Joint Renewable Electricity Supply for Europe and its Neighbours

- Transfer to Other World Regions and China -

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Abstract

Diminishing natural resources and global climate change are threatening the peaceful course of human development. A fundamental prerequisite for alleviating these dangers is to convert our energy system to renewable generation technologies that neither consume exhaustible resources nor degrade environmental quality despite continuous operation. Therefore the questions have to be answered of how the future electricity system should be structured, which techniques should be used and, of course, how costly the shift to a renewable electricity supply might be. This also raises the question of how far we can get with the existing technologies and what costs are to be expected if one applies technologies at their present costs, which is meant as a worst-case assumption. It is apparent, however, that taking into account only currently available technologies at their actual costs would constitute a worst-case cost assumption, since future developments will unquestionably improve economic performance. But on the other hand it is a conservative approach not overstraining the fantasy with optimistic cost assumptions and therefore it is resulting in a sound basis for further considerations. The above-named questions have constituted the focus of a study to determine the minimum cost of an electricity supply realized for Europe and near-proximity Asian and African regions [Czi 05]. The approach includes the option of supplying electrical energy to national economies not only or mainly from domestic resources but likewise in cooperation with neighbouring countries and distant regions using appropriate transmission systems to interconnect all participants within a wide-supply area containing huge renewable energy resources. The freedom for international cooperation between the nations opens up for synergetic benefits. Many of the nations within the area of consideration (see Figure 1) are emerging nations bounding on Europe with renewable potentials far in excess of national demand. Furthermore low population densities in deserts, steppes, tundra, and other regions largely devoid of human settlement neighbouring the European Union, however, may more easily allow for the expansion of wind power capacities and other renewable capacities than in highly populated areas. Very interesting resources are e.g. the huge potentials of wind energy of the coastal regions of Morocco and Mauritania which are particularly advantageous due to their summer peaks in production, which are the reverse of seasonal conditions in Europe. Solar electricity from concentrating parabolic arrays could likewise complement the output of wind farms in Germany, both inland and offshore. Due to these and further circumstances, the possibilities of wide-area interconnection – via the relatively cost-effective HVDC (High Voltage Direct Current) transmission - promise unprecedented economic and technical benefits for all participating nations. Based on the results of the scenarios this paper may try to give a hint at the transferability of the strategies - found to be effective for Europe and its neighbours – to other regions. Hereby the Chinese situation and peculiarities will be in the focus of the considerations.

Scenarios: Cost-Optimised Electricity Supply Entirely with Renewable Energies

Taking the starting points mentioned above scenarios for a future electricity supply entirely with renewable energies have been developed at the Institut für Solare Energieversorgungstechnik (ISET) in Kassel. Various concepts have been studied for providing renewable electricity to Europe and neighbouring regions. Therefore an extensive region (s. **Figure 1**) with approx. 1.1 billion inhabitants and an electricity consumption of roughly 4000 TWh/a has been analysed to determine the available potentials for a future energy system. This process has taken into account data from ECMWF (European Centre for Medium-Range Weather Forecasts) as the meteorological basis and the population density as a restrictive factor for the wind energy potentials or estimated roof areas in all countries within the shown regions for determining the roof top photovoltaic potentials, combined with data on solar irradiation from ECMWF and National Center for

Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR), wind speeds, and also temperatures used e.g. for photovoltaic electricity production and for solar thermal electricity production [ERA-15] [NCEP 99]. Moreover other renewable resources such as biomass and hydropower have been investigated or included at the level of current knowledge. All this has been fed into mathematical optimisation routines which have been applied to the question of which renewable resources with their individual temporal behaviour at different sites and with different yields should be used, and how selection should be made to achieve optimum cost performance. (A linear optimisation with roughly 2.45 million restrictions and about 2.2 million free variables was employed to find the best combination in each scenario.). The optimisation takes into account the temporal behaviour of the combined consumption of all countries within every individual region shown in the figure as well as all requirements imposed by resource-constrained production. Both sets of data, electricity demand and temporal behaviour of the possible production, have been compiled for optimisation (using time series with three-hour intervals) for all of the 19 regions which are to be supplied with electricity. The optimisation process ensures that supply will meet demand at any time, while determining if and to which extent any potential source is to be used, and how every part of the supply system will operate, including the dimensioning and operation of a HVDC grid that is superimposed on the current grid infrastructure. The criterion of optimisation is the minimization of overall annual costs of electricity when fed into the regional high-voltage grids, enabling these costs to be compared directly with those from regular power stations feeding into the conventional AC-high-voltage grid. However, the economic optimisation of all power plant operations for a time frame greater than, or equal to, three hours has simultaneously been included using sets of time series extending over one year.

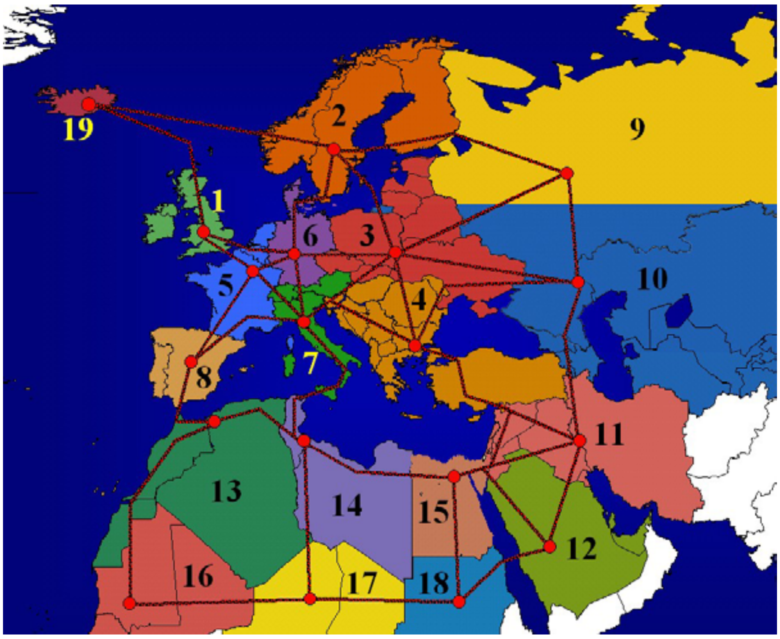

Figure 1: *Possible electricity supply area divided into 19 regions with schematic representation of potential electricity transmission paths using HVDC to the geographic population centres of the*

- **Base-Case Scenario**

The promising results for the base-case scenario – which assumes an electricity supply system implemented entirely with current technology using only renewable energies at today's costs for all components (see [Czi 01] and [Czi 04] for more detailed information on underlying assumptions) – indicate that electricity could be produced and transported to the local grids at costs below 4.7 €ct/kWh, which hardly differs from the case of conventional generation today. (At gas prices in 2003 of about 2.4 €ct/kWh for industrial consumers in Germany [EC 04], electricity from newly erected combined-cycle gas power stations had already reached a significantly higher level of 5 - 6 €ct/kWh$_{el}$.) In the resulting optimal configuration for this scenario, nearly 70% of the power originates from wind energy produced from wind turbines with a rated power of 1040 GW. A HVDC (High Voltage Direct Current) transmission system connects the good wind sites with the centres of demand while also powerfully integrating existing hydropower storage facilities, thus providing backup capacities that are enhanced by regional biomass power and given additional support by solar thermal electricity production. Electricity is generated from biomass at 6.6 €ct/kWh$_{el}$ after proceeds from heat sales have been factored in. This result lies significantly above the average price level, yet the backup capability is essential to reduce the overall cost of the entire system. About 42% of the electricity produced is interregionally transmitted via the HVDC-System whereby the total transmission losses sum up to 4.2% of the electricity produced. Another 3.6% loss is production which neither can be consumed at the time it is produced nor be stored for later use within the pumped storage plants and therefore is produced in excess. These two losses may be considered quite acceptable for an electricity supply only using renewable energies.

- **Scenario with Transport Restrictions**

By contrast, if interregional transmission is not allowed in a restrictive decentralised scenario, excess production increases significantly to 10% of the production, and additional backup power as well as backup energy employing other resources become necessary within individual isolated regions to meet the demand, leading to great additional expenses. In one scenario, fuel cells powered with renewable hydrogen produce electricity at about 20 €ct/kWh_{el} (which is already quite optimistic if the hydrogen is produced from renewable energies), raising the net electricity costs to over 8 €ct/kWh_{el} on the average. For Region 6 (Germany and Denmark), this restrictive "decentralized" (insular) strategy would lead to costs of electricity higher than 10 €ct/kWh.

- **Scenarios with Reduced Costs for Individual Components**

The effect of cost changes for individual technologies and components was also investigated in particular scenarios. One aim was to find the costs at which PV could cost-effectively contribute to the supply. Therefore a series of scenarios has been calculated where the PV costs successively have been divided by two. As a result PV has not been chosen by the optimisation until costs have been halved three times. This major cost reduction for PV was found to enable this technology to provide a significant contribution to the electricity supply. If all other costs remained the same, the reduction to one-eighth of current PV costs would enable an economically viable 4% contribution to overall electricity generation to be provided. The generation would nevertheless be limited to the southernmost regions – particularly to regions 12,16, 17, and 18. If the cost were only one-sixteenth of present levels, PV technologies could account for about 22% of all electricity generation, reducing generation costs compared with the base-case scenario by about 10% to 4.3€ct/kWh. Even in this case, however, photovoltaic technologies would not be used in the northern regions 1, 2, 3, 6, 9, and 19, because they could not contribute to overall cost reductions.

If the costs of the mirror fields of solar thermal power plants were reduced by half – as is anticipated in the near future – solar thermal plants would already constitute about 13% of all electricity generation. In this case, the overall electricity costs lie at 4% below those of the base-case scenario. Reducing the costs of the collector array to 40% and simultaneously lowering storage costs to two-thirds of current levels (still clearly above achievable storage costs according to recent research mentioned in [Czi 04]) would increase their contribution to 28% of the electricity produced, while the electricity generation costs would – compared to the base-case scenario - fall by about 10% to 4.3 €ct/kWh. These examples illustrate that solar thermal generation presents an economically attractive perspective for the future that can be realized fairly easily in view of minimal cost regression factors.

- **Scenario with Hydropower at Inga in the Democratic Republic of Congo**

The construction of a large hydroelectric power plant at an extremely favourable location in the Democratic Republic of Congo near Inga was also investigated for one proposed scenario (s. also [Kan 99]). The construction of a hydropower plant with a capacity of 38 GW was the decision resulting from computational optimisation. This would lower the costs of electricity by 5.3% compared to the base-case scenario due to more economic generation and incidental system benefits. A primary reason for the low costs of the electricity produced at Inga is the high average load of the hydropower plant of about 6900 FLH and the relatively low anticipated investment costs at this very advantageous site. Two-thirds of the electricity produced at Inga is transmitted over a HVDC system with 26GW capacity, connecting the generating station with Region 17, with the remainder conducted in equal amounts over two HVDC systems with a combined capacity of 12 GW, joining Inga with Regions 16 and 18.

- **Electricity Transmission within the Scenarios**

In all scenarios – with the exception of restrictive and expensive insular configurations – electricity transmission is of significant importance. The necessary converter capacity (AC⇔DC) for the HVDC grid exceeds values of over 750 GW in some cases. (This level corresponds to about one-half of the installed generation capacity of all production facilities in the scenario regions.) The grid is used to achieve smoothing effects among different resource-dependent generation capacities using renewable energies, and to provide access to hydroelectric plants and to distributed biomass power plants both with their intrinsic storage capacities for wide-area backup applications. In the base-case scenario, for instance, about 42% of the electricity generated is transmitted via the HVDC system between the regions within the supply area. Measured against the total electricity costs the cost of the transmission system amounts to 7% of which the main part of 5% is contributed by the transmission lines and cables. HVDC transmission has a higher intrinsic system stability than AC lines. Furthermore the transmission system of the base-case scenario is highly redundant due to the fact that the thermal limit of the transmission lines is about twice the rated power and due to the fact that between almost all regions two or more systems are designed to be built parallel. But nevertheless if further redundancy was seen as desirable this could be achieved relatively inexpensively. A somewhat extreme idea would be to erect two whole systems of transmission lines in parallel. This would mean that the costs of transmission lines and cables would double but at the same time the losses would decrease due to the doubled cross section and thus the overall cost increase would only be about 3% ensuring a degree of immunity against faults, which is by far higher than stipulated that for today's systems.

Transferability of the Results to other regions and particularly to Chinese conditiones

It is highly probable that the results gained from the scenarios can be transferred to other world regions, since every continent has its own renewable resources with different temporal production characteristics within a radius connectable via HVDC transmission.

In some continents or regions hydropower is not exploited at the comparably high degree as it is in Europe. This can be seen comparing the regions in highly industrialised world regions such as Europe or parts of the USA and other regions i.e. in Africa or Asia depicted in **Figure 2**. Here in particular the Chinese mountainous regions are to be mentioned which have vast unexploited potentials. Since storage hydropower is of high importance for backup purposes within the scenarios this may be considered as a problem as long as it is not clear to which extent the hydro potentials can be used for electricity production and which storage capacities might be installable within the Chinese Mountains or other world regions of interest with comparable conditions. Such uncertainties would have to be studied in detail to come to reliable conclusions about the transferability of the scenario results to these regions. But it is not unrealistic to expect that the presence of huge unexploited hydropower potentials such as the potentials in China are a clear indication of their transferability.

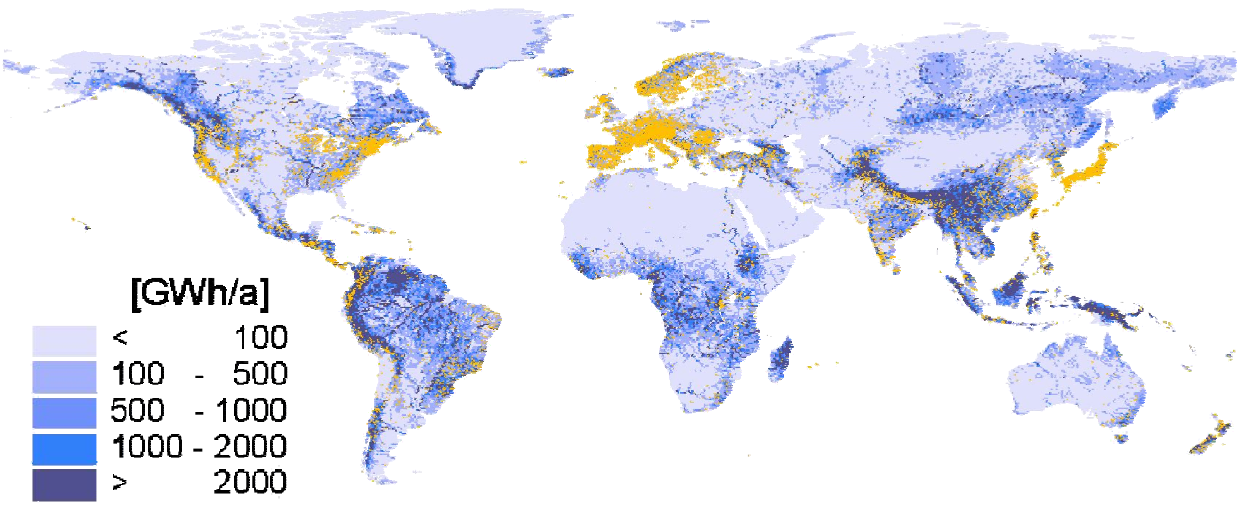

Figure 2: *Gross Hydropower Potential of 0.5° x 0.5° Cells Worldwide and Hydropower Plants (Sources: Data on water runoff from WaterGAP, Center for Environmental Systems Research, University of Kassel, processing and mapping by B. Lehner, assisted by G. Czisch, 2003 / to be published)*

The Solar energy potentials can be detected quite well with the available low resolution data used for this scenario study, showing good conditions in China and many other regions world-wide (see [Czi 01] and [Czi 04]).

In the case of wind energy the situation is a bit more challenging. Some huge regions are characterised by very rugged mountainous terrain where the detection of good wind sites is much more difficult than in smooth terrain. This results in the fact that many very good wind sites might remain hidden if meteorological data with low spatial resolution are used to search for the potentials, as done for the scenario study described here. This may be illustrated in the following.

- **Inadequacies of transferability due to underestimations of wind conditions**

There can be found many examples for the circumstance that the wind data – with low spatial resolution - used for the scenarios significantly underestimate the real wind conditions in mountainous terrain. In the case of southern Morocco, for instance, measurements have shown that load factors of far more than 4500 FLH may be assumed directly on the coast at favourable locations [ER 99]. In this still relatively smooth terrain the average annual production gained from data used for the scenarios show load factors of 3400 FLH. This indicates some underestimation even in this relatively simple case with smooth terrain. Similarly in Kazakhstan, where measurements and other investigations likewise indicate that yields significantly over 4000 FLH may be expected [BMW 87] [Nik 99] which have to be compared with 2600 FLH derived from the scenario data. The higher the topographical complexity of the terrain, the more significant the underestimation tends to be. Wind potentials in [CGM 03] calculated by Risø for the mountainous region at the Gulf of Suez in Egypt represent the most extreme underestimation of wind conditions in any complex terrain known thus far to the author. A comparison of the map and the data given in [CGM 03] with the data depicted in Figure 3 indicates a maximal average production of roughly 2200 FLH only at low spatial resolution (like the data derived from ECMWF data, which form the basis of the scenarios), while the high-resolution Risø data correspond to 6000 FLH (for better comparison, see also [Czi 01]). Even if this example is particularly extreme, such underestimation is rather typical of complex terrains, making clear that there must be substantially better wind potentials worldwide at many places than can be inferred from the data bases used for the scenarios.

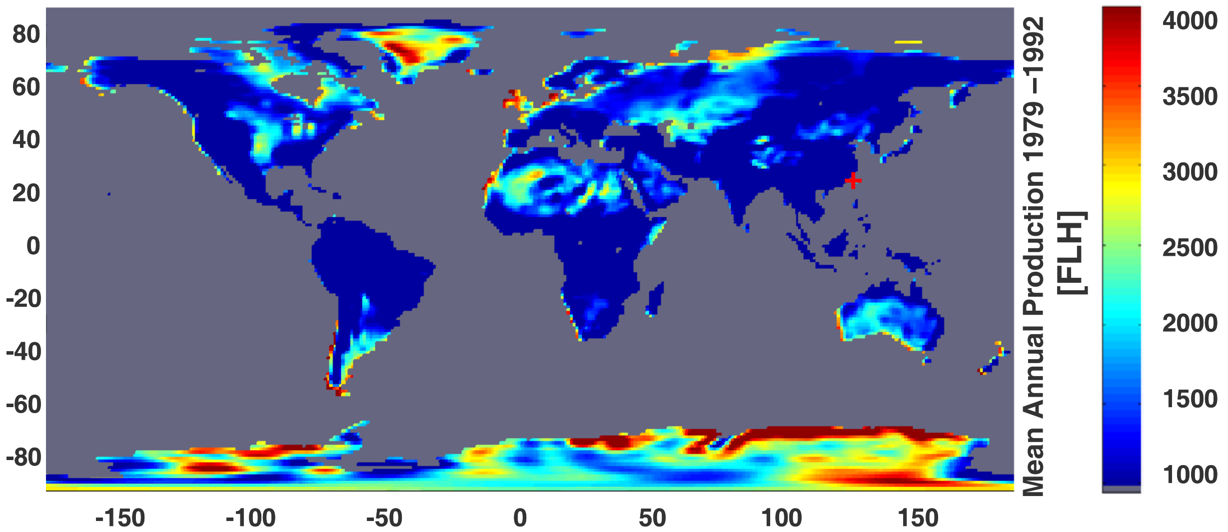

Figure 3 *Potential of average annual electricity production from wind energy of the years 1979 – 1992 by conventional wind energy converters with hub heights of 80 meter; meteorological data: ECMW. The red cross indicates an area depicted in* ***Figure 4*** *.*

This expectation can be convincingly proven by comparing the conditions for electricity production from wind energy shown in Figure 3 with high resolution data for parts of the Chinese mountainous coast areas [EGH+02] or many other regions, for example, in the Americas or South East Asia (s. e.g. [AWS 01]).Some of the Chinese data are depicted in Figure 4 which shows a small region marked in Figure 3 as the area on the left hand side of the red cross. The low resolution data on land sites illustrated in Figure 3 show only annual production values of 1000 FLH and slightly above. In fact most sites depicted in Figure 4 have marginal production potentials not even worth to be differentiated (white areas). But – and this can not be found using data of low spatial resolution – there are many sites with excellent wind conditions. I.e. the red areas in Figure 4 represent average wind speeds of 8.4 - 9.5 m/s at 30 m above ground. This would roughly correspond to 9.6 – 11 m/s at a hub height of 80 m which may be appropriate for an annual production of

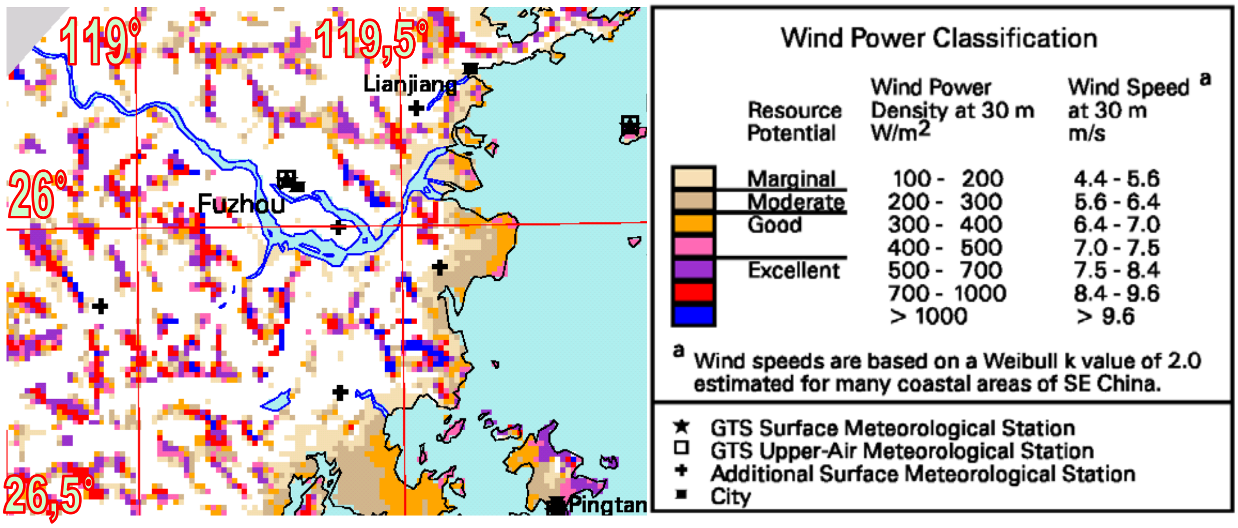

Figure 4: *Possible electricity supply area divided into 19 regions with schematic representation of potential electricity transmission paths using HVDC to the geographic population centres of the regions*

4000 – 5000 FLH. The blue areas in Figure 4 most likely would allow for even higher production. This Chinese example once more shows that data of low resolution may correctly represent the average wind conditions in larger areas with complex terrain but completely fail to give the right impression of the real condition at favourable smaller subareas. But also the potentials within the favourable subareas may sum up to quite remarkable potentials and therefore must be known to seriously work out possible pathways for the future electricity supply. Most areas in China are characterised by very complex mountainous terrain. Therefore data of low resolution may only give hints at the wind conditions. But having in mind the examples mentioned before it is not very prophetic to expect that China has many very interesting sites for the use of wind power spread over large areas of the whole country which might together provide huge wind potentials. On the one hand this allows for the estimation that wind energy could be the dominating source of electricity also in china and the results of the scenarios can be transferred as well to Chinese conditions. On the other hand it is clearly indicated that the uncertainty translating the scenarios from Europe to China is relatively high. Thus overcoming the uncertainty would mean to elaborate high resolution data for the whole of china. These must be appropriate to allow for better estimations of the wind energy potentials as well as the temporal behaviour of the potential production. To remove the last uncertainties would demand for developing scenarios for China which are based on data with high spatial and temporal resolution.

- **General statements about the transferability of the scenario results**

It is clear that the general result of the scenarios for Europe and its neighbours – a low-cost but nevertheless totally renewable electricity supply is possible if the renewables are used in a huge powerfully interconnected supply area – holds for most areas of a size similar to the European/Transeuropean example. In some cases technical problems resulting from higher requirements for the accuracy of data or unavailable information about the future development of the use of hydropower and its possible designability lead to higher uncertainties. If these problems were overcome, a much more reliable assessment would be possible. In the light of such an assessment the details would of course have to be adapted to the local conditions but the general positive conclusion of the feasibility of an economically viable renewable electricity supply can be expected to hold anyway. Furthermore there is no technical reason why, for example, southern Africa or eastern Asia should not be linked in the long run by an HVDC system to the supply area considered in the scenario study. So a future system might spread over some continents, gaining further advantages from further expansion thus allowing for even better solutions to the future electricity supply.

Generel Conclusions drawn from the Scenarios

The fundamental technical prerequisites for an electricity system realized entirely with renewable energies have already been fulfilled. The different scenarios show a broad range of various possibilities for a future electricity supply solely employing renewable energies and thus provide a sound basis for political decision. The following can be deduced:

1.) An entirely renewable and thus sustainable electricity supply is possible even if only current technologies are used.

2.) The costs of electricity don't have to lie far above today's costs even if very conservative assumptions are made. At today's prices for all components, the price of electricity doesn't have to be higher than from a newly erected combined-cycle gas power plant. The annual difference in cost compared with the current national bill for electricity, which typically may account for roughly 2 to 3% of the gross national product, would impose only a few per mill of the gross national product as an additional burden on the industrial countries within the supply area of the scenarios, thereby constituting a highly rational alternative to the predictable consequences of climate change and declining fossil fuel resources. Foreseeable cost reductions – particularly for renewable energy technologies – make a comprehensive renewable energy system both conceivable and potentially more economic than all current means of providing electrical energy. However, the costs are dependent on the future system configuration, and could be reduced by ongoing technical progress, or be negatively influenced by wrong energy policies.

3.) A Transeuropean renewable electricity system would simultaneously enable the realization of a combined strategy for developmental assistance and climate protection as a win-win arrangement for all participating states. This becomes obvious since on the one hand the investments necessary are relatively small compared to the gross national product (GNP) of the industrial countries but on the other hand they are quite large in comparison with the GNP of many countries at the periphery of the supply area which would be the source of the renewable electricity for the industrial countries involved. Therefore to follow such a concept of a joint renewable electricity supply for Europe and its neighbours would among other implications mean developing a form of development aid worthy of the name which may rather take the character of an economic cooperation, based on the needs of both sides.

4.) It is very reasonable to estimate that the general results of the scenarios can be transferred to other world regions even if in some cases some more detailed information – especially on the local wind conditions - would be welcome to reduce uncertainties. The latter e.g. applies to China where the rough mountainous terrain causes problems with resource assessment.

The problem of converting our electricity system to one that is environmentally and socially benign is therefore much less a financial or technical issue, being instead almost entirely dependent on political attitudes and governmental priorities. There is more than enough evidence to justify a confident call for a comprehensive transition to a sustainable electricity supply, bearing in mind that a broad variety of solutions is possible. Responsible political decisions are now imperative for allocating the necessary technical, scientific and economic resources to achieve this goal.

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