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Electric utility resource planning using Continuous-Discrete Modular Simulation and Optimization (CoDiMoSO)

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ABSTRACT

Electric utility resource planning traditionally focuses on conventional energy supplies such as coal, natural gas, and oil. Nowadays, planning of renewable energy generation as well as its side necessity of storage capacities have become equally important due to the increasing growth in energy demand, insufficiency of natural resources, and newly established policies for low carbon footprint. In this study, we propose to develop a comprehensive simulation based decision making framework to determine the best possible combination of resource investments for electric power generation and storage capacities. The proposed tool involves a combined continuous-discrete modular modeling approach for processes of different nature that exist within this complex system, and will help the utility companies conduct resource planning via employed multiobjective optimization techniques in a realistic simulation environment. The distributed power system considered here has four major components including (1) energy generation via a solar farm, a wind farm, and a fossil fuel power station, (2) storage via compressed air energy storage system, and batteries, (3) transmission via a bus and two main substations, and (4) demand of industrial, commercial, residential and transportation sectors. The proposed approach has been successfully demonstrated for the electric utility resource planning at a scale of the state of Florida.

1. Introduction

Electric utility resource planning is the selection of power generation and conservation (i.e., storage systems) resources to meet customer demands for electricity over a multidecade time horizon (Hobbs, 1995). Conventionally, the long-term planning of electric power systems focuses on the determination of the operational capacities of only fossil fuel based energy generation systems. However, estimates are that conventional sources of energy can only meet our energy demands for another 50–70 years. Therefore, in an effort to find alternative forms of energy, the world has turned to hybrid conventional-renewable energy sources (e.g., solar, hydro, wind, geothermal, ocean and biomass) as a solution. Today, the majority of the citizens of the world are uniting to support the increasing role of renewable energy in our lives, and the stakeholders of electric utility planning seek optimum ways to actively involve the renewable energy (which was once viewed as an 'alternative' source of energy) in satisfying our energy needs in the upcoming decades.

Electricity production, primarily from burning coal, is the major source of most emissions of carbon dioxide (CO_2), which contributes to global warming by trapping heat in the earth's atmosphere; sulfur oxides (SO_x), which are the main cause of acid rain that can make lakes and rivers too acidic for plant and animal life, and damage crops and buildings; and nitrogen oxides (NO_x), which are combined with other chemicals to form ground-level ozone (smog) in the presence of the sunlight (Intergovernmental Panel on Climate Change, 2011; Likens, Driscoll, & Buso, 1996; US Environmental Protection Agency, 1997; Goddard Institute for Space Studies, 2010). Renewable energy has a much lower environmental impact than conventional sources of energy and can significantly reduce the emission of greenhouse gases. Furthermore, renewable energy sources are free, (no associated operational or purchasing costs for the source), and are sustainable (hence these sources never run out). Other advantages of utilizing renewable sources of energy include a stimulated economy and an increased number of job opportunities, improved national security and independence on foreign oil supplies in contrast to the use of fossil fuels which makes the US vulnerable to political instabilities, trade disputes, embargoes and a variety of other impacts, since more than 53% of US's oil has been imported as of 2003 (WORC, 2003). Due to these advantages and needs, the involvement of renewable sources in our electric power generation at the utility scale is inevitable and hence capacities of various kinds of renewable energy generation (e.g., wind and solar) as well as storage systems (e.g., compress air energy storage systems, batteries, and super-capacitors) should be considered in

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line with capacities of the conventional fossil fuel based means of energy generation for the long term survival of the utilities while incurring optimum multicriteria objectives (e.g. investment and operational costs, environmental impact) given increased market competition.

On the other hand, there are several challenges against the implementation of an effective capacity planning at the utility scale. First, power systems are very large scale and complex due to their uncertain, interactive and dynamic features. Second, the consequences (economic, reliability, or environmental) of alternative strategic resource planning scenarios should be evaluated at an integrated manner for various players (e.g., consumers, suppliers, government). Third, the planning process is further complicated by the growing uncertainty due to future load growth, resource availability (i.e., utilization, lifespan, and performances of power plants), construction (i.e., times, costs, and performances of newly introduced resources), regulatory and economic environment in which utilities operate, and raising environmental concerns such as global warming. Lastly, the long term planning of power industry is considerably affected by the competition in various sectors of the market including generation, transmission and distribution.

In this study, we propose a novel Continuous-Discrete Modular Simulation and Optimization framework (CoDiMoSO) in order to accurately estimate the capacity requirements of electric power generation and storage, involving conventional as well as renewable sources of energy generation. The framework developed in this work enables various stakeholders of electric utility resource planning devise the best possible capacity plans, detailing the rated capacity for each energy generation and storage alternative included in the capacity plan, while saving from computational resources and costs. The goal of the optimization model is to minimize the financial investment of building, and operational cost of maintaining the combined renewable and fossil fuel based energy generation systems as well as minimizing the environmental impact (measured through the amount of greenhouse gases produced) while meeting the requested commercial, industrial, residential and transportation demand.

The CoDiMoSO decision making framework proposed in this research is composed of four modules for evaluation, and another one for optimization. The generation module (Module G) captures the functional details and characteristics of energy generation at the utility scale and includes renewable (solar and wind farms), and fossil fuel-based (coal, oil, and natural gas) energy sources. The storage module (Module S) encapsulates the attributes of various energy storage components that amass the excess production of energy such as NaS and Pb-Acid types of batteries, and compressed air energy storage systems (CAES). The transmission and distribution grid elements such as the step-up and step-down substations and inverters are included in the transmission module (Module T), and variable demand arising from industrial, commercial, transportation, and residential customers as well as their seasonal and daily fluctuation is captured in the demand module (Module D). Finally, the optimization module (Module O) helps utilities determine the best possible combination of investment options that will result in minimized cost and environmental damage. Continuous-discrete modeling methodologies are used in the modeling of Module G, Module S, Module T, and Module D depending on the nature of the sub-system; and meta-heuristics are utilized for the solution mechanism of Module O. Because the literature on resource planning of electric utility systems that incorporates real data at this scale and scope is infrequent, the acquisition of realistic data has been an additional challenge in this study. Here, the necessary data has been collected from various reliable sources such as the National Renewable Energy Laboratory (NREL) for solar irradiation profiles; the Energy Information Administration (EIA) and the Florida Public Service Commission (FPSC) for electricity consumption; EIA for fossil fuel energy production; EIA, Sharp, Mitsubishi and SunPower for cost and operational characteristics of PV panels; EIA, Siemens, GE, and Mitsubishi for cost and operational characteristics of Wind Turbines; and EIA for cost and operational characteristics of CAES. The constructed CoDiMoSO tool is used to (1) test impacts of several factors such as different conflicting objectives (e.g., minimum investment and operational cost, and minimum environmental hazard); future demand growth; efficiencies in PV panels, wind turbines, fossil fuel operating power plants, CAES, and batteries; and losses in transmission lines; on the total cost of the integrated generation and storage system and (2) to find an optimal investment policy of renewable and fuel-based generation, as well as storage capacity. While the proposed tool has been demonstrated for the sunshine state of Florida, the proposed CoDiMoSO framework is built with a generic approach so that it can be adopted for various other utilities in different states, or different countries.

The rest of the paper is organized as follows: Section 2 provides the background and literature survey in the electric utility resource planning problem; Section 3 then describes different underlying components (e.g. generation units, loads, sunshine, wind, and storage units) of the energy system considered in this research, and the proposed modeling approach which involves a continuous-discrete modular simulation and optimization technique; Section 4 describes the designed experiments and results obtained to demonstrate the proposed approach; finally, Section 5 summarizes the conclusions derived from this study together with the future venues of the presented work.

2. Background and literature survey

The goal of electric utility generation expansion planning is to seek an optimal generation capacity expansion system to meet demand in the most economical manner, subject to reliability and environmental constraints (Maricar, 2004; Stoll, 1989; Wang & McDonald, 1994). The specific aim of electric utility integrated resource planning is to integrate supply-side and demand-side options in meeting customer energy-service needs and environmental improvements in a least-cost manner (Hobbs, 1995; Maricar, 2004).

In the past three decades, the electric power system resource planning, including generation, demand, storage and distribution, has faced dramatic changes due to the development of more efficient resources, via the advances in technology and policy variations based on increased environmental awareness concerns. These changes have created a variety of options in resource components (i.e., generation, demand, storage, transmission, and distribution) that need to be addressed considering different criteria and constraints that these options bring about. To this end, researchers have attempted to address the aforementioned high-stakes problem of electric utility resource planning under uncertainty at different scales and scopes by proposing various techniques focusing on generation expansion planning and integrated resource planning of electric utilities. The solution attempts proposed in the literature can be classified into two major categories including economic-analytical approaches and simulation approaches.

From the perspectives of economic and analytical approaches, Malik (2001) presents a technique to model demand-side management (DSM) programs into production costing analyses within the framework of equivalent load duration curve, and frequency and duration method. Also the importance of incorporating the cycling costs of power plants in the cost-effectiveness analysis of DSM programs is presented. Similarly, Hobbs and Nelson (1992) apply a bi-level nonlinear programming method to the electric utility