Model-based design of control strategies for a sophisticated building energy system in a school and sports complex

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Kurzfassung

Viele öffentliche Gebäude in Deutschland werden derzeit noch von konventionellen, oft technisch veralteten Anlagen mit Energie versorgt. Um die laufenden Kosten für Strom und Heizung des Gebäudes zu senken und dennoch die Investitionskosten niedrig zu halten, sind der Einsatz erneuerbarer Energien, eine Systemoptimierung in der Planungsphase sowie eine begleitende Optimierung der Anlagensteuerung während der Betriebsphase sehr wichtig. Die notwendige Komplexität heutiger Anlagenkonfigurationen und die Abhängigkeit regenerativer Erzeugersysteme von Umweltfaktoren erfordern dabei modellbasierte Untersuchungsansätze.

In diesem Beitrag wird ein solcher Prozess am Beispiel eines Schulkomplexes mit dem Sanierungsziel 80% Verbrauchseinsparung für Erdgas vorgestellt. Das System mit BHKW, Wärmepumpen, saisonalem Eisspeicher und lokalem Wärmenetz sowie dynamischen Heiz- und Kühllasten wurde unter Nutzung von SimulationX/Green Building modelliert. Für weitere Steuerungsoptimierung und ‚in-the-Loop'-Tests wurde das Modell als FMU exportiert.

Abstract

In many German public buildings heat and power are still provided by conventional systems. Often these are already worn out or poorly adjusted. To reduce running costs for electricity and heating and still keep investment costs low, renewable energy use, a system optimization during

the planning phase as well as operational monitoring and optimization of the system control algorithms are very important.

Due to the complexity of today’s energy system configurations and the dependence of renewable energy systems on environmental conditions, this is best done with model-based analyzing approaches.

In this paper such a process is described regarding the complete refit of a school and sports complex. The project goal is 80% reduction of natural gas making the school an example for future projects of this kind. This is achieved by using decentralized renewable sources for electricity as well as heat. The system which utilizes CHP, heat pumps, a local heating grid and a seasonal ice-storage-tank was simulated using SimulationX/ Green Building. For further optimization of control algorithms and ‘in-the-loop’-testing, the model was exported as functional Mockup Unit (FMU).

Introduction

The school and sports center Nägelsee consists of several buildings housing an elementary, primary and secondary school as well as multi-functional gym and indoor swimming pool. In the past, the buildings were connected by a local heating grid which was supplied by gas-fired boilers.

Currently a complete refit is taking place to improve energetic standards and to minimize running cost for electricity and heat. Project goal is to reduce natural gas demand by 80%.

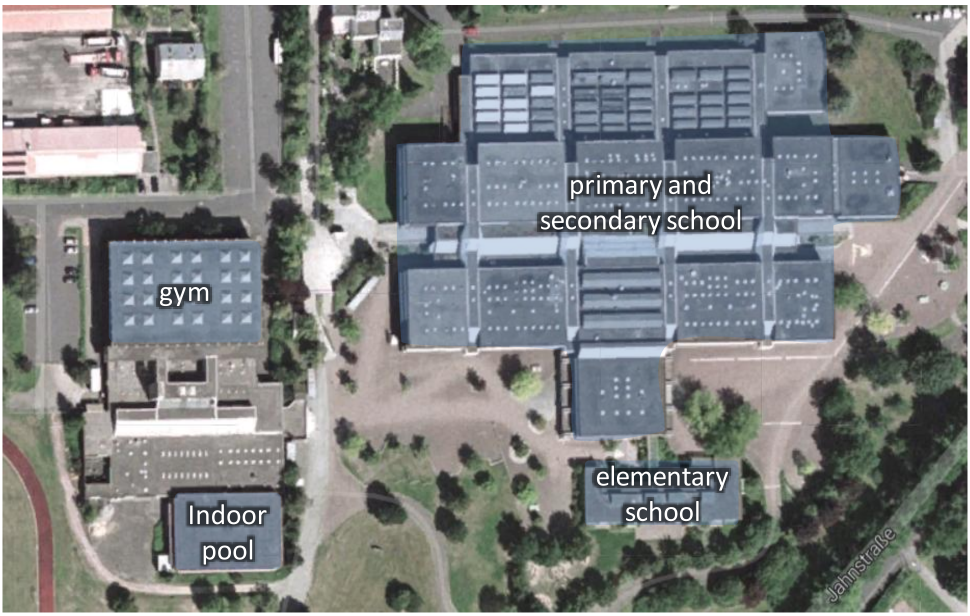


Figure 1: aerial view on the building complex [1]

To achieve this goal and to significantly reduce the carbon footprint the buildings as well as the technical utilities need a complete refit. The new concept incorporates modern building materials, renewable sources and a complex building automation system to reduce energy demand as much as possible. However, basic requirements are a reasonable investment and low future running costs. To meet these challenges, extensive scrutinizing and a suitable modeling environment are needed.

The whole project and the demonstrated technologies shall become a role model for a wide range of public buildings. In order to gain lots of experience, the project is assisted by a detailed monitoring campaign. One of the monitoring's most important tasks is to integrate the students and to make resource-efficiency perceivable.

New Building Energy Supply System

To meet such a challenging efficiency target, the new technical concept is based on heat pumps in combination with photovoltaic generators.

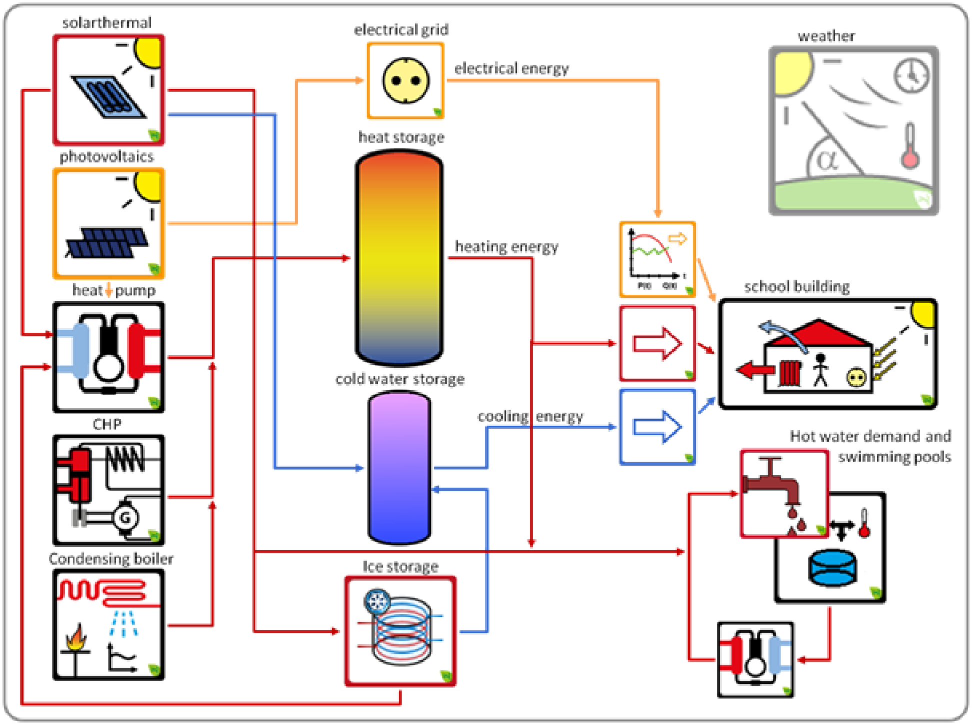


Figure 2: the new energy supply system of the school and sports complex

Heat sources are low temperature environmental heat absorborbers, a large seasonal ice storage tank or the cooling system depending on operational mode. These are complemented by a combined heat and power unit (CHP) for electricity production, a large hot water tank for daily storage, waste water heat recovery and condensing boilers as backup systems.

On demand side, energy consumption is minimized by adaptive lighting and a ventilation system with heat recovery which is controlled via air quality. To keep efficiency high, the heat is distributed at low temperature levels in different grids for heating (low), pool heating (medium) and domestic water (high) as well as cooling with temperatures just below environment temperature. One optimization goal is to provide cooling completely from the ice storage tank. Because of the high energy amount needed for the phase-change at 0°C, the recuperation of this tank is an efficient source for the heat pumps in winter.

Due to the complex system structure and the interactions between generation, storage and consumption as well as extensive control and optimization tasks, empirical control strategies are no more suitable. New holistic control approaches thus require detailed system modeling and simulation-based analyzes.

Modeling Concept

For modeling and first validation of the concept on systems engineering level SimulationX and Green Building Library were used. The component models like heat pumps or CHP were calibrated to manufacturer datasheets where available (c.f. [3]). New systems like waste water heat recovery were modelled according to functional concept and underlying physical processes. Some models like hot water storage or distribution and mixing valves were adapted to planned automation sensors' output characteristics.

The power, heat and cooling demand were simulated in a previous campaign [2]. These results were integrated into a versatile and interactive demand model.

Firstly, system model and resultant simulation results were used to optimize system layout, components' sizes and overall control strategy. All adaptions were based on main optimization goals, minimizing carbon footprint, running costs as well as required investments.

Additionally, the complete model was exported as a Functional Mockup Unit (FMU) [4] and is currently used by project partner Fraunhofer ISE to develop and optimize the adaptive control algorithms.

In a third step, the model will be calibrated with measured data from operational monitoring and used for additional simulation runs to better understand the system operation.

Simulation Model and first Results

Basically, most components of the overall simulation model were taken from the basic model set of SimulationX/Green Building library (e.g. stratified heat storage, simple cold storage, heat pumps, condensing boilers, CHP). All Green Building models have been designed regarding one holistic modeling approach [3], fast and accurate interactive system simulation, reduced internal model complexity, easy-to-handle parameter specifications. Other components which are not available in Green Building or were needed in a modified way were adapted or created new following the same modelling philosophy [3].

One main challenge was a physically as well as numerically accurate modeling of the complex hydraulics. Depending on current output temperature each heat producer is connected to the suitable temperature level at grid or storage tank. The consumers are modeled as power consumption trajectories. They 'choose' their required temperature from the three available grids. The requested power is translated into a volume flow and output temperature depending on input temperature.

Low temperature levels are preferred regarding efficiency reasons. Basic control strategy adjusts heat production to heat consumption at each temperature level, keeping volume flow through the storage tank at a minimum.

New pipe and pump elements were needed to simplify the task of matching more than fifty volume flows in the system. This is also important for the real system since most pumps are volume flow controlled to reduce pressure losses to a minimum.

The function of a consumer 'choosing' valve has been developed which analyzes the incoming as well as the required temperatures to choose, with some rules for hysteresis, the most appropriate heating circuit. In cases where no heating grid provides an adequate flow temperature the valve will choose the warmest one. As an example Figure 3: shows the function of the low temperature switching valve. In the shown case the reference temperature remains constantly at 40°C. At the beginning heating circuit 3 (HK3) is chosen for heat supply, since HK3 provides lowest overtemperature regarding reference level. Because of temperature drop at HK3 heat supply switches from HK3 to HK2. After about 15 hours the warmest temperature level deceeds reference temperature. From this time on always the warmest circuit is chosen. The resultant output temperature always stays at selected heating circuit's level.

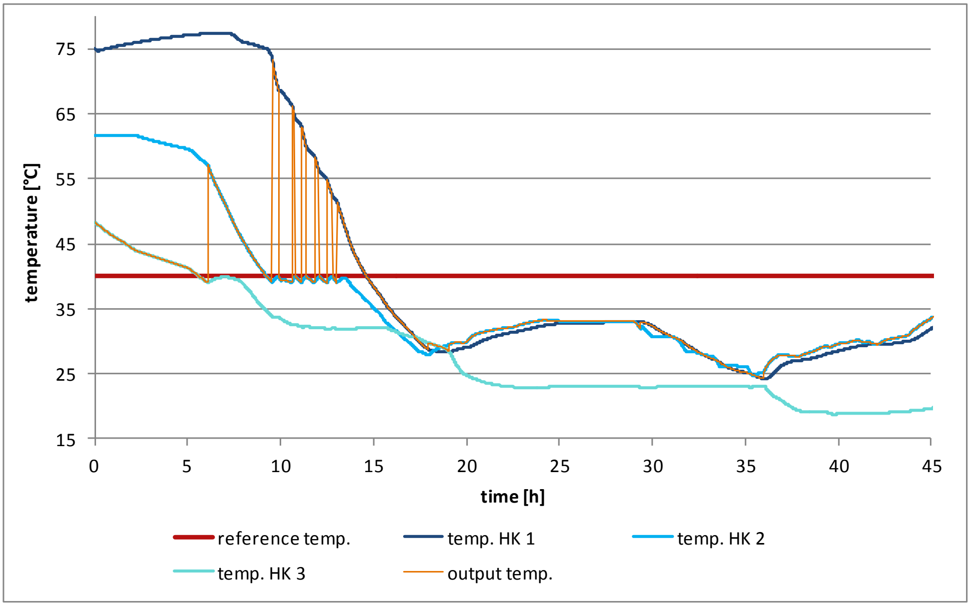


Figure 3: function of the temperature switching valve

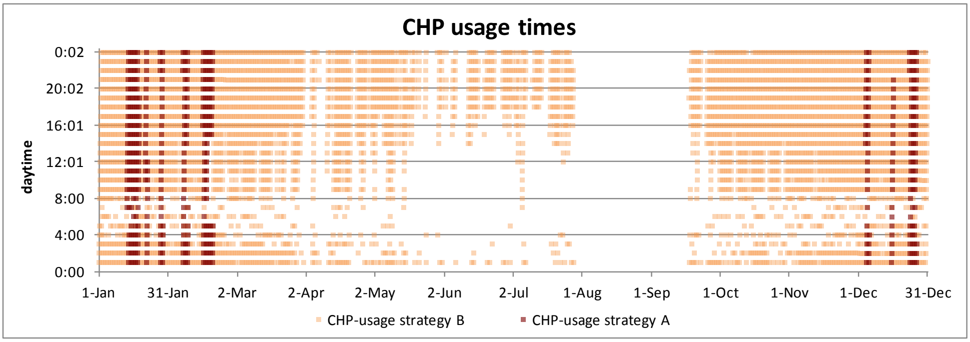
Another project internal development is the heat recovery from waste water. Here the accruing waste water volume flow is gathered in a collecting tank. Once this container is filled, the water gets transferred into another container, where it is cooled down to a preset level (here down to 2 °C), before it is going to be discharged into the public sewer. The transfer between the tanks and the heat dissipation can be triggered from outside the FMU, because the regained heat is used exclusively for heating the pool water, so it can be useful to first use the waste water heat when the pool content is too cold before another source is used. This model also was used in the beginning to find the optimal sizes for the two tanks as well as the heat pump depending on existing annual waste water amount and temperatures.

Other adapted models are the solar absorbers. They consist of black bundled tubes and are primarily used for heat exchange with the surrounding air. Due to the dark surface they absorb additional energy by solar radiation as well. In the complex system the absorbers have four main tasks:

- heat source for the three heat pumps,
- regeneration of the ice storage in the autumn months,
- direct heating of the pool water,
- nightly cooling of the cold storage.

Since SimulationX/Green Building only includes models for conventional solar thermal installations, either as flat or as tube collectors, another new model was developed using characteristic trajectories provided by the manufacturer. As an interesting result of system simulation, cases of absorber usage for direct heating can be left out regarding controller implementation because of low maximum temperatures.

A last additionally developed model refers to functionality of a seasonal ice storage tank. Basic modeling idea assumes in a simplified manner that the tubes of the heat exchanger inside the tank are long enough to enable a complete match of the ice storage temperature and the water-glycol mixture. Overall energy balance is calculated depending on heat and cold inputs and outputs as well as gains and losses to the surrounding air and soil. This way, complex (and data limited) 3D-modelling of the tanks internal piping and icing behavior can be avoided.



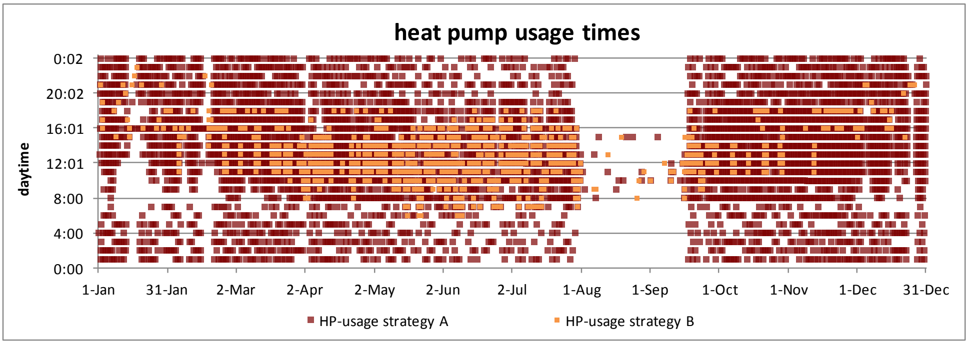


Figure 4: Visualization is important to easily interpret results; usage of CHP (top) and heat pump (bottom) for domestic water supply depending on operational strategy: A - dark, B - light [3]

For the given system configuration the calculations showed, that it is much more important to freeze the ice in winter for summer cooling than to reheat the storage in summer.

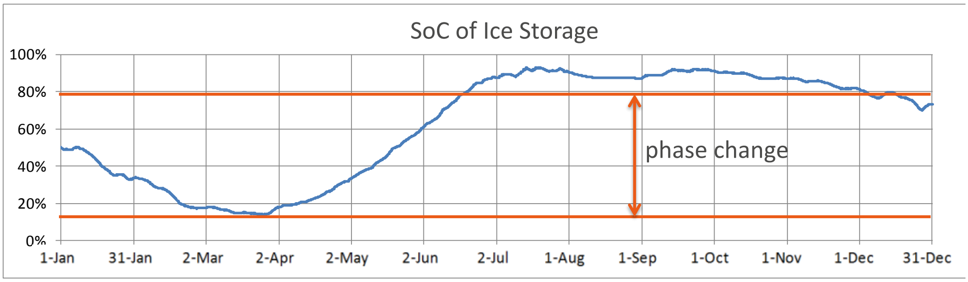


Figure 5: typical 'state of charge' of ice storage with melting heat

In the first simulation runs the input of the pre-simulated demand model was used as control input for heat and power production. Corresponding result were close to the optimal strategy. Later runs and test controllers used environment temperature, storage tank and pool as input values. This is not sufficient since small input changes have a huge impact on the system operation making the system instable and inefficient. Figure 4: shows CHP and heat pump usage with different storage temperatures as input value.

To simplify the model usage for testing control strategies, all of the scattered control parameters and sensor values were collected into a control-API block. To this block, either a simulated controller in Modelica code (i.e. the model validation controller) or an external controller can be connected via FMI. For the optimization runs of Fraunhofer ISE, whole model is exported as FMU for Co-Simulation [4]. For these test runs, an external controller uses the same API to connect to the model internal sensors.

Monitoring and Validation

Previously presented paragraphs show analyzes and results of a currently ongoing research project. Currently, building reconstruction and technical refit take place. First monitoring values are currently evaluated. Based on the monitoring data collected in the following months, the component models will be validated in detail. This is especially important regarding the environental heat absorbers and the ice storage tank.

The heat absorbers are the main source for heat pumps and have a huge impact on overall system efficiency. Yet modelling their related shadowing, boundary layer and connectors is not viable without FEM and within the given timeframe. Therefore the models will be refined as a white box based on measurements. Another major goal of the monitoring is the idenfication of control problems and system parameters for later optimization to achieve the overall goal. This way, an efficient technical solution for similar buildings can be defined which costs even less.

Summary

This paper shows how SimulationX and the ‘Green Building’ Package were used to model and analyze a system of innovative power supply components and storages in a complex building energy system.

The problem of manifold connections and operating modes could be solved by creating new abstraction models which will significantly reduce the effort in modeling complex hydraulics. The resulting models are numerically stable enough to export them via FMI for further control optimization.

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- TU Dresden, Building Energy Systems and Heat Supply
- EA EnergieArchitektur GmbH
- EA Systems Dresden GmbH

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