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Fuzzy Portfolio Optimization of Onshore Wind Power Plants

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Abstract

In this paper we apply fuzzy set theory to the portfolio optimization of power generation assets, using a semi-mean absolute deviation (SMAD) model as a benchmark and a fuzzy semi-mean absolute deviation (FSMAD) model for comparison. The two models are applied to five onshore wind power plants in Germany considered for the portfolio analysis. The results show that the combinations of favorable assets for efficient portfolios are very similar, although the portfolio shares are markedly different. Also, the return and risk span of the SMAD model are much broader than those of the FSMAD model. The highest returns are generated by portfolios based on the latter model. Offering less portfolio choices, the FSMAD model thus facilitates decision-making. This is in compliance with the notion that portfolio optimization by fuzzy set theory is able to better account for the decision-maker's preferences under real-world conditions.

Keywords: Monte Carlo simulation, Mean-variance portfolio analysis, Fuzzy set theory, Wind power

1. Introduction

Portfolio optimization applied to energy technology investments is useful, as return-risk considerations in the capital-intensive energy businesses play a central role just like in financial markets (for a recent review of the relevant literature, see Madlener, in press). Portfolio theory, introduced by Harry Markowitz in 1952, was initially used mainly to model, analyze, and optimize portfolios of financial assets, but also laid the foundation for the development of modern finance theory. The goal of portfolio optimization, on the one hand, is

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the maximization of return and, on the other hand, the minimization of risk. Still, in the context of power plant portfolios, i.e. real assets, the return and risk measures to be used need to be specified more carefully.

A number of studies have demonstrated the applicability of portfolio theory to power generation assets (for a useful review of the literature see Madlener, 2012). One of the first studies in this field is Bar-Lev und Katz (1976), focusing on the regulated US energy market. Awerbuch and Berger (2003) investigate the energy portfolio of the EU-15[1] and find portfolio diversification effects through the use of different energy production technologies. Krey and Zweifel (2006) deal with energy portfolios in the US and Switzerland, using the seemingly unrelated regression (SUR) estimation method for the modeling of correlated shocks among power generation costs. Borchert and Schemm (2007) model a portfolio of onshore wind power plants at fictitious, spatially non-diversified locations with the Markowitz optimization method, but extend the approach by using the conditional value at risk (CVaR) as a risk measure. Roques et al. (2009), by applying mean-variance portfolio theory, focus on the diversification of wind power locations at the European level. When optimizing spatially diversified wind parks, the differing remuneration schemes in the countries studied have to be taken into account as well. Westner and Madlener (2009b) study this issue in the context of portfolios of cogeneration plants[2].

Rombauts et al. (2011) investigate the diversification effects for wind power, taking into account cross-border transmission capacity constraints. They consider three models for addressing the case of zero, infinite, and some positive limited value transmission constraints.

Portfolio optimization by means of fuzzy set theory is a relatively young subfield of portfolio analysis. The focus so far was on applications in financial markets, for instance by Ramaswamy (1998) or Tanaka and Guo (1999), who aimed at finding an improved modeling approach for tackling the uncertainties and risk attitudes of investors, relative to what can be achieved by means of the classical optimization approach of Markowitz. Decision-makers are often subject to societal and economic influences that can bias the results from an optimization approach. Therefore, the approach followed in portfolio analysis by means of fuzzy set theory is to find a satisficing rather than an optimal solution, i.e. one that is sufficient to meet a decision-maker’s aspiration levels and preferences (Watada, 1997: p.220).

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[1] The EU-15 comprises all member states that were part of the European Union before the Central and Eastern European extension in 2003.

[2] For combined heat-and-power generation (CHP, cogeneration), similarly to wind power, there also exist a number of different remuneration systems across countries.

A useful review of the literature on how to transfer fuzzy portfolio selection procedures from financial to energy markets has recently been provided by Glensk and Madlener (2010).

In this paper, we demonstrate how fuzzy portfolio optimization can be applied to real assets in the energy sector, and in particular to a portfolio of onshore wind power plants in Germany that comprises five spatially diversified wind parks.

The remainder of this paper is organized as follows. In Section 2 we provide a brief introduction to the current situation regarding wind power in Germany. This includes the German system of guaranteed feed-in tariffs for promoting renewables, and economic aspects of wind power plants. Section 3 contains a discussion of mean-variance portfolio analysis applied to real assets, which is followed by the consideration of different risk measures. Subsequently, we show how fuzzy set theory can be applied to portfolio selection problems, and we introduce a fuzzy portfolio selection model as an alternative to the more conventional models used. The semi-mean absolute deviation (SMAD) is adopted as a benchmark risk measure. In section 4, based on our computations, we propose a portfolio optimization strategy that takes into account possible differences in the return-risk preferences of an investor. The results are compared to those obtained for the SMAD model. Section 5 summarizes the findings from our study and concludes.

2. Electricity generation from wind power: economic aspects

Below, we first provide an overview of the diffusion of wind power in Germany (section 2.1), followed by a presentation of the feed-in tariffs for onshore wind power plants according to the Act on Granting Priority to Renewable Energy Sources (Erneuerbare-Energien-Gesetz, EEG) (section 2.2) and a description of the economic modeling of wind power plants adopted in our study (section 2.3).

2.1 Wind power utilization in Germany: facts and figures

In July 2013, there were more than 23,400 wind turbines in operation in Germany, with a total installed capacity of almost 32,400 MW. In the first half of that year alone, the capacity increase was around 1,150 MW, due to 427 newly erected wind turbines. Thereof, 105 MW (or 21 wind turbines) were offshore wind turbines and about 22.7 MW (or 7 wind turbines) were (onshore) repowered plants[3]. Vice versa, 52 wind turbines with a total installed capacity

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[3] Repowering refers to the replacement of older wind turbines with lower capacity by modern, more powerful ones (see e.g. Himpler and Madlener, 2011; Madlener and Schumacher, 2011).

of about 18.1 MW were dismantled (Deutsche Windguard, 2013). The federal states (*Bundesländer*) with the highest installed capacities are Lower Saxony, Brandenburg, and Saxony-Anhalt, whereas the largest shares of the potential annual yield in net electricity consumption are to be found in Mecklenburg-Vorpommern, Saxony-Anhalt and Schleswig-Holstein (Deutsche Windguard, 2013; Statista, 2013).

If we consider the average installed capacity per wind turbine, there exists a noticeable trend towards turbines larger than 2 MW, compared to plants in the three-digit kW range that were common at the beginning of the 1990s (Neddermann, 2010). The costs of a new 2 MW plant with a rotor diameter of 90 m and a nacelle height of 105 m amount to about €2.2 million *ex work*; further costs of about 30% for the infrastructure in the wind park itself may occur on site (Kühn, 2007: p.17). Germany is still the leader within Europe with regard to the total installed wind power capacity as well as in terms of newly installed capacity; although China, the US and other countries are catching up rapidly (BWE, 2013). Wind power is thus an important component in the German energy mix, contributing about 9% of final electricity consumption, and will also play an important role in the future in achieving the renewable energy goals of the German government (cf. "Leitszenario 2009"; Burger, 2013)[4].

2.2 Feed-in tariffs for electricity from wind power plants

For more than twenty years, Germany has enacted laws for promoting renewable energies. In 1990, the Stromeinspeisungsgesetz (StrEG) was put into force; ten years later, in 2000, its successor, the Erneuerbare-Energien-Gesetz (EEG) entered into force. The two pillars of the EEG are, on the one hand, the guaranteed purchase, transmission, and distribution of renewable electricity (§8 EEG, 2009). On the other hand, there is a right to receive remuneration for this kind of electricity (§16 EEG, 2009). Without the EEG support scheme it would mostly be unprofitable to operate such green power plants, as the investment costs, despite technological progress and learning effects, are still relatively high. The effectiveness of the EEG becomes evident when considering the continuously rising shares of renewable energies in power production, but also when looking at the many countries that have in the meantime introduced similar renewable energy promotion schemes.

In the following, the feed-in tariffs granted for wind power are considered in more detail, with a special focus on onshore wind power plants. The base tariff for onshore WPP is 5.02 €-

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[4] For the year 2020, the "Leitszenario 2009" requires a share of renewable energies in gross electricity consumption of 40%, for the year 2050 even 50% (BWE, 2010a).

cents per kWh, whereas in the first five years after putting the plant into operation, an increased rate of 9.2 €-cents per kWh (initial remuneration) applies[5]. This duration is prolonged according to the EEG, i.e. by two months per 0.75% of the reference yield, by which the yield of the plant undercuts 150% of the reference yield, i.e. if the plant is situated at a location with less favorable wind conditions (§29 EEG, 2009). The reference yield is the yield of a reference plant at a reference location, calculated according to Appendix 5 of the EEG. It refers to a period of five years (FGW, 2010a). Reference yields for all common manufacturers and types of WPP can be found on the website of the Fördergesellschaft Windenergie e.V. (FGW). There, one can also find templates for the computation of the prolonged initial remuneration. The reference yield is computed as follows:

$$\Delta = \left(1.5 - \frac{SE}{RE}\right)266, \tag{1}$$

where Δ is the additional time span of the initial remuneration after expiry of the first five years (expressed in months), SE the electricity production (in kWh) of the WPP in the first five years after being put into operation, and RE the reference electricity production yield according to the EEG in the location of the WPP (FGW, 2010b).

An additional so-called ‘system service bonus’ of 0.5 €-cent per kWh (cf. §29(2) No. 4, EEG, 2009) is also paid for the duration of five years for electricity from plants that were erected between Dec 31, 2001 and Jan 1, 2009, and that, due to a retrofit to be effected before Jan 1, 2011, fulfill certain requirements regarding the improvement of grid integration (§66(1) No. 6, EEG, 2009).

According to §30 EEG, special rules continue to be applied for new, more modern plants replacing less powerful plants, the so-called repowering of plants. For these, a bonus of 0.5 €-cent per kWh is paid, provided the new plant produces at least double and no more than quintuple the amount of electricity generated by the old plant, and that it starts feeding in no earlier than ten years after the old, replaced plant was put into operation. The annual decrease of the remuneration rates is 1%, in order to provide incentives for cost reductions (or, vice versa, to account for cost reductions that occurred in order to avoid a widening of the profit margin). Table 1 provides an overview of the feed-in tariffs provided in the EEG 2009 for onshore-wind power plants, also considering the repowering and the system service bonuses, respectively.

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[5] Note that the feed-in tariffs according to the EEG 2009 are valid from the beginning of 2009. For previous years, the corresponding earlier EEG versions are relevant (see also Table A.2).

Table 1: Overview of remunerations for onshore WPP and degressions over time, 2009–2015 (EEG 2009)

Year of putting into operation [year]	Initial remuneration [ct/kWh]	Repowering bonus [ct/kWh]	System service bonus [ct/kWh]	Base remuneration [ct/kWh]
2009	9.20	0.50	0.50	5.02
2010	9.11	0.50	0.50	4.97
2011	9.02	0.49	0.49	4.92
2012	8.93	0.49	0.49	4.87
2013	8.84	0.48	0.48	4.82
2014	8.75	0.48	-	4.77
2015	8.66	0.47	-	4.73

Source: BWE (2010b)

2.3 Economic modeling of wind power plants

If one wants to transfer the return-risk considerations from financial to energy markets, care has to be taken that the terms are adjusted according to the new situation. On equity markets, one has to deal with investors who check shares and bonds with regard to their advantageousness. On energy markets, in contrast, projects are scrutinized before realization in order to avoid poor investments. In our study, we consider wind power projects, i.e. the planning and realization of wind parks. Brigham and Gapenski (1997) see some parallels between the valuation of shares and that of investment projects, and describe standard methods for conducting such economic evaluations, for instance the net present value (NPV), internal rate of return (IRR), modified internal rate of return (MIRR), profitability index (PI), payback (PB), and discounted payback (DPB) approaches.

Due to the relative simplicity of all these methods, in practice often several investment valuation methods are combined with each other. The NPV method still seems to be the single preferred method for the valuation of a project’s cost effectiveness (for more information regarding the comparison of the various methods and their pros and cons, see e.g. Brigham and Gapenski, 1997). As the NPV method is also frequently applied in the evaluation of energy projects, we decided to use this approach in the case study presented later on. In the NPV method, the cash flows are discounted with the capital cost over the lifetime of the project and then added up, i.e.:

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+k)^t} - I \, , \tag{2}$$

where CF_t denotes the cash flow in period t, k the discount rate, and I the total investment cost for the project considered. This method can be used both for projects in the planning phase and such already in operation. Whether or not an investment is profitable is determined by the sign of the NPV. If it is positive, then the investment can be expected to be profitable, whereas if it is negative, the investment should be avoided (Brigham and Gapenski, 1997: p.394). The cash flow with respect to a wind power project can be calculated as:

$$CF_t = R_{el\_S} - C_{O\&M} - \delta - CC\,, \tag{3}$$

where R_{el_S} are the revenues from electricity sales, $C_{O\&M}$ are the costs (fixed and variable) of operation and maintenance, δ is the depreciation, and CC the capital costs (see Westner and Madlener, 2009a: p.21). Later on, we will use linear depreciation over an assumed lifetime of 20 years. The annual capital costs can be calculated as:

$$CC = \left(I - (t-1)\delta\right)WACC. \tag{4}$$

The $WACC$ (weighted average cost of capital) is the interest rate with which the capital costs are discounted, computed as:

$$WACC = \frac{EC}{TC}c_{EC} + \frac{DC}{TC}c_{DC}(1-s)\,, \tag{5}$$

where EC denotes equity capital, c_{EC} cost of equity capital; DC debt capital, c_{DC} cost of debt capital, TC total capital ($EC + DC$), and s the tax rate which the firm is subject to.

In the literature, several approaches for the valuation of wind power projects exist. Here we want to again explicitly discuss the individual procedures and the specific variables considered. Borchert and Schemm (2007) use an annual return from the revenues of power sold via the EEG as well as the spot market and annual cost. The risk factors used are the revenues from the feed-in of electricity from wind power plants, split up into a volumetric and a price component. The uncertain price component is given by the possibility to choose between the feed-in tariffs according to the EEG and the spot market price. The uncertain volumetric component is given by the uncertain (stochastic) supply of wind. Moreover, annual operating costs are considered as uncertain and also modeled as a risk factor (Borchert and Schemm, 2007: p.316).

Roques et al. (2009) first optimize wind energy output by maximizing wind energy production, given a minimization of the hourly variability of production, and then maximize production given a minimization of the variability of peak-load hours (Roques, 2009: p.5).

Madlener et al. (2009) identify sources of risk for offshore wind power plants and show the application of the discounted cash flow (DCF) method for a concrete project example. As a risk measure, they use the cash flow at risk (CFaR). The study allows conclusions to be drawn about the economic merits of the investment project considered; the NPV (2) of the wind park investigated is calculated on the basis of the annual cash flows (3). The fluctuating wind supply is the only risk factor addressed, since the remuneration according to the EEG is fixed (over a period of 20 years), and since the selling of the electricity on the spot market is not explicitly modeled. Operating costs are also assumed as fixed.

3. Theoretical framework

In this section, we first briefly introduce the portfolio analysis after Markowitz (section 3.1), followed by a discussion of risk in a portfolio context and alternative risk measures that can be adopted (section 3.2). Section 3.3 presents some basics of fuzzy sets and the use of fuzzy set theory in a portfolio optimization context, while section 3.4 reports on the model that is later used for the empirical analysis.

3.1 Portfolio analysis after Markowitz

Still today, Harry Markowitz's paper "Portfolio Selection", published in 1952, describes an important tool in portfolio analysis and provides some background to the risk-return framework. The goal is to determine portfolios[6] that match with the prevailing preferences of an investor. Both historical stock data and expert opinions are used as information sources (Markowitz, 2008: p.2). The two most important characteristics of investments in financial assets are the uncertainty with regard to the returns, $E(R_i)$, and the correlation between the returns of the various assets, ρ_{ij} (Markowitz, 2008: p.4)[7].

The expected returns from the entire portfolio, $E(R_p)$, are computed as follows:

$$E(R_P) = \sum_{i=1}^{n} x_i E(R_i), \tag{6}$$

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[6] A portfolio in the sense of Markowitz is a large number of financial assets (Markowitz, 2008: p.2).

[7] Theoretically, the correlation values can range between -1 and +1. In the case of a correlation of -1, the risk of a portfolio can be fully compensated for an adequate splitting of the individual components. In contrast, in the case of a correlation of +1, the shares are concurrent and no diversification effects can occur (von Nitzsch and Rouette, 2008: p.34).

where $E(R_i)$ denotes the expected values of the individual components in the portfolio relative to the entire portfolio, x_i the shares of the individual components in the portfolio relative to the entire portfolio, and *n* is the number of assets. The risk, i.e. the uncertainty with regard to the returns of the entire portfolio, is represented by the standard deviation σ_P:

$$\sigma_P = \sqrt{\sum_{i=1}^{n} x_i^2 \sigma_i^2 + \sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq j}}^{n} x_i x_j \sigma_i \sigma_j \rho_{ij}}\ , \tag{7}$$

where σ_i denotes the standard deviation of asset *i*, σ_i^2 the variance of a certain component *i* in the portfolio, and ρ_{ij} the correlation between two different components of the portfolio.

3.2 Risk measures in a portfolio context

As mentioned in the previous section, the risk of a portfolio in Markowitz' approach is determined by the standard deviation σ_P (eq. (7)), which depends strongly on the correlation between the individual portfolio components. Moreover, this parameter has a big impact on the portfolio diversification effect as well as on the total portfolio risk. On the other hand, it may lead to computational problems, such as the need to use quadratic programming methods, in order to solve the proposed model. However, because in reality shares in a portfolio hardly correlate with each other negatively, it is almost impossible in practice to construct a riskless portfolio. And although the size of a portfolio can reduce the diversifiable risk, the market risk still remains (Brigham and Gapenski, 1997: p.162). The diversifiable risk stems from random events of a particular company whose shares are held in the portfolio. For the case of a sufficiently large portfolio, there will always be a company willing to compensate the negative effects by own positive events. The market risk in most cases concerns all participants; examples are inflation, recession, and war (Brigham and Gapenski, 1997: p.164).

Different risk measures can be used for the modeling of risk. The variance and the standard deviation computed thereof are a weighted average of the deviations from the expected revenues, indicating by how much the actual return is higher or lower than the expected return (Brigham and Gapenski, 1997: p.151). Given the fact that investors only consider the negative deviation from the expected value as a risk, Markowitz himself already suggested back in 1959 (Markowitz, 1959) using the semi-variance as a risk measure, which only considers values below the expected value (Fang et al., 2008: p.4).

Another representation, mathematically similar to the variance, is the mean absolute deviation (MAD), which uses the deviation from the mean value in absolute numbers. In this case, analogical to the semi-variance, the semi-mean absolute deviation (SMAD) is proposed as a risk measure in situations where only negative deviations are to be considered. When comparing the Markowitz with the MAD approach, Konno and Yamazaki (1991) found that the results hardly diverge. Moreover, the correlation coefficients are no longer needed, and linear instead of quadratic programming can be applied when using MAD or SMAD as a risk measure. Simaan (1997) investigated the proposition that when applying the MAD model, the covariance matrix no longer needs to be specified, and found that higher estimation errors have to be accepted (Fang et al., 2008: p.4). However, a great advantage of using the MAD remains, viz. that it leads to a linear programming problem in the further calculations, whereas if the variance is used, a quadratic programming problem needs to be solved (Konno und Koshizuka, 2005: p.893).

Mathematically, the SMAD is similar to the variance as well, and thus also to the MAD. The SMAD is half of the MAD and thus has the advantage that only half of the restrictions (in comparison to the MAD) have to be considered for solving the problem (Chiodi et al., 2003: p.247). Thus the positive characteristics of the MAD remain, viz. that only a linear instead of a quadratic problem needs to be solved, and that the correlation coefficients do not need to be known. For these reasons, later on we use the SMAD as a risk measure for the fuzzy portfolio optimization model.

In practice, further risk measures are used for the computation of market price risks, such as for example the Value at Risk (VaR) and the Conditional Value at Risk (CVaR)[8].

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[8] The VaR belongs to the so-called ‘downside risk measures’, which consider, just like the semi-variance and the SMAD, only negative deviations, i.e. losses (in contrast, the standard deviation is a two-sided risk measure, because both positive and negative deviations are taken into account). The VaR denotes the largest loss a portfolio cannot exceed within a period [0, T] and a pre-specified probability: the confidence interval (Kremer, 2008: V). The problem is that the VaR is not subadditive when applied to a non-normally distributed portfolio. This means that the sum of the risks of partial portfolios can be lower than that of the aggregated total portfolio and thus can be “computed” by advantageous splits in partial portfolios with a lower total risk. The Conditional VaR (CVaR) represents the expected loss of a portfolio, given that it is above that of the VaR. This measure, in contrast to the VaR, is coherent, which means that it guarantees a consistent risk measurement in the portfolio context (Borchert und Schemm, 2007: p.314) and thus is better suited for portfolio analysis.

3.3 Fuzzy portfolio optimization

3.3.1 Fuzzy sets and fuzzy logic

The term “fuzzy sets” was coined in 1965 by L.A. Zadeh (Zadeh, 1965). “Fuzzy” means “blurred” or “not sharp”. It is easiest to understand the term when it is compared to classical sets theory, where objects can either belong to a set or not, and there are no intermediate steps of memberships. In other words, the bivalence principle applies, according to which, for instance, the parameter values “yes / no”, “true / false”, “1 / 0” or “member / no member” exist (Kanani, 2004: p.437). In contrast, a fuzzy set also allows for blurred states. Zadeh defines a fuzzy set as follows:

> *“A fuzzy set is a class of objects with a continuum of grades of membership. Such a set is characterized by a membership (characteristic) function which assigns to each object a grade of membership ranging between zero and one.”* (Zadeh, 1965: p.338)

In mathematical form, a fuzzy set *A* can be specified as follows (Zimmermann, 2001: p.12):

$$A=\left\{\left(z,\mu_A\left(z\right)\right)\middle|z\in Z,\mu_A\left(z\right)\in\left[0,1\right]\right\}, \qquad (8)$$

where Z is a basic set with elements z and $\mu_A(z)$ the membership function of an element $z\in Z$ to set *A*. The interval $[0,1]$ of the membership function is also referred to as the so-called “membership space” *M*. If $\mu_A(z)$ only takes the values 0 or 1, it is called an ordinary set.

To explain this principle, let us consider the age of a power plant. According to the classic sets theory, a plant is either old (“1”) or new (“0”), cf. Figure 1 (left plot); in a fuzzy set we could also foresee gliding increments or transitions of age, such as brand-new, new, middle-aged, old and very old (i.e. values of between “0” and “1”), cf. Figure 1 (right plot) (Kanani, 2004: p.435).

Today, fuzzy set theory is applied in various fields. Probably the most widespread area is that of fuzzy regulators; in 1974, for the first time, in Europe the steam production of a power plant was equipped with a fuzzy regulator; in 1987, the metro of Sendai in Japan got fuzzy control. The approach for technical applications with fuzzy set theory is a first step to converting the exact input values via a membership function into (blurred) fuzzy inputs (*fuzzification*). Next, the values are treated after linguistic rules in a further process (*fuzzy inference*).

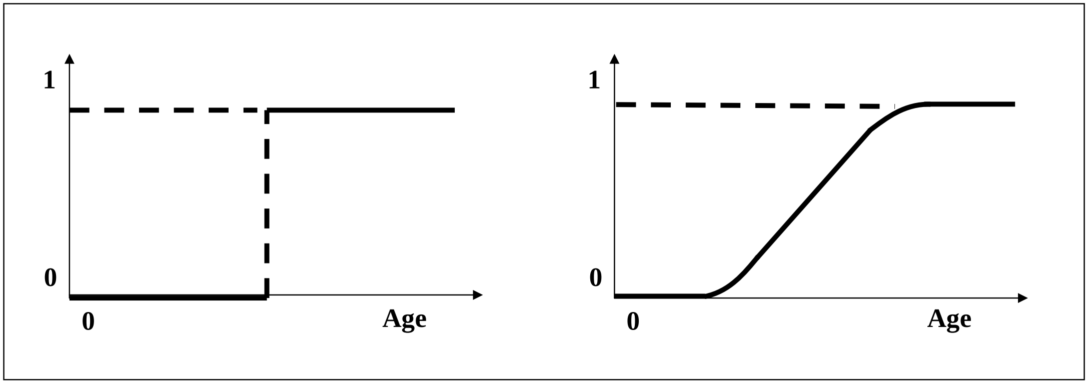

Figure 1: Comparison between classical and fuzzy set theory: age of a power plant

Source: Kanani (2004: 435-436)

The output of this process is again fuzzy numbers, which in a last step have to be transferred into exact output figures (*defuzzification*) (Kanani, 2004: p.443). Further fields of application are fuzzy expert systems, fuzzy data analysis, fuzzy picture processing, fuzzy databases (Kanani, 2004: p.450), and fuzzy portfolio analysis, the latter of which is introduced in the following for further use.

3.3.2 Portfolio analysis with fuzzy set theory

The mean-variance approach for portfolio selection based on probability theory presented in section 3.1 above is not always an ideal tool to describe reality. The conditions in the real world are mostly suboptimal. In many cases, neither goals nor constraints and consequences of possible action can be determined precisely. Normally, one uses probability theory in such cases and equals imprecision and randomness, which, however, is a doubtful assumption (Bellman and Zadeh, 1970: p.141) that must have negative implications for the results of such models. Randomness is the uncertainty about the membership or non-membership of an object to a set. With the help of fuzzy set theory, the danger of a false representation of reality by a more precise representation of the imprecision or uncertainties can be mitigated, viz. by grading the membership of an object to a fuzzy set. Bellman and Zadeh (1970: p.142) also claim that the mathematical operations for fuzzy set theory are simpler than those used in probability theory. The reason is that the value of the probability in probability theory corresponds with the simpler-to-approach membership function in fuzzy set theory.

Based on the fuzzy set theory of Bellman und Zadeh (1970), goals, constraints and decisions have to be defined as a next step. Assuming G_p fuzzy goals with $p = (1,...,P)$ and

C_q fuzzy constraints with $q = (1,...,Q)$, a fuzzy decision *D* is defined as (Bellman and Zadeh, 1970: p.149):

$$D = \{G_1 \cap ... \cap G_P\} \cap \{C_1 \cap ... \cap C_Q\} \tag{9}$$

with the membership function μ_D

$$\mu_D(z) = Min\{\mu_{G1}(z) \cap ... \text{ fi } \mu_{GP}(z) \cap \mu_{C1}(z) \text{ fi } ... \text{fi} \, \mu_{CQ}(z)\}. \tag{10}$$

The optimal decision is described by the set

$$D^O = \left\{ z^* \in Z \middle| z^* \in \arg\max \mu_D(z) \right\}. \tag{11}$$

Figure 2 shows these relationships.

In the meantime, these foundations have served as the basis for more sophisticated models used in portfolio optimization. In the first monograph on this topic, Fang et al. (2008) summarize the research results of the last years in the area of fuzzy portfolio choice. They present the model of Ramaswamy (1998), which is based on a linear membership function, and consider potential market scenarios (Fang et al., 2008: p.5). In another model, proposed by Watada (2001), the degree of satisfaction of profit and corresponding risk is described by logistic membership functions (Fang et al., 2008: p.6). León et al. (2002) also introduced a method, aimed at solving the problems of models with linear constraints. Their approach is based on the introduction of hard and soft constraints, in order to reflect the special structures of constraints in linear and quadratic programming problems. Further approaches and detailed mathematical descriptions of the models introduced can be found in (Fang et al., 2008).

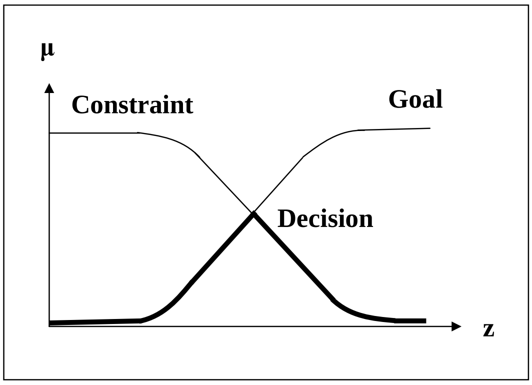

Figure 2: Decision based on fuzzy objective and constraint

Source: Bellman and Zadeh (1970: p.149)

3.4 Model used: fuzzy portfolio optimization with SMAD as risk measure

The semi-mean absolute deviation (SMAD), i.e. the risk measure introduced in section 3.2 above, is now described in some detail by referring to the model introduced by Konno and Koshizuka (2005). This model serves both as the basis for the fuzzy optimization model described further below, and later on for the actual empirical analysis.

The two goals of the SMAD model depicted in model (12) are, on the one hand, the minimization of risk and, on the other hand, the maximization of the returns under certain restrictions (Konno and Koshizuka, 2005: p.898):

$$\begin{aligned}
&\min \frac{1}{T}\sum_{t=1}^{T} y_t \qquad\qquad (12)\\
&\max \sum_{i=1}^{n} x_i E(R_i)\\
&\text{s.t.} \quad y_t \geq -\sum_{i=1}^{n}\left(R_{it} - E(R_i)\right)x_i\,, \quad t = 1, 2, \ldots, T\\
&\sum_{i=1}^{n} x_i = 1\,,\\
&x_i \geq 0\,,\\
&y_t \geq 0\,,
\end{aligned}$$

where R_{it} is the return from portfolio share i in period t, and y_t refers to the negative deviation between the realization of the portfolio return and its expected value at time t over a time span T. This 2-objective portfolio selection model can be solved either through the minimization of the portfolio risk for a given required return level or, alternatively, through the maximization of the return for a given predetermined risk level. In both cases, the determination of the required return and predetermined risk level is difficult *a priori*. The decision-maker would have to state precise and justifiable numbers for both values. Fuzzy set theory offers the possibility to approximate these values.

Note that it is not trivial to find solutions that match the decision-maker’s aspiration levels regarding return and risk of the portfolio. Hence it is suggested to apply a “cut and try” method and to search for general solutions for the expectations. If an expectation level can be satisfied within a certain span, this level is expressed as a fuzzy number with just this span (Watada, 1997: p.225).

From these considerations we obtain the membership functions for return and risk. Their form is in this case S-shaped, i.e. non-linear and logistic. The logistic form is preferred to the trapezoidal form, as the latter is partly linear and thus for certain values no unique solution exists (Watada, 1997: p.227). The non-linear membership function of the expected return of the portfolio is given as (Watada, 1997):

$$\mu_R(E(R_P)) = \frac{1}{1+\exp[-\alpha_R(E(R_P)-R_M)]}, \tag{13}$$

where R_M is the point at which the membership function of the expected return takes the value 0.5 (cf. Figure 3, left plot).

The non-linear membership function of the portfolio risk $V(x)$ is (Watada, 1997):

$$\mu_V(V(x)) = \frac{1}{1+\exp[\alpha_V(V(x)-V_M)]}, \tag{14}$$

where V_M is the point at which the membership function of the risk takes the value 0.5 (cf. Figure 3, right plot). α_V is determined by the decision-maker and expresses the degree of satisfaction with the portfolio's risk.

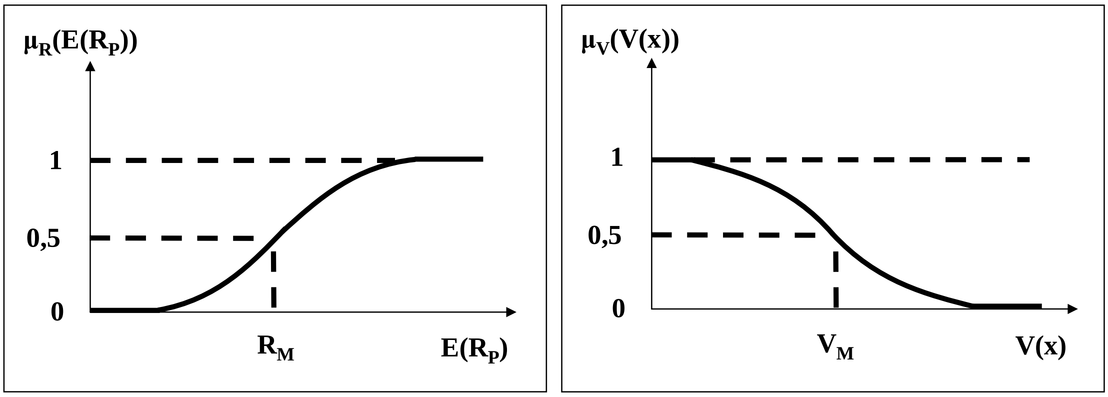

Figure 3: Membership function of the portfolio return (left plot) and portfolio risk (right plot)

Source: Own illustration, based on Watada (1997: p.228-9)

The parameters α_R in eq. (13) and α_V in eq. (14) determine the shape of the membership functions μ_R and μ_V, with $\alpha_R > 0$ and $\alpha_V > 0$. With increasing values of α_R and α_V, the blurredness of the functions diminishes. The magnitude of the two parameters is determined according to the method introduced by Vasant (2006). The values R_M and V_M can be calculated as follows (Watada, 1997: 231):

$$R_M = \frac{R_{necessity} + R_{sufficiency}}{2}, \tag{15}$$

$$V_M = \frac{V_{necessity} + V_{sufficiency}}{2}. \tag{16}$$

$R_{necessity}$ is the return level that is considered to be the minimum necessary one by the decision-maker for satisfying his/her needs, i.e. which must not be undercut. $R_{sufficiency}$ refers to the sufficient return level which satisfies the needs of the decision-maker and which constitutes an upper bound. $R_{necessity}$, for non-linear (i.e. in our case logistic) membership functions, is at that point along the x-axis at which the membership function of the return takes a value of about 0.01. Correspondingly, $R_{sufficiency}$ is found at a value of the membership function of about 0.99. $V_{necessity}$ is the maximum risk level which the decision-maker is willing to accept and that can be approximated for a value of the membership function of about 0.99. $V_{sufficiency}$ is the risk level that satisfies the needs of the decision-maker and that can be found at a value of the membership function of about 0.01 (Watada, 1997: p.232).

The values for $R_{necessity}$, $R_{sufficiency}$, $V_{necessity}$, and $V_{sufficiency}$ are determined following Zimmermann (1978: p.46). To this end, a vector maximum problem with two objective functions for return and risk has to be solved. From the entire solution of the problem, the two optimal solutions (one for the return and one for the risk) are chosen.

These solutions, plugged back into the target function, then yield the four values searched for. Hence R_M and V_M can be determined by using (15) and (16). Following Bellman and Zadeh (1970), the maximization principle applies, i.e.:

$$\eta = \min\{\mu_R(E(R_P)), \mu_V(V(x))\}, \tag{17}$$

and thus, according to Watada (1997: p.230) and Fang et al. (2008: p.71), the following portfolio optimization model can be specified:

$$\max \eta \tag{18}$$

$$\text{s.t.} \qquad \eta + \exp(-\alpha_R(E(R_P) - R_M))\eta \leq 1,$$

$$\eta + \exp(\alpha_V(V(x) - V_M))\eta \leq 1,$$

$$\sum_{i=1}^{n} x_i = 1,$$

$$x_i \geq 0, \quad i = 1, 2, \ldots, n,$$

$$0 \leq \eta \leq 1.$$

Based on the reformulations presented in Watada (1997) and Fang et al. (2008), respectively, with $\Lambda = log \frac{\eta}{1-\eta}$ and the previously introduced SMAD model (12), model (18) can be rewritten as the following linear programming problem, which can be solved with simple algorithms:

$$\max \Lambda \tag{19}$$

$$\text{s.t.} \quad \alpha_R E(R_P) - \Lambda \geq \alpha_R R_M,$$

$$\Lambda + \frac{\alpha_V}{T} \sum_{t=1}^{T} y_t \leq \alpha_V V_M,$$

$$y_t + \sum_{i=1}^{n} (R_{it} - R_i) x_i \geq 0, \quad t = 1, 2, \ldots, T,$$

$$\sum_{i=1}^{n} x_i = 1,$$

$$x_i \geq 0,$$

$$y_t \geq 0, \quad t = 1, 2, \ldots, T,$$

$$\Lambda \geq 0.$$

4. Case study: fuzzy portfolio optimization of five German wind farms

The wind park portfolio considered in our case study consists of five wind parks distributed all over Germany. *Wind park 1 (WP1)* was put into operation in 2004 and is located in the federal state of Saarland. It consists of three wind turbines of the GE 1.5 sle type (General Electric), with a total capacity of 4.5 MW. *Wind park 2 (WP2)*, erected in 2007, is located in the northwestern part of North-Rhine Westphalia near the Dutch border, and comprises four S77 wind turbines (Nordex), with a total capacity of 6 MW. *Wind park 3 (WP3)* is situated in northern Lower Saxony, near the city of Hamburg, and was put into operation in 2003. It consists of four wind turbines of the type AN Bonus (Siemens) and has a total installed capacity of 5.2 MW. *Wind park 4 (WP4)* lies in Saxony-Anhalt (put into operation in 2007), with ten wind turbines of type V90 (Vestas) and 20 MW of installed capacity, and is the largest park included in the portfolio analysis. *Wind park 5 (WP5)*, finally, consists of five wind turbines of type S77 (Nordex) and two of type NM 60 (NEG Micon[9]), with a total capacity of 9.5 MW. The park is situated in the north-Hessian mountains and was put into operation in 2004. Table 2 provides an overview of the wind parks included in the portfolio.

Table 2: Wind parks considered in the portfolio analysis

Wind park (Federal State)	**Type of wind turbine**	**No. of wind turbines**	**Installed total capacity [MW]**	**Put into operation [year]**
WP1 (Saarland)	GE1, 5sle, General Electric	3	4.5	2004
WP2 (North-Rhine Westphalia)	S77 (100 m nacelle height),Nordex	4	6	2007
WP3 (Lower Saxony)	AN Bonus, Siemens	4	5.2	2003
WP4 (Saxony-Anhalt)	V90, Vestas	10	20	2007
WP5 (Hessen)	5 x S77 (85 m nacelle height), Nordex and 2x NM 60, NEG Micon	7	9.5	2004

Source: ABO Wind Reference list (Nov 21, 2010)

4.1 Technical characteristics

In the following, the five types of wind turbines represented in the wind parks are described regarding their technical characteristics. The rated power of the turbines lies between 1–2 MW, as is common for onshore plants installed between 2003 and 2007. The rated power is achieved by a wind speed larger than or equal to the rated wind speed. In our case, it is in the range of between 13–15 m/s. Due to the weight of the rotor, the plant switches on only above a certain speed, in this case at wind speeds of 3–4 m/s. If a certain wind speed is exceeded, the plant automatically switches off to avoid damage. This switch-off speed of the wind turbine in our portfolio ranges between 20–25 m/s. The nacelle height is 68 m for the smallest and 105 m for the largest plant. The rotor diameter lies between 60–90 m. Thus, the swept rotor area ranges between 2,827 and 6,362 m^2, depending on the diameter of the rotor.

The material of the (in our case always tri-bladed) rotor is glass fiber reinforced (GRP) plastic. The rotation speed of the rotor is either fixed or variable. In the first case, this implies that a wind power plant achieves its aerodynamic optimum only at a certain wind speed, but can be coupled directly to the grid. In the second case, it implies the continued safeguarding of the aerodynamic optimum, but without direct feed-in of the electricity, which leads to higher investment costs (BWE, 2010c).

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[9] In 2004, NEG Micon was taken over by the wind turbine manufacturer Vestas.

Power regulation for smaller plants is realized via stall regulation, i.e. via the effect of stall in the case of non-adjustable rotor blades. Larger plants have a pitch regulation, where the rotor blades beyond a certain wind speed are put into the wind direction and thus have no torque (Konstantin, 2009: p.332). The reference yields of the plants apply for five years, as already described in Section 2.2, and lie between about 12–31 GWh. A distinct relationship between rated power and nacelle height and higher reference yields exists; Table 3 provides a summary.

Finally, it can be said that the wind turbines do not differ markedly in principle. If we cast an eye on Tables 2 and 3, we can see that the rated power and the nacelle height rise with the year of being put into operation. This emphasizes the trend mentioned in Section 2.1 towards larger and more powerful plants ("upscaling").

Table 3: Technical characteristics of the wind turbines considered

Characteristic	AN Bonus [a]	GE 1.5 sle [b]	NM 60 [c]	S77 [d]	V90 [e]
Power					
Declared capacity [MW]	1.3	1.5	1	1.5	2
Nominal wind speed [m/s]	15	14	14	13	14
Switch-on wind speed [m/s]	3	3	3-4	3.5	4
Switch-off wind speed [m/s]	25	25	20	25	23
Rotor					
Diameter [m]	62	77	60	77	90
Swept rotor area [m^2]	3019	4657	2827	4657	6362
No. of blades	3	3	3	3	3
Rotation speed fixed / variable [rpm]	13	18.4	12	9.9-17.3	9-14.9
Material	GFK	GFK	GFK	GFK	GFK
Control- and safety system					
Power limitation	Active stall	Pitch	Stall	Pitch	Pitch
Tower					
Nacelle height [m]	68	85	80	85	105
Reference yield [f] [kWh]	13,731,599	20,534,273	12,315,870	19,797,726	30,697,642

Sources: [a] WEM AN Bonus (Nov 21, 2010), [b] WEM GE 1.5 sle (Nov 21, 2010), [c] WEM NM 60 (Nov 21, 2010), [d] Nordex (Nov 21, 2010), [e] WEM Vestas (Nov 21, 2010), [f] FGW (2010a) (reference yield for a nacelle height of 100 m: 20,764,676 kWh)

4.2 Economic characteristics

The economic parameters include, apart from the investment and operating costs, the energy yields and the tariff rates, also parameters such as the WACC and the capacity factor, which will be introduced in the following. The investment expenditures for wind power plants are composed of the component for the plants themselves (100%) and location-specific additional costs of construction (30–40%). These costs include the foundations of the plants, the grid connection, the preparation of the sites, transportation and assembling, as well as planning, authorization, and financing costs (Konstantin, 2009: p.339). Typical prices for the wind turbine classes relevant for our portfolio are reported in Table 4.

Table 4: Typical prices of wind turbines

Power category [kW]	Nacelle height [m]	Price wind turbine *ex works* [€/kW]
1000	50–70	830–900
1300	70–90	900–1050
2000	60–90	830–950

Source: Konstantin (2009: p.338)

For the wind parks investigated, we have data for the investment costs in only two cases, whereas for the other parks the investment costs had to be estimated on the basis of the available data and the values provided in Konstantin (2009: p.338). From these considerations, we estimated the location-specific construction costs to be about 30%, resulting in total investment costs of 130% compared to the costs resulting from multiplying the individual wind turbine costs with the number of turbines per wind park (cf. Table 5).

Annual power production from a wind power plant, also referred to as energy yield, has to be determined separately for each individual location and plant. For the calculations, the power curve of the WPP, the yearly average wind speed at the location and at nacelle height, and the distribution of the wind speed are required (Konstantin, 2009: p.334). In contrast, an annual yield calculation based on full-load hours does not provide useful (ibid, p.337).

We take the energy yields for our wind parks from the expert’s report of the company Anemos, which was made on behalf of ABO Wind AG. These energy yields correspond to a maximum value, which can fluctuate by a safety mark-down (also stipulated in the expert’s report), so that a minimum energy yield remains.

The remuneration is according to the EEG, where first the duration of the initial remuneration has to be determined for each location. Five years are stipulated in the EEG and there is a possibility of prolongation in case certain requirements are met (cf. section 2.2). From this, and using eq. (1), the values for the reference yields provided in Table 3, and the prevailing maximum energy production of the wind parks given in Table 6, we obtain values of between 12–14 years for the prolonged initial remuneration. When using the minimal energy production, the prolonged initial remuneration would even be paid for a longer time period. To be on the safe side, we calculated conservatively with the shorter duration. The calculation results can be found in Table A.1 (Appendix). The tariff remains constant for the entire duration of the initial remuneration, i.e. it is not subject to degression. After its expiry, the tariff of the basic remuneration applies for that year in which the initial remuneration expires. The basic remuneration is then paid until the end of the expected operating lifetime (BMU, 2010).

Table 5: Economic characteristics of the wind parks considered

	WP1	WP2	WP3	WP4	WP5
Technical lifetime [a]	20	20	20	20	20
Remaining lifetime [a]	13	16	12	16	13
Total investment cost (130%) [€]	59,750,002	81,900,003	56,840,002	247,000,003	123,160,003
Number of turbines	3	4	4	10	7
Investment cost per turbine (100%) [€]	4,596,154	6,300,000	4,372,308	19,000,000	9,473,846
Operating cost share [%/a]	4.3	4.3	4.3	4.3	4.3
Initial remuneration [a] [ct/kWh]	8.7	8.19	8.9	8.19	8.7
Base remuneration [a] [ct/kWh]	4.36	4.23	4.41	4.32	4.36
Duration initial remuneration [a]	5	5	5	5	5
Prolonged duration initial remuneration [a] [a]	14	14	14	12	14
Total duration initial remuneration [a]	19	19	19	17	19
Duration base remuneration [years]	1	1	1	3	1
Max. energy production [kWh/a]	10,605,000	14,121,000	9,495,000	57,498,000	20,917,000
Safety markdown [b] [%]	12	11,6	8	6	7
Min. energy production [kWh/a]	9,332,400	12,482,964	8,735,400	54,048,120	19,452,810
Capacity factor Min / Max [a] [%]	24 / 27	24 / 27	19 / 21	31 / 33	23 / 25

Sources: [a] Own calculations, [b] Wind expert's opinion of Anemos on behalf of the ABO Wind AG (Nov 23, 2010)

The tariff for the initial remuneration for the park operating since 2003 is based on the EEG 2000, whereas the other parks receive an initial remuneration according to the EEG 2004. The basic remunerations for all parks are paid according to the EEG 2009 (for detailed computations, see Tables A.2 and A.3 in the Appendix).

The WACC is assumed to be 7.5% (i.e. due to a lack of information, not computed according to eq. (5)). For each wind park we would have needed the exact equity and debt quotas, and estimation did not seem to be appropriate[10].

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[10] PricewaterhouseCoopers sees the general WACC of the energy supply industry at 6–7% (PwC, November, 2010). The Danish energy supplier, Dong Energy A/S, gives WACC values for the year 2004 for German onshore wind power plants during the construction phase at 6.5–7.5%, and during their operating life of between 6–7% (Balle, 2004). In contrast, the German Windguard GmbH sees the current WACC for wind power projects in Germany at 7.5% (Deutsche Windguard, November, 2010). Based on the assumption that since 2004 a rise in

An important value for the valuation of wind power plants is their capacity factor. It relates the actual energy yield per annum to the theoretically achievable yield given by installed capacity and maximum annual operating hours. In the literature, capacity factors of between 20–40% (RERL, 2010) are provided, for low-wind years sometimes even values that are below the 20% limit (BWEA, 2010). For the wind parks investigated, the capacity factor for the computation with a maximum energy yield lies between 21–33%, with a mean value of 27%. When computing with minimal energy production, we obtain values of between 19–31%, with an average of 24%. Table 5 provides a summary of the economic parameters and parameter values used. For the operating costs, a bandwidth of 3–5.6% of the *ex works* price of the wind turbines per year can be found in the literature (cf. Table 6). In our calculations we use the mean value of 4.3%.

Table 6: Typical operating costs of wind turbines

Position	**Value range [%]**
Routine maintenance (contract-based)	0.5–0.8
Repair costs	1.0–2.0
Insurances	0.5–0.8
Land rent	0.5–1.0
Technical monitoring, administration	0.5–1.0
Total	**3.0–5.6**

Source: Konstantin (2009: p.340)

4.3 Results

On the basis of the economic parameters introduced in section 4.2, we first calculate the annual cash flow for the individually remaining operating lifetime[11] of the five wind parks using eq. (3), after which we calculate the NPV using eq. (2). Note that in order to account for the different sizes of the wind parks the NPV is given in per unit terms (€/kW).

In a next step, we conducted a Monte-Carlo simulation with 100,000 random runs using the software package Crystal Ball® for determining the probability distribution of the wind parks' NPVs. Note that in this analysis the only random variable is the annual energy yield, as

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the WACC has happened, in our computations we refer to the last-mentioned reference and also assume a WACC of 7.5%.

[11] For the calculations, the remaining lifetime is considered, measured from the beginning of year 2011. For simplicity, we assume that all parks were connected to the grid on January 1 of the initial year of operation. Furthermore, we assume that the feed-in tariffs according to the EEG apply, starting at the beginning of the year, irrespective of whether or not a revised version of the EEG entered into force during the concerned year or not.

all other variables are assumed to be constant. The results obtained are reported in Table 7. The two most important factors for the explanation of the various NPVs are the rate of the initial remuneration (in all cases, over the major part of the time) and the capacity factor, which is why we have also included them for the overview in Table 7. Apart from the standard deviation computed by Crystal Ball®, the SMAD is also reported in Table 7 as the risk measure used in the computations that follow.

Table 7: Results Monte Carlo simulation

	WP1	**WP2**	**WP3**	**WP4**	**WP5**
Mean expected NPV [a] [€/kW]	309	128	238	617	275
Standard deviation [a] [€/kW]	56	58	28	35	31
SMAD [b] [€/kW]	24.5	25.2	12.3	15.3	13.3
Initial remuneration [b] [ct/kWh]	8.7	8.19	8.9	8.19	8.7
Average capacity factor [b] [%]	25.5	25.5	20	32	24

Sources: [a] Own calculations with CrystalBall®, [b] own calculations

The highest NPV of 617 €/kW is achieved with WP4, which enjoys only a modest initial remuneration over a shorter time horizon[12], but which has a much higher capacity factor than all other wind parks considered. This makes clear that the most important criterion for a profitable wind park is the choice of location with good wind conditions. The standard deviation is at 35 €/kW, which in comparison to other parks is certainly not the lowest, but one that can be accepted given the high NPV. WP1 and WP5 are similar with respect to their NPVs of 309 €/kW and 275 €/kW, respectively, which is due to their similar value of the initial remuneration and capacity factor. The standard deviation of WP1, however, is at 56 €/kW and thus almost twice as high as the one of WP5, which makes the benefit of WP1 dubious with regard to the portfolio idea.

WP3, exhibiting the lowest capacity factor, features an NPV of 238 €/kW, and thus still has a marked advantage vis-a-vis WP2 with an NPV of only 128 €/kW. Additionally, WP2 features a standard deviation that is double that of WP3, which seems to render WP2 unprofitable. The results for the mean values and standard deviations reveal that WP2 should definitely not be included in such a portfolio. Moreover, WP1 does not seem to be able to compensate the higher risk by a somewhat higher return than that of WP5. Anyway, the optimal shares of all wind parks in a portfolio can only be stated using portfolio selection

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[12] A look at Table 6 shows that WP4, in comparison to the other parks, receives the initial remuneration two years less, viz. 17 instead of 19 years.

model; in our case first the FSMAD model and, in a next step, the comparison with the SMAD model.

4.3.1 Results FSMAD model

In a next step, on the basis of the data from the Monte Carlo simulation, we solve the fuzzy semi-mean absolute deviation (short: FSMAD) model (19), with the help of a software program developed and owned by the Institute for Future Energy Consumer Needs and Behavior (FCN, RWTH Aachen University). Also, the values of the parameters needed in the FSMAD model, such as R_M and V_M , as well as α_R and α_V , were generated through this program by the methods described in section 3.4. Table 8 contains the results of the FSMAD model. Apart from the seven possible portfolios shown, also their respective NPV and the risk (SMAD) are shown. We can see that only WP3 and WP4 are contained in the portfolios (P), WP4 even with a dominant share of between 94.34–100%. Consequently, the NPV moves strongly in the area of the mean NPV found by Monte Carlo simulation of 617 €/kW for WP4 (cf. P7 with 100% WP4). The lowest NPV of P1 lies at about 595 €/kW. This portfolio contains, apart from WP4 with 94.34%, also WP3 with 5.66%. The risk level in all portfolios varies from 15.14 €/kW and 15.31 €/kW and varies only very modestly overall.

Table 8: Results FSMAD model

Portfolio	**WP1**	**WP2**	**WP3**	**WP4**	**WP5**	**NPV [€/kW]**	**Risk [€/kW]**
P1	0.00%	0.00%	5.66%	94.34%	0.00%	595.35	15.14
P2	0.00%	0.00%	4.71%	95.29%	0.00%	598.92	15.17
P3	0.00%	0.00%	3.77%	96.23%	0.00%	602.49	15.19
P4	0.00%	0.00%	2.83%	97.17%	0.00%	606.06	15.22
P5	0.00%	0.00%	1.88%	98.12%	0.00%	609.63	15.25
P6	0.00%	0.00%	0.94%	99.06%	0.00%	613.20	15.28
P7	0.00%	0.00%	0.00%	100.00%	0.00%	616.76	15.31

Source: Own calculations, based on FCN software

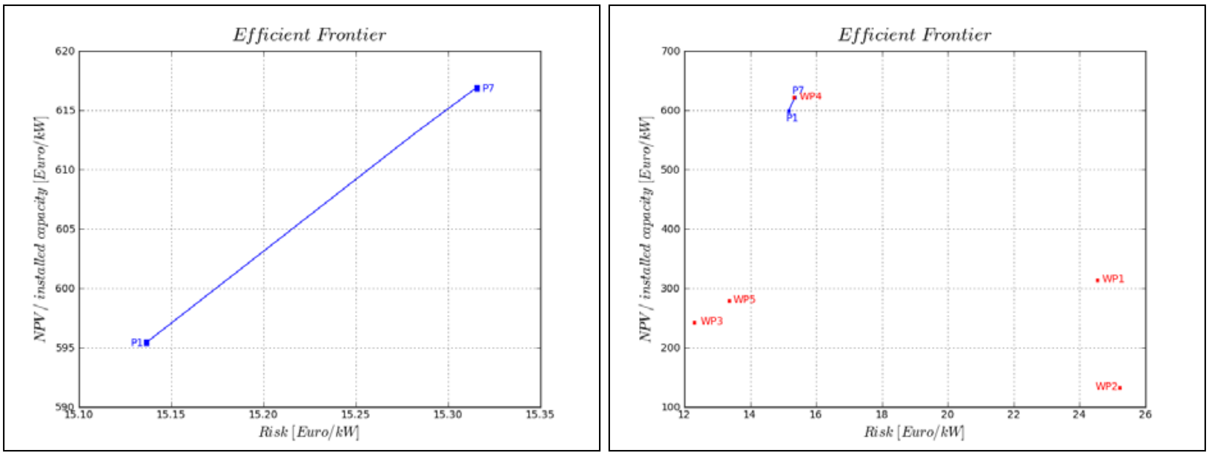

Figure 4: Efficient frontier FSMAD model, without (left plot) and with wind parks (right plot)

Source: Own illustration, based on FCN software

Figure 4 (left plot) depicts the efficient frontier gained from the results of the FSMAD model. All points on the straight line between P1 and P7 are possible portfolio combinations of the wind parks analyzed. Figure 4 (right plot) depicts the same efficient frontier as Figure 4 (left plot), but now in relation to the location of the individual wind parks. To this end, first the risk of all parks, i.e. their SMAD, has to be computed, which, however, is straightforward on the basis of the data from the Monte Carlo simulation already reported in Table 7. Note that the scale of the returns and risks reported here is larger than that in Figure 4 (left plot), as also the non-efficient parks with low return and high risks are shown. By this representation it becomes particularly evident that WP1 and WP2, because of their high risk and relatively low NPV, are not considered in the portfolio. Moreover, it becomes clear that WP4 is considered, due to its high return (above average), and that inclusion of WP3 makes sense from a risk perspective, even though its share in the portfolio is small. Furthermore, one can see that points P7 and WP4 at the upper edge of the efficient frontier coincide in a point, which shows that P7 only consists of WP4.

Based on the FSMAD model and the parameters obtained from the calculation of the programs used, a decision-maker would only consider WP3 and WP4, with the above-mentioned shares, in the portfolio.

4.3.2 Results SMAD model

Next, we compare the results by solving the semi-mean absolute deviation model (SMAD model) depicted in (12). All data required are already available from the Monte Carlo simulation performed earlier on; the results from these computations are reported in Table 9.

Table 9: Results SMAD model

Portfolio	WP1	WP2	WP3	WP4	WP5	NPV [€/kW]	Risk [€/kW]
P1	0.00%	0.00%	100.00%	0.00%	0.00%	238.29	12.27
P2	0.00%	0.00%	100.00%	0.00%	0.00%	238.29	12.27
P3	0.00%	0.00%	100.00%	0.00%	0.00%	238.29	12.27
P4	0.00%	0.00%	83.70%	16.30%	0.00%	300.00	12.76
P5	0.00%	0.00%	57.27%	42.73%	0.00%	400.00	13.56
P6	0.00%	0.00%	30.85%	69.15%	0.00%	500.00	14.35
P7	0.00%	0.00%	4.43%	95.57%	0.00%	600.00	15.15

Source: Own calculations, based on FCN software

There is no change to the wind parks contained in the efficient portfolios compared to the FSMAD model. Wind parks WP3 und WP4 are still those that, in various combinations, form the efficient portfolios, while WPs 1, 2, and 5 are again totally excluded. However, note that the difference is exactly in the shares of WPs 3 and 4 in the efficient portfolios. Whereas in the efficient portfolios for the FSMAD model, WP3 was contained at a maximum of 5.66%, here, using the SMAD model, it is included even with 100% (see P1, P2 and P3). This also explains the wider scale of the returns and risks in comparison to the FSMAD model, that ranges from 238–600 €/kW (return) and 12–15 €/kW (risk).

Another portfolio, P4, contains WP3 at 83.7% and WP4 at 16.3%. Further combinations along the efficient frontier are possible until shares of 4.43% (WP3) and 95.57% (WP4) are reached (P7). Figure 5 (left plot) depicts these outcomes.

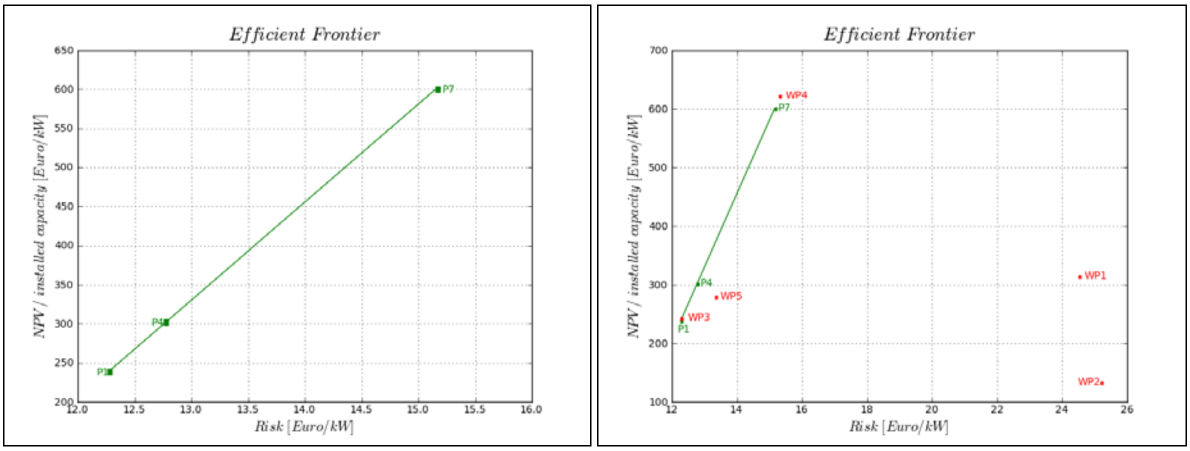

Figure 5: Efficient frontier SMAD model, without (left plot) and with wind parks (right plot)

Source: Own illustration, based on FCN software

Figure 5 (right plot), apart from the efficiency frontier of the SMAD model, also contains the various wind parks and their return-risk characteristics. As already stated for the FSMAD model, WP1 and WP2 have a risk that is too high for being considered. In contrast, WP5 has a return that is too low given its risk level. For this model, at the lower end of the efficient frontier the two points P1 and WP3 coincide, which means that P1 only contains WP3.

On the basis of the SMAD model, a decision-maker would choose a portfolio that consists of the two WPs 3 and 4. The shares of the two parks would be at 100% for WP3 and about 95% for WP4, which is the difference to the portfolios according to the FSMAD model.

4.3.3 Comparison FSMAD and SMAD model

At this point, we now want to present a comparison of the results obtained from both models, depicted graphically in Figure 6. One can see that the FSMAD efficient frontier essentially leads to an elongation of the efficiency line of the SMAD model and, compared to that, only offers a very narrow selection of return-risk possibilities. The best possible returns can only be found by using the FSMAD model (cf. Figure 6, P7 green und P7 blue). Note, however, that the risk associated with a higher return increases for the case of the FSMAD model.

The differences between the two models can be explained by the fact that the decision-maker's preferences enter into the results of the FSMAD model and restrict the solution space. In our case, the preferences are such that a return of 595.35 €/kW can just still be justified, i.e. matches the $R_{necessity}$, whereas a return of 616.76 €/kW is considered to be sufficient, corresponding to $R_{sufficiency}$ (cf. Table 8). As here no higher returns can be obtained than those of WP4 alone, it is possible that $R_{sufficiency}$ is set higher in reality. The same is true for the risk: the maximum risk the decision-maker is willing to accept lies at 15.31 €/kW (cf. Table 8) or even higher for higher returns. But since no higher returns can be generated than those for a risk level of 15.31 €/kW, this value in this case forms the frontier. The lower value of the risk that a decision-maker considers acceptable, i.e. that must not be undercut, lies at 15.14 €/kW. With this, and the restrictions imposed on the return, the entire efficiency frontier of the SMAD model is discarded from the consideration in the FSMAD. The SMAD model in this case shows portfolio opportunities that the FSMAD decision-maker is not interested in, as he/she prefers a higher risk and a higher return to a somewhat smaller risk and a drastically lower return.

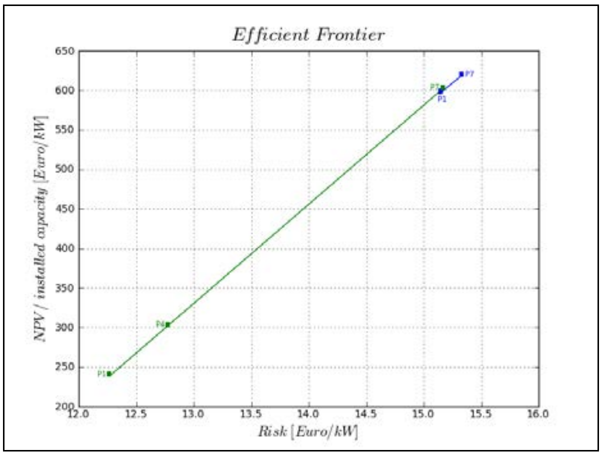

Figure 6: Comparison of efficient frontiers FSMAD and SMAD model

Source: Own calculation, based on FCN software

Hence it is true that for portfolio optimizations with fuzzy set theory, the preferences of the decision-maker on the basis of configurations and data of the model are better reflected, and thus a more precise picture of reality can be gained. In any case, the result from the FSMAD model reduces the possibilities that the decision-maker has to choose from. This can be an advantage vis-à-vis the solution from the SMAD model, where the set of possible choices is larger and thus the decision-making more difficult. The decision, i.e. whether a lower return and lower risk (Figure 6, P1 green) or higher return and higher risk (Figure 6, P7 green) portfolio, which on the basis of the SMAD model would still have to be decided, is taken from the decision-maker in the FSMAD model. The reason is that here the span between which return and risk can vary is only very small.

However, we cannot conclude from the results of either model that one of them is “better” than the other. For such an assessment, the efficient frontier of the model would have to be beyond the other one and thus, either in the case of the FSMAD or the SMAD model, portfolio opportunities would have to be shown that yield higher return for the same level of risk. This is definitely not the case here. Hence we can state that a portfolio optimization based on fuzzy set theory reduces the final portfolio choice of a decision-maker through the application of his/her preferences. A precondition is that the preferences are captured correctly in the model.

5. Summary and conclusions

In this paper, we have introduced a fuzzy portfolio optimization approach that is applied to a portfolio of heterogeneous onshore wind power plants in Germany comprising five different wind parks located in different parts of the country.

In a first step, we have considered the economics of power generation from wind, including the guaranteed feed-in tariff scheme in Germany and the economic modeling of wind power plant projects. Parallels between the valuation of equity shares on financial markets and the investment planning for projects, in our case related to the energy market, were made and methods for the realization of the investment plans discussed. The particular focus of our analysis was on the computation of the NPV of a wind power project.

In a second step, we have provided the theoretical framework for our specific case study. We started off with a short introduction to Markowitz' portfolio theory. Then, we introduced various risk measures usable in the portfolio context and the foundations of fuzzy set theory as a basis for the subsequent fuzzy portfolio optimization. We have presented two alternative models: a semi-mean absolute deviation (SMAD) model that serves as the basis for the actual fuzzy portfolio optimization model and that was used for the comparative analysis, and a fuzzy semi-mean absolute deviation (FSMAD) model including its derivation.

In a third step, the techno-economic characteristics of the wind park portfolio considered were described and the parameters needed for the optimization introduced and computed.

In a last step, we have discussed the results from both models and compared them with each other. In both cases, only two out of five wind parks were considered in the efficient portfolio, but with markedly different shares. The return and risk span of the SMAD model was found to be considerably broader than that of the FSMAD model, although the highest returns could only be generated by portfolios of the FSMAD model. A comparison revealed that a portfolio optimization based on the FSMAD model offers a smaller amount of portfolio choices, which, however, eventually facilitates the final decision in favor of a specific portfolio[13]. This complies with the hypothesis that a portfolio optimization by means of fuzzy set theory can better account for the decision-maker's preferences arising from the configuration and the data of the model, and thus reflect the real conditions in a better way.

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[13] In Glensk und Madlener (2010) the FSMAD model introduced here was also applied to an energy production portfolio consisting of both conventional and renewable energy technologies.

Nomenclature:

ct	Euro-cent
CVaR	Conditional value-at-risk
DC	Debt capital
EC	Equity capital
EEG	German Renewable Energies Act (Erneuerbare-Energien-Gesetz)
FSMAD	Fuzzy semi-mean absolute deviation
GRP	Glass fiber reinforced plastics
IRR	Internal rate of return
kWh	kilo-Watt-hour
m	meter
MAD	Mean absolute deviation
MW	Megawatt
NPV	Net present value
s	second
SMAD	Semi-mean absolute deviation
SURE	Seemingly unrelated regression estimation
TC	Total capital
VaR	Value at risk
WACC	Weighted average cost of capital
WPP	Wind power plant
WP	Wind park

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Appendix

Table A.1: Calculation of the prolonged initial remuneration

Wind park	No. of wind turbines	Reference yield WPP [kWh]	Min 5-year yield WPP [kWh]	Max 5-year yield WPP [kWh]	Min prolonged initial remuneration [months; yrs]	Max prolonged initial remuneration [months; yrs]
WP1	3	61,602,819	46,662,000	53,025,000	170; 14	198; 16
WP2	4	83,058,704	62,414,820	70,605,000	173; 14	199; 17
WP3	4	54,926,396	43,677,000	47,475,000	169; 14	187; 16
WP4	10	306,976,420	270,240,600	287,490,000	150; 12	165; 14
WP5	7	123,620,370	97,264,050	104,585,000	174; 14	190; 16

Source: Own calculations

Table A.2: Initial remuneration

Year	2002	2003	2004	2005	2006	2007	2008
Initial remuneration [ct/kWh]	9	8.9	8.7	8.53	8.36	8.19	8.03
EEG version	2000	2000	2004	2004	2004	2004	2004
Degression [%]	1.5	1.5	2	2	2	2	2

Source: EEG (2000), EEG (2004), own calculations

Table A.3: Base remuneration according to EEG 2009

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017
Base remuneration [ct/kWh]	5.02	4.97	4.92	4.87	4.82	4.77	4.73	4.68	4.63
Degression [%]	1	1	1	1	1	1	1	1	1
cont.									
Year (cont.)	2018	2019	2020	2021	2022	2023	2024	2025	2026
Base remuneration [ct/kWh]	4.59	4.54	4.49	4.45	4.41	4.36	4.32	4.27	4.23
Degression [%]	1	1	1	1	1	1	1	1	1

Source: EEG (2009), own calculations

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