# Evaluation of Long-Term Scenarios for Power Generation and District Heating at Stadtwerke München

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## Introduction

Stadtwerke München (SWM) operates several district heating grids as well as a power plant fleet for heat and electricity generation in the Munich area. Strategic decisions regarding operation and development of these utilities must be made. For decision support purposes, a variety of scenarios is evaluated monetarily up to the year 2040. The scenarios are shaped for instances of declining of heat dissipations through increasing the insulation of buildings, permanent shutdown of a power plant due to the termination of its lifetime, incurring investment cost for replacing generation facilities, or of expanding geothermal power plants in Munich.

These scenarios are created by using an energy economic model that covers value chains of power and heat generation. Subsequently, a unit commitment model finds the least-cost dispatch of available generation resources for a specific scenario. The energy economic model and the unit commitment model were both developed at SWM and have the company code name of EW-model (in German: "Energiewirtschaftliches Modell") and KEO (in German: "Kraftwerkseinsatzoptimierung"), respectively. The results obtained from KEO are then imported into the EW-model to solve fundamental problems such as the profitability of electric heaters and the best time to utilize them or cost-benefit assessment for investments in heat storages for district heating. In other words, the EW-model is concerned with a long-term overview of revenues, costs, fuel consumption and demand, as well as analyzing the impact of different decisions. Meanwhile, KEO is used for calculation purposes.

The EW-model and KEO are independent modeling tools. The EW-model is fully implemented in MS Excel and Visual Basic, while KEO is developed in GAMS. An MS Excel interface is designed to link KEO to the EW-model and to an SQL server database. Thus, the complete data transfer from the EW-model to KEO and back is done automatically. The self-development of the models leads to a better response to SWM's requirements and also a more precise interpretation of results for employees.

The outline of this paper is as follows: Section "Long-term Unit Commitment Optimization" describes KEO in detail. After general remarks, the diagram of a waste-fired power plant and the mathematical model of a waste boiler are discussed. The explanation of other power plants is not provided due to the space limit. For more details reference is made to [1]. The concept of the EW-model together with its interactions with KEO are presented in Section "Energy Economics Model". The paper concludes with a summary and a short outlook.

## Long-term Unit Commitment Optimization

In the EW-model long-term scenarios from 2017 to 2040 are developed. To perform a profit analysis in the EW-model, data such as current revenue, fuel consumption, and $CO_2$ emissions are found via running an hourly unit commitment optimization.

DOI 10.1007/s00287-014-0852-y

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**Abstract**

Stadtwerke München operates a power plant fleet for covering the demand in district heating grids of Munich. Both district heating grids and the power plant fleet will be facing major changes in coming years. In order to assess the impacts of these changes in technical and economic terms, a software solution has been developed at Stadtwerke München containing a long-term unit commitment optimization tool as well as a superior model for scenario building and profit analysis. An in-depth overview of this software solution is presented in this paper.

This unit commitment problem is solved by KEO. It was developed with mixed integer programming in GAMS. CPLEX 12.5.1.0 is used as a solver. In performance tests, CPLEX was superior compared to Gurobi and Xpress. KEO is executed by a RX600 with 1 TB of RAM and 32x2 GHz. This server is exclusively available for running KEO.

The SWM power plants in the Munich area that are modeled in KEO consist of the following equipment:

- three gas-fired power plants (gas turbine or combined cycle) with cogeneration unit (CHP)
- one waste-fired power plant (CHP)
- one coal-fired power plant (CHP)
- six gas-fired heating plants
- geothermal plants (in operation or in accordance with the expansion plan at SWM).

Figure 1 illustrates generation plants and district heating grids of SWM in Munich. Although SWM possesses some hydro and photovoltaic power plants in addition to small generation units, they are not embedded into KEO. These units are neglected not only because they are not linked with optimization of district heating plants, but also because system services and avoided grid charges are not part of the

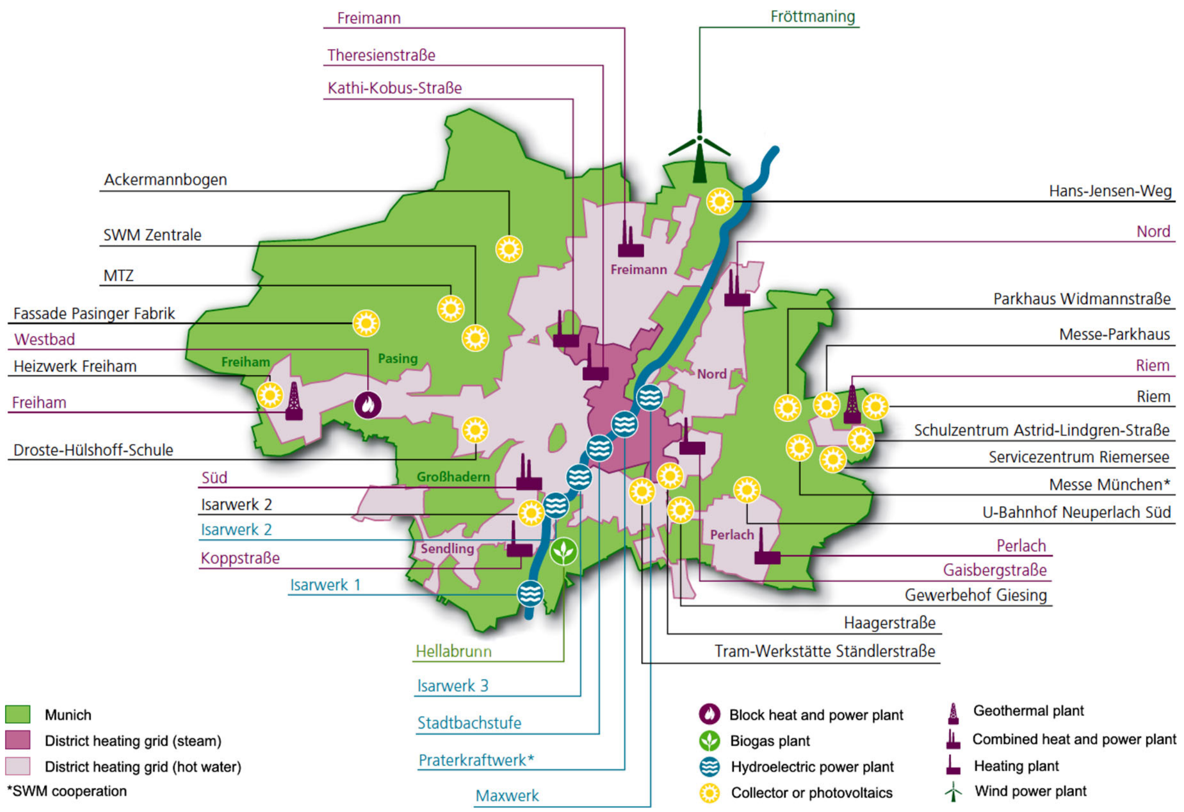

*Fig. 1 Overview of the generation plants and district heating grids of SWM in Munich*

optimization. Heating plants which are used only in the case of system failure are not modeled either since unplanned outages are not simulated by KEO. Therefore, more facilities are shown in Fig. 1.

The aim of the unit commitment optimization in KEO is to maximize profit. Suppose there is a set of generation units $I$, a discrete time frame $T$ with 1-hour intervals, a set of district heating grids $H$, and a set of fuels $J$. The revenue is gained by selling electricity $\mathrm{ELT}_{t,i}$. The costs are formed by fuel consumption $\mathrm{Fuel}_{t,j}$, $\mathrm{CO}_2$ certificates $\mathrm{CO}_{2_{t,i}}$ and taxations on heating plants $\mathrm{Taxes}_{t,i}$,

$$\max \mathrm{Profit} = \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J} \mathrm{ELT}_{t,i} - \mathrm{Fuel}_{t,j} - \mathrm{Taxes}_{t,i} - \mathrm{CO}_{2_{t,i}} \qquad (1)$$

The revenues from sales in district heating grids are not included in the objective function of KEO because the coverage of the district heating demand $\mathrm{Demand}_{t,h}$ in all grids for any time is a hard constraint,

$$\mathrm{Heat}_{t,h} = \mathrm{Demand}_{t,h} \quad \forall t \in T; h \in H \qquad (2)$$

In the following, the modeling of the waste fired power plant "Nord 1, 3" is discussed. Figure 2 shows the diagram for units 1 and 3 of the combined heat and power plant "Nord", where waste is burned. The garbage contract C_W is shown on the left. It reflects the minimum and maximum waste that can be burned per hour. A minimum amount of waste must always be burned since the storage capacity is limited. The costs of waste are also defined by the contract.

The waste boilers WB 11, WB 12, WB 31, and WB 32 are connected to C_W. Garbage is burned in the furnace of the boilers and as a result steam (black lines) is generated. The steam is transferred to the 40-bar bus. Thereafter, the steam is conducted to the steam turbines T30 HP (HP is a contraction of high pressure) and T10, as well as to the pressure reducing station 40–8 bar (40 to 8 bar).

The steam expands in the turbines and generates electricity. The electricity generated is transferred to the ELT bus (dashed lines) and is sold on the electricity market. The exiting steam of T30 HP contributes partially in electricity generation in T30 LP (LP is a contraction of low pressure). The outlet of T30 LP is connected to the auxiliary condenser T30 COND. The low energy steam of turbines is transferred to the 8-bar bus. This bar is connected to three heat exchangers WT_SGI, WT_HWN, and WT_HWF. Steam is transferred through the heat exchangers to the steam grid SGI and to the hot water grids HWN and HWF (dotted lines).

In the mathematical modeling of the power plant fleet and grids a wide array of parameters and constraints are considered. However, due to space restrictions it is not possible to explain them here. Examples of these constraints are priority in activating facilities, the maximum gradient of operation, and an instrument to run or shut down a facility. However, to show the modeling methodology, the mathematical model of the waste boilers WB 11, WB 12, WB 31, and WB 32 is presented.

Using a transfer function, the relationship between fuel consumption $\mathrm{FuelIn}_{t,i}$, efficiency $\mathrm{Efficiency}_i$, and district heating generations

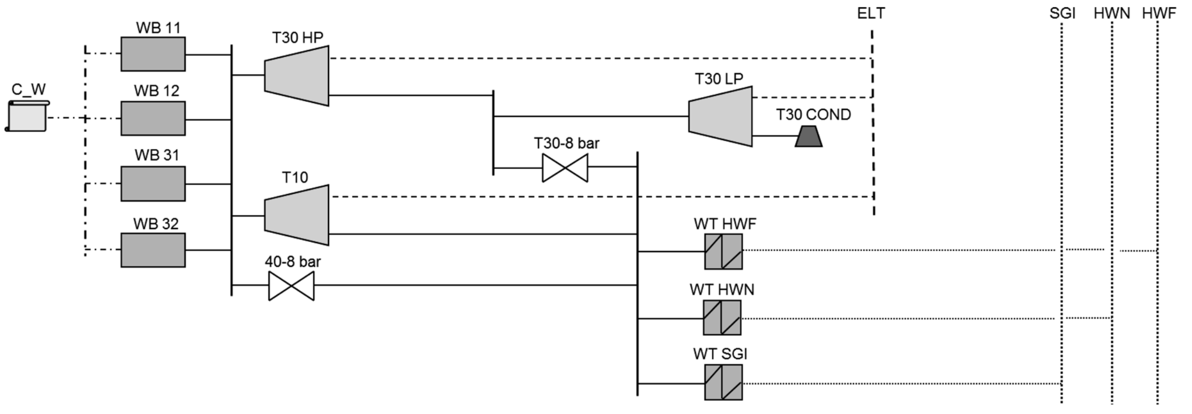

***Fig. 2 Schematic of blocks 1 and 3 of Nord***

$\mathrm{HeatOut}_{t,i}$ is produced,

$$\mathrm{FuelIn}_{t,i} * \mathrm{Efficiency}_i = \mathrm{HeatOut}_{t,i} \quad \forall t \in T; i \in I \quad (3)$$

The produced thermal energy of the waste boiler must be within predefined performance limits $\mathrm{MinLim}_i$ and $\mathrm{MaxLim}_i$. The binary variable $\mathrm{OnOff}_{t,i}$ determines whether or not the waste boiler $i$ is running at time $t$.

$$\mathrm{OnOff}_{t,i} * \mathrm{MinLim}_i \leq \mathrm{HeatOut}_{t,i} \quad \forall t \in T; i \in I \quad (4)$$

$$\mathrm{OnOff}_{t,i} * \mathrm{MaxLim}_i \geq \mathrm{HeatOut}_{t,i} \quad \forall t \in T; i \in I \quad (5)$$

An operation variable is also used to determine whether the waste boiler is started at time $t$ ($\mathrm{Start}_{i,t} = 1$). The waste boiler starts whenever it is in operation at $t$ and was not in operation at $t-1$,

$$\mathrm{OnOff}_{t-1,i} - \mathrm{OnOff}_{t,i} + \mathrm{Start}_{t,i} \geq 0 \quad \forall t \in T; i \in I \quad (6)$$

The minimum operation time and down time can be applied either by defining start-up costs or by using time constraints. However, activation and deactivation of a waste boiler does not occur frequently and it is difficult to estimate the start-up costs. Therefore, the second approach is chosen. In the model, the operation of the waste boiler is limited by time constraints. These values can be determined by monitoring the boiler performance,

$$\mathrm{Start}_{t,i} * \mathrm{MinOn}_i - \sum_{t^*=t}^{t+\mathrm{MinEin}_i-1} \mathrm{OnOff}_{t^*,i} \leq 0 \quad (7)$$

$$\forall t \in T; i \in I$$

$$\mathrm{Start}_{t,i} * \mathrm{MinOff}_i - \sum_{t^*=t-\mathrm{MinOff}_i}^{t-1} \mathrm{OnOff}_{t^*,i} \leq \mathrm{MinOff}_i \quad (8)$$

$$\forall t \in T; i \in I$$

Additional information on the district heating grids and power plants in Munich and KEO can be found in [1]. This publication also presents how CPU time can be reduced by 1 hour for each scenario of the EW-model. These approaches can be briefly expressed as:

- decomposition of the planning horizon into individual days held in 5-day blocks, as was implemented in the first version of KEO;
- parallelization of computations, since the optimization problem can be solved independently for every single day;
- parameter tuning in CPLEX;
- implementation of an automatic interface from the EW-model and the SQL server database to KEO and from KEO to the EW-model;
- using an MS SQL server database instead of MS EXCEL for holding the input data and the calculation results,
- reduction of the data stream by waiving of more than two decimal places;
- using a faster computer; here RX600 with 1 TB of RAM and 32 cores, each 2 GHz.

## Energy Economics Model

The EW-model primarily serves the study of strategic issues that have a significant and far-reaching impact on the company's earnings or are located in the distant future. Therefore, these analyses are not covered by the common tools of corporate planning and control. In essence, the EW-model facilitates the analysis of long-term scenarios for the value chain of power and district heating generation (see Fig. 3). Short-term and small-scale profitability calculations for pending investment decisions, however, are performed by separate tools from other departments. In contrast, the long-term consequences of such investments are assessed by the EW-model if necessary.

The EW-model, on the one hand, contains input variables for the unit commitment optimization,

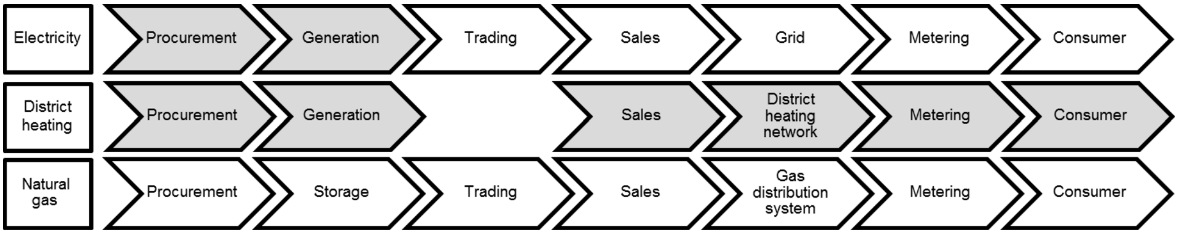

*Fig. 3 Realized (grey) and planned (white) elements of the value chain at the EW-Model*

such as the district heating load to be covered in the grids, the electricity prices (in hourly intervals), the fuel prices, and the availability of different generation systems. On the other hand, all relevant data for mapping revenue and cost are stored in it.

EW-model scenarios can differ in various aspects such as:

- different energy and $CO_2$ price scenarios (e. g., different assumptions for the $CO_2$ prices in the future);
- modifications in the power plant fleet (e. g., construction of new power plants in different locations or termination of the lifetime of existing power plants in different years, including consideration of maintenance expenses);
- expansion planning of the district heating grids in terms of better coverage of existing grids or grid development in new areas, and thus, changes in sales volume;
- sales decline in district heating grids due to the increased insulation of buildings, higher standards, or changes of policy;
- distribution scenarios and retail price models;
- implementation of investment options (replacement infrastructure, electric heaters, heat storage, interconnections of district heating grids, expansion of geothermal plants based on SWM's road map).

Great benefits may be gained, for example, by the examination of the proposed geothermal development for the district heating supply or from the variation of the lifetime of cogeneration plants. The influences of external factors such as a stronger rise in $CO_2$ prices in the future due to political interferences or the impact of national legislation (such as KWKG, EEG or tenancy amendments) have been evaluated several times.

In this context, propositions about revenues, costs, production volumes, fuel consumption, and $CO_2$ emissions are possible. The cost and revenue calculations for electricity and district heating generation can be performed either collectively or independently. These analyses vary from annually for individual cost elements to hourly for individual plants.

Electricity revenue is based on the projection of electricity prices at the stock market up to the year 2040. These are the result of a fundamental long-term model for the European power plant fleet. A brief overview of the parameters of the fundamental long-term model and the results from the model findings is provided in Mühlhäuser and Roth [2]. The fundamental model is not discussed in this work. On the revenue side, sales and price developments in district heating are additionally entered in the EW-model.

On the cost side, besides to the costs of primary energy consumption and $CO_2$ emissions, which are imported from KEO, the data for determination of the capital and operating costs of the power plants and grids are maintained in the EW-model. These data consist of costs of existing power plants and grids. Furthermore, the EW-model encompass the resulting cost of future expenditures on power plant constructions or grid renovations and reconstructions.

The outputs of the unit commitment model, primary energy consumption, and electricity sales in particular, are entered into the EW-model. Thus, the EW-model is the upstream system in interaction with KEO. On the one hand, it contains scenarios which should be calculated in KEO. On the other hand, it enables the analysis of the results of KEO.

In order to provide a rapid orientation into the EW-model and also facilitate modifications in it, the EW-model was implemented in MS EXCEL. Almost all the calculations and outputs of the results are implemented via Visual Basic. The main results of the EW-model, in addition to the standard tables, are presented as charts and can be automatically exported into a PowerPoint file. Currently, two employees are working with the EW-model and considering its modular structure, and an additional work force, for the purposes of further development or investigations, can be employed without incurring large expenses. The detailed and systematic documentation of all sources and input data makes the underlying technical and economic energy knowledge readily available.

The model validation was and is done by an intensive exchange with the Department of Power Generation. With the help of concrete weeks from spring and fall (transitional period) as well as summer and winter, the results of KEO are analyzed. The colleagues of the Power Generation Department compare the results with their own calculations and combine them with their practical experiences. During these tests important parameters can be identified. The correct mapping of the district heating grids with their bypasses and the lifetime of power plants have a strong effect on the results. Other important parameters in unit commitment are fuel and $CO_2$ price forecasts.

Back-testing is done only to a limited extent. The EW-model and KEO consider the average values of the outside temperature and the district heating sales of the various networks. In addition, in KEO no fault is simulated. Generation equipment and grids are considered as either fully available or unavailable during a calendar year. As a long-term planning tool, KEO has been equipped without system services and optimization against the coupling point (for avoided grid charges); although a comparison of the calculation results with the actual equipment is used. This comparison, however, must be limited to the basic plant operation as well as minimum and maximum limits of district heating and electricity production per plant.

Due to the low CPU time in KEO a variety of scenarios can be calculated in a very short time. Therefore, the generation and evaluation of scenarios in the EW-model is the limiting factor for the whole software solution. The EW-model and KEO facilitate the calculation of creative and extreme scenarios. Consequently, this combination leads to a better understanding of the overall system. In 2013, 150 scenarios were created and evaluated. The EW-model is a fully accepted solution for long-term examinations within the company because output data, assumptions, and final results are transparent. Furthermore, the model joins the know-how of various areas within the company. For this purpose, all output data and assumptions were and are being adjusted across SWM. These data are documented in the EW-model. These cross-departmental exchanges provide a major benefit for the company.

## Conclusion and Outlook

In this work, a software solution comprising two separate models (the EW-model and KEO) was presented. The software assists decision-makers at SWM in strategic planning regarding district heating grids and generation facilities. KEO as a unit commitment optimization model developed in GAMS was introduced and the way it provides computational results to the EW-model was described. The emphasis of this work regarding KEO is its low CPU time.

The combination of the EW-model with company-wide coordinated premises and KEO with a very low CPU time gives SWM great competitive advantages. Thus, decision alternatives in various scenarios are assessed in a transparent and comprehensible way. Without KEO and the EW-model, these assessments would be highly limited, demanding, and less transparent.

Future perspectives for the development of the EW-model exist to various extents. It is planned to add the value chain of gas and electricity grids in Munich. In addition, the trading and sales package should be integrated into the EW-model. Ultimately, using stochastic optimization techniques, the scenarios can be assessed under uncertainty conditions.

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