# Transition to a Fully Renewable Power System in Europe

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

*Published in:*
Proceedings of the 10th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants

*Publication date:*
2011

*Document Version*
Accepted author manuscript, peer reviewed version

*Citation for published version (APA):*
Bruun Andresen, G., Heide, D., Rasmussen, M. G., & Greiner, M. (2011). Transition to a Fully Renewable Power System in Europe. In *Proceedings of the 10th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants* (pp. 322-325)

# Transition to a Fully Renewable Power System in Europe

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

*Abstract*-- **We introduce a top-down stylized model to analyze the impact of a transition to a European power system based only on wind and solar power. Wind and solar power generation is calculated from high-resolution weather data and based on the country specific electricity demand alone, we introduce a model of the conventional power system that facilitates simple spatio-temporal modeling of its macroscopic behavior without direct reference to the underlying technological, economical, and political development in the system. Using this model, we find that wind and solar power generation can replace conventional power generation and power capacity to a large degree if power transmission across the continent is made possible.**

*Index Terms*—**wind power, solar power, large-scale integration, Europe, numerical modeling, power transmission.**

## I. INTRODUCTION

THE design of a fully renewable power system for future Europe depends on the weather. The weather determines how much wind and solar power generation is best for Europe, how much and what kinds of storage [1], balancing [2] and power transmission are needed, and how much fossil and nuclear power generation is still required during the transitional phase. Simple spatio-temporal modeling on high-resolution weather data, electricity consumption time series, and the physics of complex networks provide quantitative answers to these important questions. Included in the analysis are 27 European countries, and we model hourly conventional and renewable power generation over a continuous period of 8 years.

### *A. A top-down stylized model*

In order to find the optimal transitional path, we introduce a top-down stylized model of the present day power system. The model facilitates simple spatio-temporal modeling of the macroscopic behavior of the power system without direct reference to the underlying technological, economical, and political development in the system. A set of simple rules, aimed at minimizing the conventional power system, are then used to calculate the power system composition and dynamics for a fixed amount and mix of renewable power production [3]. In addition, the model calculations provide direct and quantitative answers to the consequence and the large potential benefits of introducing a strong continental power grid in the European system.

## II. METHOD

Below is a short description of the data which forms the basis of the analysis and an introduction to the top-down modeling approach.

### *A. Data description*

Normalized wind and solar power generation is derived directly from historical weather data with a spatial resolution of 50 x 50 km$^2$ and a temporal resolution of 1 hour. The data set covers both on and off-shore regions for 27 European countries and spans the 8-year period 2000-2007. The geographic extend of the data set is shown in Fig. 1, where the calculated potentials for wind and solar power are indicated by their respective average capacity factors.

To obtain the absolute power output at a given location we apply capacity scaling factors to each grid cell. The scaling factors reflect the assumed installed wind and solar power capacity at that location, and combined, all such scaling factors form maps of the installed wind and solar power capacities. Fig. 1 indicates one such layout as hatched areas. These layouts are based on the national EU-2020 targets of Europe where emphasis is given to the most attractive European sites.

The electricity demand (or load) for all 27 European countries is obtained on a regional basis with hourly resolution. Regions typically consist of the domain of a single transmission system operators (TSO) and inside each region power is assumed to flow freely. In this analysis, we generalize further, and assume that power can flow freely within the borders of each country. Fig. 2 shows the combined hourly demand for all 27 European countries in the data set.

Additional details on the origin and processing of the weather and load data can be found in the appendix of [1].

---

G. B. Andresen is with Aarhus School of Engineering, Aarhus University, DK-8000 Denmark (e-mail: gba@ase.au.dk).

D. Heide is with Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe University, DE-60438 Frankfurt am Main (e-mail: dheide@fias.uni-frankfurt.de).

M. G. Rasmussen is with Aarhus School of Engineering, Aarhus University, DK-8000 Denmark (e-mail: mgr@ase.au.dk).

M. Greiner is with Aarhus School of Engineering, Aarhus University, DK-8000 Denmark (e-mail: greiner@imf.au.dk).

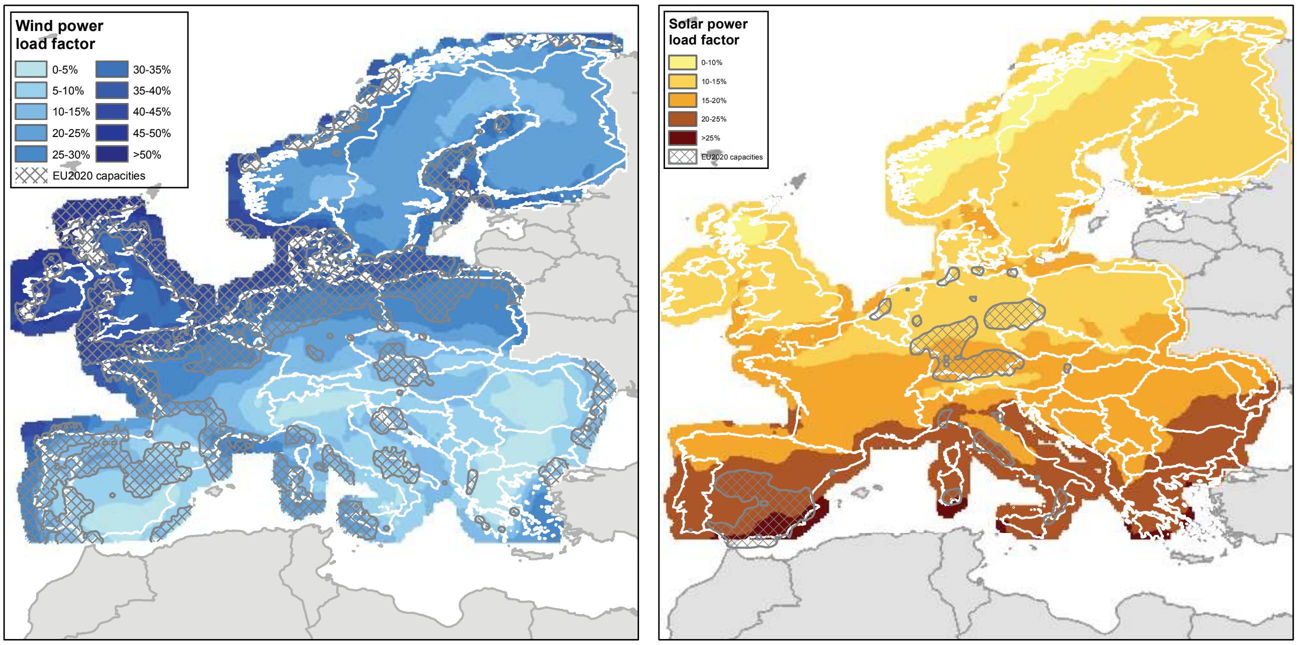

Fig. 1. Maps showing the 27 European countries included in the analysis. Hashed areas indicates the preferred placement of wind and solar power according to the EU-2020 goals. In color we show: Average power output of a standardized wind turbine scaled to its rated peak capacity, i.e., the wind power capacity factor (Left panel). Average power output of a standardized solar PV unit scaled to its rated peak capacity, i.e., the solar power capacity factor (Right panel).

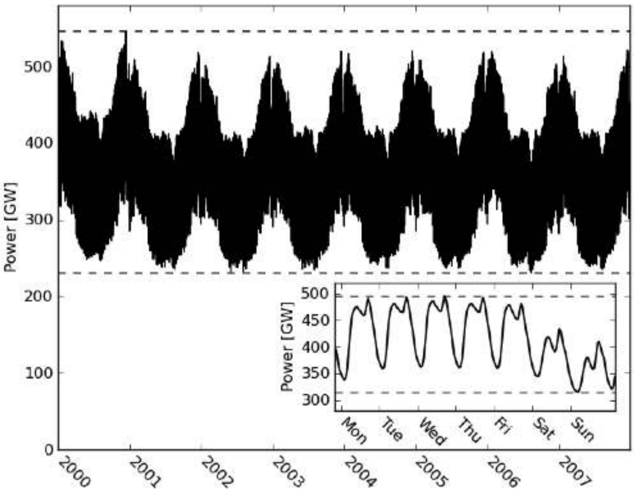

Fig. 2. Combined hourly electricity demand for the 27 European countries included in the study during the 8-year period 2000-2007. The inset shows the load during a typical week in more detail. Note that an exponential increase of the demand of approximately 1-2% per year has been removed for each country. The data has subsequently been scaled to 2007 values.

### *B. The top-down modeling approach*

In a power system with a high share of weather driven renewable power generation, the supporting flexible system must satisfy the residual load that remains after subtracting the available power generation from the actual load. Generally, the residual load must be satisfied for each country, but depending on the capacity of cross-border transmission lines, flexible resources and renewable power generation can be shared between some or all countries in order to do so.

In the following, we define the supporting system and propose a set of simple operational rules which allows power generation to be assigned with different levels of flexibility similar to those associated with base load, intermediate load, and peak load power generation. Doing so allows us to make a bridge between the traditional power system of today and a future power system with very high shares of weather driven power generation and provides a tool to estimate at what level weather driven power generation is able to replace flexible conventional power generation, in particular, base load power generation.

In order to identify a natural distinction between different levels of flexibility in the traditional power system, we identify a set of three simple patterns of repetition found in the electricity load time series for all 27 countries in the data set. These are: a seasonal, a weekly, and a daily pattern. The seasonal pattern generally distinguish winter from summer, but varies significantly from country to country, as it depends on seasonal changes in the local environment and events such as national holidays. The weekly pattern distinguishes weekend days from workdays with a lower average load during the former, for all countries. Finally, the daily pattern is characterized by large night-day variations in the load, and distinct peak-hours, typically, during morning and evening. As a rule of thumb, the difference between the maximum and the minimum load hour during any 24-hour window amounts to about 20-40% of the daily maximum, depending on the country. As an example, Fig. 2 illustrates the seasonal, weekly, and daily patterns of the combined European load. Associated with each of the three patterns is a distinct time scale and amplitude. In order to meet the electricity demand, the underlying power system must have sufficient regulation power that can be dispatched at the appropriate time scales.

Combining the properties of the three patterns identified in the load time series with the fact that different power plants have different ability to regulate their output, we define a simple model of the present-day power system: First, regulating capacity which can be dispatched on time scales in the interval 1 to 24 hours is associated with the daily pattern, and a country specific minimum sufficient peak capacity of an intra-day flexible system is derived directly from the high-frequency component of the load time series. The remaining low frequency component of the load time series is then analyzed in a similar way to find the minimum sufficient peak capacity that can be dispatched on time scales in the interval 1 to 7 days. This capacity is associated with an intra-week subsystem. Finally, a minimum sufficient peak capacity that can be dispatched on time scales longer than one week, remains. This capacity is associated with a seasonal power subsystem.

The simplified power system, described above, makes use of the smallest possible set of power capacities in the sense that the minimum capacity for each subsystem is identified in order of the most to the least flexible system. The capacities are designed to fully cover the load during 99% of the 70128-hour-long data set and to avoid any excess power generation when applied to the load curve they are derived from. The rules allow any residual load with a maximum smaller than or equal to the combined power of the three flexible systems to be met, and ensure that the most flexible systems are utilized to minimize excess production.

## III. RESULTS

The power capacities of the three present-day conventional subsystems are calculated from the electricity demand curve for each individual country as, presently, only few European countries rely on transmission as a means of balancing the electricity demand. Summed over all countries this leads to aggregated capacities of: 272 GW for the seasonal system, 133 GW for the intra-week system, and 165 GW for the intra-day system.

In the following we distinguish between two cases: In the first case, we assume the European power system to be the sum of isolated national power systems. We name this case *closed borders*. In the second case, dubbed *open borders*, we assume free flow of power between all countries.

Fig. 3 shows the average power generation and power capacities of the seasonal, intra-week, and intra-day power systems as a function of the total wind and solar power penetration for open and closed borders. The average wind and solar power generation is shown as well. The corresponding minimum power capacities of the flexible systems are shown in the inset of the figure. Both in the case of open and closed borders, about 25% renewable power can be included in the power system without incurring excess generation. However, in the case of closed borders this only leads to a small decrease in the required power capacity of the seasonal subsystem. In contrast, about 30% of the installed seasonal capacity can be shut-down in the case of open borders, most of which can be attributed directly to installed capacities of wind and solar power, while a smaller amount is a consequence of sharing balancing capacities and reducing fluctuations in demand and generation through aggregation. When the average wind and solar power generation is between 25% to 75% of the average demand, the dominant source of fluctuations in the residual load changes from fluctuations in electricity demand to fluctuations caused by wind and solar power generation. In this interval, the seasonal capacity decrease at a lower rate for both open and closed borders, and complete integration of all renewable power generation can only be achieved in the case of open borders, high-lighting the need for cross-border power transmission. Beyond 75%, excess power generation is also present in the case of open borders, and when the average renewable generation exceeds 100% of the demand excess power generation cannot be avoided as annual generation exceeds the demand. The rate of decrease of seasonal power capacity stabilizes at approximately 75% for both open and closed borders. However, in the case of closed borders the rate of decrease has an asymptotic behavior and never falls below a certain point (not shown), whereas for the open borders the seasonal capacity becomes zero at a combined wind and solar penetration of approximately 125%. For a penetration of approximately 160%, the capacity of the intra-week system too becomes zero, leaving the intra-day system as the sole flexible supporting system for wind and solar power generation.

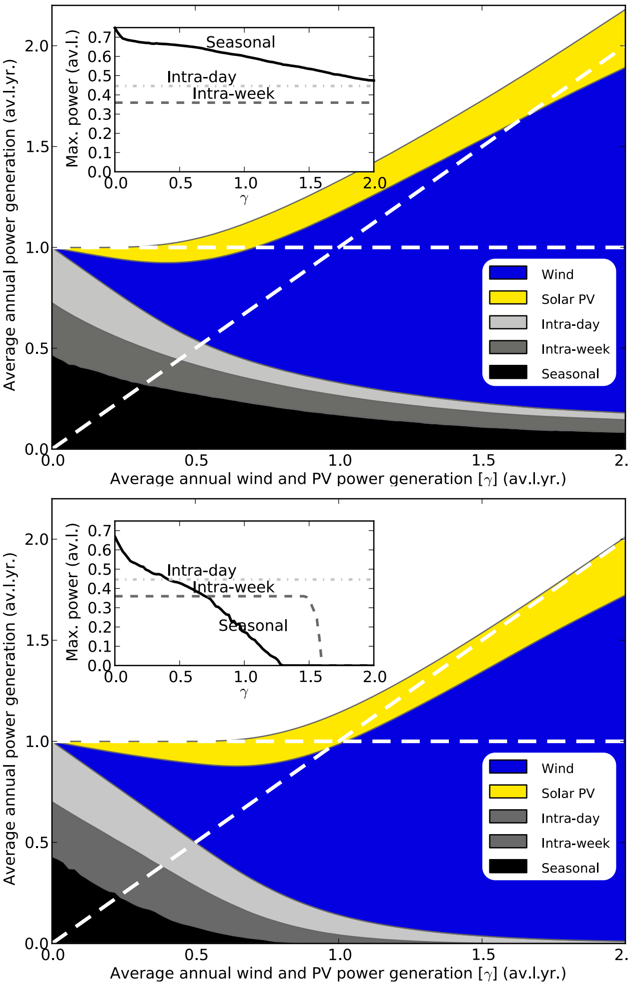

Fig. 3. Average annual power generation of the flexible intra-day, intra-week, and seasonal systems vs. average annual combined wind and solar PV power generation in units of an average load year (av.l.yr.). The average power generation of wind and solar are shown as well. The inset shows the corresponding power capacities of the three flexible systems. Two cases are shown: closed borders (upper panel), i.e., no power transmission across the national borders, and, open borders (lower panel), i.e., unlimited power transmission between all countries.

## IV. CONCLUSION

Based on high spatio-temporal resolution modeling of wind and solar power generation and fundamental properties of the present day European power system, we conclude that wind and solar power generation can replace approximately 50% of the least flexible power generation in the European power system without incurring large amounts of excess power generation. However, it is not possible to replace conventional power capacity while retaining a high level of security of supply if a high degree of power transmission across the national borders is not in place. Beyond a penetration of 50%, cross-border power transmission is also needed to minimize excess power generation. However, if power can flow freely between the countries of Europe, wind and solar power can replace all slowly flexible base load power generation at a penetration of approximately 125% and all intermediate flexible power generation at a penetration of approximately 160%. Highly flexible power generation of a capacity similar to that used to balance the day-night difference in the load of today will have to be maintained throughout a transition to a fully renewable Europe.

## V. ACKNOWLEDGMENT

We would like to thank Jan Scholz for fruitful discussions. Morten Grud Rasmussen is supported by Carlsbergfondet.

## VI. REFERENCES

[1] D. Heide, L. von Bremen, M. Greiner, C. Hoffmann, M. Speckmann, and S. Bofinger, "Seasonal optimal mix of wind and solar power in a future highly renewable Europe", *Renewable Energy*, vol. 35, pp. 2483-2489, 2010.

[2] D. Heide, M. Greiner, L. von Bremen, and C. Hoffmann, "Reduced storage and balancing needs in a fully renewable European power system with excess wind and solar power generation" *Renewable Energy*, vol. 36, pp. 2515-2523, 2011.

[3] G. B. Andresen, D. Heide, M. G. Rasmussen, and M. Greiner, “Transition to a fully renewable European power system”, manuscript in preparation.

## VII. BIOGRAPHIES

**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.

**Morten Grud Rasmussen** was born in Lidkøping 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.

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.

**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.