Realisable Scenarios for a Future Electricity Supply based 100% on Renewable Energies

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Abstract

In view of the resource and climate problems, it seems obvious that we must transform our energy system into one using only renewable energies. But questions arise how such a system should be structured, which techniques should be used and, of course, how costly it might be. These questions were the focus of a study which investigated the cost optimum of a future renewable electricity supply for Europe and its closer Asian and African neighbourhood. The resulting scenarios are based on a broad data basis of the electricity consumption and for renewable energies. A linear optimisation determines the best system configuration and temporal dispatch of all components. The outcome of the scenarios can be considered as being a scientific breakthrough since it proves that a totally renewable electricity supply is possible even with current technology and at the same time is affordable for our national economies. In the conservative base case scenario, wind power would dominate the production spread over the better wind areas within the whole supply area, connected with the demand centres via HVDC transmission. The transmission system, furthermore, powerfully integrates the existing storage hydropower to provide for backup coequally assisted by biomass power and supported by solar thermal electricity. The main results of the different scenarios can be summarized as follows:

- A totally renewable electricity supply for Europe and its neighbourhood is possible and affordable.
- Electricity import from non-European neighbour countries can be a very valuable and substantial component of a future supply.
- Smoothing effects by the use of sources at locations in different climate zones improve the security of the supply and reduce the costs.
- A large-scale co-operation of many different countries opens up for the possibility to combine the goals of development policy and climate politics in a multilateral win-win strategy.

To aid implementation, an international extension of the ideas of the German energy feed law (or similar other schemes around the world) is proposed for the follow-up treaty to the Kyoto climate accord.

1 Introduction

At the first Risø Energy Conference in 2003 [GiebelEtAl 2003] we have shown that the large-scale transport of renewable energy, in particular wind energy, via HVDC (High-Voltage Direct Current) is possible from some wind-rich regions around Europe to the centre of Europe with reasonable cost and with large development benefits for the installing countries. At the second Risø Energy Conference in 2005 [GiebelEtAl 2005] we presented calculations showing that due to the large differences in resources, it can be cheaper to use better wind resources further away (in this case, Egypt) than to use just average resources in Northern Europe, even factoring in the transport over large distances. Meanwhile, since the first Risø Energy Conference in 2003, the evidence both scientific and from personal impression of climate change and the human contribution to it has grown significantly.

In this paper we want to present a framework for the implementation of the ideas shown in the previous papers, and the clear benefits of the large-scale distribution and transport of energy with a HVDC overlay grid. Using such a grid on top of the existing high-voltage grid on the continental scale enables Europe and the surrounding region to create all of its electricity solely from renewable sources. An optimisation procedure shows that the overall cost for the new system is comparable to the old one. Wind energy then creates about 70% of the overall generation, with hydropower and biomass making up the remainder.

2 The International Energy Feed Law

The German energy feed in law was one of the biggest success stories for new renewable energies in the world. To worldwide extend this success an international feed in law would be very helpful and if carefully arranged would conceivably promote the use of renewable energies more than any other measure. One possibility for Germany would be to extend the existing EEG (Energieeinspeisegesetz, energy feed-in law) to an agreement which can be ratified by other nations or to bring a similar arrangement on the international agenda coming into operation as soon as two countries have signed the agreement.

The EEG commits the utilities in Germany to accept any feed in of electricity from wind power and other renewable sources into the electrical net. It furthermore commits the utilities to provide an appropriate electricity network, sufficient to take the renewable electricity. Additionally, the EEG commits the utilities to pay a definite minimum feed in tariff for the renewable electricity – dependent on the kind of renewable source used for its production. The total payment is distributed accordingly to the end users electricity consumption of the utility's customers. One of its outcomes was the rapid growth of electricity production from wind energy which made Germany the world leading wind energy nation despite its mostly mediocre resource. Other countries with good success of wind power installations all have a similar law, e.g. Spain, Denmark (although there the success stopped after the drastic reductions in payments the new centre-right government 5 years ago), or Austria. Most other support schemes did not have the success that some form of feed in law has. This effect is most notable in Great Britain, where despite the great resource there was little wind energy activity for many years.

The international energy feed law is to be used further as a component of the energy policy and its effect should be improved. Essentially, either the EEG should be extended or a new set of rules should be created that promotes the development of renewable energies in form of an international agreement, which interested states can accede to by ratification. Together these states follow the aim to develop a rapid growth of the use of renewable energies and commit themselves on a long-term basis to change to a sustainable CO_2-neutral electricity supply. The financing of cost of electricity is to be distributed, as with today's EEG, proportionately according to the respective electricity consumption of the final customers within each country. Deviating from the German EEG, more like the Spanish feed in regulation, it seems sensible that only extra costs above a certain minimum are to be paid by the new community of responsible states. This minimum is to be agreed upon with each country signing the agreement.

This international feed in law should, at least in the longer run, contain three steps to create an appropriate internationally effective instrument. The first step is to pay for the electricity fed into the electricity network of each country. Therefore it might be necessary to agree within that treaty that the costs of extension of the national electricity network are also included into the feed in tariff if e.g. the good resources are far away from the existing network and if the country might not be able to easily afford the expenditures. The feed in tariff has to be built in such a manner that the energy specific tariff is lower at better sites but still stimulates the search for the best sites. The second step should allow to produce the renewable electricity within one country and consume it in neighbouring countries, whereas the third step would allow for renewable electricity to be transported across third countries. This would involve developing rules for third party access in non-signatory states. This third step aims to stepwise erect an international renewable electricity supply system. Following these three steps it can be ensured that large favourable potentials of renewable energies can be used also in countries, which have small energy consumption or are economically not easily able to afford the use of their renewable potentials. In this way these potentials can be placed into the service of the climate and the resource policy understood as an international task. This form of "EEG" can thereby either be started bilaterally between Germany and other states, or on the European level, or most preferable as an international agreement, whereby in particular an anchorage in the UN appears expedient. However, the time is ripe to start pushing this idea into the follow-up treaty to the Kyoto treaty. In 2009, the potentially decisive Conference Of the Parties is going to be here in Copenhagen. We propose therefore this mechanism to be developed as a new variant of the CDM, or as a third instrument besides JI and CDM.

Such an international "EEG" could become a kind of development assistance for states in the south and the east of the European Union and world wide, which simultaneously would be of advantage by the use of highly economical potentials and thus cheap renewable electricity for the richer industrialised countries involved. Thereby a substantial effect of an international "EEG" should be to open for the use of particularly favourable locations for different renewable energies to include them into an international system acquiring more economical solutions for climate protection than could be found with single-handed national attempts.

International co-operation in the field of electricity production and transmission opens up the possibility of a sustainable electricity supply using only renewable energies which would, even if only current technologies were used, be only slightly more expensive or even cheaper than our current electricity supply. The underlying calculations are based on today's relatively high renewable technologies prices [Czisch 2005]. In the case of an approximately optimal use of the renewable resources and available techniques, costs of electricity from renewable energies would probably lie under the current prices of comparable electricity from new fossil fired power plants. Thus a conversion to renewable energies could most likely lead to economical savings, which become continually larger as the renewable electricity generation becomes cheaper due to further techno-economic progress. For example, the learning curve parameter of wind energy is between around 15%, which means that for every doubling of the installed capacity (at current rates, this happens every few years), the price of wind power drops 15%. Keep in mind that the price of most renewable power generation is pretty much fixed once the initial investment has been taken. The same cannot be said for any power generation option including a fuel price risk.

To describe the advantages of a large-scale exchange of renewable energy arising from the implementation of the international EEG in Europe and surroundings is the scope of the next section.

3 100% Renewables: a realisable Vision

Both the resources problem and the extent of the looming climate change make a change of course in humankind's use of energy sources appear inevitable. Independent of the question of the level on which energy consumption can be stabilized, clarification of the technical and economic possibilities for the future energy supply is necessary. Promising options exist in the use of renewable energies in their whole variety.

[Czisch 2005] concentrates on the technical aspects of the electricity supply as a partial aspect of the energy supply. Electricity supply is increasingly gaining in importance and can be seen as a key to a sustainable energy supply; Worldwide electricity production is currently responsible for 10.5 Gt_{CO2} or almost 45% of the total anthropogenic CO_2 emissions from fossil fuels stem from big power plants with an annual exhausts of more than 0.1 Mt CO_2 [IPCC 2005]

In his study the possibilities of a largely CO_2 neutral electricity supply for Europe and its closer neighbourhood were examined on the basis of different scenarios, whereby the scenario area actually covers about 1.1 billion inhabitants and an electricity consumption of about 4000 TWh/a. The focus was the question of how the electricity supply should be developed to lead to the most economic solution. This question was considered, for example, for scenarios based only on techniques available today. Also examined was the possible influence which the use of some new technologies – in so far as they are still under development – could have on the future options of the electricity supply, on the basis of some examples. The conception of the future electricity supply was aimed to meet criteria of the greatest possible objectivity, to provide genuine comparability of different resulting scenarios.

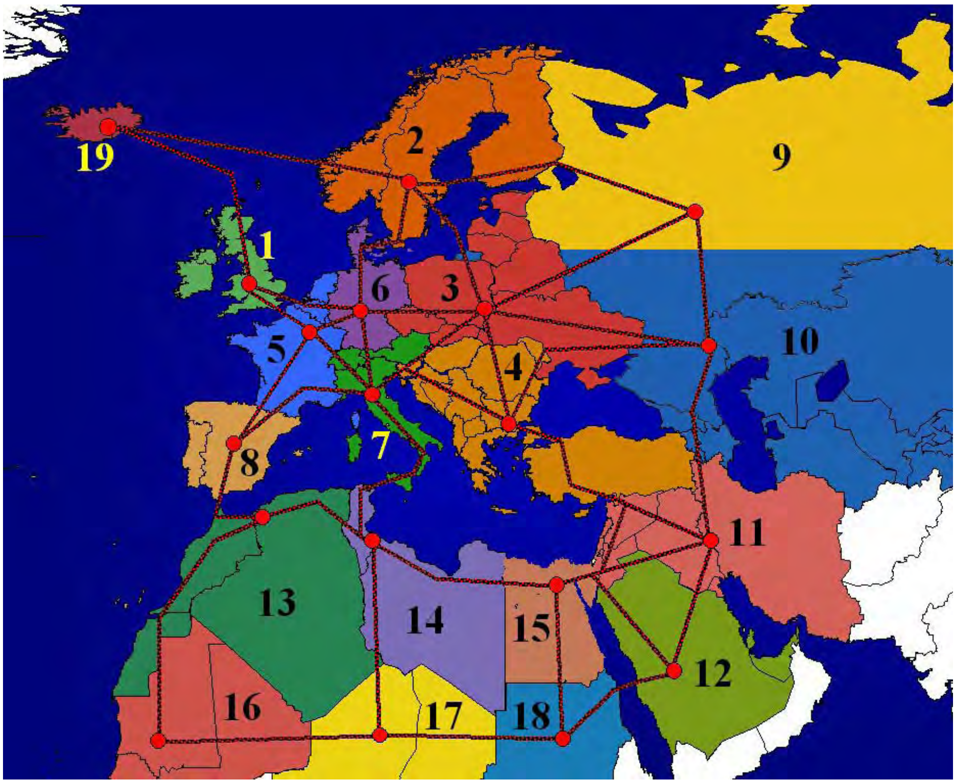

Figure 1: Possible electricity supply area divided into 19 regions with schematic representation of potential electricity transmission paths using HVDC to the geographic population centres of the regions.

To achieve this aim a mathematical optimization approach was implemented. The target of the optimization was to find the ideal system of power plants and transmission systems to provide the least cost solution for a realistic electricity demand close to the current demand. As options for the electricity production the use of renewable energies with hydro-electric power plants, wind energy converters, energy towers [ABZ 2004], biomass power stations as well as solar and geothermal power stations are considered amongst others. Dependent on the selected conditions, this resulted in different scenarios establishing a broad basis for future political decisions. The scenarios present options for a future organization of the electricity supply and point out the impact of different - also political conditions.

Before calculating the scenarios, the different potentials of renewable energies and their characteristics had to be determined in high temporal and spatial resolution. This set up a reliable data basis allowing answers to the questions associated with a spacious renewable electricity supply, without resorting to unverified assumptions. The characteristics of the different systems for energy conversion and transport also had to be studied and are discussed together with their associated costs and the potentials within the dissertation.

The starting point is a conservative base case scenario. It is a scenario for an electricity supply relying entirely on renewable energies, all of which are based on technologies available today and calculated with today's costs of all components. This base case scenario can accordingly be understood as a kind of conservative Worst Case estimation for our future options of a renewable electricity supply.

As a result of the optimization for the base case scenario, the largest proportion of the electricity production is from wind energy. Biomass and currently existing hydropower take over the predominant part of the back-up function within the supply area which is interlinked with powerful HVDC (high voltage direct current) transmission. The calculated costs of electricity production and HVDC transmission are about 4.65 €ct/kWh and therefore relatively close to the current costs of electricity produced with conventional technologies.

They are actually lower than today's prices on the electricity stock exchange in Germany (The monthly average price for the cheap Cal-08 in 2007 always was roughly between 5.2 and 5.6 €ct/kWh [EEX 2007].). In all scenarios - except the relatively expensive restrictively "decentralized" ones which exclude cross-national electricity transport via HVDC - the electricity transport plays an important role. It is used in order to realize smoothing effects of the weather-dependent electricity production from renewable sources, to make the best production sites accessible for common use and to enable the use of hydropower as well as the decentralized biomass with its inherent storage capability for common duties within the supply area. Thus electricity transport proves to be one of the keys to an economical electricity supply. This again can be interpreted as a recommendation for action for political decision-makers, who thus should deliberately pursue international co-operation in the field of renewable energy use and include in particular the issue of international electricity transmission.

The scenarios constitute a detailed and reliable basis for crucial political and technological decisions about our future electricity supply. They show that - even under conservative assumptions - an exclusively renewable electricity supply is possible with international cooperation and could be realized without any significant economic problems. This places the responsibility for future action in the field of policy. A substantial task of the policy-makers would be to organize the necessary international co-operation and to develop legal and economic instruments like the international EEG for a transformation of our electricity supply. Thereby, not only a reasonable path to a CO_2-neutral electricity supply would be taken, but beyond that excellent perspectives for the development of poorer neighbour states of the European Union and Europe could be opened.

4 Detailed Results from the Scenario Studies

Various concepts have been studied for providing renewable electricity to Europe and neighbouring regions. This process has taken into account reanalysis 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 Centers 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 1999]. 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 as well in Figure 1) 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.

4.1 Base-Case Scenario 100% Renewables

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 [Czisch 2001] and [Czisch 2005] 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 2006 of about 3.5 €ct/kWh for industrial consumers in Germany [EC 2007], electricity from newly erected combined-cycle gas power stations had already reached a significantly higher level of 7 - 8 €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.

4.2 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 becomes 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.

It is also possible to fix the minimum amount of electricity which has to be produced locally without restrictions in transport. One scenario was calculated where each region had to produce 50% of its yearly demand within its own borders. While not an actual being a restriction on transport, this mandate only relatively slightly reduces the total transmitted amount of electricity to 36% of the total production. The cost of electricity is 8.6% above the one of the base case scenario. The generation mix changes hereby to more offshore wind energy and less solar thermal production.

4.3 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 again and again have been divided by two. As a result PV has not been chosen by the optimisation until costs fell to one-eighth of its current cost. 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 just above 12% (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 Saudi Arabia and the southern Saharan countries or the 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 are 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 [CS 2004]) 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.

4.4 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 1999]). 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 (Chad and Niger), 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.

4.5 Scenarios with Technologies Under Development

Since the implementation of the base case and similar scenarios will take many years, an attempt has been made to include some promising power generation technologies already on the horizon. A somewhat speculative scenario includes the use of energy towers (see [ABZ 2004] and [ACGZ 2006]). Should the assumptions used for energy towers hold true, especially the economic ones, then – according to the optimisation - those power plants would dominate with a generation equivalent to 49% of the total annual electricity consumption in the scenario area. The overall generation cost is with just below 4.1 €ct/kWh about 12% less than in the base case scenario. Solar thermal generation is completely replaced by the optimisation, but also large shares of wind power as well as a minor shares of biomass use. This scenario shows that further development of this technology might be worth while. Therefore research into the technology is needed, aiming to reduce the financial risk involved with building such a type of power plant and focussing on everything necessary to build a prototype of this kind of power plant which has not yet been tested. Generally, one can derive from that result that there should be more research grants and more venture capital devoted even to speculative ideas, which might have the potential to deliver energy at low prices and from different renewable sources.

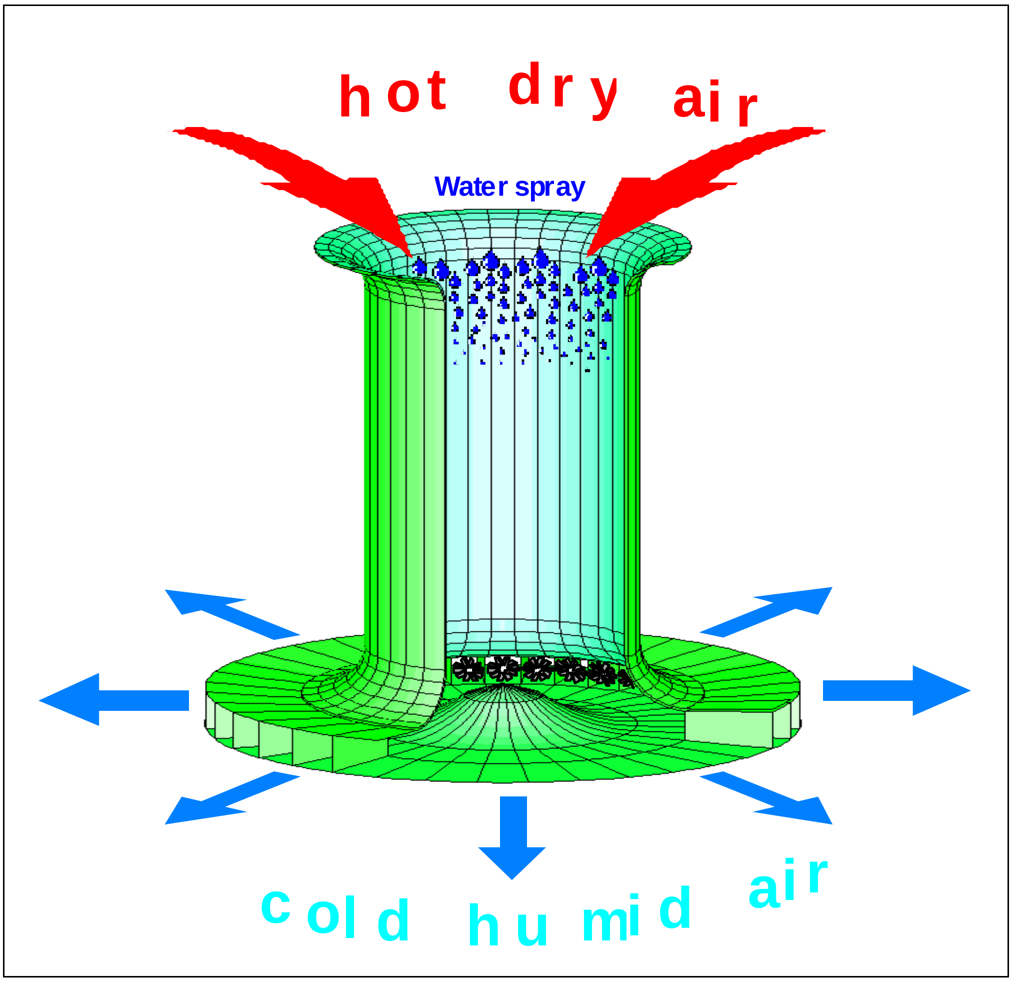

Figure 2: The principle of the energy tower. Hot air streams from above into a large tube, water is injected to cool the air, which falls down and drives some turbines at the bottom of the shaft.

4.6 Electricity Transmission within the Scenarios

In all scenarios – with the exception of the restrictive and expensive insular configurations – electricity transmission is of significant importance. The necessary converter capacity (AC⇔DC) for the HVDC grid reaches 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 in 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.

5 The International EEG as Implementation Vector in Kyoto II

In the largest part of the paper, we have shown that it is possible to supply all of "Greater Europes" electricity needs solely with the use of renewable energy and large-scale transmission of that electricity. This would create a large zone of mutual interdependence, as the EU creates an economic interdependence amongst the European states which can be considered as stabilising factor. On the other hand this kind of interdependence has some similarity with the dependencies in the current fossil fuel based system. But with significantly more different renewable sources from many different countries and therefore with higher intrinsic stabilising diversification the dependency from single partners is clearly relieved if compared to the fossil driven system. With the gradual depletion of fossil sources the amount of sources declines in the fossil system. On the contrary the sources for renewable production become more and more and therefore potentially more distributed with technological progress. Furthermore, due to the nature of renewable energy, which is much more distributed and creates many more local jobs, the wealth created is more spread out in the population. If this large-scale implementation of renewable energy could be managed, it would therefore be for the benefit of larger parts of the countries involved and of larger parts their population than oil revenues typically are.

In the current Kyoto protocol, there are two main mechanisms for international carbon avoidance: the Clean Development Mechanism CDM and Joint Implementation JI. While the CDM is between developed countries and developing ones, JI describes the modalities of joint carbon projects between developed countries. The International EEG would be both between developed countries themselves and developing countries, therefore it is hard to see for the authors whether it should be anchored in one of the two tools or whether it should become its own tool in the coming round of negotiations. The probably decisive Conference of the Parties will be held 2009 in Copenhagen, on invitation of the Danish Ministry of the Environment. We launch this idea now to allow for thorough discussion of the idea, and to allow time for preparative diplomacy before the conference itself.

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