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Merit order or unit-commitment: How does thermal power plant modeling affect storage demand in energy system models?

F. Cebulla*, T. Fichter

German Aerospace Center (DLR), Institute of Engineering Thermodynamics, Department of Systems Analysis and Technology Assessment, Germany

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A B S T R A C T

Flexibility requirements in prospective energy systems will increase to balance intermittent electricity generation from renewable energies. One option to tackle this problem is electricity storage. Its demand quantification often relies on optimization models for thermal and renewable dispatch and capacity expansion. Within these tools, power plant modeling is typically based on simplified linear programming merit order dispatch (LP) or mixed-integer unit-commitment with economic dispatch (MILP). While the latter is able to capture techno-economic characteristics to a large extent (e.g. ramping or start-up costs) and allows on/off decision of generator units, LP is a simplified method, but superior in computational effort.

We present an assessment of how storage expansion is affected by the method of power plant modeling and apply a cost minimizing optimization model, comparing LP with MILP. Moreover, we evaluate the influence of wind and photovoltaic generation shares and vary the granularity of the power plant mix within MILP.

The results show that LP underestimates storage demand, as it neglects technical restrictions which affect operating costs, leading to an unrealistically flexible thermal power plant dispatch. Contrarily, storage expansion is higher in MILP. The deviation between both approaches however becomes less pronounced if the share of renewable generation increases.

1. Introduction

With growing shares of variable, renewable electricity (VRE) generation in power systems, ensuring sufficient flexibility will play a crucial role as the temporal and spatial mismatch between demand and supply increases. Definitions of flexibility are broad (see Refs. [1,2,8]), however, the term is commonly understood as the ability to decouple electricity demand and supply to balance variations in the net load [52] (which, in turn, is defined as the electricity load minus the generation from VRE). It is likely that the temporal variability of VRE generation will go along with an increase in storage demand to prevent the aforementioned temporal mismatch [3,4,13,22,43]. Moreover, higher shares of VRE generation will require a more flexible operation of thermal power plants to meet steeper net load ramps (see Ref. [52]).

1.1. Literature review

Model-based quantifications of future storage demand result in rather diverse ranges (see for example Kondziella and Bruckner [5] or Droste-Franke et al. [6]), depending on the spatial (I), temporal (II), and technological resolution (III) as well as the underlying modeling approach (e.g. for thermal power plant modeling in energy system models).

(I) Spatial resolution refers to the number of model-regions within an observation area. It affects the distribution of generation capacities, power demand as well as the transmission grid topology within the observation area. Required storage capacities have been derived for different observation areas and spatial resolutions,[1] e.g. by Brown et al. [7] for a small exemplary region (1), for Texas in Denholm and Hand [8] (1), for California in Solomon et al. [9] (12), for Germany in Babrowski et al. [10] (400), for the U.S. Western Electricity Coordinating Council in Mileva et al. [11] (50),

* Corresponding author.
E-mail address: felix.cebulla@dlr.de (F. Cebulla).

[1] The number of model-regions within the observation area is shown in brackets.

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for Europe in Rasmussen et al. [12] (1) and Bussar et al. [13,22], and for a worldwide analysis in Plessmann et al. [14] (1).

(II) The impact of temporal resolution (hourly vs. sub-hourly or the appropriate choice of representative time periods) in optimization models has been analyzed with regard to ramp flexibility and system costs [15], day-ahead utility scheduling through unit-commitment [16,17], and for operation scheduling in energy scenarios with high shares of VRE generation [18,53].

(III) In this study, technological resolution is referred to the way storage is considered in models. The literature ranges from representations of single generic storage [19–21], to storage categories (e.g. short-, mid-, long-term) [22,23], or to more detailed modeling of actual technologies [24,25,43].

As shown, storage demand quantifications underlie various aspects and the understanding of such dependencies and quantifying the amount of storage demand is therefore essential for dimensioning future energy systems. Yet, the influence of assumptions in thermal power plant modeling on storage demand has not been considered so far.

Two main approaches of thermal power plant modeling in optimization models can be found in the literature: Detailed mixed-integer linear programming (MILP) approaches that optimize the unit-commitment and economic dispatch of the thermal power plant fleet and simplified linear programming (LP) where the dispatch of thermal power plants follows solely the merit order. Both approaches determine the optimal generation schedule, minimizing the operating costs of power plant dispatch, subject to device and operating constraints [26,28], sometimes denoted as *operating*, *dynamic* or *unit-commitment constraints*. MILP however, includes integer (or binary) decision variables, allowing on/off consideration of single power plant units or groups, which again enables greater technological detail (e.g. part load efficiencies, ramping behavior, or minimum offline times).

The influence of increasing shares of VRE generation and their effect in different modeling approaches for thermal power plants has been analyzed for example by Brouwer et al. [27] or Abujarad et al. [28]. The former provide a comprehensive overview of how much VRE generation impacts reserve requirements, curtailments of VRE generation, displacement of thermal generator, and resource adequacy. Abujarad et al. [28] review different approaches for generation scheduling, such as heuristics (e.g. priority lists), mathematical methods (e.g. MILP or LP), or meta-heuristics (e.g. genetic algorithms), providing a qualitative assessment of their advantages and short-comings when considering increasing penetration levels of VRE and storage systems. Abujarad et al. [28] underscore the importance of storage as an additional flexibility option, that can enable improved power system reliability or smoothing of load patterns. As both [27] and [28] review the current state of research, they cannot, by definition, provide a quantitative assessment how electricity storage demand is affected by the modeling approach for thermal power plants.

Other studies specifically compare linear programming with unit-commitment. Abrell et al. [29] for example, compare various LP and MILP formulations for power plant start-ups and ramping, assessing its influence with regard to power plant dispatch and marginal prices of electricity generation. The latter is also research focus of Langrene et al. [30], who investigate the role of technological detail (*dynamic constraints*) in a MILP approach on marginal prices. Raichur et al. [31] analyze the influence of technological detail (*operating constraints*) in power plant modeling with regard to electricity generation associated emissions for two real power systems (New York, Texas). The study mainly relies on scenario data from the year 2010; it is therefore difficult to transfer their conclusions to power systems with higher shares of VRE generation. Through the implementation of an integrated utility dispatch and capacity expansion optimization tool, Palmintier [58] shows that the importance of technological detail (*operating constraints*) in power plant modeling increases with greater requirements for flexibility owing to higher shares of VRE generation. Neglecting such technical constraints within capacity expansion optimization can lead to sub-optimal generation portfolios. Poncelt et al. [53] compare the utility dispatch through LP (*merit-order model*) with a MILP model, evaluating whether the influence of the temporal resolution or the influence of the technical detail in power plant modeling is more striking. The analysis is performed for different observation years which, in turn, are characterized by different shares of VRE generation up to 50%. Most recently, Stoll et al. [51] provide a broad comparison of a MILP power plant approach with LP for temporal resolutions of 1 h or 5 min and for differently sized energy systems (Colorado-based test system versus Western Interconnection model). Using PLEXOS [32], their analysis assesses the impact on production cost, VRE curtailment, CO_2 emissions, and generator starts and ramps. Though comprehensive in terms of evaluated modeling assumptions on various metrics, the study only analyzes the dispatch of an exogenous capacity mix with a relatively low share of VRE penetration (up to 30%). Moreover, the two compared energy systems also show several differences in the relative installed capacity of some technologies (e.g. coal fired power plants, gas turbines). By reason of the latter we argue that some effects therefore cannot be solely attributed to the power plant modeling approach.

1.2. Novelty and contribution

As energy system models become more diverse, their complexity grows, imposing new challenges with regard to computational effort and solution accuracy. As a result, the following questions arise: To which extent do simplifications affect the model's outcome? Under consideration of the model calculation times, which degree of detail is sufficient, without generating large errors? To the best knowledge of the authors, the influence of the modeling approach for thermal power plants on storage demand (i.e. storage expansion) and utilization, especially in highly renewable energy scenarios, has not yet been analyzed. We assume that dynamic behaviors and associated costs of thermal power plants—such as start-ups, ramping and minimum down times—might have an effect on storage demand. Furthermore, we think that a certain amount of resolution with regard to technical parameters of power plants and the number of represented units is needed since neglecting technical restrictions and aggregating too heavily might lead to a significant deviation from the optimal solution. We therefore quantify the future storage expansion in exemplary energy systems, emphasizing the influence of the modeling approach for thermal power plants, the degree of aggregation in a MILP unit-commitment clustering approach and the influence of different VRE and photovoltaic (PV) generation shares.

2. Methodology and data

2.1. The REMix model

We use the linear bottom-up optimization model REMix (**R**enewable **E**nergy **Mix**) which minimizes the total system costs of an energy system under perfect foresight. The system costs are comprised of the annuities of the overnight investment costs of capacity expansion as well the operating costs of the utility dispatch. The latter includes fuel, emission certificates as well as operations and maintenance costs (O&M). The model's decision variables are capacity dispatch and expansion, which are optimized for each model interval. A cross-sectoral approach enables the