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Smart Grid Integration of an Existing Office Building: Modelling and Simulation of Adaptation Strategies

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Abstract

The development of smart grids makes possible the introduction of dynamic electricity rates, with prices changing each hour. Dynamic rates can reflect the temporal dependency of supply and demand for electrical power and network capacity, thus avoiding load peaks and promoting the use of fluctuating renewable energy sources. We present a simulation model that studies the electricity demand for heating and cooling modern office buildings in the context of dynamic electricity prices. The model permits the simulation of scenarios in which existing thermal energy reservoirs (warm and cold water tanks) are used for the smart grid integration by means of adapted control strategies. The adaptation to dynamic electricity rates – and thus indirectly to the fluctuating supply of wind and solar power – is achieved solely by changing the control of the existing infrastructure without changing the infrastructure itself.

Keywords: Smart Grid, Demand Shaping, HVAC, Simulation, DESMO-J

1. Introduction

Smart grids are becoming increasingly important in modern electricity supply. They integrate all actors involved such as producers, consumers and network assets into a single system with coordinated communication and control (Smart Grids European Technologie Platform 2010). One way to coordinate the components is through price signals, with the prices for electrical energy fluctuating over the short term on the basis of current supply and current demand. The advantage of dynamic rates lies in having a signal that is easy to understand in the whole system that tends towards equilibrium at least in a functioning market. In this way electricity rates are imaginable that hand down fluctuating purchase prices from the producer at the exchange to the end consumer (Gantenbein et al. 2012).

Heating and cooling buildings is the part of an overall energy consumption with the greatest unused savings potentials attainable by means of more intelligent control strategies (Hilty et al. 2006; Erdmann/Hilty 2010). The utilization of these potentials is being discussed today in the context of the sustainability of smart homes (see Blumendorf 2013 for a survey). Some approaches rely on a massive expansion of sensors in buildings (Li et al. 2013) or include the decentralized production of electrical energy (Price et al. 2013). The study presented here has a narrower focus in that it explores the savings potential for an existing building solely by modifying the control strategy (thus comprising a pure software component) and the resulting more efficient use of thermal storage capacities in the building. No additional sensors, actors or other hardware components are installed and no changes made to existing assets. We merely assume that the control system is informed about the electricity rates, enabling it to shift load created by the operation of the heat pumps to periods of lower prices.

The present paper is based on a similar publication in German (Bornhöft et al. 2013) and on the master's thesis by Sutharshini Rasathurai at the University of Zürich (Rasathurai 2012).

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In contrast to similar studies considering heat pumps as flexible load (e.g., Hong et al. 2013), we did not attempt to explicitly model the thermal characteristics of the building. They were implicitly taken into account by using empirical time series of heat and cold demand from within the building. Whereas other simulation studies of the effect of hourly pricing aim to assess the overall potential for a large area (such as New York City, see Kim/Kiliccote 2012), our study has the objective to assess one specific building with regard to changes to the control strategy.

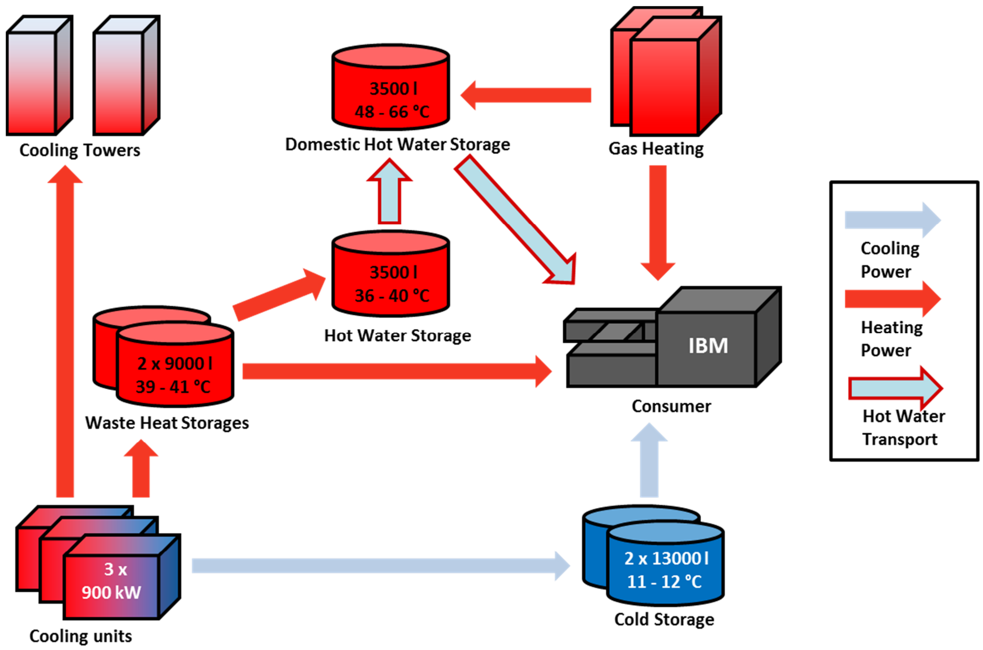

Figure 1
Relevant heat and cold production, consumption, storage and transport processes of the system under study

Modern combined heating and cooling installations like the one in the office building of IBM Switzerland in Zürich-Altstetten use the waste heat given off by cooling equipment. They also have water tanks for temporary storage of the heat and cold produced.

In cooperation with the IBM Research Laboratory Zurich we developed a simulation model in order to investigate the degree to which an adaptation of the present system and its control could move the purchase of electrical energy towards times of lower electricity prices, in particular by more efficient use of the existing thermal storage units. The resulting possible savings of energy costs for operating the building creates an incentive to shift the consumption towards times of greater supply and lower demand, which reduces the load on the grid and promotes the use of fluctuating renewable energies for electricity generation. The use of simulation techniques for this made it possible to test complex hypotheses and scenarios regarding control and the electricity rate.

We decided to use discrete event simulation to investigate the present question, because all external variables such as the change in electricity prices and non-linear changes in internal variables – such as when the maximum charge of a reservoir is reached – can be formulated as discrete events.

The simulation framework DESMO-J (Discrete Event Simulation and MOdeling in Java) was used for modelling. DESMO-J provides the modeller with components for model building as well as for carrying out and evaluating simulation experiments. The design of the model-specific functions, however, is left to the model builder (Page/Kreutzer 2005).

The energy consumption data needed for modelling were acquired in the form of time series with the automation software from Comsys Bärtsch AG, which controls the real system (the heating and cooling system in the building under study). These data and the specification of the technical installations were provided by IBM Switzerland for a master's thesis at the University of Zürich (Rasathurai 2012).

We analysed both a summer and a winter scenario, derived from empirical data (time series of the heat and cold used in the building during the selected periods with a temporal resolution of 15 minutes, as well as meteorological data). The savings potentials from adapting the controls were calculated for both periods both with the existing and the hypothetical dynamic electricity rate. The dynamic rate was based on the actual spot market prices of the time under consideration, so that we can assume that the variability is realistic over the course of the day and week.

2. Modelling the system under study

A deterministic model was chosen because the variance in demand for heat and cold as well as the electricity spot market could be included by the use of empirical time series. A great variation was found in the time-dependent demand for hot water, heat and cold and in the spot market prices for electrical energy (which were used for the hypothetical scenario of a dynamic rate). The load curves for demand were simulated for 15-minute intervals, based on the measured data, and the spot market prices for electrical energy were used in the model on the interval of one hour, as given by the exchange.

Before developing the simulation model we identified the relevant components to create the conceptual model. The components can be distinguished in components for production, consumption or transport of heat. A few simplifications were made in the model. Thus we abstracted from concrete temperature levels and modelled directly the heat transport resulting from the temperature differences. Storage capacities were determined from the specification of the storage containers with minimal and maximal temperatures. In the following, for purposes of clarity, we shall speak of the transport and storage of "cold", although physically it is a matter of transferring heat in the opposite direction. Heat (and cold) transports are assumed to be linear, i.e. the power (work done per time unit) is constant between two discrete time points. Consequentially we abstracted from temperature-dependent efficiency deviations.

We shall describe in the following the individual relevant elements of the real system and their representation in the model. There is a detailed description in Rasathurai (2012).

Consumers: Consumers are those components for which the system prepares hot and cold water for use in the office building. The water provided is used primarily for air conditioning, space cooling via cooling ceilings, server cooling, space heating, and domestic hot water. The load curves of the various consumers are known for the time under study. In the simulation of the various scenarios they are used as time series of demand to which supply is adapted by the controls, i.e. the demand is given and the supply can change depending on the control strategy.

Cooling units (heat pumps): Cooling units use electrical energy to cool water. That gives off heat, which should be used if possible. The real system contains three cooling units with a maximum power rating of 900 kW each. Three are taken as a single logical unit in the model. Since the units can be turned on and off individually, and are only operated above a minimal power level, the total power can be set between 150 kW and 2700 kW.

Storage units: The storage units serve to keep water available at a certain temperature. Given a temperature difference with another medium, a storage unit can be used to either warm or cool it.

The storage units are described by means of their heat capacity in the model. This is derived from the maximum and minimum temperatures, the (constant) water mass in the unit and the specific heat capacity of water. When a heat storage unit is “emptied“, the temperature of the contained water changes from the current level (which is constrained by a set maximum) to the set minimum level; when a cold storage unit is “emptied“, the temperature changes from a current low value (which is constrained by a set minimum) to the set maximum level. The cold storage units, heat storage units and one storage unit for domestic hot water are modelled 1:1 as they exist in the real system. An existing second storage unit for domestic hot water (48 – 66 °C) is however excluded. It has little significance for the model because the stored energy has to be primarily provided by the natural gas boiler due to the high temperature required, and the price for natural gas does not depend on the time of consumption.

Energy flows: In addition to the input of electrical energy, we regard the transport of heat energy from one component of the system to another. This happens either indirectly through the use of heat exchangers or directly through the transport of water to the other component.

In the model the flows of heat and cold are shown in simplified form as constant power output during a time period between two discrete events. They are limited by the capacity of the storage units. Furthermore, there is a limitation to the power absorption of the waste heat storage unit. It reflects the maximum power of the heat exchanger between the cooling units and the waste heat storage unit. There is also a limitation to the supply of warm water in that only a limited part of the heating power required can be supplied by stored waste heat. That is a consequence of the difference between the temperature in the domestic water storage unit and the temperature required by consumers.

Cooling towers: The cooling towers serve to distribute heat energy into the ambient environment. They were not modelled as entities, and represent the flow of heat from the system caused by exhausted storage capacities whenever waste heat is produced while the waste heat storage units are completely full.

Natural gas heating: The gas heating serves to heat water. Demand for space heating and warm water is always first covered by stored waste heat. Any demand exceeding that level is satisfied by the gas heaters.

Controls: The control of the system determines at what time which parts of the installation are operated with what power based on a set of rules. We ignore the power used for the ICT equipment of the control system, because the ratio of the energy consumed by ICT to the energy saved by ICT (Coroama/Hilty 2009) is in this case close to zero.

In the model we are concerned primarily with the conditions under which the cooling units (heat pumps) are operated with what power level. Current and expected consumption levels, electricity prices, storage unit levels and the power output of the heat pumps inform the control strategy, which sets the power level of the cooling units and decides when to load or empty thermal storages.

3. Implementation

The model was built in the process-oriented modelling style. The persistent elements of the model such as storage units, chilling machines and the natural gas heaters were therefore modelled in DESMO-J as `a SimProcess`. The central element of the model is the control process. It is informed of changes in demand and electricity prices changes by means of `externalEvent`s. In addition, the storage units send the information on the attainment of maximum and minimum levels in the control processes.

The control process determines the operating output of the coolers according to the recorded strategy depending on the load condition of the storage units, current demand, the current and future electricity prices and the maximum output of the coolers. Furthermore it activates the dependent flows and initiates any heating by natural gas when necessary.

A characteristic feature of our approach is the modelling of flow changes by discrete events. For each storage unit the load condition, current loading rate and a time stamp are defined in order to model the energy input and outflow and the resulting temperature change. Whenever an event results in flow towards the storage unit, the time stamp is set for the current simulation time. Furthermore, the future event that the storage unit will be fully loaded, is noted in the event list for the future time point calculated. If the load process of the storage unit is interrupted by an external event, the storage unit performs an update of its load condition and deletes the event of complete loading from the event list. For further information on modelling in DESMO-J please refer to Page und Kreutzer (2005), and to Rasathurai (2012) on the specific model.

We chose the discrete-event simulation paradigm for this study due to the importance of discrete events in the system (reaching threshold levels, switching machines on and off), and we chose DESMO-J for the implementation due to its general applicability, flexibility and the extensive experience embodied in this type of simulation package.

4. Results

We simulated three main scenarios, each one of which contained the above-mentioned summer and winter scenarios as variants (sub-scenarios). First the actual state was reconstructed for use as a reference scenario. This reference scenario was used to validate the model on empirical data and also served as a reference for the other two scenarios. Then a scenario with a new control and the current electricity rate (high/low rate) was investigated (called "Scenario I"). Finally we studied a scenario with both the new control and a hypothetical smart grid rate oriented around the spot market (called "Scenario II").

4.1 Reference scenario

In the simulation – as in reality – the needs of the various consumers in the building determine the behaviour of the system.

Under the existing control strategy "stored cold" is used to cover the cooling demand. If the storage status sinks to about 50%, the control activates the cooling equipment and loads the cold tanks up to about 75% of their capacity. Waste heat is used on occasion. In the study period in December 2011 the rate with which energy was transferred to the waste heat storage was 50 kW on average, and in June 145 kW on average.

The electricity rate currently used is "ewz.naturpower" (ewz 2012) of the Zürich Electricity Works. It contains a high rate from Monday to Saturday, 6 am to 10 pm, and a low rate the rest of the time. Additional costs are incurred for the highest 15-minute consumption peak. However, the control strategy used in the reference scenario (as in reality) does not adapt to this simple time-of-use tariff.

The simulated energy consumption values were compared with real consumption data to validate the model. For December 2011 the simulation yielded a power consumption of 45,789 kWh, compared with a real consumption of 43,397 kWh. The simulated waste heat and gas consumption values of 30,603 kWh and 144,289 kWh were compared with real values of 35,142 kWh and 139,776 kWh.

For June 2012 the simulation yielded an electricity consumption of 101,485 kWh, a utilization of waste heat of 31,371 kWh and a gas consumption of 12,939 kWh. These values were compared with real values for an electricity consumption of 92,216 kWh, a utilization of waste heat of 30,638 kWh and gas consumption of 13,680 kWh.

We therefore assume that the model simulates the real system with acceptable accuracy. The small deviations result presumably from the idealizations and simplifications mentioned above.

4.2 Scenario I: New control strategy

In order to use the savings potential of variable electricity prices, the storage units have to be loaded during low prices and discharged purposefully during high prices. The new control strategy has the cooling units used intensively when it is apparent that the next electricity price change will be an increase. In this way the current cooling demand is to be covered directly and the cooling tanks loaded as fully as possible. In case the electricity price drops at the next change, the stored energy is used to cover demand. Not before the cooling tanks are exhausted is current demand then covered by operating the cooling machines. This strategy therefore assumes a minimum of information about price developments (rising/falling).

One component of this strategy is also to increase the capacities of the storage units nominally, as far as technical specifications allow. The temperature ranges used were increased as follows:

- Cold tanks from 11 – 12 °C to 5 – 12 °C (capacity from 30.23 kWh to 211.68 kWh)
- Hot water tanks from 36 – 40 °C to 36 – 41 °C (capacity from 16.28 kWh to 20.35 kWh).

In Scenario I this new control strategy was used on the existing electricity rate, i.e. the strategy adapts to the simple time-of-use tariff that differentiates between day and night power, making use of the extended thermal storage capacity.

4.3 Scenario II: New control strategy plus hourly pricing

The hourly pricing assumed in Scenario II uses hourly fluctuating prices oriented on the spot market prices, i.e., "real-time pricing".

Since, though, in our case no hourly pricing is offered to the final consumer, we designed a hypothetical dynamic rate ourselves. The bases for this rate were taken from the currently selected rate (ewz 2012) and the prices on the European Electricity Exchange in Leipzig (eex 2012). There auctions are held on the provision and purchase of electrical energy over the period of a certain hour of the following day (Madlener/Kaufmann 2002). After conclusion of the electricity auction the electricity provider knows the time-dependent market prices. Thus he could anticipate the prices with a dynamic rate and inform the final customers about the hourly electricity prices for the following day.

On the basis of the average prices per kWh that are paid by the provider to the exchange, and the average prices that the final customer has to pay, a factor results for the additionally incurred cost of transport, the profit margins of dealers, etc. The current spot market prices of the time under consideration were used to simulate dynamic electricity prices and multiplied with the factor mentioned above for the final customer price. Scenario II takes this hourly price as its basis and uses the same expanded control strategy as Scenario I.

4.4 Comparison of scenarios

The simulation results for the scenarios defined above are shown in Figure 2. There the average energy costs are shown in CHF per month for the three scenarios. The results show that especially in summer, when a great demand for cooling exists, considerable savings potentials exist both through the use of the new control strategy given the existing rates (17%) and through the new control strategy given dynamic prices (31%).

In winter, on the other hand, the savings attainable by producing cold and heat at times with low electricity prices is smaller and amounts to about 10%, which comes about in Scenario I.

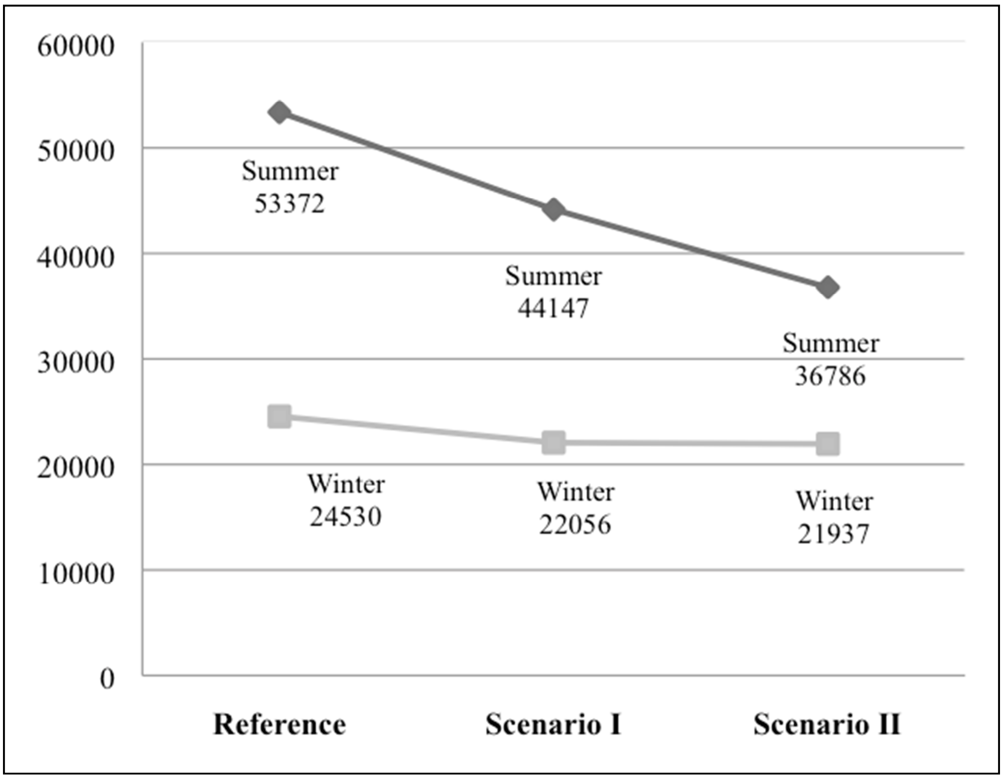

Figure 2
Simulation results; energy costs in CHF/month

5. Conclusion

An efficient control strategy of chilling machines (heat pumps) in combination with buffering storage of heat and cold could significantly reduce the energy costs of the IBM Switzerland office building, if the electricity rate were dynamized as in the simulation. These savings potentials result from the fact that the operation of the chilling machines is shifted to times of relatively lower electricity prices. This effect is essentially reinforced by expanding the capacity of the storage units by extending their permissible temperature ranges.

The savings potentials come about especially in the summer months, because at that time the demand for cold is especially high. Part of the potential is attributable to the new control strategy's optimal utilization of cheap night power. Utilization of further phases of cheap electricity – caused by having an electricity rate oriented towards the exchange – leads to a further savings. Possibly even greater efficiency potentials could be found if the time horizon for the loading strategy of the storage units were expanded.

Looking more closely at the power characteristic of the heat pump to better use its design point and the annually changing ambient temperatures could lead to a better heat utilization and make possible further savings especially in the winter months.

Even if the existing model provides a good estimation of the saving potentials, a more detailed model could certainly produce more precise results. Subsequent work will focus on improving the modularity and flexiblity of the model.

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