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A stochastic model for scheduling energy flexibility in buildings

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ABSTRACT

Due to technological developments and political goals, the electricity system is undergoing significant changes, and a more active demand side is needed. In this paper, we propose a new model to support the scheduling process for energy flexibility in buildings. We have selected an integrated energy carrier approach based on the energy hub concept, which captures multiple energy carriers, converters and storages to increase the flexibility potential. Furthermore, we propose a general classification of load units according to their flexibility properties. Finally, we define price structures that include both time-varying prices and peak power fees. We demonstrate the properties of the model in a case study based on a Norwegian university college building. The study shows that the model is able to reduce costs by reducing peak loads and utilizing price differences between periods and energy carriers. We illustrate and discuss the properties of two different approaches to deal with uncertain parameters: Rolling horizon deterministic planning and rolling horizon stochastic planning, the latter includes explicit modeling of the uncertain parameters. Although in our limited case, the stochastic model does not outperform the deterministic model, our findings indicate that several factors influence this conclusion. We recommend an in-depth analysis in each specific case.

1. Introduction

According to the IEA [1], demand side activities should be the first choice in all energy policy decisions that aim to create more reliable and sustainable energy systems. Demand side activities integrated with smart grid technologies [2] represent a wide variety of benefits for different stakeholders in the energy value chain and society as a whole. Examples are: cost reductions for consumers, increased ability to integrate intermittent renewable power generation and electric vehicles, improved energy system reliability and less costly network reinforcements [3–6]. Many studies quantify the potential benefits from demand side activities [7–11] with respect to reductions in cost, peak demand and emissions. In this paper we will present a decision-support model that can be used to control the demand side flexibility in a building.

A price elastic inverse demand curve is a simplified representation of flexible demand [12,13]. This representation is not sufficient to describe demand response, as it lacks an explicit link to the underlying physical energy system and thereby also an interrelation between time periods. It disregards the fact that changing the load in one period may affect demand and the feasible decision space in later periods. Several authors have addressed demand response in short-term multi-period optimization models. Conejo et al. [14] introduce a real-time electricity demand response model for a household or a small business where a minimum daily energy-consumption level must be met, constrained by maximum and minimum hourly load levels. Gatsis and Giannakis [15] split the load of a residence into three components: one “must-run”, one adjustable where the total amount must be met over the scheduling horizon and finally one that can be reduced, but at the dissatisfaction of the end-user. In Refs. [16] and [17] the concept of deferrable loads is introduced with limits for start- and end-time in addition to minimum and maximum load levels and total load. A combination of the above-mentioned concepts is presented by Hong et al. [18], who describe an approach to allocate load among individual appliances. Loads are categorized into non-shiftable, shiftable and controllable. In addition to reducing cost by shifting loads from high-price to low-price hours, their model seeks to reduce the number of peak demand hours. Finally, [19] and [20] take into consideration that some types of loads cannot be interrupted or changed when first started. In real life, different appliances will fit into variations of the above representations.

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Our main contribution is to synthesize these different load classes into an integrated model of the building energy system. While the articles above focus on electricity only, we also capture the possible interaction between the electric and thermal appliances, and this increases the flexibility potential. Del Granado and Wallace [21] is an example of a paper that includes both electric and heat loads. Moreover, they cover self-generation of electricity and heat from several energy carriers. Their target is to quantify the value of electricity storage. However, they do not include flexible loads or interaction between the heating and electric appliances in the building.

Interaction between electricity and heat is covered by many articles focusing on the scheduling of combined heat and power facilities. For instance, Mitra et al. [22] present a detailed model covering all technical constraints for co-generating units, including fuel switching and the possibility to sell surplus electricity to the market. Alipour et al. [23] in addition cover power-only generators, heat storage and demand response in terms of shiftable load. However, the load is represented at an aggregated level for the customers. A general representation of energy systems in buildings is the "Energy hub concept" that was initiated at ETH [24]. An energy hub is an integrated system where inputs are multiple energy carriers, like electricity, natural gas and district heating. Inside the hub we find appliances for energy production, conversion and storage, like solar panels, wind turbines, water heaters and batteries. Finally, outputs from the energy hub are services to meet certain loads such as electricity, heating and cooling. Papers [25] and [26] apply the energy hub concept on smart grid and demand response. These papers focus specifically on residential buildings, while we want to develop a model that can also capture other types of buildings and appliances.

The papers referenced above all base their price model on the concept of time-differentiated prices. Several such price models exist, denoted day-ahead pricing, real-time pricing, time-of-use pricing, critical peak pricing, to mention a few. For an overview of time-differentiated price models, see Refs. [13,27–29]. Other price models differentiate between consumption level, denoted progressive power tariffs, like inclining block rates [16] or subscribed power [30], where the marginal price increases with the quantity consumed. Furthermore, some price models include a peak power fee, sometimes denoted demand charge [31], where the contract contains an element to be paid based on metered maximum hourly or quarterly power out-take over a certain period. For example, all Nordic buildings above a given size have some kind of peak power fee. Due to increased dynamics from fluctuating renewable energy generation, charging of electric vehicles and other types of demand, the focus on price models that penalizes load peaks is expected to increase [32]. We take this into consideration in the scheduling decision process. This issue is disregarded in the papers mentioned above.

An additional challenge with the peak power fee is that we do not know upfront what time the peak load will occur or its magnitude. In general, all load values for the scheduling horizon are uncertain. The referenced papers above disregard this fact. Furthermore, if our problem contains generation from sources like solar or wind, these values will also be uncertain. Finally, the electricity prices may be uncertain at the time we make the scheduling decisions. In this paper we propose a model that considers that some parameters may be uncertain when making the scheduling decisions and to analyze the effect from disregarding this uncertainty.

The contribution from this article is three-fold:

- A general and integrated representation of energy systems in buildings covering multiple energy carriers, generation/conversion technologies, storage appliances and electric and thermal loads classified by their flexibility properties
- A price model that also includes peak power fees
- Explicit representation of uncertain parameters

We illustrate this by including a small case-study and discussing the effect of disregarding uncertainty when modeling demand side flexibility.

The remainder of this paper is organized as follows: in Section 2 we describe how to model the internal energy systems and load flexibility classes. The scheduling problem and the mathematical formulation are described in Section 3. We document and present results from a case study in Section 4.

2. Internal energy system modeling

We base our model for the energy system in a building on a further development of the energy hub concept [24] and introduce the notion of an internal energy system. A building can have one or multiple internal energy systems, each consisting of converter units that convert one energy carrier to another. Examples include: electricity to hot water, gas to electricity and wind to electricity. Each internal energy system has a specific energy carrier that serves loads, e.g. electricity specific loads (PCs, lights, fans), hot water specific loads (space heating and tap water) and cooling specific loads (cooling server rooms). We include conversion technologies as intermittent energy generation from energy sources like the sun and wind. For the sake of generality, we will use the term energy carrier also for input to these. Conversion units generating power based on intermittent energy are not dispatchable. Units that are dispatchable are constrained by ramping limits, minimum up-time when started and minimum down-time when stopped, efficiency parameters and maximum levels.

We model direct connection as a special type of converter, where the energy carrier is imported into an internal energy system without conversion. In general an energy carrier can also be exported from the building through a direct connection. We also allow one or multiple storage units in each of the internal energy systems. Storage units may represent appliances like electric batteries or hot water tanks. Storages are parameterized with volumes, maximum charging and discharging capacities and related efficiency factors. Finally, each internal energy system may have several load units. These may be a physical appliance, a group of physical appliances or a virtual component, like a room.

We base the load unit class definitions on a synthesis of the concepts described in the introduction. We choose to split into two shiftable (in time) load types, two curtailable load types and one inflexible load type.

For **Shiftable load units** the total load must always be met, but it may be moved within a given time interval. Examples of load shifting units are washing and drying processes where the choice of operating period is not critical, as long as the process is ready by a deadline. Charging of batteries for electric vehicles is another example. Within this class we further distinguish between **Shiftable profile load units** (that can be moved, but where the energy profile cannot be changed) and **Shiftable volume load units** (where the total volume must be met over a set of time periods, but the profile can change within limits).

For **Curtailable load units** the load may be reduced without being replaced, at a possible disutility (loss of comfort, loss of income or added costs) for the user. Examples are stopping industrial processes or dimming lights. We distinguish between **Reducible load units** where the load can be reduced down to a certain level without switching off, and **Disconnectable load units**, where the unit is either on or completely off. Rules and parameters regulate