

Efficient electricity production portfolios taking into account physical boundaries

by

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Abstract

In this paper the efficiency of the electricity generation portfolio of BKW, a major Swiss utility, is analyzed. By applying mean-variance portfolio theory to the current and to possible future generation mixes, efficient frontiers are derived. The analysis based on relative changes in generation costs is complemented by an actual costs analysis. Moreover, a method that takes into account physical boundaries using the so-called capacity factor is presented in order to translate the obtained portfolio allocations into physical quantities, i.e. into required installed capacities. It is shown that the method gives useful insight regarding future investment plans and provides valuable support for investment decision makers.

1 Introduction

Over the last three decades, the world electricity consumption has increased with an average annual rate of 3.7% (see Figure 1), while growth in total primary energy supply was only 2.1% [1]. In most industrialized countries the demand for electric energy is increasing and substantial energy shortfalls are expected within the next twenty years if no measures will be taken in the near future. In Switzerland, for instance, the domestic electricity consumption exceeded the domestic electricity supply for the first time ever in the year 2005. There are three solutions to compensate these shortfalls: increase power imports, considerably enhance energy efficiency and/or increase domestic production. As most European countries face similar situations,

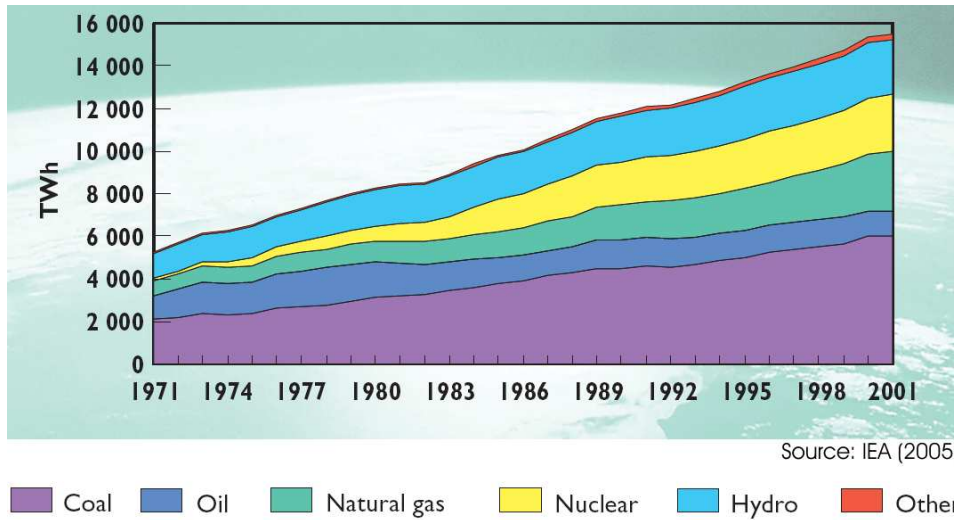


Figure 1: World electricity generation excluding pumped storage. Category "Other" includes geothermal, solar, wind, combustible renewables and waste.

import strategies are not likely to be economical solutions and efficiency gains are often compensated by increasing demand for electricity. In the third case, investment strategies resulting in a financially and technically optimal production portfolio must be formulated. One approach to do this is the application of the mean-variance portfolio theory to power generation assets. This provides information about the risk-return structure of a chosen electricity generation mix.

Production portfolio selection, however, is subject to boundary conditions of different nature. Investors give special emphasis to financial aspects, whereas at the same time technical as well as legal limitations must be taken into account. These different aspects may sometimes contradict each other. Though it might, for instance, be rewarding in financial terms to hold a one-asset portfolio exclusively composed of wind power plants, the power supplier might not be able from a legal point of view to guarantee continuous power delivery to its consumers due to the limited availability of production from wind power plants. Other types of portfolios may not respect the Kyoto protocol and its regulations on CO_2 emissions [2]. Although in liberalized electricity markets priority will be given to financial aspects, portfolio construction will thus be limited by legal and physical boundaries. Mean-variance portfolio theory, however, lacks a direct relation to physical quantities; it neither indicates the required installed capacities nor incorporates availability of supply.

In this paper, the production assets of BKW, a major Swiss utility, are modeled as mean-variance portfolio and methods to incorporate availability of supply and to identify required capacities are introduced, discussed and

applied.

The remainder of this paper is structured as follows. Section 2 gives an overview of the methods used for the analysis. Section 3 presents the results of the study of BKW's current portfolio and examines possible future scenarios. Section 4 concludes the paper.

2 Methods

2.1 Portfolio theory and energy: review of the literature

Before the 1950s investors tended to assess risks and returns of individual assets when constructing their portfolio. The standard way of investment was to choose those assets, which offered the highest expected return at minimal risk. This reasoning might lead to the construction of single-asset portfolios composed of one commodity with good risk-return characteristics. In 1952 Harry Markowitz published a paper about portfolio selection [3]. He was the first to consider diversification as necessary for the construction of efficient portfolios and gave a first mathematical formalization of the idea of diversification in investments.

Whereas Markowitz describes how an individual or an institution can select an optimum portfolio, William F. Sharpe extends Markowitz' findings and determines how the aggregate of investors will behave, and how market prices and returns are set. The model explaining this general equilibrium relationship is the so-called standard capital asset pricing method (CAPM) [4].

Bar-Lev and Katz are the first to apply portfolio theory to energy assets. In [5] they analyze fossil fuel procurement in the U.S. electric utility industry. The purpose of their study was to determine to what extent utilities had been using scarce resources efficiently. They construct efficient frontiers of fuel procurement for different regions within the U.S. and compare them with the actual performance of regional utilities. They find out that, while generally utilities efficiently diversified, their portfolios are characterized by high risks and high returns. Furthermore, they suggest that the regulatory framework makes utilities go for high-risk options.

Awerbuch and Berger [6] evaluate the potential application of portfolio theory to the development of efficient generating portfolios for the European Union (EU-15). They include the risk of the different relevant generating cost streams in their study: fuel, operation and maintenance, and construction period costs. Their results show that existing and projected EU generating mixes are sub-optimal from a risk-return perspective. Their analysis indicates that more efficient portfolios can be constructed by adding technologies such as renewables with high fixed costs but low variable costs to the portfolio. Their assessment is limited to risk and cost measures, although taking into account externality costs and sustainability would favor renew-

able energy technologies even further with respect to fossil-fuel generated electricity.

Yu [7] presents a short-term market risk model based on the Markowitz mean-variance portfolio theory. The model is suitable for assessing the risk of profit making competitive power producers in a multi-pool setting. In this study the covariance matrix reflects different developments of fuel prices across regional electricity markets. Yu includes transaction costs and other practical constraints, which results in a mixed integer programming model. The resulting efficient frontier is neither smooth nor concave. In addition, the paper considers potential extensions of the model such as the inclusion of random fuel prices and the extension to other energy markets like natural gas and oil markets.

Krey and Zweifel [8] apply portfolio theory to determine efficient electricity-generating technology mixes for Switzerland and the United States. Shocks in generation are found to be correlated. For this reason, the authors use the seemingly unrelated regression estimation (SURE) to derive reasonably time-invariant estimates of the covariance matrix. Their results in the case of Switzerland suggest that, in order to maximize the expected return, a shift towards nuclear and solar power production would be efficient. The minimum risk portfolio, i.e. the one with minimum variance, would mainly contain nuclear power and storage hydro. For the U.S., the maximum expected return portfolio contains coal and wind power, while the minimum variance portfolio is composed of coal, nuclear, oil and wind.

Doherty et al. [9] assess the role wind generation may play in future generation portfolios. In a first step, the authors determine least-cost generation portfolios taking into account the physical traits of wind power, i.e. they consider its intermittent character in contrast to conventional dispatchable generation and the consequences for generation adequacy. In a second step, they apply mean-variance portfolio theory and examine the effect of adding wind generation to an existing portfolio. Their results illustrate that the fuel-related electricity cost volatility is reduced if increased amounts of wind generation are added to fossil fuel portfolios.

2.2 Portfolio theory basics

Portfolio theorists generally define a portfolio as a set of investments composed of securities. A security is simply a decision affecting the future. The totality of such decisions constitutes a portfolio [10]. Portfolio management aims at finding efficient portfolio mixes, i.e. its purpose is to maximize expected return for any given possible risk level.

Let p be a multi-security portfolio composed of n securities with $i \in [1, \dots, n]$. The allocation vector \vec{x}_p indicates the share (percentage) of security i in

portfolio p :

$$\vec{x}_p = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \quad (1)$$

Portfolio theory uses two numbers to characterize a portfolio. The first one is the *expected return*. Let R be the vector of expected returns of the individual securities:

$$\vec{R} = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{bmatrix} \quad (2)$$

With these definitions, the expected return of a portfolio can be calculated as the sum of the expected returns of the individual securities weighted by their respective share:

$$R_p = \sum_{i=1}^n x_i R_i = \vec{x}_p^T \cdot \vec{R} \quad (3)$$

The second number that is used for describing the performance of a portfolio is the *standard deviation* of its returns σ_p , being the square root of the variance σ_p^2 . The standard variation is a measure for the risk associated with holding a portfolio. If the individual security returns were independent variables, the portfolio standard deviation would simply be the weighted sum of all individual standard deviations. Security or asset prices, however, are generally dependent and thus correlated variables. A measure of the linear association between two variables is the *covariance*. The covariance matrix \mathbf{Cov}_p ¹ contains the covariance values between the returns of any asset i with the returns of any other asset j for all $i, j \in [1, \dots, n]$:

$$\mathbf{Cov}_p = \begin{bmatrix} cov_{11} & \dots & cov_{1n} \\ \vdots & \ddots & \vdots \\ cov_{n1} & \dots & cov_{nn} \end{bmatrix} \quad (4)$$

If i equals j , the covariance is simply the variance of asset i . By means of the covariance matrix, the variance of a portfolio can be calculated in the following way:

$$\sigma_p^2 = \sum_{i=1}^n \sum_{j=1}^n x_i x_j cov_{ij} = \vec{x}_p^T \cdot \mathbf{Cov}_p \cdot \vec{x}_p \quad (5)$$

¹All matrices are represented in bold font.

With equation 3 and by restating equation 5 in a different way, portfolio optimization can be described through the following set of equations and inequations:

$$\left\{ \begin{array}{l} (1.) \quad R_p = \sum_{i=1}^n x_i R_i \\ (2.) \quad \sigma_p^2 = \sum_{i=1}^n x_i^2 \sigma_i^2 + \sum_{j=1, j \neq i}^n x_i x_j \text{cov}_{ij} \\ (3.) \quad \sum_{i=1}^n x_i = 1 \\ (4.) \quad x_1, \dots, x_n \geq 0 \end{array} \right.$$

Given an investor's preferences (set of indifference curves), the optimal portfolio allocation \vec{x}_p^* can be determined.

Another useful and descriptive number to describe the association between two variables is the *correlation coefficient* ρ_{ij} . It is calculated by dividing the covariance by the standard deviation of asset i and the standard deviation of asset j :

$$\rho_{ij} = \frac{\text{cov}_{ij}}{\sigma_i \sigma_j} \quad (6)$$

A correlation coefficient of +1 corresponds to a perfect positive linear relationship between the returns of asset i and j . If $\rho_{ij} = -1$, there is a perfect negative linear relationship between the two variables. If the variables are independent, the correlation coefficient is 0. The converse, however, does not hold true because the correlation coefficient detects only linear dependencies between two variables.

By diversifying a portfolio, i.e. by dividing investments into 2 or more assets that are less than perfectly correlated, one is able to reduce risk without reducing return at the same time. This is the so-called portfolio effect. Figure 2 shows how the risk-return characteristic of a portfolio with two assets changes when the correlation coefficient increases from -1 to 1. It can be observed that a portfolio constructed with two assets, whose correlation coefficient equals 1, yields no portfolio effect because risk and return change linearly as the portfolio allocation changes from 100% of asset A to 100% of asset B. The lower is the correlation coefficient, the greater is the portfolio effect. If there is a decreasing linear relationship between assets A and B ($\rho = -1$), the investor has the possibility to construct a portfolio without risk.

A rational investor will not consider every possible portfolio, but will choose among those lying on the so-called efficient frontier. The efficient frontier indicates the points which offer the highest possible return for each possible amount of risk. Figure 3 shows an efficient frontier (green line) for a simple two-assets example and points out the minimum variance portfolio.

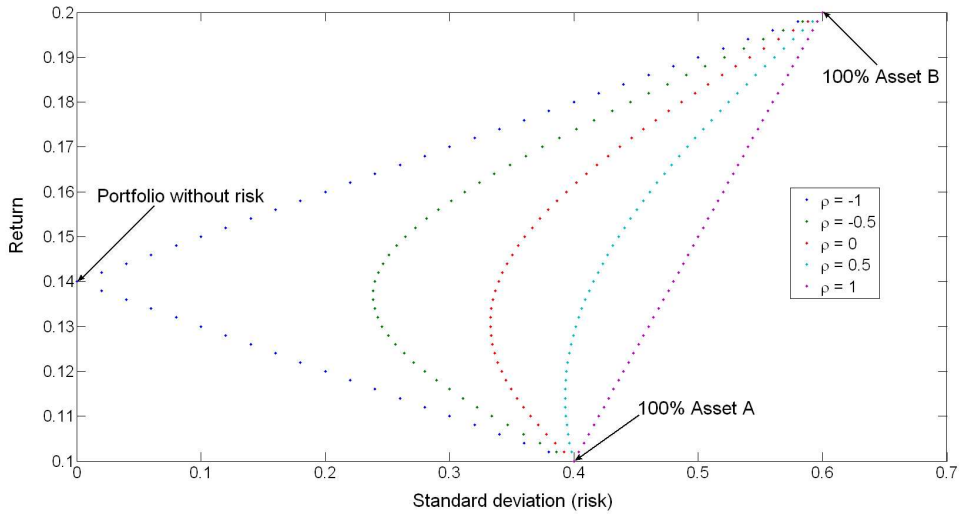


Figure 2: Mean-variance curve of a two-assets portfolio as function of the correlation ρ_{12} .

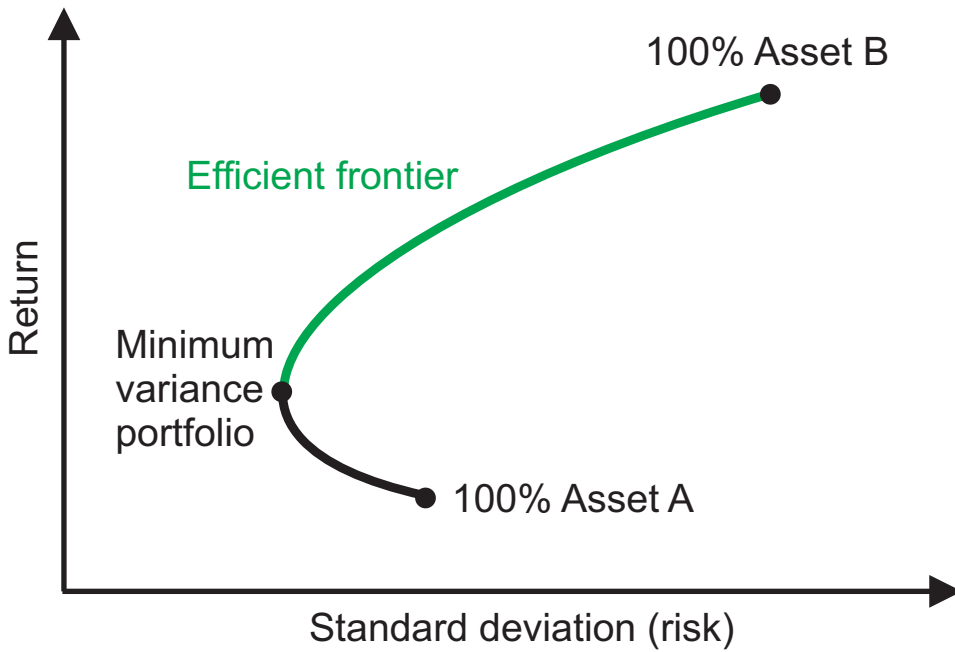


Figure 3: Efficient frontier for a two-assets example.

2.3 Portfolio theory applied to electricity generation assets

To be able to apply portfolio theory to electricity generation, one has to define the return of an electricity generation technology. In finance, the return of an investment is given as difference between the received and expended amount of money divided by the expended money:

$$return = \frac{receipt - expenditure}{expenditure}$$

In the field of electricity generation, different methods can be applied to describe the return of an asset.

Awerbuch's analysis, for instance, is based on estimated levelized generation costs measured in US cents/kWh [6]. These costs are inverted to obtain a return measure in kWh/invested US cents. Unlike return in finance, this return measure is not dimensionless. One could make it dimensionless by multiplying it with the price of electricity (US cents/kWh). However, this would introduce the problem of choosing an appropriate electricity price. Electricity prices exhibit short-term fluctuations and thus, using daily electricity market prices would introduce further uncertainties.

Another possibility is to adopt the definition used in finance. This means that the return is modeled as the change rate of electricity generation costs. Risk is defined as the standard deviation of the return, usually referred to as volatility. For the here presented analysis, it was decided to apply this type of modeling as it is often possible in econometrics to stationarize time series by differentiation. Working on the yield rather than on the costs themselves thus leads to the treatment of stationary processes, which is more convenient.

If y_t represents the observed costs at time t , then return and risk results as follows:

$$return = -\frac{y_t - y_{t-1}}{y_{t-1}} \quad (7)$$

and

$$risk = \sigma_{return} \quad (8)$$

This definition implies that the return is negative when costs increase, which is a quite intuitive definition. Hence, maximizing return means minimizing the increase in generation costs or, in an even better case, maximizing the decrease in generation costs.

2.4 Data handling

Most data has been provided by BKW as monthly costs for fuel, operation and maintenance (O&M), and capital investment. In addition, data was also taken from the NEA/IEA report "Projected Costs of Generating Electricity" [11]. Concerning the possibility to purchase electric energy - either for operating pumped-hydro storage plants or simply for long and short term

purchasing on the market - price data from the EEX² was used. Moreover, information about uranium prices was retrieved from the web site of UxC³.

The time series data was analyzed by means of the Dickey-Fuller test in order to choose between trend-stationary and difference-stationary models [12]. To determine the variance for each technology, the GARCH⁴ model was applied [13, 14].

3 Results

3.1 Current BKW portfolio

In a first step, the current production portfolio of BKW is analyzed. This portfolio consists of

- 61 % nuclear production
- 27 % pumped-storage production
- 12 % run-of-river production

A negligibly small amount of energy is produced by decentralized generation units.

Econometric analysis of the available data, as mentioned above, yields the estimation of the parameters relevant for portfolio analysis. Tables 1 and 2 summarize the results for the three technologies present in the BKW portfolio as well as for gas and coal power plants:

Table 1: Returns and actual costs of technologies.

Technology	Return	Actual costs (CHF/MWh)
Nuclear	-0.03%	52.0
Run-of-river	0.00%	50.0
Pumped-storage	-0.08%	60.0
Gas	-0.25%	67.2
Coal	-0.06%	58.1

The results of the calculations for a portfolio containing the three technologies that are currently present in the BKW portfolio are shown in Figure 4. The brown dots represent all possible portfolios, while the other four points illustrate portfolios with only one technology and the position of the current BKW portfolio (yellow dot). For the sake of readability, the diagram represents a limited number of points for possible portfolio allocations. But of course, any allocation within the feasible region, i.e. also points between

²EEX: European Energy Exchange (www.eex.de)

³UxC: Ux Consulting Company (www.uxc.com)

⁴GARCH: Generalized Autoregressive Conditional Heteroscedasticity

Table 2: Covariance matrix.

Technology	Nuclear	Run of river	Pumped storage	Gas	Coal
Nuclear	0.0001	0	-7.49E-06	3.01E-05	1.72E-05
Run-of-river	0	0.0009	0	0	0
Pumped-storage	-7.49E-06	0	1.96E-04	3.17E-06	1.94E-05
Gas	3.01E-05	0	3.17E-06	3.37E-04	8.80E-05
Coal	1.72E-05	0	1.94E-05	8.80E-05	2.25E-04

the brown dots, can be chosen. The diagram shows that the current BKW portfolio lies very close to the efficient frontier. Furthermore it almost coincides with the minimum variance portfolio, which consists of:

- 61.14 % nuclear production
- 32.33 % pumped-storage production
- 6.52 % run-of-river production

This result is in accordance with the common assumption that investors in general and above all electric utilities behave in a risk-averse way. This means that BKW has almost no further potential to reduce its risk. By choosing a less risk-averse strategy, the expected return can be increased, though.

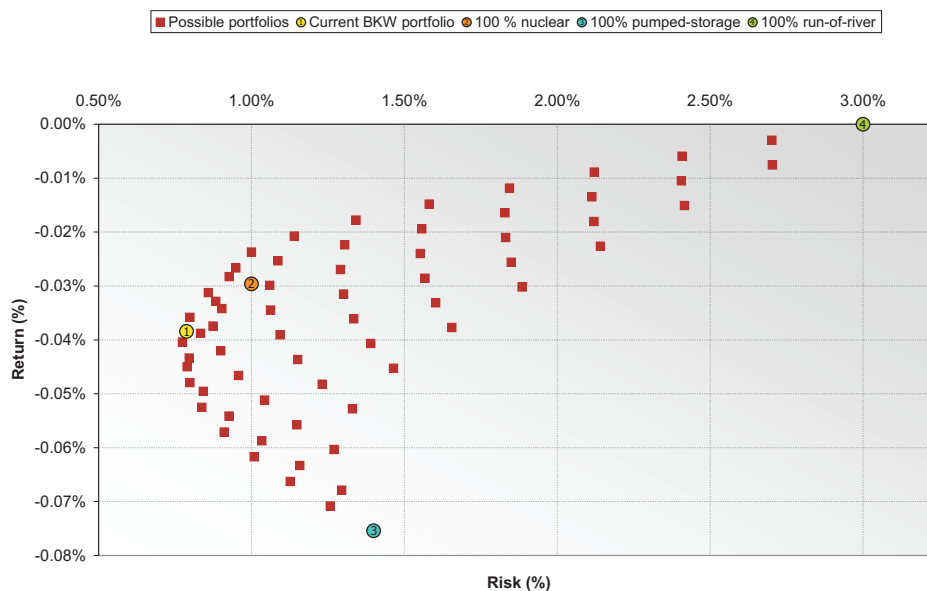


Figure 4: Risk-return diagram and position of the current BKW portfolio.

Up to now only risk and return have been considered. As mentioned above, return in our case is defined as negative change rate of production costs. The following section extends the study with an actual costs analysis.

Actual costs analysis

The definition of return chosen for this study neglects the relevancy of unit costs as such. Only the change rate of costs is covered by this definition. This is analogous to the view of a financial investor, who is rather interested in the expected rate of return than in the price of a share itself. For electricity generation assets this means that a technology with a consistent decrease of unit costs figures prominently in a production portfolio no matter how high its actual costs are. However, as also pointed out in [8], current energy generation companies do not adopt the point of view of an investor. They rather want to generate electricity at minimum costs. In order to take into account also this "current user" view, an actual costs analysis was done.

The results of this analysis are illustrated in the 3D-diagram in Figure 5, where the actual costs of energy production of each portfolio are plotted over the risk-return graph. One can see that there is a strong correlation between actual costs and their yield. When actual costs are high, the portfolio tends to exhibit a high cost increase, too. Accordingly, one can conclude that in this case the analysis of portfolios on the basis of relative cost changes is appropriate. Thanks to the strong correlation between actual unit costs and their change rate, the investor view and the current user view are compatible.

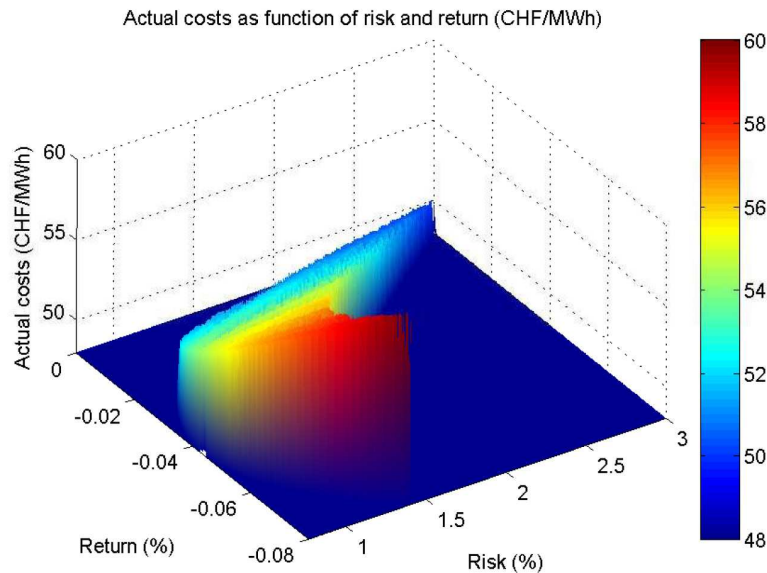


Figure 5: Risk, return and actual costs of portfolios with three technologies (nuclear, pumped-storage and run-of-river).

3.2 Future scenarios for the BKW portfolio

Like many other generation companies, also BKW targets a substantial increase in generation capacity during the coming decades. However, due to several reasons, its current generation technology mix imposes limits concerning capacity extensions. The physical potential for an expansion of hydro power capacity, both run-of-river and pumped-storage, has virtually exhausted. Nuclear electricity generation is controversially discussed within society and furthermore nuclear power plants are associated with long planning and construction periods. This means that new additional generation technologies may be considered. The following paragraphs illustrate how adding gas and coal power plants impacts the risk-return structure of the current BKW portfolio. With hydro power being widely accepted, the introduction of coal and gas fired power plants and the gradual replacement of nuclear power plants is considered as a possible future scenario.

Figure 6 shows the effect of adding, in a first step, gas power plants to the existing generation mix.

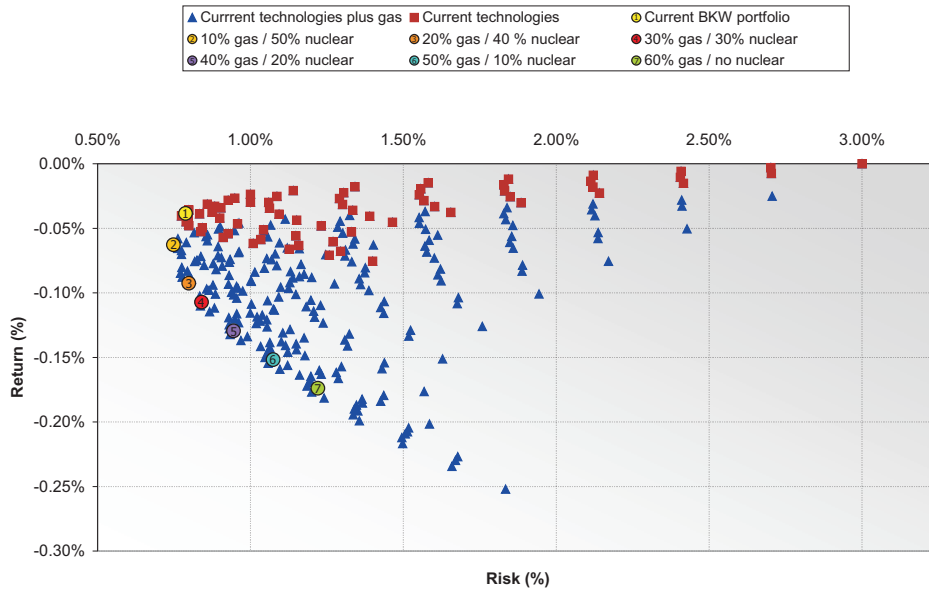


Figure 6: Impact of a gradual substitution of nuclear through gas on the portfolio risk-return structure.

The brown dots represent the possible portfolio allocations with the current three technologies (nuclear, run-of-river, and pumped-storage), whereas the blue dots show all possible allocations when including gas power plants in the portfolio. As one can see, adding gas power plants substantially increases the feasible region within the risk-return space. By adding a small 10% portion of gas to the current BKW portfolio (yellow dot) and reducing

the share of nuclear, portfolio risk can be further reduced, even though this happens at the expense of a simultaneous reduction of return. But Figure 6 also shows that a further substitution of nuclear through gas would not make sense. Risk would increase and return would decrease at the same time.

Figure 7 repeats the allocations feasible with currently used technologies (brown dots) and additionally illustrates the possible range of technology mixes when including both gas and coal (blue dots).

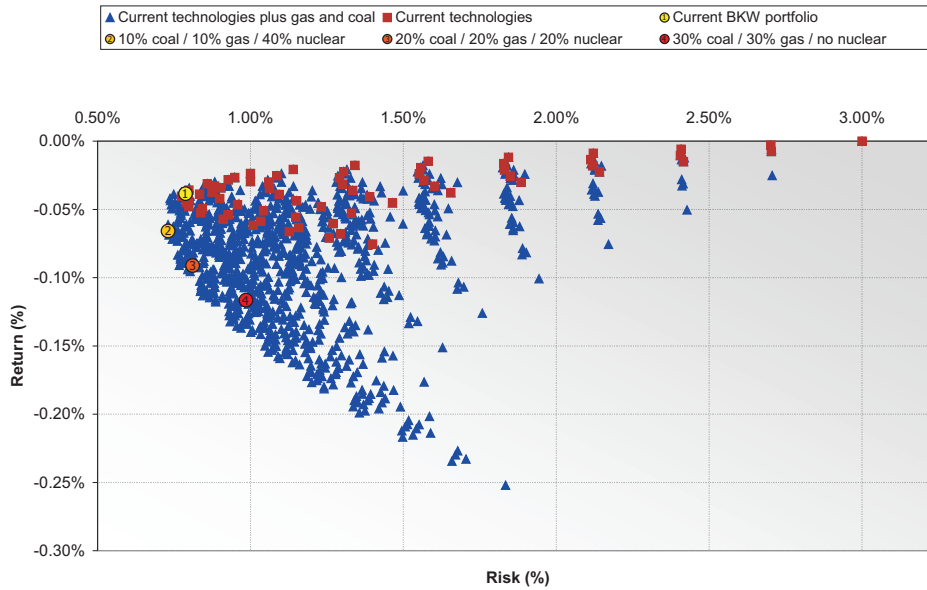


Figure 7: Impact of a gradual substitution of nuclear through gas and coal on the portfolio risk-return structure.

The effect is similar to the one observed in Figure 6. Adding small portions of gas and coal leads to a further diversification of the portfolio and thus to a reduction of risk, even slightly more than in the case where only gas is added. A further substitution of nuclear through gas and coal, however, is not efficient.

One can conclude that gas and coal power plants are viable options for BKW to extend its production capacity. The share of the corresponding installed capacities, however, should stay on a relatively small level. Otherwise, the generation portfolio would become inefficient. The following sub-chapter presents a method that concretely determines these required installed capacities based on the results obtained by the application of mean-variance portfolio theory.

3.3 Relation to physical quantities

Portfolio theory lacks a direct relation to physical quantities. It neither indicates the required installed capacities nor incorporates availability of supply. Unavailability of power plants and unusable capacities, however, are important factors to consider when planning investments in generation assets.

There are several reasons for power plants being unavailable or unusable. First of all, power plants can be out of service or operating at reduced output for some time due to planned maintenance or outages. A second reason is that the output of a power plant is reduced because demand for electricity is too low or because the price of electricity is below the marginal production costs. This accounts for most of the unused capacity of peaking power plants. When dealing with intermittent renewable energies like wind, solar or hydro power, there is a third reason for unused capacities. The corresponding power plants themselves may be available, but not their "fuel" (wind, sunlight or water).

In order to take into account these physical boundary conditions and limitations, the so-called *capacity factor* (CF) is used. The CF is defined in the following way:

$$CF = \frac{E_{annual}}{P_{rated} * N_{annual}} = \frac{P_{average}}{P_{rated}} \quad (9)$$

where

E_{annual}	amount of energy generated in one year
P_{rated}	rated capacity of the power plant
N_{annual}	number of hours in one year
$P_{average}$	average annual plant output power

This means that the capacity factor of a power plant is the ratio of the actual output of a power plant over a time period and its output if it had operated at full capacity over this time period. Table 3 shows for five technologies the assumed average rated capacities per power plant, the capacity factors and the resulting amount of energy generated in one year by one power plant.

Looking at Table 3, one might wonder why the average rated capacity for nuclear power plants is relatively small. This value is specific to the BKW portfolio, where the only nuclear power plant, located in Mühleberg, has a capacity of 355 MW. The capacity factor for gas power plants refers to combined cycle gas turbines and is therefore higher than the usual values for pure peaking gas power plants. This value has been chosen because gas power plants in Switzerland are particularly discussed both as an alternative

Table 3: Average rated capacities per power plant, capacity factors, and energy generated per year by one power plant.

Technology	Average rated capacity per power plant [MW]	Capacity factor	Energy generated per year [GWh]
Nuclear	355	0.90	2798.8
Run-of-river	22	0.45	86.7
Pumped-storage	180	0.23	362.7
Gas	300	0.60	1576.8
Coal	600	0.75	3942.0

to nuclear power plants as well as as a bridging technology until new nuclear power stations can be commissioned.

By means of the average rated plant capacities and the corresponding capacity factors, one is able to calculate the necessary number of power plants for any possible portfolio allocation. In order to give an illustrative example, the required number of power plants for realizing the minimum variance portfolio for the case of the five considered technologies (nuclear, run-of-river, pumped-storage, gas, and coal) was determined. This was done for two different cases. The first one concerns the production capacity necessary to cover the electricity consumption in the BKW service area in the year 2000, which was 9 196 GWh. The second case refers to the projected electricity consumption within the BKW supply region in the year 2035. Until 2035 the Swiss Federal Office of Energy expects a 29% increase with respect to the year 2000 [15], which would then result in an electricity demand of 11 863 GWh in the BKW service area. The results regarding the required number of power plants for these two cases are stated in Table 4.

Table 4: Required number of power plants in the BKW portfolio in the years 2000 and 2035 with regard to the minimum variance (MV) portfolio, based on the average rated capacities listed in Table 3.

Technology	Share in the MV portfolio	Number of power plants for 9 196 GWh (2000)	Number of power plants for 11 863 GWh (2035)
Nuclear	47.79%	1.57	2.03
Run-of-river	5.58%	5.92	7.63
Pumped-storage	26.02%	6.60	8.51
Gas	6.80%	0.40	0.51
Coal	13.81%	0.32	0.42

As the assumed average plant capacities are chosen according to the concrete characteristics of the BKW production park, the resulting values

for the required numbers of power plants are values specific to this particular production park. For other generation companies with different average rated capacities, e.g. with a higher average capacity for nuclear power plants, the numbers would differ.

The values for the required numbers of power plants reflect the characteristic trait of mean-variance portfolio theory, viz that it yields continuous values for portfolio allocations due to the assumption of perfect divisibility of assets. As power plants are non-dividable assets built in discrete size units, this poses a problem when aiming at realizing exactly the desired portfolio allocation. This problem can be overcome in different ways. Either the size of power plants to be built has to differ from the assumed average capacity in order to obtain the proper amount of installed capacity or, where this is no feasible solution, the construction of a new power plant can be undertaken in cooperation with other generation companies so that the own share in total capacity corresponds to the required amount of power with regard to the envisaged portfolio allocation.

4 Conclusion

Mean-variance portfolio theory has been applied to the portfolio of a major Swiss utility. The efficient frontier for the current generation mix has been derived and it has been shown that the current BKW portfolio is close to the minimum variance portfolio. In addition, the efficiency of possible future generation mixes has been analyzed considering different scenarios. Furthermore, the mean-variance portfolio theory has been extended with two analyses to illustrate the physical meaning of a resulting portfolio. On the one hand, a third dimension has been introduced to show the actual average production costs per MWh. On the other hand, the projected total annual production is divided into the respective number of installed capacity per technology by using the capacity factor concept. This second analysis identifies how many units of which technology need to be built in order to obtain the defined portfolio. The suggested method has proven expedient and gives useful insights concerning future investment plans. It helps to identify required installed capacities based on calculated portfolio allocations and provides valuable support for investment decision makers.

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