This is the postprint of an article published in Energy vol. 84 (2015), p. 840-845, available online at: http://dx.doi.org/10.1016/j.energy.2015.03.037

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

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Abstract: Demand-side management (DSM) 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.

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1 Introduction

The application of demand-side management (DSM) 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 (Strbac 2008). DSM can further provide a means of accommodating growing power generation from fluctuating renewable sources (Aghaei and Alizadeh 2013) and may also help to address carbon emissions constraints (Bergaentzlé et al. 2014). Moreover, the demand side is viewed as a potentially relevant source for the provision of reserves. For example, Falsafi et al. (2014) identify the potential of demand response in a smart grid setting to accommodate uncertainties in wind power generation forecasting. Koliou et al. (2014) 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, Miara et al. 2014). DSM may refer to increased responsiveness to real-time prices; for example, Alcott (2012) analyzes the repercussions of elastic demand concerning efficiency and welfare, or Borenstein (2005) further elaborates on distributional implications. Likewise, DSM may refer to load shifting between periods, temporary load shedding, or both of the latter like in Paulus and Borggrefe (2011) or Keane et al. (2011). 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. (2010) and Bradley et al. (2013): 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 (2003) provide an early detailed assessment for Germany. EPRI (2009) present an extensive review for the U.S., and Gils (2014) 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 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 (2011) 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. (2012) analyze the impact of DSM on renewable penetration in an island setting with the TIMES model, but do not document DSM restrictions. It can be inferred from the TIMES documentation (Loulou et al. 2005) 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 (2011) 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 (2011) 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, in 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 (2011) 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. (2011) 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 (2011) and Richter (2011), they include an energy balance equation for load shifts, requiring overall shifted energy to be zero over each optimization period (i.e., 36 hours), but do not include further restrictions on the shifting duration. Hayes et al. (2014) as well as Falsafi et al. (2014) 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 (2013) model flexible operation of heat pumps combined with various types of thermal storage. Fehrenbach et al. (2014) 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 (2012) or Allcott (2012) just rely on price-sensitivity of demand and do not include explicit load shifting at all. In contrast, De Jonghe et al. (2014) 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. (2014) 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. 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. 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 (2008). 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. (2014) 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. (2014) 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.

$$dh_t \leq \sum_{l=0}^{L-1} dd_{t-l} \qquad \forall t \qquad (1)$$

$$dh_t \leq \sum_{l=1}^{L} ds_{t+l} \qquad \forall t \qquad (2)$$

$$dh_t = dh_{t-1} + dd_t - ds_t \qquad \forall t \qquad (3)$$

Assuming a delay time L of the DSM process, (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, (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.

$$dd_t \leq C^{dd} \qquad \forall t \qquad (4)$$

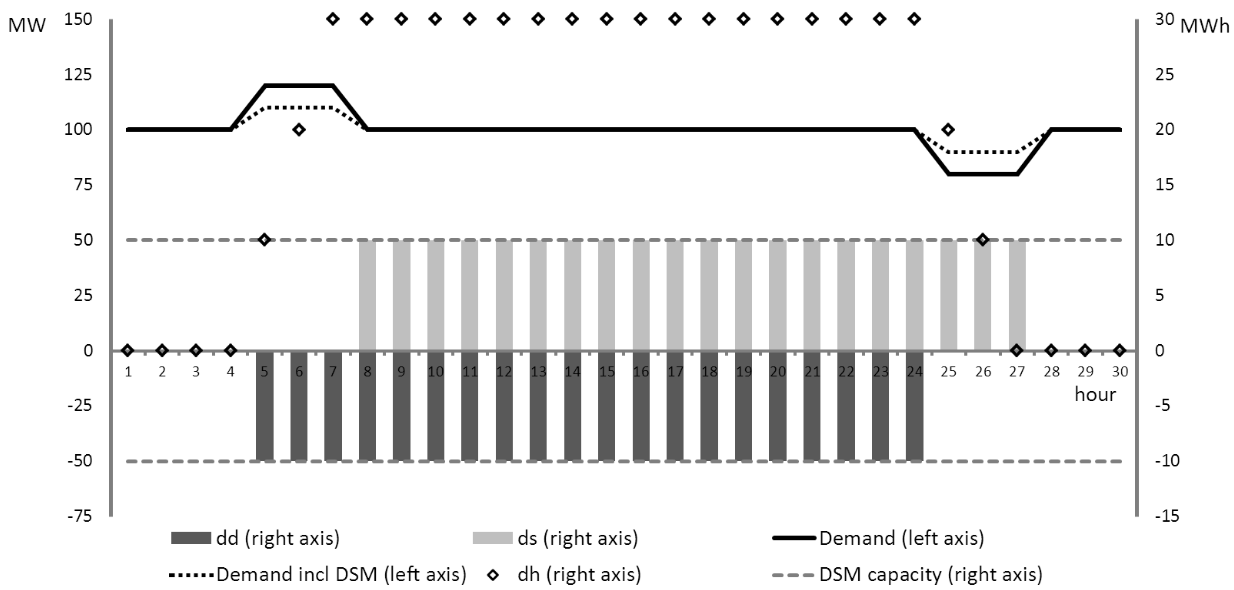
$$ds_t \leq C^{ds} \qquad \forall t \qquad (5)$$

Equations (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.

Combining (1-5) results in largely compelling patterns of DSM utilization. Yet the formulation allows single DSM units to shift demand both up *and* down within the same period at full capacity rating. While this may be considered as a small distortion on first sight, it allows for undue DSM recovery, and may ultimately result in a serious overestimation of longer-term load shifts. This is exemplified by the following numerical example, which is carried out with a stylized dispatch model that minimizes variable costs.

Consider a case with only two generation technologies, one with low marginal costs (100 MW) and one with high costs (20 MW). Demand is flat at 100 MW in most hours, but there is a peak situation with 120 MW and an off-peak situation with 80 MW. A DSM technology is present with a delay time L of 3 hours, hourly load shift capacities $C^{dd} = C^{ds}$ of 10 MWh, and negligible marginal costs. The formulation presented by Göransson et al. leads to the the DSM pattern shown in Figure 1. After the first three hours of delayed demand, demand on hold stays at the maximum possible level of 30 MWh for many hours. This is made possible by repeatedly dispatching both dd_t and ds_t at full capacity in each hour. This can be interpreted as an instance of "undue recovery", as it means that demand served is instantaneously compensated by new demand delayed within the same DSM process. For clarification, let us adopt a "granular" interpretation of the DSM potential, in which the overall capacity consists of a large number of small single units that can either increase their load at full capacity rating *or* decrease it, or are inactive in any given hour. Then, the pattern displayed in Figure 1 implies that the *same* granular units are dispatched upward and downward simultaneously. The formulation thus effectively circumvents the delay time restriction.

Figure 1: A case of undue recovery

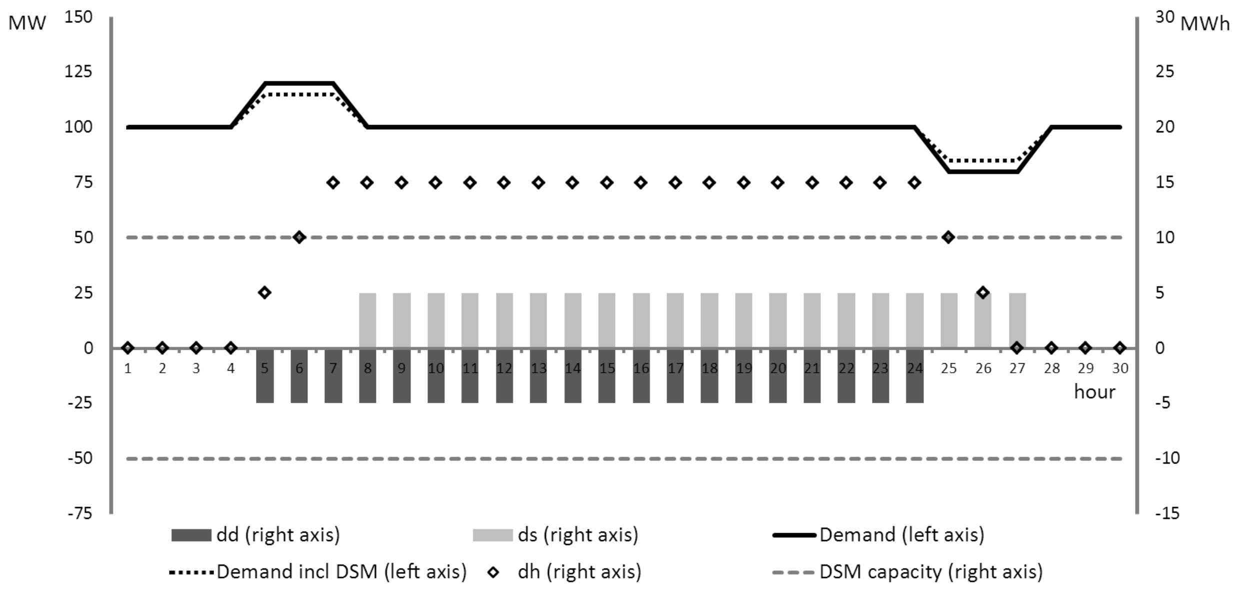


As a remedy of this problem, introducing an additional constraint on maximum hourly load shifting is proposed. An additional equation (6) implies that the same DSM capacity cannot shift demand up and down at full capacity at the same time. Without loss of generality, suppose that $C^{dd} \geq C^{ds}$. Then dd_t has not only to be smaller than C^{dd}, as required by (4), but is further constrained by same-period upshifts of demand ds_t according to (6). At the same time, (6) constrains ds_t further than (5) if dd_t is larger than the difference between C^{dd} and C^{ds}. From a granular DSM perspective, (6) ensures that each granular DSM unit can only be shifted once, either up or down, in each period. Note that for $C^{dd} \geq C^{ds}$, (6) implies equation (4), which therefore does not have to be explicitly included. A similar reasoning applies if $C^{dd} \leq C^{ds}$.

$$dd_t + ds_t \leq \max\{C^{dd}, C^{ds}\} \qquad \forall t \qquad (6)$$

Let us return to the stylized example discussed above, this time including equation (6). Figure 2 shows that the DSM capacity is no longer fully utilized in both directions at the same time. Rather, only half of the capacity (5 MWh) is used in any period, such that each portion of demand delayed can be released by a corresponding level of demand served in due time. Demand on hold accordingly remains at 15 MWh, which is only half of the level that would be possible during shorter load shifts, and also only half of the level of the flawed model. Accordingly, one drawback of the model proposed by Göransson et al.–an overestimation of longer-term load shifts–may be effectively cured by the adjustment proposed here.

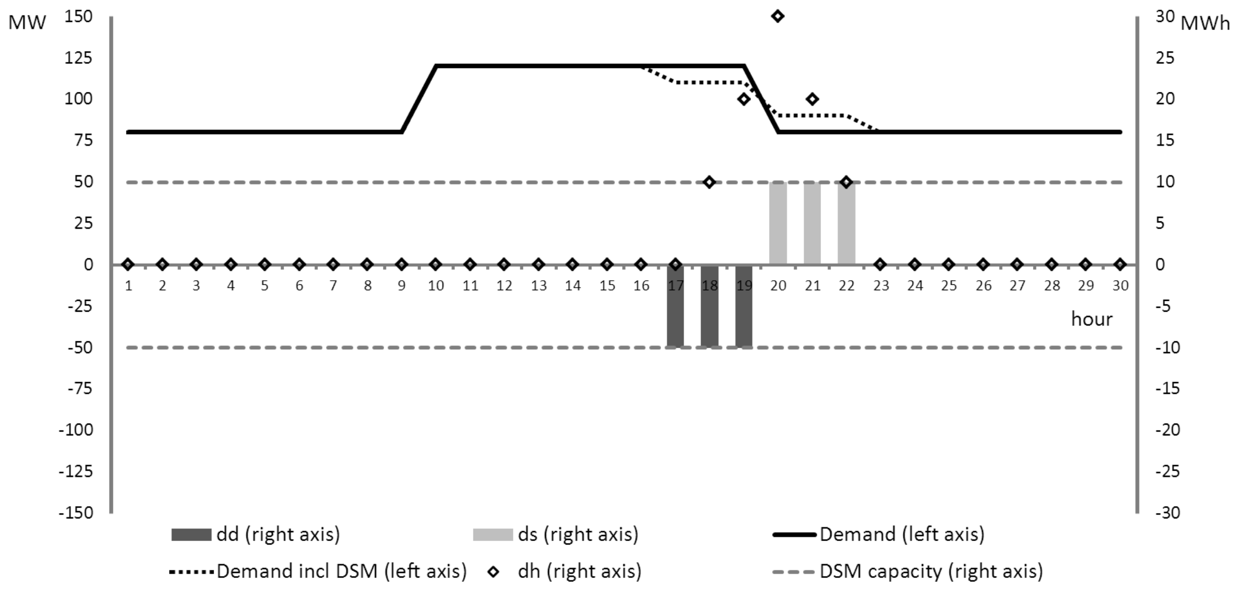
Figure 2: A case without undue recovery



3 Benefits of an alternative DSM formulation

A further shortcoming of specifying a DSM model according to (1-5) is related to the specific temporal structure imposed on load shifts. More precisely, loads first have to be put on hold, i.e., shifted down, and afterwards have to be served. It is, however, not possible to start the DSM process with an upward load shift. This may not adequately represent the real-world capabilities of various DSM processes which are in fact able to increase power consumption when in baseline operational mode, such as, for example, cold storage houses. This problem is illustrated by drawing on another stylized numerical example. Here, the same generation and DSM capacities as above are assumed, but load temporarily increases from 80 to 120 MW. Figure 3 shows that demand is put on hold at the end of the temporary load distortion. In contrast, an inversed load shift does not occur at the beginning of the distortion, as negative load shifts in, say, period 10 cannot be served by positive shifts in previous periods.

Figure 3: Specific temporal structure of load shifts according to Göransson et al. (2014)



While sticking to the DSM model provided by equations (1-6), this problem could in general be solved by including a corresponding second set of parameters, variables, and equations which start with positive demand shifts. Yet this approach would entail an unnecessary increase in the number of variables and equations. It would also require assigning real-world DSM potentials, which may in fact be able to shift loads in both directions in the first place, partly to both stylized DSM representations. In the following, a more parsimonious model is thus introduced which solves these problems.

Positive variables DSM_t^{up} and $DSM_{t,tt}^{do}$ are introduced which represent hourly load shifts in upward or downward direction. These resemble ds_t and dd_t, with the exception that $DSM_{t,tt}^{do}$ has two time-related indices. $DSM_{t,tt}^{do}$ represents downward load shifts effective in hour tt to compensate for upward shifts in hour t. In doing so, downward load shifts are directly tagged to the respective upward shift. Equation (7) ensures that every upward load shift is compensated by according downward shifts in due time, which may take place either before the upward load shift, after it, or both. Equations (8-9) restrict maximum hourly upward and downward shifts to installed capacites C^{up} and C^{do}, just like (4-5) in the above formulation. Note that only one of these two equations is relevant, depending on which restriction is tighter; the other constraint is implicitly rendered by (10). If, for instance, $C^{do} \geq C^{up}$, (9) contains redundant information and can be ignored. Equation (10) is the respective counterpart to (6). Note that this formulation does neither require a variable for the overall energy being shifted at a certain point in time, such as dh_t, nor a respective balance equation corresponding to (3).

$$DSM_t^{up} = \sum_{tt=t-L}^{t+L} DSM_{t,tt}^{do} \qquad \forall t \qquad (7)$$

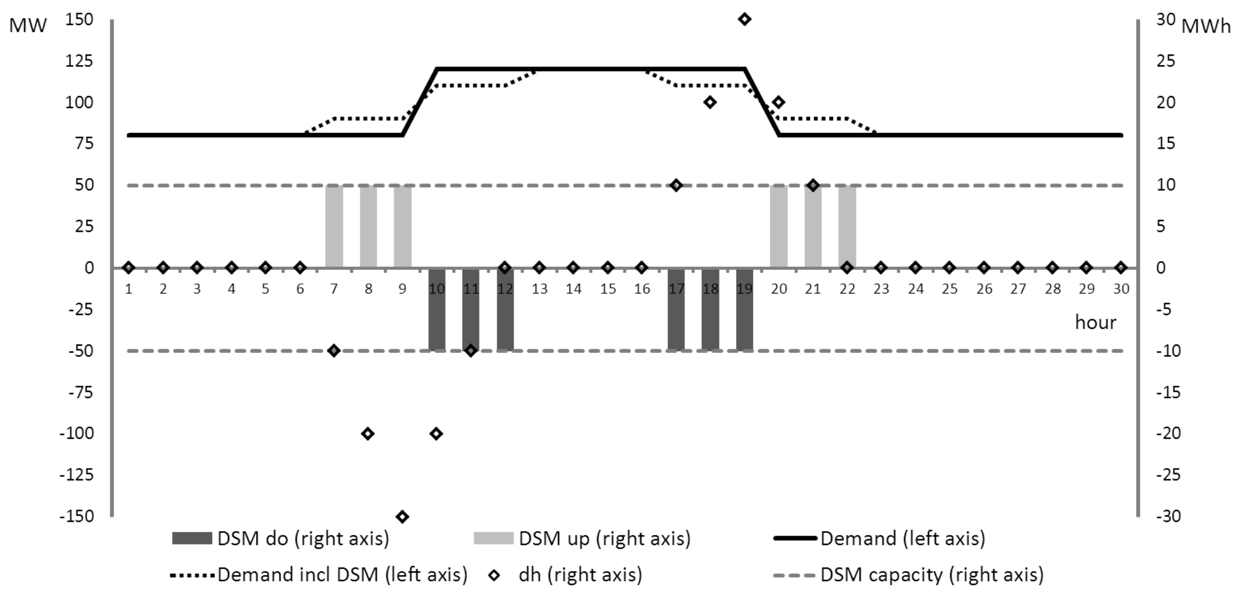
$$DSM_t^{up} \leq C^{up} \qquad \forall t \qquad (8)$$

$$\sum_{t=tt-L}^{tt+L} DSM_{t,tt}^{do} \leq C^{do} \qquad \forall tt \qquad (9)$$

$$DSM_{tt}^{up} + \sum_{t=tt-L}^{tt+L} DSM_{t,tt}^{do} \leq \max\{C^{up}, C^{do}\} \qquad \forall tt \qquad (10)$$

The numerical example presented above is revisited, this time with a DSM representation according to equations (7-10). Figure 4 shows that load shifts now occur at both sides of the load distortion, as demand can be shifted up in periods 7 to 9 with corresponding recovery in periods 10 to 12. The level of shifted energy accordingly doubles in this stylized example. The figure also includes the cumulative level of demand on hold, dh_t, for illustrative purposes, although this variable is not necessary for the functioning of the mechanism. Note that dh_t is interpreted as a free variable here. Demand on hold is negative in the initial periods as demand is shifted up first.

Figure 4: A more realistic temporal structure of load shifts



The real-world applicability of the approach to model DSM presented here may be further improved, for example by including losses related to load shifting. These could be readily incorporated by including an appropriate efficiency factor η on the left-hand side of (7').

$$DSM_t^{up}\eta = \sum_{tt=t-L}^{t+L} DSM_{t,tt}^{do} \qquad \forall t \qquad (7')$$

Introducing a recovery time may constitute another meaningful extension of the model, as many real-world DSM processes are not allowed to cycle continuously. An additional equation (11) enforces a recovery time R by demanding that the cumulative upward load shift over the whole recovery time does not exceed the maximum upward energy of one DSM cycle. This formulation effectively prevents excessive DSM utilization without requiring, for example, integer variables.

$$\sum_{tt=t}^{t+R-1} DSM_{tt}^{up} \leq C^{up} L \qquad \forall t \qquad (11)$$

4 Discussion of limitations

While the novel DSM formulation proposed in section 3 entails several benefits compared to the previous literature, some caveats remain. To begin with, real-world DSM applications may entail specific technical intricacies as well as seasonal restrictions that are not captured by equations (7)-(11). For example, load shifting capabilities of DSM processes related to heat or cold storage facilities can depend on both the season (heating periods) and the outdoor temperature. Likewise, η in equation (7') may not only depend on the outdoor temperature—seasonal or daily patterns could be introduced by adding a temporal index η_t—but also on previous DSM activities, as well as respective production or consumption levels of the underlying processes. Proper modeling of DSM in the context of district heating networks may involve additional restrictions related to interactions of, for example, combined heat and power units, electrical boilers, heat pumps, or solar thermal technologies. In any case, it is not the aim of this article to provide a detailed bottom-up analysis rooted in the characteristics of single processes, but to adopt a top-down perspective, wishing to contribute in the field of stylized power system models. Nevertheless, the proposed formulation should conveniently serve as a basis for more specific elaborations suited to the respective research focus.

In addition, the DSM model presented here may–although linear–involve numerical issues. Especially in case of very long delay times L, the summing terms of equations (7), (9) and (10) may result in increased solution times. At the same time, the differences to the model proposed by Göransson et al. may be smaller in real-world applications compared to the stylized examples presented here.

It should also be noted that the DSM model focuses on the hourly wholesale power market. Many real-world DSM applications have delay times shorter than one hour. Including DSM contributions to short-term ancillary service markets, such as reserve provision, would require changes in the model formulation. What is more, as with many power system models, perfect foresight is assumed. This results in optimal DSM patterns which may not be achievable by myopic real-world agents.

Finally, a significant challenge remains for DSM modelers, namely to derive realistic, reliable and sufficiently aggregated input parameters. In particular, assigning meaningful numbers to C^{do}, C^{up} and L is indispensable in order to derive meaningful conclusions on the system impacts of DSM.

5 Conclusions

In the context of increasing shares of fluctuating renewable power sources, increasing network congestion and growing generation adequacy concerns in many power systems around the world, demand-side management is likely to gain greater importance: flexible loads can be a means to alleviate these issues and may help re-shaping the electricity system. Accordingly, a proper representation of DSM merits increasing attention by power system modelers. With regard to analyses dealing with, for example, fluctuating renewable generation, carbon emissions constraints, network restrictions, or capacity adequacy, it is important to incorporate DSM constraints in a complete and consistent way. Otherwise, the modeled DSM patterns and the related system impacts may be severely flawed, yielding potentially biased policy implications.

Building on a model formulation put forward by Göransson et al. (2014), which serves as the point of reference for this analysis, the introduction of an additional constraint is suggested that resolves the problem of undue DSM recovery. In doing so, overestimations of longer-term load shifts can be avoided. In a stylized quantitative example, this decreases the energy that is shifted by DSM to only around 50 percent of the level of the flawed benchmark model. Further, an alternative DSM model is introduced that is both concise and linear and further increases the real-world applicability of demand-side management modeling by not imposing a specific temporal structure on DSM shifts. In another stylized example, the DSM formulation presented here increases the level of shifted energy by 100 percent compared to Göransson's benchmark formulation. In more applied settings, seeking a more comprehensive representation of actual energy systems, quantitative effects may not be as pronounced as in the stylized settings presented here. Notwithstanding, the same reasoning applies for large-scale energy models. Whether the first or the second effect quantitatively dominates depends on the characteristics of the respective load profile. In any case, preventing DSM units from undue recovery is essential in order to capture one of the very limitations of demand-side processes: a restricted temporal scope for energy shifts. Otherwise, the assessment of DSM's capabilities may be greatly overestimated in many applied energy system models.

Because of its linear and parsimonious formulation, the DSM model proposed here could readily be included in a wide range of numerical models dealing with the power system or the energy system as a whole, as well as in agent-based models. The new approach of modeling DSM presented in this paper may thus not only contribute to the academic strand of DSM-related literature, but also fosters improvements of applied and policy-relevant modeling activities. Notwithstanding, determining reliable parameters of real-world DSM technologies, such as shifting capacities and durations as well as related cost parameters, remains a challenge for DSM modelers.

Acknowledgements

The authors thank Clemens Gerbaulet and Hans Dieter for fruitful discussions, and three anonymous reviewers for their helpful comments. This work was carried out in the project "StoRES – Storage for Renewable Energy Sources", supported by the German Ministry of Economic Affairs and Energy (BMWi), and formerly by the German Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), FKZ 0325314.

Appendix

Table 1: Sets, indices, parameters and variables

Item	Description	Unit
Sets and indices		
$l \in L$	Delay time	Hours
$t, tt \in T$	Time periods	Hours
Parameters of the Göransson et al. model		
C^{dd}	Installed capacity for hourly demand delayed	MWh
C^{ds}	Installed capacity for hourly demand served	MWh
Variables of the Göransson et al. model		
dd_t	Hourly demand delayed	MWh
dh_t	Cumulative hourly demand put on hold	MWh
ds_t	Hourly demand served	MWh
Parameters of the Zerrahn-Schill model		
C^{do}	Installed capacity for hourly downward shifts	MWh
C^{up}	Installed capacity for hourly upward shifts	MWh
η	Efficiency factor	-
R	Recovery time	Hours
Variables of the Zerrahn-Schill model		
$DSM_{t,tt}^{do}$	Hourly upward load shifts for hour t in hour tt	MWh
DSM_t^{up}	Hourly upward load shifts	MWh

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