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Operating policies for energy generation and revenue management in single-reservoir hydropower systems

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ABSTRACT

We study the reservoir management problem in hydropower plants, and propose operating policies to maximize the average annual energy generation or the average annual revenue. Under revenue maximization, our policies allow for short-term electricity price variations to be incorporated into the long-term plan. First, we provide a detailed review of hydropower plant operation, focusing on implicit stochastic optimization approaches and integration of energy price variations in reservoir management. Then, we explain non-linear programming models that we developed for obtaining operating policies with different characteristics. We evaluate and compare the operating policies through a case study. Policies characterized by dynamic end-of-month storage levels are shown to perform much better than the policy with an optimal static end-of-month storage level, and it has been further shown that the dynamic policies perform quite close to the theoretical upper bound. Finally, we show that maximizing the average annual energy and maximizing the average annual revenue objectives yield considerably different operating policies and using one policy in place of the other may result in significant loss of benefit or resource.

1. Introduction

Increase in population and economic growth causes energy consumption to increase. According to the International Energy Agency (IEA), world total energy consumption has more than doubled in 2013 compared to that in 1973, and the total electricity consumption has almost quadrupled during that period [1]. IEA defines solar, wind, geothermal, hydropower, bioenergy and ocean power as sources of renewable energy, and states that the role of renewables continues to increase in the electricity, heating and cooling and transport sectors.

Currently, hydropower is a major renewable energy source, providing 16% of world electricity [1] and a record 6.8% of global primary energy consumption [2]. Especially in emerging economies and developing countries, planning and construction of a large number of hydropower plants have been initiated in the past decade. Of the 281 hydroelectric power plants in Turkey under operation, around 80% are dam-type whereas the remainder are run-off river-type as of 2012 [3]. However, necessary emphasis has not been placed on the evaluation of the environmental and social consequences of these hydropower plants. Besides the daunting initial investment needs, new plants come with far-reaching ecological consequences [4]. If policies to effectively operate the existing plants are developed, this would alleviate the need for excessive construction of new power plants.

The main goal of this study is to develop operating policies which can be used for guidance in reservoir operation and evaluate their performances. Operating policies, which are widely used to guide the system operators in decision making for long term reservoir operation, are named as “operating rule curves” in the reservoir management literature [5,6] and we will use the term “rule curve” in the remainder of the text. Rule curves provide target end-of-month operating levels or end-of-month storages in the reservoir [7]. A specific rule curve needs to be derived for each reservoir, ideally, using optimization techniques. However, in practice, reservoirs are generally operated in an ad-hoc manner, using the results of the simulation models and the judgement of the reservoir operator based on experience-based knowledge [8,9]. In this study, rule curves that provide guidance in reservoir operation are determined through nonlinear programming models. In the following section, a detailed overview of reservoir operations is presented. While doing so the gaps in the literature are highlighted and how this study intends to fill the gaps is pointed out.

2. Overview of reservoir management

Past studies on management of reservoir operations use either heuristic

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approaches such as evolutionary algorithms [10,11] or mathematical programming based optimization approaches when deriving the rule curves. Hossain and El-Shafie [12] provided a review of optimization techniques developed to solve reservoir operation problems. The choice depends on the complexity of the objective and the structure of the reservoir system. Methods for optimization of reservoir operations can roughly be classified into two as; deterministic optimization and stochastic optimization. See Singh and Singal [13] for an overview.

A reservoir system can be characterized as a stochastic system due to the randomness in certain factors (model inputs) such as inflows to the reservoir, evaporation, or required periodic demand for water [14–16]. For example, in a recent optimization study, Kocaman et al. [17] proposes a stochastic programming model to account for the demand uncertainty when making investment decisions of renewable energy systems. Deterministic optimization methods do not explicitly incorporate the randomness in the model inputs into the method, but rather either use past historical data of inputs or future forecasts as if the forecasts are exact. The rule curve provides the operating policy that best achieves the selected objective throughout the simulation period or period-of-record (i.e. period for which historical data is available). When past data is used, as in our study, the assumption is that the hydrological situation, mainly inflows to the reservoir, will be similar to those of the simulation period and thus rule curve will achieve the selected objective in the future as well (see [18] and [19] for other studies that use historical data).

Deterministic optimization methods for optimization of reservoir operations can be exemplified by linear programming, nonlinear programming, deterministic dynamic programming, or network flow optimization [8,12]. As the systems get more complex, the corresponding mathematical models become large-scale and each of these methods may suffer due to the size of the model. In that case, some approximation algorithms are developed to find optimal or near-optimal solutions. For instance, successive linear/quadratic programming techniques can be applied to solve a non-linear programming model [18,20,21]. For example, Yoo [22] represented hydropower energy as a linear combination of weighted reservoir storages and releases, but they did not analyze production capability of hydropower energy over the inflow reliability. The reservoir operation problem in this study has a nonlinear objective function and constraints. Although the nonlinearity of the objective function introduces difficulty, non-linear programming provides a more accurate model, and is more appropriate for real-time operations. Since in this study a single-reservoir is under consideration, it is possible to obtain the optimal solution using nonlinear optimization packages.

The output of the deterministic optimization methods are the storage levels associated with each time point in the period-of-record, i.e., an operation plan for that specific inflow series. Thus, in the raw form it is not possible to directly adopt these results for reservoir operation in real-time. Labadie [8] states that outputs of these optimization models require post processing of the results in order to develop operation plans. This approach is named as implicit stochastic optimization (ISO) for which the key issue is to abstract operating rules by learning from deterministic optimization results [23]. Many recent studies adopt the ISO approach to obtain operation plans for reservoir systems. Kim et al. [24] generated synthetic inflow data over 100 years and used piecewise-linear operating rules for single reservoir operation. Vicuna et al. [25] investigated climate change impacts on high elevation hydropower generation using perturbed daily and monthly hydrologic data based on climate change signals associated with four climate change scenarios. In a recent study, Celeste and Billib [26] utilized the long-term forecast of the mean inflow for a given future horizon rather than the prediction of current-month inflow. They noted that improved results might be generated using more sophisticated approaches for forecasted inflow. The method proposed in this study falls into the class of ISO methods, in that a deterministic nonlinear program is solved to obtain a rule curve. However, in contrast to the general ISO approach, post-processing of the storage levels is not necessary. The mathematical model is constructed such that, the output of the model can directly be used as guidance for real-time operation of the reservoir. The performances of the proposed rules are tested using the historical data, and it is shown that substantial benefits over a naive policy (i.e. a policy that tries to keep the reservoir at a fixed best operating level) can be achieved.

Past studies consider a variety of objectives in reservoir operations. A common objective is maximizing the hydropower generated from the reservoir. Some other objectives studied are maximizing the revenue [27,28], maximizing the energy generated with respect to the energy demanded [29], minimizing water shortage [11], minimizing the water consumption rate [30], maximizing utilization of the installed capacity of the plant [31], and mitigating flood risk [32]. Turkey is the second richest country in terms of hydropower potential after Norway in Europe. However, currently only 35% of the estimated economical potential is utilized. One of the reasons for limited utilization is the risk in economic feasibility: renewable energy has higher capital costs than fossil-fueled systems [33]. To ensure economic feasibility, especially for private investors, the revenue potential must exceed the capital investment requirement. This makes maximization of average annual revenue generated a relevant objective.

If a hydropower plant is concerned with revenue generation, the electricity prices, which the generated energy is sold at, must be taken into account when determining the revenue maximizing rule curves. In Turkey, a competitive electricity market was established in 2001, and the current form of the market has been in effect since December 2009 [34]. The electricity market consists of three sub-markets, namely; day-ahead, intra-day and the balancing-power market. In the day-ahead market, the participant firms submit their bids in the form of (price, quantity) tuples for energy sale or energy purchase for the following day. An optimization model is run to balance "supply" and "demand" and as a result *hourly market exchange prices (clearing prices)* and *market exchange quantities* are obtained. The following day, transactions take place based on the clearing prices. In our study, we derive rule curves taking the perspective of both a non-profit organization (such as government) and a for-profit firm. In Turkey, as of 2016, there are a total of 285 private, for-profit firms with share of 72% of the total installed capacity, and the remaining 28% is generated by Electricity Generation Inc. (EÜAŞ), a state-owned enterprise [35,36]. A few of the private firms are major players (such as ENKA, EnerjiSA, Limak Enerji) and their share in the installed capacity is around 3–5% [37]. Others are small firms, whose energy generating quantities will not affect the market clearing price or clearing quantity significantly. We evaluate two objectives separately: maximizing the energy generation and maximizing the revenue. When maximizing revenue, the hourly day-ahead prices are taken as the prices which the energy can be sold at. We make the assumption that, since the size of the firm is small, it can sell whatever energy is generated at the market clearing price. Finally, we analyze how decisions under one objective affect those under the other objective.

In our study, under both objectives, operating policies are derived for a long-term planning horizon. This approach is different than those in the literature, since in reservoir operation, optimization models with revenue maximization objective consider hourly time steps and aims short-term operation scheduling, typically one day. For applications such as hydropower generation, a longer time step may not be sufficient to model the desired system operations since hydropower reservoirs commonly make releases based on energy prices that fluctuate on a sub-daily basis [38]. Yuan et al. [39] proposed an enhanced particle swarm optimization algorithm to solve optimal daily hydro generation scheduling problem and demonstrated the method on a test network composed of four reservoirs. Wang [40] studied a similar hydropower scheduling problem for a larger system, namely Fujian hydro system which involves 27 hydropower plants for a 24-h planning period. A time horizon of one day divided into 24 h intervals is utilized