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Backup flexibility classes in emerging large-scale renewable electricity systems

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ABSTRACT

High shares of intermittent renewable power generation in a European electricity system will require flexible backup power generation on the dominant diurnal, synoptic, and seasonal weather timescales. The same three timescales are already covered by today's dispatchable electricity generation facilities, which are able to follow the typical load variations on the intra-day, intra-week, and seasonal timescales. This work aims to quantify the changing demand for those three backup flexibility classes in emerging large-scale electricity systems, as they transform from low to high shares of variable renewable power generation. A weather-driven modelling is used, which aggregates eight years of wind and solar power generation data as well as load data over Germany and Europe, and splits the backup system required to cover the residual load into three flexibility classes distinguished by their respective maximum rates of change of power output. This modelling shows that the slowly flexible backup system is dominant at low renewable shares, but its optimized capacity decreases and drops close to zero once the average renewable power generation exceeds 50% of the mean load. The medium flexible backup capacities increase for modest renewable shares, peak at around a 40% renewable share, and then continuously decrease to almost zero once the average renewable power generation becomes larger than 100% of the mean load. The dispatch capacity of the highly flexible backup system becomes dominant for renewable shares beyond 50%, and reach their maximum around a 70% renewable share. For renewable shares above 70% the highly flexible backup capacity in Germany remains at its maximum, whereas it decreases again for Europe. This indicates that for highly renewable large-scale electricity systems the total required backup capacity can only be reduced if countries share their excess generation and backup power.

1. Introduction

The dispatchable electricity generation facilities that are widespread today were mainly constructed with the aim of matching demand requirements. They split more or less into three flexibility classes, which are able to follow the typical load variations on the intra-day, intra-week, and seasonal timescales; see Fig. 1. During the day, variations in the load are usually due to human activity. Furthermore, the load is reduced during weekends and public holidays, and seasonal changes lead to higher load in the winter due to longer nights and increased heating demand. Examples of current slowly flexible generators are nuclear and lignite power plants, coal and combined-cycle gas power plants are medium flexible, and open-cycle gas turbines are highly flexible.

This mix of conventional power generation plants is going to change. In order to mitigate the negative impact of climate change, some countries (like Germany and Denmark) are following ambitious targets on reducing CO_2 emissions and on increasing the integration of renewable energies [2]. Both targets pressure the existence of some of the conventional power plants, in particular the lignite and coal power plants. As to the second target, the increasing share of weather-driven variable renewable energy sources (VRES) – mainly wind and solar PV power – poses new challenges, and in particular leads to an increase in fluctuations of the residual load. This requires more highly flexible backup power plants. Slowly flexible power plants will be less needed, but phasing them out too early might turn out to be a mistake.

In highly renewable electricity systems the same three flexibility timescales as in the conventional power systems are also present [1]. They are determined by the weather variations which cause the wind and solar power generation to fluctuate. The

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Nomenclature

VRES	variable renewable energy sources
PV	photovoltaics
DE	Germany
Agg.	aggregated Europe
av.l.h.	average load hours
T	total number of hours
t	specific hour of the time series
$L(t)$	load
$\langle L\rangle$	mean load
$L_R(t)$	residual load
$W(t)$	wind generation
$S(t)$	solar generation
γ	gross share of VRES
α	wind fraction
i	flexibility class
m_i	maximum rate of change
$B_i(t)$	power output
K_i	power capacity
K_{tot}	total power capacity
c, w_i	capacity weight parameters
d, v_i	dispatch weight parameters
E_{miss}	missing energy
E_{excess}	excess energy
f_i	utilization fraction
Φ	optimization function
q	quantile of fully covered hours
N_{miss}	number of partly covered hours

intra-day timescale is called the diurnal timescale and is most clearly seen in the solar power generation following the availability of sunlight; see again Fig. 1. Wind variations are dominated by synoptic weather patterns in Europe, which fluctuate on the timescale of three to ten days [3]. These weekly fluctuations also have an effect on the solar irradiation and thus the solar photovoltaic (PV) production. Finally, seasonal changes are observed, with typically more wind power production and less solar PV generation in winter and vice versa in summer.

To include a large share of variable renewable energy, the energy system has to become more flexible. There is a considerable spread in the interpretation of what flexibility in the electricity system actually means, ranging from the more direct definition of the ability to react to variability, e.g., [4], and uncertainty of forecasts of variable generation [5], to more indirect policy, regulation, and market implementation issues of making balancing energy and power available, e.g., [6]. Depending on the complexity of the modelled system, different flexibility metrics have been proposed or reviewed. Metrics based purely on the properties of the residual load at given shares of variable generation are defined by Tarroja et al. [7]. They allow insight into principal properties of the flexibility requirements of the dispatchable part of an energy system. In a similar setting, Huber et al. [8] focus on flexibility needs based on (residual) load gradients over different time intervals and spatial scales in Europe. Additional metrics can be defined in dispatch simulations, e.g., to measure the difference between forecast and actual (residual) load [9], missing or surplus energy, or missing or surplus power [10] (see [11] for a comprehensive summary). These also include different metrics for the (in-) sufficiency of flexibility in the systems, such as the loss of load expectation or the number of unserved hours [9]. This study concentrates on the challenges posed by ramp rates in the residual load, measuring the quality of the flexible system in terms of unserved energy.

Dispatchable generators are not the only possible source of flexibility. Recent studies considered the influence of storage (e.g., [12]), transmission grid extension (e.g., [13]), demand-side-management, curtailment, system integration with the heating (e.g., [14]) and transport sector (e.g., [15]), economic efficiency (e.g., [16]), forecast errors, and combinations thereof. Kondziella and Bruckner [17] provide a thorough review of different technical, economic, and market based modelling approaches and requirements for the different aspects of flexibility demand. A range of more specialized flexibility metrics for these options is reviewed by Østergaard [18].

This paper analyses a stylized model of the European electricity system, consisting of weather-based wind and solar PV generation and historical load data from Ref. [1] with hourly resolution. These are assumed to be complemented by dispatchable generation of three flexibility classes, which are designed to follow the load and the renewable power generation on the diurnal, synoptic, and seasonal timescales, respectively. To define the three flexibility classes, maximum ramp rates are assigned in a top-down manner. Their total capacities as well as their dispatch are treated as optimization variables. Similar flexibility classes are also defined in Ref. [19], where a Fourier-like decomposition of the residual load is used to estimate flexibility requirements, but their model focuses on a optimal decommissioning of the currently installed capacities.

First discussions of the explicit impact of the dominant meteorological timescales on the required backup infrastructure of

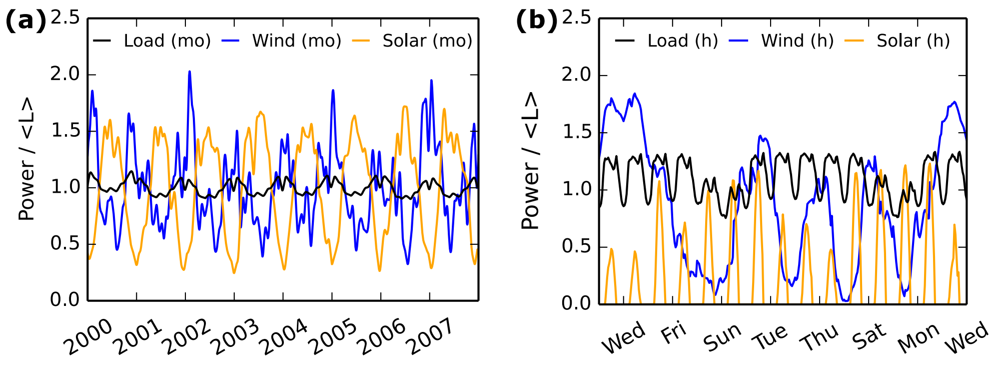

Fig. 1. Examples of time series of load and weather-based wind/solar generation in Germany based on data described by Heide et al. [1]. (a) All eight years of data, smoothed over one month to see long-term trends. (b) Hourly load and generation for two example weeks in October 2000. All time series have been normalized to an average load of one.