Journal of Cleaner Production 181 (2018) 449–459

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# How much electrical energy storage do we need? A synthesis for the U.S., Europe, and Germany

Felix Cebulla [a], Jannik Haas [b, *], Josh Eichman [c], Wolfgang Nowak [b], Pierluigi Mancarella [d]

[a] German Aerospace Center (DLR), Institute of Engineering Thermodynamics, Department of Systems Analysis and Technology Assessment, Germany
[b] Department of Stochastic Simulation and Safety Research for Hydrosystems (IWS/SC SimTech), University of Stuttgart, Germany
[c] National Renewable Energy Laboratory, United States
[d] Department of Electrical and Electronic Engineering, The University of Melbourne, Australia, School of Electrical and Electronic Engineering, University of Manchester, UK

A R T I C L E I N F O

*Article history:*
Received 6 October 2017
Received in revised form
16 January 2018
Accepted 18 January 2018
Available online 3 February 2018

*Keywords:*
Expansion planning
Electrical energy storage (EES)
Energy storage systems (EES)
Power system flexibility
Renewable energy integration
Low-carbon systems

A B S T R A C T

Electrical energy storage (EES) is a promising flexibility source for prospective low-carbon energy systems. In the last couple of years, many studies for EES capacity planning have been produced. However, these resulted in a very broad range of power and energy capacity requirements for storage, making it difficult for policymakers to identify clear storage planning recommendations. Therefore, we studied 17 recent storage expansion studies pertinent to the U.S., Europe, and Germany. We then systemized the storage requirement per variable renewable energy (VRE) share and generation technology. Our synthesis reveals that with increasing VRE shares, the EES power capacity increases linearly; and the energy capacity, exponentially. Further, by analyzing the outliers, the EES energy requirements can be at least halved. It becomes clear that grids dominated by photovoltaic energy call for more EES, while large shares of wind rely more on transmission capacity. Taking into account the energy mix clarifies—to a large degree—the apparent conflict of the storage requirements between the existing studies. Finally, there might exist a negative bias towards storage because transmission costs are frequently optimistic (by neglecting execution delays and social opposition) and storage can cope with uncertainties, but these issues are rarely acknowledged in the planning process.



## 1. Introduction

Renewable energy sources are variable, uncertain, and location-specific. Thus, their integration into power systems requires flexibility. Flexibility can be understood as the ability to balance the residual load (electricity load minus variable renewable energy, VRE) (Huber et al., 2014). It can be provided by transmission and distributions grids, by the supply side (flexible power plants or curtailment of VRE), by demand-side management (DSM, including new loads as part of the electrification of demand such as electro-heating and cooling, e-mobility, and power-to-gas), and by electrical energy storage (EES) (Kondziella and Bruckner, 2015; Lund et al., 2015; Pamparana et al., 2017; Ren and Ren, 2018; Haas et al., 2018; Rahmann et al., 2016). This study will focus on EES requirements.

During the last 30 years, much research on different EES technologies has been produced. These frequently include a varied spectrum of batteries (Poullikkas, 2013; Longo et al., 2014), pumped-hydro plants (PHS) (Rehman et al., 2015; Deane et al., 2010), compressed air energy storage (CAES) (Budt et al., 2016), and hydrogen with the option for reconversion to electricity ($H_2$) (Götz et al., 2016; Barthelemy et al., 2017), among others (Wicki and Hansen, 2017). Several recent studies (Lund et al., 2015) (Luo et al., 2015; Amirante et al., 2017; Chen et al., 2009; Aneke and Wang, 2016; Ferreira et al., 2013), provide comprehensive reviews of these technologies. A widely accepted conclusion is that there is no storage option that outperforms all others (Chen et al., 2009). Hence, planning with a *combination* of storage options is a direct consequence.

Examples of studies that plan the required storage capacity for power systems with large shares of renewable energy (RE) are (Ueckerdt et al., 2017; Inage, 2009; Mileva et al., 2016; Frew et al., 2016; Hand et al., 2012; Frew, 2014) for the U.S. or (Ueckerdt et al., 2017; Inage, 2009; Bertsch et al., 2016; Bussar et al., 2016; Zerrahn and Schill, 2015; Scholz et al., 2017; Bussar et al., 2015; Brouwer et al., 2016) for Europe. However, these studies result in

* Corresponding author.
*E-mail address:* jannik.haas@iws.uni-stuttgart.de (J. Haas).

https://doi.org/10.1016/j.jclepro.2018.01.144
0959-6526/

a wide range of storage requirements, which makes it difficult for the policy maker to identify clear recommendations. Many methods, assumptions, and modeling approaches in storage expansion planning exist, as systemized in ref. (Haas et al., 2017), which may help to explain the variances in the results.

To date, there are a few initial efforts in systemizing the flexibility requirements. One example is the book from (Droste-Franke 2015) which, based on studies from around 2010, comprehensively explains the flexibility requirements for Europe and Germany for different shares of renewables. (Kondziella and Bruckner 2015) follow that line and, in 2016, provide an updated review of flexibility demand. (Koskinen and Breyer 2016) provide a summary of global and trans-continental storage demand. Finally, (Doetsch et al 2014). review different reports, which analyze the need for EES in the German and European energy system. Most recently, (Zerrahn and Schill 2017) provide a comprehensive review of storage planning with a focus on the modeling approach. Unexplained differences in the prognosed EES requirements remain, calling for a systematization of the many available storage expansion studies, particularly in the light of their derived storage capacity.

On the above premises, we analyzed and systemized recent EES expansion studies for three regions with strong renewable targets (U.S., Europe, and Germany), including 17 studies and over 400 scenarios. Our study makes three fundamental contributions to the literature:

i) for each region, we compare the obtained storage energy and power capacity requirements for VRE shares;
ii) as these studies result in a very broad range of storage sizes, we further narrow down the range of storage requirements by analyzing the main drivers, including the impact of different power mixes (photovoltaic- or wind-dominated);
iii) we discuss the impact of the electrical network modeling on the storage requirements.

Altogether, our findings provide direction to energy modelers regarding where to put effort when modeling future energy systems, as well as to policymakers towards a more precise understanding of the storage requirements.

Section 2, below, describes the analyzed studies. Section 3 presents the ranges of storage requirements found and discusses the main drivers. Finally, Section 4 draws the conclusions.

## 2. Methods

Our approach consists of three steps. First, we collect and systemize data from recent studies about storage expansion planning (Section 2.1). Second, we analyze and describe the models of the selected studies (Section 2.2) to then synthesize the storage requirements and filter unfit scenarios in our third step (Section 2.3). More detail on these steps will follow.

### 2.1. Data collection and systematization

Meeting environmental goals has triggered many studies about planning power systems with high shares of renewable technologies in the last couple of years. From the existing literature, we looked for studies that detail the storage requirements explicitly (storage expansion planning) and that range from 2009 to early 2017. A selected study should include scenarios with high shares of renewables and provide the specifics on the generation mix.

We decided to focus on the U.S. and Europe, as they are large continental grids and global drivers for storage demand. We also decided to contrast the results of such large grids with a smaller geographic region. Germany was chosen given the many available studies and the country's ambitious renewable energy target.

We paid special attention to the storage power capacity (in $GW_{el}$) and energy capacity ($TWh_{el}$), and the associated shares of VRE and generation mix. We defined VRE shares as the sum of all variable power generation (e.g. from photovoltaic (PV) or wind systems) over a time period (typically one year) divided by the overall power generation[1] (Heide et al., 2011). Further, as a basis for systematization and synthesis, we recorded how the grid is modeled, whether other flexibility options were considered, and other relevant assumptions.

Most of the studies provided this information as part of their bodies or as supplementary materials. If absent, we contacted the corresponding author directly. All this data was compiled into a database.

### 2.2. Selected studies

Following the selection criteria explained above, we considered the following EES studies: (Ueckerdt et al., 2017; Inage, 2009; Mileva et al., 2016; Frew et al., 2016; Hand et al., 2012; Frew, 2014; Bertsch et al., 2016; Bussar et al., 2016; Zerrahn and Schill, 2015; Scholz et al., 2017; Bussar et al., 2015; Brouwer et al., 2016), (Steffen and Weber, 2013; Budischak et al., 2013; Kühne, 2016; Pape et al., 2014; Babrowski et al., 2016; Steffen and Weber, 2012; Adamek et al., 2012; Hartmann, 2013).

For the U.S., we considered the renowned studies “Renewable Electricity Futures” of the National Renewable Energy Laboratory (NREL) (Hand et al., 2012) and “Prospects for Energy Storage in Decarbonised Power Grids” from the International Energy Agency (Inage, 2009). Relevant journal publications and PhD thesis are (Ueckerdt et al., 2017; Mileva et al., 2016; Frew et al., 2016; Budischak et al., 2013; Frew, 2014), respectively.

Selected studies for Europe include the recognized report “Roadmap Storage” (Pape et al., 2014) from Fraunhofer/RWTH Aachen/Environmental Law Foundation. Analyzed energy journal publications are (Bertsch et al., 2016; Bussar et al., 2016; Scholz et al., 2017; Bussar et al., 2015; Brouwer et al., 2016). The report from the International Energy Agency (Inage, 2009) and the journal publication (Ueckerdt et al., 2017) mentioned above also provide scenarios for Europe.

Germany clearly is a region included in the models of the European studies. However, the studies frequently do not explicitly provide the results of one country; rather they refer to the continental storage need (with the exception of (Bertsch et al., 2016; Pape et al., 2014) that indeed provide the details for Germany). Hence, the following studies are specifically made for Germany. We included the well-known study from the VDE (Association for Electrical, Electronic & Information Technologies) (Adamek et al., 2012), recent journal publications (Zerrahn and Schill, 2015; Steffen and Weber, 2012, 2013; Babrowski et al., 2016), comprehensive PhD theses on the topic (Kühne, 2016; Hartmann, 2013), and the already mentioned publications of Europe that also detail Germany (Bertsch et al., 2016; Pape et al., 2014).

The summary of the considered studies is shown in Table 1. For a more detailed description, please consult the appendix.

### 2.3. Admissible scenarios

The explored studies contain 527 scenarios. Not all scenarios are suitable, however, for comparison. We excluded those that differ

[1] The VRE share can either refer to the gross power generation or the satisfied power demand. The former includes losses (e.g. from storage self-discharging or transmission losses) and the second neglects them.