OSCOGEN

Optimisation of Cogeneration Systems in a Competitive Market Environment

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Summary of specified general model for CHP system

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1 Introduction

Due to the liberalisation of the energy sector the situation for companies of this sector has drastically changed. The planning of the operation of existing and new plants consequently require an update accounting for the new possibilities - companies trading energy among themselves on market places. Thus the aim of the research project OSCOGEN consists in the development of a tool for optimising the operation of CHPs within this new market.

In the following a brief description of the optimisation model is given. After the scope and objectives of the tools have been presented (Chapter 2) the elements entering the optimisation model are described. First the balance of supply and demand is presented (Chapter 3), then the formulation of the model for the different technical elements (Chapter 4) and different contracts (Chapter 5) are described and after that the objective function (Chapter 6) is discussed. Also the legal and environmental aspects of interest
(Chapter 7), relevant uncertainties (Chapter 8) that occur in the model and the development environments (Chapter 8) are briefly discussed.

2 Scope and objectives of the tools

The general requirements for the planning process of a CHP plant with respect to the uncertainties of the liberalised market are as follows:

- *efficient:* the economic operation optimum should be identified rapidly
- *robust:* the crucial restrictions should be fulfilled even if parameters of the stochastic variables for the uncertainties are not exactly known
- *reliable:* under changes in the uncertain values, the optimisation results should not show strong oscillations. Even with large changes in the uncertain values, the results should be satisfactory.
- *effective:* the complexity of the model should be compared with the costs reductions due to optimally operating conditions
- *environmental friendly:* emissions of dangerous substances and consequences for the environment should be taken into account in the optimisation procedure

The unit commitment problem can be handled at two different time scales: short-term and long-term planning. Short-term planning considers planning horizons up to two weeks and with intervals ranging from 15 minutes up to one hour. In contrast, long-term optimisation means working with time horizons from one month up to three years. In order to avoid the long-term model from becoming too complex, time resolution will not be very detailed. Additionally some restrictions can be simplified to reduce complexity.

2.1 Short-term optimisation

Three optimisation problems are essential for short-term optimisation and will be solved by the planned tool:

- Optimisation without electricity market, but with given heat and electricity loads
- Optimisation with electricity markets after the market places have closed
- Optimisation with electricity markets before market exchanges have taken place

The unit commitment problem without electricity markets with given heat and electricity load is the basic problem to be dealt with. Different structures of CHPs systems and storage possibilities have to be considered; so the tool can be adapted to very different situations and many applications. Moreover, a precise cost structure and a detailed model to include and consider all possible technical restrictions has to be incorporated within this tool. Very different restrictions can be thought of (e.g. restriction for start-up processes, restriction for reserve) and it is important to take them into account in optimising the operation of the special CHP under consideration. Furthermore, it has to be made clear which input quantities are really uncertain and which of them can be determined. Properly dealing with the uncertainties that can not be resolved is important in the optimisation process to avoid wrong schedules.

The optimisation problem with electricity markets after the end of the bidding process is very similar to the problem described before. Since the market places are already closed, no extra electricity can be bought or sold. Thus in principle, the situation is the same as if the markets were not considered at all, except for changing some of the input parameters by taking into account the bids that have taken place.

Considering the third problem – optimisation before market exchanges have taken place – one is faced with a different problem. In this case, more input parameters are uncertain and the role of these stochastic quantities is more fundamental. It is meaningful to estimate the own costs for generation of electricity in contrast to possible offers of competing power plants. The most important question to be answered is whether to produce electricity on one's own or to buy it at the market places. Based on the estimated costs for self-production, bids can be made. One important aim of the optimisation tool in these cases is the determination of the lower bound of the bid function for own generation. The first two optimisation problems can be viewed as special cases of the last one.

With the help of this tool, electricity trading shall be simplified for companies operating CHPs.

2.2 Long-term optimisation

Similar to the planned features for the short-term optimisation tool, the following features for the long-term optimisation tool can be defined.

- Support for long term unit commitment
- Decision support for contract negotiations

The main difference is that in the long-term optimisation the decision maker has to pay much more attention to the risks inherited in unit commitment. The aim is not only to maximise the profit, but also to do this at low risk. Emphasis will lie on the optimisation of unit commitment with respect to contract negotiations. Different strategies regarding contract management (e.g. aspects of risks) have to be considered and to be implemented. To support the decision maker within the process of contract negotiations, the tool should provide information on marginal costs of the actual negotiated contract.

Certain groups for standard contracts have to be defined, so that new data from the contract management system can easily be included into the optimisation model.

3 Balance of supply and demand

A balance of supply and demand has to be achieved for heat, electric power and fuel at each time point of the total time interval.

For the electric power, the sum of the electricity bought under different contracts and produced by all units in the system should at least equal the electric load[1]. The balance of supply and demand is a generalisation of the load restrictions in non-liberalised markets. For the heat the sum of the produced heat should at least equal the heat load. The possibility of buying heat is not assumed in this model. For both the power and heat balances each unit that can produce electric power or heat has to be counted in the appropriate relation. Units that produce both electric power and heat thus appear in both restrictions.

The fuel used for the different units is provided either by immediate delivery or taken from storage. Some fuel is sold to end customers via contracts or is stored in a fuel storage. The sum of the fuel bought under different contracts and taken from the storage should then equal the sum of fuel used in the different units, delivered to the storage and sold under different contracts. There are also maximum and minimum restrictions for the fuel storage.

For power plants with boilers producing steam for several steam turbines a balance for the steam is necessary as well.

4 Technical elements

The technical elements of the model can be divided into three groups; Power producing units, heat producing units and heat storage units. Three different types of power producing units are

[1] Due to technical restrictions mentioned below the amounts of electricity produced can not be chosen arbitrarily small (e.g. minimum electric power production). Thus demanding strict equality would lead to non-solvable problems.

included; extraction condensing steam turbines, back-pressure extraction steam turbines and gas turbines and gas motors. They can also be included in the heat producing units since they can produce both electric power and heat. Other elements of the heat producing units are boilers and heat exchangers.

To build a realistic model, many technical details of the operation of the special power plant under consideration have to be carefully thought about. Due to the technical setting of the different units of the system under consideration restrictions appear for the maximum and minimum power and heat that can be produced by the units at each time point. A binary variable is used to indicate the operation state (on _off) of each unit.

There are also restrictions for minimum operating times for each unit as well as for minimum down times. Binary variables are used for indicating the start up and shut down of a unit and in combination with the binary variable indicating the operation state the start-up and shut-down events can be described in the model. The consideration of start-up and shut-down events is important since they are related to special costs.

4.1 Power and heat producing units

The power and heat producing units are described in equations where the inlet energy flow is a function of the outlet heat flows and the electrical power is a function of the outlet heat flows. Technical limits for the different flows are also included. A time dependent term describing the operation status (on-off) for the units is included in the equations and in the inequalities describing the technical limits.

For the extraction condensing steam turbine the inlet energy flow is the inlet steam flow and the outlet heat flows consist of the extraction steam flows and the heat flow through the condensing part. Figure 4.1 shows the feasible solution set for electric power and steam flow output. Allowed operation modes are limited by: maximal and minimal inlet steam flow (or maximal boiler output) (bound1 and 2), maximal and minimal generated power (bound 5 and 6) and maximal and minimal ratio between heat flow through the condensing part and inlet steam flow to the turbine (bounds 3 and 4). Heat exchanger capacity is also a limiting factor (Bound 7). There are no limits of steam extraction in the schematic. All bounds, except maximal and minimal power generated, depend on temperature levels in the district heating system. The boilers for the steam turbines are handled in the same way as described for the heat producing boiler unit described below.

The difference in the equations for the back–pressure extraction steam turbine compared to the equations for the condensing-extraction steam turbine is that there is one less outlet heat flow since the heat flow through the condensing part is not relevant here. Consequently also the limits related to this heat flow is absent as well.

For the gas turbine and gas motor the inlet energy flow is the fuel input and compared to the above described power and heat producing units there is only one outlet heat flow. For

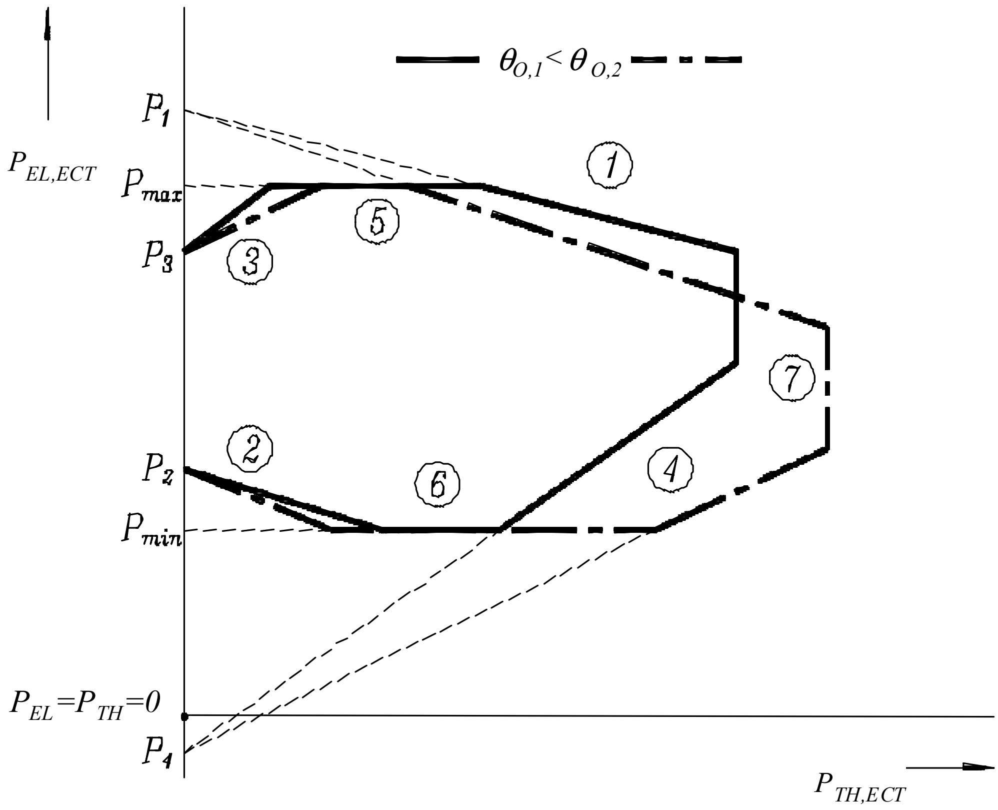

Figure 4-1: Condensing extraction turbine – set of operation modes. Operation at two different hot water outlet temperature levels are shown. The solid line represents a lower temperature level than the dotted line.

the gas turbine description the coefficients in the linear equations are time dependent because the characteristic behaviour is dependent on the outdoor temperature.

4.2 Heat producing units

For the heat producing units the model describes the relation between the inlet and outlet energy flows. A minimum and maximum limit is also included for the outlet energy flow.

For the boilers the inlet energy flow is represented by the fuel consumption and the boiler heat output flow is the outlet energy flow. A time dependent term describing the operation status (on-off) is included in the relations and in the description of the technical limits.

For the heat exchangers both the inlet and outlet energy flows are heat flows. The on-off option is not included for the heat exchangers.

4.3 Heat storage

The heat storage is considered to be a first order dynamic process described by the following equation: $\frac{dE}{dt} = Q_{in}(t) - Q_{out}(t) - Q_{loss}(t)$

Where E is the amount of stored heat, Q_{in} is the inlet flow of heat, Q_{out} is the outlet flow of heat and Q_{loss} is the loss of heat. The system can be linearised by piecewise constant inflow and outflow from a storage in a subinterval period.

The amount of stored heat and the inlet and outlet heat flows are bounded by constant capacity limits.

The terminal condition for the amount of stored heat must be taken care of in the model. This can be done either by assuming equal amounts of stored heat in the beginning and the end of the time period under consideration or by including a shadow price of the amount of stored heat at the end of the time period in the cost function.

5 Contracts

Within a liberalised market, contracts become more and more important. To act successfully on the market, it is necessary to include the new possibilities gained through contracts into the CHP optimisation model. The tool for CHP optimisation is not to be a tool for handling contracts, which means that only certain contracts which have to be optimised are considered. Contracts with fixed prices and without flexibility of delivered or sold energy are summarised to one contract, whereas contracts including many different strategies are modelled in detail.

The model includes buying contracts without flexibility, with take-or-pay conditions and with capacity charge and selling contracts with and without shut-down possibilities.

5.1 Contracts without flexibility

These contracts notably include full service contracts for which the power and heat demand cannot be influenced by the utility. However it is subject to some uncertainty, for example the influence of the weather. This has to be taken into account when building up the stochastic model.

5.2 Take-or-pay-contracts

This type of contract is included in the model for buying electricity and fuel. When the optimisation period is longer than the validity of the take-or-pay contract the amount of bought electricity or fuel is the sum of the flow bought at each time point multiplied with the time period.

If the optimisation period is shorter than the validity of the take-or-pay-contract the demand within the optimisation period is unknown. A possible solution is to divide the time period of validity of the contract into short sub periods and take a decision what fraction of the whole contract volume will be used in the different sub periods. Often, it is more practicable to work with upper and lower bounds for the demand. These bounds, for example, can be taken from a model for long-term optimisation. Another possibility is to derive the shadow or reservation price for the take-or-pay contract from a long-term optimisation. This shadow price is then included in the objective function .

5.3 Contracts with capacity charges

Capacity charges denote that not only the amount of the delivered fuel is paid for but that there is also a charge for the capacity. In the gas sector it is common to charge the highest daily deliveries. There are different clauses. For example the 2 or 3 highest peaks of the gas delivery within a year are charged. Furthermore there exists the restriction that these peaks have to be separated by a fixed number of days.

For such contracts, the appropriate time interval is a day, since it is practical use to calculate the peaks for daily demands. In the model the number of peaks and the level for each peak is defined. Each peak level is valid for at least the fixed number of days the peaks have to be separated by. A binary variable is introduced to indicate if a certain peak level is valid a certain day. For each day the value of the actual peak has to be greater than the daily delivered amount. It is also necessary to include a binary variable for indicating the start day for each peak level. The restriction that the peaks have to be separated by a fixed number of days and that the peak level is started only once during the optimisation period can then be taken care of. Once a peak has been reached, the deliveries are optimised by choosing the amounts so that they do not lie over the peak. This is done until another peak is reached.

The approach described above can be used for long-term optimisation when the optimisation period is much longer than the contract duration. In the case that the optimisation period is even shorter than the temporal distance between two peaks, the situation is slightly different. In such situations, the actual peak is given. The arising question is if the height of this peak is optimal or if an even higher peak can lead to lower costs. An unknown variable is introduced and the peak level plus this variable has to be greater than the daily delivered amount.

In situations where the optimisation period is longer than the distance between two peaks but still shorter than the contract duration, a splitting in sub-periods is necessary. Further research is needed to find a useful procedure for the division into sub-periods.

5.4 Shut-down contracts

Shut-down contracts allow the provider to reduce the amount of sold fuel/electricity to zero for certain time intervals. Thus either the promised amount is delivered or the customer gets the information that the next time the supply will be reduced. For contracts of this type a binary variable, indicating whether the provider can the deliver or not, is introduced.

There may be additional restrictions on the operation of the shut-down contracts, e.g. the numbers of shut-down periods.

6 Objective function

The aim is to maximise the total profit of the CHP system. Therefore, in a liberalised market the goal function can be defined as the difference between total turnover and total costs. In contrast to former optimisation problems, the goal function is defined as a maximising problem, as the load of electricity is not an exogeneous parameter, which has to be reached with minimum costs. Nowadays, in liberalised markets, companies seek to raise their profit by producing extra electricity and selling it. Thus take as objective function

$$\max PROFIT = \max\{TURN\_OVER - COSTS - CHANGES\_IN\_STOCKS\},$$

where the maximum is taken over all variables describing the operation of all units of the power plant.

All sales of electricity, heat and fuels at each time point contribute to the total turnover. Clearly, the sales are a result of market prices and the quantity of electricity, heat or fuel, sold.

The electricity, heat and fuel sales can be calculated as the sum of the total contracts sold. For the electricity sales there are different prices for peak-time and for off-peak time and therefore the price for electricity depends on the time step.

The total costs involved for the production of heat and electricity can be divided into two groups whether they depend on time or not. The time dependent costs included in this model are the operation costs (sum of start-up, real operation costs and shut-down costs for each unit within the power plant) and the time dependent contract costs for both electricity and fuels. The costs for the supply of electricity and fuel also have to be added. In the case of linear tariffs the costs are proportional to the used energy. If there are quantity dependent prices, the used electricity or fuel has to be divided into the different ranges with different prices.

Time independent costs resulting from take-or-pay contracts (again both for electricity and fuels) constitute the time independent share of the total costs. In a first step it is assumed that the price is constant, independent on the amount of electricity or fuel bought. Additionally the costs for contracts with capacity charges have to be added.

The changes in stocks is the changes in the fuel storage during the optimisation period.

7 Legal and environmental aspects

Among the legal aspects valid for the countries included in this project, there are two types of aspects that should be included in the CHP optimisation model. The first one is whether there exists a minimum price for power produced by cogeneration systems. Most certain this minimum price is then connected to restrictions for the operation of the CHP system, for example the restriction that a certain percentage of the power produced has to be produced in cogeneration mode as in Germany or restrictions for the fuel used as in Switzerland.

The other legal aspect of importance is if there exists economical support for CHP produced power. This can be either through subsidies or tax refunds. The restrictions in this case can be minima and/or maxima for the power generation capacity and/or restrictions for the total efficiency.

Concerning the environmental aspects the emissions of CO_2, NO_x and SO_2 are of interest. The emissions are dependent on the fuels and process units used. For the CO_2 emissions simple linear relations between the emissions and the fuel consumption should be useful. The relations for the NO_x and SO_2 emissions may be more complex due to different burning processes and flue gas cleaning processes. For the CO_2 emissions also the process unit dependence may be omitted.

If there are limits for the total emissions of the compounds these will be included as restrictions in the model. Fees for the emissions will instead influence the cost term of the objective function. In some cases the costs for the emissions are already connected to costs for the fuel, for example CO_2 and sulphur taxes.

In the future also trading with emission certificates could become relevant. In this case the objective function has to be extended to include either earnings from selling certificates on avoided emissions or costs for purchasing emission rights.

8 Relevant uncertainties

Uncertain parameters of the model are realised as stochastic variables with certain assumptions about their probability distribution. Thus the question arises which of the many possibly uncertain parameters are really necessary to be treated as stochastic variables. It is the variance of the uncertain parameters that plays an important role. Very small variances of a parameter may in some cases be neglected, whereas parameters with big variances should be modelled very precisely. If most of the parameters have only small variances, a deterministic version of the model is expected to yield as good approximate results as the stochastic version.

Another important item is the estimation of the parameters of the probability distributions of the different uncertain parameters of the model. Practical and empirical experience is crucial for reasonable estimates of the distributions.

In the model discussed here, the following variables could in principle be treated as uncertain:

- electric load demand,
- thermal load demand
- prices at the spot market
- price at future markets

The uncertainties of the prices may be so high that deterministic optimisation will not result in useful solutions. Other uncertainties, such as plant failure or political uncertainties, could in principle also be dealt with by the model, but in a first step they will be left aside in order to reduce complexity.

In the case of short-term planning, some uncertainties may be resolved by approximating the stochastic values of the parameters because the time of change of the uncertain parameters is much shorter than the time interval arising in long-term planning.

9 Development Environments

Two different development environments are used; GAMS and MATLAB.

GAMS is a mathematical software package designed for linear and non-linear optimisation. Without practical restrictions concerning the number of unknowns, parameters or restrictions, it is very well suited for numerically solving models for the unit commitment problems.

MATLAB on the other hand was primarily intended for matrix calculations. It is an integrated technical computing environment that combines numeric computation, advanced graphics and visualization, and a high-level programming language.

As MATLAB can solve only small linear optimisation problems, it was decided to use GAMS for the mixed integer linear formulation of the optimisation models. These linear models will be solved by CPLEX – a solver developed for large linear mixed integer problems. A non-linear version of the model will be implemented in MATLAB as the genetic algorithms which will solve the non-linear problem need to know the explicit model formulation.

10 Final remarks

As a first step a linear model is build. Then further details are incorporated, including uncertainties treated as stochastic parameters and non-linearities. As mentioned before the prices as well as the electric and thermal load demands are the most uncertain parameters of the model. The non-linearities of most importance are those appearing for the technical limitations. The solution of the optimisation problem with non-linearities is to be found using genetic algorithms. In a first step, for a still simplified model including some non-linearities, implementations of genetic algorithms have to be developed and tested. Afterwards, the complex models will be solved with these algorithms.

The computer time needed for optimisation must be considered when including further details of the model and discretising time. A good compromise between precise model formulation and optimisation time needs to be determined.

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