Optimal Configuration of a Renewable-based Electricity Supply Sector

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Abstract: - Proposed emission reduction targets as well as the scarcity of fossil fuel resources make a transition of the energy system towards a carbon free electricity supply necessary. Promising energy resources are solar and wind energy. The high temporal and geographical variability of these resources is challenging for their integration. This study focuses on the question how 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 the European level. The paper describes the applied simulation technique, based on linear optimization, employed to combine an adequately precise geographical coverage with high temporal resolution. 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

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-25 30% of the total greenhouse gas emissions fall on the electricity sector [2]. The usage of less carbon intensive technologies is necessary to meet challenging emission reduction targets and also to deal with the scarcity of fossil fuels.

Projections of the global energy mix in macroeconomic models, i.e. integrated assessment models, which integrate greenhouse gas emission reduction targets show that within the coming century an important share of renewable energies is required to accomplish 550 ppmv and 440 ppmv 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 world-wide electricity demand [4, 5, 6]. Biomass is geographically flexible; It can be transported to locations of high demand - an increase in trade with biomass is projected for South America for instance [7]. Other renewable resources such as wind, solar and hydro energy may only be utilized at specific sites and hours. These sites are not necessarily located in proximity to densely populated areas, where the demand for electricity is high [5, 6, 8]. The competiveness of these resources depends on the distance between areas of high renewable potential and load centers as well as accessible transport technologies. Additionally, the very short term variability of wind and solar resources poses problems to their integration from a technical and an economic point of view [9, 10]. Smoothing effects of dispersed generation may alleviate this problem. Not only the statistical smoothing effects through an enlargement of the sample, also interseasonal anticorrelations as well as time shifts and beneficial effects of energy generation on opposite hemispheres may provide a competitive situation for the deployment of renewable energy resources [11, 12, 13, 14].

A detailed, realistic analysis of the utilization of renewable energies can thus 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 level.

On the one hand, the two scales allow addressing 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 ideal generation sites, energy mix and energy flows are determined in the European model. The global model 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. 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 four parts. In section two the methodology and the model framework is described. The validation of the methodology is described in section three. Section four lines out the database developed and employed. The last section shows results of both models 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. Model formulation and optimization process are realized with the application of the General Algebraic Modeling System (GAMS) software package.
The optimization is carried out for one typical year with hourly temporal resolution. The geographical resolution naturally differs in the European and the global model. High resolution is required as it allows to address the effects of dispersed renewable energy generation and their high variability in time and space.
Ideal energy- and capacity mixes as well as interregional energy flows are determined based on the minimization of overall system costs, prescribed in equation (1).

$$
\begin{aligned}
z = &\sum_{r\in reg}\sum_{p\in proc(reg)}(K_{Inv}(p).NCAP(r,p)+K_{FIX}(p).CAP(r,p)+\sum_{t\in T}K_{VAR}(p).Ein(r,p,t))\\
&+1/2.\sum_{r\in reg}\sum_{r'\in reg}\sum_{p\in Tr(r,r')}(K_{Inv}(p).NCAP(r,r',p)+K_{FIX}(p).CAP(r,r',p)\\
&+\sum_{t\in T}K_{VAR}(p).Ein(r,r',p,t)) \qquad (1)
\end{aligned}
$$

CAP describes the total installed capacity while *NCap* represents the newly invested power production, storage, and transport technologies available at each region. *Ein* is the energy input in process *p* operating in region *r* at time step *t*. $K_{\mathrm{Inv,Fix;var}}$ are the annuity of the investment, fixed and variable costs.
Overall system cost 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 of renewable energies and technical limits of the power plants (see [15,16, 17]). 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 areas for installation of wind parks and solar thermal power generation systems, described in 3.1.
Furthermore, techno-economic parameters of power plants and power transmission technologies are integrated. Modern technologies are assumed as well as realizable cost reduction and efficiency improvement trends due to learning rates in accordance with the literature [18, 19].
Due to the high temporal and spatial resolution the number of degrees of freedom of the system, i.e. the parameters to be determined by the optimization, is of magnitude 10^5, while the matrix containing the restrictive equation has approximately 10^6 entries. The sparsity of the matrix makes the solution of the optimization possible. However restrictive equations concerning storage usage and dynamic behavior of the power plants result in stronger coupling of consecutive time-steps. The solution of the optimization is carried out with the solver CPLEX, employing the barrier methodology [20].

3. Model Validation

To validate the methodology, it is verified, whether the model does reproduce today's electricity mix on a global level. In order to do so, the existing power plant capacities are implemented to the model regions and the electricity mix per model region is compared to the real electricity mix.
For the determination of currently operating power plant capacity per fuel, the world electric power plant database [21] has been used. Based on the technical life time of different power plants, projections to 2050 are carried out. The power plant database does not include detailed information about the geographic location of the power plants, In order to assign the power plants to the model regions, the geographical information has been extracted from CARMA (Carbon Monitoring for Action). This combination of the datasets provides a GIS dataset of power plant capacity and electricity production in 2000 and 2007 on a world-wide scale [22].
The geographic distribution of power plants by fuel type is visualized in Fig. 5.
The input parameters per model region for the validation of the model comprise:

- Power plant net electric capacities
- Interregional transport capacities, which is only available for UCTE interconnected area
- Electrical load profiles based on actual net electricity consumption of year 2000, EIA [23]
- Hourly time series of capacity factor for wind energy based on wind speed data from World Wind Atlas [24]
- Hourly time series of solar direct-normal and global horizontal irradiation [25]
- Techno-economic parameters of power plants [18, 26]

The objective of the validation is to examine whether the model can simulate the actual situation to a reasonable extent by comparing the results of the model to actual electricity production data categorized by technology and fuel types provided by CARMA [22]

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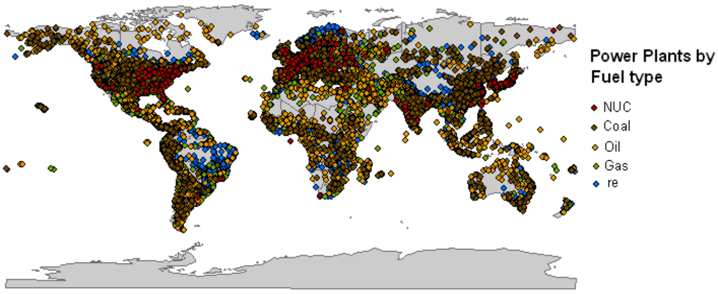

Figure 1: Geographic distribution of power plants categorized by fuel type, based on data from [21, 22][1]

Different factors may limit the accuracy of the validation. Regional differences in techno-economic parameters of power plant technologies, availability factors of operating units, domestic fuel price deviations from international prices due to the existence of subsidies, and specific seasonal characteristics of hydro power production can have negative impacts on the accuracy of the model. Hence, resulted production values may differ from the actual data to various extents in cases. To circumvent these shortcomings, throughout the calibration process, sensitivity analyses have been performed based on different techno-economic parameters of power plants, availability factors, and fuel prices and the results at each stage have been compared with the actual production data.

The resulting model outcome and its comparison to power production shares for different technology types in reality (provided by CARMA) is visualized in Figure 2.

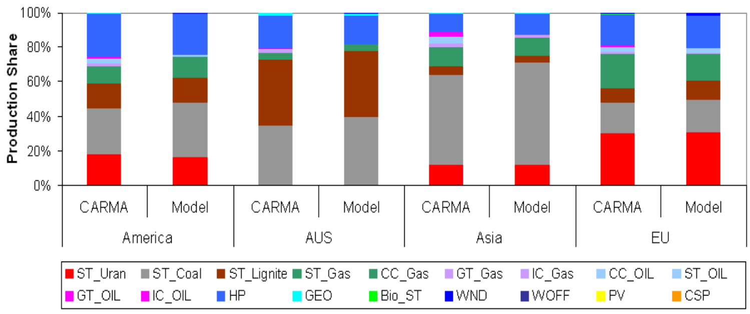

Figure 2: Comparison of model production shares per technology types and continent with CARMA database (real case); year 2000[2]

According to the Fig. 2, the modelled production shares are consistent with actual data. However, there exist deviations, which results on one side from the deviations of domestic fuel prices from international market values as a result of the existence of subsidies and different transport costs. Already within Europe differences in fuel prices for natural gas for instance can reach more than 100%: 0.04 €/kWh$_{therm}$ in Germany and 0.015 €/kWh$_{therm}$ in Bulgaria [27]. As a result, we see a higher deviation in Asia due to the high deviations of fossil fuel prices in the Middle East and China from international market prices. The other effect is that in most cases coal power production results from the simulation is higher than actual data, while the contribution shares of peak power technologies such as Gas turbines are estimated to be lower. This results from the fact that Combined Heat and power is not yet simulated in detail due to the data inadequacy. On the other hand we assume perfect foresight of a central planner, as contrarily to other studies [28] no stochastic variation of model input parameters is included in the model. Gas power plants however often are used to satisfy unexpected load fluctuations and their usage may thus be underestimated by the deterministic model.

4. Energy Supply and Demand Data

4.1. Solar and Wind Energy Potential

In order to evaluate the global technical potential of solar electricity, the global irradiation dataset produced in the SeaWiFS project is applied here [25]. We spatially rescaled this dataset for a homogenous grid with a resolution of 2.5˚x2.5˚ and approximated the hourly values based on the earth's rotation and orbit around the sun.

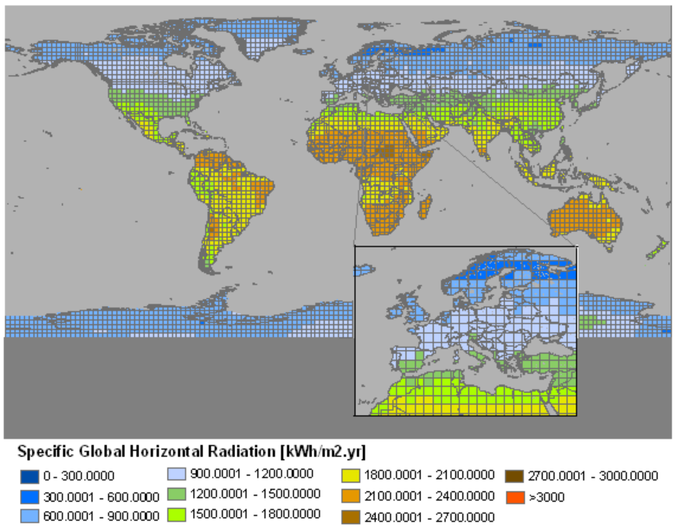

Figure 3: Annual global horizontal radiation [kWh/m²], Meteorological data from [25]

For the European scale hourly data of global and direct irradiation is taken from [29, 30] and readjusted for model regions. Resulting values for the annual global horizontal radiation per m² are visualized in figure 3.

Global data of wind velocities for on- and offshore sites is taken for both models from the World Wind Atlas in a six hour temporal and 2.5° spatial resolution [24]. For the purpose of modeling with high temporal resolution,

[1] NUC: Nuclear Power, re: Renewable Energies

[2] ST: Steam Turbine, CC: Combined Cycle, IC: Internal Combustion, GT: Gas Turbine, HP: Hydro Power, Bio: all Biofuels and Biomass, WND: Wind Onshore, WOFF: Wind Offshore, PV: Photovoltaic, CSP: Concentrated Solar Power

hourly values are approximated by linear interpolation. The transformation from wind velocity to active power output has been done using data from modern existing wind turbines for onshore and offshore sites [31]. Results are shown as Full Load Hours of a 3 MW Turbine in Figure 4.
The total capacity permissible to be installed at each model region is determined based on detailed analyses of technical potential of solar thermal electricity and wind energy [5, 6].

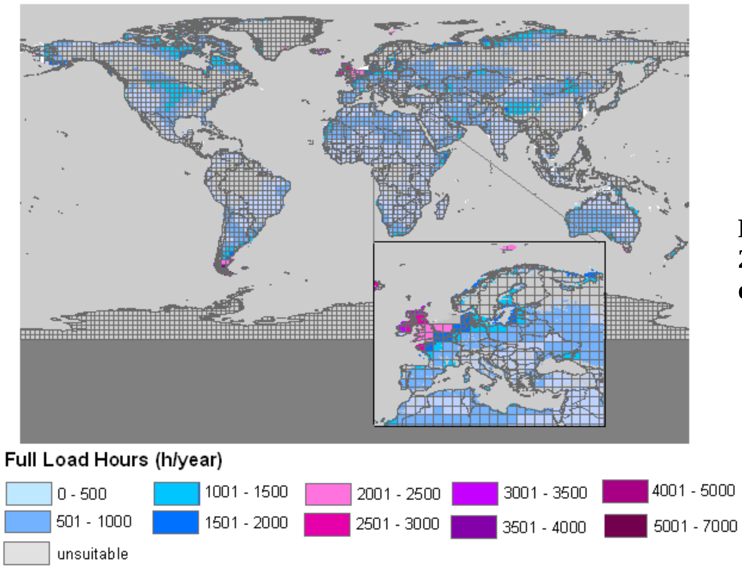

Figure 4: Realizable annual wind energy production on suitable land sites in full load hours of WT: V9-3.0 MW [31], Meteorological data from [24]

4.2. Load Data

Geographically aggregated projections of the global electricity demand for the time period 1990 to 2100 based on three IPCC scenarios (A2, B1, and B2) are available at IIASA Greenhouse Gas Initiative (GGI) database [32]. To derive values for each grid cell, electricity demand has been spatially disaggregated, based on the spatial distribution of population from GGI database [32].
Hourly load data for all UCTE members, Nordel interconnected area and United Kingdom are available [33, 34], as well as load values for selected other regions [35, 36]. Hourly load values for each model region are approximated based on the linear combination of existing normalized load curves shifted for relevant time zones.

4.3. Geographical Scales

We compare the results of the application of the described methodology on the global and 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 are mainly limited to a coarse spatial resolution of up to 15 aggregated regions [13, 18, 37]. Here, model regions are determined not only based on the political borders, but also according to the geographic distribution of electricity demand and renewable supply structure. 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.

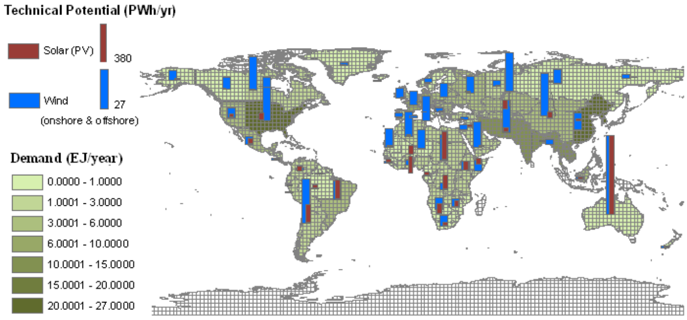

Figure 5: Global geographic distribution of demand in 2050 and Renewable Technical Potential, Meteorological data [24, 25], Load data [32]

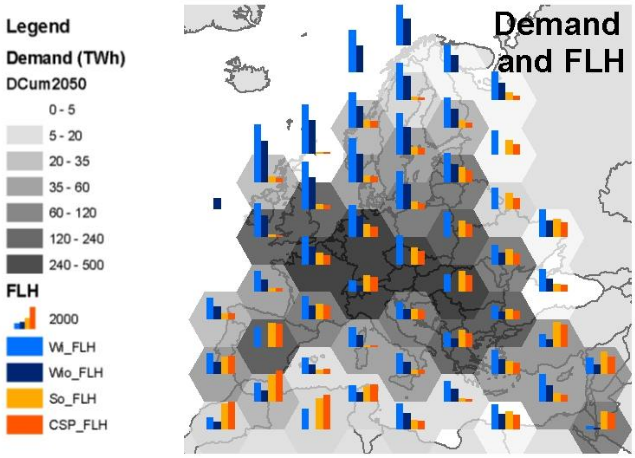

Figure 6: European geographic distribution Renewable Technical Potential and demand in 2050, Meteorological data [29, 30, 24], Load data [32][3]

Geographic distribution of technical potential of Renewable electricity and demand in year 2050 is visualized in Figures 5 and 6 for the model regions. Low technical potential of solar electricity is attributed to Northern Africa according to Tzeutschler, 2005 [5] due to the limited suitability of this area.

5. Scenario-based Analysis

5.1. 100% Renewables Scenario Setup

The starting point for the analysis of the system behavior is a 100% Renewables scenario. This is considered as an ideal case for a prospective electricity supply system,

[3] FLH: Full Load Hours, Wi: Wind Onshore, Wio: Wind Offshore, So: Solar Photovoltaic, CSP: Concentrated Solar Power

relying on the maximal feasible 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 on- and offshore sites, centralized PV, and concentrating solar power systems - without storage of thermal power - are considered. These power plant types can be installed in each region according to their technical potential described in 3.1. The availability of suitable areas for wind- and solar-energy thus determines inter alia the ideal generation sites.

Table 1: Ideal scenarios and underlying assumptions

Scenario	Underlying Assumptions
Link	• High cost reduction and efficiency improvement for renewable technologies • 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) • Suitable and limited suitable sites may be utilized for renewable electricity production. • Supply area is interconnected via HVDC with low investment cost [26]
NoLink	• Supply area is not interconnected
Link-Sto	• Storage is possible

Several boundary conditions such as power transmission network capacities, available storage systems, fuel prices, and climate policies may have significant impacts on the optimal system 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 technologies are projected to be low, while the backup technology is considered to be an expensive option. This approach allows determining the maximal feasible share and the ideal mix of renewable resources.

5.2. 100% Renewables Scenario Results

5.2.1 Aggregated Results

Total installed capacities of power generation and storage are illustrated in figure 7; figure 8 shows the produced electricity by type, excess production, and total annual demand.

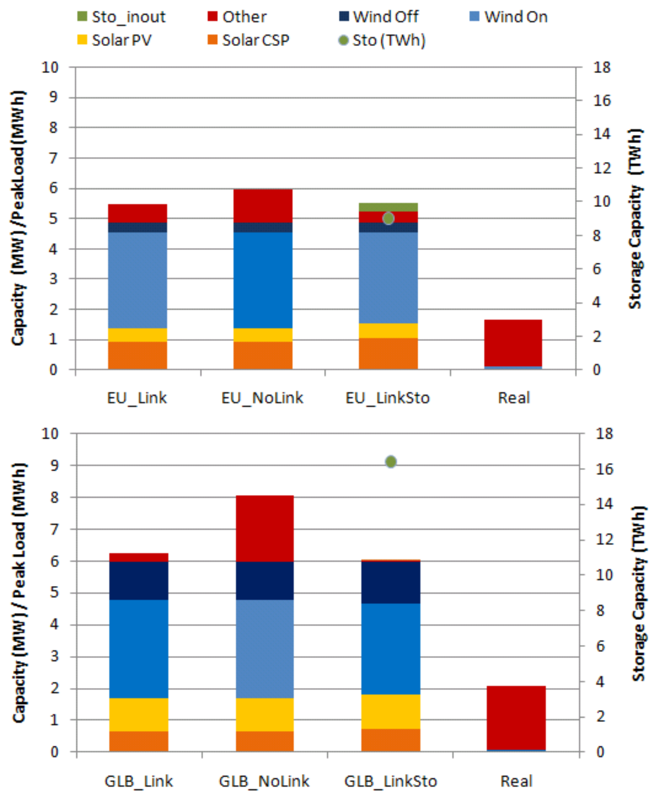

Figure 7: Total capacity for ideal scenarios at European and global scale together with existing capacities [23]

On the global and the European Level, the comparison of the real capacities to the scenario results show, that a system integrating high shares of variable, renewable resources cannot be run as efficiently as a today's fossil fuel-based energy system. The installation of large overcapacity is necessary to satisfy shares of up to 80% of the electricity demand with renewable energies. In the global case approximately twice as much capacity would be needed while in the European case the total power plant capacity triples.
The comparison between the scenarios "Link" and "NoLink" 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 usage, and the necessity of backup capacity is reduced, in the global case by a factor of nearly 8, on the European level by a factor of 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. However the overproduction level is higher in the global case, which is partly due to the lower production limits assumed for the global model.

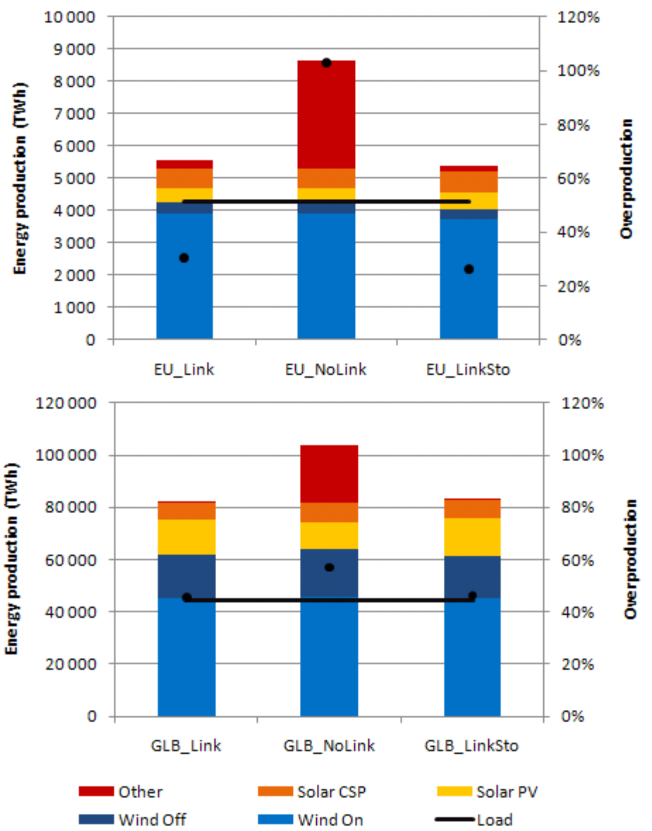

Figure 8: Total energy production for the ideal scenarios at European and global scale together with the relative amount of overproduction

When storage is included ("Link-Sto"), the system needs even less backup capacity. Additionally, according to Figure 8 the inclusion of storage and interregional transport lead to the reduction of system inefficiency measured in excess production. This is the share of produced electricity that can neither be consumed, nor can be economically stored.

5.2.2 Ideal Generation Sites, Flows and Energy Mix

The geographical resolution of the models allows identifying promising generation sites as well as ideal energy flows.

The global geographic distribution of produced energy resulting from the optimization is shown in Figure 9.

Centralized PV is distributed among the most promising locations. Promising on- and offshore sites for the installation of wind energy converters also result from the optimization. In the "NoLink" scenario additional backup power is installed within individual isolated regions according to the regional load values. This leads to the increase of overall power generation capacity compared to the "LinkCost-" Scenario.

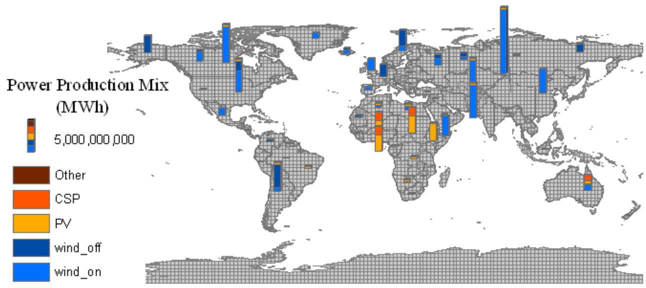

Figure 7: Geographic distribution of optimal energy production at global scale, Scenario "Link"

The European ideal energy mix is depicted in figure 8. The high potential for wind energy on the northern European coasts 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 [5].

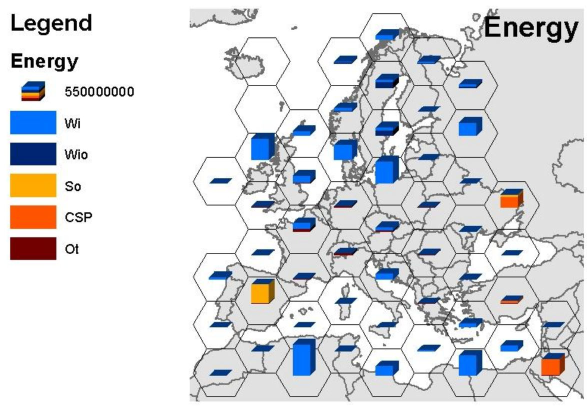

Figure 8: Geographic distribution of optimal energy production at EU Scale, Scenario "Link"

Scenarios "Link" and "LinkSto" are characterized with high interregional energy flows. In the "Link" and "LinkSto" scenarios 48% and 60% of total produced electricity is interregionally transported. In the global as well as the European model several HVDC transmission highways between the modelregions of up to 200 GW capacity are required to transport this vast amount of electricity.

Optimal ideal energy flows through the global supergrid 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 5) results in its contribution as one of the main exporting regions. Import of wind electricity from Alaska offshore sites through Far East to Eastern part of China also is realized in the optimization.

In the European interconnected area, 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.

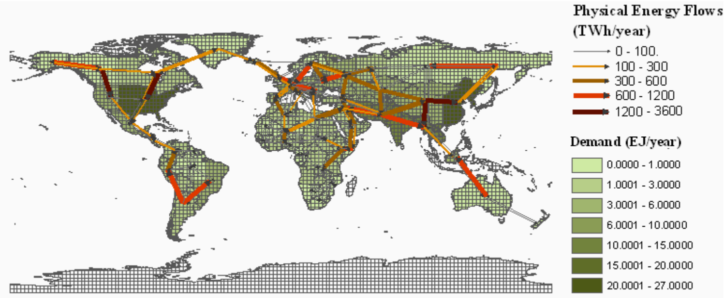

Figure 11: Ideal Annual Energy flows at global scale for the „Link“ Scenario

The energy flows, resulted from the optimization at European level, are shown in figure 10 and are in accordance with the supply and demand pattern sketched in figure 4. 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 [32]. It therefore shows important electricity import and export.

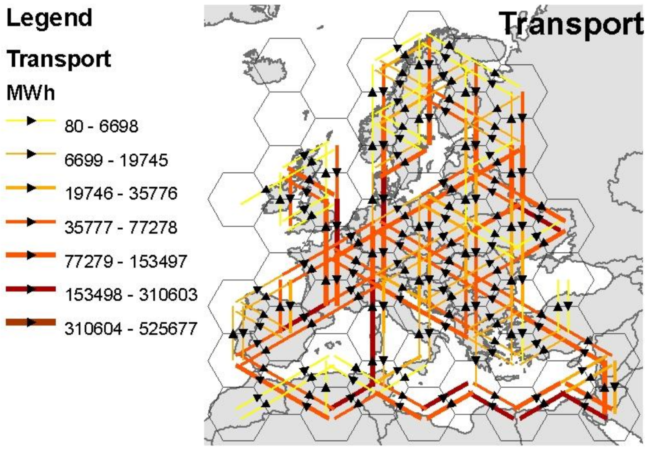

Figure 10: Maximal energy flows in Europe for the „Link“ Scenario

Five options to exchange electricity between North Africa and Europe are considered as options in the model: Gibraltar, Sardinia, Sicily, Greece and the Middle East, of which the trans-Mediterranean linkage through Sardinia is used most extensively. Going back to figure 6 this can be easily understood, as in this linkage allows to import electricity directly to high load centers such as France and Northern Italy. This preference of the electricity flow is also confirmed in investigations based on this model concerning the import of solar energy from North Africa [38].

The hourly temporal resolution allows us to furthermore analyze the satisfaction of demand in each time-step. Figure 11 shows the electricity mix in Europe for the Link-scenario.

The typical weeks comprised in the optimization are evenly distributed over the year, such that the seasonal usage of the resources can be modeled. Figure 11 shows, that in Europe, in winter more wind energy is used, while in the summer weeks solar energy becomes more prominent. As also shown in Heide at al. 2010 and Grotz 2009 [11, 39] the system profits from the interseasonal anticorrelation of solar and wind energy in Europe.

In the mean time the interdiurnal rhythm of solar energy makes it less attractive In total less than 20% of the power production stem from solar energy in this scenario, approximately 75% from wind and 5% from the backup technology “Other”.

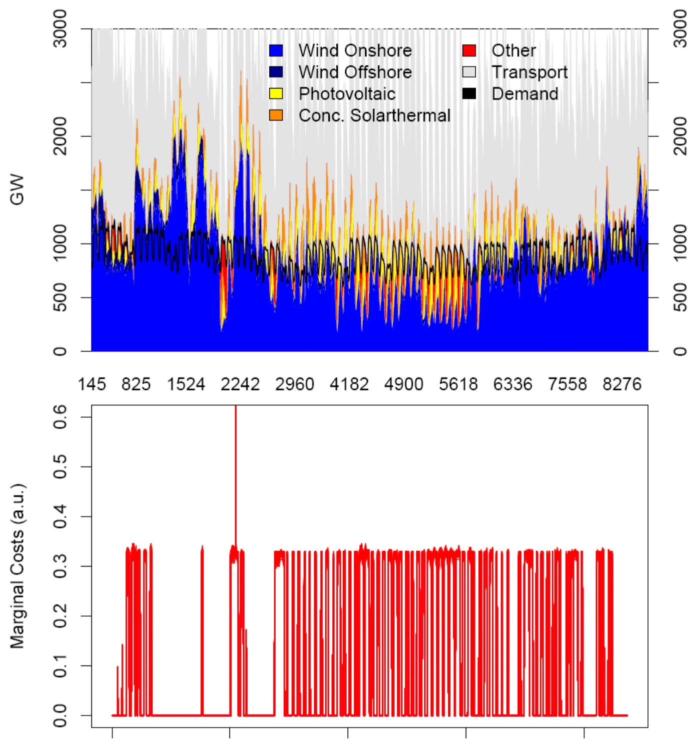

Figure 11: Energy Mix in Europe and marginal costs of demand in arbitrary units for the 100% Link Scenario. The modeled 12 weeks are shown here.

In order to accomplish a share of more the 80% renewables in the satisfaction of load, a considerable amount of overproduction is necessary. The gray area shows the total amount of electricity transport in Europe for each time-step. Its magnitude exceeds in many time-steps the total power production. In this ideal scenario the backup capacities are located in proximity to the load centers. Therefore the electricity grid is used less whenever backup power plants provide a substantial share of the total power production.

The lower box of Figure 11 depicts the dual variable of the commodity equation. The commodity equation is the boundary condition to the minimization ensuring satisfaction of demand in each time-step and model region. The dual variable of this equation gives the marginal costs of demand, i.e. the electricity price. High supply with renewable energies results in overproduction and vanishing marginal costs of electricity in hours, when high supply of renewable energy is available.

5.3 Mitigation Scenario

In this section a scenario is presented, which can be situated between the actual situation and the ideal structure presented in section 4.2. In this mitigation scenario, the CO_2 reduction trend proposed by International Panel on Climate change (IPCC) working group1 for stabilizing CO_2 at 550 ppmv is implemented [40].

In the analyzed mitigation scenario, conventional power plants as well as renewable-based technologies are included. Associated long term efficiency improvements and realizable cost reductions are approximated based on [18, 41, 42]. The economic parameters of the technologies are represented in table 2.

Table 2: Economic parameters of power plants [18,41,42]

	Investment ($US\$_{2000}/kW_{el}$)	Fix Cost ($US\$_{2000}/kW_{el}/a$)	Var. Costs ($US\$_{2000}/kWh_{el}$)
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 [22]. 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, while 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.

In Europe the wind turbines are placed in the model regions with high potential for wind energy [43, 44]: the southern and eastern Scandinavian coast, the northern and eastern sea and the coast and shores of Great Britain. Consequently major extensions of the UCTE grid are necessary between France and the UK and between Denmark / Germany and Sweden / Norway. The capacity of these two HVDC cable - links resulting from the optimization exceeds 100 GW.

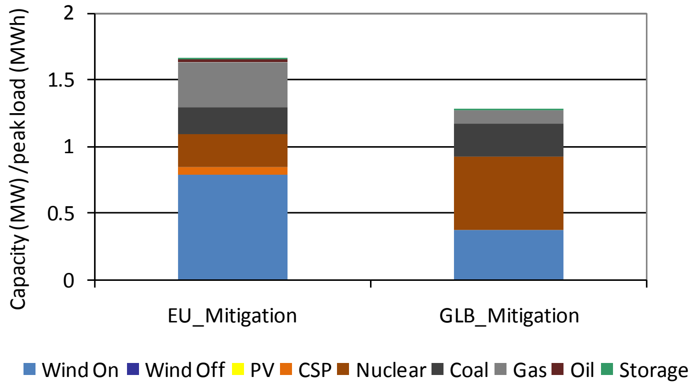

Figure 12: Share of capacities by fuel type for the mitigation scenario

In total the larger share of conventional plants results in less electricity network extensions than in the 100% Renewable scenario. Compared to the ideal scenario, the transport capacity in the mitigation scenario reaches 4% of total transport capacity in the "Link" scenario at European scale. At global level, this value reaches 7.5%.

6. 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 with high temporal resolution. Through linear optimization of overall costs ideal power generation capacities, promising sites for installation of renewable technologies 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. However the methodology does not include detailed technical representation of the power plants and the load flow nor accounts for the stochastic nature of several input parameters. Multiperiod optimization can only be performed based on exogeneous parameters.

The application of the methodology allows to examine the role of a powerful grid and of storage. On both scales, the European and the global scale, a powerful grid allows to reduce the need for backup capacities. The smoothing effects through dispersed generation, which occur on the global scale, are more significant compared to the European model. For this reason the storage is used less extensively in the global model. On the other hand, the model results show, that the supply of the global and the European electricity demand with high shares of renewable energies yields considerable overcapacity and overproduction.
Individually the models show the importance of storage and transmission systems for the integration of renewables on both scales to alleviate the problem mentioned above. The comparison of the scales allows evaluating 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.

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