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Emission-Constrained Hydro-Thermal Scheduling

A Unified State-Space and Scenario Tree Framework for Multi-Stage Stochastic Optimization: An Application to Emission-Constrained Hydro-Thermal Scheduling

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In hydro-thermal scheduling problems, one is interested in determining the optimal operating policy for the use of hydro and thermal resources in order to minimize total expected costs of fulfilling the demand for electricity over a given time horizon.

To understand the trade-offs present at hydro-thermal scheduling problems, we look at the consequences when operating hydro assets in a »wrong« way. Therefore, consider Figure 1. When using electricity excessively from water and a dry season happens, then the hydro-reservoirs are empty (or at a low level) which may lead to an electricity rationing (we assume that the power system is hydro-dominated implying that the installed capacity of the non-hydro assets typically does not suffice to meet the electricity demand alone). This shortage of electricity is typically seen as a very bad event and penalized by significant financial fines (e.g., by the regulator or by fines through breach of contract). Contrary to this aggressive usage of water, one can operate the hydro assets very conservatively and only generate electricity from water when the reservoirs are (close to) full. In case of a wet season, water may have to be spilled as the installed capacity of the electric generators at the dams or the electricity demand is too small. The spilled water is an opportunity cost. Thus, the task is to find a balance between the opportunity cost of spilling water and the penalties for rationing electricity.

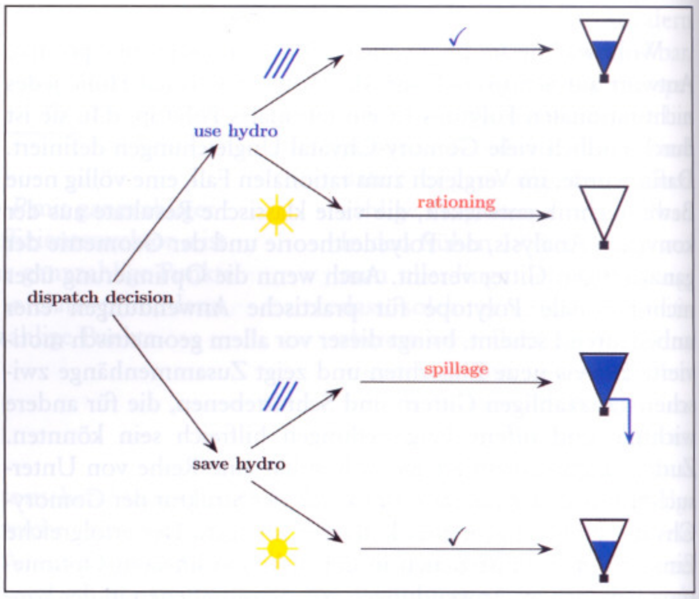

Figure 1

Originally proposed in 1991 by Pereira and Pinto, stochastic dual dynamic programming remains to date as the most efficient algorithm which is able to cope with inflow uncertainty and a detailed representation of a system's characteristics. The corresponding software SDDP of the PSR Company is used in over 30 countries around the world. My dissertation extends this methodology in several ways. Let us have a brief look at my contributions which is then followed by a more detailed discussion of the methodology and the industrial applicability.

My dissertation has the following three main contributions:

1. Fuel prices and electricity demand uncertainty for hydro-thermal scheduling problems which are subject to inflow uncertainty. This is accomplished by incorporating the scenario tree approach towards the modeling of uncertainty into the dynamic programming framework. This is novel and can be seen as a unification of the discrete, »tree-community« and the continuous, »Markov Chain-community«.
2. CO_2 emission cap effects on power systems operation cost and operation policy for hydro-thermal scheduling problems which are subject to inflow uncertainty. The proposed optimization model allows us to calculate the marginal CO_2 emission prices for a power system via the dual multipliers of the reservoir constraints. This provides insights on the effects of CO_2 caps on the operational part.
3. Joint modeling of several uncertainties along with their correlation in a deregulated electricity market. A sub-model is used to generate those price forecasts and a stochastic optimization model is proposed leading to a fundamental approach towards electricity price and CO_2 emission allowance spot prices.

The first contribution of my dissertation is an extension of the current multi-stage stochastic programming methodology by embedding the stochastic dual dynamic programming algorithm into a scenario tree framework, thus allowing to additionally dealing with uncertainties related to the evolution of demand and fuel prices. From a practical standpoint, this is an innovation as fuel price and electricity demand uncertainty could not be taken into account in hydro-thermal power systems so far, and from a technical standpoint, this is a new approach unifying the state-space and scenario tree framework.

Fuel prices and electricity demand are heavily influenced by political and macro-economic decisions. For instance, imagine that the OPEC announces an increase in oil extraction or that the global economy slows down. In both cases, the oil price is expected to decrease. To capture such events via political and macro-economic scenarios seems appealing and natural.

The importance of such an approach was made evident by the global economic crisis of 2008 when several countries experienced huge variations in demand and faced sudden and sharp increases in fuel costs due to oil price swings, with implications not only on total incurred costs but also regarding security of supply. This experience was most dramatic in the Central American countries, leading to this project.

The impact of taking into account demand and fuel price uncertainty may reach beyond the operational scheduling problem and extends into supply adequacy and load supplying capability issues. The incorporation of fuel price uncertainty might be especially useful when maximizing profits in a deregulated energy market. Typically, risk constraints are taken into account in such models, penalizing a certain risk exposure. There are the hybrid stochastic dynamic programming / stochastic dual dynamic programming algorithms for hydro-thermal profit maximization models which can adopt the results of this project in a straight forward way. We see a big potential of this approach for fuel price uncertainty in such an environment.

Despite the uncertainty surrounding the design of a mechanism which is ultimately accepted by nations worldwide, the necessity to implement measures to curb emissions of greenhouse gases on a global scale is consensual. The electricity sector plays a fundamental role in this puzzle and countries may soon have to revise their operating policy directives in order to make them compatible with additional constraints imposed by such regulations.

The second contribution of my dissertation is a modeling approach for greenhouse gas emission quotas which allows these constraints to be incorporated into the stochastic dual dynamic programming algorithm. The focus is on mid-term stochastic optimization problems of a hydro-thermal power system which is subject to CO_2 emission quotas. This problem is important for society and timely, as world leaders and international organizations discuss the roles and responsibilities of each country and sector of economic activity in the path towards a sustainable future. When deciding on the imposition of emission quotas, one of the main concerns for each country is the impact of such limitations on the competitiveness of its industrial activities and the potential side effects on its economy. The existence of a quota and penalties associated with its violation may have huge effects in terms of decreasing economic activity and additional costs related to energy efficiency projects, higher energy costs and eventual acquisition of additional quotas in international markets.

Since the emission quotas are to be established for each country as a whole, it will be up to each government to decide how they are going to be divided among each sector – and this is exactly where the problem we study in this project comes into play. Having a limit on the total CO_2 emission allowance over a year directly affects the way system operators define the operating schedule of each plant since a new element must now be factored into the equation on top of the usual sources of uncertainty such as demand and inflows. While it is desirable that the generation of dirty plants is replaced by that of cleaner alternatives, this comes at a cost which must be borne by society. It thus becomes imperative that policy makers are able to estimate the increase in costs when defining the share of quotas to be allocated to the electricity sector and the fines associated with their violations.

Managing an annual emission allowance is somewhat similar to managing water reservoirs since one must determine the optimal tradeoff between consuming parts of the limited amount of a resource in the present moment or saving it for future use. The decision to deplete the CO_2 stock on hand may only be assessed in terms of its expected future costs which depend on the evolution of hydrological conditions. For example, consuming emission quotas in the present – thus preventing their use in future time stages – may prove useful if a high inflow scenario occurs and hydro plants are able to meet a higher share of demand. Thus, a reservoir model for the CO_2 emission quota has been proposed, respecting the stage decomposition framework of stochastic dynamic programming methods. This reservoir model allows for CO_2 allowances to expire at given times. From a modeling point of view, this is practically of high importance as it is currently implemented in the EU Emission Trading Scheme.

The third contribution of my dissertation applies the greenhouse gas emission constraints towards a profit maximization model for electric utilities in a deregulated electricity market. The utility is subject to CO_2 emission quotas where allowances are traded in a market environment. The proposed model includes the stochastic parameters in the hydro inflows, fuel prices, electricity market prices and CO_2 emission allowance prices. The importance and novelty of this approach is that the developed methodology allows capturing all major correlations among these uncertainties. In particular, the influence of hydro-inflows on electricity spot prices and CO_2 emission allowance prices are modeled as well as the influence of fuel prices on electricity spot prices and CO_2 emission allowance prices.

In conclusion, my dissertation extends the stochastic dual dynamic programming algorithms to cope with additional uncertainties driven by political and macro-economic forces, the deregulation of the electricity markets, and the appearance of CO_2 emission allowance markets.