# Optimization of the Utilization of Renewable Energy Sources in the Electricity Sector

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*Abstract:* - Emission reduction targets as well as the scarcity of fossil resources make a transition of the energy system towards a carbon free electricity supply necessary. Promising energy resources are solar and wind energy. The challenging characteristics of the high temporal and geographic variability of these resources make a systematic analysis of the integration necessary. Subject of this study is the how such a renewable-based energy system ideally should be designed. We investigate the optimal structure of a prospective renewable-based power supply system on two different scales: on the global and on a European level. The paper describes the applied simulation technique employed to combine an adequately precise geographical coverage with high temporal resolution. A linear optimization algorithm determines the cost optimal configuration of the prescribed energy system. As results we obtain ideal energy mixes, generation sites, storage and interregional power transmission capacities required for different scenarios of highly renewable supply.

*Key-Words:* - Renewable Energy, Simulation, Linear Optimization, Power Supply, Geographic Information System (GIS), Supergrid, Energy System Model

## 1. Introduction

Global greenhouse gas emissions, the increasing demand for electricity and the scarcity of fossil fuels suggest that the reorganization of the existing energy system is necessary. The electricity sector plays an important role in the reduction of anthropogenic green house gas emissions. 21% of the global greenhouse gas emissions stem from energy generation [1]; in Europe 33% [2] of the emissions fall on the electricity sector. The use of less carbon intensive technologies is therefore necessary to meet challenging emission reduction targets.

Projections of the global energy mix in macroeconomic models, i.e. integrated assessment models, which integrate greenhouse gas emission restriction targets show that within the coming century an important share of renewable energies is needed in order to accomplish 550 ppm and 440 ppm emission reduction targets [3]. Here mostly solar and wind energy are proposed as well as biomass.

The technical potential of renewable energy resources is largely sufficient to cover the electricity demand worldwide. Detailed insights of the technical potential of wind, solar and biomass energy can be found in the literature [4, 5, 6, 7, 8]. While biomass is geographically flexible – it can be transported to locations of high demand and an increase in trade with biomass is projected for South America [9] – other renewable recourses such as wind, solar and hydro energy may only be utilized at specific sites and at specific hours. These sites are however not always located in proximity to densely populated areas, where the demand for electricity is high [7, 8, 10]. The competiveness of a variable renewable energy resource depends on the distance between areas of high renewable potential and load centers as well as accessible transport technologies. These characteristics of the system have to be taken into account, when the deployment of renewable energy sources is studied.

Additionally, the very short term variability of wind and solar resources poses problems to their integration. Here a dispersed generation may be helpful, as this can accomplish smoothing effects. Not only the statistical smoothing effect through an enlargement of the sample, also interseasonal anticorrelations as well as time shifts and beneficial effects of energy generation on opposite hemispheres may be useful for the deployment of renewable energy resources [11, 12, 13, 14].

A detailed and realistic analysis of the utilization of renewable energies can therefore only be accomplished with a high temporal and geographical resolution. In this paper, we present results, which are based on a simulation methodology that meets this requisite. The central question of the analysis is: How should a renewable-based energy system ideally be structured?

The question is studied on two scales: the global and the European scale in hourly temporal resolution.

In the global model a resolution with regions of about 2000 km size is accomplished, which allows to map differences within continents or even within big countries.

The European model is resolved to a mesoscale, where the regions have 600 km size.

On the one hand the two scales allow to adress distinct questions concerning the energy system structure. The European model is a tool to analyze an increasing share of renewables in the system and the beneficial effects of a European Supergrid. Precise projects can be tested concerning their technical feasibility as well as economic and ecologic effectiveness. Starting from the end-point of the mitigation towards a full renewable supply in a first step the ideal generation sites, energy mix and energy flows are determined. The global model on the other hand is developed to study how, in a prospective energy supply structure, the transport of electricity between continents, timezones and hemispheres allows gaining profit from interseasonal and interdiurnal variations of renewable energies. Also here stepwise an analysis from ideal cases to more realistic ones is carried out.

Common to both models is not only the methodology, but the quest for ideal energy flows in a highly renewable case.

The paper is divided in three parts. In section two the methodology and the model framework is described. Section three lines out the database developed and employed. The last section shows results of the global and the European model for different scenarios and draws comparisons between the two.

## 2. Model Framework and Analysis Methodology

The analysis of the integration of renewable energies on the global and European scale is carried out through the application of an energy system model, based on linear optimization.

The ambiguity between the advantages of a dispersed renewable energy supply and the resulting need of substantial electricity grid extensions is the problem to be addressed by the model. Ideal energy- and capacity mix as well as ideal energy flow between the energy source and the areas of high load are determined in the model by linear optimization of the overall costs. In order to take into account effects of dispersed renewable energy generation and the high variability of these resources in time and space, high resolution is implemented.

The optimization is carried out for one typical year in an hourly resolution. The regional resolution naturally differs in the European and the global model. The European model is divided in mesoscale regions of 300 km radius, while the global model comprises 51 regions.

The objective function $C$, the total costs of the system, contains all parameters describing the energy system:

$$\begin{aligned} C = &\sum_x [CapNew(x)\,K^{Inv} + Cap(x)K^{Fix} + \sum_t E(x,t)\,K^{Var} \\ &+ CapNew_{Sto}(x)\,K^{Inv} + Cap_{Sto}(x)K^{Fix} + \sum_t E^{Sto}(x,t)\,K^{Var} \\ &+ \sum_y CapNew_{Tr}(x,y)K^{Inv} + Cap_{Tr}(x,y)K^{Fix} + \sum_t E_{Tr}(x,y,t)\,K^{Var}] \end{aligned}$$

$E$ is the energy output in region $x$ at timestep $t$, $Cap$ the installed capacity and $CapNew$ represents the new Capacities. $K^{Inv,Fix;var}$ are the annuity of the investment, fix and variable costs. Analogously $E_{Sto}$ and $E_{Tr}$ are the stored and transported energy.

Trough minimization of the overall system costs, the economically most efficient configuration of the system can be determined. This minimization is subject to restrictive equations, which describe the energy system, such as the satisfaction of demand, transport and storage losses, conversion losses, technical potential for renewable energies and technical limits of the power plants (see [15,16,17]).

An overview on the general structure of the model is presented in figure 1. As it is illustrated in the diagram, hourly time series of the meteorological data, the technical potential for renewables and the hourly load curves for each model region serve as model inputs.

Hourly values of the capacity factor for wind energy converters and solar radiation are considered as constraints on the operation level of renewable technologies. Restrictions on the permissible level of newly installed capacities are approximated based on GIS (Geographical Information System) datasets of suitable area for installation of wind parks and solar thermal power generation systems, described in 3.1 and 3.2.

Furthermore, techno-economic parameters of power plants and power transmission lines, such as costs, efficiency and power change, are feed to the model. Modern technologies are assumed as well as realizable cost reduction trends due to learning rates in accordance with literature [18, 19].

Through a detailed evaluation of input parameters a reliable data basis with a high level of temporal and spatial resolution is set up, which allows to properly mimic the geographic dependencies of energy supply and demand, as well as the short term variability of the renewable resources.

Model formulation and optimization process are realized with the application of General Algebraic Modeling System (GAMS) software package [20].

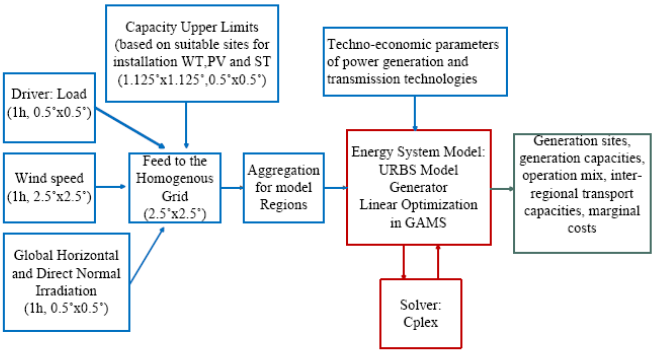

**Figure 1: Model Setup**

# 3. Energy Supply and Demand Data

## 3.1. Solar Energy Potential

Global and European datasets of solar irradiance are used for the computation of the capacity factor for the models [21, 22, 23].

For the global model the SeaWiFS data is used, which is available on a 720x 360 (0.5˚x 0.5˚) rectangular grid and includes 3-hourly direct normal and global horizontal irradiance, diffuse fraction and zenith angle values for the time horizon from 1991 to 1993. We spatially rescaled this dataset for a homogenous grid with a resolution of 2.5˚x2.5˚ and approximated the hourly values.

For the European scale hourly data of global and direct irradiation is taken from [21, 22] and readjusted for the model regions. The resulting values for the annual specific global horizontal radiation are visualized in figure 2.

Total capacity permissible to be installed at each model region is determined based on a detailed analysis of the technical potential for solar thermal power plants by P. Tzscheutschler [7]. This analysis includes landuse, land slope and infrastructural restrictions. Promising sites in our models comprise suitable and limited suitable areas in the nomenclature by P. Tzscheutschler [7].

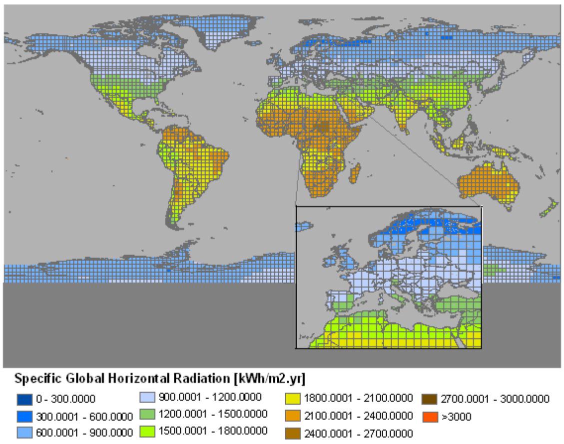

**Figure 2: Annual specific global horizontal radiation, Meteorological data from [21]**

## 3.2. Wind Energy Potential

Global data of wind velocities for on- and offshore sites is taken for both models from the World Wind Atlas [24]. Based on measured values, this dataset offers modeled wind speeds for a grid with a resolution of 2.5˚x 2.5˚. The base data represent six-hour wind speed values for the time horizon from 1992 to 2001 at 50 meter above the ground. For the purpose of modeling with high temporal resolution, hourly values are approximated. The transformation from wind velocity to active power output has been done using data from modern existing wind turbines for onshore and offshore sites [25].

Limits to the available area for the installation of wind parks are taken from an elaborate analysis of the technical potential for wind energy by O.Brückl [8]. This data is projected to a 1.125˚x 1.125˚ grid. The result of the calculation is the annual wind energy production on land sites in full load hours of wind turbine V90-3.0 MW, which can be seen in figure 3.

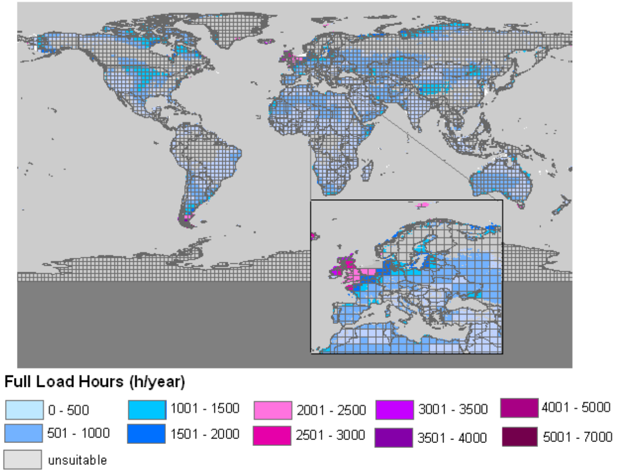

**Figure 3: Realizable annual wind energy production on suitable land sites in full load hours of WT: V9-3.0 MW [25], Meteorological data from [24]**

## 3.3. Load Data

Geographically aggregated projections of the global population for the time period 1990 to 2100 are available at IIASA Greenhouse Gas Initiative (GGI) database based on three scenarios (A2, B1, and B2) from the IPCC Special Report on Emissions Scenarios (SRES) [26].

To derive values for each grid cell, electricity demand from IIASA Greenhouse Gas Initiative (GGI) database has been spatially disaggregated, based on the spatial distribution of population [27].

Hourly load data for all UCTE members for the time period 2006 to 2009, Nordel interconnected area and the United Kingdom are freely available [28, 29]. Load values for other regions have been obtained by personal communication with local transmission system operators [30, 31]. Hourly load data for the year 2007 were made available for 32 countries. However, for a number of countries comprising Malaysia, Uganda, Thailand, Mali, Niger, Jordan, Australia, Lebanon, and Tunisia we could only gain access to average monthly or typical daily load curves for winter and/or summer.

For the global model the hourly load values for each model region are approximated based on the linear combination of existing normalized load curves shifted for relevant time zones. Although this procedure will not fit the actual demand pattern, it will serve the purpose to get a rather appropriate estimation of load patterns and to deal with data inadequacy. For the European model the UCTE load curves are used in combination with the population data.

### 2.4. Geographical Scales

In this paper we compare the results of the application of the described methodology at two different scales: the global and the European scale. In the global model a resolution with regions of about 2000 km size is accomplished. In the European model the regions have 300 km radius. .

The world model comprises 51 aggregated regions. Global macroeconomic energy models (for example [EFDA TIMES, Multiregional MARKAL, REMIND, MERGE, NICE, FUND]), are mainly limited to a coarse spatial resolution of up to 15 aggregated regions [14, 18, 32, 33, 34]. The presented model not only has a substantially larger number of regions, but also allows high temporal resolution. Furthermore the regions are determined not only based on political borders, but also according to the geographic distribution of electrical load profiles and renewable supply structure.

Geographic distribution of technical potential of Renewable electricity and load in year 2050 is visualized in Figure 4 for the model regions.

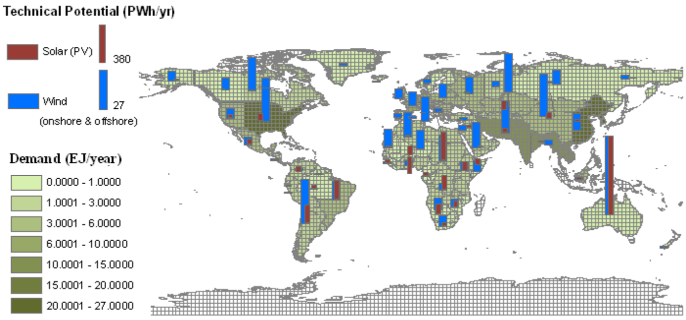

**Figure 4: Global geographic distribution of Load in 2050 and Renewable Technical Potential, Meteorological data [21,24], Load data [26]**

In the European Model a hexagonal shape for the regions is chosen. This allows a uniform and six fold interregional transport structure for each model region. The size of the regions is in accordance with the resolution of the meteorological data.

## 3. Scenario Based Analysis

### 3.1. 100% Renewables scenario setup

The starting point for the analysis of the system behavior is the so-called 100% Renewables scenario. This is considered as an ideal case for prospective electricity supply system, relying on the maximal possible share of renewable energy sources.

Conventional power generation technologies are aggregated to one backup technology named “other” in this scenario. As promising options for renewable electricity production, wind energy converters for onshore and offshore sites, centralized PV, and concentrating solar power systems are considered. The optimization of the system for this scenario allows addressing the question of how such a system integrating a maximal share of renewable energies should be structured in order to lead to the most economic solution.

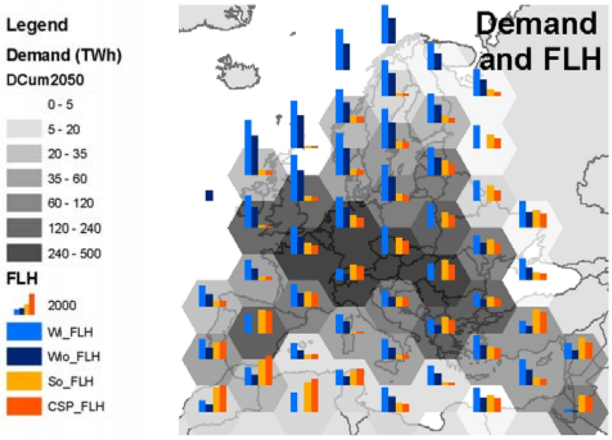

**Figure 5: European geographic distribution Renewable Technical Potential and Load in 2050, meteorological data [21,24], Load data [26]**

Several boundary conditions such as transmission network capacities, availability of storage options and capacities for different regions, fuel prices, and climate policies may have significant impacts on the optimal structure. For the comparison of the dynamic behavior of the global and the European system the first two points – storage and transport – are crucial. We therefore present three scenarios, which allow to quantify the benefits of a powerful transmission network and of the availability of storage in a supply system with maximal share of renewables.

In all scenarios shown in Table 1, costs for renewable energies are projected to be low, while the backup capacity is considered to be an expensive option. This approach allows determining the maximal feasible share and the ideal mix of renewable resources. In the first scenario “LinkCost-NoSto” the transport capacities between the model regions can be expanded with realistic costs. The advantages of a powerful electricity transport grid are examined by comparing the results of the “LinkCost-NoSto” Scenario with one, where no energy transport between the model regions is allowed for (“NoLink-NoSto”). The effects of the possibility for energy storage are studied in the “LinkCost-Sto” Scenario.

### 3.2. 100% Renewables scenario results

#### 3.2.1 Aggregated results

We show the aggregated results of the optimization for the above described scenarios in figures 6 and 7. These include the cost optimal structure of the renewable-based power generation mix, as well as the required level of backup power at different framework conditions.

**Table 1: Ideal scenarios and underlying assumptions**

| Scenario | Underlying Assumptions |
|---|---|
| LinkCost-NoSto | • High cost reduction and efficiency improvement for renewable technologies<br>• Lower production limit for renewables As a percent of load (wind-on:45%, Wind-off:10%, PV: 30%, and CSP: 15%; in the European model this limit is not implemented in order to investigate the optimal share of renewables)<br>• Suitable and limited suitable sites can be utilized for renewable electricity production.<br>• Supply area is interconnected via HVDC with low investment cost [35] |
| NoLink-NoSto | • Supply area is not interconnected |
| LinkCost-Sto | • Storage is possible |

Figure 6 shows the capacities of the generation and storage technologies; Figure 7 shows the produced electricity by fuel type, excess production, and total annual demand.

On the global and the European Level, we can see that it is not possible to run a system integrating high shares of variable, renewable resources as efficiently as a system of dispatchable, fossil fuel-based technologies. The actual installed capacity in Europe is about 760 GW [36], while at global scale it reaches 10 TW [37]. Over-installation of capacities occurs due to the limited availability of the renewable resources. Solar resources are utilized to a smaller extent in Europe than at the global scale, as here the potential for solar energy is comparatively low.

The comparison between the scenarios “LinkCost-NoSto” and “NoLink-NoSto” shows that with an interconnection of the model regions smoothing effects among weather dependent renewable power generation units can be achieved. Most promising sites are made accessible for wide-area, and the necessity of backup capacity is reduced, in the global case by a factor of nearly 8, in the European by a factor 2. World-wide utilization of renewable energy resources in an interconnected infrastructure leads to the reduction of resource variability to a higher extent compared to the European interconnected structure. When storage is included (“LinkCost-Sto”), the system needs even less backup capacity. Additionally, according to Figure 7 the inclusion of storage and interregional transport lead to the reduction of system inefficiency due to excess production. This is the share of produced electricity that can neither consumed, nor can be economically stored.

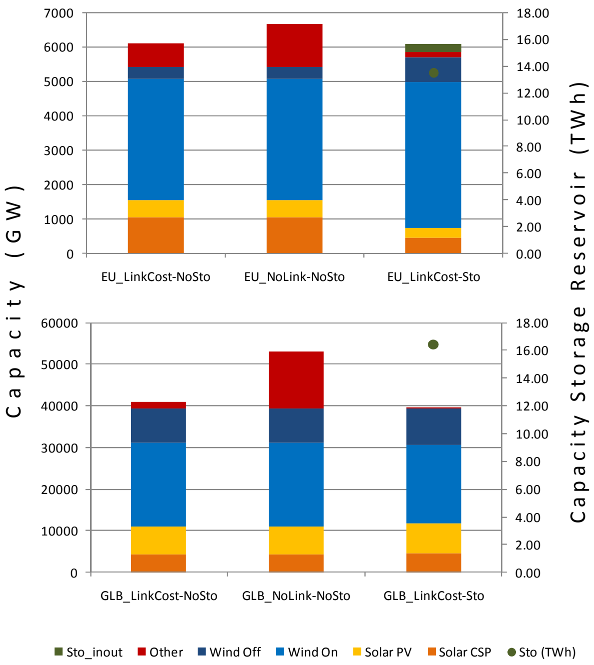

**Figure 6: Total power plant capacity for the ideal scenarios at European and global scale**

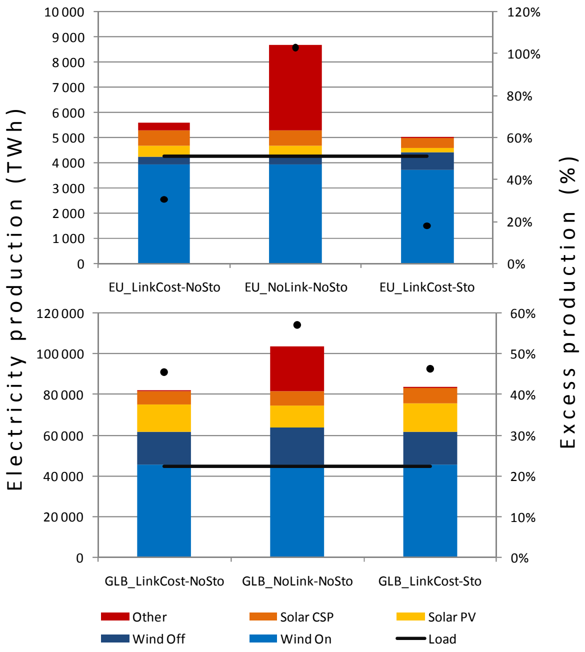

**Figure 7: Total energy production for the ideal scenarios at European and global scale**

### 3.2.2 Global ideal generation sites and flows

The geographical resolution of the model allows identifying promising generation sites as well as ideal flows which are described in the following.

The global geographic distribution of produced energy resulting from the optimization is shown in Figure 8. Centralized PV is distributed among the most promising locations: North America, South America, Middle, Western (countries located in the southern of Sahara) and

Southern Africa, Central Asia (Kazakhstan) and Eastern Asia (China), and Australia. Promising onshore and offshore sites for the installation of wind energy converters also result from the optimization.

In the “NoLink-NoSto” scenario additional backup power is installed within individual isolated regions according to the load of the model region. This leads to the increase of overall power generation capacity for satisfying the same level of electricity demand compared to the “LinkCost-NoSto” Scenario, which results in additional expenses.

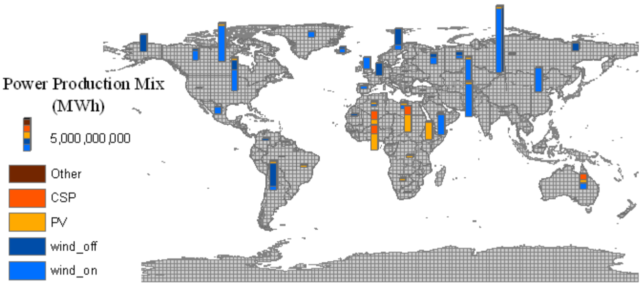

**Figure 8: Geographic distribution of optimal energy production for a maximal share of renewable energies at global scale, Scenario “LinkCost-NoSto”**

The scenarios “LinkCost-NoSto” and “LinkCost-Sto” are characterized with high interregional energy flows. In the “LinkCost-NoSto” and “LinkCost-Sto” scenarios 48% and 60% of total produced electricity is interregionally transported.

Physical energy flows through the global super grid, resulting from the optimization, are illustrated in Figure 9. One noticeable feature is the major energy flows to the projected high load centers of south-east Asia, China and India. Highly concentrated technical potential of wind and solar electricity in Australia (Figure 4) resulted in its contribution as one of the main exporting regions. Significant energy flows also occur from Kazakhstan with high potential of renewable sources to Middle East. Import of wind electricity from Alaska offshore sites through Far East to Eastern part of China also is realized in the optimization. In European interconnected area the major flows take place from Britannia to Western Europe, and North Africa through southern Europe to central Europe. Another interesting feature is the exchange of wind electricity from Alaska through Canada to western U.S. Additionally renewable electricity is imported from Argentina with significant level of renewable supply to the northern part of South America.

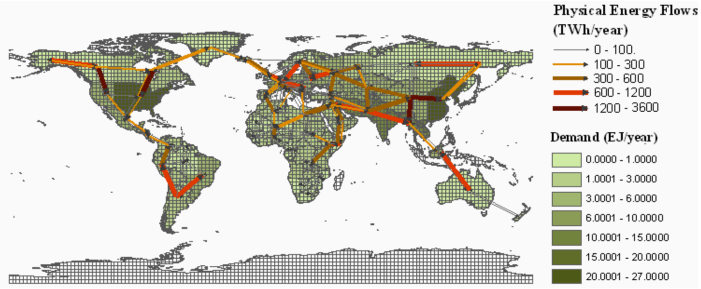

**Figure 9: Ideal Annual Energy flows at global scale for the „LinkCost-NoSto“ Scenario**

### 3.2.3 European ideal generation sites and flows

The European ideal energy mix is depicted in figure 10. The high potential for wind energy on the northern European costs in Scandinavia and Great Brittan results in an important share of wind energy in the overall supply. Solar energy is used in southern regions, like Spain and the Middle East. In Northern Africa mainly wind energy is used. The little contribution of solar energy from this region is due to the low technical potential assigned to this region [7].

The energy flows shown in figure 11 result from the supply pattern and the areas of high load, which can be seen in figure 5. Major flows lead from northern Africa to the areas of high load in central Western Europe (France, BeNeLux, Germany). This region is additionally supplied with wind energy from Scandinavia. The south-eastern part of Europe – having a high potential for solar energy – is projected to have high electricity demand in 2050 [26]. It therefore shows important electricity import and export.

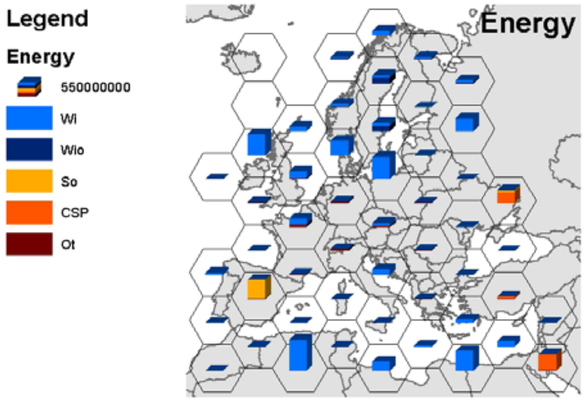

**Figure 10: Geographic distribution of optimal energy production for a maximal share of renewable energies at European Scale, Scenario “LinkCost-NoSto”**

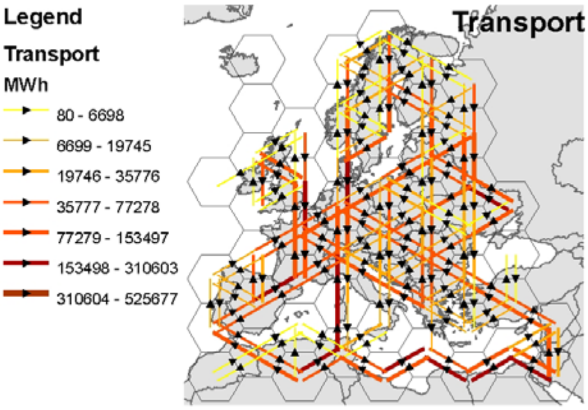

**Figure 11: Maximal energy flows in Europe for the „LinkCost-NoSto“ Scenario**

### 3.3 Mitigation Scenario

In the 100% Renewable scenario a system with a maximal share of renewable energies is studied and existing power plants are not taken into account. In this section a scenario is presented, which can be situated between the actual situation and the ideal structure presented in section 3.2. This mitigation scenario is based on emission reduction targets of the Intergovernmental panel for climate change (IPCC).

In 1994, IPCC working group 1 published a set of concentration profiles for stabilizing atmospheric green house gases at 350, 450, 550, 650 and 750 ppmv [38]. In the mitigation scenario, which is again is analyzed at global and the European scale, the mitigation scenario proposed by IPCC Working group1 for stabilizing CO2 at 550 ppmv is implemented [39].

Associated long term efficiency improvements and realizable cost reductions are approximated based on [18, 40, 41].

In the analyzed mitigation scenario, conventional power plants as well as renewable-based technologies are included. The economic parameters of the technologies are represented in table 2.

**Table 2: Economic parameters of power plants [18,40,41]**

| | Investment (US2000/$\text{kW}_{\text{el}}$ | Fix Cost (US2000/$\text{kW}_{\text{el}}$/a) | Var. Costs (US2000/$\text{kWh}_{\text{el}}$) |
|---|---|---|---|
| Wind On | 750 | 20 | 0 |
| Wind Off | 1300 | 40 | 0 |
| Solar PV | 2200 | 12 | 0 |
| Solar CSP | 1840 | 18 | 0 |
| Coal | 1400 | 19.75 | 0.00108 |
| Gas | 500 | 35 | 0.000648 |
| Oil | 500 | 0.003 | 0.00072 |
| Nuclear | 2000 | 60 | 0.000216 |
| Storage | 600 | 6.83 | 0 |

In the European model, the nuclear energy production is limited to the current level of nuclear power production [42]. In the global model, we investigated the role of nuclear power as an emission-free technology, and the realizable extensions of this technology are investigated only based on the optimization analysis without implementing any additional constraint.

The power generation capacity mix is visualized in Figure 12. In the mitigation scenario, at the European level, wind energy converters provide an important share of the supply. Gas power plants contribute as major peak load operating technologies and nuclear power and coal serve as base load. In the global model the cost optimal solution is characterized by a greater share of nuclear power, followed by wind electricity.

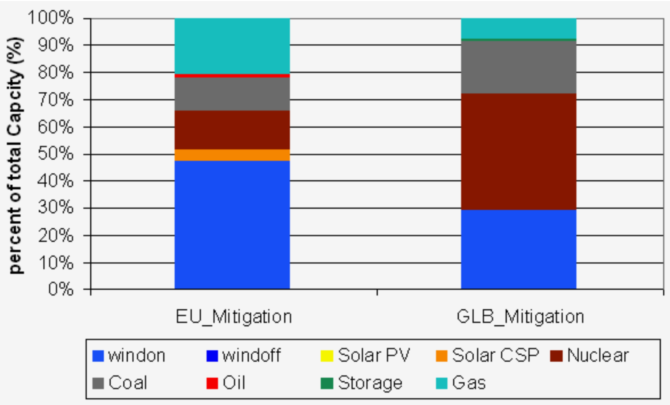

**Figure 12: Share of capacities by fuel type for the mitigation scenario**

The larger share of conventional plants results in less electricity network extensions. In comparison to the ideal scenario, the transport capacity in the mitigation scenario reaches 4% of total transport capacity in the “LinkCost-NoSto” scenario at European scale. At global level, this value reaches 7.5%.

## 4. Conclusion

In this study, two models at different scales, developed for the analysis of long term evolution of the power supply system, are presented. The modeling approach is the combination of an adequately precise geographical coverage and high temporal resolution. Through linear optimization of overall costs ideal power generation capacities, promising sites for installation of renewable technologies, optimal operation schedule of the power station park as well as inter-regional power transmission capacities are determined. Results of the simulation are discussed for different realizations of the ideal 100% Renewables scenario as well as a mitigation scenario.

The applied simulation technique is adequate to properly mimic the geographical dependencies of energy supply and demand as well as short term intermittent patterns of renewable resources and may be regarded as a reliable analysis tool, allowing answers to the questions associated with renewable electricity supply without resorting to unverified assumptions.

The methodology is applied to investigate the benefits of dispersed renewable energy production. The role of a powerful electricity transmission network is examined as well as the role of storage. On both scales, the European and the global scale, a powerful grid allows to reduce the need for backup capacities. In the global model the backup capacity is divided by 8, in the European, by 2.

The smoothing effects through dispersed generation, which occur on the global scale, are bigger than the European ones. For this reason the storage is used less extensively in the global model, than in the European model. Storage is only used for intradiurnal balancing and has a big, but not unreasonable huge capacity.

In a more realistic mitigation scenario we show a low carbon energy mix, where nuclear energy is assumed to play different roles globally and in Europe. In this scenario wind energy is used to a big share in combination with gas-plants as peak load capacities. Again in the global model less balancing power – gas – is necessary, than in the European case. In this mitigation scenario, still based to a large extend on dispatchable power plants, the need for transmission network capacities reduced significantly.

Individually the models show the importance of storage and transmission capacities for the integration of renewable for both scales. The comparison of the scales allows to evaluate the variation of the smoothing effects of dispersed supply on different scales and shows the independency of the basic dynamics of the system from the scale.

It is worth mentioning here that the so-called transshipment energy system models, which neglect load flow restrictions and other technical characteristics of the power transmission network, can lead to suboptimal results. The presented results do not account for this and further research in this topic using power flow models is necessary. Another possible improvement of the presented methodology is to improve the geographical resolution, i.e. reduce the size of the model regions, by integration of small scale meteorological data.

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