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A time consistent risk averse three-stage stochastic mixed integer optimization model for power generation capacity expansion

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ABSTRACT

We propose a multi-stage stochastic optimization model for the generation capacity expansion problem of a price-taker power producer. Uncertainties regarding the evolution of electricity prices and fuel costs play a major role in long term investment decisions, therefore the objective function represents a trade-off between expected profit and risk. The Conditional Value at Risk is the risk measure used and is defined by a nested formulation that guarantees time consistency in the multi-stage model. The proposed model allows one to determine a long term expansion plan which takes into account uncertainty, while the LCoE approach, currently used by decision makers, only allows one to determine which technology should be chosen for the next power plant to be built.
A sensitivity analysis is performed with respect to the risk weighting factor and budget amount.

1. Introduction

In this paper we consider the problem of a power producer who has to determine the optimal technology mix of conventional generation and generation from Renewable Energy Sources (RES), in order to plan power generation capacity expansion over a long term horizon. Given the available budget, long term investment decisions depend on investment costs and operational costs of different generation technologies; regulatory requirements (such as the Green Certificate scheme and the Emission Allowances Trading scheme) and uncertainty of prices (fuels, electricity, CO_2 emission allowances and Green Certificates) play an important role and have to be taken into account (see Conejo et al., 2010). Power producers usually analyze investments in new power generation technologies by means of the Levelized Cost of Electricity (*LCoE*), a standard business tool that evaluates the investment in a single plant or single technology. By this analysis the decision maker can rank investments in different technologies and determine which technology should be chosen for the next power plant to be built. The *LCoE* embeds information on the financial structure of the investment, but it does not account for the power producer's market share, i.e. the amount of electricity demand satisfied by his own production; moreover, the *LCoE* does not take into account uncertainty, with every parameter involved in the computation representing an expected value.

The approach we propose provides a *policy* regarding the installation plan to be implemented in the medium to long run. It gives information about how many plants *of each technology* should be built and when these installations should be initiated. In our modeling framework stochasticity is considered explicitly by scenarios unrolling over a

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multi-stage tree. The recoursive multi-stage approach provides greater flexibility to the power producer's decision process, since decisions about opening new power plants can be spread over different periods of time and only implemented if the corresponding scenario realizes. Exercising the option of opening a new plant depends on the evolution of profits under the different stages: this is accounted for in the objective function, which contains terms related to the recourse actions. Measurements of the quality of the solution may also be considered, based on the work by Maggioni and Wallace (2012).

Our model is intended for a price-taker power producer, i.e. a producer who cannot influence the electricity price.

The model determines the investment plan associated to an optimal trade-off between the Net Present Value of profits and the risk of getting a negative impact on the profit due to the realization of undesired scenarios: this weighted combination of expected profit maximization and risk minimization undoubtedly may be perceived as a more general approach than *LCoE*, see (Bjorkvoll et al., 2001; Conejo et al., 2010; Vespucci et al., 2011a,b, 2013, 2014). The trade-off between Net Present Value of profits and risk is expressed as the convex combination of expected discounted profits and a suitable risk measure, namely the Conditional Value at Risk (*CVaR*).

When considering risk in multi-stage stochastic optimization, it is important to ensure, at every node in every stage, that planned decisions are consistent with actual decisions. This concept, known as "time consistency", has been borrowed from dynamic programming and it has been addressed by several authors in the context of multi-stage stochastic programming (see e.g. Philpott and de Matos, 2012; Rudloff et al., 2011; Ruczcynski, 2010). In order to ensure time consistency in a multi-stage framework, the *CVaR* risk measure has to be suitably defined. The use of a time consistent *CVaR* ensures that the flexibility and optimality of a dynamic policy will not be modified by unplanned future decisions: indeed, the first stage decisions of a time inconsistent policy are in general suboptimal, since this policy would not be followed in the future by an actual implementation. The requirement of a time consistent *CVaR* has a high impact on the complexity of the problem, but it guarantees a reliable solution.

Models for power generation capacity expansion have been proposed by several authors. Early approaches consider a vertically integrated system, where a monopolistic operator, in charge of both production and transmission, has to define a strategic power generation capacity expansion plan with the aim of minimizing production costs (see e.g. Booth, 1972; Stoughton et al., 1980). For this class of models an early stochastic approach is in Noonan and Giglio (1977), where a mixed-integer multi-period model is proposed for determining type and size of power plants to be built in a particular point in time: in this model the risk of having unmet demand is modeled as a chance constraint, with demand represented by a normally distributed random parameter. More recent models define the power generation capacity expansion problem as a two-stage (Albornoz et al., 2004), multi-stage (see e.g. Shiina and Birge, 2003) or multi-criteria (Han et al., 2009) decision problem in a relatively long time horizon with the aim of maximizing profit. Use of time consistent risk measures in the context of multi-stage power generation capacity expansion has not been considered in any of these works.

Our work mainly focuses on designing a risk averse time consistent multi-stage stochastic mixed integer optimization model by using an extension of our previous results (see Vespucci et al., 2011a; Vespucci et al., 2011b; Vespucci et al., 2013). In Genesi et al. (2009) a Monte Carlo approach to the problem has been used. The remainder of the paper is organized as follows. Section 2 provides an introduction to the *LCoE* analysis as a standard tool for determining the most profitable production technology; the introduction is complemented with an application to analyze the profitability of different production technologies. Section 3 introduces the main concepts and notation to be used in our multi-stage mixed integer linear programming approach, including the risk aversion strategy to be used. Section 4 specializes the risk aversion strategy presented in Section 3 to take into account the effects of time consistency in the decisions. Section 5 reports the computational experience for the case study. Using a time consistent risk measure we analyze the hedging effect, as the weighting parameter varies between zero and one, against the negative impact on profit in case an unfavorable scenario occurs. A further set of analyses is then performed to study the impact on profits and on investment decisions of different budget levels. Section 6 concludes and outlines future research work.

2. The Levelized Cost of Electricity

The *LCoE* is a standard business tool that evaluates the investment in a single plant or single technology. It defines the price at which electricity must be sold from a specific source in order to break even over the life span of a given technology.

The *LCoE* computation considers several internal cost factors, which can be roughly classified as CAPital EXpenditures, for costs concerning investments, and OPerational EXpenditures, for costs concerning fuel, maintenance and other operational costs. Generally, *LCoE* is the cost that averages the CAPEX and OPEX over time. For the sake of completeness we computed this value also including incentives to power production from RES, which results in a lower *LCoE* value for these technologies. The *LCoE* is defined by the equation

$$\sum_{t=1}^{n} \frac{E_t \cdot LCoE}{(1+r)^t} = \sum_{t=1}^{n} \frac{I_t + M_t + F_t + T_t + \pi_t^{GC} \cdot GC_t + \pi_t^{CO_2} \cdot Q_t}{(1+r)^t}, \qquad (1)$$

where r is the discount rate, computed as the weighted average cost of capital, n is the number of years in the industrial life of plants of the considered technology and t is the year index: for year t, $1 \leq t \leq n$, E_t is the electricity production, I_t is the investment expenditure, M_t is the operations and maintenance expenditure, F_t is the fuel expenditure, T_t is the amount of taxes paid, GC_t is the number of Green Certificates, Q_t is the amount of CO_2 emitted, and π_t^{GC} and $\pi_t^{CO_2}$ are the Green Certificate price and the emission permit price, respectively.

The *LCoE* computed for four technologies, namely coal, Combined Cycle Gas Turbine (CCGT), nuclear and wind, are reported in Table 1. Each project is assumed to be uniquely financed by equity capital. We included the electricity price in order to obtain, for each production source, the related Net Present Value. This enabled the deployment of a profit oriented evaluation tool to be used for comparison with our planning model. Data has been withdrawn from different sources and values for each entry are averaged over the different sources (among others, see Electricity Working Group, 2008; GPRA reports, 2008; Lazard, 2008; M.A.R.K.A.L. Inputs, 2008; McKinsey, 2007). Revenues obtainable and related stochasticity are not considered. Due to stochasticity, profit stemming from producing energy through different sources can vary to a large extent. *LCoE* tends to be larger when a producing technology has not yet reached maturity and steadily decreases after that. The point in time where the *LCoE* equals the price of electricity in the grid is called *grid parity*.

Table 1
LCoE estimates for coal, CCGT, nuclear and wind onshore.

	Coal	CCGT	Nuclear	Wind onshore
Lifetime (years)	25	20	40	20
Interest rate (percentage)	7.53	7.53	7.53	7.53
Overnight capital cost (M€/MW)	1	0.47	2.45	1
Capacity factor (percentage)	90	70	91.3	26.3
Fixed O&M cost (M€/(MWyear))	0.02	0.0095	0.07	0.02
Variable O&M cost (€/MWh)	0.17	0.025	0.46	0
Efficiency (percentage)	44	56	34	–
Fuel cost (€/MWh)	8.33	29.975	1.54	–
Energy price (€/MWh)	106	106	106	106
NPV/Investment	1.641	1.426	0.771	1.431
LCoE	72.79	91.478	72.705	−0.850