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Differentiated Energy Services: Multiple Arrival Times and Multiple Deadlines ⋆

Yanfang Mo [*,**] **Wei Chen** [**] **Li Qiu** [*]

[*] *The Hong Kong University of Science and Technology, Kowloon, Hong Kong (e-mail: ymoaa@connect.ust.hk, eeqiu@ust.hk)*
[**] *University of California at Berkeley, Berkeley, CA 94720, USA (e-mail: wchenust@gmail.com)*

Abstract: The supply/demand balance problem plays a pivotal role in the electricity grid, especially when an increasing proportion of power is generated from renewable resources. Enormous supply/demand models have been put forward in order to handle the balance problem in the smart grid, in the presence of high renewable penetration. This has brought an awareness that the flexibilities in the demand can be exploited to alleviate the burden on the supply. In view of this, we apply and study differentiated energy services, which distinguish demands in terms of their available flexibilities. As a starting point, we concentrate on two problems regarding adequacy. On the one hand, we find both numerical and analytical ways to check the adequacy of a supply. On the other hand, we characterize the adequacy gap in the case of an inadequate supply.

Keywords: Smart grids, supply/demand balance, demand response, $(0,1)$-matrix completion, flow network theory

1. INTRODUCTION

For the purpose of sustainable development (Azapagic and Perdan, 2011), more and more renewable resources, such as solar and wind energy, are being exploited to generate electricity. In spite of the alluring advantages of renewables, the inherent uncertainty and intermittency of renewable energy have inevitably posed great challenges to the establishment and maintenance of a sustainable power system. Particularly, this raises worldwide concerns about how to balance the supply and demand in consideration of the deeper penetration of renewables.

A natural approach is to compensate for the fluctuation in the demand by way of reserve generations. Such *supply side* approach has already been put into practice and also proven successful when the majority of power is still generated from traditional resources such as fossil fuels. However, due to the increasing amount of renewable generations, the supply side approach requires considerable quantities of reserves at the expense of both economical and environmental benefits. See, for instance, Helman et al. (2010), Ortega-Vazquez and Kirschen (2010), and Halamay et al. (2011).

With the growing development of the smart grid, the *demand side* approach, widely known as *demand response*, has raised the growing interest of engineers and scientists. It focuses on exploiting the flexibilities in demand to compensate for the undesirable attributes of renewable energy. Researchers are also more aware of the various flexibilities residing in different loads. Following are some typical examples of flexible loads: electrical vehicles, thermostatically controlled loads, residential pool pumps, commercial HVAC (heating, ventilation and air conditioning) systems and other smart appliances. Successful attempts at such loads have been made in Tan and Varaiya (1993), Clement-Nyns et al. (2010), Galus et al. (2010), Meyn et al. (2013), and Hao and Chen (2014), to name just a few. Loads may be deferable, intermittent or modulated depending on their respective natures and such flexibilities can make room for the volatilities of renewables. The GRIP (grids with intelligent periphery), proposed in Bakken et al. (2011), also provides a nice framework to carry out innovations regarding the demand response.

Along the line of demand approach, a number of creative supply/demand models have been proposed. Among them, we are particularly interested in the differentiated energy services, as described by Nayyar et al. (2016) and Chen et al. (2015). Generally speaking, the electricity is no longer treated as a homogenous product with a single unit price, but a set of energy services differentiated by levels of flexibility. As the name indicates, the duration-differentiated energy services in Nayyar et al. (2016) are differentiated by their durations only, while the duration-deadline jointly differentiated energy services in Chen et al. (2015) are jointly differentiated by both the duration requirements and deadlines. In both cases, the loads are assumed to be indifferent to the actual delivery time. Moreover, the power delivery rate is assumed to be a certain constant, rather than an interval of continuous real numbers. This is reasonable especially for some smart loads in smart grid, as shown in Yilmaz and Krein (2013). In such services, a day-ahead market is considered. Based

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on estimated supply and accumulated requirements from loads, the nominal provider schedules power delivery and makes deals with other electricity providers in advance.

Two significant issues have been discussed in both aforementioned works on differentiated energy services. One is the adequacy of supply, and the other is the market implementation. In this paper, we focus on the first issue with a further complicated yet more practical setup: the differentiated energy services with multiple arrival times and multiple deadlines. To start with, we establish the necessary and sufficient conditions under which the supply can satisfy the requirements from a set of loads. Finding such an adequacy condition is equivalent to characterizing the existence of a constrained $(0, 1)$-matrix, which is closely connected with a flow network. We show that the polynomial algorithms for maximal flow can be applied to check the adequacy of the supply and simultaneously generate a feasible allocation when the supply is indeed adequate. In addition, a closed-form condition is given in terms of the nonnegativity of a structure tensor. The analytical condition physically implies that the demand tails should always be dominated by the supply tails. This coincides with the common intuition that the demand should be dominated by adequate supply. In case the supply is inadequate, the adequacy gap will be derived from the difference between the total demand and the value of the maximal flow, or equivalently, the absolute value of the minimum element of the structure tensor. A simple algorithm is presented to find a minimal feasible purchase which makes the total supply adequate.

The rest of the paper is organized as follows. In Section 2, we introduce the supply/demand model studied in this paper and formulate the main problems. In Section 3, the main results are presented, with reference to both the adequacy condition and the adequacy gap. Finally, we conclude the paper and present some promising future extensions in Section 4. The notation used in this paper is mostly standard and will be made clear as we proceed. We use $\mathbb{O}$ to denote a matrix with all elements equal to zero, and $\mathbb{E}$ to denote a matrix with all elements equal to one. Given a number a, we denote $a^+ = \max\{a, 0\}$. For an assertion $\mathcal{A}$, $\mathbb{1}(\mathcal{A})$ is assigned the value 1 if $\mathcal{A}$ is true, and 0 otherwise.

2. PROBLEM FORMULATION

In this paper, we lay emphasis on two issues in differentiated energy services with multiple arrival times and deadlines. One is under what condition the energy supply is qualified to serve all the demands (adequacy condition), while the other is the minimum amount of additional purchase in case of an insufficient supply (adequacy gap). To resolve these issues, we firstly demonstrate the supply/demand model we rely on in this paper.

2.1 Differentiated Energy Services: Multiple Arrival Times and Multiple Deadlines

The operational horizon is divided into T consecutive time slots. At each time slot t, the available supply is denoted by h_t. In addition to the two special time instances 0 and

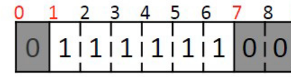

Fig. 1. An illustration of a service time specified by both the arrival time and the deadline

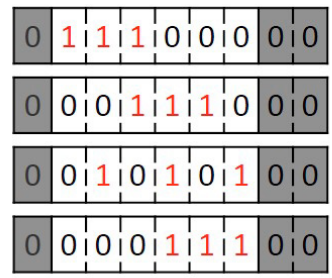

Fig. 2. Four qualified delivery results

T at both ends, the service provider points out $(\tau + 1)$ specified time instances, namely,

$$(0 = T_0) < T_1 < T_2 < \cdots < T_{\tau-1} < (T = T_\tau).$$

The demand arises from N consumers/loads, indexed by $i = 1, 2, \ldots, N$. The delivery rate from the supply to a load is constant, i.e., c units per time slot. Without loss of generality, let $c = 1$, which simply means the supply can allocate one or zero unit of power to a load at a time slot. Load i is characterized by a duration r_i and a service period specified by (a_i, d_i). This means that load i requires to be delivered r_i units within the time interval from the start of the $(T_{a_i} + 1)$th time slot to the end of the T_{d_i}th time slot. In other words, the supply has to deliver 1 unit of power to load i for r_i time slots within the respective service time. As shown in Fig. 1, over the $T = 9$ time slots in total, the specified time instances are indexed by 0, 1, 7, and 9, while the load cannot be served at the first, eighth or ninth time slots. Note that the load is indifferent to the actual delivery time provided the duration and service time requirements are satisfied.

We give four qualified power delivery results in Fig. 2, for a load i with $r_i = 3$ and the service time specified by Fig. 1. They are four different forms of the same service, among many other possible forms. Now, we can readily figure out why such services are called the differentiated energy services with multiple arrival times and deadlines, as each service is differentiated by the duration, the arrival time, and the deadline. When all the service times are presented by $(0, d_i)$, the case reduces to the duration-deadline jointly differentiated energy services in Chen et al. (2015). If further, all the loads have the same service time, specified by $(0, \tau)$, then the case reduces to the duration-differentiated energy services in Nayyar et al. (2016).

Remark 1. In the context, we assume that a series of time instances are specified by the nominal service provider in advance and consumers can only choose the service time determined by two of them. This is an operator-friendly scheme. Nevertheless, there is an alternative scheme, which seems more attractive to consumers. In this scheme, every consumer can choose a service time specified by any two time slots among the total T time slots. Then, those chosen as the arrival time or deadline are regarded as the specified time instances mentioned above. We claim that