Renewable Energy 71 (2014) 553–562

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

An integrated reservoir-power system model for evaluating the impacts of wind integration on hydropower resources☆

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A R T I C L E I N F O

Article history:
Received 22 October 2013
Accepted 10 June 2014
Available online 28 June 2014

Keywords:
Wind energy
Hydropower
Power system analysis
Dam operations
Unit commitment
River flows

A B S T R A C T

Despite the potential for hydroelectric dams to help address challenges related to the variability and unpredictability of wind energy, at present there are few systems-based wind-hydro studies available in the scientific literature. This work represents an attempt to begin filling this gap through the development of a systems-based modeling framework for analysis of wind power integration and its impacts on hydropower resources. The model, which relies entirely on publicly available information, was developed to assess the effects of wind energy on hydroelectric dams in a power system typical of the Southeastern US (i.e., one in which hydropower makes up <10% of total system capacity). However, the model can easily reflect different power mixes; it can also be used to simulate reservoir releases at self-scheduled (profit maximizing) dams or ones operated in coordination with other generators to minimize total system costs. The modeling framework offers flexibility in setting: the level and geographical distribution of installed wind power capacity; reservoir management rules, and static or dynamic fuel prices for power plants. In addition, the model also includes an hourly 'natural' flow component designed expressly for the purpose of assessing changes in hourly river flow patterns that may occur as a consequence of wind power integration. Validation of the model shows it can accurately reproduce market price dynamics and dam storage and release patterns under current conditions. We also demonstrate the model's capability in assessing the impact of increased wind market penetration on the volumes of reserves and electricity sold by a hydroelectric dam.

1. Introduction

The extent to which large scale integration of wind energy in electric power systems will impact market prices, system costs and reliability may depend greatly on the availability of sources that can quickly change (or 'ramp') electricity output [1–3]. Due to their capacity for energy storage, low marginal costs, and fast ramp rates, hydroelectric dams are often regarded as an ideal resource for mitigating problematic issues related to wind's intermittency and unpredictability [4]. In recent years, researchers have investigated a wide range of topics concerning the coordinated use of wind and hydropower. However, few studies to date have made use of comprehensive reservoir and power system models in assessing the costs and benefits of wind-hydro projects, and the development of such models remains a limiting factor in addressing a number of unanswered questions in this area.

Previous studies of wind-hydro projects can be separated conceptually into two categories of analysis: 'pairwise' and 'system-based' [4]. Pairwise analyses evaluate the costs and benefits of wind-hydro projects operated in isolation (i.e., somewhat disconnected from other elements of a larger electric power system). Simpler examples include investigations of the capacity value [5] and firm energy costs [6,7] of wind-hydro projects. More sophisticated pairwise studies have used historical market prices to represent wind-hydro projects' connection to larger electric power systems. Examples include previous research on: the value of energy storage in wind-hydro systems [8,9]; the financial and environmental costs of dams' providing a 'wind firming' service [10]; project optimization [11]; the use of dams to increase wind market penetration [12]; and the use of multipurpose dams to integrate wind energy [13]. Pairwise wind-hydro studies, particularly those

☆ This work was funded by the Hydropower Research Foundation and the U.S. Department of Energy, Wind and Water Power Technologies program.

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http://dx.doi.org/10.1016/j.renene.2014.06.014
0960-1481/

that include some consideration of a project's system context, can offer valuable insights. However, they are generally less capable of capturing the more complex, endogenous economic and operational consequences of large scale wind integration for generators and consumers [4].

More comprehensive 'system-based' models simulate the effect of wind power integration on the workings of entire electric power systems made up of many different sizes and types of generators. As such, they offer the significant advantage of being able to simulate changes in market prices and system costs that may occur as a result of wind power integration, and then evaluate how these changes could impact the use of hydroelectric dams. However, most previous system-based wind-hydro studies have been conducted by electric power utilities, and detailed modeling information (and even results) from these studies is generally considered proprietary [4]. Examples of system-based studies from academic literature include investigations of the impacts of wind-hydro projects on: the value of wind energy [14]; and the cost of reducing CO_2 emissions [15].

Few wind-hydro studies to date have taken a system-based approach. As a consequence, significant gaps in knowledge remain as to how wind power integration may impact hydropower resources. For example: in all but a few US states, hydropower meets less than 10% of total annual electricity demand; but most (if not all) system-based wind-hydro studies have focused on 'hydro dominant' systems, in which hydropower makes up a much larger percentage of total system generation. The effects of wind power integration on dam operations may be much different in a system with relatively little hydropower capacity. There has likewise been little consideration in previous studies given to the role of market type (i.e., regulated versus competitive) in framing the incentive structure for hydroelectric dams to help integrate intermittent wind energy. In addition, no system-based study has addressed the potential for wind energy to impact environmental flows downstream of hydroelectric dams. Investigation of these topics requires models that can simulate the effects of wind power integration on hydroelectric dams under a variety of structural, economic, and hydrological conditions, while also maintaining the operational complexity of interconnected reservoir and electric power systems.

At present, there are few systems-based wind-hydro studies available in the scientific literature. This work represents an attempt to begin filling this gap through the development of a systems-based modeling framework for analysis of wind power integration and its impacts on hydropower resources. The model, which relies entirely on publically available information, was developed to assess the effects of wind energy on hydroelectric dams in a power system typical of the Southeastern US (i.e., one in which hydropower makes up <10% of total system capacity). However, the model can easily reflect different power mixes; it can also be used to simulate reservoir releases at self-scheduled (profit maximizing) dams or ones operated in coordination with other generators to minimize total system costs. The modeling framework offers flexibility in setting: the level and geographical distribution of installed wind power capacity; reservoir management rules, and static or dynamic fuel prices for power plants. In addition, the model also includes an hourly 'natural' flow component designed expressly for the purpose of assessing changes in hourly flow patterns that may occur as a consequence of wind power integration.

2. Methods

The reservoir-power system model consists of: 1) an electricity market (EM) model; and 2) a reservoir system model. The EM model iteratively solves two linked mixed integer optimization programs, a unit commitment and economic dispatch problem, to allow a power system operator to meet fluctuating hourly electricity demand. A single iteration of the EM model and its two sub problems yields hourly market prices for a single 24 h period.

The reservoir system model consists of: 1) an hourly natural flow model that simulates 'natural' (pre-dam) flows at dam sites; 2) a daily reservoir operations model that determines available reservoir storage for hydropower production; and 3) a hydropower dispatch model that schedules hourly reservoir releases in order to maximize dam profits. Fig. 1 shows a schematic of the integrated reservoir (components shown in dark grey) and EM (components shown in light grey) model.

2.1. Electricity market model

The EM model was developed in order to simulate the operation of a large power system based on the Dominion Zone of PJM Interconnection (a wholesale electricity market located in the Mid-Atlantic region of the U.S). Dominion's total generation capacity is approximately 23 GW, with a peak annual electricity demand of roughly 19 GW. Using the Environmental Protection Agency's (EPA) 2010 eGrid database, each generator in the utility's footprint was cataloged by generating capacity (MW), age, fuel type, prime mover and average heat rate (MMBtu/MWh). Specific operating constraints parameters were estimated for each size and type of plant using industry, governmental and academic sources. To reduce the computational complexity of the EM model (i.e., maintain reasonable solution times) units from each plant type were clustered by fixed and variable costs of electricity and reserves, with each cluster of similar generators forming a 'composite' plant. The total number of power plants represented in the model was reduced from 68 to a more manageable, yet representative, quantity (24)—with total system wide capacity remaining the same. Each generator in the modeled system belongs to one of eight different power plant types: conventional hydropower, pumped storage hydropower, coal, combined cycle natural gas (NGCC), combustion turbine natural gas (NGCT), oil, nuclear or biomass. Table 2 of supplemental materials section shows detailed operating characteristics of each plant in the modeled generation portfolio.

The EM model has two main components: 1) a unit commitment (UC) problem that represents both 'day ahead' electricity and 'reserves' markets; and 2) an economic dispatch (ED) problem that represents a 'real time' electricity market [16].

2.1.1. Unit commitment problem

The UC problem uses information regarding the costs (variable, fixed, and start) of participating power plants to schedule the status (on/off) and generation (MWh) at each plant in the system 24 h in advance. The UC problem is responsible for meeting forecast 'day ahead' (DA) electricity demand and satisfying system wide requirements for the provision of spinning and non spinning 'reserves' (unscheduled generating capacity that is set aside for the next day as 'back up'). The objective function of the UC problem is to minimize the cost of meeting forecast electricity demand and reserve requirements over a 96 h planning horizon, given a diverse generation portfolio:

$$\begin{aligned}\text{Minimize } Z_{\text{UC}} \sum_{t=1}^{96}\sum_{j}^{J}\big[&(\text{DA\_MWh}_{t,j}{*}\text{VC}_j) + (\text{ON}_{t,j}{*}\text{FC}_j)\\ &+ (\text{SRV\_MW}_{t,j}{*}\text{VC\_SR}_j) + (\text{SRV\_ON}_{t,j}{*}\text{FC\_SR}_j)\\ &+ (\text{NRV\_MW}_{t,j}{*}\text{VC\_NR}_j) + (\text{START}_{t,j}{*}\text{SC}_j)\big]\end{aligned} \quad (1)$$

where, t = hour in planning horizon $\in\{1,2,\ldots 96\}$, j = generator in system portfolio.