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Electrical energy storage in highly renewable European energy systems: Capacity requirements, spatial distribution, and storage dispatch

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ABSTRACT

One of the major challenges of renewable energy systems is the inherently limited dispatchability of power generators that rely on variable renewable energy (VRE) sources. To overcome this insufficient system flexibility, electrical energy storage (EES) is a promising option. The first contribution of our work is to address the role of EES in highly renewable energy systems in Europe. For this purpose, we apply the energy system model REMix which endogenously determines both capacity expansion and dispatch of all electricity generation as well as storage technologies. We derive an EES capacity of 206 GW and 30 TWh for a system with a renewable share of 89%, relative to the annual gross power generation. An extensive sensitivity analysis shows that EES requirements range from 126 GW and 16 TWh (endogenous grid expansion) to 272 GW and 54 TWh (low EES investment costs). As our second contribution, we show how the spatial distribution of EES capacity depends on the residual load, which—in turn—is influenced by regionally predominant VRE technologies and their temporal characteristics in terms of power generation. In this sense, frequent periods of high VRE excess require short-term EES, which naturally feature low power-related investment costs. In contrast, long-term EES with low energy-related costs are characteristic for regions where high amounts of surplus energy occur. This relationship furthermore underlines how EES capacity distribution is implicitly influenced by technical potentials for VRE expansion.

1. Introduction

The reduction of greenhouse gas emissions is one of the main challenges of our society towards more sustainable energy supply [1]. Electricity generation from renewable resources represents a promising option to tackle this problem. However, the mismatch of electricity generation and load caused by the limited dispatchability of intermittent electricity generation such as photovoltaic (PV) or wind power—hereinafter referred to as variable renewable energies (VRE)—requires an increase of flexibility of future energy systems. While various definitions of flexibility exist (see Refs. [2,3]), the term is commonly understood as the ability of technical devices to contribute to the balancing of the residual load [4] (which, in turn, is defined as the electricity load minus the generation from VRE). More specifically, flexibility might be provided e.g. by electrical energy storage (EES) or the electricity grid. While the former option provides flexibility on a temporal level, i.e. allows shifting of energy from one point in time to another, grid expansion can be considered as a spatial flexibility, since it enables large-scale balancing of generation and demand between different regions which otherwise have to balance their internal mismatches themselves. Additional technical solutions for flexibility are demand side management, in particular in combination with new loads (electric heating, electric cooling, e-mobility, and power-to-gas) and supply-side flexibility (flexible

Abbreviations: AC, alternating current; aCAES, adiabatic compressed air storage; CCGT, combined cycle gas turbine; CSP, concentrated solar power; DC, direct current; E2P, energy-to-power-ratio; EES, electrical energy storage; EEX, European energy exchange; EnDAT, energy data analysis tool; ENTSO-E, European network of transmission system operators for electricity; GAMS, general algebraic modeling system; GT, open cycle gas turbine; H_2, hydrogen storage; Li-Ion, stationary lithium-ion battery; NC, number of cycles; NFC, number of full cycles; PHS, pumped hydro storage; PV, photovoltaic; RE, renewable energy; REMix, renewable energy mix model; SOC, state of charge; VRE, variable renewable energy.

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Table 1
Observation areas and spatial resolutions in different analyses which focus on flexibility demand calculations (number of model-regions in brackets).

Author	Model type	Observation area	Spatial resolution
[10]	Optimization	Small exemplary region	Single node
[19]	Simulation	Texas	Single node[a]
[24]	Optimization	California	Multi node (12)
[42]	Optimization	Germany	Multi node (440)
[48]	Optimization	Germany	Single node
[49]	Optimization	US: Western Electricity Coordinating Council	Multi node (50)
[4]	Simulation	Ireland, Germany, Italy[b]	Single node[c]
[20]	Simulation	EU 27 + offshore regions	Single node[c]
[11,12]	Optimization	Europe, Middle East, North Africa	Multi node (21)
[50]	Simulation	Worldwide	Single node[c]

[a] Small import and export capacities <1 GW exist.
[b] The study includes 27 European countries, excluding Malta and Cyprus and including Norway and Switzerland, focuses, however, on the three countries listed in the table.
[c] Although the observation area includes several regions, each region is analyzed isolated as one model-region (no grid).

power-plants, curtailments of VRE) [5,6]. In this work, we focus on flexibility provided by EES which is characterized both in terms of necessary power and energy related capacity.

1.1. Literature review

Current research addresses the question of future EES requirements typically via model-based analyses, often emphasizing the quantification of EES capacity for different energy scenarios [7–13]. Reviews for the required EES capacity in Europe are, for example, provided by Kondziella and Bruckner [6] or Droste-Franke et al. [14]. These publications show broad ranges of required EES capacity[2] in the current research, highlighting the necessity of a thorough examination of the underlying assumptions in the original studies.

In this sense, storage requirements have been studied with regard to different renewable energy (RE) shares [7,16–20], wind-to-PV generation ratios [4,13,21], weather years or climate effects [22,23], cost assumptions [8,12], and the representation of the electric grid [12,16,24]. Moreover, the resulting EES capacities in model-based assessments are influenced by the applied modeling approach (I), different temporal (II), technological (III), and spatial resolutions (IV). A profound review of methods, challenges, and trends for flexibility requirements (including EES) is provided by Haas et al. [25].

(I) Storage requirements have been analyzed with the help of various modeling approaches; some of the most prominent ones are optimizations (e.g. in [8,9,13,24,26–30]) and simulations (e.g. in [17,18,31–33]). While optimizations derive an ideal energy system under the premise of their objective function (e.g. minimal system costs [13] or efficient RE integration [26]), simulations have a predictive or explorative view [34], relying on energy balance accounting methods, dispatch strategies (*merit order*), or time-series analyses. By this means, simulations might not find the optimal solution, however, typically enable a higher temporal (e.g. 6 min in [33]), technological (e.g. multi-sectoral approaches in [35,36]), or spatial resolution (e.g. 146 regions in [32]).

(II) The influence of the temporal resolution has been studied in an optimization model for ramp flexibility as well as for system costs in Deane et al. [37]. Pandzic et al. [38] and O'Dwyer and Flynn [39] use a unit-commitment model to study day-ahead utility scheduling of power plants. The studies find that sub-hourly resolutions are desirable for assessing the ramping flexibility of power plants. However, if system costs are the main evaluation criterion, hourly resolutions are sufficient. Pfenninger [40] uses down-sampling, clustering, and heuristics to reduce the temporal resolution (initial time-series in hourly resolution) in energy systems models and studies their effects on computational performance, dispatch, installed capacities, and system costs for a UK power system. The author concludes that—particularly in energy scenarios with high VRE shares—the temporal resolution should be preferably on an hourly basis or better. In the contrary, Pfenninger points out that if the modeling includes EES, the need for high sequential temporal resolutions can be reduced. However, the author also states that there are no clear recommendations regarding which temporal resolution is most suitable and emphasizes that the influence strongly depends on the model setup as well as the input parameters.

(III) Technological resolution can either refer to the abstraction level in the modeling approach to characterize the technologies or to the considered energy sectors in the model-based analysis.

With regard to the technological representation of storage, the literature shows numerous approaches, ranging from representations of a single generic storage [41], to storage classes (e.g. short-, mid-, long-term, without further details on the assumed technologies, see Ref. [11]), or detailed representations of actual storage technologies [9,13,27,42].

Model-based quantifications of EES requirements typically only analyze the power sector. If other sectors are included (e.g. with transportation, heating, or cooling), the approaches typically rely on accounting frameworks on an annual basis (e.g. in [35], [36]) or optimizations which use a simplified temporal resolution in terms of representative time periods (e.g. in [43,44]). Multi-sectoral analyses based on an hourly basis, for example, can be found in the work of Thellufsen and Lund [45], Lund et al. [46], or Schaber et al. [47].

(IV) Storage requirements have been analyzed for several observations areas with different spatial resolutions within the models, i.e. the number of model-regions. The latter plays an important role, as it defines the distribution of capacities, generation, electricity load, and transmission grid topology within the observation area. Table 1 gives an overview regarding spatial examination areas and resolution in different studies (number of model-regions in brackets).

1.2. Contributions and novelty

As illustrated in the literature review, the question of the required EES capacity has been tackled by a substantial amount of studies for various energy scenarios and under different assumptions, applying a broad spectrum of methods. Additionally, several valuable insights can be derived from the literature review.

First, current research indicates that the importance of EES will rise significantly with higher shares of VRE power (>80%) and analyses, therefore, should emphasize such systems.

[2] For a fully renewable European energy system the storage power capacities range from 500GW to 900 GW and 80 to 400 TWh [14].