Valuing Investments in Multi-Energy Generation Plants under Uncertainty: A Real Options Analysis

by

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Abstract

In this paper, a valuation method for multi-energy generation plants is presented. The operational flexibility of such plants is modeled using the Energy Hub concept - a modeling approach that has been developed in the "Vision of Future Energy Networks" project at ETH Zurich. The economic value of an Energy Hub including its flexibility is calculated by means of a Monte Carlo simulation method that generates a large amount of possible price paths for the input and output energy carriers of the respective hub configuration. The proposed Energy Hub real options model can be used to identify prospective hub configurations for future energy systems given the uncertainty concerning the future development of energy prices. In illustrative examples, the method is applied to two different Energy Hub configurations. Furthermore, sensitivity analyses with respect to different parameters such as the discount rate or price volatilities are carried out.

1 Introduction

In the past, different energy infrastructures have been operated separately in most cases. However, a trend towards increasing integration can be observed in recent years. An example for this development is the rising number of distributed combined heat and power (CHP) plants, which establish a connection between gas, electricity and, in some cases, district heating networks. The project "Vision of Future Energy Networks" at ETH Zurich aims at systematically analyzing systems that involve multiple energy carriers in order

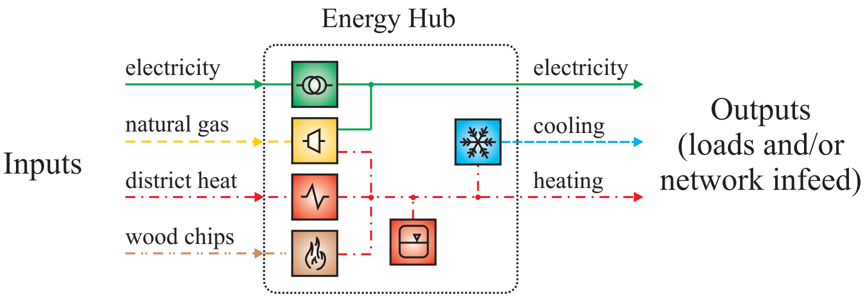

Figure 1: Example of an Energy Hub with the following elements: Electric transformer, microturbine fired by natural gas, heat exchanger, wood chips furnace, heat storage and absorption chiller.

to design optimal structures for future energy systems in the long term. Within this project, the Energy Hub concept has been developed [1]. Generally speaking, an Energy Hub is an integrated system of units that is able to convert and store multiple energy carriers. An illustrative example of an Energy Hub is shown in figure 1.

In this paper, an Energy Hub is considered as a profit-maximizing generator that converts a certain number of input energy carriers into multiple output energy carriers. On the one hand, its elements can be viewed as multi-staged modular investment opportunities, i.e. a hub can be upgraded step-by-step with further elements. On the other hand, an Energy Hub provides operational flexibility in the sense that one output energy carrier can be provided by using different input energy carriers. Another more evident aspect of operational flexibility is that the Energy Hub can be kept idle if input and output prices are such that it would not be profitable to operate it. In liberalized energy markets, fluctuating energy prices and the related financial risks have gained significant importance. In the coming years, the volatility of energy prices is expected to increase further due to aspects such as intermittent infeed from renewable energy sources, increasing scarcity of fossil fuels and rising speculative trade with energy commodities. Therefore, the volatility of prices will become an essential factor to consider for investment decisions.

A concept that takes into account the flexibility to react to volatile market prices is the real option approach [2]. In the real option concept, uncertainty even represents a positive factor as a driver of value because downside risks can be limited and the upside potential of volatility can be exploited by flexible operation.

Electricity prices in competitive markets show a relatively high short-term volatility. One important reason for the high volatility of electricity prices compared to other energy carriers is the fact that electricity cannot be stored easily at low cost. Other energy carriers such as natural gas or heat, for which technically feasible and economical storage solutions exist, exhibit a much lower price volatility. One focus of the "Vision of Future Energy Networks" project is to analyze interactions and synergies between different energy carriers and to design systems that are able to take advantage of their complementary characteristics in a technical but also economic respect. The key concept of the project - the Energy Hub - can be considered as multi-energy generation plant.

The real options approach has been widely applied to electricity generation assets as well as to cogeneration plants [3]- [6]. In this paper, by modeling an Energy Hub as a real option, the real options approach is extended and generalized for an arbitrary number of input and output energy carriers. In this way, we provide a real option valuation method for general multi-energy generation plants focussing on the value of the operational flexibility offered by an Energy Hub.

The remainder of the paper is structured as follows. Section 2 describes the methods and price models used for the real options analysis of Energy Hubs. Section 3 presents the results of a comparison between different hub configurations and a sensitivity analysis. Section 4 concludes the paper.

2 Methods

In this section, it is described how an Energy Hub can be modeled as a real option. For this purpose, the Energy Hub modeling concept is introduced in a first step. In a next step, the real option valuation method making use of Monte Carlo simulation is outlined. Eventually, the application of this valuation method to the Energy Hub concept is presented.

2.1 The Energy Hub modeling concept

The following description of the Energy Hub concept is based on [7]. The Energy Hub concept is a generic model describing the conversion of multiple input energy carriers into multiple output energy carriers. This conversion can be realized by one or several converter devices. The Energy Hub model aggregates the mapping from energy inputs to energy outputs in the so-called converter coupling matrix $\mathbf{C}$. Considering the general representation of an Energy Hub in figure 2, the relation between all power inputs $\mathbf{P^{in}}$ and all power outputs $\mathbf{P^{out}}$ can be formulated as follows:

$$\underbrace{\begin{bmatrix} P_{\alpha}^{out} \\ P_{\beta}^{out} \\ \vdots \\ P_{\omega}^{out} \end{bmatrix}}_{\mathbf{P^{out}}} = \underbrace{\begin{bmatrix} c_{\alpha\alpha} & c_{\beta\alpha} & \cdots & c_{\omega\alpha} \\ c_{\alpha\beta} & c_{\beta\beta} & \cdots & c_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ c_{\alpha\omega} & c_{\beta\omega} & \cdots & c_{\omega\omega} \end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix} P_{\alpha}^{in} \\ P_{\beta}^{in} \\ \vdots \\ P_{\omega}^{in} \end{bmatrix}}_{\mathbf{P^{in}}} \tag{1}$$

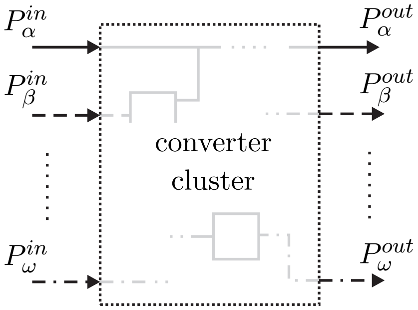

Figure 2: Model of energy converters with inputs $P_\alpha^{in}, P_\beta^{in}, \dots, P_\omega^{in}$ and outputs $P_\alpha^{out}, P_\beta^{out}, \dots, P_\omega^{out}$.

In the general case, the entries of the coupling matrix represent both converter efficiencies and so-called dispatch factors. When the total input of one energy carrier is split up to several converters, these dispatch factors define the percentage of the total input that is dispatched to a certain converter. For example in the case of two converters using the total input power P_α, a dispatch factor of $\nu_{\alpha 1} = 0.6$ means that 60% of P_α are dispatched to converter 1 and 40% to converter 2.

Including the Energy Hub model in the real option method that is described in the following subsection allows for the valuation of multi-energy generation plants.

2.2 The real options approach

Real options analysis applies option valuation techniques to capital budgeting decisions. In general, real options analysis is used when the value of a project is contingent on the value of some other underlying variables, e.g. prices of input and output energy carriers. A real option is the right - but not the obligation - to make a business decision. Typically, it is the right to make or abandon a capital investment. However, the option can also consist in the right to flexibly operate or keep idle a power plant. Real options are often contrasted to standard techniques of capital budgeting such as the discounted cash flow method, where only the most likely outcomes are considered, and the possibility of, e.g., flexibly operating a power plant is thus not valued adequately.

In order to value a multi-energy generation plant in a fair way including the value of flexible operation, we follow the approach of Cavus in [8], i.e. an Energy Hub is modeled as a series of call options. Owning an Energy Hub is analogous to disposing of a series of call options, where each option gives the right to generate energy carriers in exchange for paying the costs of the necessary input energy carriers and variable operation and maintenance costs. These choices represent a right and not an obligation because it can be decided not to generate energy if it is not profitable to do so. Furthermore, since one output energy carrier can possibly be generated using several input energy carriers, the dispatch of energy inputs can be optimized, which provides another form of flexibility. Making use of these operational options, Energy Hubs are able to profit from the upside potential of price uncertainty while they will not suffer to the same extent from the downside risk.

There are three generic main classes of methods for the valuation of (real) options:

- *Analytic closed form solutions.* This method solves a stochastic differential equation (SDE). By analytically solving the SDE, the option value can be expressed as direct function of input parameters such as the asset price. The Black-Scholes formula for the valuation of options that are contingent one one random factor and the Margrabe formula, which is used for the valuation of exchange options with two random factors, are well-known analytic solutions.

- *Tree building methods.* These methods try to approximate a continuous price process via a discrete lattice. Commonly used methods apply a binomial or trinomial lattice. The binomial model was first proposed by Cox, Ross and Rubinstein [9]. It is the basis of the dynamic programming solution to the valuation of American options.

- *Simulation methods.* These methods determine the option value via numerical simulation of a large set of possible price paths. A commonly used class of methods is Monte Carlo simulation. Monte Carlo simulation is relatively easy to implement, is applicable to path dependent options, and can handle multiple stochastic factors. The last property makes it particularly suitable for valuing complex options whose payoff depends on two or more stochastic variables such as energy prices. The main disadvantage of Monte Carlo methods is the significant amount of computing time needed for a good approximation of the "true" option value.

In view of the adequacy of Monte Carlo methods for complex valuation problems with multiple sources of uncertainty, this method was chosen for valuing multi-energy generation plants. An introduction to the modeling of energy prices and derivatives using Monte Carlo methods is given in [10]. In the application presented in this paper, the Monte Carlo technique consists in simulating several thousands of possible price paths for input and output energy carriers. Price process models such as log-of-price mean reversion or the Pilipovic model, which assumes a two-factor representation of the price behavior, are assigned to the considered energy carriers. The option payoffs are calculated for each price path, averaged and discounted to a chosen date. In this way, the value of a multi-energy generation plant is determined.

2.3 Energy price modeling

Using the Monte Carlo method, in principle any price process can be chosen to model energy prices. The flexibility of the Monte Carlo Method even gives the possibility to assign different price paths to different energy carriers. A simple approach, which represents the main characteristics of the energy price processes, is to model the energy prices as log-of-price mean reversion processes. With this assumption the natural logarithm of a certain energy carrier can be expressed as follows:

$$dy = \kappa(b - y)dt + \sigma dz \tag{2}$$

where y is the natural logarithm of the energy carrier price π, κ is the mean reversion rate, b is the long-term equilibrium value of y, σ is the price volatility and dz is a random normally distributed variable with a mean of 1 and a variance of dt. The discrete approximation of equation (2) is used to generate price paths for the Monte Carlo simulation:

$$y_{t+1} = y_t + \kappa(b - y)\Delta t + \sigma\epsilon\sqrt{\Delta t} \tag{3}$$

where ϵ is a normally distributed random variable with a mean of 0 and a variance of 1.

Correlations between price paths of different energy carriers are taken into account applying the Cholesky decomposition to the correlation matrix (cf. appendix A in [11]). By means of the this decomposition method, the correlation matrix $\mathbf{\Omega}$ is factorized:

$$\mathbf{\Omega} = \mathbf{L}\mathbf{L}^T \tag{4}$$

where $\mathbf{L}$ is a lower triangular matrix. In order to generate a vector $\boldsymbol{\epsilon_{corr}}$ with normalized variates being correlated according to the correlation matrix $\mathbf{\Omega}$, a vector $\boldsymbol{\epsilon}$ of independent normalized variates is generated in a first step. Multiplying this vector $\boldsymbol{\epsilon}$ with the matrix $\mathbf{L}$ obtained by Cholesky decomposition yields the vector $\boldsymbol{\epsilon_{corr}}$:

$$\boldsymbol{\epsilon_{corr}} = \mathbf{L}\boldsymbol{\epsilon} \tag{5}$$

$\boldsymbol{\epsilon_{corr}}$ contains one entry per energy carrier. A sample of correlated gas, electricity and heat prices generated in this way is shown in figure 3.

2.4 Optimal dispatch and calculation of option values

The first step in the calculation of the value of a multi-energy generation plant is to compute the daily profits from operation. Assuming a daily time step for the energy price simulation[1] and an operation of the plant during

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[1] The time resolution of the energy price simulation can easily be changed to other time steps, e.g. to hourly or weekly time steps, depending on the time horizon of the model.

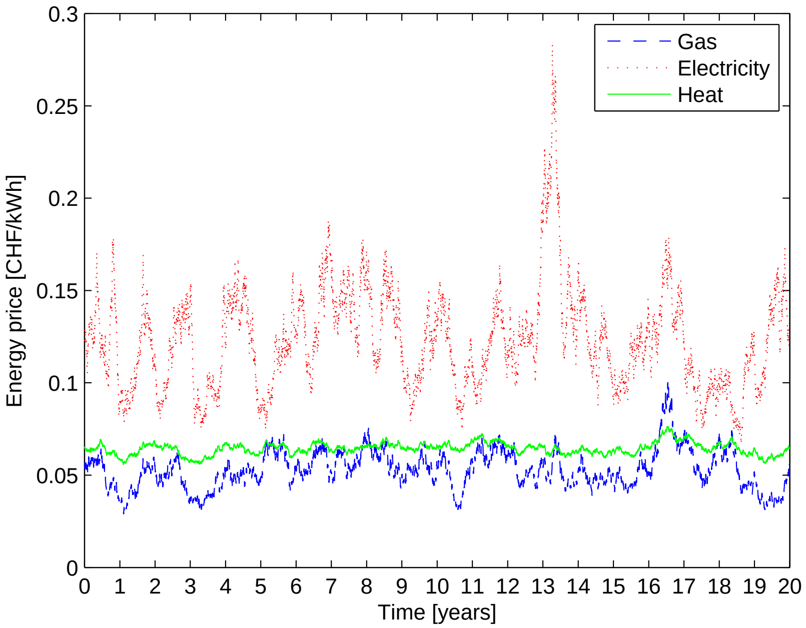


Figure 3: Correlated gas, electricity and heat price paths with volatilities $\sigma_{gas} = 0.4$, $\sigma_{el} = 0.5$ and $\sigma_{heat} = 0.1$, and correlation factors $\omega_{gas,el} = 0.4$, $\omega_{gas,heat} = 0.8$ and $\omega_{el,heat} = 0.2$.

n_{hours} hours per day, the daily profits F_d for each set of simulated price paths of the input and output energy carriers can be computed:

$$F_d = \left(\sum_i \left(P_i^{out} \cdot \pi_i^{out} \right) - \sum_j \left(P_j^{in} \cdot \pi_j^{in} \right) \right) \cdot n_{hours} \tag{6}$$

where P_i^{out} and P_j^{in} are the output and input powers respectively, and π_i^{out} and π_j^{in} are the prices of input and output energy carriers at a discrete time step of the price simulation.

The input and output powers are determined by optimizing the dispatch of the multi-energy generation plant. For this purpose, the Energy Hub model is used. In the model presented in this paper, optimal operation means maximization of daily profits. The simulated energy prices are used as input to the optimization. For each set of simulated energy prices, i.e. at every time step of the simulation, the following optimization problem is solved:

Maximize

$$f\Big(\mathbf{P^{in}}, \mathbf{P^{out}}\Big) = \sum_i \left(P_i^{out} \cdot \pi_i^{out}\right) - \sum_j \left(P_j^{in} \cdot \pi_j^{in}\right) \tag{7}$$

subject to

$$\mathbf{P^{out}} - \mathbf{C}\,\mathbf{P^{in}} = \mathbf{0} \tag{8}$$

and

$$\mathbf{P^{out}_{min}} \leq \mathbf{P^{out}} \leq \mathbf{P^{out}_{max}} \tag{9a}$$

$$0 \leq \boldsymbol{\nu} \leq 1 \tag{9b}$$

by varying $\mathbf{P^{in}}$ and $\boldsymbol{\nu}$ depending on the energy prices π_i^{out} and π_j^{in}. Equation (9a) ensures that minimum and maximum output limits of the converters are respected. The vector $\boldsymbol{\nu}$ gathers all dispatch factors which are defined according to the hub configuration and the number of energy carriers that are split up [12]. At each simulation time step, the value of the objective function $f\big(\mathbf{P^{in}}, \mathbf{P^{out}}\big)$ is used to calculate the daily profits F_d according to equation (6). As the daily profits are determined via an optimal dispatch, negative profits are excluded by the optimization algorithm; the minimum profit is 0 and the daily profits F_d thus equal the daily option payoffs H_d. If another method, which does not inherently exclude negative profit values, is used to calculate the daily profits F_d, the daily option payoffs become

$$H_d = max\left[F_d; 0\right] \tag{10}$$

The daily option payoffs on each path of simulated energy prices are discounted and summed up for the whole depreciable life of the plant T to obtain the present value (PV) of the Energy Hub on each individual simulation path:

$$H_d = \sum_{t=0}^{T} H_{d,t} \cdot e^{-rt} \tag{11}$$

r is the continuous risk-adjusted discount rate.

Eventually, the value of the Energy Hub is obtained by averaging the payoffs of all N simulated sets of energy price paths:

$$V = \sum_{n=1}^{N} H_{path} \cdot \frac{1}{N} \tag{12}$$

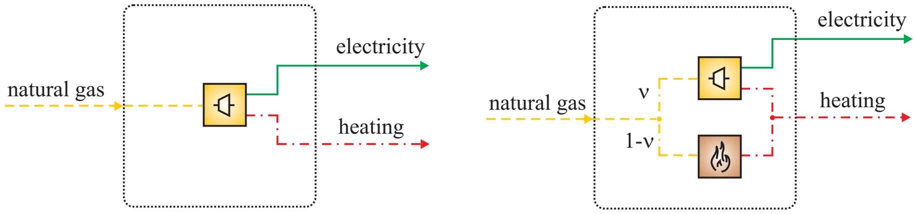
The value of the Energy Hub V can then be compared with its capital investment costs I. If $V > I$, the investment is profitable given the assumptions made in the modeling process. If $V < I$, the investment costs exceed the value of the Energy Hub, and one would disregard an investment in this Energy Hub configuration.

Including an optimal dispatch in the valuation method implies high computational efforts. However, as the time horizon of the investments to be valued is at least several years or rather decades, this aspect should not represent a prohibitive barrier. By taking into account optimal adaption of generation dependent on given energy prices, a detailed representation of an Energy Hub's operational flexibility is obtained. This feature of the presented model is of particular importance given the fact that real-time pricing is expected to play a major role in future electricity systems.

3 Results from application examples

3.1 Comparison of two different Energy Hub configurations

Using the above described Monte Carlo valuation method, two different Energy Hub configurations are analyzed - a basic Energy Hub with a CHP unit and a more flexible Energy Hub being composed of a CHP and a gas furnace. Figure 4 depicts both configurations.



a) b)

Figure 4: Two Energy hub configurations with a) a CHP unit and b) a CHP unit and a gas furnace.

The technical characteristics of the CHP unit and the gas furnace are listed in table 1. The rating of the gas furnace is such that it can it can generate 30% of the heat power provided by the CHP at rated capacity.

Table 1: Converter parameters.

CHP unit	
Electrical efficiency	$\eta_{CHP,el} = 0.3$
Thermal efficiency	$\eta_{CHP,heat} = 0.5$
Rated electrical capacity	$P_{max}^{out,CHP,el} = 60$ kW
Gas furnace	
Thermal efficiency	$\eta_{GF,heat} = 0.9$
Rated thermal capacity	$P_{max}^{out,GF} = 30$ kW

The coupling matrix $\mathbf{C_{basic}}$ for the basic configuration with the CHP is very simple:

$$\mathbf{C_{basic}} = \begin{bmatrix} \eta_{CHP,el} \\ \eta_{CHP,heat} \end{bmatrix} = \begin{bmatrix} 0.3 \\ 0.5 \end{bmatrix} \tag{13}$$

The coupling matrix $\mathbf{C_{flexible}}$ for the flexible configuration includes the dispatch factor ν because the total natural gas input is split up in two parts - the part $\nu \cdot P_{gas}^{in}$ going to the CHP and the part $(1-\nu) \cdot P_{gas}^{in}$ that is dispatched to the furnace:

$$\mathbf{C_{flexible}} = \begin{bmatrix} \nu \cdot \eta_{CHP,el} \\ \nu \cdot \eta_{CHP,heat} + (1-\nu) \cdot \eta_{GF,heat} \end{bmatrix} = \begin{bmatrix} \nu \cdot 0.3 \\ \nu \cdot 0.5 + (1-\nu) \cdot 0.9 \end{bmatrix} \tag{14}$$

The parameters for modeling the prices of the three energy carriers natural gas, electricity and heat as mean reversion processes are given in table 2.

Table 2: Parameters of mean reversion processes.

Gas	
Price volatility	$\sigma_{gas} = 40\%$
Mean reversion rate	$\kappa_{gas} = 1.69$
Initial price	$\pi_{gas,0} = 0.054$ CHF/kWh
Electricity	
Price volatility	$\sigma_{el} = 50\%$
Mean reversion rate	$\kappa_{el} = 1.69$
Initial price	$\pi_{el,0} = 0.12$ CHF/kWh
Heat	
Price volatility	$\sigma_{heat} = 10\%$
Mean reversion rate	$\kappa_{heat} = 1.69$
Initial price	$\pi_{heat,0} = 0.065$ CHF/kWh

A mean reversion rate of 1.69 means that the half-life[2] of the mean reversion process is $t_{1/2}$=ln(2)/1.69 years $\approx$ 5 months. The data for the initial prices are based on tariffs from the gas supplier in the city of Zurich *Erdgas Zürich* for natural gas (as of April 2009), from the municipal electric utility of the city of Zurich *ewz* for electricity on the medium-voltage level (as of January 2009) and from the district heat supplier in Zurich *Fernwärme Zürich* for district heat (as of January 2009). We assume that the level to which energy prices revert back in the long-term is equal to the initial prices, i.e. in this application example, we have $b = ln(\pi_{i,0})$ for all energy carriers. The correlation matrix for the energy carrier prices is assumed to be as follows:

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[2] The half-life is the time it takes for the price to revert half way back to its long-term level from its current level if no more random shocks arrive.

$$\boldsymbol{\rho} = \begin{bmatrix} \rho_{gas,gas} & \rho_{gas,el} & \rho_{gas,heat} \\ \rho_{el,gas} & \rho_{el,el} & \rho_{el,heat} \\ \rho_{heat,gas} & \rho_{heat,el} & \rho_{heat,heat} \end{bmatrix} = \begin{bmatrix} 1 & 0.4 & 0.8 \\ 0.4 & 1 & 0.2 \\ 0.8 & 0.2 & 1 \end{bmatrix} \tag{15}$$

Furthermore, it is supposed that the Energy Hub is operating during 8 hours per day, i.e. $n_{hours} = 8$, and the payoffs are discounted at a risk-adjusted discount rate of 7%.

As the coupling matrix $\mathbf{C_{basic}}$ does not contain any dispatch factors, no optimal dispatch has to be carried out. Instead, having calculated the daily profits F_d which may become negative, the option valuation can be done directly according to equation (10). Simulating 1,500 sets of daily energy prices over an assumed depreciable life of 20 years and calculating option values with the above described valuation method, one obtains the distribution of present values of the basic Energy Hub configuration shown in figure 5.

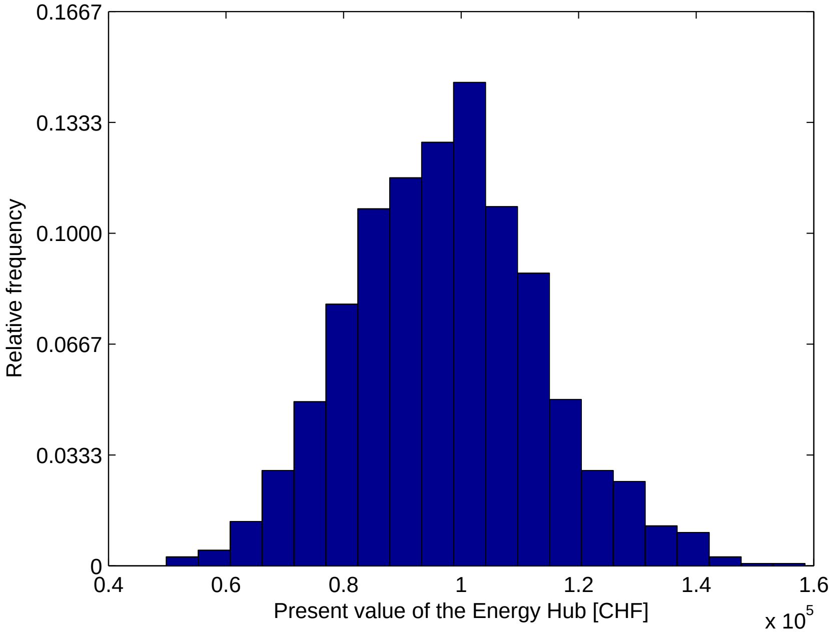

Figure 5: Distribution of the simulated present values of the basic Energy Hub configuration with CHP unit.

The basic Energy Hub configuration has a standard deviation of 16,117 CHF and a mean present value of 97,540 CHF. Supposing investment costs of 1,360 USD/kW (≈ 1,700 CHF/kW[3]) for the CHP unit including the heat recovery system [13], this results in total investment costs of about 100,000 CHF.

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[3] Used exchange rate (from June 2004): 1 USD = 1.25 CHF

This means that, given the made assumptions, one would rather not invest in this Energy Hub configuration.

The value of the flexible Energy Hub configuration with CHP and additional furnace is computed using the optimal dispatch procedure described in section 2.4, i.e. at each simulation time step the optimal gas input power and the optimal dispatch factor is determined depending on the input and output energy prices given from the price simulation. Applying the presented Monte Carlo valuation method, the distribution of present values results as depicted in figure 6.

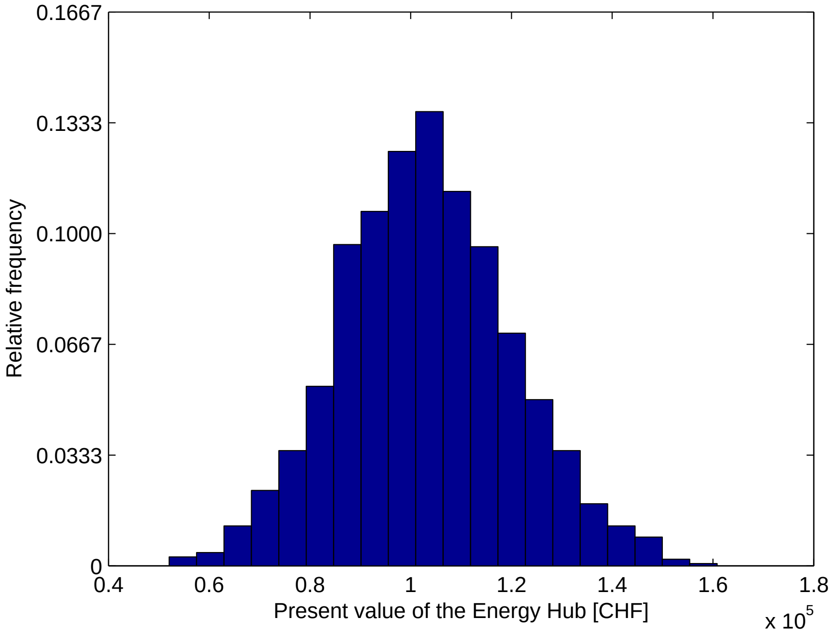

Figure 6: Distribution of the simulated present values of the more flexible Energy Hub configuration with CHP unit and furnace.

The additional flexibility offered by the gas furnace increases the present value to 103,080 CHF. This is about 5,500 CHF more than for the basic hub configuration. However, the standard deviation is 17,042 CHF, which is slightly higher than for the basic configuration.

Having this quantitative information at hand, an investor can compare the two alternatives with respect to present values, involved risk expressed by the standard deviation, and capital investment costs. In this way, the method provides valuable decision support and enables investors to make decisions taking into account the financial risks arising from energy price volatility. Furthermore, by means of comparing hub configurations with different converter devices, promising structures for the design of future energy systems can be identified.

3.2 Sensitivity analyses

In order to determine the main parameters influencing the value of an Energy Hub, sensitivity analyses with respect to the discount rate, the volatility of the electricity price and the correlation between electricity and gas prices have been carried out for the basic hub configuration.

Figure 7 shows the Energy Hub's present value as a function of the discount rate ranging from 4% to 10%. The dashed line indicates the total capital investment cost for the 60 kW CHP unit still assuming costs of approximately 1,700 CHF/kW. It can be observed that the break-even discount rate is slightly below 7%. This means that for lower discount rates, the investment would be profitable whereas at discount rates higher than 7%, one would not invest. Furthermore, it can be seen that the discount rate has a significant influence on the value. Choosing, e.g., a discount rate of 10% instead of 7% decreases the value of the project by about 20,000 CHF. Interpreting the discount rate as reinvestment rate, a company considering the investment can value the Energy Hub at a discount rate that corresponds to the rate of return for the company's investments on average and then compare the obtained value with the capital investment cost. In

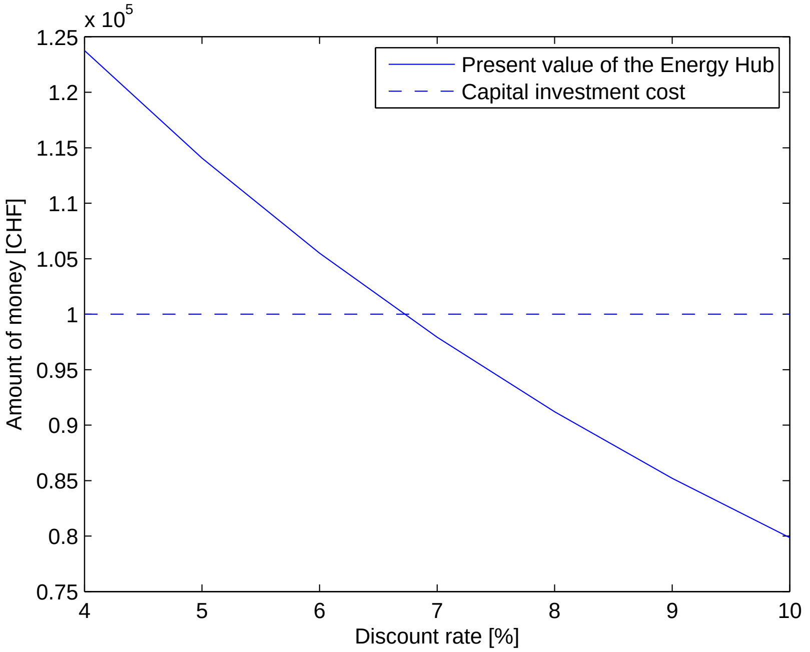

Figure 7: Sensitivity of the Energy Hub's present value to the discount rate.

this way, the opportunity cost of the Energy Hub investment is confronted with the average profitability of the company's projects.

The solid line in figure 8 depicts the present value of the Energy Hub as a function of the electricity price volatility σ_{el}. Please note that the scale of the axis of ordinates is different from the scale used in figure 7. If σ_{el} increases - ceteris paribus - the value of the Energy Hub increases, too. A higher volatility of the electricity price increases the number of times the Energy Hub can benefit of upwards price fluctuations by making use of its operational flexibility. However, the downside risk does not increase to the same extent because the Energy Hub is not operated if operation would entail financial losses. Thus, although high volatility is commonly associated with risky markets where the probability for losses is high, the higher volatility of the electricity price together with the flexibility of the Energy Hub adds value to the investment opportunity.

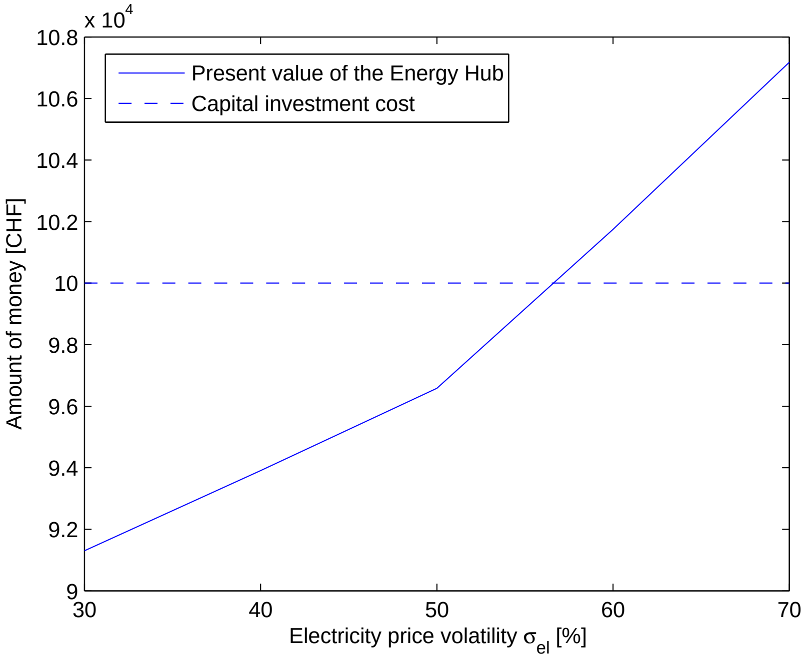

Figure 8: Sensitivity of the Energy Hub's present value to the volatility of the electricity price σ_{el}.

Finally, the sensitivity of the Energy Hub's present value to the correlation between electricity and gas prices is analyzed. The results of this analysis are shown in figure 9. For the sake of readability, the scale of the axis of ordinates is again different from the ones used in figure 7 and figure 8. For increasing correlation values, one can observe a decrease in the Energy Hub's present value. This can be explained by the fact that an in-

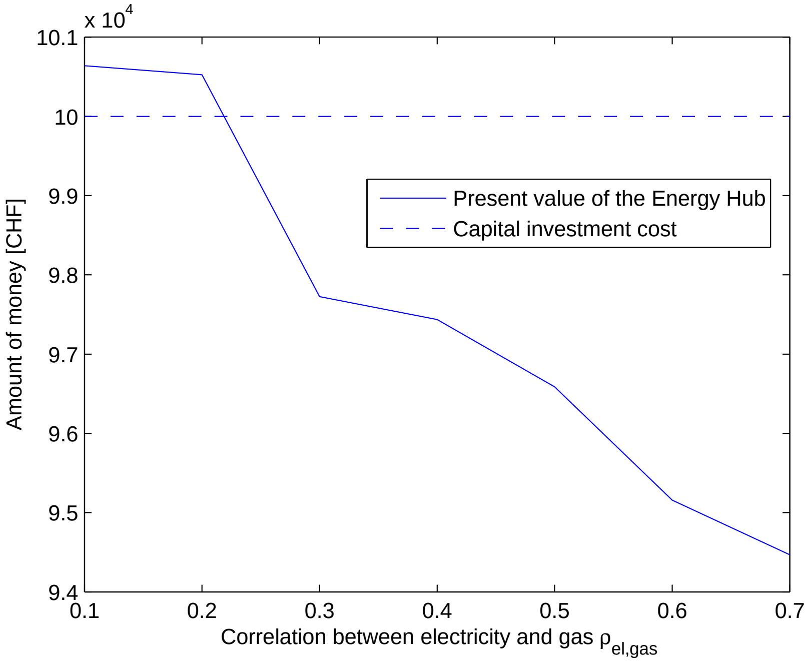

Figure 9: Sensitivity of the Energy Hub's present value to the correlation between electricity and gas $\rho_{el,gas}$.

creasing correlation between both prices decreases the number of situations where high electricity prices coincide with low natural gas prices. Hence, a high correlation between gas and electricity makes the Energy Hub less profitable. This means that the present value of a multi-energy generation plant is higher in an environment with loosely correlated prices of energy carriers.

Comparing the results of the three sensitivity analyses shows that the value of the Energy Hub investment option is very sensitive to the chosen discount rate whereas it is less sensitive to the electricity price volatility and the correlation between electricity and gas.

4 Conclusions

The option valuation model presented in this paper represents a generalization of real options applications to power generating assets or CHP plants. Using the Energy Hub concept, it is possible to model multi-generation plants with an arbitrary number of energy inputs and outputs as a series of call options. In so doing, the Energy Hub real options model can be used to identify prospective hub configurations for future energy systems given the uncertainty concerning the future development of energy prices.

In contrast to standard techniques for evaluating investment projects, such as the net present value method, the real options approach allows for including strategic and operational flexibility in the analysis.

As the model is flexible from a modeling point of view both regarding the modeling of converters via the coupling matrix and the modeling of energy prices, it could also be used to value storage devices in an environment with volatile energy prices. For such an analysis, the storage device would have to be included in the coupling matrix as described in [14] and the time step of the price simulation would have to be adapted accordingly.

Although it might prove difficult to exactly estimate the parameters needed for a real options analysis, the method provides also significant value in terms of qualitative insights. By means of a sensitivity analysis, general qualitative relations can be revealed. In this respect, the real options framework is a useful guide for identifying crucial parameters for future investments in multi-energy generation plants.

Acknowlegdements

The authors would like to thank ABB, AREVA T&D, Siemens, and the Swiss Federal Office of Energy for supporting the research project ”Vision of Future Energy Networks”, as well as the other members of the project team for discussions and support during the preparation of this paper.

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