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Scheduling coupled photovoltaic, battery and conventional energy sources to maximize profit using linear programming

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ABSTRACT

To address the increase of electricity demand, the need for reducing carbon dioxide, and the reduction of available fossil fuel resources, renewable energy sources are being recruited. Specifically energy generated by photovoltaic (PV) cells is becoming one of the most promising alternatives. In this context, this paper presents an optimization model for the scheduling problem where conventional and photovoltaic sources of energy are scheduled to be delivered to satisfy energy demand. The optimization model is formulated as a Linear Program (LP) with a bounded number of variables and constraints. The respective solution can be obtained in polynomial time and provides the optimal combination or schedule of energy generated from different sources (conventional, renewable and battery storage) such that the total demand is satisfied and the profit is maximized. Numerical results demonstrate the effectiveness and the generality of the scheme.

1. Introduction

To face the increase of the electricity demand, the reduction of fossil fuel resources and the need for reducing carbon dioxide emissions, utility companies have turned to grid connected renewable power systems. PV generation is one of the most promising renewable sources of energy [1]. Moreover, recent advances in energy storage, which have been a barrier to realizing the potential benefits of renewable energy, have enabled the deployment of solar PV storage facilities fully integrated into a utility power grid. An example of such a facility is the *Prosperity Energy Storage Project* managed by the Public Service Company of New Mexico (PNM) in New Mexico, the first US solar PV storage facility fully integrated into a utility's power grid [2]. One of the primary functions of the battery storage at the Prosperity Site is to solve the problem of intermittency in the solar PV production due to rapid variations in irradiance. However, the batteries can also be used to shift peak PV production to be in phase with peak demand.

Multiple factors need to be investigated to determine how energy should be distributed from difference sources. In the traditional model, electric power is delivered unidirectionally from a conventional power plant to the distribution substation to the customer. However, with the advent of alternative sources of energy and advances in energy storage technologies, a challenge and opportunity presents itself in determining how to optimally schedule the energy generated from difference sources to satisfy total demand.

This paper addresses the optimization problem where coupled photovoltaic, battery storage and conventional sources of energy are scheduled to satisfy a certain energy demand and maximize profit. The paper models the scheduling problem as a Linear Program (LP) with a finite number of constraints and variables. Using numerical examples, the effectiveness of the proposed LP is demonstrated.

The paper is organized as follows. Section 2 discusses related work. Section 3 provides an overview of the system and presents terminology. Section 4 presents the mathematical model and its complexity. Section 5 shows numerical results, and Section 6 concludes.

2. Related work

Many authors have addressed optimization issues in the context of renewable energy. Hill [3] proposes a solution for an optimization problem that focuses on minimizing the costs paid by a specific customer when meeting demand using conventional and solar energy. Hourly increments of time for a whole week are used to minimize cost. Power supplied by the solar energy source and battery are assumed free. Limits on charging and discharging rates are enforced. Switching the battery operation from a charging state to a

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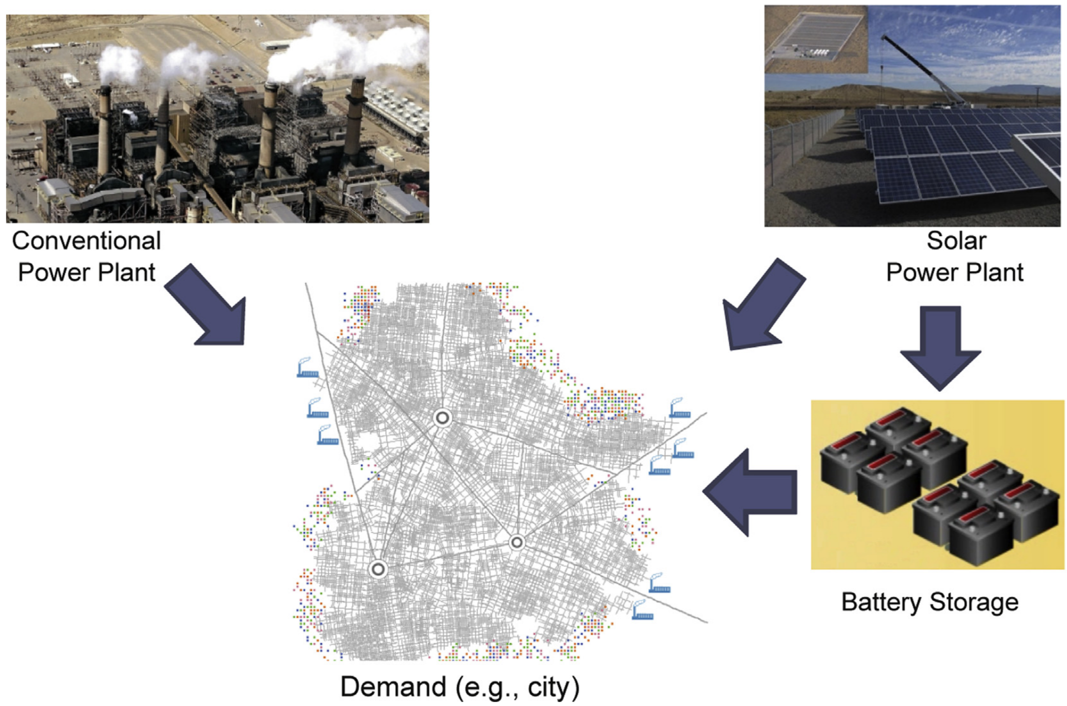

Fig. 1. Illustration of the energy scheduling problem with two sources of energy and battery storage that need to satisfy an energy demand.

discharging state and back are assumed detrimental to battery life and are tracked in the algorithm. Nottrott et al. [4] minimize the amount of energy purchased by a customer from the electrical grid when the demand can be met by the electrical grid, solar and battery storage. The customer can also sell energy to the grid. They find that the net value of the battery increased when operated on the optimized schedule. Riffonneau [1] minimizes the final value of cash flow using a power scheduling algorithm based on dynamic programming in a coupled system. The solar generator, batteries and converter are modeled based on parameters which include temperature, battery aging and power input. Lu [5] minimizes the cost of conventional sources of energy in a combined conventional/PV/battery storage system. Multiple conventional thermal sources are used and the start-up and shut-down costs of the thermal units are included in their optimization. The optimization is performed with a Lagrangian relaxation-based algorithm. Zhang et al. [6] minimize the total cost of a hybrid system which potentially incorporates wind, photovoltaic and battery sources. Marwali et al. [7] use Lagrangian relaxation and dynamic programming to minimize a function of the conventional (thermal) contribution to the grid. Many effects are accounted for including battery and photovoltaic capacity as well as ramp rates for conventional thermal contributions. Teng [8] uses a genetic algorithm to optimize charging and discharging of battery storage systems to minimize line losses incurred during stages of the charging process. Abbaspour et al. [9] use a mixed integer non-linear programming formulation to optimize profits from the operation of a conventional gas generator coupled with wind power and compressed air energy storage. Vijay et al. [10] use convex optimization to maximize the production of clean water in a plant powered by solar power with battery reserves.

Our approach takes the perspective of the utility company and optimizes profit. The algorithm is computationally fast and can produce scheduling projections under a minute. In addition, the algorithm is general enough so that it can run over multiple days using hours or fractions of an hour. Convergence is demonstrated when the increments of time are decreased.

3. Terminology

This paper presents a strategy to maximize profit by determining the optimal scheduling of a coupled photovoltaic, battery storage and conventional system. The proposed scheme can optimize scheduling for increments of time ranging from minutes to hours. Fig. 1 illustrates the system. Assuming two different sources of energy, conventional and solar, the terminology in Table 1 will be used in the rest of the paper. The unit of energy is the kilowatt-hour (kWh).

Table 1
Notation used to model the power scheduling problem. The subscript *i* refers to hour *i*.

Notation	Meaning
B_{start}	Initial energy stored by battery (kWh)
B_i	Battery energy at time interval *i* (kWh)
$B_{\min}$	Minimum battery storage allowed (kWh) (imposed to avoid deep cycling)
$B_{\max}$	Maximum battery storage allowed (kWh)
C_i^C	Cost to supply a kWh by the conventional power plant
C_i^{PV}	Cost to supply a kWh by the solar power plant
C_i^B	Cost to supply a kWh by battery storage to grid
D_i	Energy (kWh) demand
$E_i^{PV_{prod}}$	Energy (kWh) produced by the solar power plant
$E_{\text{Discharge}}^B$	Maximum discharge energy (kWh) in 1 h from battery storage
E_{Charge}^{PVB}	Maximum energy (kWh) that can be used to charge battery storage
E_i^C	Energy (kWh) discharged by the conventional power plant to satisfy demand
E_i^{PV}	Energy (kWh) discharged by the solar power plant to satisfy demand
E_i^B	Energy (kWh) discharged by the battery storage to grid
E_i^{PVB}	Energy (kWh) used by the solar power plant to charge battery storage
H_i	Charge ($/kWh) by electrical utility company to customers
P_i^C	Profit per energy unit ($/kWh) from the conventional plant
P_i^{PV}	Profit per energy unit ($/kWh) from the solar plant
P_i^B	Profit per energy unit ($/kWh) from the battery storage