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# Optimal demand charge reduction for commercial buildings through a combination of efficiency and flexibility measures

Yuna Zhang[a,*], Godfried Augenbroe[b]

[a] Baumann Consulting, Inc., Washington D.C., United States
[b] Georgia Institute of Technology, Atlanta, GA, United States

## HIGHLIGHTS

- A new decision making framework to reduce annual electricity bills of commercial buildings.
- Optimal selection of demand charge reduction measures for three different types of commercial buildings.
- Evaluation of energy flexibility measures, energy efficiency measure and renewable energy for demand charge reduction.

## ARTICLE INFO

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Energy cost saving
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## ABSTRACT

A substantial part of electricity bills in commercial buildings can consist of demand charges. Lowering the peak power and/or reducing the hours that a power threshold is exceeded can drastically reduce demand charges. The ability to do so by dynamic, operational adjustments reflects the "energy flexibility" of the building. This paper targets the optimal combination of design and operational measures in a retrofit or new design project that delivers the most effective way of reducing demand charges by increasing energy flexibility and efficiency of commercial buildings. This goal is achieved through an analysis of all feasible energy consumption and peak reduction measures in different building types and in different use contexts. A search algorithm that compares all possible interventions will deliver the optimum. This leads to a stochastic optimization approach with recognition of the effects of all possible sources of uncertainty. This paper evaluates the measures that are commonly adopted to decrease energy consumption and increase energy flexibility, including (1) upgrading building components and installing energy efficient equipment; (2) applying dynamic building load control strategies; (3) installing a rooftop photovoltaic panel array. Operational interventions include the manipulation of thermostat settings and the voltage reduction of lighting and appliances (in some cases including HVAC components) in the building, which may cause some level of thermal and visual discomfort during certain periods. In order to support retrofit and design improvement decisions, an approach is developed to find the optimal mix of measures that maximize the net present value of the investment in all measures over twenty years for the owner. This paper analyzes the optimal solutions for three commercial building types, office, hospital, and retail. The paper suggests a modeling and optimization framework that can be used by building designers and operators to make optimal investment decisions to reduce demand charges. The paper shows a novel support of the decision making by building operators when faced with the opportunity to reduce demand charges.

## 1. Introduction

Most owners of commercial buildings may not realize that demand charges can easily make up 70% of their buildings' monthly utility bills [1]. Demand charges represent the penalty levied by the utility provider on an electricity customer, particularly for big electricity consumers in the power grid. Demand charges are typically a direct result of the shape of the power duration curve of the building, in particular, the hours that a certain power level is exceeded in a given billing period. According to the recently published data from the survey of EIA in 2016 [2], the growth of floorspace inside commercial buildings has been twice as fast as the growth of commercial buildings since 2003, which implies a trend of increased occupancy, number of equipment, and area of conditioned space in the average commercial building. As a direct result, the electricity usage of new commercial buildings such as office, hospital, retail buildings may keep increasing with size, despite the

* Corresponding author at: 1424 K St NW #500, Washington D.C., 20005, United States.
*E-mail address:* Y.Zhang@baumann-us.com (Y. Zhang).

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**Nomenclature**

| | |
|---|---|
| $a$ | coefficient of productivity loss |
| $b$ | coefficient of productivity loss |
| $P$ | productivity loss |
| $T$ | temperature (°C) |
| $n$ | number of observations |
| $K$ | Kernel function |
| $x$ | independent variable matrix |
| $\hat{f}$ | estimator of the response |
| $\Delta T$ | temperature change |
| $\theta$ | the $p$-dimensional vector of parameters |
| $\xi$ | the $p$-dimensional vector of non-adjustable parameters |
| argmax | the solution that maximizes the value of the function |
| $\Theta$ | solution space |
| $E$ | expectation |
| $NPV()$ | NPV calculation function |
| $V_{limit}$ | value constraints |
| $Prob_{limit}$ | probability constraints |

*Superscript/subscripts*

| | |
|---|---|
| $H$ | bandwidth matrix |
| $i$ | indices of observation pairs |
| $*$ | solution set |

*Acronyms*

| | |
|---|---|
| ASHRAE | American Society of Heating, Refrigeration, and Air–Conditioning Engineers |
| COP | coefficient of performance |
| CPP | critical peak pricing |
| DER | distributed energy resource |
| DOE | Department of Energy |
| DR | demand response |
| EEM | energy efficiency measure |
| EFM | energy flexibility measure |
| EIA | Energy Information Administration |
| EPC | energy performance calculator |
| HVAC | heating, ventilation and air conditioning |
| kW | kilowatt |
| kWh | kilowatt hour |
| max | maximum |
| min | minimum |
| NPV | net present value |
| PV | photovoltaic |
| SCE | Southern California Edison |
| SHGC | solar heat gain coefficient |
| TOU | time-of-use |

improved energy efficiency of newer buildings. With increased peak power, a growing number of commercial building owners may face the problem of paying far more than what they actually consume due to their increased share in the cost of the grid infrastructure. This share is billed in the form of demand charges. Therefore, it becomes significant for commercial building owners and operators to realize the role of these demand charges in their monthly bills and to take effective measures to reduce them. It should be noted that demand charges are a "distortion" in the economics of electricity consumption. They effectively charge an electricity customer for a larger share of the infrastructure based on their peak power usage. As such it can be expected that over time the distortion will disappear when new business models of the utility companies take over. There is no clear indication that the latter is going to happen in the near future.

In the process of establishing the power distribution network, most capital funding is allocated for the construction of hardware infrastructure, such as transformers, relays, and cables, etc. The larger size of transformers and cables induce greater cost. Therefore, the most expensive part in constructing the power grid is not to meet the estimated average total electricity demand but to deliver the needed local capacity and to guarantee the stability of the power grid. In order to maintain the stability, the capacity of the grid needs to meet peak demand even during the most severe usage periods. Failing to meet this capacity requirement may lead to blackouts and even threaten public safety on a large scale, such as the Chicago power blackout in 1995, the California power outage in 2000, and the blackout that occurred in 2013 in the New York City [3]. Power outages occur usually as a result of local weather events, possibly as the result of high winds, downed trees, and power lines. Large-scale power grid failures, such as brownouts and incidental black-outs, typically occur during an extended heat wave when the peak electricity usage exceeds the capacity of the power grid. The occurrence of temporary power spikes necessitates inefficient investments in the construction of the power grid. They are necessitated by the fact that the distribution network needs to be capable of handling the peak demand throughout a year. For example, if a factory only has one day of high-intensity operation during the whole year, the power grid still needs to offer the appropriate network capacity to meet this level of demand. Although it is hard to pinpoint the extra investment necessitated by a single large peak consumer, the general attitude of the utility companies is to charge these consumers a collective penalty, which should be a fair reflection of the investment that utilities spend to serve the peak load during a given time window and in a certain sub-net of the grid. Therefore, large commercial buildings are charged an additional amount of demand charges beside the basic cost according to their electricity consumption. The utility decides the threshold and the time window of the peak occurrence based on internal (and for the public mostly hidden) cost-revenue calculations. In one type of policy, the usage of electricity during the identified time window in a given year determines the electricity price a building will pay in the following twelve billing months. Since the power grid's transmission and distribution systems are sized for the maximum load of the customers using the supply system, the cost driver for providing the transmission and distribution service is the peak demand. In order to better align the cost of operating those systems with a customer's use of the system, a demand charge is applied to the maximum demand that is recorded on the customer's meter during a specified time period (typically a month) and sometimes during a specific time window of every day.

Demand is defined as "the rate at which electric energy is used at any instant or averaged over any designated period of time and is measured in kilowatt (kW)," in EIA's glossary of energy terms [4]. In reality, the demand kW is measured by the electric meter as the highest average demand in any 15-min period during the month. This is counted as the amount of electric load required by the customer's electric equipment operating at any given time. Transmission and distribution utilities must have sufficient electric capacities such as properly sized transformers, service wires and conductors to meet customers' kW demand. The demand in kW is recorded for billing the demand charge each month and then reset on the bill cycle date. A customer's 10 kW demand operating for one hour equals 10 kW hours (kWh), which is the cumulative kWh reading on the meter. In order to level out the recovery of the fixed cost of the transmission and distribution system necessary to serve the customer's maximum demand, the grid operator will monitor the peak demand and apply a demand related billing amount to big electricity consumers whose peak demand exceeds the determined threshold in the grid.