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On the representation of demand-side management in power system models

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ABSTRACT

DSM (demand-side management) merits increased attention by power system modelers. Numerical models should incorporate DSM constraints in a complete and consistent way. Otherwise, flawed DSM patterns and distorted conclusions on the system benefits of demand-side management are inevitable. Building on a model formulation put forward by Göransson et al. (2014), it is first suggested to include an additional constraint that resolves the problem of undue DSM recovery. Afterwards, an alternative model is introduced that does not impose a specific temporal structure on load shifts and thus increases the real-world applicability of DSM modeling. The formulation presented here, which is both concise and linear, could readily be included in a wide range of numerical models.

1. Introduction

The application of DSM (demand-side management) in power systems recently gains increasing attention in many countries. DSM may help to increase power system efficiency by reducing peak generation capacity requirements and by improving the utilization of both generation and network assets [25]. DSM can further provide a means of accommodating growing power generation from fluctuating renewable sources [1] and may also help to address carbon emissions constraints [3]. Moreover, the demand side is viewed as a potentially relevant source for the provision of reserves. For example, Falsafi et al. [9] identify the potential of demand response in a smart grid setting to accommodate uncertainties in wind power generation forecasting. Koliou et al. [16] argue that the demand-side could be a relevant source for balancing, but current market design hinders its participation in reserve markets.

There is no common definition of demand-side management, and many authors differentiate only vaguely between DSM, demand response, and (temporarily) increased energy efficiency (for example, Ref. [18]). DSM may refer to increased responsiveness to real-time prices; for example, Alcott [2] analyzes the repercussions of elastic demand concerning efficiency and welfare, or Borenstein [4] further elaborates on distributional implications. Likewise, DSM may refer to load shifting between periods, temporary load shedding, or both of the latter like in Ref. [19] or [15]. DSM may be realized in industrial, commercial or domestic applications. In the case of load shifting, which is in the focus in the following, overall power demand does not change over the whole time frame considered; yet some fraction of load may be moved between single hours, for example from periods with high power prices or binding network constraints to hours with lower prices or lower congestion. Practical experiences as well as costs and benefits of DSM programs actually implemented in Europe are reviewed by Torriti et al. [26] and Bradley et al. [5]: the former come to the conclusion that slow diffusion is due to limited policy support; in this vein, the latter call for a broader economic welfare perspective beyond isolated studies when it comes to assessing DSM potentials. In the literature, substantial potentials for DSM applications in different sectors and countries are reported. Stadler and and Bukvić-Schäfer [24] provide an early detailed assessment for Germany. EPRI [8] present an extensive review for the U.S., and Gils [11] carries out a comprehensive comparative study on DSM potentials for 40 European countries.

Many power system models incorporate some form of DSM representation. Yet given the growing importance of DSM, surprisingly little attention is drawn to the intricacies of load shifting. A proper representation of DSM requires not only a maximum power restriction on hourly load shifting, but also consistent time-related constraints which ensure that load changes in one direction are adequately evened out by changes in the opposite direction in

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due time. An incomplete representation of these constraints may result in distorted levels of DSM utilization and, accordingly, flawed assessments on the capabilities and benefits of DSM in power systems.

Previous model analyses largely do not incorporate these restrictions in a coherent way. For example, Schroeder [23] focuses on DSM modeling, but merely includes an hourly power restriction and an overall energy balance equation for the whole time frame considered. Pina et al. [20] analyze the impact of DSM on renewable penetration in an island setting with the TIMES (The Integrated MARKAL-EFOM System) model, but do not document DSM restrictions. It can be inferred from the TIMES documentation [17], published by the International Energy Agency, that the model includes no more than an hourly power restriction and an overall energy balance constraint on DSM. Paulus and Borggrefe [19] differentiate between load shedding and load shifting and also include the provision of reserves by DSM. Load shifting is modeled similar to power storage with an additional energy balance equation for certain time intervals. Load shedding processes are constrained by an overall seasonal energy restriction. It should be noted that Paulus and Borggrefe [19] do not present an analytical representation of their DSM formulation. This can only be found in an older conference paper version. The details of the formulation still remain somewhat opaque, particularly the specifics of the intervals considered, as well as the interplay of restrictions related to storage size and shifting time. It further remains questionable if DSM can be modeled in a setting with single type days in a meaningful way. In a related setting, Richter [22] considers restrictions with regard to both hourly load shifts and overall energy shifted in specific subsets of the whole time frame considered, but is rather vague about how these subsets are implemented. Keane et al. [15] model DSM in a unit commitment framework. They also differentiate between load shifting and shedding (here called “clipping”). Similar to the models proposed by Paulus and Borggrefe [19] and Richter [22], they include an energy balance equation for load shifts, requiring overall shifted energy to be zero over each optimization period (i.e., 36 h), but do not include further restrictions on the shifting duration. Hayes et al. [13] as well as Falsafi et al. [9] merely consider hourly power constraints and do not include any time-related restrictions on load shifting.

Another strand of the literature covers DSM potentials related to particular thermal applications. In these specific cases, the analytical formulation poses different challenges, as electric load shifts can be represented as thermal storage. For example, Hedegaard and Balyk [14] model flexible operation of heat pumps combined with various types of thermal storage. Fehrenbach et al. [10] extend the TIMES model to include thermal DSM, with a focus on the interaction of cogeneration, heat pumps and thermal storage.

Many other papers dealing with demand response, such as Choi and Thomas [6] or Allcott [2], just rely on price-sensitivity of demand and do not include explicit load shifting at all. In contrast, De Jonghe et al. [7] model demand response in a unit commitment framework by not only including hourly own-price elasticities, but also cross-price elasticities to account for load shifts between hours. Yet this approach still does not ensure a zero net balance of load shifts in a given period of time.

The goal of this paper is twofold. On the one hand, an improvement of a DSM model recently published by Göransson et al. [12] is suggested. Second, an alternative model is introduced that allows for an even more realistic DSM representation. The formulation remedies some of the shortcomings in the previously reviewed state-of-the-art literature. In contrast to many other analyses, Göransson et al. [12] use a concise yet comprehensive DSM model. While this deserves merit, the model can be improved by introducing an additional constraint on maximum hourly load shifts, which implies that a DSM unit cannot shift demand up and down at full capacity at the same time. In addition, an alternative formulation is proposed that—in contrast to Göransson's model—does not impose a specific temporal structure on load shifts. The alternative formulation allows for starting DSM processes either with upward or downward shifts, which advances both the flexibility and the realism of DSM representations in energy models. The model could readily be implemented in a wide range of applications. Ref. [27] present a first application in a stylized dispatch and investment model with a focus on power storage. Importantly, the DSM formulation proposed here does not aim to give a detailed account on the operational constraints of specific DSM processes like, for example, Ramanathan and Vittal [21]. Rather, a generic representation of DSM from a power system modeler's perspective is provided.

2. Improving the DSM formulation presented by Göransson et al

Göransson et al. [12] introduce a concise, linear, and largely convincing method of including DSM in a power system model. Yet there are two drawbacks. First, their formulation allows for undue recovery of load shifts which may violate the time-related shifting constraint. Second, load shifts always start with a delay of demand, i.e., with a downward adjustment of load. This section focuses on the first drawback, while section 3 addresses the second one.

Göransson et al. [12] represent DSM as follows. Note that Göransson et al. also include a spatial resolution with a regional index i, which is excluded in the following for the sake of brevity. A table containing all sets, indices, parameters and variables is included in the Appendix.

$$dh_t \leq \sum_{l=0}^{L-1} dd_{t-l} \quad \forall t \tag{1}$$

$$dh_t \leq \sum_{l=1}^{L} ds_{t+l} \quad \forall t \tag{2}$$

$$dh_t = dh_{t-1} + dd_t - ds_t \quad \forall t \tag{3}$$

Assuming a delay time L of the DSM process, Eq. (1) constrains cumulative demand put on hold dh_t at time t by the sum of hourly delayed demand dd_t over previous $L-1$ periods, including the current hour. Likewise, Eq. (2) constrains dh_t by the sum of hourly demand served ds_t over the next L hours. Equation (3) is the balance of cumulative demand on hold, given its previous period level and the net of demand delayed and demand served. dh_t, dd_t and ds_t may all be measured in MWh, or MWh per hour, respectively. In a model with hourly time steps, MWh and MW are essentially equivalent. Furthermore, restrictions on maximum hourly load shifting (4 and 5) can be inferred from what Göransson et al. provide in written form (section 2.2.4, page 865). These are not explicitly stated in the paper.

$$dd_t \leq C^{dd} \quad \forall t \tag{4}$$

$$ds_t \leq C^{ds} \quad \forall t \tag{5}$$

Eqs. (4)–(5) ensure that hourly delayed demand does not exceed an hourly threshold capacity C^{dd}, and hourly demand served may not exceed its threshold capacity C^{ds}. Although not stated by the authors, it can be reasonably inferred that dh_t, dd_t, and ds_t are all positive variables. Otherwise, excessive levels of demand on hold would be possible.