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An optimal day-ahead load scheduling approach based on the flexibility of aggregate demands

X. Ayón [a,*], J.K. Gruber [b], B.P. Hayes [c], J. Usaola [a], M. Prodanović [b]

[a] Department of Electrical Engineering, Universidad Carlos III de Madrid, Avenida de la Universidad 30, 28911 Leganés, Madrid, Spain
[b] Electrical Systems Unit, IMDEA Energy Institute, Avda. Ramón de la Sagra, 3, 28935 Móstoles, Madrid, Spain
[c] Department of Electrical and Electronic Engineering, National University of Ireland Galway, University Road, Galway, Ireland

HIGHLIGHTS

- Flexibility modelling of aggregated demands from different buildings.
- Optimal scheduling based on load constraints linked to the building occupant comfort.
- The potential of load aggregation to increase flexibility and the aggregator profit.
- The method is tested through a case study representing a small geographic area.

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ABSTRACT

The increasing trends of energy demand and renewable integration call for new and advanced approaches to energy management and energy balancing in power networks. Utilities and network system operators require more assistance and flexibility shown from consumers in order to manage their power plants and network resources. Demand response techniques allow customers to participate and contribute to the system balancing and improve power quality. Traditionally, only energy-intensive industrial users and large customers actively participated in demand response programs by intentionally modifying their consumption patterns. In contrast, small consumers were not considered in these programs due to their low individual impact on power networks, grid infrastructure and energy balancing. This paper studies the flexibility of aggregated demands of buildings with different characteristics such as shopping malls, offices, hotels and dwellings. By using the aggregated demand profile and the market price predictions, an aggregator participates directly in the day-ahead market to determine the load scheduling that maximizes its economic benefits. The optimization problem takes into account constraints on the demand imposed by the individual customers related to the building occupant comfort. A case study representing a small geographic area was used to assess the performance of the proposed method. The obtained results emphasize the potential of demand aggregation of different customers in order to increase flexibility and, consequently, aggregator profits in the day-ahead market.

1. Introduction

Demand side flexibility is gaining importance due to the rise in distributed renewable generation, increasing energy demand, and lower predictability in the electricity markets. A high level of demand flexibility is crucial in order to cope with less predictable energy flows, and mitigate against price volatility. It is also required to create a level playing field for emergent market services and to maintain a secure network and a high-quality supply of electricity [1]. The economic benefit of DR is based on its ability to substitute peak power generation capacity and on its competitiveness compared with short to medium-term storage technologies [2]. Moreover, temporal variations in DR application highlight the particular importance of load profiles in the assessment of DR potential.

Traditionally, only large industrial customers had access to Demand Response (DR) schemes, selling their flexibility and participating in the electricity market on an individual basis. In contrast,

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* Corresponding author.
E-mail addresses: xayon@pa.uc3m.es (X. Ayón), jorn.gruber@imdea.org (J.K. Gruber), barry.hayes@nuigalway.ie (B.P. Hayes), jusaola@ing.uc3m.es (J. Usaola), milan.prodanovic@imdea.org (M. Prodanović).

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Nomenclature

Indices

k	time interval to compensate flexible load, h
t	time interval, h

Variables

$P_{k,t}^{pback}$	payback power at k from non-residential flexible energy taken at t, kW
P_t^{flex}	non-residential flexible demand taken at t, kW
P_t^{load}	total demand bid in the market at t, kW
P_t^{nresi}	net flexible non-residential demand from heating and cooling loads at t, kW
P_t^{resi}	shiftable demand from residential electrical devices at t, kW

Constants and data

π_t	electricity market price at t, €/kW h
d	duration of the market time period, h
E_{resi}	daily shiftable residential energy, kW h
N_h	optimization horizon
N_k	maximum time for flexible load payback
N_s	number of periods for residential load shifting
P_t^{comf}	Non-residential demand from the use of the comfort temperature in period t, kW
$\overline{P_t^{agr}}$, $\underline{P_t^{agr}}$	upper and lower limits of the aggregate residential demand at t, kW
$\overline{P_t^{agnr}}$, $\underline{P_t^{agnr}}$	upper and lower limits of the aggregate non-residential demand at t, kW
$\overline{P_t^{tag}}$, $\underline{P_t^{tag}}$	upper and lower limits of the total aggregate demand at t, kW

smaller residential and commercial customers generally have not participated in the markets to date, as their individual demands were considered too low to have an effect at the system level. However, the demand flexibility offered to the electrical system can be greatly increased by aggregating these smaller loads. In this way, an aggregator may act as a market intermediary [3] that encourages smaller customers to increase their DR contributions (or to directly control their flexible loads) and trades their flexibility (as portfolio optimization) in electricity markets.

A good overview on the most common DR methodologies can be found in [4–6]. Demand flexibility in the residential sector can be achieved by using common household appliances (e.g. washing machines, dryers, dishwashers, etc.), electric vehicles or heating systems [7]. Previous research has examined the provision of demand flexibility through scheduling of home appliances [8,9], or through user responses to time-of-use electricity pricing [10,11]. Domestic thermal loads such as electric water heaters have also been applied as flexible demand resources, particularly in colder climates [12,13].

In commercial buildings heating, ventilation and air-conditioning (HVAC) demands represent suitable candidates for DR [14,15]. Building thermal dynamics allows demand flexibility to be introduced by temporarily changing indoor temperature conditions without reducing occupant comfort. A number of papers focus on demand flexibility from HVAC systems in both residential and non-residential buildings. In [16], the electricity consumption during specific hours of a day is either maximized or minimized by adjusting the HVAC load, while maintaining thermal user comfort. In [17], the potential impacts of the individual responsive appliances were studied and the results revealed that almost all the benefits could be achieved by harnessing the flexibility of heating and ventilation systems, although this study was conducted in a Nordic country.

A key consideration in such studies is the impact of adjustments in HVAC control setpoints on user comfort. The international standards ISO 7730:2005 [18] and ASHRAE 55:2013 [19] deal with indoor climate and the range of factors which influence user comfort levels. These standards provide guidelines on acceptable building temperature levels, and also provide information on what temporary excursions from the standard temperature ranges are can be allowed without adversely impacting user comfort.

Many works quantify flexibility from commercial buildings (e.g. offices), but few of them use it in the electricity market. In [20], a methodology for computing the flexibility of buildings and its cost is proposed and a case study on an office building reveals a large variation in both flexibility and cost depending on time, weather, utility rates, building use and comfort requirements. In [21], a coordination framework for leveraging demand flexibility from buildings is proposed, and the demand flexibility of an office building is quantified, finding difficulties in achieving tasks' shift-ability and lack of significant price differentiation between off-peak and peak periods.

In [22], the aggregation of detached houses is carried out to investigate the benefit of heating load flexibility for the aggregator and the consumers in the Nordic day-ahead market. Consumer participation is rewarded with flexibility or comfort based bonuses. However, the results are optimistic because it assumes perfect forecasts for demand, spot prices, and residual supply curves. Also, it shows that flexibility provides more benefit when it is optimized with inflexible demand and that massive building structures receive more bonus, whereas efficient insulation tends to decrease the amount of bonus.

In this work, the aggregator is assumed to be an entity representing the role of a retailer, a flexibility manager and a balance responsible party or market agent. A more detailed explanation of these functions can be found in [23–25]. This entity agrees with its customers to directly control their electricity consumption of their flexible loads (HVAC loads from commercial customers and smart appliances from residential customers) [26,27]. These flexible demands can be shifted along a given time period depending on the nature of the process [28], but the amount of daily energy to be consumed is known and previously agreed between the aggregator and its customers. This type of agreement is not considered in the work proposed here. At last, it is assumed the non-residential customer thermal comfort is ensured by the control of the indoor temperature that depends on the building thermal inertia, time, weekday, season and occupancy pattern.

To measure the demand flexibility of the aggregation of different buildings, we use the demand flexibility ratio that is the difference between the upper and lower limits of the aggregated demand regarding the total flexible demand at a certain time. The demand flexibility ratio and the aggregator daily average profit from its participation in the day-ahead market will be analyzed by using a case study based on the aggregation of different building types. The optimal demand will be disaggregated to simulate the impact of the optimal load scheduling on individual buildings. It will be shown the indoor temperatures remain within the desired range even when there is no linear relation between the energy demand and the indoor temperature. The results will demonstrate that an adequate aggregation of different building types allows the aggregator to achieve significant economic profits in the day-ahead market.