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A novel energy service model and optimal scheduling algorithm for residential distributed energy resources

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ABSTRACT

We propose a novel decision-support tool that aims to optimize the provision of residential energy services from the perspective of the end-user. The tool is composed of a novel energy service model and a novel distributed energy resources scheduling algorithm. The proposed model takes into account the time-varying demand and benefit that end-users derive from different services, and assigns the benefit to the energy that realizes the service. The scheduling algorithm determines how distributed energy resources available to the end-users and under their control should be operated so that the net benefit of energy services is maximized based on the energy service models, and their technical characteristics and capabilities. The scheduling is a challenging optimization problem; hence, a heuristic simulation-based approach based around cooperative particle swarm optimization is used. The paper presents a case study where this decision-support tool is used to optimize the provision of desired energy services in a 'smart' home that includes a number of controllable loads, energy storage and photovoltaic generation.

1. Introduction

A prominent manifestation of economic progress in our modern society is the consumption of energy services. Therefore, the welfare of citizens relies heavily on the reliability of commercial energy supply most especially that of electricity. The current electricity industry is designed and has evolved with the primary purpose of generating and making available the required electricity demand regardless of magnitude and location within the transmission and distribution networks. There is also a huge imbalance in investment decisions: on a per kWh basis, the demand-side makes a larger investment with respect to the consumption of energy services than that of the supply side with respect to generating and making electricity available. However, decision-making is centralized and focused on the optimal operation of the generation and transmission sectors, while the consumers are treated as passive participants and price-takers in the market.

The projected increase in demand for energy services and the concern on depleting fossil fuels and climate change introduce modern challenges to the aging electricity infrastructure. It has been widely perceived that there is a need to transform the current electricity industry into a form that would support sustainable energy service consumption. This may be achieved by formally incorporating the provision of energy services to the operation of the industry; that is, the industry should focus on the provision of energy services instead of just making electricity available at all power receptacles.

A path toward this transformation is the utilization of technical instruments like energy efficient practices and equipment, distributed energy resources (DER) such as embedded generators, storage, and controllable load, and by employing distributed decision-making to manage these resources. The transformation may also be achieved by using economic instruments like dynamic electricity tariffs in the form of real-time pricing, peak demand charges, and feed-in tariff, among others [1]. Several electric utilities have already adopted some of these instruments and have demonstrated promising potential.

Numerous financial and technical benefits can be derived from energy efficiency and DER [2–4]. However, knowing the nature of these benefits may not be enough to persuade consumers, retailers and distribution utilities to actively invest in these practices and technologies. The uptake may be stimulated by providing the consumers with decision-making instruments that could enable them to evaluate the potential impacts of installing these resources, and to make operational decisions once these resources are acquired. Several utilities have already demonstrated that demand response through price-based signals can reduce peak electricity demand.

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However, potentially more peak and cumulative demand reduction can be achieved if the consumers are enabled by decentralized and intelligent decision-making tools.

This paper aims to provide an avenue for consumers to participate in the decision-making process with respect to the optimal operation of the electricity industry. In particular, this paper presents a decentralized energy service decision-support tool that

a. consumers can use to simulate and to assess the potential impacts of adopting energy efficient measures and installing DER,
b. consumers can use to make intelligent decisions with respect to the operation of their controllable DER, and
c. incorporates user preferences in terms of perceived benefits and flexibility with respect to their required services.

We have described the decision-support tool and demonstrated its capabilities using a simple example in an earlier paper [5]. In this paper, we investigate its application to a more complex scheduling problem involving a 'smart' home with more DER and being subject to a broader range of electricity tariff structures.

2. The energy services decision-support tool

This paper presents a decision-support tool that consumers can use to optimize the acquisition of their energy services. The tool consists of an approach for modeling energy services and a DER scheduling algorithm. The energy service models are based upon end-users putting value to the benefit derived from their various energy services requirements. Using these models, the scheduling algorithm (or scheduler) maximizes the net benefit derived from these energy services by proposing a strategy for how to operate the available DER.

2.1. Modeling energy services

Energy services are energy forms, commodities and processes from where end-users ultimately appreciate and derive the value of commercial energy carriers like electricity and gas [6]. Some of the common forms of energy services are space conditioning, water heating, illumination, information processing and communications. The demand for an energy service depends on several factors, most notable are occupancy patterns, end-user preferences and habits, time of day and day of week, and season of the year.

End-users put value to the energy services they use, not to the amount of electricity the equipment that deliver these services consume [7]. The value of an energy service originates from the comfort, convenience, products and profits it brings to the end-user. The end-user either perceives or may directly quantify the benefit of an energy service, or a combination of both. As example, a residential end-user may be willing to pay several dollars a day for his house to be heated on cold nights (perceived value). On the other hand, a semiconductor processing plant owner could compute the thousands of dollars he would lose for each hour that his plant is not running (directly quantified). The value of an energy service to an end-user may depend on the time of the day, weather, and social externalities, among others. To illustrate, the benefit of having a bright work area in an office building is certainly higher during the day than during the night.

Energy services may be modeled by specifying the temporal variation of their demand and perceived benefits. The demand may be described by specifying the required temporal changes to a physical variable directly related to the service, like the hourly temperature in a room or the volume of hourly consumption of hot water. It may also be described by the actual energy consumption of the end-use equipment used to deliver the service.

Benefit may be assigned to an energy service in several different ways. The simplest approach is to assign a fixed value to a service regardless of the amount of consumed electric energy or duration of delivery. As an example, an end-user may perceive that the benefit of having a warm shower during the winter season is $10/day. To incorporate the total amount of energy that realizes a service and its duration in the benefit model, we can assign a monetary value to each unit of energy that realizes the service for each hour that it is utilized. As an example, the benefit of hot water service may be quantified by putting a dollar value to each unit of thermal energy contained by the hot water consumed every hour. The thermal energy content of water may be thought of as the "energy equivalent" of the hot water service.

This approach allows a distinction to be made between the energy that realizes the energy service and the actual electricity consumption of the end-use equipment. We are putting value on the energy service itself and differentiating that value from the cost of electricity consumption. The temporal variation of benefit of a service can therefore be represented by the hourly variation of the value of each unit of "energy equivalent."

It is generally difficult to determine the monetary equivalent of an energy service. Some users can readily identify the benefit of a particular service while others cannot. Nevertheless, the proposed model enables the users to adjust the benefits until they are satisfied with the efficiency of service provision.

Fig. 1 shows how the modeling approach can be used to model the demand for and benefit of hot water service in a house. The demand may be represented by the hourly volume of hot water consumption or by the required hourly amount of "energy equivalent." The benefit is represented by the hourly variation of the monetary value assigned to each unit of "energy equivalent." The figure depicts that the residents put different levels of benefit to the hot water service and the value is not necessarily correlated with the amount of hot water consumption.

The demand for shiftable and interruptible services like washing and pool pumping may not be represented as a change of some variable or "energy equivalent." In place of an hourly variation of demand, a narrative description may be given. For example, the demand for the dish washing service may be described as "the dish washing service requires 1 kW of electricity over a period of 1 h, and the washer may run anytime between 8 PM and 11 PM." Benefit is modeled by assigning a positive benefit value to the "energy equivalent" on those hours when the service should be delivered, and a negative value (or cost) on those hours when the service should not provided.

The relationship of the "energy equivalent" of a service, $U_{ES}(t)$, to the actual electric energy consumption, $P_e(t)$, is determined for each service to be modeled. The relationship heavily depends on the physical processes occurring within the end-use equipment and the service itself. The determination is straightforward if the equipment instantly converts electricity to the end-use energy or

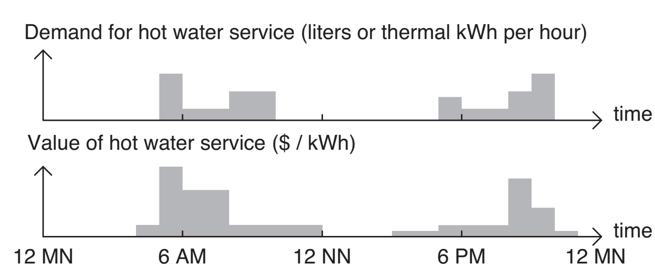

Fig. 1. An example of how to use the proposed energy service model to describe the demand for and benefit of hot water service in a house.