Large-scale Integration of Renewable Energies and Impact on Storage Demand in a European Renewable Power System of 2050

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Abstract\textsuperscript{†}

Driven by decreasing prices for photovoltaic (PV) systems and incentive programs of different governments almost 100 GW of PV and over 100 GW of wind turbines (WT) have been integrated in the European power system today (2014). In some areas, the electricity generation already exceeds the demand, pushing the existing transport infrastructure to its limits in certain hours. In order to reach the European Commission’s targets for 2050, the system integration will at some point require flexibility sources independent of conventional generation in order to keep today’s standard in security of supply. There are several sources of flexibility. Together these flexibility sources will ensure the match of demand and supply at any given time. Energy storage systems can provide this flexibility by shifting of load in time while transmission grids provide the shift of load in space. Up to a certain extent, transmission capacity and storage capacity can replace each other, i.e. storage can reduce the load on transmission infrastructure by mitigating local peaks in load and/or generation.

For the transition to a fully renewable energy system in 2050, major changes have to be achieved in the structure of the power supply system. The simulation tool GENESYS is a holistic approach to optimize the allocation and size of different generation technologies, storage systems and transnational grids of a European power system. The source code for the simulation tool is available free of charge under a public license. It can be freely parameterized by the user which allows the study of different electricity systems under the users’ assumptions with regard to load, generation potential and cost structure of the different system components.

This publication will give an introduction to the simulation framework, the system model and the optimization strategy. Optimization results obtained with GENESYS for a fully renewable electricity system and a cost structure expected for 2050 will
be presented together with sensitivity analyses investigating the main assumptions. The focus is the optimal allocation of PV and WT in a European electricity system, the resulting demand for storage capacities of different technologies and the capacity of the overlay grid.

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1. Introduction

Since the European Commission presented target values [1] for the greenhouse gas emissions, the evolution of the current system was characterized by the large-scale integration of various renewable energy sources. Until 2013 total capacities of 117 GW wind power generators and around 78 GWp PV generators have been installed in different setups into the current system. The first process phase of integration is still ongoing, without coordination, driven by cheap PV on rooftops, where further integration was without major impact on the system until recently. The feed-in of wind energy from offshore wind parks and onshore turbines in the coastal regions are a big challenge for grid operators in periods of strong wind. To counter this, they have presented a ten year development plan [5] for the expansion of the transport capacities. This work can give an outlook regarding the future needs for grid expansion and integration of storage units in case of high penetration of renewable generators in the end of the transformation process in 2050. Those components will become major sources of flexibility, where flexibility is a system requirement to guarantee system stability. Already today, power supply companies start searching for their position on new markets [7] arising.

The utilized tool employs the Covariant Matrix Adaption-Evolution Strategy (CMA-ES) developed by N. Hansen [3] to optimize the components of a European Power system. The operation is calculated by a hierarchical management, which is able to efficiently operate storage units of different technologies over periods of several years without perfect foresight of the future situations. In similar works [9], [10] a linear programming (LP) approach is done to calculate the operation of a future power system. The problem complexity often sets limits on the simulation timeframe, and thus especially long term storages can only be run under certain limits, which we want to avoid. This work will also provide a closer insight into the programs sensitivities concerning the mix of available technologies.

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
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<td>WT</td>
<td>Wind turbine</td>
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<td>CMA-ES</td>
<td>Covariance Matrix Adaption-Evolution Strategy</td>
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<td>LP</td>
<td>Linear Programming</td>
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<td>NTC</td>
<td>Net transfer capacities</td>
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<td>PH</td>
<td>Pumped Hydro</td>
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<tr>
<td>EUMENA</td>
<td>Europe, Middle East and North Africa</td>
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<td>HVDC</td>
<td>High voltage direct current</td>
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<td>H2</td>
<td>Hydrogen</td>
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<tr>
<td>LCOE</td>
<td>Levelized cost of electricity</td>
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<td>SOC</td>
<td>State of charge</td>
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<td>ES</td>
<td>Evolutionary strategy</td>
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<td>FLH</td>
<td>Full load hour</td>
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2. Methodology

2.1. GENESYS Power System Model

The power system in the GENESYS tool is modelled in the form of interconnected regions with power exchange via adjustable net transfer capacities (NTC). The standard parametrization, which is used in this publication, represents the geographical region of Europe, Middle East and North Africa (EUMENA). There are 21 regions in total which are connected to their neighbors via 49 modelled connection lines. For the power exchange via NTC, the high voltage direct current (HVDC) technology is most suitable, because it allows easy calculation of exchanged power and has efficiency advantages compared to AC technology, especially for long distances. In each region the model contains one unit of each available technology, which represents the accumulated power (and respectively storage) capacity of the region. The hourly generation from the renewable generators in the model is calculated as product of the installed power capacity times a time series value for the respective technology (WT or PV). The hourly load is calculated as fraction of the normalized annual load from a historic time series multiplied with the assumed total annual load of the respective year. Each region in the model can access individual generation and load profile time series, which were generated from historic measurements, bought from MeteoGroup [4], and the ENTSO-E publicly available load records [8].

The model of the storage system components is depicted in Fig. 2. There are three different parts: charger, discharger and one reservoir unit, the latter represents the energy capacity $E_{\text{storage}}$. The charger and discharger represent power units, which contain parameters like efficiency and the actual power of the unit. In case of batteries, power electronics are parameterized. In case of pumped hydro storage (PH), there are bidirectional water turbines. The hydrogen (H2) storage is charged by an electrolyser and discharged by a combined cycle turbine. The power electronics and water turbines are modelled as one bidirectional unit, while for hydrogen the charger and the discharger are separate units. Each unit has a power capacity rating ($P_{\text{charge}}$, $P_{\text{discharge}}$) and a respective efficiency for the power unit operation ($\eta_{cg}$, $\eta_{dcg}$). In this simplified model, the reservoir losses are accounted to the charger and discharger. The efficiency of the storage $\eta_s$, which is shown in Fig. 2, is split up $\eta_s^{1/2} \cdot \eta_s^{1/2}$ as simple average over time, the value from Tab. 3, which depicts $\eta_s^{1/2}$ is multiplied by the charging losses and discharging losses respectively. The roundtrip efficiency is calculated via

$$\eta_{\text{roundtrip}} = \eta_{cg} \cdot \eta_s^{1/2} \cdot \eta_{dcg}.$$
The cost of the system components is calculated using the annuity method [6], which allows comparing between the costs of different components based on their economic value. The resulting cost of electrical energy represents the levelized cost of electricity (LCOE). The respective parameters for the system components parametrization are shown in Tab.1. The parameter of efficiency for the battery storage is relatively low, because a high temperature system like NaS has been assumed.

2.2. Operation strategy of the power system

The residual load within the power system needs to be balanced for all hours by means of the operation of storage and grid exchange power units in a 100% renewable system. For a total period of 5 years, we calculate the hourly residual load from historic measurements of wind speed and solar irradiation with the installed capacities of wind power and solar power generators in the respective system configuration. The optimization’s objective function is the minimization of the total operation cost, which is strongly influenced by the penalties which are added for hours of remaining positive residual load. To avoid these penalties, a hierarchical management strategy for the available flexibility options (grid and storage) has been developed (see Fig. 1). The strategy is applied consecutively for each hour respecting the results of preceding hours and having a perfect foresight horizon of 24h for the storage operation. By this method, hours of peak load can be identified and adequately supplied by a combination of all available power units of different technologies. The calculation is done for each region within the system, while between the regions the utilization of existing NTC is calculated between the hierarchy steps (grid balance). On each step of the hierarchy the different available power units (charger or discharger), are sorted in a priority list according to the current state: 1st criterion is the efficiency; the 2nd criterion is the future state of charge (SOC) in the connected reservoir of the region, to utilize units with higher SOC more often. The 1st criterion prioritizes the high
efficient short term technologies like batteries. The grid balance is executed between neighboring regions in the first step and then remaining NTC is utilized in the subsequent hierarchy steps.

2.3. Optimisation of system composition

An evolutionary strategy (ES), based on the CMA-ES [3], was implemented in the calculation tool to optimise the system composition depending on the operation cost. The power rating or energy capacity of each system component is a free variable for the optimization. This represents a 238-dimensional solution space for the CMA-ES. The algorithm uses a stochastic method to calculate a set of \( n = 151 \) system compositions (ensemble) for each generation. According to the empirical results from the parent generation, it determines the mean value of the distribution of the \( n/2 \) best performing systems in the ensemble and generates a new full ensemble around it. This process is different from genetic algorithms, where a crossover of existing genes is calculated. The CMA-ES uses a set of experience parameters which help to become independent of high population numbers, yet can avoid local minima and premature convergence.

2.4. Setup of the standard scenario as reference

The standard scenario setup, which is used as reference for the sensitivity analyses, consists of the full region setup with 21 regions and no limit for the NTC of the connections. As previously described, there are three storage technologies available, a battery technology, pumped hydro storage and hydrogen storage. Each region has a lower self-supply boundary of 80% as boundary, which means it has to harvest 80%+ of its consumed energy from own generation units. There are no upper or lower boundaries for the installation of renewable energy generators. This setup allows a free ratio between generation capacities of WT and PV and calculates no penalties for curtailment. The exemplary results were calculated with a technology parametrization for 2050. The electricity consumption for 2050 was extrapolated to 6.250 TWh/a in EUMENA and is based on the assumption of electrification in the transportation sector and increasing standard of living in today’s less developed regions.

3. Results

3.1. Results for the standard scenario

The results of the standard scenario in Fig. 3 show a generation power of 4.550 GW, which splits up into PV and WT in a ratio of 60:40 on global scale for the EUMENA regions. The allocation in the different regions shows that there is usually a certain technology dominating, as typically a significant difference in the LCOE for generation occurs from the perspective of the weather potentials. Only the Northern Africa region shows a smaller difference, which results in coexistence of both technologies. The totally generated electricity from PV was 3.900 TWh/a, which equals to an average of 1.400 full load hours (FLH), while WT had a significantly higher average value of 2.000 FLH and a total generation of 3.700 TWh/a. The system setup requires a significant amount of storage systems, which are distributed over the system. The capacity of long term gas storage systems needs to be as high as 800.000 GWh, while for electrolyser a total power of 900 GW and for combined cycle gas turbines a power of...
550 GW are required. The demand for middle and short term storage is lower, 2.700 GWh water reservoir storage and 1.600 GWh of battery systems are required with a power of 190 GW for water turbines and 320 GW of battery power. The peak load in this system is about 1.030 GW, which equals the amount of all storage output units. The distribution of storage power units in the system is shown on the right map in Fig. 3. The amount of grid as second flexibility source next to storage is calculated in GW*km, the grid momentum. Of the modelled 46.000 km HVDC lines, the optimisation results in a utilisation of 36.000 km with a grid momentum of 503.000 GW*km, as shown in Fig. 5. The distribution of number of connections with a certain NTC has a multimodal shape and shows a spread up to 50 GW for one single line. The dominant mode of this distribution indicates that most connections show a NTC of 5-10 GW. From this optimisation scenario the LCOE results in 9.67 ct/kWh. The pie chart in Fig. 4 depicts that 68% of the total cost accounts to the investment in renewable generator capacities while storage systems have a share of 24% and the remaining 8% share of the LCOE is required for grid investments as second flexibility source.

3.2. Sensitivity analysis for storage technologies.

A sensitivity analysis was conducted to evaluate the impact, which different technologies or possible restrictions on the system have.
The first sensitivity scenario was to limit the NTC between the different regions to show the impact of grid as flexibility source. The variation was conducted by defining upper limits for the NTC of all available connections in steps of 2.5 GW from 15 GW down to 2.5 GW. The maps in Fig. 7 show that the limit of NTC strongly influences the distribution of generator types. Increasing the limitation to less GW results in a stronger mix of PV and Wind generators within the regions. This effect can be observed especially in the central European regions. The impact on storage demand becomes clear when examining Fig. 6, the graph depicts the change of the long term gas storage capacity relative to the standard scenario in dependency of the NTC. It shows a strong correlation between the available flexibility from the grid represented by the NTC and the necessary flexibility from long term storages.

The second sensitivity which has been investigated is the availability of different storage technology options. The first scenario part is the removal of PH as middle term storage option, the second part is removal of all storage technologies suitable for short term options (PH and batteries) and the third part is the removal of long term gas storage. These sensitivities were investigated via the LCOE. This allows to use one indicator for evaluation of the results. Fig. 8 shows the LCOE of the three technology constraint scenarios, which were described before, in comparison with the standard scenario. The standard scenario shows the least cost for electricity while the lack of long term storage technologies shows a strong increase of 24% compared to the full technology mix in the standard case. In this setup, the only storage technology to be used is the pumped hydro systems, while no batteries are economic. The two scenarios ((2) with no pumped hydro storage or (3) no pumped hydro and no batteries) show only marginal increase of the system cost and slight influence on the ratio between wind generators and PV.
4. Discussion

The results of the standard scenario show a combination of system elements for a fully renewable sources based future system is possible. With a good mix of several technologies for generation and flexibility it is possible to generate electricity at low cost. The allocation of generator capacity is clearly dominated by the potentials - which can be extracted from the time series - and results in a distinct favorite technology for almost every region. The results in the distribution of grid capacity shows, that there only exist few routes where an extension of electrical transport capacity above 20 GW is economic. This is the case for example for the transit between Great Britain and France, where high generator capacity of wind energy is to be found in Great Britain. The sensitivities which were calculated show that changes in the technology mix lead to increased LCOE. Limiting the possible NTC between the regions leads to increased cost, due to an increased amount of regions, where reduced transport capacities lead to mixed generation capacities. By mixed generation capacities synergies of complementing generation characteristics of PV and WT compensate the lack of energy flexibility supplied via NTC. Furthermore this leads to an increased demand for long term storage. In case of the storage technology mix, only the constraint of long term storage options leads to significant increase in LCOE. In this case a higher share of WT can be found in the system and pumped hydro systems are installed to compensate temporal fluctuations. Because of a high amount of water turbines in this case, batteries are not necessary to an economic mix.
5. Conclusion

The combination of different flexibility options for spatial and temporal balancing of the fluctuations in a future power system entirely based on renewable generators, can lead to economic constellations, which are able to supply energy at low cost. Any restriction to the mix of technologies, which characterize the spatial flexibility options, like NTC, or especially long term storage, will result in a significant increase of electricity cost. However, short term and medium term storage technologies don’t show strong interdependencies, but mutual exchangeability.

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References