Location-Dependent Valuation of Energy Hubs with Storage in Multi-Carrier Energy Systems

Florian Kienzle, *Student Member, IEEE,* and Göran Andersson, *Fellow, IEEE*

***Abstract*—In this paper a valuation method for energy hubs containing storage devices is presented. An energy hub is an integrated system of units, e.g. a combined heat and power (CHP) plant and a battery, which allows the conversion and storage of multiple energy carriers. To determine the economic value of an energy hub, its operation is modeled as a series of call options. Taking into account the hub's flexibility to change its output power(s), this series of call options is valued with a Monte Carlo simulation method that calculates an optimal dispatch of the hub for a large amount of possible price paths of the input and output energy carriers. Using the nodal prices from an optimal power flow analysis (OPF) of a system of interconnected energy hubs, each hub can be valued depending on its location. By means of the proposed energy hub real options model, integrated systems of conversion and storage devices can be valued considering both their position in the network and their ability to flexibly adapt their operation to volatile market prices.**

***Index Terms*—Power generation investment, real options analysis, optimal power flow, nodal prices, energy storage, multiple energy carriers.**

I. INTRODUCTION

The research project ”Vision of Future Energy Networks” (VoFEN) at ETH Zurich aims at providing a framework for the systematic analysis of systems involving multiple energy carriers. Distributed generation and technologies that establish a coupling between different energy infrastructures, e.g. CHP plants, are of particular importance for the development of this framework. The key concept in the VoFEN project is the energy hub [1]. An energy hub is an integrated system of units being able to convert and store multiple energy carriers. A generic example of an energy hub is shown in Fig. 1.

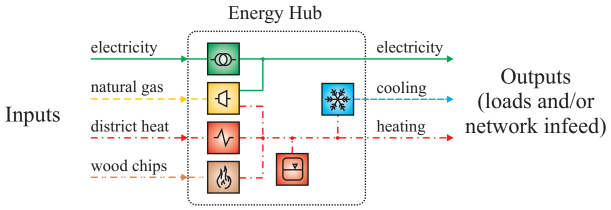


Fig. 1. Example of an Energy Hub with the following elements: Electric transformer, microturbine fired by natural gas, heat exchanger, wood chips furnace, heat storage and absorption chiller.

Depending on its configuration, an energy hub can provide a certain output carrier by using several input carriers. The hub in Fig. 1, e.g., can supply its load with heat via the microturbine, the district heating system and the wood chips furnace. This redundancy together with the possibility to store energy allows to flexibly adapt the hub's operation and outputs to a changing environment (e.g. prices or loads to be supplied). With an expected increase in the share of intermittent power sources and the prospective introduction of real-time pricing elements in future electric power systems, this flexibility of an energy hub is of particular importance.

A concept that takes into account the flexibility to react to volatile market prices is the real options approach [2]. In the real options concept, uncertainty can even represent 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. In this paper an energy hub is considered as a profit-maximizing entity that converts and stores multiple energy carriers depending on prices of input and output carriers and on loads that have to be supplied. The operation of a hub is modeled as a series of call options. Using a real options approach allows for a fair valuation of an energy hub as integrated system of conversion and storage elements. Furthermore, by using nodal prices resulting from an optimal power flow (OPF) analysis of a system of interconnected hubs, it is possible to include location-specific price information in the analysis.

Including storage devices and location-dependent prices into the model represents an extension of a previous paper which outlined a basic real options model of an energy hub [3]. Real options analysis has previously been applied to electricity generation assets as well as to cogeneration plants [4]-[6]. In this respect, the energy hub real options model presented in this paper represents a generalization of the real options approach for an arbitrary number of input and output energy carriers.

The remainder of the paper is structured as follows. Section II provides a description of the energy hub real options model and the corresponding valuation method. Section III presents the results of two application examples illustrating the method. Section IV concludes the paper.

II. METHODS AND MODELING

In this section it is described how the operation of an energy hub can be modeled as a series of real call options and which method is used to value this series of options.

A. Energy hub

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. Furthermore, energy carriers can be stored in the hub by means of one or more storage

---

This work was supported by ABB, AREVA T&D, Siemens, and the Swiss Federal Office of Energy.

Florian Kienzle and Göran Andersson are with the Power Systems Laboratory, ETH Zurich, 8092 Zurich, Switzerland. {kienzle, andersson}@eeh.ee.ethz.ch.

devices. The energy hub model aggregates the conversion from energy inputs to energy outputs in the conversion coupling matrix $\mathbf{C}$. The storage coupling matrix $\mathbf{S}$ describes how changes in the storage levels affect the output powers of the hub. With the matrix $\dot{\mathbf{E}}$ describing the change in the storage levels, the relation between the hub input powers $\mathbf{P}^{\mathbf{in}}$ and the hub output powers $\mathbf{P}^{\mathbf{out}}$ can be formulated as follows:

$$\mathbf{P}^{\mathbf{out}} = \mathbf{C}\,\mathbf{P}^{\mathbf{in}} - \mathbf{S}\,\dot{\mathbf{E}} \tag{1}$$

A more detailed derivation of the energy hub model with storage devices can be found on p. 25 ff. of [7]. The energy hub model described by (1) is the basis for the real option valuation method being developed in the following subsections.

B. Monte Carlo 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. Generally speaking, 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 an energy hub in an adequate 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. This series of call options gives the owner of an energy hub the right to generate energy carriers in exchange for paying the costs of the necessary input energy carriers as well as 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. Finally, including storage in an energy hub offers another degree of freedom. Making use of these operational options, energy hubs are able to profit from the upside potential of price volatility while they will not suffer to the same extent from the downside risk.

There are several method classes for the valuation of (real) options, e.g. analytic solutions like the Black-Scholes formula or tree building methods such as the binominal model by Cox, Ross and Rubinstein [9]. A third class of methods uses numerical simulation to determine the option value. Monte Carlo simulation is one method inside this class. Given the fact that multiple stochastic variables such as energy prices can be handled by Monte Carlo simulation methods, this approach was chosen for valuing energy hubs whose main characteristic is the possibility to provide multiple energy carriers. The main disadvantage of Monte Carlo methods is the significant amount of computing time needed for a good approximation of the ”true” option value. An introduction to the modeling of energy prices and derivatives using Monte Carlo methods is given in [10]. For the model 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 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 an energy hub can be determined.

C. Energy price modeling

Due to the flexibility of the Monte Carlo method, in principle any price process can be chosen to model the evolution of energy prices. For the purpose of illustrating the energy hub real options model, a simple price model, which represents the main characteristics of energy price processes, has been chosen: the log-of-price mean reversion process. With this price model, 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:

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

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 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 with a daily resolution generated with the method described above is shown in Fig. 2.

For the valuation of energy hubs with storage, the assumption of a daily price resolution, i.e. only one price per day, is not sufficient. Instead, a finer time resolution, e.g. hourly price profiles, have to be chosen for the price modeling in order to adequately assess the intra-day operation of a storage device. In this case, the variable y in (2) and (3) does not represent the natural logarithm of the price itself, but a scaling factor with a mean value of 1, i.e. $b = 0$. For each day of a run in the Monte Carlo simulation, this scaling factor is calculated

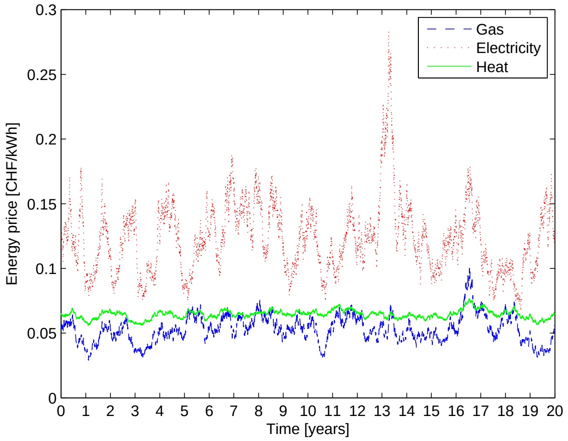


Fig. 2. Correlated gas, electricity and heat prices (Δt=24h) with volatilities $\sigma_{gas} = 0.4$, $\sigma_{el} = 0.5$ and $\sigma_{heat} = 0.1$, and correlation coefficients $\omega_{gas,el} = 0.4$, $\omega_{gas,heat} = 0.8$ and $\omega_{el,heat} = 0.2$.

and multiplied with an assumed hourly base price curve of the respective energy carrier. In this way intra-day price changes due to different energy demands at different times of the day are taken into account.

D. Optimal dispatch and option valuation

The basis for the calculation of an energy hub's value is to computation of the daily profits from operation. Depending on the time resolution of the energy price simulation, each day is divided into N_t periods. With this definition the daily profits F_d for each set of simulated price paths of the input and output energy carriers can be computed:

$$F_d = \sum_{t=1}^{N_t} \left(\left(\mathbf{P_t^{out}} \cdot \boldsymbol{\pi}_\mathbf{t}^\mathbf{out} \right) - \left(\mathbf{P_t^{in}} \cdot \boldsymbol{\pi}_\mathbf{t}^\mathbf{in} \right) \right) \tag{6}$$

where $\mathbf{P_t^{out}}$ and $\mathbf{P_t^{in}}$ are the vectors of the output and input powers at each instant of time t, and $\boldsymbol{\pi}_\mathbf{t}^\mathbf{out}$ and $\boldsymbol{\pi}_\mathbf{t}^\mathbf{in}$ are the corresponding prices of input and output energy carriers.

The input and output powers are determined by optimizing the dispatch of the energy hub. 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

$$f\left(\mathbf{P_t^{in}}, \boldsymbol{\nu_t}, \mathbf{E_t}\right) = \sum_{t=1}^{N_t} \left(\left(\mathbf{P_t^{out}} \cdot \boldsymbol{\pi}_\mathbf{t}^\mathbf{out} \right) - \left(\mathbf{P_t^{in}} \cdot \boldsymbol{\pi}_\mathbf{t}^\mathbf{in} \right) \right) \tag{7}$$

subject to

$$\mathbf{P_t^{out}} - \mathbf{C}\,\mathbf{P_t^{in}} - \mathbf{S}\,\dot{\mathbf{E}}_\mathbf{t} = \mathbf{0} \tag{8a}$$

$$\mathbf{E}(t = 1) = \mathbf{E_1} \tag{8b}$$

$$\mathbf{E}(t = N_t) = \mathbf{E_{N_t}} \tag{8c}$$

and

$$\mathbf{P_{min}^{out}} \leq \mathbf{P_t^{out}} \leq \mathbf{P_{max}^{out}} \tag{9a}$$

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

by varying the input powers $\mathbf{P_t^{in}}$, the dispatch factors $\boldsymbol{\nu_t}$ and the storage levels $\mathbf{E_t}$ depending on the energy prices $\boldsymbol{\pi}_\mathbf{t}^\mathbf{out}$ and $\boldsymbol{\pi}_\mathbf{t}^\mathbf{in}$. The equality constraints (8) comprise the power flow balances at the hub output and two set of equations guaranteeing that the storage devices have the desired level at the beginning and at the end of each optimization period. Equation (9a) ensures that minimum and maximum output limits of the converters are respected. The vector $\boldsymbol{\nu_t}$ in (9b) gathers all dispatch factors which are defined according to the hub configuration and the number of energy carriers that are split up [7]. At each simulation time step, the value of the objective function $f\left(\mathbf{P_t^{in}}, \boldsymbol{\nu_t}, \mathbf{E_t}\right)$ is used to calculate the daily profits F_d according to (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 set of paths 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 for each individual simulation run:

$$H_{run} = \sum_{t=0}^{T} \left(H_{d,t} \cdot e^{-rt} \right) \tag{11}$$

r is the continuous risk-adjusted discount rate. Eventually, the value of the energy hub is obtained by averaging the payoffs of all N simulation runs:

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

The value V of the energy hub 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.

E. Nodal prices from multi-carrier OPF

The value of an energy hub is obviously dependent on the level of energy prices at the place where it is located. In order to take into account this location-dependency in the valuation method, a two-step procedure is proposed. The first step consists in an OPF analysis of a system of interconnected hubs. A detailed description of the mathematical formulation of the multi-carrier optimal power flow problem can be found in [12]. One type of results of such an analysis are the locational marginal prices, often referred to as nodal prices, of each energy carrier. In a second step, the obtained nodal prices are used as an input to the log-of-price mean reversion process model. The nodal prices are assumed to represent the long-term mean values around which prices fluctuate and to which prices revert back. Hence, the natural logarithms of the nodal prices are used as values for the parameter b in (2) and (3). As projections for future load growth or plans for the construction of new lines are often available, such parameters can be included in an OPF analysis covering the expected lifetime of the energy hub investment. In this way, factors influencing the energy price level at a specific location and thus impacting on the profitability of the investment can be taken into account in the valuation process.

III. APPLICATION EXAMPLES

The following two application examples demonstrate the proposed method for the valuation of a series call options consisting in the right to flexibly operate an energy hub. The first one illustrates the location-dependent valuation of energy hubs valuing one particular energy hub configuration at different places in the network. The second one applies the method to three different hub configurations demonstrating the valuation of energy hubs with storage devices.

A. Location-dependent valuation

The first step of the location-dependent valuation consists in an OPF analysis to determine the nodal energy prices. In this application example, which is based on [13], we consider the system shown in Fig. 3. Each of the four regions R1 to R4 has a certain demand for heat and electricity and is connected to an electricity and gas network. The local energy conversion devices available in the regions are represented in an aggregated way by the energy hub configuration shown in Fig. 4. The hubs contain a gas furnace and a CHP unit. The latter one establishes a physical link between the natural gas and the electricity network.

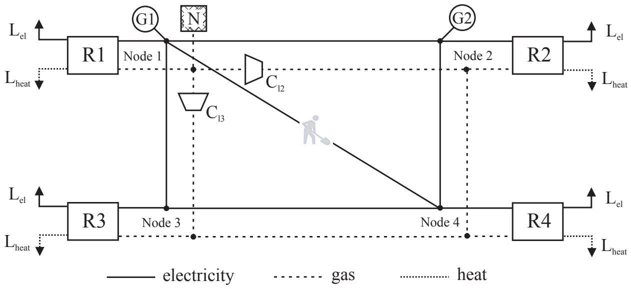


Fig. 3. System with four hubs interconnected by a natural gas and electricity system. The four hubs represent the regions R1 to R4.

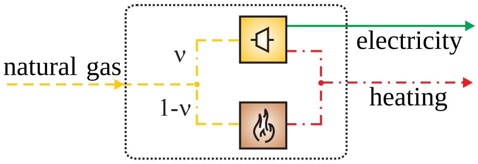


Fig. 4. Energy hub with a CHP unit and a gas furnace.

The complete system data for the networks, hubs, generators, gas source and compressors is given in table I. The generators and the gas source are assumed to have quadratic cost functions with the parameters a_i, b_i and c_i. Using this system data and assuming an annual electricity load growth of 2% in region R4, an OPF is run for each year of a period of 20 years to analyze the effect of the increasing load on nodal energy prices. This analysis is done for two different cases. The first case is the system depicted in Fig. 3 without the electricity line from node 1 to node 4. In the second case it is assumed that an electricity line from node 1 to node 4 is built and goes into operation after 10 years.

TABLE I
4-REGION EXAMPLE SYSTEM PARAMETERS.

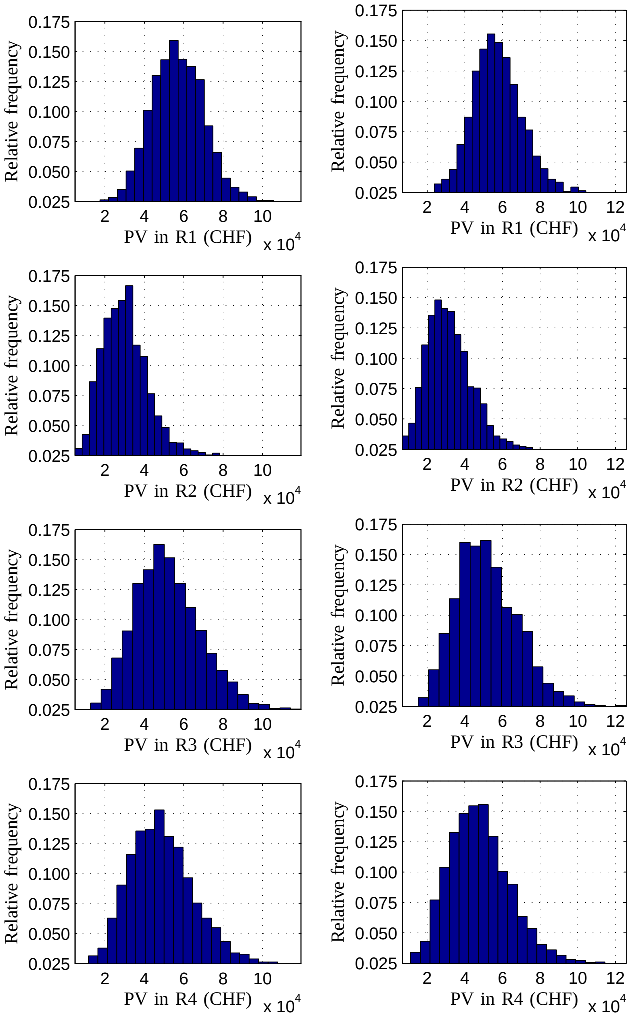
Element data	
el. line 1-2	$Z_{12} = 0.3 + j0.9$ pu, $Y_{12} = j1.5 \cdot 10^{-6}$ pu
el. line 1-3	$Z_{13} = 0.2 + j0.6$ pu, $Y_{13} = j2.5 \cdot 10^{-6}$ pu
el. line 2-4	$Z_{23} = 0.1 + j0.4$ pu, $Y_{23} = j3.5 \cdot 10^{-6}$ pu
el. line 3-4	$Z_{23} = 0.1 + j0.4$ pu, $Y_{23} = j3.5 \cdot 10^{-6}$ pu
el. line 1-4	$Z_{23} = 0.1 + j0.4$ pu, $Y_{23} = j3.5 \cdot 10^{-6}$ pu
Generator G_1	slack type, $V_1 = 1\angle 0°$ pu, $a_{G_1} = 0$ mu, $b_{G_1} = 10$ mu/pu, $c_{G_1} = 0.0010$ mu/pu^2
Generator G_2	PQ type, $a_{G_2} = 0$ mu, $b_{G_2} = 12$ mu/pu, $c_{G_2} = 0.0012$ mu/pu^2
All gas pipelines	$k = 4$
C_{12}, C_{13}	$k_{C_{12}} = k_{C_{13}} = 0.5$ pu^{-1}
Gas source N	slack type, $p_1 = 1$ pu, $a_N = 0$ mu, $b_N = 5$ mu/pu, $c_N = 0$ mu/pu^2
CHP	$\eta_{CHP,el} = 0.30$, $\eta_{CHP,heat} = 0.40$
Gas furnace	$\eta_{GF,heat} = 0.75$
Loads	$L_{el,i} = 1 + j0.1$ pu + 2% annually for region R4, $L_{heat,i} = 2$ pu
Limitations	
Nodes $m = 2, 3, 4$	$0.9 \leq \lvert V_m \rvert \leq 1.1$ pu $0.8 \leq p_m \leq 1.2$ pu
Generator G_2	$0 \leq P_{G_2} \leq 4$ pu, $0 \leq \lvert Q_{G_2} \rvert \leq 4$ pu, $0 \leq \lvert P_{G_2} + jQ_{G_2} \rvert \leq 5$ pu
C_{12}, C_{13}	$1.2 \leq \frac{p_m}{p_k} \leq 1.8$

In a next step the resulting yearly sets of nodal energy prices are used as long-term mean values for the log-of-price mean reversion price model, which is used for the valuation of individual energy hubs placed in one of the four regions. The other parameters of the mean reversion price processes of the three considered energy carriers are given in table II. Valuing the hubs according to the method described in section II with a total of 2000 runs for the Monte Carlo simulation gives the results shown in Fig. 5

TABLE II
PARAMETERS OF MEAN REVERSION PROCESSES.

Price volatilities		
σ_{gas} = 40%	σ_{el} = 50%	σ_{heat} = 10%
Mean reversion rates		
κ_{gas} = 1.69	κ_{el} = 1.69	κ_{heat} = 1.69
Price correlations		
$\rho_{gas,el}$ = 0.4	$\rho_{gas,heat}$ = 0.8	$\rho_{el,heat}$ = 0.2

The distribution of present values of energy hubs in the regions R1 and R3 is similar for both cases. The hubs in region R2 have a higher mean value for the case with the electricity line from node 1 to 4 being in operation after 10 years. This is due to the fact that gas prices in region R2 go down after the commissioning of the electricity line while electricity prices stay roughly at the same level. Thus, region R2 becomes more interesting for investments. Hubs in region R4 have a lower mean present value with the new line because electricity prices at node 4 drop when the line is put into operation due to the possibility of direct power transmission from the cheap generator G1 to node 4.



(a) No Line Built (b) Line Built

Fig. 5. Subfigure (a) shows the results for the hub values when no line is built. Subfigure (b) shows the results when at $t = 10$ years an electricity line is built between region 1 and 4. (PV = present value)

B. Valuation of energy hubs with storage

In order to illustrate the procedure for valuing energy hubs with storage devices, the proposed method is applied to three different hub configurations: a hub with CHP unit only, a hub with CHP unit and heat storage, and a hub with CHP unit and electricity storage. The CHP and storage parameters are listed in table III.

TABLE III
CHP AND STORAGE PARAMETERS.

CHP unit	
Electrical efficiency	$\eta_{CHP,el} = 0.33$
Thermal efficiency	$\eta_{CHP,heat} = 0.57$
Rated electrical capacity	$P_{max}^{out,CHP,el} = 20$ kW
Storage (heat and electricity)	
Min./Max. energy content	$0.5/10$ kWh
Min./Max. power	$-3/3$ kW
Charge/Discharge efficiency	$0.9/0.9$
Standby losses	0.1 kW

Please note that for the sake of a clear illustration of the method the storage parameters are the same for heat and electricity storage. A hub has to be operated such that it always guarantees the supply of the head load depicted in Fig. 6. The hub's electricity output is flexible and only limited by the CHP's electrical capacity. Electricity is assumed to be sold to the market with the aim of profit maximization. The base profiles of the prices of all energy carriers are also shown in Fig. 6.

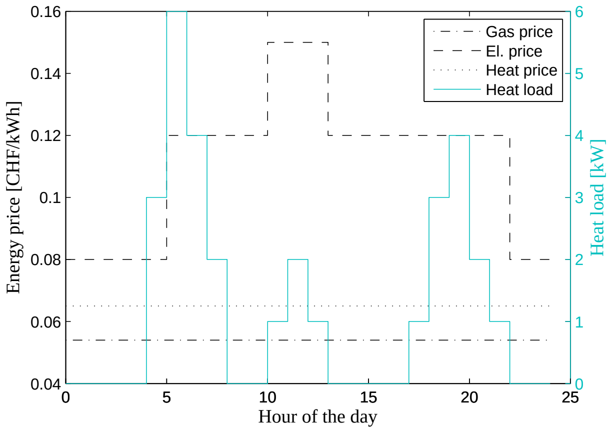
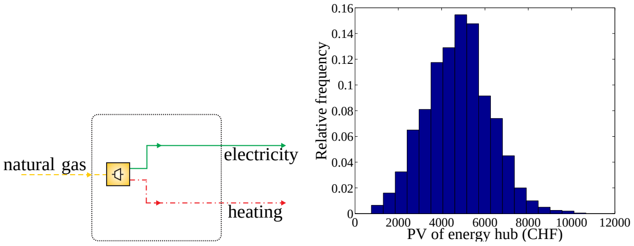


Fig. 6. Base profiles of energy prices and heat load, given at an hourly resolution.

For the valuation these base price profiles are multiplied with a random scaling factor, which is calculated for each day of a run in the Monte Carlo simulation according to (3). The parameters for the mean reversion process are assumed to be the same as for the previous example (see table II). The depreciable life of the hubs is assumed to be 20 years. In order to avoid prohibitively long simulation times, only one year of operation is simulated and it is assumed that this year is representative for the whole lifetime of the plant. Valuing the three energy hub configurations under consideration with 2000 simulation runs gives the results shown in Fig. 7 to Fig. 9.

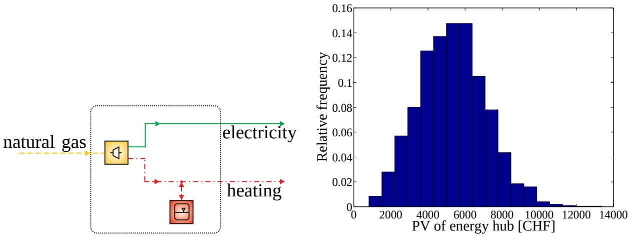


(a) (b)

Fig. 7. Energy hub without storage. Subfigure (a): Energy hub configuration; subfigure (b): Distribution of present values (PV).

The energy hub configuration without storage (Fig. 7) has a mean present value of 4754 CHF and a standard deviation of 31%. Due to the heat load the energy hub has to supply there is no flexibility in operation with the configuration without storage. Electricity is produced by the CHP and sold to the market whenever there is demand for heat.

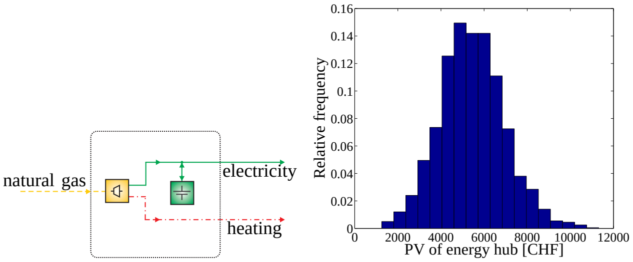
The mean value of the energy hub configuration with heat storage (Fig. 8) is 5320 CHF at a standard deviation of 34%. The higher value of this configuration results from the operational flexibility provided by the heat storage. At times



(a) (b)

Fig. 8. Energy hub with heat storage. Subfigure (a): Energy hub configuration; subfigure (b): Distribution of present values (PV).

of high electricity prices when the CHP's electricity output is most valuable, more electricity can be produced, and the heat storage is used as a buffer for the simultaneously generated heat, which can later be supplied to the heat load.



(a) (b)

Fig. 9. Energy hub with electricity storage. Subfigure (a): Energy hub configuration; subfigure (b): Distribution of present values (PV).

Finally, the energy hub with electricity storage (Fig. 9) offers the possibility to directly exploit price fluctuations in the electricity market. Therefore, this configuration provides the highest value with 5454 CHF at a relatively low standard deviation of 27%.

IV. CONCLUSIONS

The real options model for energy hubs presented in this paper represents a generalization of real options applications to power generating assets or CHP plants. Using the energy hub approach, it is possible to value integrated systems of conversion and storage devices with an arbitrary number of energy inputs and outputs in a fair way. Furthermore, the model allows for a seamless integration of location-dependent price information. In contrast to standard capital budgeting techniques such as the net present value method, the real options approach takes into account strategic and operational flexibility in the analysis. This characteristic of the model is particularly important given that real time pricing is expected to play a significant role in the operation of future electric power systems. The ability of distributed generation units being possibly combined with storage devices to react to changing prices is adequately valued with the energy hub real options model. The proposed method can thus provide valuable information for investment decisions with regard to flexibly controllable generation and storage units in future energy systems.

ACKNOWLEDGEMENTS

This work was developed within the ”Vision of Future Energy Networks” project. The authors would like to thank their colleagues at ETH Zurich for support and discussions during the preparation of this paper as well as W. de Bruin and Y. Liu for their valuable work which delivered important input for this paper.

REFERENCES

[1] M. Geidl, G. Koeppel, P. Favre-Perrod, B. Klöckl, G. Andersson, and K. Fröhlich, “Energy hubs for the future,” *IEEE Power and Energy Magazine*, vol. 5, no. 1, pp. 24–30, 2007.

[2] A. Dixit and R. Pindyck, *Investment under uncertainty*. Princeton University Press, 1994.

[3] F. Kienzle and G. Andersson, “Valuing investments in multi-energy generation plants under uncertainty: A real options analysis,” in *IAEE European Conference 2009*, Vienna, 2009, pp. 1–16.

[4] D. Gardner and Y. Zhuang, “Valuation of power generation assets: A real options approach,” *ALGO Research Quarterly*, vol. 3, no. 3, pp. 9–20, 2000.

[5] C. Weber and O. Woll, “Valuation of CHP power plant portfolios using recursive stochastic optimization,” in *International Conference on Probabilistic Methods Applied to Power Systems*, 2006, pp. 1–6.

[6] K. M. Maribu and S. E. Fleten, “Combined heat and power in commercial buildings: Investment and risk analysis,” *The Energy Journal*, vol. 29, no. 2, pp. 123–150, 2008.

[7] M. Geidl, “Integrated Modeling and Optimization of Multi-Carrier Energy Systems,” PhD thesis, 2007.

[8] M. Cavus, “Valuing a power plant under uncertainty,” in *Real options: Evaluating corporate investment opportunities in a dynamic world*. Financial Times Prentice Hall, 2001, pp. 113–137.

[9] J. C. Cox, S. A. Ross, and M. Rubinstein, “Option pricing: A Simplified Approach,” *Journal of Financial Economics*, no. 7, pp. 229–263, 1979.

[10] J. Putney, “Modelling energy prices and derivatives using Monte Carlo methods,” in *Energy modelling and the management of uncertainty*. London: Risk Books, 1999, pp. 71–89.

[11] A. Eydeland and K. Wolyniec, *Energy and power risk management*, ser. Wiley Finance. John Wiley & Sons, 2003.

[12] M. Geidl and G. Andersson, “Optimal power flow of multiple energy carriers,” *IEEE Transactions on Power Systems*, vol. 22, no. 1, pp. 145–155, 2007.

[13] W. de Bruin, “Analyzing the value of energy hubs in multi-energy distribution systems,” Bachelor thesis, Power Systems Laboratory, ETH Zurich, 2009.

Florian Kienzle (S’07) received hisDipl.-Ing. degree in energy engineering from the Otto-von-Guericke University Magdeburg, Germany, in 2006. In June 2006, he joined the Power Systems Laboratory of ETH Zurich, Switzerland, and is currently working on his Ph.D. dedicated to risk assessment and development of investment strategies for multiple energy carrier systems. Florian Kienzle is a student member of IEEE and IAEE.

Göran Andersson (M’86, SM’91, F’97) obtained his M.S. and Ph.D. degree from the University of Lund in 1975 and 1980, respectively. In 1980 he joined the HVDC division of ASEA, now ABB, in Ludvika, Sweden, and in 1986 he was appointed full professor in electric power systems at the Royal Institute of Technology (KTH), Stockholm, Sweden. Since 2000 he has been full professor in electric power systems at the Swiss Federal Institute of Technology (ETH), Zurich. His research interests are in power system analysis, simulation and control. Another research interest is future energy and power systems. He is a member of the Royal Swedish Academy of Engineering Sciences and Royal Swedish Academy of Sciences, and he is active in IEEE PES. He was the recipient of the IEEE PES Outstanding Power Educator Award 2007.