Investigating Optimal Configuration of a Prospective Renewable-based Electricity Supply Sector

Tino Aboumahboub\(^1\), Katrin Schaber\(^2\)
Peter Tzscheutschler\(^1\), Thomas Hamacher\(^2\)
\(^1\)Institute for Energy Economy and Application Technology, \(^2\)Research group for Energy and Systems Studies
\(^1\)Technische Universität München, \(^2\)Max Plank Institute for Plasma Physics
\(^1\)Arcisstrasse 21, 80333 München - \(^2\)Boltzmannstrasse 2, D-85748 Garching, München
GERMANY
E-Mail: tino.aboumahboub@tum.de, kschaber@ipp.mpg.de

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 subject of how a renewable-based energy system ideally should be designed. We investigated the optimal structure of a prospective renewable-based power supply system on two different scales: on the global and on a European level. This 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 greenhouse 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 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 time points. These sites are not necessarily located in proximity to densely populated areas, where the demand for electricity is high [5, 6, 8]. The competitiveness 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. 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 [9,10,11].

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 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 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 addressing 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.

\[
\text{CAP} = \sum_{p} \left( K_{\text{cap}}(p) \cdot N\text{Ccap}(r, p) + K_{\text{HC}}(p) \cdot \text{CAP}(r, p) + \sum \sum K_{\text{rad}}(p) \cdot \text{Em}(r, p, t) \right) + \frac{1}{2} \left( \sum \sum \sum (K_{\text{cap}}(p) \cdot N\text{Ccap}(r, p', t) + K_{\text{HC}}(p) \cdot \text{CAP}(r, p)) \right) + \sum K_{\text{rad}}(p) \cdot \text{Em}(r, p', t, f) \]

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.

\[
\text{CAP} = \sum_{\text{p}} \sum_{\text{r}} \sum_{\text{t}} \left( K_{\text{cap}}(p) \cdot N\text{Ccap}(r, p) + K_{\text{HC}}(p) \cdot \text{CAP}(r, p) + \sum K_{\text{rad}}(p) \cdot \text{Em}(r, p, t) \right) + \frac{1}{2} \sum_{\text{p}} \sum_{\text{r}} \sum_{\text{t}} \sum_{\text{r'}} \left( K_{\text{cap}}(p) \cdot N\text{Ccap}(r, p', t) + K_{\text{HC}}(p) \cdot \text{CAP}(r, p') \right) + \sum \sum K_{\text{rad}}(p) \cdot \text{Em}(r, p', t, f) \]

\[ (1) \]

\( \text{CAP} \) describes the total installed capacity while \( \text{NCap} \) represents the newly invested power production, storage, and transport technologies available at each region. \( \text{Ein} \) is the energy input in process \( p \) operating in region \( r \) at time step \( t \). \( K_{\text{Inv,Fix,Var}} \) 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 [12,13,14]). 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 [15, 16].

3. Energy Supply and Demand Data

3.1. Solar and Wind Energy Potential

In order to evaluate the global technical potential of solar electricity, the global irradiation dataset produced for SeaWiFS is applied here [17]. 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 [18, 19] and readjusted for model regions. Resulting values for the annual specific global horizontal radiation are visualized in figure 1.

Global data of wind velocities for on- and offshore sites is taken for both models from the World Wind Atlas [20]. 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 [21]. Results are shown as Full Load Hours of a 3MW Turbine in Figure 2. 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].
3.2. 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 [22]. To derive values for each grid cell, electricity demand has been spatially disaggregated, based on the spatial distribution of population from GGI database [22]. Hourly load data for all UCTE members, Nordel interconnected area and United Kingdom are available [23, 24], as well as load values for selected other regions [25, 26]. Hourly load values for each model region are approximated based on the linear combination of existing normalized load curves shifted for relevant time zones.

3.3. 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 [11, 15, 27]. 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. Geographic distribution of technical potential of Renewable electricity and demand in year 2050 is visualized in Figures 3 and 4 for the model regions. Low technical potential of solar electricity is attributed to Northern Africa according to [5] due to the limited suitability of this area.

4. Scenario-based Analysis
4.1. 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 a prospective electricity supply system, 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 are considered. These power plant types can be installed in each region according technical potential described in 3.1. The availability of suitable areas for wind- and solar-energy thus determines inter alia the ideal generation sites.

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 quantifying 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.

Table 1: Ideal scenarios and underlying assumptions

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Underlying Assumptions</th>
</tr>
</thead>
</table>
| 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 [28] |
| NoLink   | • Supply area is not interconnected |
| Link-Sto | • Storage is possible |

4.2.100% Renewables Scenario Results

4.2.1 Aggregated Results

Total installed capacities of power generation and storage are illustrated in figure 5; figure 6 shows the produced electricity by type, excess production, and total annual demand. 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 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.

When storage is included (“Link-Sto”), the system needs even less backup capacity. Additionally, according to Figure 6 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.

4.2.2 Ideal Generation Sites and Flows

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 7.

Figure 5: Total capacity for ideal scenarios at European and global scale together with existing capacities [29]
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 3) 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 1: 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 [22]. It therefore shows important electricity import and export.

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

4.3 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 CO₂ reduction trend proposed by the International Panel on Climate change (IPCC) working group I for stabilizing CO₂ at 550 ppmv is implemented [31]. 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 [15, 32, 33]. The economic parameters of the technologies are represented in table 2.

Table 2: Economic parameters of power plants [18,32,33]

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Investment (US$2000/kWel)</th>
<th>Fix Cost (US$2000/kWe/a)</th>
<th>Var. Costs (US$2000/kWhel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind On</td>
<td>750</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>Wind Off</td>
<td>1300</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Solar PV</td>
<td>2200</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>Solar CSP</td>
<td>1840</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>Coal</td>
<td>1400</td>
<td>19.75</td>
<td>0.00108</td>
</tr>
<tr>
<td>Gas</td>
<td>500</td>
<td>35</td>
<td>0.000648</td>
</tr>
<tr>
<td>Oil</td>
<td>500</td>
<td>0.003</td>
<td>0.00072</td>
</tr>
<tr>
<td>Nuclear</td>
<td>2000</td>
<td>60</td>
<td>0.000216</td>
</tr>
<tr>
<td>Storage</td>
<td>600</td>
<td>6.83</td>
<td>0</td>
</tr>
</tbody>
</table>

In the European model, the nuclear energy production is limited to the current level of nuclear power production [34]. 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.

5. 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. Multiperiod optimization can only be performed based on exogeneous parameters.

The application of the methodology allows to examine the role of a powerful grid is 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.

Individually the models show the importance of storage and transmission systems for the integration of renewables on both scales. 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.

References:


[25] Yvonne Zickermann, Approximation of Typical Load Curves for Different Continents and Climate zones, Internal Report, Institute for Energy Economy and Application Technology (IfE), Faculty of Electrical Engineering, TU München, 2005


