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Optimal Combination of Storage and Balancing in a 100% Renewable European Power System

Morten Grud Rasmussen, Gorm Bruun Andresen, Dominik Heide, Martin Greiner

***Abstract*—We model the mismatches between wind and solar power generation and load for any combination of wind and solar power generation and for any level of penetration of these. The approach is based on high-resolution tempo-spatial meteorological and electricity load data. Based on these mismatch time series, we analyze the balancing needs and the effect of introducing both large and smaller scale energy storages. We investigate the interplay between storage and balancing in a future, highly renewable European power system, and we show that the synergy between storage and balancing is significant. Even a small but efficient storage reduces balancing needs significantly due to its influence on intra-day mismatches. We show that a combination of a smaller, efficient storage in combination with a larger, low-efficiency hydrogen storage and hydro balancing is feasible with an excess generation of only 3‰ at an optimal wind-solar mix of around 60-40.**

***Index Terms*—balancing, energy system design, Europe, large-scale integration, numerical modeling, solar power generation, storage, wind power generation**

I. INTRODUCTION

A fully renewable European power system will depend on a large share of weather dependent sources, primarily wind and solar power. The optimal ratio between and necessary amount of wind and solar power depends on transmission [1], balancing and storage resources and climate and load characteristics. Based on meteorological data, it has been shown that even with unlimited transmission within Europe, a scenario with only wind and solar power in combination with either balancing [2] or storage [3] alone requires a very large amount of excess generation in order to become feasible. We study the intermediate – and more realistic – scenarios in between where energy storages are backed up by balancing.

II. METHOD

Meteorological and electrical load data for 27 European countries and scaling of a capacity layout based on the national EU-2020 targets with higher priority given to more attractive sites have been used to create a model of the generation—load mismatch time series. Using these mismatch time series, the filling level of a storage with given properties and the reduced mismatch time series have been calculated. The resulting mismatch time series was then either first treated by secondary storage or directly used to determine the balancing needs.

A. *Data description*

Historical weather data from the 8-year period 2000-2007 with a tempo-spatial resolution of 50 x 50 km^2 x 1 hour was used to derive normalized wind and solar power generation for each grid cell. The data covers 27 European countries (including their off-shore regions).

For each grid cell a scaling factor for wind and solar power generation was chosen to reflect the assumed installed wind and solar power capacity based on the EU-2020 targets and the attractiveness of the sites. These capacity layouts where then scaled to fit any given level of penetration of wind and solar power generation. In combination with the normalized wind and solar generation the scaled capacity layouts where then used to derive a power generation time series for the 27 countries.

The electrical load time series is based on data from the transmission system operators (TSO), which was de-trended and scaled to 2007 values. The generation—load mismatch time series are aggregated over the 27 countries ignoring transmission losses and bottlenecks.

The scaling parameters are parameterized in the following way: α_W and α_S denote the relative share of wind and solar power generation, and the total generation of wind and solar power is denoted by γ.

Additional details on the processing of the weather and load can be found in the appendix of [3].

B. *Storage modeling*

The interaction between generation—load mismatch time series, storage and balancing are modeled using a "storage first" policy, meaning that as much excess generation as possible is stored and as much as possible of a negative mismatch is covered by using stored energy. Conversion losses in and out of the storage are modeled by storage efficiencies η_{in} and η_{out}. For hydrogen storage, the

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efficiencies are around 0.60 in both directions (i.e. a round-trip efficiency of 0.36). More details on the modeling of the storages can be found in [4].

III. RESULTS

A. Optimal mix

In a scenario with sufficient transmission capacity and with a high-efficiency storage with an energy capacity of at least three hours of average load, the optimal mix between wind and solar power lies in the vicinity of 60% wind and 40% solar power generation, at least when the combined penetration lies between 50% and 150%. See Fig. 1.

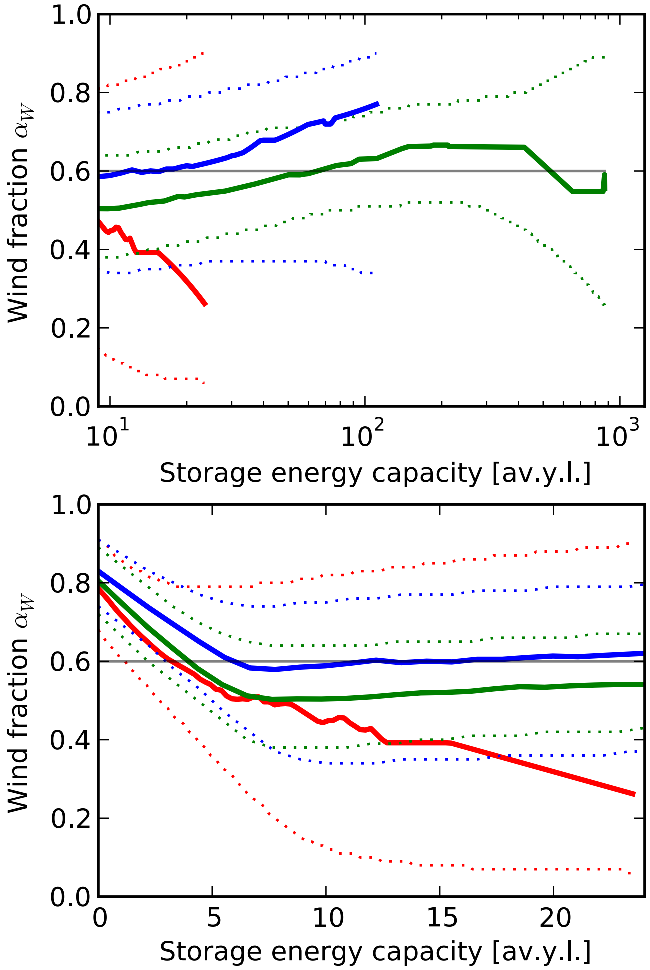

Fig. 1. Top: Optimal mix as a function storage energy capacity for $\gamma = 0.75$ (red), 1.00 (green) and 1.25 (blue) and the upper and lower limits for α_W resulting in a balancing energy need less than or equal to the balancing energy needed for the optimal mix and the same storage energy capacity plus 1 percentage point op balancing (dotted lines). The choice $\alpha_W = 0.60$ is indicated by a grey line. Bottom: Excerpt of the plot for storages less than 24 average hourly load (av.h.l.).

B. A 6-hour storage

The resulting needed balancing energy for an optimal and 60% wind mix, respectively, for storages larger than approximately 6 average hourly load (av.h.l.) are almost equal, and much reduced as compared to no storage. See Fig. 2. Note that this does not necessarily have to be a purely physical storage; it may also be realized by a large degree of demand side management (DSM).

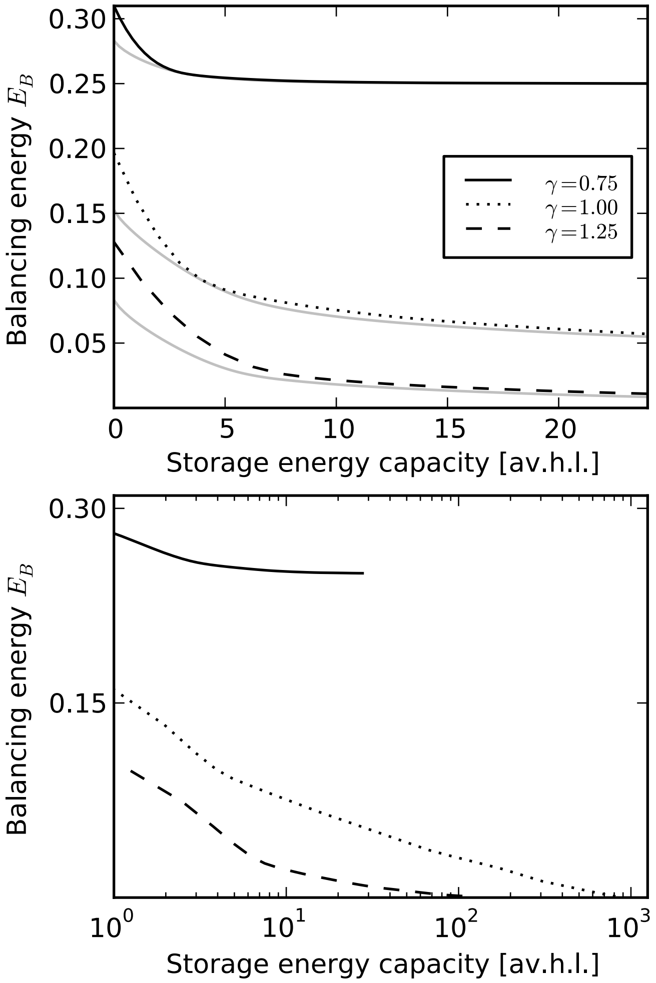

Fig. 2. Top: Needed balancing energy for optimal (gray) vs. 60% (solid, dotted and dashed black) wind mix as a function of storage energy capacity for $\gamma = 0.75$ (solid), 1.00 (dotted) and 1.25 (dashed). Note the drastic initial drop and the very small difference between 60% wind mix and optimal mix at around 6 av.h.l. and upwards. Bottom: Same plot for a larger range of storage energy capacities (logarithmic scale).

C. Hydrogen storage and hydro balancing

These results suggest the introduction of an efficient 6-hour storage (at least for γ around 1 and larger). As can be seen in Fig. 2, the balancing energy needs for $\gamma = 1.00$ and with a 6-hour storage is still around 9%. To lower this number, we model a secondary (hydrogen) storage and assume that balancing is provided by the approximately 150 TWh/yr hydro balancing available in northern Scandinavia and the Alps. This amounts to around 4.6% of balancing.

The European hydrogen storage potential is for the most part concentrated to salt caverns in northern Germany. A pessimistic estimate on the storage potential in these caverns is around 25 TWh. We compare the three scenarios: (1) no secondary storage, (2) 25 TWh secondary hydrogen storage and (3) unlimited secondary hydrogen storage. We also consider the same scenarios without a primary high-efficiency storage. See Fig. 3.

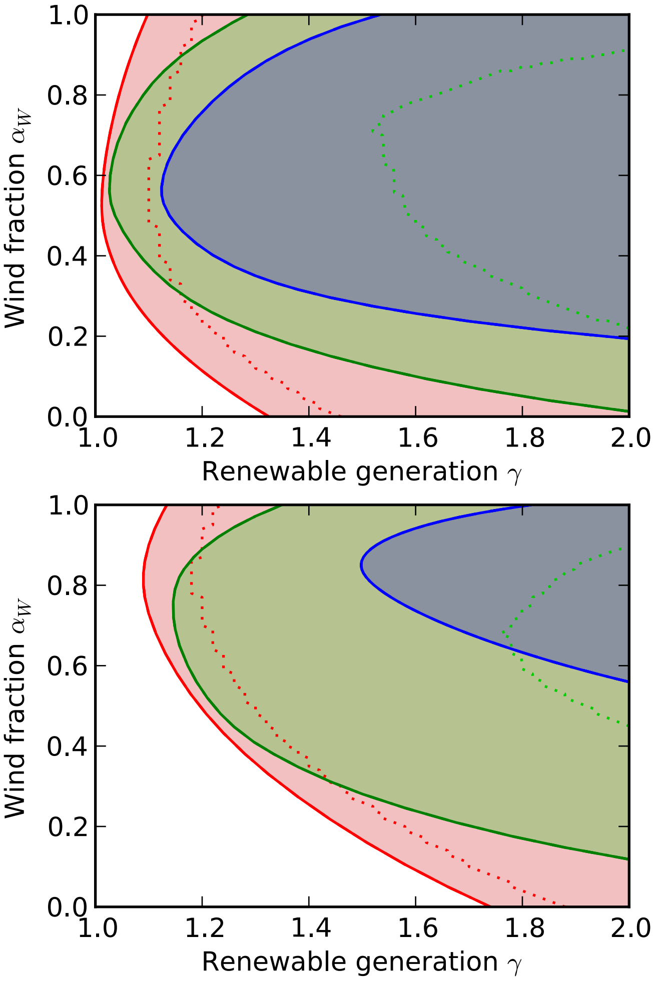

Fig. 3. Top: Contour plots indicating which γ–α_W combinations lead to a balancing need equal to or less than 150TWh/yr for the three scenarios: Unconstrained hydrogen storage energy capacity (red), constrained (25 TWh limit) hydrogen storage energy capacity (green) and no hydrogen storage (blue) (apart from the 6 hour lossless storage that is also present in the first two scenarios). The solid lines indicate where the 150 TWh suffice. The dotted lines indicate the left limit for the zero balancing region. Bottom: Same plots for a scenario without a 6-hour storage.

IV. CONCLUSION

Based on high-resolution tempo-spatial weather data and electricity load data from an 8-year period, we conclude that with a high-efficiency storage (possibly realized in part by demand side management), the optimal mix between wind and solar power generation for a highly integrated Europe is around 60% wind and 40% solar, at least when the combined penetration reaches around 75% or above. For a 100% renewable power system based on wind and solar power, a high-efficiency 6-hour storage significantly reduces the need for balancing. In combination with hydrogen storage and hydro balancing, a fully renewable power system is possible with a combined penetration of only 100.3%.

V. ACKNOWLEDGMENT

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VII. BIOGRAPHIES

Morten Grud Rasmussen was born in Lidköping in Sweden, on December 22, 1981. He studied at Aarhus University, Denmark where he received the degree of M.Sc. in 2007 and later Ph.D. in mathematics in 2010.

He has provided important new insights to the analysis of translation invariant quantum field theory models.

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Gorm Bruun Andresen was born in Odense in Denmark, on February 19, 1982. He studied at Aarhus University, Denmark where he received the degree of M.Sc. in 2008 and later Ph.D. in physics in 2010.

As member of the ALPHA collaboration at the international research laboratory CERN, he made significant contribution to the pioneering efforts to trap antihydrogen, recently published in *Nature*, 2010.

He is currently employed as postdoc at the Aarhus School of Engineering, Aarhus University, where his area of research is in the field of large-scale energy system engineering.

Dominik Heide was born in Frankfurt, Germany, on August 5, 1977. He studied at Frankfurt University, where he received the diploma in 2006 and later the Ph.D. in physics in 2010.

At the Max Planck Institute in Göttingen, Germany, he worked on models of pattern formation in the visual cortex and on numerical methods to integrate the partial differential equations describing these systems.

Starting in 2006, he started to work on large-scale energy system analysis, first at the Frankfurt Institute for Advanced Studies and from 2010 on as postdoc at the Aarhus School of Engineering. Starting in June 2011, he started to work for the German Aerospace Center, Stuttgart, in the Systems Analysis and Technology Assessment group.

Martin Greiner was born in Cheverly, MD, USA on March 30, 1963. He graduated with a degree in theoretical physics from the Justus Liebig University in Gießen, Germany.

He has been a research scientist at the University of Arizona, the Technical University and the Max-Planck Institute for the Physics of Complex Systems in Dresden, at the Duke University, and at Siemens Corporate Research & Technology in Munich.

Since 2010 he is a professor in system engineering at Aarhus University. His current fields of interests include fully renewable energy systems, wind energy and the physics of complex networks.