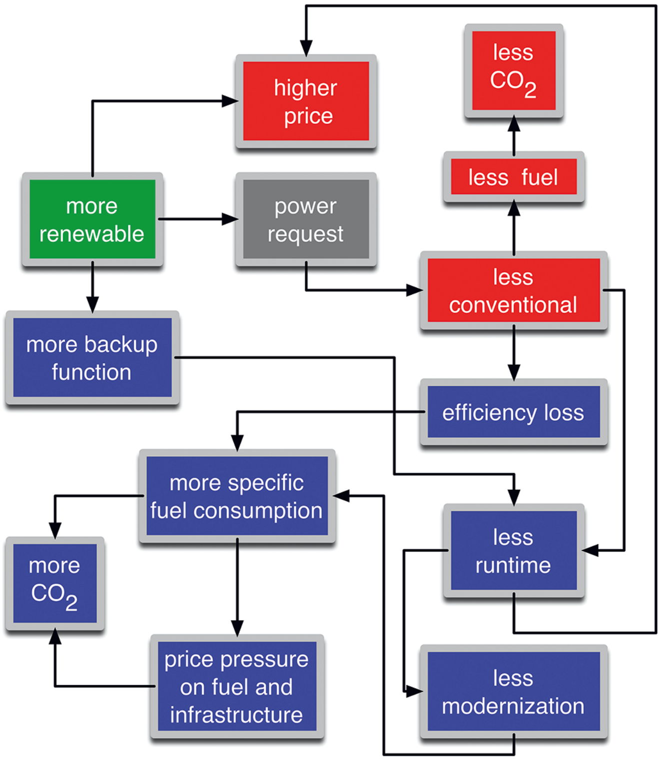

Fig. 10. – Schematic representation of some intended (red) and unintended (blue) effects of the co-existence of a conventional and a renewable power generation system under different regulatory schemes.

as the stakeholders are so interlaced in details that the overall function of the system has come out of sight. This is no surprise if we consider the complexity of the situation indicated with fig. 3 and the deliberate unwillingness of some stakeholders to recognize the systemic character. A documentation of the evolution of this situation can be found on the Internet under `www.solarify.de`.

A solution to these unwanted effects could be the gradual removal of the fossil electricity generation system [11] ("decarbonization"). This would also have beneficial consequences on the economics of electricity generation, as the dual cost of infrastructure would reduce and we would pay a smaller fuel bill. Unfortunately, such a scenario is not realistic without the contribution of chemistry allowing for grid-scale long-term energy storage in the chemical bonds of solar fuels if we maintain high the target function of availability of electricity. Figure 11 shows schematically the annual time profile of the power load and of the contributions from renewable sources now and in estimated 30 years from now.

The data are schematic, as many influences [12] affect the detailed shapes of the curves without, however, changing their generic aspects. The intermittent nature [12, 13] of

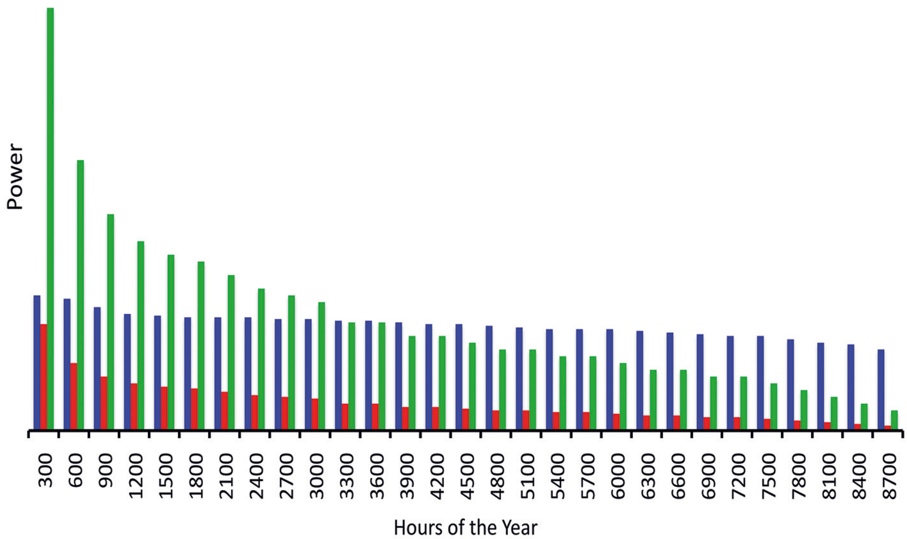

Fig. 11. – Annual load profile of energy system. The schematic representation may be representative for the German system. Blue: power demand, red: contribution of renewable sources (wind, PV, ratio about 4:1) today, green: after 4-fold expansion of the renewable infrastructure.

primary electricity from light and wind leads to a delivery curve inherently different from the load profile. Highly undesirable are the steep maximum and the long tail structure. This cannot be compensated even by massive expansion of the installed capacity. The tail end deficit in renewable power requires the use of chemical fuels compensating the lack of wind and light. This means that for the required work during the last ca. 10% of the year we need to maintain much of the conventional electricity generation infrastructure. The consequences of fig. 10 can thus not be fully avoided by phasing out the existing power generation technologies.

We thus will always need material energy carriers in the form of chemical [14] fuels. This is not only true for the electricity sector of the energy system here considered but likewise and even more critical for the transportation sector [15] not considered here. The fuels can be either fossil or solar [16]. With high expectations in availability, climate protection and independence, the contribution of solar fuels will become more relevant and in long time scales of possibly a century indispensable. The size of the supply gap and the existence of the fossil energy infrastructure both request that solar fuels should be compatible with present fossil fuels. This is a challenge for chemistry as several long-studied issues of catalytic petro-chemistry (such as Fischer-Tropsch synthesis [17], methanol chemistry [14, 18] and CO_2 methanation [19]) need better solutions than we have today.

The urgency of the integration of excess renewable electricity in the demand structure of the existing electricity supply is illustrated with fig. 12. The accumulated contribution

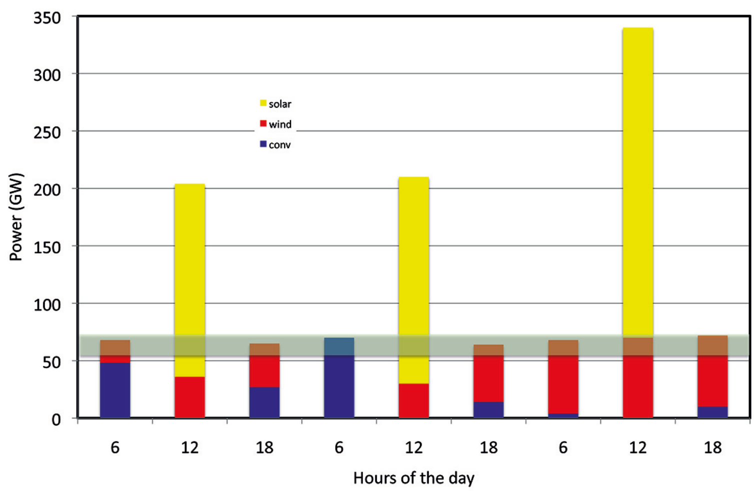

Fig. 12. – Electrical power generated in Germany during 3 days in April 2013. The light green bar indicates the power requirement during this time. Note the enormous flexibility of the conventional generation park required to accommodate the REN. Adapted from ref. [20].

of REN and conventional power generation at 3 time points (morning, noon and evening) is indicated as produced power in relation to the demand given as range over the 3 days shown. The enormous excess power from the solar-generating infrastructure can be seen. It is to be noted that also for this unneeded power we have to pay the EEG fee.

The excess primary electricity shown in figs. 11 and 12 creates a challenge for the distribution system and for the overall economics of the energy system if not adequately treated. The steep initial spike in REN (fig. 11) should not be fully used in the long-distance distribution system in order to avoid system capacity that is used only for a minimal time during the year. The power may be given away for free locally on grounds of its unpredictable availability or it should not be generated. The remaining excess over the demand may be used by a combination of applications. The part of short temporal availability could be used by applications that require minimal investment cost (thermal applications *e.g.* in central heating plants and in installations for co-generation of heat and power). Chemical energy storage is the adequate solution for the remaining more frequently available surplus. Hydrogen from water electrolysis can be used in a solar refinery to produce with CO_2 chemicals for use in other sectors of the energy system (power to chemicals [21], power to gas [13]). Due to its low overall efficiency, back-generation to electricity is only a solution with lower short-term priority. The production of chemicals has the dual function of saving CO_2 emission in other parts of the system and of consuming CO_2 from preferably stationary sources. Some of these will have to prevail for a long time [16] in order to fill the supply gap between demand and primary electricity shown in fig. 11.

Chemical energy storage as indicated in fig. 5 is an essential part of an electrical power system based largely on renewable generation. The required capacity for the storage part is a fraction of about 10–20% of the grid capacity depending on the efficiency and cost of conversion electricity in chemical bonds. As long as sufficient fossil fuel is available it will be economical and useful to convert electricity into higher value energy carriers than electricity (transportation fuels [22], feedstock for chemical industry [23]). This application allows for the development of the technologies and is expected to bring down the specific cost of the conversion processes. This relatively small part of the power system is important for the overall economics as it solves a substantial part of the integration problem between supply and demand illustrated in fig 11. The time span for this development may be estimated [14] to be about 20 years.

This long time to realization does not mean that we may slow down our activities in chemical energy conversion research (see the first part of ref. [21] and ref. [24]). None of the technology components needed for grid scale application in intermittent operation are available [13] in any verified form. The key critical components are the generation of chemical bonds from electrical energy. Water splitting and generation of solar hydrogen most easily accomplish this. The challenges are the same if this is done directly by photo-electro-catalysis or by electrolysis. Not issues of technical optimization but fundamental challenges in the understanding of the elementary steps during water splitting [25] are here the challenges.

It is then desirable to use hydrogen only for large-scale energy storage but not to bring it into the hands of end users. Both power density arguments and the missing infrastructure as well as the need to develop novel combustion strategies with fuel cells (possible but systemically unnecessary at present) request that at least for a first period in sustainable energy supply the combustion devices that we know (IC motors, turbines, power stations) should remain in use and we better transform the hydrogen with CO_2 into carbon-based solar fuels. We accept the loss in total energy efficiency and the complexity of the closed CO_2 cycle indicated in fig. 5 for the enormous simplification of integrating REN and solar fuels into the multiple energy systems existing in the world now. One further must not underestimate economic and societal resistances to massive large-scale infrastructural changes and new uses of energy when one plans for a migration path of the energy system.

The dimension [12] of about 10% of the volumes shown in fig. 9(A) lets us expect that decades are required to develop the existing approaches into proven technologies with operational practice and reliable figures of merit. In order to generate the knowledge required for chemical energy storage we formulate 5 lines of research [26] desires:

- Systems research is needed to understand the overall systemic boundary conditions of the integration of renewable energy. As the boundary conditions in the 4 subsystems (electricity, mobility, process heat, heating and cooling of houses) of a given energy system change with time and there are several types of energy systems in the world we have to expect continuous work on system analysis delivering parameters for all subsystems (design parameters, resource estimates, regulatory conditions acceptance parameters). The results should help guiding the other research lines that in turn provide input into the scenario definitions required. Effects as indicated in figs. 10, 11, 12 must be avoided.

- Energy storage systems of grid scale [13,27] need to be built as demonstrators using the existing technologies with their deficits. With such projects being exposed to influences of the whole energy system (intermittent operation, unexpected events) it will be possible to identify critical needs in science, to get practical system operation experience including safety and reliability information and to collect economical information. Non-technical aspects of such path finding large-scale projects (planning with society, financing) can be solved and the acceptance in the society for these technologies should be sought.

- A test phase of operating these installations with transparent results will have to follow. During this test phase essential improvements in materials, components and in the energy system integration are expected to result from targeted research. Some of these aspects such as the use of earth-abundant materials and the intermittent operation cause challenges that need to be addressed at the earliest possible time.

- Solutions for chemical energy conversion that emerged conceptually [19, 28] but were not yet sufficiently developed to reveal their technological potential should be moved forward to a demonstration scale of about 0.1 MW electrical energy equivalent. This is still small for application but sufficiently large to discover many hurdles [13, 14, 29] for implementation. Such scaled instruments will create many new research challenges both in process and material sciences.

- Fundamental science is needed to support the grid-scale demonstrators and the associated applied research. It will have to deal with a spectrum of topics [30] including the mechanisms of key chemical reactions involved, chemical engineering, material science and with operational aspects. These efforts need complementing by searches for novel solutions of chemical energy storage [31] within boundary conditions of integration and sustainability. In this way a portfolio of technology options can emerge that we may need to meet the specifically different challenges of energy systems. As example, the storage technologies in Germany [12] may be central, large and complex whereas the same purpose can only be met with simple and decentralized systems [32] in countries without a fully developed grid infrastructure.

Although these tasks require already the coordinated response of chemical science there are additional research areas of high priority for the energy transformation. Among them are processes and materials for increased energy efficiency. Besides revolutionary projects such as flameless oxidation for power generation [9] (all types of fuel cells) the wide area of material improvements [33] for incremental optimization of the generation and utilization of energy are most relevant. This is well known [14,34], yet not well solved. The management of the raw material change of the chemical industry [35] and material requests from the building industry (cement, insulation) are as relevant as chemical solutions for better batteries [36]. Effective exploitation of biomass [30, 37] and waste resources hold complex challenges for designing reactions and processes. Chemistry has developed a large number of potential concepts also in the storage of surplus electricity such as electro-reduction [38] or photo-electro-reduction [39] of CO_2 for fuel generation addressing these challenges. Their transformation into impacting technologies is difficult. Fundamental aspects of chemical knowledge are missing precluding rational development strategies for potential solutions found by synthetic intuition. Critical to this end is a continuous exchange of information between science and economy orchestrated by politics as advocated in fig. 3. This exchange includes also a constant debate about priorities with an understanding of the different time scales required for different tasks

This enumeration is not simply a wish list for more resources in science (although possibly needed) but brings with it the request for prioritizing projects. The research topics indicated are critical bottlenecks for integrating fossil and renewable energy streams. Without solving these tasks and in particular learning the conversion of electrical energy into chemical energy at large scales, the usefulness of REN remains limited and at a mere conceptual level. Consequently, research into alternatives or optimization of electricity generation with solar energy is still important but gets a lower priority as in the foreseeable future integration is more important for the energy system transformation than optimization.

In conclusion, the now more clearly visible requirements for the desired transformation of the energy systems towards more sustainability require from chemistry substantial efforts. Solutions for chemical energy conversion are needed as fast as possible to gain operational experience and to demonstrate the viability of the approach. The lack of chemical energy storage now should, however, not be used as excuse for discontinuing the implementation of primary electricity generation under suitable regulatory conditions for all technologies of power generation. Chemistry has to fulfil further numerous tasks in material development (see the last part of ref. [33] and ref. [40]), for energy efficiency projects [14, 41] and in the design and implementation of novel concepts for solar fuels independent from electrical power generation [42] (artificial leaf, see fig. 5). The function of chemistry in the power-generating arena is seen, however, as vital for bringing forward the whole energy system transformation that has already implemented irreversibly the infrastructure of renewable power generation.

The true grand challenge of the energy system transformation initiated in some countries is not to locally optimize the system to sustainability as defined by climate protection. Then only a limited effect can be achieved as seen from fig. 1. In addition, the economic and societal costs are enormous as incurred with the complex societal system (see fig. 3) and will not lead to the intended climate effect. This can be presently studied in the German energy system. The problem of energy supply lies much deeper. If the world population grows in size and energy demand as presently, then there will not be sufficient resource supply for all of us. Political instability and warfare will grow to get access to the necessary resources. It is thus one of the most pressing challenges of science and politics to provide a model of a migration path on how an existing society with its economy (or even the global economy) can transform from a fossil into a post-fossil era. This is critically necessary outside and beyond the climate protection issue and may be considered as a protection measure for the whole mankind.

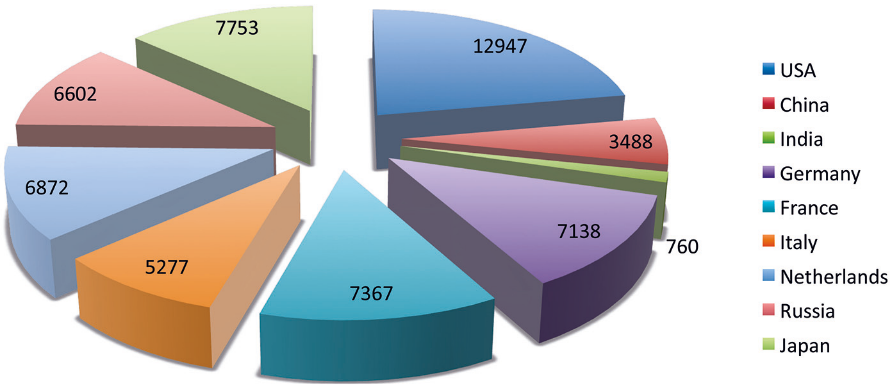

Fig. 13. – Annual consumption of electrical energy in different countries in 2012. The numbers indicate kWh per person. (Source BMWI 2014.)

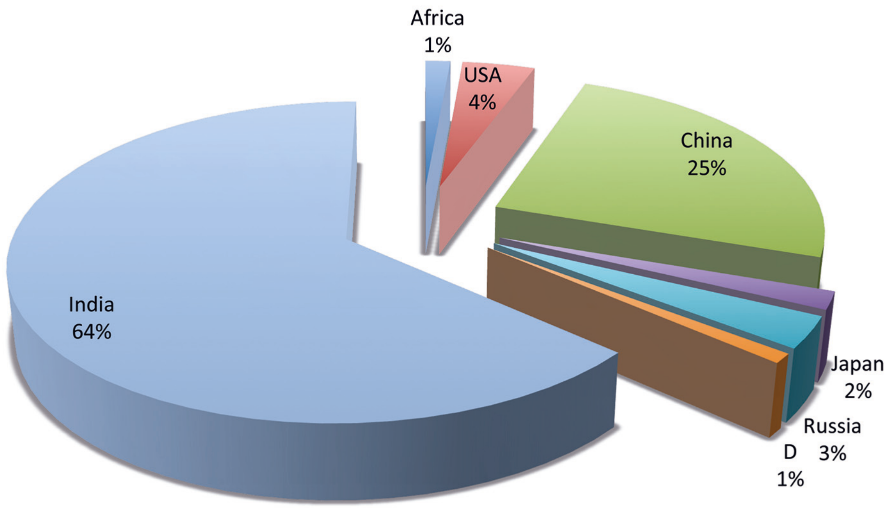

Fig. 14. – Hypothetical CO_2 emissions in an energy system where an average 7000 kWh/persona is characteristic and the generation is done largely with a technology mix as today. Disclaimer: This is not a scenario or a prediction!

Some numbers may illustrate this ultimate motivation for an engagement in energy science and technology. If we consider the consumption of electricity per person in different countries then we recognize enormous imbalances. This can be seen from fig. 13.

If we compare the numbers between India and the average values of the "first world" (Europe) and consider the different numbers of people in these regions then we can see the dynamics and also the stress on our global resources, independent from the change in global CO_2 emission. The following *Gedankenexperiment* should illustrate this. We extrapolate the CO_2 emission data from fig. 1 into a hypothetical future in which we define that the global electricity consumptions should not exceed 7000 kWh/a and person. This would mean some savings in Europe, some massive reductions in USA, a moderate increase in China and a massive increase in India. We omit here growth rates in Africa, as no good numbers were available. The trend is estimated to be the same and the consequences will even be more dramatic than under the strongly simplified assumptions made. The hypothetical CO_2 emission diagram like in fig. 1 would then look as shown in fig. 14.

This diagram is no scenario or prediction but merely an illustration for the above made points. It is extremely urgent, to begin with the evolution of the migration path that helps China and India to cope with the energy system change. The energy system change in Germany is irrelevant for global effects. Its only purpose can be to generate role models and migration options in the working environment of a wealthy economy. We have to illustrate that it is possible to generate a sustainable energy system without ruining economic opportunities. We further should develop, implement and export the necessary technologies to be used in generation, distribution and conversion of sustainable energy systems. The local and personal “cosiness factor” in Germany, the economic battles of our industries and our ideological debates we currently see on extreme options for the energy system transformation are highly counterproductive to any good intention, be it climate protection of preservation of peace and fruitful societal development.

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