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A Comparison of Methodologies Incorporating Uncertainties into Power Plant Investment Evaluations

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Abstract

This paper offers a comparison of techniques proposed to deal with uncertainties existing in power system expansion planning. Diverse approaches developed or applied over the past two to three decades are surveyed and classified into the conventional and new ones according to their predominant application in the regulated and liberalized time. Based on the current literature, conclusions on the potential of developing new methodologies able to meet the requirement of power plant investment evaluations in the coming years are drawn.

1 Introduction

The United Kingdom stands as a pioneer in Europe, for being the first country to have undertaken the restructuring of its electricity market. Since then, liberalization has been gradually implemented in the electricity sector of other countries. The main objective pursued by the liberalization of electricity markets is to reduce costs by increasing competition in the wholesale and retail sectors, where traditional monopolies had always prevailed. Under this new framework power plant investors have to take various additional concerns into account in their decision-making. The most significant of these concerns is the exposure to diverse uncertainties, both in relation to the market fundamentals and to the strategy of their competitors. Therefore, the development of methodologies capable of incorporating and effectively handling relevant uncertainties into investment evaluations is a new challenge, one that researchers are taking up.

In the next sections, we will briefly introduce the most important changes on the electricity market brought along by liberalization, and the major uncertainties that need to be taken into consideration when planning new power generation projects.

1.1 Changes through market liberalization

We will describe the most significant changes in the electricity industry since the liberalization focussing on three aspects: the ownership and thus investors of power plants, benchmarks for evaluating power plants investment projects and regulatory policies designed to guarantee the adequate electricity supply.

In the pre-liberalization times generating utilities were mostly state owned and operated. With liberalization the electricity sector was entirely or partly opened to private investors. Prior to liberalization the goal in power plant investment and operation was cost minimization. With the penetration of private investors into the market and increased competition, that goal switched to profit maximization. In regulated markets the main concern while planning for new capacity was to offer a sufficient supply. Generators were not under pressure, since all the costs relating to the power supply, even those costs resulting from their adversarial decisions, could eventually be transferred to the consumers. But with the market liberalization electricity prices are no longer fixed at a previously negotiated tariff, but set by the market equilibrium. In other words, generators have to take a loss for their own account.

Electricity has always been a commodity under much more uncertainties than other common ones. The great capital intensity and long lead time of most power plants make it even more difficult to ensure an adequate delivery solely depending on the market mechanism. For the liberalised electricity market, diverse concepts are developed to ensure system reliability. The most important ones are *energy only*, *capacity payment*, *capacity market* and *reliability contracts* [1]. In general, no company has an obligation to invest in new power plants. In the case of shortage of generating capacity, these mechanisms should create incentives for new investments. In the German market for example, the energy only principle is implemented. This leaves the creation of investment incentives to the market. In addition, a market for balancing energy serves to ensure short-term security on an energy and capacity payment scheme.

1.2 Main uncertainties on the regulated and deregulated electricity market

Relevant uncertainties for the power plant investment can be differentiated between the ones which all along exist but did not really play an important role due to the centralised market regulation, and the ones which have emerged under the new framework of liberalization.

Either on a regulated or liberalized market structure, demand is noticeably one of the most uncertain factors in the power plant planning. The long-term development trend of electricity demand is strongly dependent on various factors such as the growth of population, gross domestic product, employment and so on. The difficulty in properly forecasting these factors and the complexity of analysing their correlations significantly complicates the determination of the development of the demand. During the power plant investment evaluation not only the long-term trend of the demand but also the load curve must be considered. In the short-term, the load profile presents an obvious periodical cycle because of the strong dependency of the electricity demand on the meteorological conditions. Nevertheless, in the historical data many exceptions appeared which could have hardly been foreseen in time. From both points of views, ensuring a sufficient power supply or maximizing profits, demand forecasting constitutes one of the key points in power system planning.

Uncertainties associated with fuel prices were earlier not a substantial concern for power plant investors, since the increased expenses created by eventual high fuel prices could be regained through raising the electricity prices. As mentioned above the electricity prices on the liberalised market are set by the supply-demand equilibrium. Therefore, as a significant part in the operating expenses, fuel costs will eventually influence the investment profit. In the past few years fuel prices, especially of crude oil, have experienced a very high degree of volatility (from the historical low of barely10$/barrel in December 1998 to around 60$/barrel by the time of this writing). The lack of transparency on the supply side and difficulties to foresee the demand, both contribute to the price instability. Furthermore, natural gas, which serves as an important alternative resource for oil products, has for long been priced with a tight link to oil. In this respect, volatile oil prices would directly result in volatility of gas prices. Although other fuel prices show a relatively lower volatility, modelling their long-term development still presents a complex task.

Electricity is characterised as a price inelastic product since the regulated times. Still now, little elasticity of demand to prices can be identified. But conversely, changes in the generating structure caused by addition of new capacities will lead to changes in the pricing. Behaviour of other suppliers makes it nowadays even more difficult to forecast the electricity prices.

The above implies that in a liberalised environment, not only the electricity prices are set by the market, but also the selection of new generating technologies is subject to it. Technological innovation however, has always been an unpredictable and sometimes even accidental occurrence. Managing risks with a diversification of the energy mix has already been taken into consideration by power plant investors.

Just like in regulated time, energy policies related to electricity market can impact the investment decisions to a great extent. The introduction of the greenhouse gas trading system and the decision to phase out nuclear power, for example, has aroused intense discussions regarding a necessary change of the energy mix.

1.3 Paper structure

The rest of this paper is structured as follows: in section 2 diverse methods to evaluate investment under uncertainty will be introduced. They are compared according to the different techniques used to incorporate uncertainties. Section 3 consists of a case study evaluating a test power plant investment project through the application of three selected methods discussed. The final section analyzes the results and draws conclusions about the trend in the development of future methodologies.

2 Comparison of conventional and new methods with their application to power plant investments

2.1 Conventional methods for the regulated planning

The literature surveyed in this paper traces back to the mid eighties. Since then, incorporating uncertainties into power plant investment evaluations or power system expansion planning has been gradually attracting the attention of the planers. With the assumption of perfect foresight parameters such as power demand, fuel prices were formerly considered to feature a deterministic development. In order to achieve a more realistic planning, sophisticated methodologies dealing with uncertainties were added to the existing models, still restricted to meeting the future power demand with a given reliability at minimum costs. In other words, the motivation of incorporating these uncertainties into the modelling is to a great extent to avoid the cost penalty from inefficient generating structure.

In the first part of this section, an introduction of traditional approaches will be given. We focus on the ones which, during the regulated time, had been most commonly discussed in the literature dealing with power expansion planning under uncertainties. A fairly extensive working paper of the World Bank [2] suggests classifying these approaches in the following three categories: (i) stochastic optimization, (ii) robustness analysis or trade-off analysis and (iii) option value methods. In another article [3] comparing several solving methodologies addresses this issue with a different classification. In the absence of option value methods it includes the approach of deterministic equivalent in the discussion. With an in-depth sight in the methodological development, it is not difficult to conclude that the deterministic equivalent approach presents the first step towards incorporation of uncertainties, although the way on which it handles the uncertainties appeared to be too simple. The term option value derives originally from the finance market, and more specific, from the stock markets, where it is used to denote opportunities to sell or buy stock shares. Its extension for power economics can still be frequently found in recent literature. Hence, option value methods also stand for a significant subject in the research of new methods in this paper. All of these four categories are to be described next.

Deterministic Equivalent

In the deterministic equivalent approach, investment planning is formulated as a traditional linear optimization problem. To keep a clear overview, we simplify the investment planning problem with the following formulation:

$$\underset{\{L_{i,t},Q_{i,t}\}}{Min} \sum_t \sum_i (fc_{i,t} \cdot L_{i,t} + oc_{i,t} \cdot Q_{i,t}) \tag{1.1}$$

Subject to

$$L_{i,t} \geq l_{i,t} \qquad \forall i,t \tag{1.2}$$

$$\sum_i Q_{i,t} \geq D_t \qquad \forall t \tag{1.3}$$

$$Q_{i,t} \leq \rho_{i,t} \cdot \sum_{\tau=1}^{t} (L_{i,\tau} + L_i^0) \qquad \forall i,t \tag{1.4}$$

$$L_{i,t}\, ,\ Q_{i,t} \geq 0 \qquad \forall i,t \tag{1.5}$$

Where:

$fc_{i,t}$	Specific investment costs of technology *i* in time stage *t*
$oc_{i,t}$	Specific operating costs of technology *i* in time stage *t*
$L_{i,t}$	Investment variable for technology *i* in time stage *t*
L_i^0	Existing capacities of technology *i* prior to the planning horizon
$l_{i,t}$	Minimum investment capacity of technology *i* in time stage *t*
$Q_{i,t}$	Production variable for technology *i* in time stage *t*
D_t	Demand in time stage *t*
$\rho_{i,t}$	Time-dependent availability of technology *i* in time stage *t*

This intends to find an optimal power plant investment plan in terms of deciding on technologies, investing time, investing capacities as well as operating power plants, so as to meet the future demand taking into account the availability of the installed capacity.

As the name deterministic equivalent implies, it actually deals with deterministic constraints. Uncertain factors as demand and fuel prices are initially assumed to be constant for each time stage. Their values are to be estimated based on the currently best available information. Thus, the investment schedule determined by the deterministic equivalent is only optimal as viewed from the current time stage. In the succeeding stage, new forecasts are to be assumed. After updating the data investment strategies from this stage will be again decided by recalculating the optimization problem. This process recurs till the end of the planning horizon.

As already pointed out in [3], the deterministic equivalent approach does not necessarily lead to the most adequate investment plan, because the optimization in each stage is obviously just reasonable for a limited period of time. In this context, although the deterministic equivalent approach does not imply a computational complexity, it is usually not able to provide a plausible advice for the long range. Yet it might be more interesting for the projects which possess the flexibility to be readjusted during the execution process without resulting in substantial losses.

Robustness Analysis

In general, power system planning is a complex task which usually faces more than one objective. In some cases these objectives even conflict with each other. For example, while aiming at a possibly economical generation expansion, the system planner must simultaneously assure certain system reliability with extra capacities that are left unused for most of the time. The robustness analysis approach was developed to solve such problems with multiple objectives. Its principle is to find a so called robust decision with a trade-off analysis among the conflicting objectives. In [4] this methodology was further extended for its application under uncertainty.

During the first step of seeking a robust plan, all the possible scenarios are summarized. The amount of scenarios depends not only on the investment alternatives the planner might prefer, but also on the possible future states of uncertain factors. These scenarios describe all the situations the decision-maker would eventually confront after the plan is carried out. Furthermore, if the uncertainties are modeled probabilistically, a corresponding probability can be calculated for each scenario. To avoid getting into a catastrophic extent right from the start, it is recommended to carefully define the meaningful plan alternatives and relevant influencing factors. In addition, the objectives pursued in the planning should be interpreted with quantifiable functions, e.g. the minimization of the total costs or the maximization of an index for the environmental compatibility. Their values are subject to the scenario specific attributes:

$$f_r(s) = \sum_{j=1}^{J(r)} a_{r,j}(s) \qquad \forall s \in S \tag{2}$$

Here $f_r(s)$ stands for the value of r-th objective in the s-th scenario from the scenario set S. Equations contributing to compute $f_r(s)$ are $a_{r,j}(s)$, whose definition and number $J(r)$ are determined by the objectives.

After the problem formulation described above the trade-off analysis follows. The trade-off analysis intends to identify the best compromise in the set of objective values. Without considering uncertainties, the simulated scenarios are identical to the investment alternatives. Therefore, objective values of a scenario can be seen as the objective value of the corresponding investment alternative. According to [4] the dominance between two alternatives can be differentiated between the *conditional strict dominance* and the *conditional significant dominance*. The former is obtained if the selected alternative always has a better value than the other one for each objective. The latter means that the dominant alternative has at least one significantly better objective value and no significantly worse than the other candidate.

To generalize the observation to uncertain cases where the occurrence probabilities are given, risk analysis techniques like Monte Carlo simulation are applied to calculate the dominance probability of an alternative relative to another one. Dominance definitions are also extended to the *strict global dominance* and the *significant global dominance,* respectively with a predefined probability, say *p*.

On the basis of the global dominance determination of every two alternatives, the decision sets *trade off curve set* and *knee set* can be extracted. Trade off curve set consists of all the alternatives which are not strictly globally dominated by any other. A knee set is the collection of all the alternatives which are not significantly globally dominated by any other.

In the process of finding the decision set, the inferior alternatives are eliminated. In order to define the final plan, it is subsequently important to analyse the decision set by examining other additional questions as robustness of the alternatives, their performance regarding a particular objective and their flexibility.

Stochastic Optimization

Adapted from the mathematical programming, the stochastic optimization approach has been frequently applied in multi-stage investment planning under uncertainty, hence also in power system expansion planning. Its application usually bases on the scenario analysis, which identifies different states of the future depending on the possible evolution of uncertainties. The objective of stochastic optimization however, is not to find the optimal solution for each scenario, but to determine the decision that best fits all of them. Therefore, this global optimum may not be the ideal solution for some of these scenarios, but it represents the best one for the whole set.

To illustrate the application of the procedure to a power plant investment problem, we continue taking the simplified formulation (1.1) as example. First we reformulate it by adding stochastic characteristics:

$$\underset{\{L_{i,t},Q_{i,t,s}\}}{Min} \qquad \sum_{i}\sum_{t}\sum_{s} p_s \cdot (fc_{i,t} \cdot L_{i,t} + oc_{i,t,s} \cdot Q_{i,t,s})$$

(3.1)

Subject to

$$L_{i,t} \geq l_{i,t} \qquad \forall i,t \tag{3.2}$$

$$\sum_{i}\sum_{s} p_s \cdot Q_{i,t.s} \geq \sum_{s} p_s \cdot D_{t,s} \qquad \forall t \tag{3.3}$$

$$Q_{i,t,s} \leq \rho_{i,t} \cdot \left(\sum_{\tau=1}^{t} L_{i,\tau} + L_i^0 \right) \qquad \forall i,t,s \tag{3.4}$$

$$L_{i,t},\ Q_{i,t,s} \geq 0 \qquad \forall i,t,s \tag{3.5}$$

In (3.1) the specific operating cost is extended to a scenario-dependent term and an occurrence probability p_s is associated to the scenario s. In this context, the objective function is equal to the expectation of the single scenarios.

The formulation of an investment problem in a stochastic optimization model does not seem to be very difficult, assuming that potential technologies, their technical performance and evolution of uncertainties as demand and fuel costs are given. With the involvement of additional factors, hence increasing the number of scenarios, the complexity of such problem grows exponentially. Before the appearance of the sophisticated computing technology available today, the greatest challenge in applying this methodology was solving such problems. Additionally, equation (3.4) complicates the case by making it multi-stage.

In the literature on the stochastic optimization approach surveyed, the Benders decomposition algorithm [5] appears to be the most popular instrument to solve the multi-stage stochastic problem. The crucial point of applying this technique is to transfer the single complex problem into a master problem and a set of sub problems. [6] suggests dividing the power plant investment problem into an investment problem and an operation problem, each representing the master problem and the sub problems respectively. Solution via this division can be achieved by iterative optimization. To illustrate this concept, we replace the formulation (3) with (3') and (3'') as following:

Master problem:

$$\underset{L_{i,t}}{Min} \quad \sum_i \sum_t fc_{i,t} \cdot L_{i,t} \tag{3'.1}$$

Subject to

$$L_{i,t} \geq l_{i,t} \qquad \forall i,t \tag{3'.2}$$

$$L_{i,t} \geq 0 \qquad \forall i,t \tag{3'.3}$$

Sub problems:

For each $s \in S$:

$$\underset{Q_{i,t,s}}{Min} \quad \sum_i \sum_t oc_{i,t,s} \cdot Q_{i,t,s} \tag{3''.1}$$

Subject to

$$\sum_i Q_{i,t.s} \geq D_{t,s} \qquad \forall t \tag{3''.2}$$

$$Q_{i,t,s} \leq \rho_{i,t} \cdot \left(\sum_{\tau=1}^{t} L^*_{i,\tau} + L^0_i \right) \qquad \forall i,t \tag{3''.3}$$

$$Q_{i,t,s} \geq 0 \qquad \forall i,t \tag{3''.4}$$

Where:

L^* Optimal solution of the master problem $(3')$

During the optimization, the master problem $(3')$ is to be updated during each new iteration. This is done by changing the so called "Benders cut" θ and the additional linear constraint associated with θ (see Figure 1).

A convergence test is introduced to control the termination of the iterative optimization process by examining the upper bound UB and the lower bound LB, which are initially set to the positive and negative infinity. The iteration procedure continues until the convergence constraint is fulfilled.

The scheme of optimizing problem (3) using the Benders decomposition technique is shown in Figure 1.

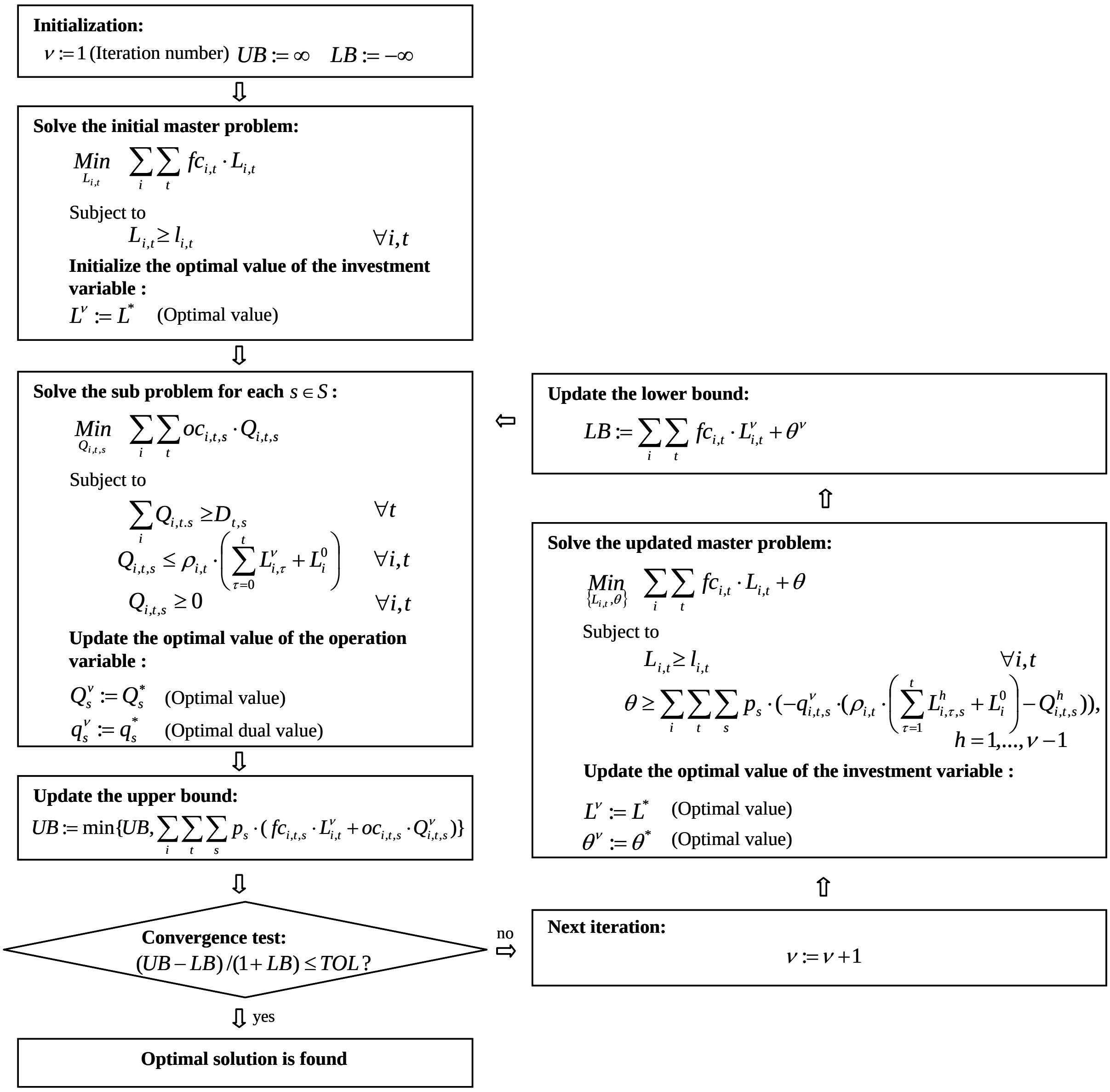

Figure 1: Illustration of optimizing power plant investment with Benders decomposition technique

Thanks to the notable progress in computing techniques made in the last decade, many softwares capable of solving large mathematical programming problems are now available. The difficult process of Benders decomposition is already embedded in the solvers of these softwares, which can be applied to a properly formulated problem, without the user having to possess detailed knowledge about the technique. Such a solver (CPLEX) is for example provided by the mathematical programming software GAMS, and was used to solve the E2M2s model developed in [7], on which an exemplary calculation of the case study in this paper is based.

The Option Approach

Contrary to the methodology described before, the option approach examines the profitability of an investment project and not only its costs. The term “option” here differs somehow from its origin on the financial market, where an option is an instrument to protect against risks. An unexercised investment can be seen as an option, because the opportunities for delaying, canceling and eventually switching to other projects are kept alive. However, the investment should feature the irreversibility and the flexibility, i.e. the ability to wait, as defined in [9]. The irreversibility denotes that the investment becomes valueless if it is identified to be unprofitable. Its expenditure, which represents sunk costs, can not be regained through selling the equipment or using it for other purposes. In fact, this property exists to a certain degree in most cases.

The distinct principle that differentiates the option approach from the traditional net present value rule is the pricing of the flexibility with an option value. Using this approach, investors expect a return which not only covers the costs, but also the option value. The ability to wait is valuable and sometimes can bring great benefit, because it allows obtaining more explicit information about the evolution of uncertain factors.

Prior to the market liberalization, the option approach was not commonly applied to the power plant investment problems as the other ones. Some reasons are considerable. Firstly, the way the option approach evaluates an investment, i.e. according to its profitability, is not conventional. Some authors (e.g. [2]) argue that the maximization of profits for the pre-liberalized power market should lead to the same result as the minimization of costs, since the demand is unchanged. This hypothesis however does not hold for an imperfect market, where the prices are not set by the competition equilibrium. Another reason could consist in the lack of flexibility to delay an investment on the regulated market. Despite these unfavorable concerns, some basic ideas to adapt the option approach in power plant investment can still be identified. In [9] for example this method was applied to a two-stage investment project which should decide whether to install one 200-MW coal-fired plant or two 100-MW oil-fired plants to meet a yearly demand increase of 100 MW. While assuming the demand increase to be known, uncertain fuel prices are taken into account. In this case the scale is compared to the flexibility. Although the lager coal plant complies with the economy of scale, investing in an oil plant in the first year provides the possibility to switch in other technology if the oil price turns to be disadvantageous.

In recent years the option approach has attracted much more attention, not only in the evaluation of investment problems, but also in the operation of power systems. In the next part of this section we are going to discuss this approach once again, this time in the framework of a liberalized market.

2.2 New methods for the liberalized market

It is not very exact to define the methods as new ones, since they already existed and were applied in the time before market liberalization. They are seen as new in the light of the modification and extensions required to make them fit for the new environment.

In contrast to the power generation planning of the regulated era, decision on power investment on the liberalized market are done based on the profitability rather than on system adequacy. As indicated by the macroeconomic theory, the maximum of social welfare could be reached by the profit maximization of each individual market participant. However, this doctrine is only tenable under the assumption of a perfect market. Some electricity markets do not fulfill this prerequisite despite being liberalized. As an example, although the German market is 100% liberalized, it can be better described as an oligopoly, where the four largest utilities still possess the dominant positions. On the other hand, electricity consumers do not respond to the price change as much as before. Therefore classical economic rules may not be suitable for electricity markets and supplementary instruments should be developed to provide a secure power supply.

Discounted Cash Flow Approach

The discounted cash flow (DCF) approach was introduced in an OECD report [15]. It takes uncertainties into account in a general way, in which a discount rate is assumed for the estimation of all major cost components. The determination of this discount rate bases on an assessment of various uncertainties with different scenarios. The OECD study states that companies can apply the DCF approach at comparing different technologies, with predefined internal target for return on equity. To additionally handle uncertainties in revenues, the authors advise to estimate another discount rate for revenues different than the one for costs.

Based on the recent update of an OECD study [16], a methodology to calculate the so called "Average Lifetime Levelised Electricity Generation Cost" is introduced. The principle is to find a reference cost of a project by making the present value of its total costs equal to the present value of its revenues over the lifetime. Equation (4) explains this methodology in the mathematical context.

$$\sum_{t=0}^{T}\frac{p^{*}\cdot E_t}{(1+r)^t}-\sum_{t=0}^{T}\frac{I_t+M_t+F_t}{(1+r)^t}=0 \tag{4}$$

Where:

p^{*}	Reference cost to be defined
r	Risk-adjusted discount rate
E_t	Electricity generation in the year t
I_t	Investment expenditures in the year t
M_t	Maintenance expenditures in the year t
F_t	Fuel expenditures in the year t

By solving (4) p^{*} can be calculated by applying the following formula:

$$p^{*}=\frac{\sum_{t=0}^{T}(I_t+M_t+F_t)\cdot(1+r)^{-t}}{\sum_{t=0}^{T}E_t\cdot(1+r)^{-t}} \tag{5}$$

Using the reference costs to estimate different investment options offers the calculation simplicity and the comparison convenience. However, the selected discount rate is not self explanatory since the way how the discount rate is determined by including all uncertainties into this factor is obscure. Furthermore, whether it is appropriate to treat uncertainties in each year based on the same discount rate is also questionable.

Real Options Approach

In section 2.1 an introduction for the basic principle of the option approach and a preliminary example of its application to the power plant investment problem were provided. The adaptation of the financial option for real assets investment, which is therefore named “real options”, had been discussed over the last two decades. It was however not widely accepted on the regulated power markets. Due to the enormous change of market fundamentals since the liberalization, many researchers have involved the real options approach in their analysis of some aspects of the power system e.g. utility investment and unit commitment. Botterud et al. [10] devises a model to calculate the optimal power generation investment strategy under both centralized social welfare and decentralized profit objectives. In [11] this model is even extended to analyze the effect of investment incentives on the system adequacy of an electricity market with the capacity payment mechanism. Roques et al. [12] deal with an interesting observation on the liberalized power market that individual investors tends to prefer fossil fuel technologies (carbon, nature gas) against nuclear power. They explain this issue by showing the decrease of the option value of the nuclear technology with a rising correlation between electricity, gas and carbon prices. In order to consider the behavior of other market participants in investment decisions Murto [13] develops a method combining the real options approach with game theory to incorporate the competitive interaction into investment evaluations.

Since this paper concentrates on the evaluation of power generation projects, the methodology developed by Botterud is fairly representative for an application of the real option approach. He illustrates the differentiation of the real option theory from the classical net present value (NPV) method with the diagram of Figure 2.

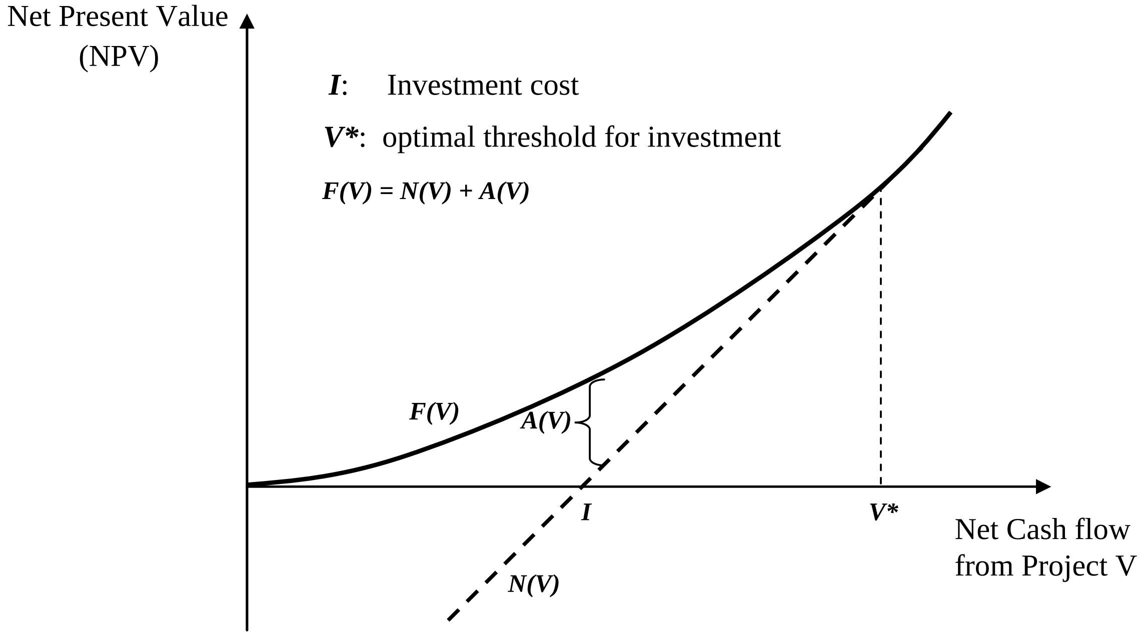

Figure 2: Illustration of the difference between the real options approach and the NPV method

The curve *N(V)* shows the NPV over the range of potential net cash flow of the project. The classical NPV method would suggest investing as soon as the net cash flow exceeds the investment costs *I.* According to the real options theory, it should however not yet be invested until the NPV of the project exceeds the value of the investment option. The option value $F(V)$ results from the NPV of the project plus an additional value $A(V)$ of postponing the investment decision to wait for more information about future trends of uncertainties. In this context, decision-making using the static NPV method treats the investment rather as a “now or never” task.

In the multi-stage model developed in [10], demand is the only factor considered as uncertain. A long-term and a short-term uncertainty are taken into account. Furthermore, to quantify the risk aversion of the investor, a risk-adjusted discount rate is used. The model underlies the objective of maximizing the social welfare or the investment profit by determining the optimal technology and investment timing. To solve this model the stochastic dynamic programming is used for a backward optimization. Because the dynamic programming implies a great mathematical complexity and it does not belong to the scope of this paper, it will not be discussed in detail.

The model in [10] unfortunately has some limitations, since the electricity market is considered as a single-agent system. Thus the interaction between different market participants is disregarded. It is also assumed that investors are purely price taker. But on the competitive power market, electricity price could be influenced to a great extent, e.g. when a new large scale power plant becomes available. To take the impact of new capacities on the electricity prices into the model, Keppo and Lu [14] include the price effect in the calculation of the option value, considering that not only the value of the new plant but also the value of other existing plants of the investor is subject to market prices. The value of a real option can then be extended to the following expression:

$$F(V) = N(V) + A(V) - L(V) \tag{5}$$

The term $L(V)$ demonstrates the lost value due to lowered market prices being caused by the investment. A similar conception can be found in [17] where the author defines the value of a company as the composition of its operative, strategic real options and the value of its real assets calculated on the basis of the adopted strategy.

A significant advantage pointed out in [9] as well as in [17] is that applying the real options approach avoids the selection of a risk-adjusted rate. The investment evaluations calculate directly with the risk-free rate while including uncertainties with their stochastic profiles in the evaluation process.

Although the application of the real options theory in the power system presents a substantial progress in the methodology development, but the transfer of this concept from the finance market is frequently criticized due to the imperfection of the electricity market and lower liquidity on its trading possibilities. Therefore, pricing of a real option based on the market is difficult [18]. Another difficulty is indicated in the acquisition of option-specific input data as stochastic coefficients describing the volatility of the fuel price development.

2.3 Method comparison

In this part we present a brief review of the surveyed methods by comparing them according to four characteristics, as illustrated in Table 1.

		Stochastic	Dynamic	Analytical	Computational complexity
Pre-liberalization	**Deterministic Equivalent**	-	-	-	low
	Robustness Analysis	√	-	-	low
	Stochastic Optimization	√	-	√	high
	Option Approach	√	√	√	very high
Since liberalization	**Discounted Cash Flow Approach**	-	-	-	low
	Real Options Approach	√	√	√	very high

Table 1: Comparison of discussed methods

3 Case study for a test project

In this section the results of the application of three selected approaches introduced in section 2 to a case study are presented. It is important to note that data used for this case study is basically assumed for an exemplary calculation and does not reflect the reality.

In this example a company plans to invest in new capacities to meet the increase in demand in 2 consecutive years with an expected constant growth rate of 100 MW in each period. The two technologies available for this company to invest in are coal fired or gas fired plants. Due to technical constraints each coal and gas plant can only be built with a net installed capacity of 200 MW and 100 MW respectively. Demand and operating costs of the coal plants are assumed as certain. The evolution of the operating costs of gas plants on the other hand is assumed to present a given stochastic profile during the planning period and a constant growth rate afterwards. It is also agreed that the selected power plants could be ready for operation at the beginning of each year. In order to provide a comparable base, the lifetime and full load hours of both plants are equally set to 40 years and 5000 hours. A discount rate of 10% is chosen for the following calculations.

In Table 2 the parameters of the two plant types and the development of their operating costs are presented. The gas price in these two years is assumed to be particularly volatile.

	Capacity Cap_i [MW]	Investment costs fc_i [Mio. €]	Operation costs in base year [€ / MWh]	Operation costs growth rate		
				t=1	t=2	t=3…40
Coal fired plant	200	180	20	5%	5%	5%
Gas fired plant	100	50	40	$Pr_{50\%}$: 50% $Pr_{50\%}$: -50%	$Pr_{50\%}$: 50% $Pr_{50\%}$: -50%	5%

Table 2: Data of two candidate technologies

The stochastic profile given in Table 2 results in four scenarios for the development of future operation costs of the gas fired plant:

Scenarios S	**Probability** p_s	**Operation costs of the gas fired plant** $oc_{2,t,s}$ [€/MWh]	
		t=1	**t=2**
1	25%	60	90
2	25%	60	30
3	25%	20	30
4	25%	20	10

Table 3: Scenarios of future operation costs of the gas fired plant

We first formulate this investment project in a stochastic optimization problem aiming at the minimization of total costs during the planning period.

$$\text{Min} \quad \sum_{i=1}^{2}\sum_{t=1}^{2}\sum_{s=1}^{4}\left(\frac{fc_i \cdot Cap_i \cdot u_{i,t}}{1.1^{t-1}} + \frac{p_s \cdot oc_{i,t,s} \cdot Q_{i,t,s}}{1.1^{t}}\right) \tag{6}$$

Subject to

$$\sum_{i'=1}^{2} Q_{i,t.s} \geq D_{t,s} \qquad \forall t,s$$

$$Q_{i,t,s} \leq \sum_{\tau=1}^{t} u_{i,\tau} \cdot Cap_i \qquad \forall i,t,s$$

$$Q_{i,t,s} \geq 0 \qquad \forall i,t,s$$

$$u_{i,t,} \in \{0,1\} \qquad \forall i,t$$

Where:

$u_{i,t,}$: Binary decision variable, 1 stands for the investment in the technology *i*

The optimal solution of this project based on the stochastic optimization suggests an investment of a gas fired plant with 100 MW capacity for each period, with a total expense of 146.7 Mio. € during the planning period.

Further we apply the two approaches discussed as the new methods in the evaluation of the case study project. Three alternative investment plans are predefined and listed in Table 4.

Alternative 1 suggests an investment in 200 MW of capacity with one coal fired power. This respects the economy of scale rule. In contrast, Alternative 2 builds just the capacity which is required in each year and chooses a gas fired plant for each period. Alternative 3 combines both options by adding the exact capacity needed for the first year and a larger scale coal plant for the remaining time.

	t=1		t=2	
	Coal [MW]	Gas [MW]	Coal [MW]	Gas [MW]
Alternative 1	200	0	0	0
Alternative 2	0	100	0	100
Alternative 3	0	100	200	0

Table 4: Considerable investment alternatives

In the first step, the levelised cost method is applied to evaluate these three alternatives. The present value of total costs and the average lifetime levelised generation cost are calculated:

	p^* [€/MWh]	pv_{total} [Mio. €]
Alternative 1	56.32	525
Alternative 2	77.47	677
Alternative 3	64.08	692

Table 5: Calculation result with levelised cost method

According to the comparison in Table 5, Alternative 1 is obviously the most economical variant, not only regarding its average levelised costs, but also the present value of its total costs.

For the next evaluation, we use the real option theory to examine again the three investment alternatives.

Alternative 1 does not need to be modified and the present value of its total costs over the lifetime corresponds to the calculation result above. Alternative 2 and Alternative 3 will further be seen as an investment option which gives the possibility to wait for more information about the gas price development trend in the second year. If the gas price tends to be higher, which would raise the operation costs in the first year, the investor could switch the decision to a coal fire plant with lower fuel costs, or stick to the initial plan of building another gas plant. Based on this, we can calculate the present value of this option with the following formulation:

$$
\begin{aligned}
OV &= 50 \text{ Mio.€} \qquad\qquad (7)\\
&+0.5\times\Big(\frac{40 \text{ €/MWh}\times 1.5\times 100 \text{ MW}\times 5000\text{h}}{1.1}+\frac{180 \text{ Mio.€}}{1.1}-\frac{90 \text{ Mio.€}}{1.1^2}\\
&\qquad \sum_{t=2}^{40}\frac{20 \text{ €/MWh}\times 1.05^t\times 200 \text{ MW}\times 5000 \text{ h}}{1.1^t}\Big)\\
&+0.5\times\Big(\frac{40 \text{ €/MWh}\times 0.5\times 100 \text{ MW}\times 5000 \text{ h}}{1.1}+\frac{50 \text{ Mio.€}}{1.1}
\end{aligned}
$$

$$
\begin{aligned}
&+\frac{20\text{ €/MWh}\times 200\text{ MW}\times 5000\text{ h}}{1.1^{2}}\\
&+2\times\sum_{t=3}^{40}\frac{20\text{ €/MWh}\times 1.05^{t\text{-}2}\times 100\cdots\text{MW}\times 5000\text{ h}}{1.1^{t}})
\end{aligned}
$$

$$= 455\text{ Mio.€}$$

The present value of this option is significantly lower than that of Alternative 1. Therefore, building a gas fired plant in the first year and keeping the option for the following year should be the preferred decision.

As the evaluation result shows, the real options approach attaches additional value to the investment flexibility. The coherence between uncertainties and investment decisions can be quantitatively presented by real option models with the implication that the more uncertain the future is, the more valuable the option is and the longer the investment time will be delayed [18].

4 Conclusion

The methods discussed in this paper cover the main categories commonly used during the regulated time and those methods that are being extended for their application in the liberalized markets. The way each method incorporates uncertainties into power plant investment evaluations was described and compared. Through a case study the meaning of dealing with uncertainties in the decision making was demonstrated, and it was shown that it could lead to a totally different result than based on purely deterministic assumptions. Of all the methods described in this paper, the real options approach represents a novel approach with the ability to quantitatively estimate the flexibility of choosing between available technologies, determining investment timing and defining investment scale.

As shown in this paper, most methods dealing with uncertainties demand their quantitative description. Therefore, methodologies able to precisely model the uncertainties will be required to further improve these methods and their applicability. On the other hand, higher accuracy on the description of uncertainties may dramatically increase the complexity of the decision problem due to the stochastic and dynamic properties. Therefore, the development of methodologies to identify the significant influencing factors is another necessary and challenging task.

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