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A scalable and robust approach to demand side management for smart grids with uncertain renewable power generation and bi-directional energy trading

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ABSTRACT

This paper investigates the energy cost minimization problem for smart grids with distributed renewable energy resources. Unlike earlier research studies that either have assumed all the appliance jobs are interruptible or power-shiftable and that the electricity prices as well as the availability of renewable resources are known, this paper focuses on more challenging scenarios in which appliance jobs are non-interruptible and non-power-shiftable, the electricity prices vary with the overall load of the entire grid in real-time, and the renewable power generation is uncertain. Because home solar systems are widely available, this paper assumes that each consumer in the grid can have a photovoltaic system and a side battery. Collected solar energy can be used to meet a consumer's individual power demand, stored in the battery for future use, or sold back to the grid during peak hours to lower electricity bills and the overall load on the entire grid. To solve this problem, a two-stage robust optimization model is proposed, and the C&CG method is utilized to solve it. However, to solve the problem more efficiently when the number of consumers and appliance jobs is large, a second approach called SRDSM is proposed. The SRDSM algorithm consists of two parts: The first part is a job scheduling algorithm that minimizes electricity costs for all consumers. The second part is a power management algorithm based on dynamic programming that reduces the energy cost further by utilizing renewable energy. The numerical results show that, although the C&CG method produces optimal solutions, the SRDSM algorithm is much more scalable and efficient when the problem size is large.

1. Introduction

With climate change and a rising awareness of environmental protection, legacy power grids face many challenges. For example, the general public is becoming increasingly opposed to the use of fossil fuels because they are one of the biggest sources of air and water pollution. Legislations and/or regulations are also becoming increasingly restrictive regarding the construction and operation of new grid facilities. This not only increases the cost of power generation but may also lower grid adequacy because utility companies are forced to set aside more of their budget for cleaning the pollutants released from burning fossil fuels and thus have less money to invest in capacity expansion. In contrast to fossil fuels, generating electricity from renewable energy produces little to no air and water pollutants or global warming emissions. As such technologies have matured, they have become one of the most effective and prevalent tools for environmental protection. Increasing numbers of consumers are installing renewable power generation systems locally in their homes. Several states and local governments in the US are also advancing policies to encourage greater deployment of renewable technologies. Take the City of Lancaster, California, for instance. It has required newly-built houses to feature a home photovoltaic system since January 1st of 2014 [1]. However, this greatly changed the centralized power generation and dispatching model of legacy grids. In addition, each form of renewable energy has its own disadvantages. For example, wind and solar energy are intermittent in nature since they rely on the weather for their source of power. Slow wind or abundant rain can result in significant reductions in energy production. Using batteries can mitigate the problem to some extent, but the usage of battery power must be carefully planned.

In response to these challenges, a significant amount of effort has been devoted to the development of technologies for grid modernization, which forms the foundation of smart grids. A smart grid can be defined as an electricity network that can intelligently integrate the actions of all consumers connected to it – generators, consumers, and those that do both – in order to efficiently deliver sustainable, inexpensive, and secure electricity [2]. By adopting the advanced

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metering infrastructure (AMI), a smart grid is capable of collecting and distributing energy demand, supply and price information between consumers and utility companies in real time. With such two-way communication, consumers can alter their energy use based on the price information provided by the AMI to lower their electricity bills, and utility companies can adjust their power generation schedules and can set electricity prices accordingly and instantly to minimize power generation costs and to achieve better demand-side management (DSM). In recent years, many DSM strategies for smart grids have been proposed to help consumers optimize their energy use (either renewable or non-renewable) and to aid power grids with shifting load from peak hours to off-peak hours and integrating renewable energy generation units. For example, [3] studied Peak-to-average ratio (PAR) and energy cost minimization problems in smart grids. Under the assumption that adequate tariffs are adopted to differentiate energy usage by time and level and that appliance jobs are interruptible and power-shiftable, the authors proposed an algorithm based on game theory that can achieve global optimal performance when there are a single utility company and multiple consumers connected to the grid. [4] considered a similar problem except that consumers were equipped with batteries. Their proposed algorithm attempted to minimize the PAR of the power grid by charging consumers' batteries at low-demand periods and discharging the energy at high-demand periods. [5] proposed a load scheduling algorithm to minimize energy cost for residential homes in a smart grid. In their system model, each residential home can have renewable energy sources and energy storage. Nevertheless, the energy prices at different times of the day were assumed to be fixed and given. [6–8] also studied load scheduling problem in smart grids. In [6], each appliance job was required to consume energy according to a known power dissipation profile. This means that once an appliance is started, it cannot be interrupted. The authors proposed an exact solution based on branch-and-bound and a more heuristic algorithm to solve it. Unfortunately, their solution approaches did not take into account renewable energy generation and storage. In contrast to [6], a photovoltaic system and energy storage were added to the residential side in [7] to achieve further efficient schedule plans. Under the assumption that both electricity prices and the availability of renewable energy at different times of the day were known, the authors modeled the load scheduling problem as a mixed integer program and solved it using some off-the-shelf optimization software. In contrary to [7], the generation of renewable energy was random in [8] and the authors used robust optimization techniques to deal with the uncertainty of renewable power generation. However the proposed solution only worked when the electricity prices at different times of the day were still assumed to be known beforehand, and excessive renewable energy had to be dropped.

Since most of the works in the current literature have tended to make critical assumptions, this became the motivation for this work. In this paper, we study the energy cost minimization problem for smart grids with distributed renewable energy resources under the following assumptions: 1. There is a single utility company, and there are multiple consumers. Each consumer can have renewable energy sources and storage. 2. An advanced metering infrastructure (AMI) is implemented so that energy demand, supply, and price information can be freely distributed between consumers and utility companies in real time. 3. Each appliance is equipped with a Demand Response Switch device. 4. The grid is capable of intelligently distributing power between the consumers and the utility stations. These assumptions are in-line with many research studies in the literature, such as [9,10,3,4,11,7]. However, unlike earlier studies, we focus on scenarios where appliance jobs are non-interruptible while not making critical assumptions related to electricity prices and the availability of renewable energy. That is, the electricity prices at different times of the day vary with the total demand of the power grid in real time, which helps cut power costs for consumers with flexible power consumption schedules and reduces the peak system load. The availability of renewable energy is uncertain, and the locally generated renewable energy can be either used to meet a consumer's power demand, be stored in a battery for future use, or injected/sold back to the grid. All these make the problem both more practical and challenging. In fact, we have studied the exact problem in [12]. However, there, the distribution of renewable energy was assumed to be known, which greatly reduced the complexity of the problem. In this paper, we improve that shortcoming and propose a new solution that is able to handle the uncertainty of renewable power generation.

In summary, the key contributions of this paper are as follows:

1. We consider an energy cost minimization problem in this paper with a focus on scenarios where appliance jobs are non-interruptible; the electricity prices at different times of the day vary with the total demand of the grid in real-time, and the generation of renewable energy is uncertain.
2. The problem is modeled as a two-stage robust optimization problem. Two solution approaches, which are called column-and-constraint generation (C&CG) and scalable and robust demand-side management (SRDSM), respectively, are presented for solving the problem. The C&CG algorithm employs a master-subproblem framework that effectively solves the problem. The SRDSM algorithm, although heuristic, is much more scalable and can generate solutions comparable to the optimal solutions obtained by the C&CG algorithm.
3. Extensive numerical simulations based on actual solar radiation measurements collected from the National Renewable Energy Laboratory are conducted to evaluate the performance of the two algorithms.

2. Related works

2.1. Demand Side Management (DSM)

DSM is a measure or a collection of measures implemented to influence the demand or the customer side of an electricity meter. Many studies [9,13–15] have indicated that DSM is an effective way to reduce the peak-to-average ratio (PAR) of a power system and in turn the energy costs for consumers. Although a reduction in peak load does not necessarily decrease total energy consumption, it avoids the need for investment in power generation and transmission. [9] investigated energy cost minimization for a single oil refinery factory. By considering the inter-dependency relationships between appliances and given the electricity price in each time period, the authors formulated the problem as an integer program and solved it using CPLEX [16]. Different from [9,13] studied energy cost minimization in a residential grid network with multiple consumers and electricity prices that varied with the aggregate demand in each time period. The authors proposed a coordinated home energy management architecture in which distributed home energy management units collaborated with each other in order to keep the demand and supply balanced in their neighborhood. [14] also studied the DSM problem in residential smart grids. However, the goal was minimizing not only PAR but also appliance delays. With the assumption that appliances are shiftable and throttleable and given a predetermined PAR and consumer satisfaction thresholds, the problem was formulated as a multi-objective optimization problem. The authors proposed two distributed algorithms to solve